Forestry Commission

# REPORT ON FOREST RESEARCH 1996




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For the year ended March 1996

Forestry Commission, Edinburgh

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# *Introduction*

*by Jim Dewar, Director Research*

The Forestry Commission Research Division is the leading organisation dedicated to the conduct of research for the benefit of forestry in Britain. Research is also conducted into the growth of individual trees whether in hedgerows or the urban street, making use of the expertise of Division staff in tree pests and diseases, establishment and growth.

This Annual Report gives an account of some of the current topics being researched by staff within the Division but by being more selective the subjects are covered in more detail than in previous years. A list of the Division's major research programmes is given in Appendix 3.

Most of the Division's work is funded by the Forestry Commission but around 13% is paid for by other Government Departments, the European Union and the private sector. A list of contracts for other research customers is given in Appendix 5.

Following an internal review the Division was separated from the Forestry Authority with effect from 1 October 1995 and Director Research now reports to the Director General of the Forestry Commission. This separation is intended to reinforce the customer/contractor principle as the future basis for funding work undertaken by the Division on behalf of the Forestry Commission. Application of this principle is serving to clarify the research needs of the customer and ensure that the research undertaken is relevant to these needs. The principle is also intended to give greater flexibility for the funder in selecting research programmes but it is clear that exercise of this flexibility at a time when research funds are declining will impose additional pressures on the Division and make it difficult to maintain long term research programmes. Reconciling the need for continuity in research effort and changes in research priorities will be a major challenge for the Division under this new arrangement.

In October 1995 the Technical Development Branch of the Forestry Commission joined the Division. This brings together the researchers with those concerned with the development and practical application of new techniques on a forest scale. The Surveys Branch of the Forestry Commission joined the Division on 1 April 1996. Other organisational changes in train at the end of the year under report and which came into effect at 1 April 1996 are:

- the creation of Technical Support Units to manage the Field Stations as a service to all researchers on a customer:contractor basis;
- the closure of Forest Products Branch with the transfer of responsibilities for commissioning forest products research to the Forestry Authority;
- the amalgamation of Silviculture (South) and Plant Production Branches into a new research team 'Silviculture and Seed Research Branch'.

Along with comparable research establishments in the agriculture, horticulture and fisheries sectors of publicly funded research, the Forestry Commission's Research Division was subject to a Prior Options Review. This review was led by Mr David Henderson-Howat (FC Forest Policy Division) and supported by Mr Peter Wilson (Chief Executive, Timber Growers' Association), Mr Huw Davies (Deputy Chief Conservator, Wales) and Dr Andrew Rushworth (Scottish Office) with Mr Chris Nixon (FC) as Secretary. The Prior Options report went to Ministers in March 1996 recommending that the Forestry Commission's Research Division become an Executive Agency of the Forestry Commission. Ministers have since announced that this recommendation has been accepted with a planned implementation date of 1 April 1997.

The Advisory Committee on Forest Research provides guidance to the Commission on the quality of its research activities and the direction research should be taking. A new Committee was appointed in January 1996 under the Chairmanship of Professor Hugh Miller (see page ii for the full membership). The Committee appointed two Visiting Groups to look at the Division's work on forest pathology and biodiversity research.

The Pathology Visiting Group was led by Professor Peter Blakeman (Department of Agriculture for Northern Ireland/Queens University, Belfast) and supported by Dr Dave Houston (US Forest Service, Connecticut) and Dr Alan Rayner (School of Biology and Biochemistry, University of Bath). The Group recognised that the Division's Forest Pathology Branch is internationally renowned and provides a very sound basis for investigating diseases and disorders threatening Britain's forests. They recommended increased emphasis on molecular analytical techniques and the related support services and emphasised the need to maintain a critical mass of experienced pathologists at a time of increasing threats to the well being of Britain's trees and woodlands posed by climate change, the introduction of new organisms, and other stresses on trees.

The Visiting Group to the Biodiversity Research Programme was initiated during this report year under the chairmanship of Professor Richard Cormack (University of St Andrews) supported by Mr Rob Guest (Forest Enterprise) and Professor Michael Usher (Scottish Natural Heritage).

The Biodiversity Research Programme is at an early stage but, owing to its multi-disciplinary nature, the Advisory Committee recommended that a thorough external review should be undertaken to guide development and progress and ensure that it had every chance of meeting the aims of British forestry in support of the government's sustainable forestry programme and sustainable development strategy. The Group reported towards the end of the year under review and their report was considered at a subsequent meeting of the Advisory Committee.

We are most grateful to members of both Visiting Groups for their work and to past and present members of the Advisory Committee who have given so freely of their time.

This Committee (FRCC) brings together all the principal sponsors of forestry research of which the Forestry Commission itself is the largest single funder. FRCC now meets twice a year and seeks to avoid overlap and duplication by funding organisations, develop common strategies and ensure adequate attention to key issues. Sponsors funding intentions are reported.

During the year Mr David Foot (Head, Forestry Authority) assumed the chairmanship following the retirement of Mr Roger Bradley.

Technology Foresight Panel No.11 Agriculture, Horticulture and Forestry, actively took forward its work of 1994 and appointed a sub-group under the chairmanship of Professor Julian Evans to address the medium and long term research needs in the forestry and timber industry. Preliminary conclusions of this group are the need to focus on quality both in the growing of trees and in the manufacture of wood products and to seek ways to harness further the many diverse benefits provided by Britain's trees and woodlands. The explicit recommendations of Technology Foresight are incorporated into the *Forward look of government funded science, engineering and technology.*

On a like for like comparison, i.e. excluding Technical Development Branch and Surveys, the total number of staff in the Division declined from 295 at 1 April 1995 to 274.5 at 31 March 1996. Eight of the reductions took place as a result of an FC-wide voluntary early retirement scheme. At the end of March a further fourteen staff had been offered early retirement. While this loss of experience and expertise will be difficult to replace it is hoped that some opportunities will be created for recruiting younger people into the Division and exercising the flexibility looked for by funders.

During the year two members of staff were honoured through the award of personal chairs. Professor Julian Evans, Chief Research Officer South, was awarded a chair by the University of North Wales, Bangor. Professor Clive Brasier, Pathology Branch, was similarly honoured by Imperial College, University of London. Professor Brasier has also gained an individual merit promotion to Grade 5. An article on his current and recent work on Dutch elm disease is a major feature of this Report.

# *Farm Woodland Research in the Lowlands of Britain*

*by Ian Willoughby, Robert Matthews and Janet Methley*

The Government is supporting an expansion of forestry through the Woodland Grant Scheme and the Farm Woodland Premium Scheme. A significant proportion of all new planting is likely to take place on lowland farms, and will need to be managed by farmers as part of their agricultural business. They need specialist forestry advice and new techniques for establishing and managing woodlands. The advice and techniques need to be readily understood and applied by farmers using, where possible, existing expertise and equipment.

Research on farm woodlands aims to provide advice on:

- the prediction of timber yields for a range of species on lowland sites;
- establishment techniques;
- control of weeds on former agricultural land;
- alternative silvicultural systems.

Figure 1 summarises some of the main topics under investigation.

This article reports on progress in two research areas: the development of yield models for a number of tree species with the greatest potential application in lowland Britain, and the assessment of the advantages and disadvantages of establishing woodlands by direct sowing.

An economic assessment of farm woodlands requires an estimate of potential timber production. Most afforestation this century has been in the uplands and there is good information on the potential productivity of tree species on upland site types. By contrast, land coming out of agricultural production is likely to be on better quality lowland sites. There is considerable potential for forestry on better quality agricultural land but more information on species performance is needed to improve planning and economic analysis of afforestation schemes on these sites. Before taking the decision to plant, farmers and forest managers need site information to enable them to:

- assess the value and yield potential of different tree crops on agricultural sites;
- compare benefits of timber production with other forestry benefits for farmers;
- select the most suitable tree species for a given site type.

The assessment of potential yield of tree species, prior to planting, requires a predictive system based on the characteristics of the site.

Research funded jointly by the Forestry Commission and Ministry of Agriculture, Fisheries and Food has produced site yield relationships for ash, beech, oak, poplar, sycamore, Douglas fir, hybrid larch, Corsican pine and Norway spruce (Matthews *et al.*, 1996).

The existing method of site classification for forest inventory and production forecasting is based on the yield class system. This system requires measurements to be made of trees already growing on the site of interest. One of the aims of this research was to identify primary site factors which could be used to predict potential yield before planting takes place. An additional requirement was that these site factors should be easily understood by farmers and other growers, and also be easily measured. A review of earlier site yield studies identified three site factors that met these requirements:

- major soil groups;
- potential soil moisture deficit;
- accumulated temperature above 5.6 °C.

The geographical distribution of the major soil groups, accumulated temperature and potential soil moisture deficit were established using a combination of maps and the LandIS database maintained by the Soil Survey and Land Research Centre, Silsoe.

The project made extensive use of existing records of forest growth and yield including Forestry Commission permanent and temporary mensuration sample plots. The site factor maps and the LandIS database were used to classify the yield data according to site type. This revealed a number of site types for which no data have been collected. Further field work was carried out to obtain yield data for these site types.

Figure 1. Research areas particularly relevant to farm woodlands.

## Species selection

- Selection and improvement of ash and sycamore (with MAFF)
- Ecological site classification
- Selecting the most appropriate tree species for farm woodland sites
- Clonal performance of various clones of poplar
- Development of site yield models to predict yield class of farm woodland species from site factors. (With MAFF)

## Establishment

- Overcoming seed dormancy of farm woodland species
- Ground preparation for farm woodland establishment
- Vegetation management research-
  (a) Use of herbicides to control unwanted vegetation
  (b) Studies into alternatives to herbicides
- Improving planting stock physiology (with DOE)
- Species / cultivation /vegetation interactions on farm woodland sites in Scotland (with SAC)
- Developing outputs and costs for farm woodland operations
- Improving work methods for farm woodland operations
- Evaluation of suitable machinery for farm woodland situations, including adaption of existing agricultural equipment

## Maintenance

- Tree protection in farm woodlands
- Population ecology of deer in agricultural landscapes
- Impact of shelter in the lowlands

## Harvesting

- Evaluation of suitable machinery for farm woodland situations, including adaption of existing agricultural equipment
- Testing machinery for harvesting short rotation energy coppice

## Alternative Silvicultural Systems

- Alternative silvicultural systems for new farm woodlands-
  (a) Direct sowing of tree seed
- (b) Short rotation energy coppice (with ETSU, Mensuration, Silviculture North, ERB)
- (c) Natural colonisation
- Crofter forestry
- Design of shelterbelts on farms
- Agroforestry (with EU, Macaulay Land Use Research Institute, IGER and University of Wales)

### Key to Branches

**Tree Improvement Branch**
Selecting and improving planting material for GB conditions

**Silviculture and Seed Research Branch**
Research to improve seed handling, plant production, establishment and silvicultural practice mainly in lowland Britain

**Silviculture North**
Research to improve silvicultural practices in northern and western Britain

**Technical Development Branch**
Improving safe and cost effective forestry practice through work and method study and machinery appraisal

**Mensuration Branch**
Developing and improving methods for measuring and predicting forest growth

**Woodland Ecology Branch**
Enhancing biodiversity of woodlands and limiting impact of browsing animals

**Environmental Research Branch**
Research and environmental monitoring for sustainable forest practices

Refined estimates of the three primary site factors, as well as estimates of secondary site factors, were obtained for each sample plot site. Secondary site factors included:

- elevation above sea level;
- rainfall (summer and annual);
- continentality;
- wind exposure;
- soil pH;
- soil depth.

Three types of model were developed for predicting yield class from site factors namely nonlinear, linear and categorical models. Nonlinear and linear models have the advantages of mathematical simplicity and the ability to extrapolate predictions of yield class to site factor combinations for which no yield data are available. It was recognised, however, that the construction of these models, particularly nonlinear models, depended heavily on assumptions about relationships between yield class and site factors. Categorical models do not require so many assumptions to be made, and these were used to investigate the effects of relaxing assumptions about site yield relationships on the goodness-of-fit of calibrated models.

An initial set of over 750 linear models and 750 categorical models were fitted to the data for a given species. The models were 'maximal' in the sense that each model contained a complete combination of primary and secondary variables. Both pure linear models and linear models with quadratic terms, and both 'main-effects' categorical models and 'full' categorical models (with interactions) were fitted. In addition to the linear and categorical models, a suite of approximately 25 nonlinear models and mixed nonlinear-linear models was fitted to the data for a given species. For each model, a series of summary statistics was calculated including the $R^2$, adjusted $R^2$ and Q statistics (Matthews *et al.*, 1996). The $R^2$ statistic measures the proportion of the variation of the data accounted for by a given model. Models with high $R^2$ values are preferred, but may contain unnecessary parameters.

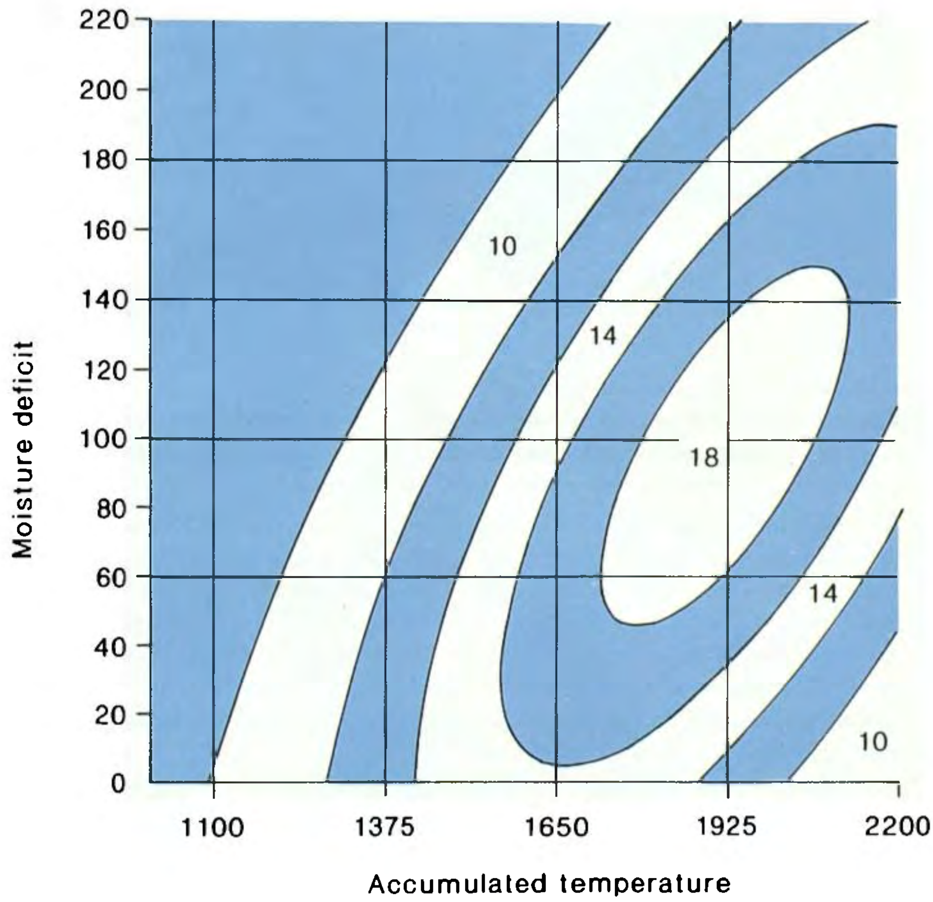



Figure 2. Predicted contours of General Yield Class with respect to accumulated temperature and moisture deficit for Douglas fir.

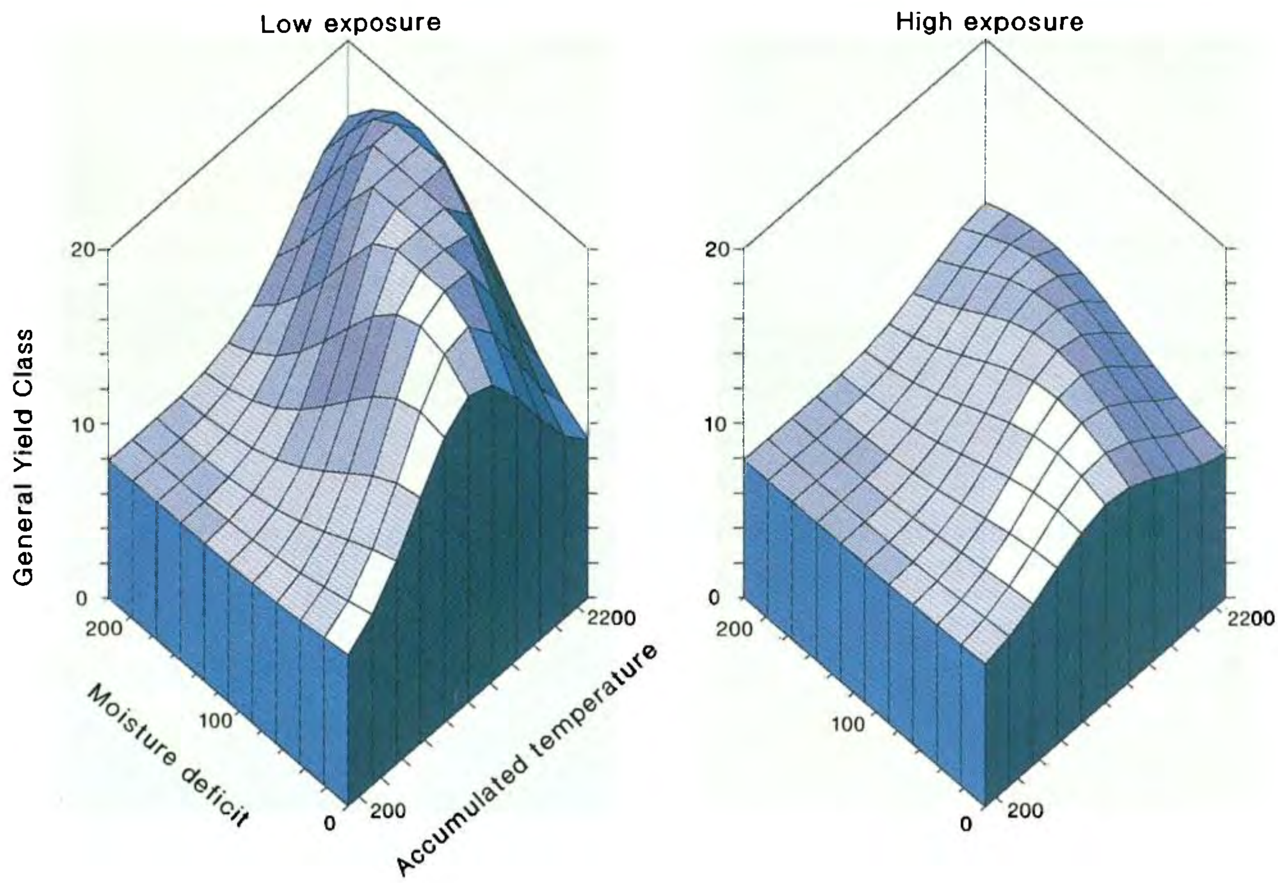



Figure 3. Three dimensional representations of General Yield Class contours with respect to accumulated temperature and moisture deficit for Douglas fir, showing effect of wind exposure score.

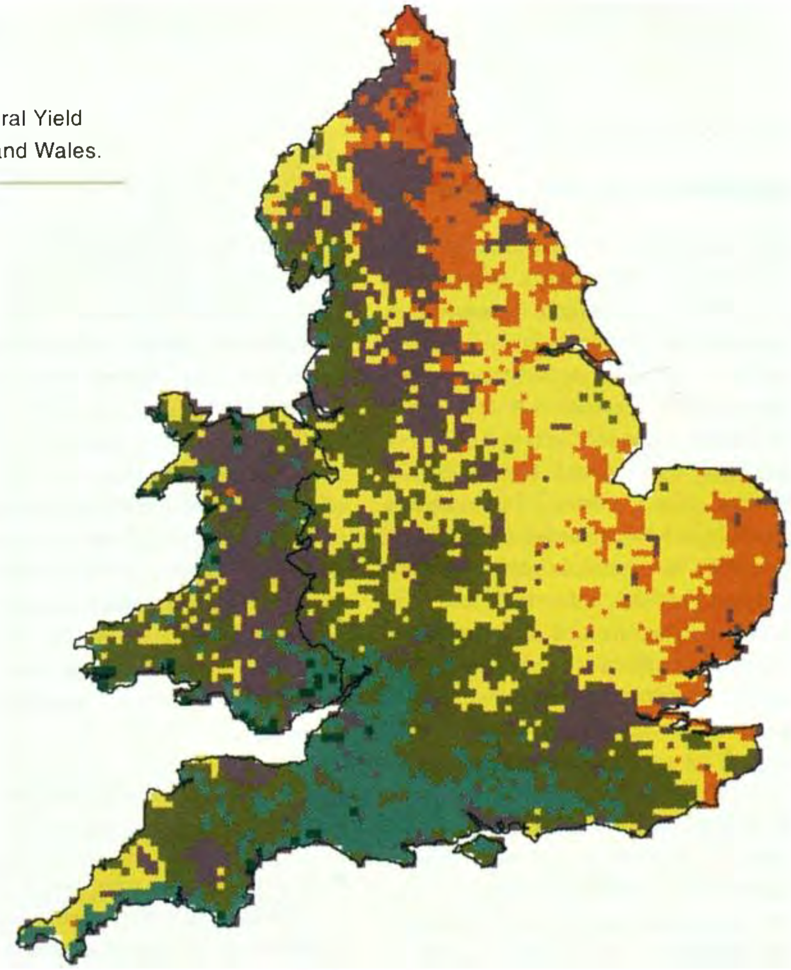
The adjusted $R^2$ and Q statistics are 'value for money' indices based on a balance between the number of parameters in a model, and the variation accounted for. High values of adjusted $R^2$ and low values of Q are preferred. For each species, eight candidate models were selected from the initial sweep of over 1500 models. Each of the eight candidate models was optimised by a process of 'backward elimination', followed by stepwise regression involving all candidate variables, using the Q statistic as the main criterion for rejecting or accepting model terms. At the conclusion of this optimisation phase, the best categorical, linear and nonlinear models were compared, and the best overall model selected.

For six out of the nine species, final model selection was straightforward. Nonlinear models were selected for four species (beech, oak, sycamore, Corsican pine) based on lowest Q, combined with high $R^2$ and adjusted $R^2$. For a further two species (ash, Norway spruce) linear models were selected based on the same criteria. For the remaining three species (poplar, Douglas fir and hybrid larch) nonlinear models were selected following a more subjective comparison of candidate models.

The predictions of the site yield models finally selected for each of the nine species can be presented in a number of ways. Figure 2, for example, shows contours of General Yield Class for the Douglas fir model with respect to the primary site variables of accumulated temperature and moisture deficit. The contours suggest that optimal conditions for the growth of Douglas fir are in the region of 1925 day-degrees C accumulated temperature and 100 mm moisture deficit, a combination that could be described as 'warm and moist'. Secondary site variables may also affect the magnitude and range of the contours. In order to draw the contours in Figure 2, the assumed wind exposure score (Quine and White, 1993) has been held constant at 10. For this particular combination of primary and secondary site variables, a GYC of 18 is predicted.

Figure 3 illustrates how the GYC contours for Douglas fir are modified by wind exposure score. For sheltered sites (windiness score 5) the GYC contours rise to a maximum of about 22. For exposed sites in lowland England and Wales (windiness score 20 in this example), the GYC contours are flattened out such that the maximum predicted GYC is only about 12. Minimum GYC is not strongly affected by wind exposure, but this feature is not universally observed for all secondary variables in all models. Using gridpoint estimates of agroclimatic variables, it is possible to generate maps showing the predicted GYC for tree species across lowland England and Wales. Two examples of such maps are shown in Figure 4 for Douglas fir (Figure 4a) and Corsican pine (Figure 4b).

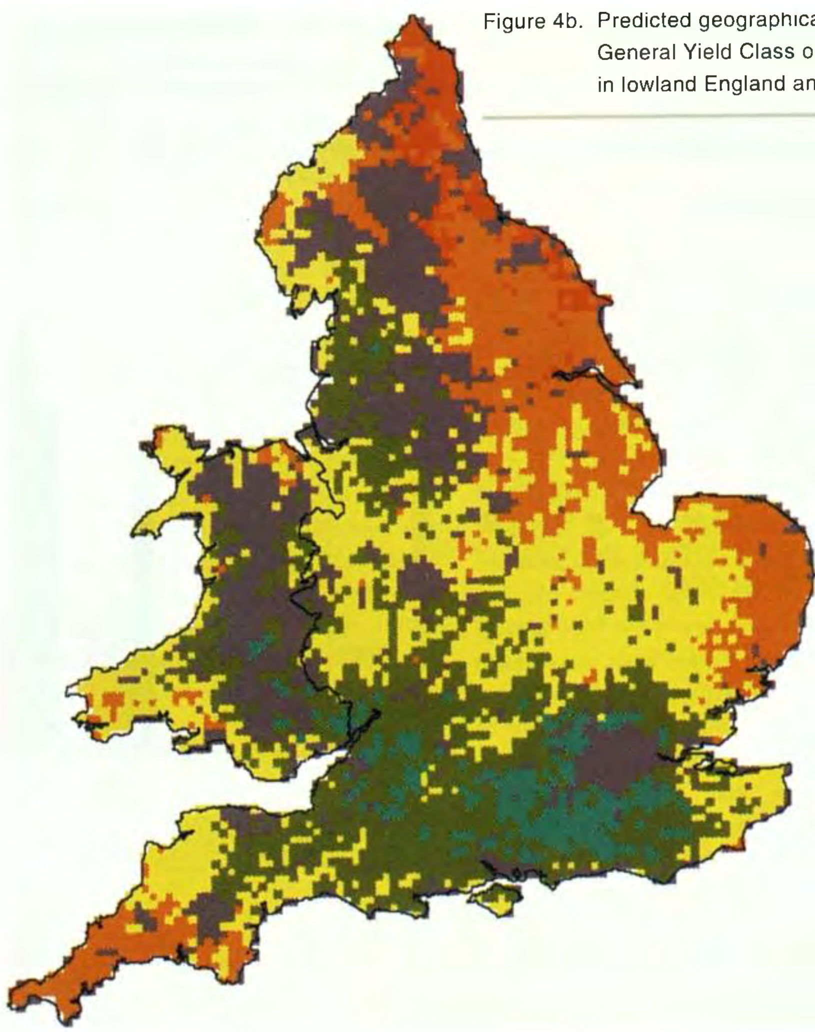
Figure 4a. Predicted geographical variation of General Yield Class of Douglas fir in lowland England and Wales.



General Yield Class

- 20
- 18
- 16
- 14
- 12
- 10
- **Not in study area**

Figure 4b. Predicted geographical variation of General Yield Class of Corsican pine in lowland England and Wales.



The site yield models have wide applications at the land use policy and regional planning level, for example production forecasting in private sector woodlands, as well as providing advice to farmers. The site classification system, based on primary and secondary site factors, has proved to be a robust tool for construction of site yield models, and has the potential to be extended to the uplands and the rest of Britain. This research has been limited by poor information on the influence of soil properties on forest yield. Better data and understanding of soil properties in relation to soil groups is a subject for future research. On the other hand, the research has benefitted from the strength of existing, nationally compatible, periodic data on the growth and yield of trees that have been collected to a consistent standard since the beginning of the century. Further work is required to improve the accuracy of the site yield models described above at field and farm level.

Much of the research on establishment of woodlands is based on the premise that rapid establishment is usually the most cost-effective technique. Whatever an owner's objectives, be they mainly conservation, recreation or timber production, rapid creation of a woodland environment should be the primary aim. Often this requires relatively intensive initial management involving for example planting well balanced healthy transplant stock at 2500 stems per hectare or greater, and practising effective weeding and protection. However, there may be other options which require less intensive use of resources including the use of herbicides. Research is continuing on alternatives to planting, including natural colonisation and natural regeneration. Direct seeding of tree seed is an example of such a research area within the farm woodlands programme, the initial results of which were collated in 1995/96.

Direct sowing or direct seeding is the process of artificially sowing tree seed directly onto the final site for the proposed woodland.

Direct seeding is an ancient technique Harmer and Kerr (1995) cite numerous references which describe a variety of techniques. For example, Evelyn (1670) advised *'Dig or plow a parcel of ground, as you would prepare it for corn, and with the corn . . . sow also a good store of keys . . . take off your corn or seed in its season, and the following year it will be covered in young Ashes'.*

The Forestry Commission has carried out over 70 experiments into direct sowing since the 1920s (Stevens *et al.*, 1990). The main conclusion from this work was that problems of predation of seed, unpredictable germination and vegetation competition were most easily managed within forest nurseries. On this basis they advised that the conventional establishment practice of planting trees raised in a forest nursery was preferable to direct seeding.

In recent years increased tree planting on former agricultural land has led to a renewed interest in the direct seeding technique. Watson (1994) described a system similar in many ways to that described by Evelyn (1670), involving the under sowing of arable crops with tree seed. Advantages claimed for the system are:

- it is cheap, with no protection or weeding operations required;
- high densities of trees may become established, giving a greater potential for the production of quality broadleaved timber and more rapid creation of a woodland environment than conventional planting;
- it uses techniques and equipment that are familiar to farmers.

Watson's method is being practised commercially on a few sites in southern England, two of which have been monitored by the Forestry Commission since they were sown. Information on machinery and costs obtained from the monitoring of a further two sites is given in Drake-Brockman (1995).

One of these sites, a fertile lowland area of 10 ha near Ledbury in Gloucestershire, was broadcast sown (except the oak which was drilled) in March 1993 with 103 000 seeds/ha of ash, sycamore, Norway maple, oak, cherry, field maple and hazel in a 35:24:15:10:9:5:2 mixture. There was also some pear seed present in a sludge applied to the site. Thirty randomly located permanent 3 m x 3 m monitoring plots were established, and at the end of each growing season the number of seedlings were counted (see Figure 5).

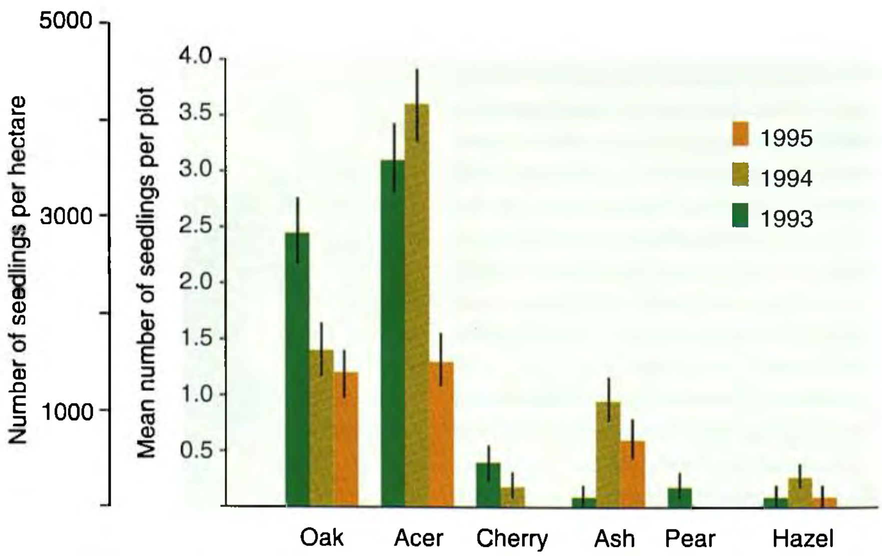



Figure 5. Ledbury direct seeding experiment - seedling numbers.

Seedling height and browsing damage were also assessed at the end of 1995. The site was not fenced and evidence of significant rabbit activity was observed throughout the period.

At both the Ledbury site, and a second site near Cirencester (data not presented), there has been a general downward trend in seedling numbers over the years. This is less apparent at the Cirencester site, but it is likely that seed fall from surrounding woodland supplemented numbers of ash and sycamore seedlings.

Analysis of plot count data using general linear models with Poisson errors showed significant differences between years. Numbers of oak, cherry and *Acer* spp. declined by nearly 50% after the first year, probably as a result of browsing from rabbits and competition for moisture from weeds. Numbers of ash increased in the second year due to germination of previously dormant seed, a common phenomenon.

Height growth was also poor at both sites. After three seasons growth average seedling height was only 18 cm at Ledbury, whereas effectively weeded and protected transplants could by comparison be expected to be over 1 m.

The objective of Watson's system is to achieve a stocking density of 10 000 trees/ha and to rely on high initial seedling density to overcome the pressures of browsing and weed competition. This tends to challenge modern silvicultural thinking advocating suitable weed control (Davies, 1987) and protection from browsing (Kerr and Evans, 1993) of planted trees.

At Ledbury after 3 years 3370 seedlings were present, with an average height of 18 cm. These stocking levels would be acceptable for protected, weeded, rapidly growing transplants.

However, the direct sown seedlings exhibited a very patchy distribution - areas of dense seedling growth were interspersed with large stretches of ground with no surviving seedlings. At this stage of monitoring it is difficult to predict whether or not 3-15 000 direct sown plants that are browsed and weed stressed, will lead to a healthy vigorous woodland of at least 2500 stems per hectare, of unforked evenly spaced trees. A woodland of carefully planted, protected and weeded transplants would probably be fully established within 5 years on a similar good quality site. It is difficult to predict how long it will take a woodland to establish using a system which relies primarily on high numbers of direct sown seeds to overcome the pressures of browsing and weed competition.

## Experiments on direct sowing

Because of this uncertainty, the Forestry Commission Research Division established three further experimental trials. Two used non-dormant oak and Scots pine seed, at sites near Barton and Desford in the National Forest in the Midlands. Dormant sycamore and ash were used at Neroche, Somerset, and the performance of both untreated and pretreated seeds were compared. The effects on seedling height and survival from sowing an agricultural cover crop (linseed at 50 kg/ha at Barton and Desford, and spring wheat at 200 kg/ha at Neroche, harvested at end of the first year), non-intervention (after initial ground preparation and sowing), and the maintenance of weed-free conditions through the use of herbicides, were investigated at all three sites. The effect of fencing individual 10 m x 10 m plots on seedling survival and growth, was also tested at the first two sites.

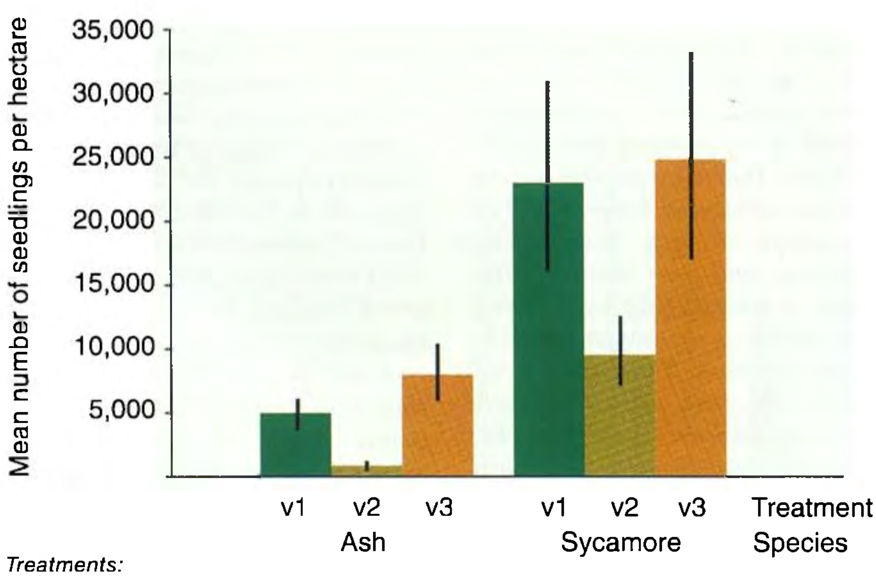
From an estimated 100 000 viable seeds per hectare sown in May 1994, an average of 60 600 oak seedlings per hectare was determined by sampling at the end of 1995 at Barton. Average height at the end of 1995 varied significantly ($P \leq 0.06$) with herbicide treated weed-free plots showing significantly greater growth (mean height of 14.0 cm) than the agricultural cover plots (mean height of 10.0 cm). Far fewer Scots pine seedlings survived at Barton - 4860 per hectare on average - although only 62 000 viable seeds per hectare were sown. Numbers of Scots pine seedlings fell dramatically to an average of 1530 per hectare by the end of 1995. There were statistically significantly more seedlings ($P < 0.05$) in the herbicide treated plots (3100 seedlings per hectare) than the no weed control (950 seedlings per hectare) or agricultural cover crops (550 seedlings per hectare).

## Desford

Watson (1994) suggested that the presence of weed vegetation can act as an alternative feeding source for rabbits, and also as a source of side shelter, and hence may protect tree seedlings. This appears to be contradicted by results at Desford (seedlings sown in April 1995) where there was a significant interaction ($P < 0.05$) between fencing and vegetation treatments - there were 240% more seedlings in the fenced than the unfenced plots where there was no weed control. Overall beneficial effects for fencing were not proved statistically, but there is no doubt that browsing can seriously reduce tree growth and survival (Stevens *et al.*, 1990).

At the Neroche site, 210 000 viable seeds per hectare of ash or sycamore were sown in May 1995. Within both the pre-treated ash plots where the seed was non-dormant and likely to germinate in the first year, and the sycamore plots, the cover crop treatment resulted in statistically fewer seedlings surviving ($P$<0.001) at the end of the growing season (625/ha ash within the cover crop plots, compared to 6563/ha in the control plots - see Figure 6). The wheat variety used grew relatively late in the season, and during the prolonged dry spell in April-June, was still actively growing, and hence competed strongly for moisture with emerging seedlings.

It may be premature to discount the benefits of cover crops on the basis of the three recently established experiments reported, but it seems clear that trees derive more benefit from weed-free conditions than from an agricultural cover crop.




*Treatments:*

v1 = control, no vegetation management.

v2 = establish cover crop of spring wheat, harvest at end of first year.

v3 = maintain weed-free conditions using herbicides.

Figure 6. Neroche direct seeding experiment - seeding numbers.

Although direct seeding is generally less reliable than planting, initial results from these recently established trials suggest it is worthy of consideration as a method of establishing woodland on lowland ex-agricultural sites provided:

(a) appropriate species are chosen, (b) adequate protection is given, and (c) effective weed control is practised. The essential requirement for (b) and (c) challenge the argument that sowing large numbers of seed alone is sufficient to establish woodland. Detailed recommendations for the use of direct sowing are given in Willoughby *et al.* (1996) and Willoughby (1996).

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# *Developing Cost-Effective Methods for Successful Restocking*

*by John Morgan and Helen McKay*

The area of restocking in Britain's forests is expected to double over the next 15 years and by the middle of the next century the majority of timber produced in Britain will be supplied from second rotation stands. The minimum recommended density at canopy closure for Sitka spruce is 2250 trees per hectare (i.e. more than 90% survival at 2 m spacing) to ensure that the timber meets the strength classes required for constructional grades of timber (Brazier and Mobbs, 1993). An aspect of continuing concern is that surveys have indicated that achieved establishment is often substantially lower than the target density.

Silvicultural principles for successful restocking have been summarised by Tabbush (1988). Factors such as plant quality, storage, lifting date, handling, cultivation and weeding have all been tested in field experiments. These factors all interact so that the success of restocking depends on their cumulative effect (Figure 2). Current experimental work aims to explore these interactions so as to recommend the most cost-effective establishment systems.

On most restocking sites, regular 2 m spacing can only be achieved following site preparation. The cost of cultivation can be justified by lower overall establishment costs, compared with those on uncultivated ground (Figure 1), due to savings in the cost of planting, beating up, protection and weeding. On certain soils, there may be longer term benefits from appropriate cultivation. For instance, on peaty gleys, excavator mounding combined with drainage can improve stability by lowering the water table level and increasing the rooting depth (Ray and Morgan, 1996).

Cultivation techniques were reviewed by Tabbush (1988) and by Nelson and Quine (1990). More detailed recommendations are being prepared for publication in 1997. Further research is now limited to later assessments of long-term experiments which began in the 1980s and evaluation of new techniques in response to industry demand. For example, in Argyll where slopes are too steep for conventional machinery, a walking excavator can be used to produce hinge mounds (Figure 3).

We carried out an experiment to compare hinge mounding and direct planting using three Sitka spruce plant types. Since ground preparation should alleviate site constraints and cause minimal environmental impact, we also looked at sediment yields due to cultivation. More sediment was collected beneath mounded plots (77 kg/ha) during the first winter but the difference was not statistically significant from direct planting (53 kg/ha). Up to 10 tonnes of soil per hectare have been eroded from plough furrows on a similar steep site.

There was a significant interaction between the survival of different plant types and the type of site preparation

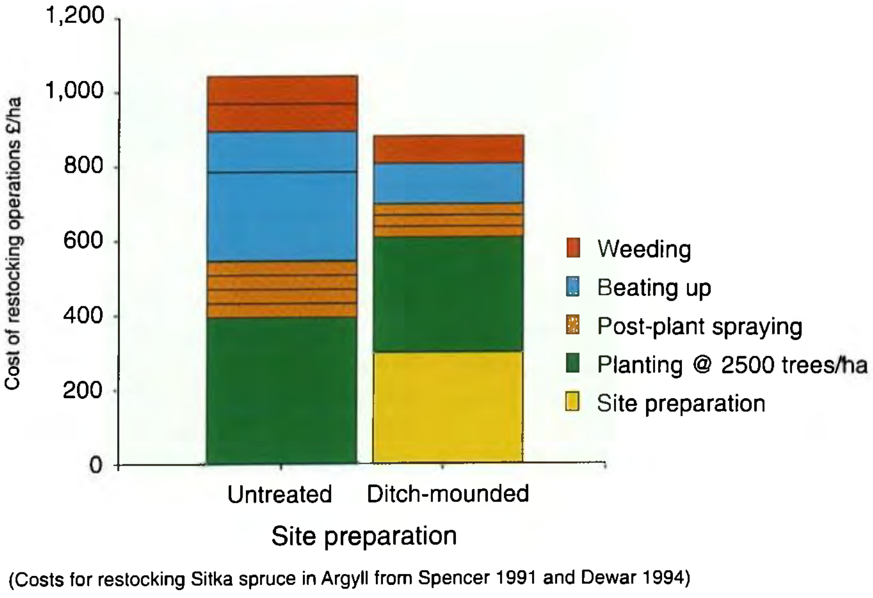
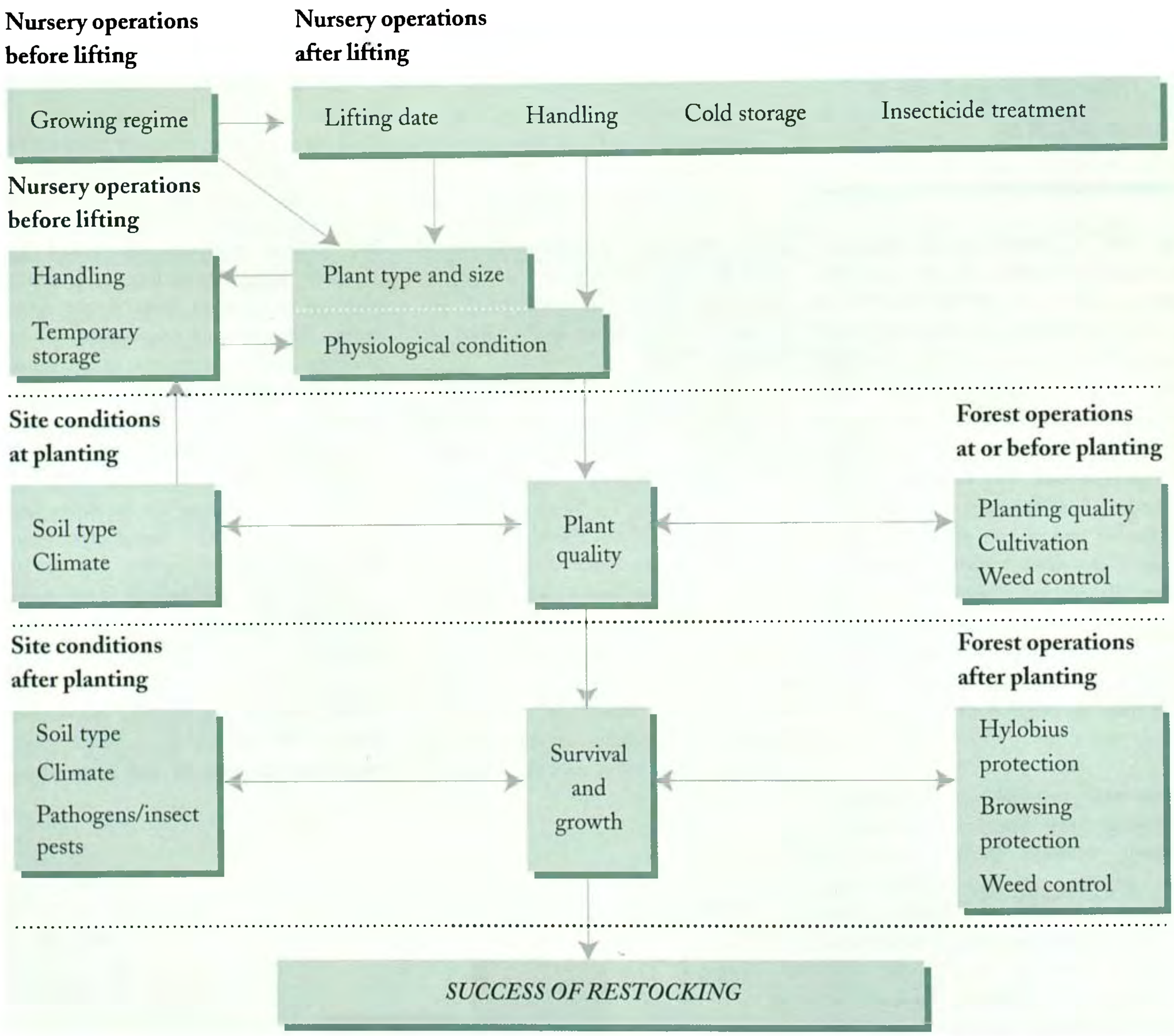



Figure 1. Establishment costs for two different restocking systems in Argyll.

Figure 2. Interaction between processes which influence success of restocking.




at the end of the first growing season (Table 1). Containerised cuttings survived better on mounds but there was no benefit to survival of larger undercut seedlings. All plant types grew better on mounds (Figures 4 and 5).

The importance of planting stock quality for restocking success has often been demonstrated. For example, the size and physiological condition of various batches of cold-stored Sitka spruce plants were measured before trees were planted on a mounded restocking site in Dumfries and Galloway. Physiological condition of the plants was acceptable on arrival at the cold store and when removed after 5 months storage at -2°C. However, some deterioration occurred during dipping with permethrin. Shoot desiccation damage, growth and survival were strongly correlated with root and needle electrolyte leakage measured after plants were dipped (Table 2). Morphological differences in root:shoot ratio explained less of the variation between samples than plant physiology.

Figures 6 and 7 demonstrate the good relationship between root electrolyte leakage (REL), survival and growth found in other studies (McKay and Mason, 1991). We use a database with REL information to supply customers with estimates of survival for a wide range of tree species. Commercial nurseries have also been supplied with information to assist with their own testing.

The quality of plants affects other aspects of restocking. A recent survey of Sitka spruce restocking showed that although first year survival was excellent (greater than 90%) many plants had suffered desiccation damage and dieback. Sturdier plants were less prone to such damage. All plants had been

Figure 3. Menzi Muck walking excavator preparing mounds in Argyll. *(51200)*


Figure 4. Direct planted tree, in an uncultivated plot in the Argyll experiment. *(51191)*

Figure 5. Tree on mound, in a cultivated plot in the Argyll experiment. *(51190)*

Table 1. Mounding by walking excavator in Argyll. First year assessments of tree height and survival.

| **A. Height at planting (cm)** | *Plant type* | | | | |
|---|---|---|---|---|---|
| *Site preparation* | 1+0 VPSS cutting | 2+0 VPSS cutting | 1u1 WSS undercut | | *Least significant difference between plant types (P≤0.05) |
| Mean of results from mounded and direct planted treatments | 11.2 | 24.6 | 32.6 | | 1.5 |
| **B. Height growth (cm)** | | | | | |
| *Site preparation* | 1+0 VPSS cutting | 2+0 VPSS cutting | 1ul WSS undercut | Mean of plant type | **Least significant difference between cultivation (P≤0.05) |
| Mounded | 14.0 | 9.6 | 11.5 | 11.7 | 1.2 |
| Direct planted | 7.6 | 4.8 | 8.6 | 7.0 | |
| **C. Survival** | | | | | |
| *Site preparation* | 1+0 VPSS cutting | 2+0 VPSS cutting | 1ul WSS undercut | | Least significant difference for interaction between plant types and cultivation ( P≤0.05) |
| Mounded | 93.0 | 96.7 | 97.4 | | 9.7 |
| Direct planted | 70.0 | 70.0 | 98.9 | | |

* No difference between cultivation treatments.

** No interaction between plant types and cultivation.

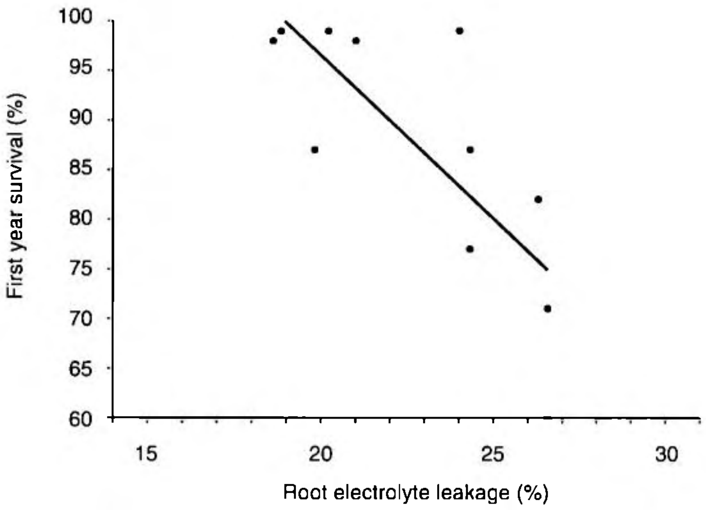



Figure 6. Relationship between root electrolyte leakage and first year survival.

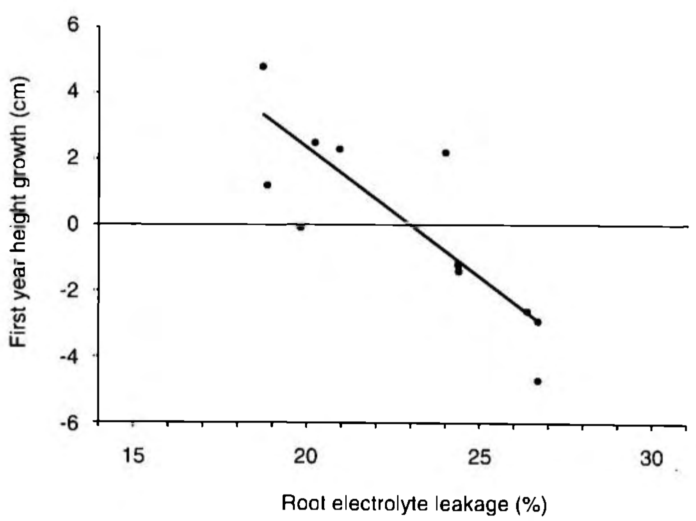



Figure 7. Relationship between root electrolyte leakage and first year height growth.

Table 2. Regression analysis between factors affecting survival and growth of dipped 1u1 Sitka spruce after one year.

| | Fitted terms (% variance accounted for and significance level; sign for $R^2$ values indicates the form of relationship) | | |
|---|---|---|---|
| *Quality index* | Desiccation damage | Height growth | Survival |
| Root:shoot ratio | -33.6 P≤0.05 | n.s. | 38.3 P≤0.05 |
| Needle leakage | 52.1 P≤0.01 | -58.3 | -49.8 P≤0.01 |
| Root leakage | 66.7 P≤0.01 | -65.7 P≤0.01 | -55.7 P≤0.01 |

dipped and there was very little damage by *Hylobius* in the first year. By contrast, *Hylobius* damage caused appreciable deaths in the second growing season. Trees were less likely to be killed by *Hylobius* if they had grown well during the first year.

The preceeding paragraphs outline the wide range of factors which must be considered when planning restocking. To help forest managers to choose the most appropriate restocking practices we have written *Guidance notes for plant supply, treatment and planting* in consultation with staff in Forest Enterprise. Further development of restocking models is planned as part of a EU funded contract. One of the priorities will be to develop a decision support system which can identify the best lifting and planting dates for managers in the nursery and forestry sectors.

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# *Disease and Pest Problems*

## *by John Gibbs and Hugh Evans*

Trees suffer from a wide range of pests and diseases. It is one of the tasks of the Forestry Commission Research Division to minimise their effects, whether by devising means to exclude potentially damaging organisms from the UK or by monitoring, managing and controlling those that are present. This article reviews the current situation and in so doing continues a tradition of reporting which has been maintained in the annual Report on Forest Research for over 30 years. Additional information on problems affecting amenity trees in England can be found in Strouts (1996). Data on general forest condition as revealed by the 1995 assessment of crown density can be found in Redfern, Proudfoot and Boswell (1996).

### Bark beetles

The eight-toothed spruce bark beetle, *Ips typographus,* is a native of mainland Europe that has never established itself in the UK (Figure 1). One hundred and forty-nine adult beetles were caught in pheromone traps at ports during 1995, many more than in any previous year since the monitoring scheme was initiated in 1985. Most beetles were reported from the east coast of England during May, but there was a catch as late as 21 September at Mostyn in north Wales. Also during 1995, adults or larvae of *I. typographus* were intercepted on timber or dunnage from Belgium, Estonia, Germany, Latvia, Lithuania, Poland, Rumania, Russia and Sweden (Figure 2). A single *I. amitinus* was trapped on 17 August at Teesport in north-east England.

### Asian gypsy moth *Lymantria dispar*

The discovery that large outbreaks of gypsy moth in Germany contained some of the Asian strain of the moth and the subsequent discovery that flying females from this strain have established in the USA and Canada, led to information campaigns and surveys in the UK during 1994 and 1995. Leaflets were distributed (Winter and Evans, 1994) and pheromone traps deployed. Nine male moths were caught during 1994, although it was thought that they had probably been blown over from the continent. No sign of larval populations was found. However, in June 1995 an infestation of larvae was found in South Woodford, London Borough of Redbridge (Figure 3). A joint exercise between the Plant Health and Seeds Inspectorate (PHSI) of MAFF, the Forestry Commission Research Division and the Forestry Authority Plant Health Branch was mounted. Initial surveys indicated that the larvae were confined to a series of 'back-to-back' gardens and that the infestation was at least two years old. Following the surveys, 107 gardens were treated with insecticide by Redbridge Borough Council (as advised by PHSI) but because the larvae were close to pupation it was considered unlikely that the infestation would be eradicated. Pheromone traps were then placed in the gardens and in the nearby Epping Forest for the moths' flight period in July. Thirty-two moths were trapped in the gardens and a further four were caught in Epping Forest, confirming that the insecticide spray had been too late to eradicate all the larvae. Surveys have subsequently been carried out for over-wintering egg masses but none has been found.

Figure 1. The eight-toothed spruce bark beetle *Ips typographus. (40711)*

Figure 2. *Ips typographus* galleries on bark from imported dunnage. *(41134)*

Figure 3. Gypsy moth caterpillar feeding on oak. *(41331)*

Preliminary results of DNA analysis of moths from the Woodford infestation indicate that many of them contain a combination of genes typical of the Asian strain, but more work on the material is required. In 1996, there will be a wider deployment of pheromone traps across southern England, and a new survey for larvae will be conducted at the infestation site. New publicity material is in preparation.

### Phytophthora disease of alder

The disease continues to cause concern and is the subject of a 3-year research programme jointly funded by the Forestry Authority and the National Rivers Authority (now the Environment Agency). It is now known to occur through much of the UK as far north as a line from Preston to Middlesborough. A survey of 1700 alder stools in plots established across southern Britain on rivers over 8 m wide (Gibbs, 1995) showed that the percentage of dying and dead trees increased from 5.2% in 1994 to 5.9% in 1995. It is estimated that this increase corresponds to some 5000 trees. High disease levels occur in some plots, for example on the river Lugg in Herefordshire (Figure 4), where 18% of the trees are dying and 12% are dead. The 1994 survey data have been examined in relation to various measures of water quality and there is some evidence for an association between disease severity and levels of total oxidised nitrogen. The causal fungus resembles *Phytophthora cambivora* in the morphology of its sexual structures. However, it also exhibits characters which distinguish it from this fungus and suggest that it may be of relatively recent origin (Brasier *et al.*, 1995). A wide range of provenances of *A. glutinosa*, and a selection of provenances of other *Alnus* species are being tested for their resistance to the disease. A fuller account of the current situation can be found in Gibbs and Lonsdale (1996).

### Dutch elm disease

The disease continues to develop in the regenerating English elm *(Ulmus procera)* populations of southern Britain. An account of recent research is given in the following article of this Report (Brasier, 1996).

### Oak dieback

Sessile oak *(Quercus petraea)* in the ancient forest of Wyre in the west Midlands regularly suffers from a

Figure 4. Phytophthora disease of alder on the river Lugg in Herefordshire. *(41339)*

Figure 5. Sessile oak in Wyre Forest showing shoot dieback in mid-summer. *(40918)*

conspicuous dieback involving the sudden death of twigs in mid-summer (Figure 5). From a study of the problem published during the year (Gibbs and Wainhouse, 1995) it is concluded that a major cause of the damage is the killing of bark by a fungus *(Sphaeropsis* sp.*)* following the 'stress' effects induced by large populations of the scale insect *Kermes* sp. There are interesting parallels with similar diebacks in *Q. petraea* reported from time to time elsewhere in Europe. Also during the year, research was concluded on a much more widely distributed dieback and decline of oak, chiefly *Q. robur*, that aroused considerable attention during the period 1989-91 (Greig, 1992). During the last few years there has been very little further mortality in the study plots although many of the surviving trees continue to be in poor condition. The causes of the dieback were never fully explained although it was thought that climatic conditions, in particular the droughts of 1983 and 1984 and the severe winters of 1984-1985 and 1985-1986 might have acted as triggers for the problem. The buprestid beetle, *Agrilus pannonicus*, once rare, colonised many of the affected trees on some of the sites, and undoubtedly contributed to the damage.

Table 1. Summary of *Bupalus* survey 1991-1996 (maximum number of pupae per square metre).

| Forest District | Unit | 1991 | 1992 | 1993 | 1994 | 1995 | 1996 |
|---|---|---|---|---|---|---|---|
| North York Moors | Cropton | 2.8 | 4.4 | 0.4 | 0.0 | 0.4 | 4.4 |
| | Dalby | 0.4 | 0.4 | 0.8 | 0.0 | 0.8 | 1.2 |
| | Hambledon | 12.0 | 4.0 | 2.8 | 2.0 | 3.2 | 6.4 |
| | Langdale | 2.4 | 14.4 | 5.2 | 1.6 | 0.0 | 4.4 |
| | Wykeham | 2.4 | 1.6 | 1.2 | 0.4 | 1.6 | 7.6 |
| Midlands | Cannock | 1.2 | 2.0 | 0.8 | 1.2 | 1.6 | 4.0 |
| | Swynnerton | 0.8 | 0.8 | 0.0 | 0.8 | 2.0 | 8.8 |
| Sherwood | Sherwood III | 0.4 | 0.0 | 0.4 | 0.4 | 0.8 | 2.0 |
| | Sherwood IV | 0.4 | 0.8 | 0.8 | 0.8 | 2.8 | 2.4 |
| Moray | Culbin | 8.0 | 2.4 | 0.8 | 2.4 | 10.6 | 18.0 |
| | Lossie | 1.2 | 1.6 | 2.4 | 6.8 | 21.6 | 18.4 |
| | Roseisle | 4.8 | 2.4 | 1.6 | 2.8 | 11.2 | 14.8 |
| | Speymouth | 3.6 | 6.0 | 3.2 | 4.4 | 10.0 | 24.0 |
| Tay | Montreathmont | 4.4 | 0.4 | 0.4 | n/s | n/s | 22.4 |
| Aberfoyle | Edensmuir | 1.2 | 0.0 | 0.4 | 0.4 | 0.8 | 2.4 |
| | Tentsmuir | 7.6 | 0.8 | 0.8 | 1.6 | 5.0 | 14.0 |

n/s = not surveyed

Figure 6. Oak photographed on 8 May 1995 showing the effects of the frosts of 19-22 April. The limits of the pool of freezing air are clearly visible. *(41311)*

### Pine looper moth *Bupalus piniaria*

Since 1954, the population of the pine looper moth has been monitored through pupal counts in various Forestry Commission plantations. Table 1 shows the highest compartment means recorded between 1991 and 1996. The general trend since 1994 has been upwards, especially in eastern Scotland where, at 24.0 pupae per square metre, Speymouth is approaching the level at which defoliation may be noticed. The 1997 survey will show if these increases have continued and whether insecticide control may be necessary.

The winter of the 1994/95 was very mild. These conditions favoured the green spruce aphid *Elatobium abietinum* and large populations developed, particularly in Wales and west Scotland. Observations at a study site at Hafren Forest in north Wales indicated that predators including lacewings, hoverflies and ladybirds were involved in a dramatic reduction in numbers by September.

The high temperatures resulted in the early flushing of many trees and shrubs and so they were highly vulnerable to the severe frosts of April 19-22. Air temperatures as low as -7°C were recorded in Hampshire and Somerset. Further frosts occurred between May 13-15 and these caused more damage, especially in northern England and Scotland. Oak and beech were the most conspicuously-affected species with trees in many low lying areas showing death of foliage over the whole crown. Elsewhere abrupt transition lines were present marking the limits of the pools of cold air (Figure 6). The frosts caused death of 4 to 6-year-old Douglas fir and Corsican pine in southern England and some damage to young Sitka spruce crops in northern England and south Scotland. The damage was comparable with that which occurred in spring 1990 and even that which occurred after the famous frosts of May 1935 (Day and Peace, 1946). Recovery growth in the broadleaved trees was good and symptoms were hard to detect by late June.

In addition to being mild, the 1994/95 winter was also unusually wet. However, it gave way to a dry late spring, and consequently conditions were unfavourable for many splash-borne foliage and shoot diseases. This had a beneficial effect on the condition of willow in southern England, much of which had suffered severely from successive annual attacks of scab caused by *Venturia saliciperda* (Strouts, 1995). However, anthracnose of London plane caused by *Apiognomonia veneta* was quite common and, unusually, was recorded as far north as Carlisle.

The months of July and August 1995 were extremely hot and August was exceptionally dry. By the middle of the latter month trees on freely draining soils and on sites which pose restrictions on rooting, were showing foliage discoloration and premature leaf fall. By contrast, trees on more water-retentive soils benefited from the full store of water at the start of the season and continued to thrive.

Birch and beech were commonly affected, with prematurely-browned trees of the latter species being evident in fields and on roadsides as far north as Invergordon. Twig and branch dieback occurred on some very dry sites. In general, newly planted trees fared well, providing that soil moisture was conserved by good weed control (Rose, 1996).

A common problem in *Alnus glutinosa* in the north of Britain was poor foliation as a result of bud mining in early spring by larvae of the moth *Epinotia tenerana* (Gregory *et al.*, 1996). Cases were seen from Lael in Sutherland to Lancashire and North Yorkshire, most of them reported out of concern that the Phytophthora disease might be involved. Other noteworthy diseases included a case of *Apiognomonia erythrostoma* on cherry in north Scotland and the first record for Scotland of *Seiridium cardinale* on *Cupressus*.

This article could not have been written without the contributions of our colleagues concerned with the diagnosis of disease (Dr S.C. Gregory, Dr D.B. Redfern, Mr D.R. Rose, Miss G.A. MacAskill, and Mrs J. Rose) and the identification of insects (Mr T.G. Winter). We are also grateful to our other colleagues in the Pathology and Entomology Branches for helpful information.

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# New Horizons in Dutch Elm Disease Control

### by Clive Brasier

Dutch elm disease (DED) first appeared in north-west Europe around 1910, and much of the seminal work on its causes was carried out between 1919 and 1934 by several outstanding Dutch women scientists[1]. UK Forestry Commission research on the disease began in the late 1920s when Dr Tom Peace began monitoring its rapid spread into Britain from its first recorded sites on the continent. By the 1940s this first epidemic had died down after causing losses of 10-40% of elms in different European countries (Figure 1). Indeed Peace, in a thorough review[2], was able to write in 1960 "unless it completely changes its present trend of behaviour it will never bring about the disaster once considered imminent". Such a change did come, however, in the late 1960s with the beginning of a second and far more destructive outbreak (Figure 1). As a consequence, a new era of Forestry Commission (FC) research on the disease began.

This research showed that the new outbreak of DED was caused by an entirely different, far more aggressive DED fungus than that responsible for the epidemic of the 1920s-40s[3], and that the new fungus had been imported into Britain on infested elm logs[4]. What followed was the catastrophic epidemic once feared by Peace. Within a decade about 20 million elms out of an estimated UK elm population of 30 million were dead. By the 1990s the number was probably well over 25 million. Studies on the new DED fungus showed that it differed from the original fungus in almost all its important biological properties. The two pathogens were later described as separate species, *Ophiostoma ulmi* (Figure 2a) being the original and *O. novo-ulmi* (Figure 2b) the new highly aggressive pathogen[5].

A variety of short-term control measures were initiated. At the same time, a wide-ranging research programme was undertaken by Pathology Branch on the processes involved in the transmission of the disease by its bark beetle vectors, the interaction between the two DED fungi, and the spread of *O. novo-ulmi* across the northern hemisphere in order to trace the disease's geographical origins and to provide a framework of knowledge upon which realistic longer term control strategies could be based. Research progress in several key areas will be outlined in this article. First, however, the present disease situation in Britain will be summarised. A general description of the disease cycle has recently been produced[6].

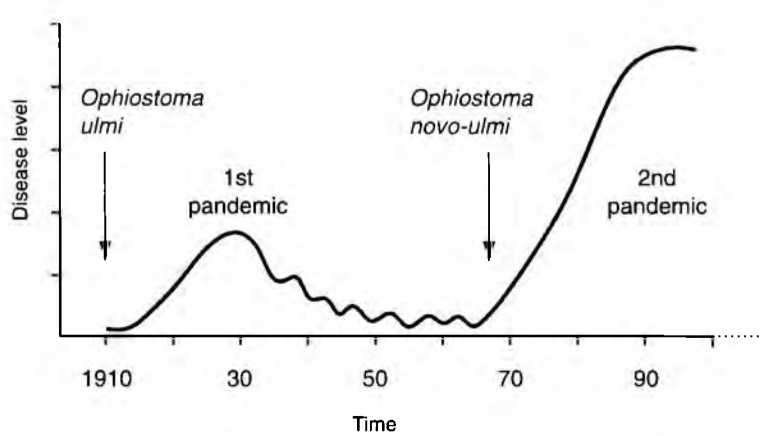
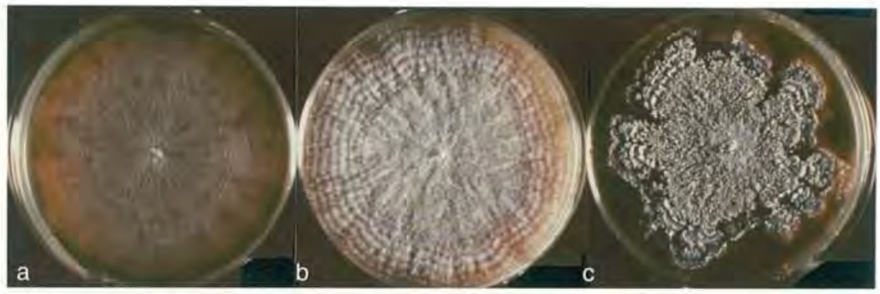



Figure 1. Approximate chronology and impact of the two pandemics of Dutch elm disease in Britain and north-west Europe. Note the decline of the first pandemic in the 1940s.

**Central and southern Britain**

Our main native elms, English elm *(U. procera)*, smooth-leaved elm *(U. carpinifolia* or *U. minor)* and wych elm *(U. glabra)*[7] are all susceptible to *O. novo-ulmi*. In lowland central and southern Britain, with predominantly English elm, the new epidemic took rapid hold during the early to mid-1970s[8], leading to the death of most mature English elm by the early 1980s (Figure 3, C-F). There were scattered escapes. Even pockets of mature elm survived occasionally, as in Brighton and Hove where the geographic situation has facilitated an effective and continuing sanitation control programme. However, once most suitable breeding material (inner elm bark) had been used by the beetles the disease virtually disappeared from many south and south-western areas, such as the Chichester-Southampton area, the Gloucester-Berkeley Vale area and the Berkshire-Surrey-Kent area, in the 1980s. During this period suckers growing from surviving roots of English elm and some smooth-leaved elm types appeared in enormous numbers, together with occasional young seedlings of wych elm. Many small hedgerow elms that escaped the disease have been allowed to mature, in some cases through careful husbandry but often through absence of hedgerow maintenance. Consequently there now exists a numerically massive and increasing elm resource, mainly of small to semi-mature *U. procera*, across much of southern Britain (Figure 3, G1). From Essex to the Welsh borders they probably number many tens of millions.

Figure 2. Characteristic colonies of the three Dutch elm disease fungi: (a) *Ophiostoma ulmi*, cause of the first pandemic; (b) *O. novo-ulmi*, cause of the current pandemic; (c) the recently discovered Himalayan Dutch elm disease pathogen, *O. himal-ulmi.*




In 1982 FC studies on the biology of *O. novo-ulmi*, on disease transmission and on the recent spread of the disease across eastern Europe (Romania to Poland) were combined to produce a prognosis for the future of the disease and of the elm[9]. This prognosis is summarised in Figure 3. As well as predicting the regeneration of the young elms, it suggested that the disease would not die down as had the first epidemic caused by *O. ulmi*, but instead, that the new DED pathogen *O. novo-ulmi* would return, in a continuing cycle, to attack the following generation of small elms once they were large enough to support beetle breeding (Figure 3, F-H). This is what is now happening in southern Britain. In 20 elm plots established by the FC across the south of England, only about 1% of regenerating elms were killed annually between 1980 and 1990, but disease reappeared on a significant scale after 1991[10]. Around the Research Station in the Farnham-Guildford area, no trace of the disease was found during 1981-1987, two separate infections were seen near Godalming in 1988, and by 1990 new infections were scattered across the whole area. By 1994-95 substantial tracts of sucker regrowth and hedgerow elms 3-12 m in height were dead or dying. The above pattern has occurred across most of the old 1970s *U. procera* disease outbreak areas. Some locations, including many parts of the Midlands, are at an earlier stage in the process (<10% diseased). Others, for example the Guildford to Heathrow area, are already quite advanced, with *c.* 50-90% of elms dead or dying in some disease pockets. Indeed the current disease situation is often remarkably reminiscent of the mid-1970s, except that the affected elms are much smaller (Figure 4). We are now approximately at points G1-G2 in Figure 3. A span of about 20 years separates this second wave of disease from the initial outbreak.

Three points should be noted. First, that the regenerating sucker elms are just as susceptible to *O. novo-ulmi* as were the parent trees from which they have developed. Second, that the sudden resurgence of disease in the 1990s probably coincides with the return of the larger elm bark beetle, *Scolytus scolytus*, to the affected areas following its disappearance in the intervening period when little suitable breeding material was available.

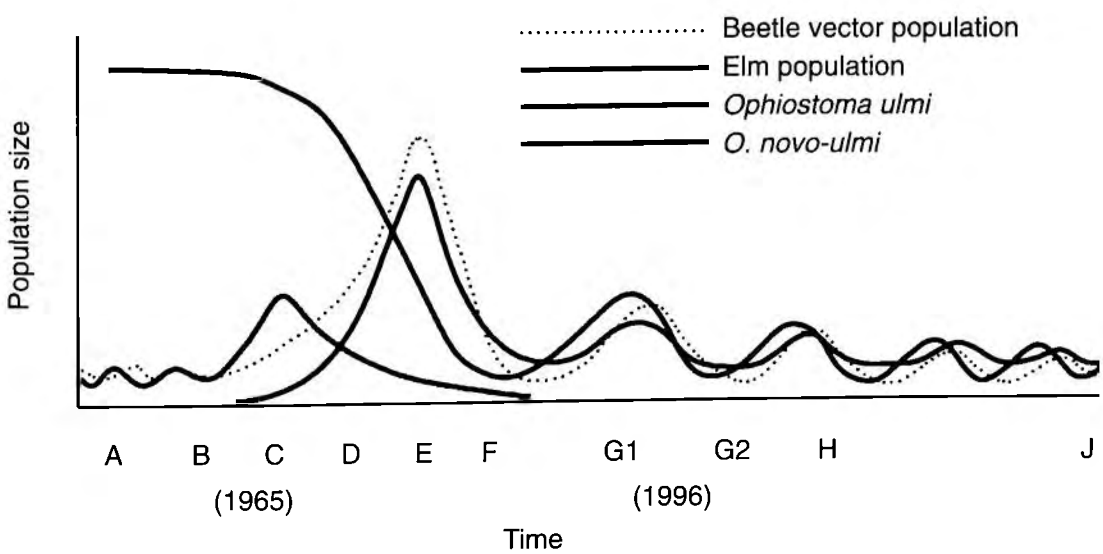



Figure 3. Progress of the current Dutch elm disease epidemic in terms of the elm bark-beetle, *O. ulmi*, and *O. novo-ulmi* populations. Modified from reference 9. See text and reference 9 for details.

Figure 4. Multiple fresh Dutch elm disease infections in a 5 m tall hedgerow of English elm near Odiham, Hampshire, July 1996. *(41576)*

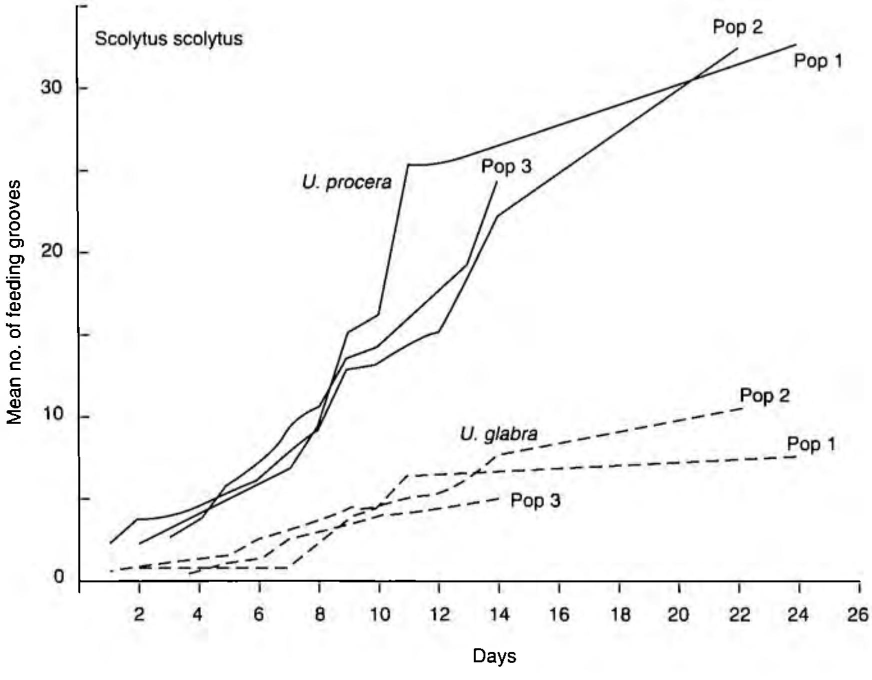



Figure 5. The preference of the larger elm bark beetle, *Scolytus scolytus,* for feeding on English elm *(U. procera)* rather than on wych elm *(U. glabra)*. Three populations of *S. scolytus* were tested. One was a *U. glabra* associated population from Scotland (Pop 3); another a *U. carpinifolia* associated population from Manchester (Pop 2); and the third a *U. procera* associated population from Devon (Pop 1). J. F. Webber, previously unpublished. See also reference 12.

*S. scolytus* probably migrated back from neighbouring parts of Britain where it has survived. The smaller beetle, *S. multistriatus,* may actually be the first to return to an area, since it can use smaller diameter branches as its breeding material. However FC research shows that *S. multistriatus* is a very ineffective vector of the disease, in contrast to *S. scolytus*[11]. Third, the best way to conserve hedgerow elms at present may be to keep them trimmed, since prominent elms are more likely to attract the bark beetles for feeding.

If a majority of the regenerating elms die over a 10-15 year period, then losses in central and southern Britain may number a million or more trees annually. Certainly DED remains by far our most destructive tree disease. However, although further cycles of disease can be expected (Figure 3, H-J), the elm will survive to provide a contribution to future landscapes. It remains an enormous potential resource.

### Cornwall and East Anglia

In the early 1970s the rate of disease progress was markedly slower in the smooth-leaved elm populations of East Anglia and the Cornish elm *(U. carpinifolia* var. *cornubiensis)* populations of the south-west peninsula[8]. The majority of mature Cornish elm and East Anglian smooth-leaved elms have now been killed by the disease. However smooth-leaved elm is highly variable[7] and even now certain local East Anglian smooth-leaved elm clones have suffered only limited losses, with some isolated trees or significant groups of mature trees surviving. Many examples are in woodlands or on woodland edges. Some of these clones are being propagated by local authorities as possible sources of resistant material for replanting. They do not necessarily posess a higher level of resistance to the Dutch elm disease fungus. Many factors can lead to reasonable 'field performance', and these clones could prove highly susceptible if inoculated. All smooth-leaved elm varieties are believed to be introduced into Britain from central and southern Europe[7] and some, being beyond their natural climatic range or site conditions, may be growing rather slowly and producing smaller springwood vessels restrictive to the fungus. Good field performance may also involve resistance to beetle feeding or breeding, or involve a natural biological control of the fungus or beetle. Some smooth-leaved elm types have very pendulous twigs when mature, a feature which could make them unattractive to the beetles for feeding.

### Scotland and north-west England

Epidemic progress has also been much slower on the predominantly wych elm *(U. glabra)* populations of Scotland and north-west England[8]. The result is that the first wave of the 1970s epidemic is still active and continuing in these areas today. At least three likely causes of this slower progression of disease are apparent. First, *U. glabra* does not sucker like *U. procera* or *U. carpinifolia*[5], hence it suffers less from disease transmission via root grafts[8]. Second, although *U. glabra* is considered even more susceptible to *O. novo-ulmi* than is *U. procera*, it is much less favoured by the bark beetles for feeding[12] (Figure 5). Third, a competitor of the elm bark beetles, the fungus *Phomopsis*, is a common, rapid invader of the bark of newly dying wych elm, thereby acting as a competitor of the elm bark beetles which normally breed in the bark.[11] *Phomopsis* appears to exert a strong natural biological control of the beetle populations of the north and west[11]. Fourth, climatic constraints probably reduce the disease activity of the pathogen by producing fewer opportunities for beetle-originated infections in the summer. The climate may also restrict the size and number of annual bark beetle generations as compared with southern Britain or continental Europe[14]. Such factors have aided a successful disease containment campaign within the Edinburgh city limits.

Nonetheless, the disease is very active in Scotland. It has moved into *U. glabra* populations that were not affected by the first DED epidemic, such as those in the Glasgow area. It is continuing to push northwards, particularly on the east coast north of Aberdeen. This northwards expansion probably reflects the fact that *O. novo-ulmi* has a lower optimum temperature for growth than did *O. ulmi*[5], and the much greater epidemic momentum that *O. novo-ulmi* has generated, allowing *Scolytus scolytus* to expand beyond its previous northern territorial limits.

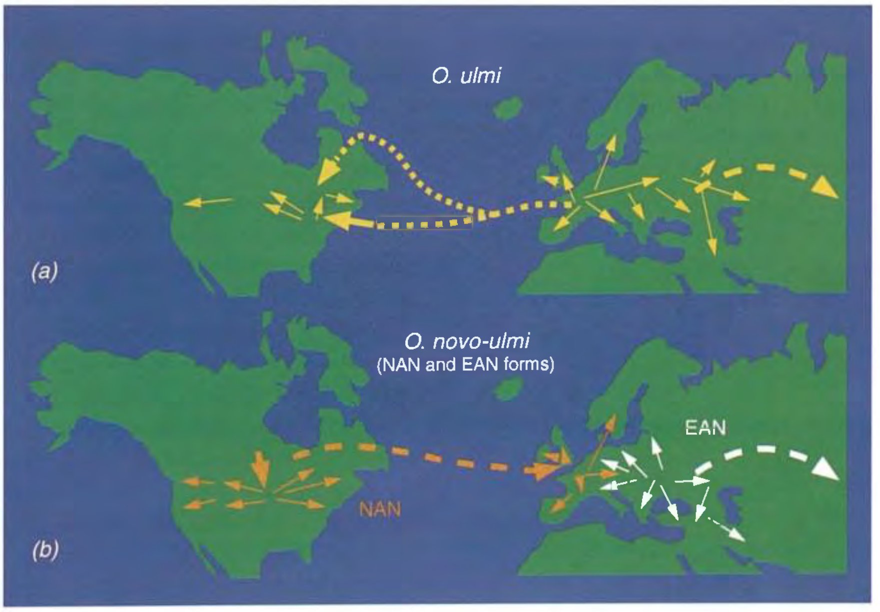



Figure 6. The spread of (a) *O. ulmi* and (b) *O. novo-ulmi* during the first and second pandemics of Dutch elm disease. Composed from Forestry Commission sample surveys of the pathogen across the Northern Hemisphere in the 1970s-1980s *(O. novo-ulmi)* and from international publications and FC surveys *(O. ulmi)*. Solid arrows show natural migration from original centres of appearance. Dashed arrows indicate subsequent spread via importation events. Note: (i) *O. novo-ulmi* exists as two distinct forms, equivalent to subspecies, called the North American (NAN) and Eurasian (EAN) races. They have different geographical distributions and their centres of original appearance and subsequent spread are shown here in orange (NAN) and white (EAN) respectively. (ii) The evolutionary and geographical origins of *O. ulmi* and of the two races of *O. novo-ulmi* remain unknown. Adapted from reference 16.

We now have a situation across both Europe and North America where the host (the elm) and pathogen *(O. novo-ulmi)* are seriously out of balance: the pathogen is too aggressive for its host (Figure 3, C-G). This is partly because *O. novo-ulmi* is an introduced pathogen that has not co-evolved with native European or North American elms. In addition, some natural enemies of the fungus or of its beetle vectors may be missing from the system.

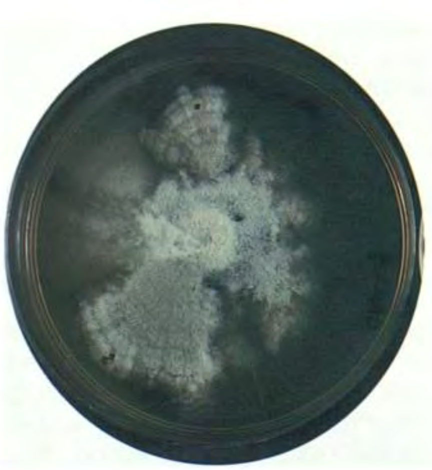
Because of this host-pathogen imbalance, traditional 'front line' disease controls such those offered by quarantine, sanitation or chemical control[8,15] have been largely overwhelmed by the sheer momentum of the epidemic or undermined by human fallibility. What is needed are radical new approaches to the problem, based on better scientific knowledge, which individually or collectively, can help restore the system to balance more quickly than nature can achieve by itself.

In discussing longer term control prospects, it is important to appreciate that Dutch elm disease, like HIV, or tuberculosis, is an international problem[16] (Figure 6) that requires an international perspective embracing the whole epidemic area - currently from North America to the western Chinese borders and south to New Zealand. Changes in pathogen behaviour occurring in Kansas or Uzbekistan today could be occurring on our doorstep tomorrow.

Main options for control include (i) reducing the effectiveness of the beetle vector population; (ii) increasing the resistance of the elm population; and (iii) lowering the aggressiveness of the pathogen. Regarding the beetle vectors, much work has been done on investigating the transmission of the disease[11] and in characterising beetle pheromones as lures for use in sanitation monitoring[14], but no new avenues for control have opened up. Recent research by the Forestry Commission has therefore concentrated on the fungus and on the elm, with special emphasis on the following.

Dutch elm disease was unknown before 1900, yet we have had two pandemics in this century each caused by a unique Dutch elm disease fungus[5,16] (Figure 1). Together, they are responsible for one of the most catastrophic environmental events this century, yet their origin remains a mystery.

Figure 7. A d-infected culture of *O. novo-ulmi*, showing the typical irregular unstable growth pattern associated with d-infection.



It is important to establish their origin (1) to understand why such explosive tree pandemics occur and whether they are likely to occur on other trees, and (2) because to identify the geographical centre of origin (or 'endemism') of the disease may present new opportunities for its biological control.

A research programme on the disease's origin was begun in 1979. Detailed surveys of the DED pathogens were carried out across Iran, parts of the former Soviet Union, central and eastern Europe and North America[16]. These produced a picture of the spread of *O. ulmi* in the first pandemic and of *O. novo-ulmi* in the current pandemic (Figure 6). China, which has often been held to be the centre of origin of DED because of its many disease resistant elm species, was surveyed in 1986. No evidence of the disease was found, though native elm bark beetles were common. It was concluded that China was most probably not the geographical origin of the disease. Two alternative hypotheses were presented. First, that *O. ulmi*, *O. novo-ulmi* or both had appeared recently via an unusual evolutionary event through human influence. Second, that they had an origin in the Himalayas, a major floristic region not surveyed for the disease[16].

In 1993 a survey was conducted in the Kullu and Sutlej valley areas, Western Indian Himalayas[17]. This led to the discovery of a third Dutch elm disease fungus, associated with beetle breeding galleries of Himalayan elm bark beetles on the local *Ulmus wallichiana*.

Typical beetle feeding wounds were also seen on the elms. The fungus has been characterised and named *O. himal-ulmi*[17] (Figure 2c). Significantly, *O. himal-ulmi* has proved to be just as pathogenic to elms as *O. novo-ulmi*, and to produce comparatively high levels of the wilt toxin, cerato-ulmin.

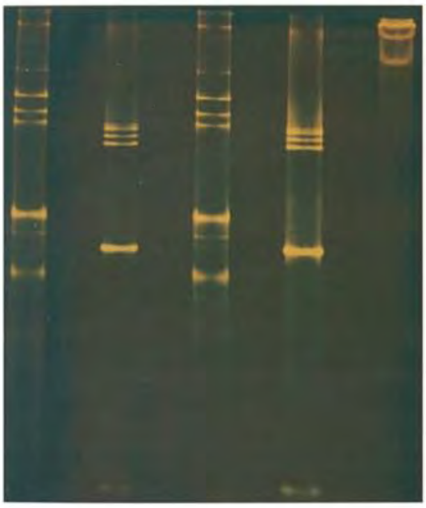
While it has not solved the question of the origins of *O. ulmi* or *O. novo-ulmi* directly, this discovery has opened up new approaches to research. First, it has raised the possibility that *O. himal-ulmi* was at some time introduced into Europe or North America, and gave rise to *O. novo-ulmi* by hybridising with *O. ulmi*[17]. This possibility is now under investigation. Second, no wilt disease was seen on elms in the Himalayas. The disease therefore appears to be relatively quiescent and endemic to the region. There is thus an opportunity to understand the natural balance between the elm, fungus and beetle vector in an endemic rather than an epidemic disease system. It may offer important new opportunities for biological control: there may be natural competitors and predators of the fungus and beetle populations in the Himalayas that are missing from the DED system in Europe and North America and could be exploited for biological control purposes[17]. Much may therefore be gained from investigating the ecology and population dynamics of the Himalayan system.

A wider issue raised by the discovery of *O. himal-ulmi* is that such a highly aggressive tree pathogen can exist unknown and unidentified in a major forest region of the world until now. This has considerable implications for our approach to quarantine and forest protection. In particular, it raises a question about the number of exotic pathogen threats not so far identified.

One approach to restoring the balance between the elm and the pathogen is to reduce the pathogen's aggressiveness. In 1983, studies on the fungus' 'tissue incompatibility system' led to the discovery that it had a disease of its own, now known as the 'd-factor'[18]. D-factors undoubtedly have the potential to reduce the aggressiveness of *O. novo-ulmi*.

D-factors are naturally occurring virus-like agents, located in the fungus' cytoplasm, which spread from one

Figure 8. How d-factors are visualised in the laboratory. The multiple dsRNA (double stranded RNA) segments of d-factors revealed on a polyacrilamide gel plate. The segments range from approximately 0.3 to 3.0 kilo-bases of dsRNA in size. *(34764)*



fungal isolate to another via hyphal fusions. They can severely debilitate *O. novo-ulmi*, inducing slow, ragged 'amoeboid' growth (Figure 7) and reduced sporulation[19]. Many different d-factors have now been identified. Most are associated with double stranded RNA segments (Figure 8), which probably encode for them[20].

Field studies using artificial beetle feeding wounds (Figure 9) show that d-factors can increase the number of *O. novo-ulmi* spores required for infection of English elm beyond the spore loads carried by most vector beetles[21]. Thus the $d^2$-factor (d-factors have been numbered $d^1$-$d^n$) increases the number of spores required for infection from *c.*1000 (healthy isolate) to *c.*50 000 ($d^2$-infected isolate). D-factors therefore have the potential to break the cycle of Dutch elm disease at the beetle feeding stage[22]. In addition, population studies on *O. ulmi* in Europe and North America suggest d-factors may have been instrumental in the unexpected decline of the first DED epidemic in Europe in the 1940s (Figure 1). Similar studies show that in the present epidemic, d-factors markedly influence the behaviour of *O. novo-ulmi* at epidemic fronts, and are involved in a remarkable and rapid change in its population structure from being clonal to being highly genetically variable[23].

D-factors are the fourth component of the DED system: it is an elm-fungus-fungal virus-beetle vector system. D-factors not only exert a natural biological control of the fungus[19,22], but may have considerable potential as artificial biocontrol agents. Consequently, they are being studied with a view to their possible release, either unmodified or genetically manipulated, for biocontrol purposes. Studies on physiological differences, molecular profiles and population structure of d-factors are underway with the support of the Pilkington Trust. These are aimed at characterising weak, moderate and strong d-factors[24,25], assessing which d-factors might be most appropriate for release and at determining how different d-factors might interact with each other if they were released. Molecular studies are also in progress with Imperial College and the Gatsby Trust on the detailed genetic structure of d-factors and on the way that they influence *O. novo-ulmi* at the cellular level[26], again with a view to manipulating them to greater ecological effectiveness. One objective is to insert the d-factor into the fungal nucleus, as has recently been achieved for a similar virus of the chestnut blight fungus. This could make a d-factor behave like a nuclear gene, and allow it to be spread more effectively among different genotypes of *O. novo-ulmi* in nature.

Recently, three places have been identified at which there is just a single clone of *O. novo-ulmi* free from d-factors. One is at the new disease outbreak in Auckland, New Zealand; one in Washington DC and the third in Oregon, USA[27]. These populations could be very suitable for an experimental release of d-factors to assess further their biocontrol potential. They are also ideal study sites because only the smaller, less effective beetle vector, *S. multistriatus*, is present. D-infected fungus of the same genotype as the local fungal clone could be released on captured beetles. If these beetles fly to join the local beetle population, the d-factor could be introduced into the fungal population. Either a single d-factor or a mixture of d-factors could be used[25].

It is hoped that an experimental release may soon be initiated. It should be emphasised that research on d-factors as biocontrol agents is relatively new, long-term and carries no guarantee of success. However d-factor influence is one of the most likely ways in which the aggressiveness of *O. novo-ulmi* will become attenuated in nature, with or without human intervention.

Figure 9. A typical beetle feeding wound in the crotch of a healthy elm twig. *(41336)*

Another way of restoring the balance between elm and pathogen would be to increase the baseline resistance of European and North American elms. One difficulty with traditional elm breeding is that it usually involves incorporating resistance from exotic Asiatic elms such as the Siberian elm, *U. pumila*, which are not suited to the UK climate and have a rather different arboreal form[15,28]. Resulting hybrid material may therefore be unsuitable in terms of their susceptibility to mild winters or late frosts, their susceptibility to other pathogens such as *Nectria*, or simply their shape. This is not to say that elm breeders will not, one day, produce a resistant elm ideal for UK requirements.

English elm, *U. procera* (Figure 10), is greatly prized in southern Britain for its 40 m height, straight bole and dense globular 'figure-of-eight' crown as well as for its timber. It is well suited to the UK climate, although probably imported from Iberia[7]. An ideal replacement for English elm would therefore be, quite simply, a disease resistant English elm (or, as appropriate, a resistant wych elm, smooth-leaved elm or Cornish elm).

Figure 10. Mature English elm, *U. procera*, showing its characteristic irregular outline. English elm grows to *c*.40 m tall. *(34764)*

In 1992 a research programme was initiated between Horticulture Research International, the Forestry Commission and Abertay University to investigate the potential for genetic manipulation of English elm. Good progress has been made to date. Forestry Commission *U. procera* clone SR4 was brought into tissue culture from leaf petioles. Nutrient and hormone conditions were then manipulated to regenerate shoots and roots from the callus tissue[29] (Figure 11). Protocols for transfer of novel DNA into living elm cells were then developed by adapting the widely applied method of using the gall bacterium, *Agrobacterium tumefasciens*. As a result, marker genes causing pigmented tissue have now been successfully and stably inserted into elm plantlets, i.e. genetic transformation of English elm has been achieved[30]. At the same time, a range of unique anti-fungal proteins supplied by Zeneca UK have been assayed for their activity against *O. novo-ulmi* in culture. A pilot anti-fungal gene may be inserted experimentally into *U. procera* shortly. Anti-beetle genes may also be considered for insertion. The activity of these genes will initially be assayed in tissue culture and regenerated plantlets and later assayed in young woody plants.

English elm is so far proving an excellent model system for genetic manipulation of broadleaved trees. Other elm species such as *U. carpinifolia, U. glabra* and *U. americana* are also under investigation. If the insertion of resistance genes proves promising during the initial trials, the material may be submitted for licensing according to current environmental regulations, with a view to testing it under field conditions. Obvious environmental concerns to be considered are the risk of 'escape' of novel DNA beyond the engineered elm plants, and the likelihood of the disruption of 'friendly' or non-target fungal or insect populations.

It is thought that any resistant English elm would be used mainly for specialised landscaping or urban requirements. Exotic hybrid elms or genetically engineered disease resistant elms are probably not the solution to problem of the abundant 'wild,' regenerating sucker or seedling elms already in the field. For these elms, it would seem more appropriate to aim for a better ecological balance between the disease and the host.

The immediate reasons for seeking to control Dutch elm disease are fairly evident. Returning the elm to its traditional place in the landscape has both high potential amenity and economic value and high historical and cultural significance. Indeed, cultural association with the elm in Britain probably dates back at least to the bronze age, when many favoured elm varieties including the English elm were probably introduced[7]. Dutch elm disease is also introduced into Britain by man, via the modern timber trade. There is therefore some responsibility to restore the loss.

The DED epidemic itself has greatly raised public awareness of trees and tree issues. It has also had a considerable influence on the general practice and philosophy of forest pathology. For example, it has underlined the dangers of introducing 'exotic' pathogens. There is clearly a risk of further 'DEDs' in the future. Learning how to control destructive epidemics following imports of exotic pathogens is part of the current learning curve of forestry practice. So too is learning to predict how such introduced pathogens may adapt to their new environment, and learning to develop and apply knowledge-based control measures within a highly complex ecological system.

Indeed, the DED experience has also underlined the value of approaching forest pathogens through an understanding of their ecology and population biology. In this context, the discrimination of *O. ulmi* from *O. novo-ulmi* on behavioural characters has demonstrated, along with similar studies, that the traditional fungal taxonomy based mainly on morphological characters provides inadequate quarantine protection for our forests: biologically distinct organisms have all too often been classified as the same species just because they are morphologically similar[31]. Population studies on the DED fungi have also raised the question of rapid evolution of forest pathogens[32]. FC research shows that *O. novo-ulmi* continues to change at a remarkable rate.[12] The resulting awareness has led to the suggestion that the newly discovered 'alder *Phytophthora*' could well be a product of recent rapid evolution[33].

Beyond these issues, the DED research programme continues to open up new avenues for control. The discovery of the 'd-factor' is an obvious example. Indeed, virus-like agents such as the d-factor may have considerable potential for control of many forest pathogens. Beetle feeding preference studies have established a new character for use in elm breeding: resistance to the beetle. Studies on transmission of DED have highlighted the beetle feeding groove as a weak point in the disease cycle and a the target area for bological control by d-factors. The discovery of the endemic form of DED in the Himalayas may present further opportunities for biological control.

Finally, it should be emphasised that other possible approaches to the control of DED continue to be explored. Indeed, much recent FC research is not covered in this review. It ranges from pilot studies on induceable resistance in elm[34], to studies on pathogenic behaviour of non-toxin producing isolates of *O. novo-ulmi*[35], to studies on the molecular evolution of the three DED pathogens[36]. With limited resources it is necessary to set clear research priorities and to concentrate the current effort on those areas considered most likely to achieve success.

Figure 11. Young plantlets of English elm, *U. procera*, regenerated from callus tissue. *(Horticulture Research International; 910306)*

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# *Ecological Site Classification*

***by Graham Pyatt***

The need for a site classification better suited to second rotation stands and to multi-purpose forestry than the present system based on soil types (Pyatt, 1970, 1977) was foreseen a few years ago. A review of methods in use in other countries (Pyatt, 1996) suggested that the *Biogeoclimatic ecosystem classification* of British Columbia, Canada (Pojar *et al.*, 1987) has many features appropriate to British forestry. It combines climate, soil moisture regime and soil nutrient regime as three principal site factors, and uses the form of humus (Green *et al.*, 1993) and the ecological preferences of 'indicator species' (Klinka *et al.*, 1989) to help assess site quality. The new system, called Ecological Site Classification (ESC), has benefited not only from the Canadian experience but also from recent developments in Europe, notably Germany (Ellenberg, 1988; Ellenberg *et al.*, 1992), France (Rameau *et al.*, 1989, 1993; Brethes *et al.*, 1992), and Belgium (Anon., 1991a, 1991b; Weissen *et al.*, 1994).

Research Information Note 260 *An ecological site classification for forestry in Great Britain* (Pyatt, 1995) has made the scope and potential uses of ESC more widely known. Meanwhile, development of the classification has continued at national, regional and forest levels. A draft of a detailed guide to ESC for Britain is in preparation, based on a detailed case study of the Forestry Authority's Grampian Conservancy in Scotland. ESC has been used to assist forest planning at Allean and South Rannoch Forests in Tay Forest District and in the Affric area of Fort Augustus Forest District. Demonstrations of ESC have been given to Forest Enterprise staff at Clashindarroch Forest, Buchan Forest District, and this forest is to be used for a trial implementation using a Geographical Information System (GIS).

Effort has concentrated on determining climatic and soil suitability criteria for individual tree species and for types of native woodlands according to the National Vegetation Classification (NVC). These criteria will provide a sound ecological basis for choice of species or NVC woodland community on any given site type. The criteria allow the site type to be rated as *optimal, suitable* or *unsuitable* for each species or for each type of native woodland. For many species it will also be possible to make a prediction of yield class according to the suitability rating. ESC can be seen as providing a quantitative framework for the NVC, showing the site types appropriate to each type of woodland (or non-woodland community).

For each tree species optimal, suitable and unsuitable ranges are assigned for three climatic factors: warmth (accumulated temperature above 5.6°C), wetness (moisture deficit) and windiness (DAMS score, see Research Information Note 230 by Quine and White, 1993) and for two soil factors: soil moisture regime and soil nutrient regime. The process is essentially a subjective one based on a wide range of literature from Britain, Europe and western North America, together with consultation of experts and potential users.

A typical use of ESC for an existing forest is shown in Table 1. For any site the factors (columns) can be grouped into locational, climatic, soil and silvicultural. The required climatic data will be available either as maps or by calculation using a computer program for a given grid reference. The required information on soil moisture and nutrient regimes will have to be collected either during a site visit or, less precisely, derived from an existing map of soil types.

The process of conversion of existing soil maps to maps of soil quality will be the most demanding and a vital part of implementing ESC.

In Table 1 the last two columns compare the yield class predicted by ESC with the actual yield class of the existing stands. This may help to refine or clarify the assessment of site quality. For example, at site 3 the actual yield class is at the lower end of the predicted range. This implies that the site is close to the margin of suitability for the species. Looking at each column, it is clear that the site is most likely to be marginal in terms of accumulated temperature. Given that other factors were not compromised, the warmer conditions (more suitable for Douglas fir) are likely to be found at lower elevations or on slopes facing south or south-west.

If each of the five factors is available in map form the criteria can be combined on a GIS to produce a map of site suitability for the species (Figure 1).

A similar process is used to devise climatic and soil suitability criteria for the types of NVC woodlands (Figure 2). These should ensure that not only are the newly created woodlands well matched to site quality in terms of tree growth, but also in terms of the ground vegetation that develops.

Research has started on the relationship between the composition of the ground vegetation and soil nutrient availability. This should provide a sound basis for the classes of soil nutrient regime and improve the potential for the use of indicator species to predict them. This three year project by postgraduate student Scott Wilson is supported by a grant from the Scottish Forestry Trust and jointly supervised with Dr Douglas Malcolm of Edinburgh University.

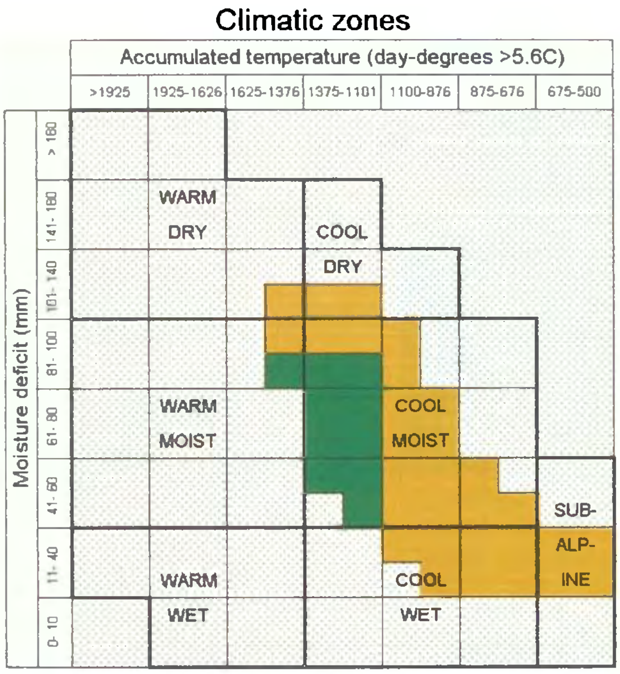
Table 1. Examples of site diagnosis and choice of species at Clashindarroch Forest, Buchan Forest District

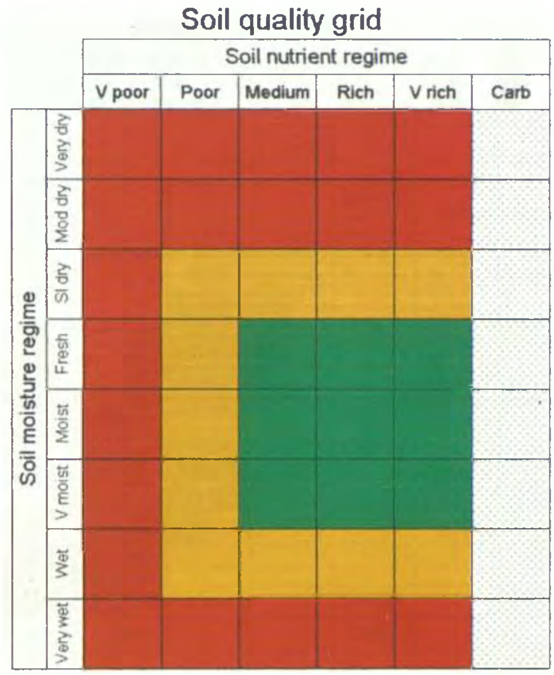
| Location | | | | | Climate | | | Soil | | | | | | Silviculture | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Site | Grid ref. | Elevation (m) | Slope (•) | Aspect | Acc. Temp. (day-deg) | Moist. Def. (mm) | Wind (DAMS) | Geology (all Dalradian) | Soil association | Soil type, humus form | Indicator species | SMR | SNR | Actual tree species | P Yr | Actual GYC | Overall suitability Predicted GYC |
| 1 | NJ487317 | 210 | 1 | NE | 1140 | 67 | 12.5 | Slates | Foudland | Alluvial brown earth, mesomull | Wood sorrel, oak fern, hard fern, tufted hair-grass | Moist | Rich | Grand fir | 36 | 20-22 | 16 to 20 |
| 2 | NJ487315 | 230 | 5 | NW | 1111 | 64 | 12.7 | Slates | Foudland | Ironpan soil, mor | Wavy hair-grass, blaeberry, cowberry | Fresh/ moist | Poor/ very poor | Scots pine | 38 | 10 | 10 to 12 |
| 3 | NJ485313 | 230 | 25 | WNW | 1111 | 64 | 11.0 | Slates | Foudland | Brown earth, mesomull | Wood-sorrel | Fresh | Medium | Douglas fir | 67 | 12 | 12 to 18 |
| 4 | NJ480310 | 250 | 25 | S | 1080 | 61 | 11.5 | Slates | Foudland | Brown earth, mesomull | Wood sorrel, common violet, hard fern, tufted hair-grass, primrose | Fresh | Medium | Beech | 58 | | 4 to 6 |
| 5 | NJ478317 | 370 | 3 | NE | 911 | 45 | 16.5 | Slates | Foudland | Podzol/ ironpan soil, mor | Heather, blaeberry, cowberry, heath rush, wavy hair-grass | Moist | Poor/ very poor | Sitka spruce | 39 | 10 | 10 |
| 6 | NJ470309 | 290 | 10 | SE | 1022 | 55 | 12.5 | Slates | Foudland | Brown earth, oligomul | Wavy hair-grass, creeping soft-grass | Fresh | Poor/ medium | Japanese larch | 32 | 8 | 6 to 10 |

Key to suitability ratings: Optimal / Suitable / Unsuitable

A banded shading indicates that the site lies between the two suitability ratings.

Figure 1. Climatic and soil suitability for Sitka spruce in Grampian Conservancy.




Tolerant of salty winds. Frost tender when young. Only QSS origins recommended, except for Sub-alpine zone where ASS should be preferred. GYC: 18-24 in optimal climates and soil qualities, 10-18 in suitable climates or soil qualities, less than 10 in Sub-alpine zone.

Intolerant of ericaceous vegetation. Ideal conditions: Very moist and Rich/Very Rich, but very susceptible to butt-rot. On Very poor soils can be used in mixture with pine or larch and given P or PK fertiliser.

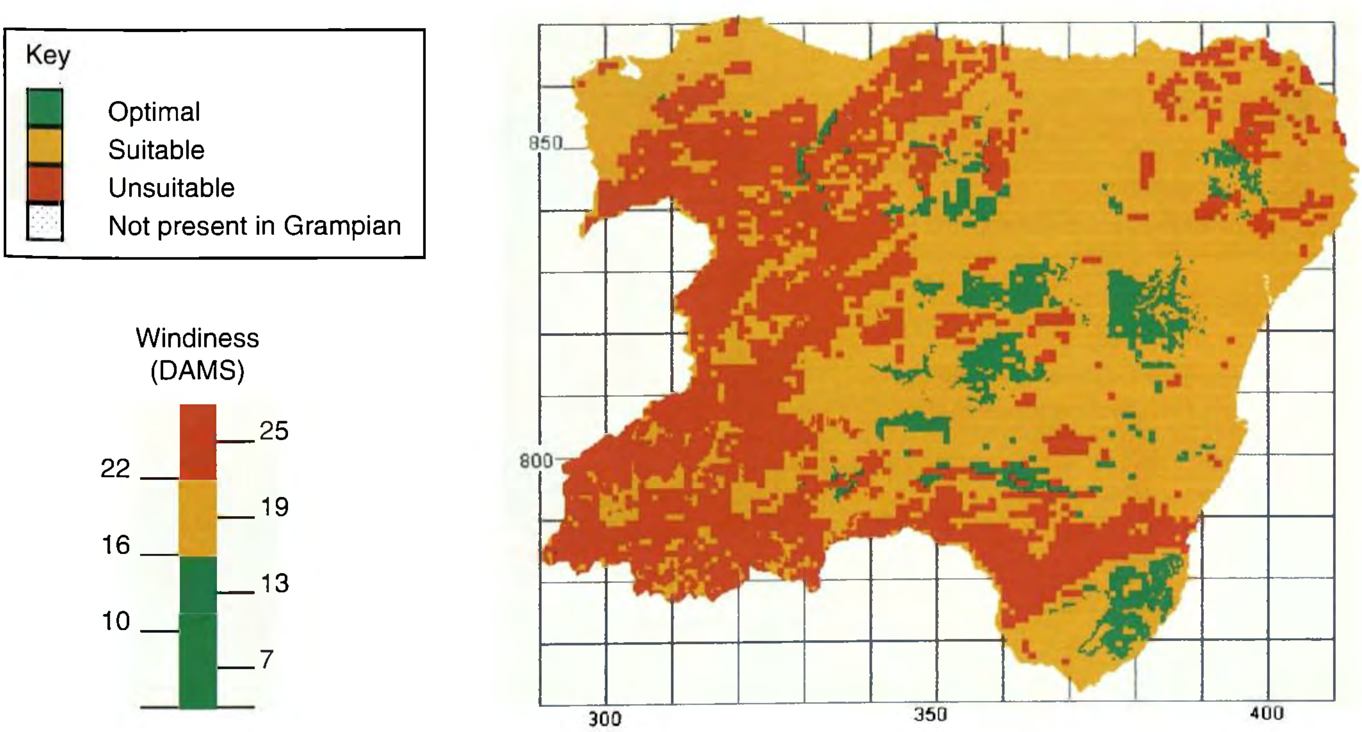
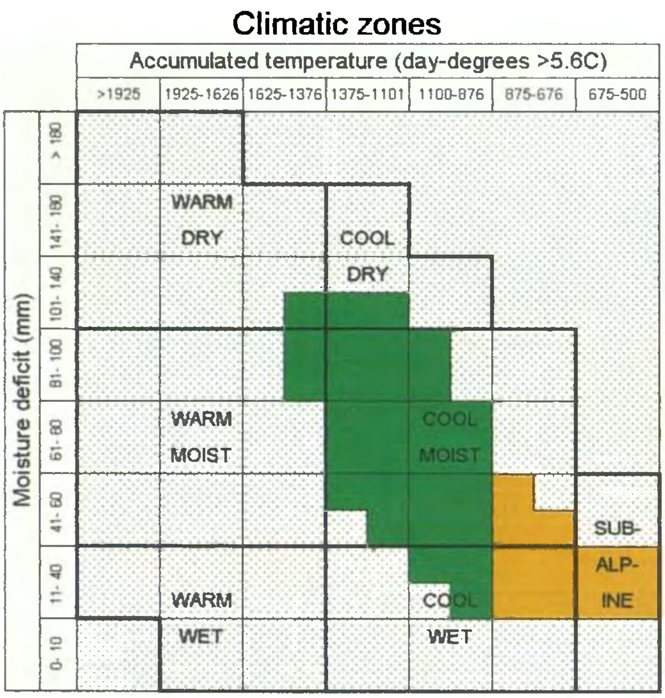
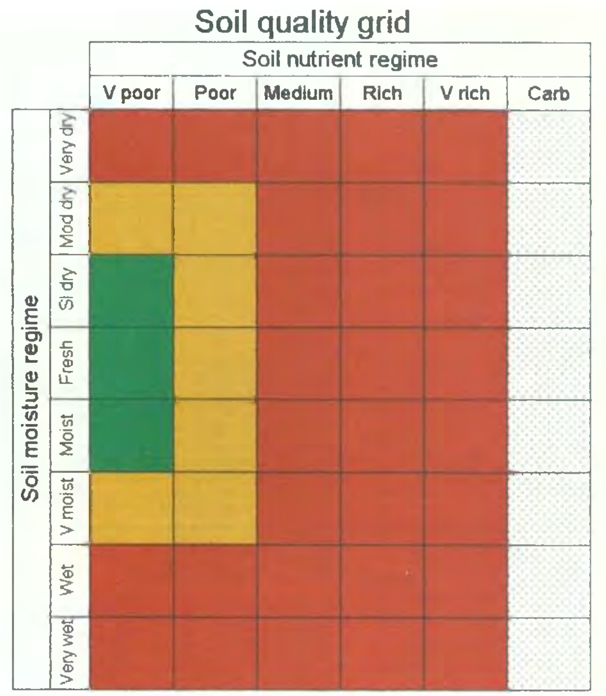


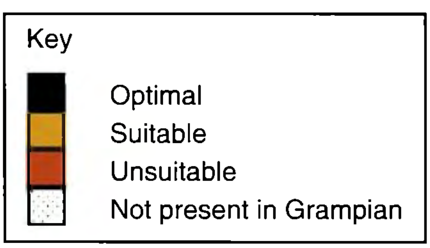
Figure 2. Climatic and soil suitability for Scots pine woodland with heather in Grampian Conservancy (NVC: part W18).

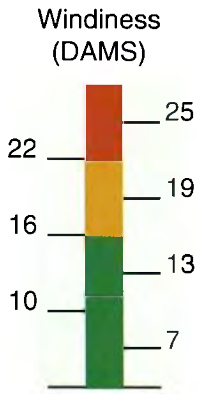


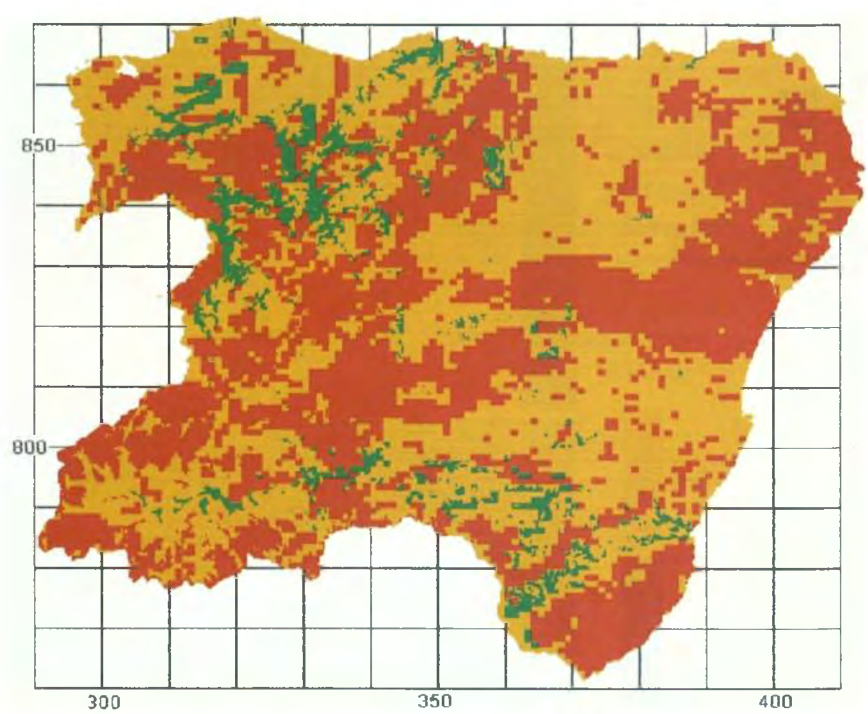

Trees will be severely windswept where DAMS>19. W18a sub-community is more typical of low elevations with larger moisture deficit.




W18a sub-community found on dry soils, W18d sub-community on very moist soils, W18c on poor SNR.



Technology transfer will be a vital part of the ESC project. The classification will be successful only if it is readily understood and used. Apart from the publications and the use of the demonstration forest mentioned above, it is proposed to develop a software version of the classification that will be able to make full use of database, spreadsheet and text files along with the mapping and other capabilities of GIS.

Fifteen countries are taking part in a European Union Concerted Action, co-ordinated by the author, on the correlation of European forest site classifications. Current methods of site classification in several European countries are similar to ESC, but the range of site conditions from the Mediterranean to northern Scandinavia is great and beyond the knowledge of any individual. The problems are made more acute by the splitting up of some countries into provinces with separate forestry policies. Over three years, the aim is to see whether a harmonised classification of site types throughout Europe could be feasible. Such a classification would stand alongside national, sub-national or local classifications and act similarly to the FAO world soil classification, by improving both the implementation of European forest policy and the international exchange of scientific knowledge.

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# *Modelling the Effects of Global Change on European Forests*

**by Mark Broadmeadow, Tony Ludlow and Tim Randle**

The atmospheric concentration of $CO_2$ has been increasing world-wide since the last century and the rate of change may accelerate as we continue to use fossil fuels (Keeling and Whorf, 1994; Houghton, 1990). Increasing $CO_2$ has a direct effect on photosynthesis and plant growth, and is expected to have an indirect effect through global warming and changes in precipitation. The effects are expected to vary between species and over different regions of Europe: the probability of drought may increase in the Mediterranean countries, with serious effects on forest growth and production, while warming and increased rainfall in Scandinavia may lead to a higher turnover of nutrients and faster growth (Viner and Hulme, 1994). The UK is on the border between increasing and decreasing summer rainfall.

The European Community contributes substantially to research in this field, giving "special emphasis to forests and woodlands because they are important to the world and are relatively less understood than other components and systems" and the EC gives a high priority to "a better understanding of growth control systems and of the control of nutrient cycles" (Fasella, 1992). Forestry Commission scientists collaborate actively in this European research.

Impact studies are being carried out in 16 open-top chambers (Figure 1) to elucidate the likely effects of elevated $CO_2$ and changing rainfall patterns on tree growth (oak, ash and Scots pine) as part of an EC project: ECOCRAFT-II. In addition, the effect of elevated tropospheric ozone is being studied.

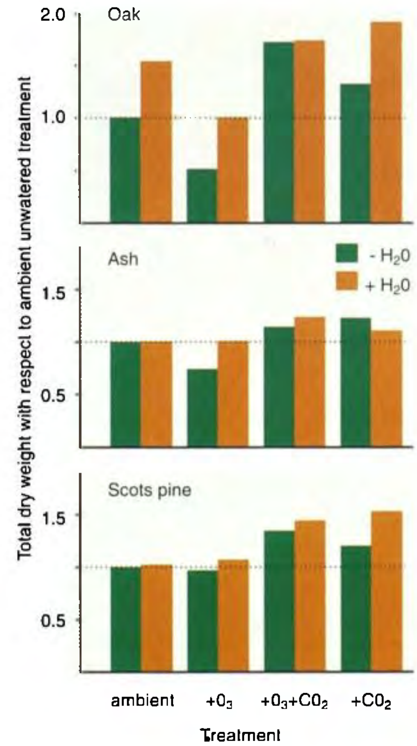


Figure 2. Growth responses of oak, ash and Scots pine to elevated $CO_2$, $O_3$ and water supply. Values are total dry weight expressed as a percentage of the unwatered ambient control.

Figure 1. Open-top chambers at Headley, Hampshire.

To date, oak has proved to be the most responsive species to all three treatments, demonstrating treatment effects of up to 76% increase in dry mass, with smaller increases seen for ash and Scots pine (Figure 2). For oak, the combined benefits of $CO_2$ and irrigation are evident from measurements of photosynthesis (Figure 3a). The beneficial effects of elevated $CO_2$ on water balance are obvious when transpirational water loss is taken into account (Figure 3b: water use efficiency is expressed as $CO_2$ uptake per unit of water loss).

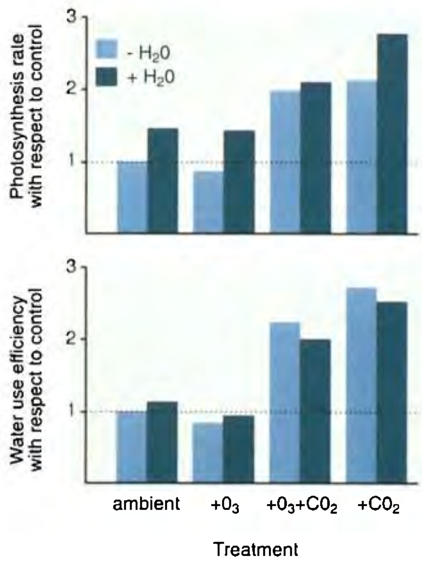


Figure 3. Gas exchange responses of oak to elevated $CO_2$, $O_3$ and water supply, measured with an LCA3 gas exchange analysis system (ADC Ltd.): (a) photosynthesis rate at growth $CO_2$ concentration, (b) instantaneous water use efficiency expressed as mol $CO_2$ assimilated per mol $H_2O$ transpired.

The impact of elevated $O_3$ may be greatest on the processes of $CO_2$ uptake and light harvesting. Large reductions in total foliar chlorophyll concentrations and in the light-and $CO_2$-saturated rate of photosynthesis were seen (Figure 4a and b). Both these responses to $O_3$ were modified by $CO_2$ and water supply with irrigation exacerbating the effect of $O_3$, and $CO_2$ providing a partial amelioration.

A reduction in total chlorophyll concentration was also seen for all irrigated treatments and may have been a response to nitrogen deficiency, given the increased growth in these treatments. The soil is a cultivated humo-ferric podzol, with nutrient levels typical of some poor forest soils in the UK, and no nitrogen supplement had been applied. Reductions in foliar nitrogen concentrations were seen for

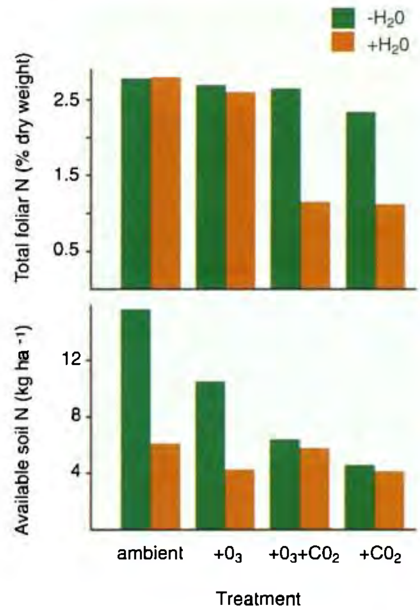


Figure 5. The effect of elevated $CO_2$, $O_3$ and water supply on (a) total foliar nitrogen concentration and (b) available soil nitrogen.

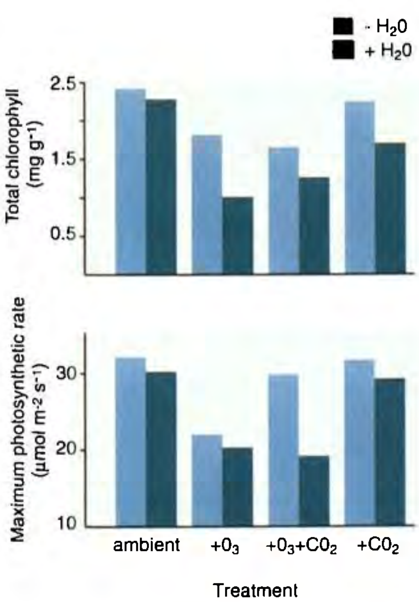


Figure 4. The responses of (a) foliar chlorophyll content measured on a leaf area basis and (b) light and $CO_2$ saturated rate of photosynthesis for oak.

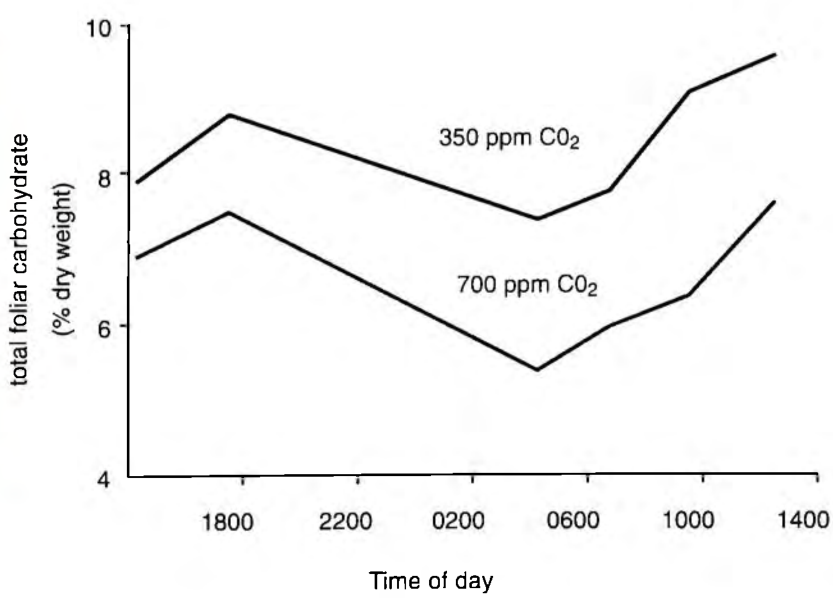


Figure 6. Diurnal course (3-4 August 1995) of total foliar non-structural carbohydrate in oak. No distinction is made between treatments apart from $CO_2$ supply.

Figure 7. Processes calculated in GROMIT.

The Forestry Commission process model (GROMIT) simulates the growth and competition between up to 14 trees in a stand, calculating the following processes:

- Light interception (both beam and diffuse light)
- Photosynthesis
- Maintenance and growth respiration
- Allocation of assimilated carbon to:
  - foliage
  - branches
  - new sapwood
  - coarse roots
  - fine roots
- Stomatal conductance
- Transpiration
- Water uptake
- Structural growth:
  - height growth
  - stem diameter
  - stem volume
  - crown diameter
  - crown depth
  - root spread

irrigated oak grown in elevated $CO_2$ (Figure 5a). These results indicate that, as growth continues and soil nitrogen levels decrease (Figure 5b), the trees may demonstrate nitrogen deficiencies and, for the larger trees grown in elevated $CO_2$, there may be a loss of photosynthetic efficiency leading to 'down regulation' or 'acclimation'. In a similar way, down regulation may occur because trees grown in high $CO_2$ have more foliage and higher water use, which the soil cannot sustain. At the leaf level, the extra carbohydrate assimilated in high $CO_2$ (Figure 6) may inhibit photosynthesis, so reducing the long-term effect of elevated $CO_2$ (Stitt, 1991).

This work has emphasised the need to perform **long-term** experiments on trees planted in typical forest soils, when attempting to predict the effects of climate change on tree growth. Even when these long-term experiments on tree seedlings and saplings are carried out, it is difficult to scale up to a mature stand using only growth data. A different approach is required, using physiological data from impact studies as inputs for process based tree growth models. To this end, the ECOCRAFT-II project uses data from the open-top chambers and the characterisation of a mature oak stand (Figures 9-11) to provide physiological inputs for the Forestry Commission process model GROMIT (Figures 7 and 8).

Such models must simulate the physiological processes of tree growth in sufficient detail to be sensitive to changing $CO_2$ and climate, and they must include the feedback loops that may be involved in down regulation. The Forestry Commission process model is also being used in another project under the EC Environment programme. In LTEEF (Long-term effects of $CO_2$-increase and climate change on European forests; EV5V-CT94-0468) 14 research groups are collaborating to test existing models, which have been developed for different purposes and at different scales, against growth and physiological data across Europe. The first aim is to measure the

Figure 8. Table of GROMIT inputs.

Inputs required for the tree growth model, GROMIT

1. Maximum $CO_2$ uptake rate at optimum temperature for the $CO_2$ treatments
2. Light level for 90% of maximum photosynthetic rate at optimum temperature
3. Light compensation point of photosynthesis
4. Optimum temperature for photosynthesis
5. Minimum temperature for photosynthesis
6. Maximum temperature for photosynthesis
7. Tissue specific respiration rates- leaf, stem, branch, coarse root, fine root
8. Dry matter conversion efficiency
9. Specific leaf area
10. Wood density
11. Foliage:sapwood ratios for branches, stems and coarse roots
12. Root:shoot ratio
13. Senescence rates of foliage, branches, sapwood, coarse and fine roots
14. Start and end of growing season
15. Optimum temperature for stomatal conductance
16. Minimum temperature for stomatal conductance
17. Maximum temperature for stomatal conductance
18. Minimum stomatal conductance
19. Maximum stomatal conductance
20. Vapour pressure deficit threshold to allow stomatal conductance
21. Soil water wilting point
22. Light extinction coefficient
23. Hourly values of radiation, temperature, vapour pressure deficit or relative humidity
24. Daily rainfall

Figure 9. Mature oak stand, planted *c.* 1930. Characterisation provides physiological and growth profiles upon which the treatment effects obtained from the impact studies can be superimposed. Canopy access is via a 20 m scaffold tower.

Figure 10. Physiological characterisation of a mature oak stand. Portable gas-exchange analysis system (LCA-3: ADC Ltd.) used to parametrise photosynthesis and transpiration profiles.

reliability of the models in predicting absolute growth and compare their responses to changing $CO_2$, temperature and rainfall. Initial results suggest that most of the models predicted growth of stem biomass reasonably well but that there were substantial differences in their response to changes. The main reason for these differences is that no one model embodies all of the processes needed for reliable predictions.

At one extreme, the models with the most detailed simulations of photosynthesis do not simulate the process of allocation of carbon to growth of different structures or water uptake. Those that simulate allocation best may not include other processes. After the first comparison of results the models are being enhanced and will be compared again with data and with each other for the final report.

When the long-term effects can be predicted with more confidence, it may be necessary to adjust the existing Forestry Commission yield tables (Edwards and Christie, 1981). Using the yield tables a forester measures the top-height of a stand and, knowing its age, finds which yield class growth curve the stand has followed to date. It is then assumed that the stand will continue along the same yield class growth curve and the yield tables provide corresponding predictions for the rest of the stand's life. In a changing climate, and with increasing $CO_2$, there may be some changes in the growth curves. The response of Scots pine to temperature was simulated with the present version of GROMIT, assuming a gradual rise of 3°C over 100 years, and suggests that the time of maximum mean annual increment would be brought forward three to four years for this scenario. The interactions of rainfall and $CO_2$ with temperature need to be simulated accurately before predictions are applied in forest management. Changes of that order could have a significant effect on the optimum time of harvesting and the expected value of a standing crop but adjustments to the yield table growth curves will not be made until the evidence is more reliable.

Figure 11. Photograph of a mature oak canopy taken with a hemispherical lens. Image analysis of this type of photograph provides data on total canopy leaf area. *(P. Meir)*

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# *Yield Model Predictions of Tree Survival in Unthinned Sitka Spruce*

*by Robert Matthews, Janet Methley and Jonathan Taylor*

There is increasing evidence that Sitka spruce does not self-thin to the extent predicted in the published yield models. As part of the development of new Sitka spruce models, the existing master table relationships, describing key stand variables, are being examined and compared with periodic measurements from permanent and temporary sample plots collected since the publication of the original models. Work is still in progress, but the relationships for predicting surviving numbers of trees have been revised.

The scientific literature was reviewed and a small number of candidate functions for estimating tree survival identified. These functions were calibrated and tested by weighted regression analysis using data from permanent and temporary mensuration sample plots. In addition to fitting the candidate functions, a more general linear and nonlinear regression analysis of the data was performed to investigate correlations between surviving numbers of trees and other principal stand variables.

The data set included stands ranging in planting spacing from 1.3 m to 2.9 m. Some stands also contained a number of multi-stemmed trees with the result that the effective initial number of trees was increased by up to 34 per cent. This complicated the analysis and required the use of adjusted planting spacings for plots containing multistems.

The equation of Reineke (1933) proved to be most reliable for estimating survival in old or high yield class stands, or stands planted at close spacings, in which inter-tree competition had become intense, with significant losses. By contrast survival was poorly estimated by Reineke's law in young stands planted at wide spacings, in which only relatively moderate mortality had occurred. For these latter stands, a hyperbolic equation in terms of stand age and top height was found to be a robust estimator of survival.

The model finally developed consisted of a combination of the hyperbolic law for estimating survival in stands prior to the onset of intense competition, and Reineke's law for estimating survival in stands experiencing significant losses. Incorporation of this model into the Sitka spruce yield models results in significant changes in yield model predictions. For example, for a stand of yield class 12 Sitka spruce planted at 1.7 m spacing (strictly 1.68 m, equivalent to 5½ feet), the original yield model (Edwards and Christie, 1981) predicts 1960 surviving trees per hectare at age 44 years, and a

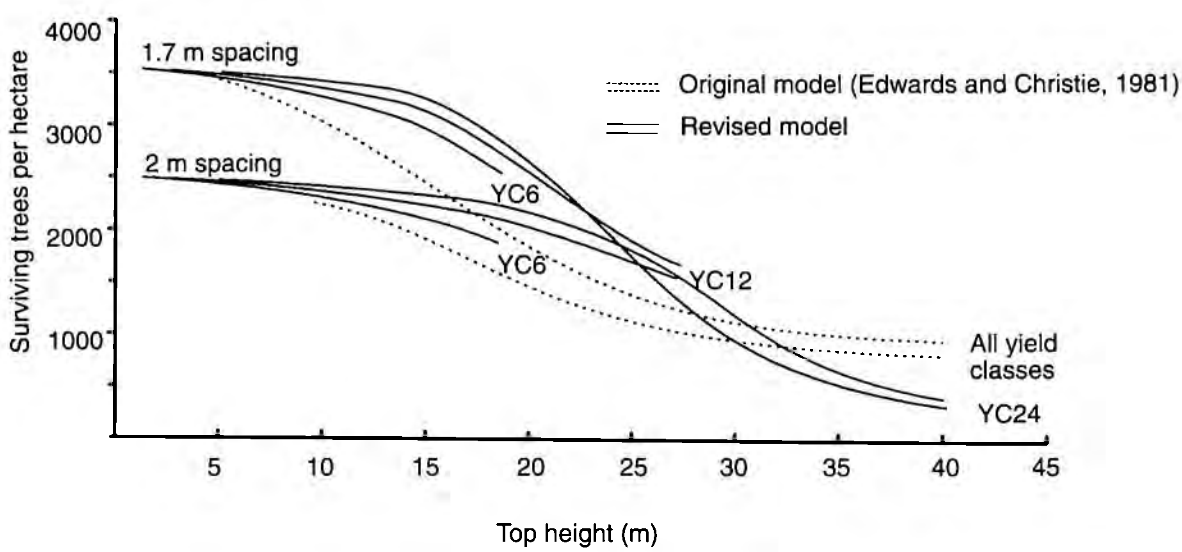


Figure 1. Comparison of predictions of surviving numbers of trees in original and revised models of unthinned Sitka spruce for planting spacings of 1.7 m and 2 m.

mean dbh (diameter at breast height, 1.3 m) of 20 cm. By contrast, the revised yield model predicts 2775 surviving trees per hectare, and a mean dbh of 16 cm. If these mean dbh estimates are used to access the assortment tables for unthinned stands, the percentage volumes to 14 cm top diameter overbark predicted by old and new models are 73% and 46% respectively. The difference in predictions made by original and revised models varies with planting spacing, yield class and stand age. This is illustrated in Figure 1, which compares the relationship of surviving numbers of trees versus stand top height in the original and revised models, for planting spacings of 1.7 m and 2 m, and yield classes of 6, 12 and 24. Yield classes 6 and 24 are the minimum and maximum yield classes represented in the original published yield models, while yield class 12 is the average yield class of Sitka spruce stands in Britain. When comparing stands of the same top height, the revised model predicts slightly higher numbers of trees surviving in high yield class stands compared to low yield class stands. On the other hand, for stands of the same age, top height will be very much higher in high yield class stands compared to low yield class stands, thus there will be fewer trees surviving in high yield class stands compared to low yield class stands of the same age. For top heights above about 30 m, survival is predicted to be lower in the revised model compared to the original model.

Figure 2 shows the development of mean dbh with age for stands planted at spacings of 1.7 m and 2 m, and yield classes of 10, 12 and 16 (representing the range of most commonly occurring yield classes), as predicted by old and new models. In general, for stands at critical harvest ages, the revised yield model predicts significantly higher surviving numbers of trees and somewhat smaller mean diameters compared to the old model. This has major implications for production planning, economic analysis, thinning policy and expected sawlog out-turn in unthinned Sitka spruce stands.

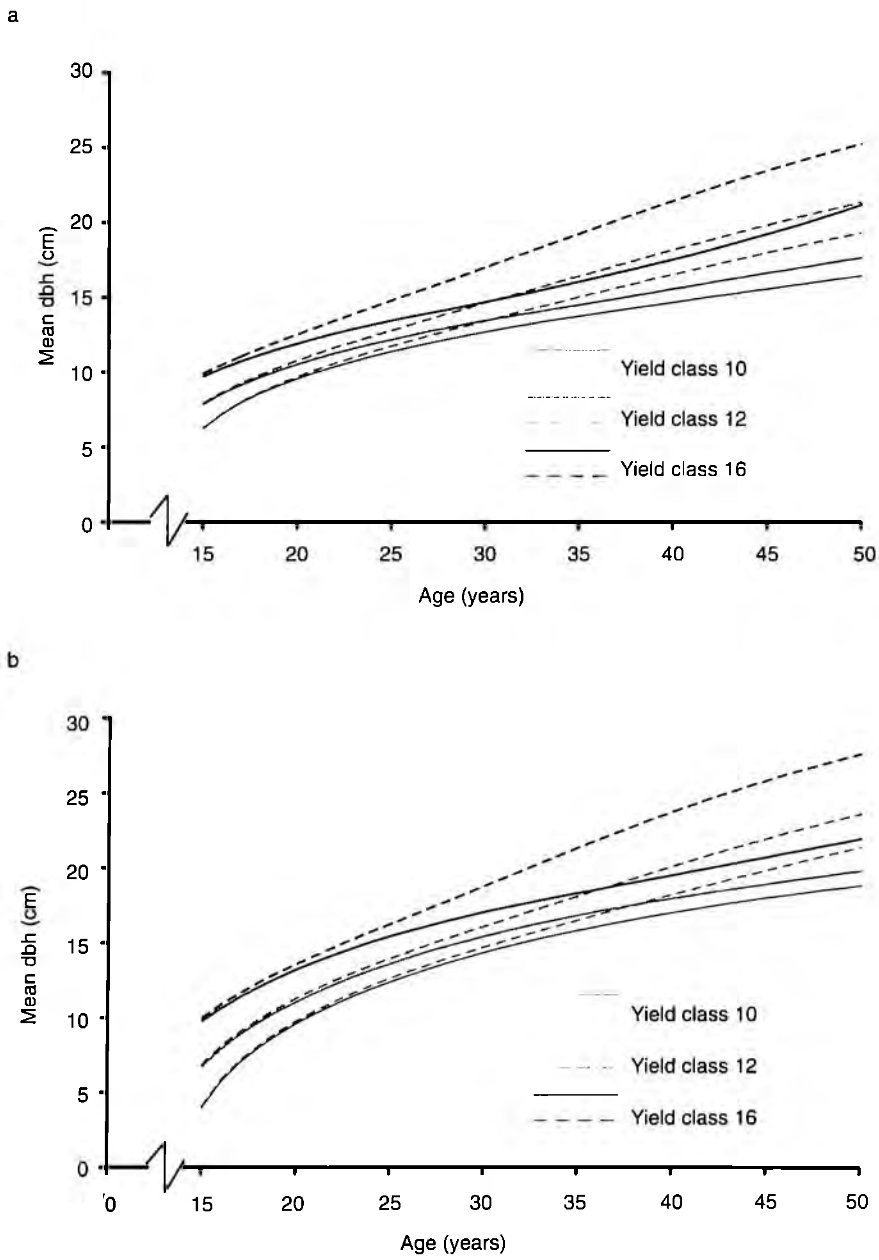


Figure 2. Comparison of predictions of surviving numbers of trees in original and revised models of unthinned Sitka spruce for planting spacings of 1.7 m (a) and 2 m (b). Dashed lines: original model; solid lines: revised model.

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# *Squirrel Population and Habitat Management*

*by Harry Pepper and Simon Hodge*

During 1995 the Forestry Commission reviewed its strategy on squirrel research and management, resulting in a paper presented at the NPI Red Alert UK Forum (Edinburgh, 17-18 October 1995). As part of the process, we consulted the conservation agencies over research priorities and opportunities for collaboration. Red squirrel research priorities are summarised in Section 5.5 of the draft Red Squirrel Species Action Plan (Biodiversity Steering Group, 1995) as:

> "Continue research on feeding ecology, bait hoppers, supplementary feeding, red/grey interactions, methods of control and eradication (e.g. immuno-sterilants), translocation, population reinforcement, habitat manipulation (including nestbox provision), and phylogenetic studies"

The need to develop increasingly effective controls for the prevention of bark-stripping by grey squirrels is outlined in Section 3.16 of the Government's sustainable forestry policy document (UK Government, 1994).

**Effectiveness of warfarin hoppers in preventing access to red squirrels**

Targeted use of warfarin represents the most effective, selective and humane method of grey squirrel control currently available, and specificity trials of the grey squirrel only hopper developed by the Research Division (Pepper and Stocker, 1993) were undertaken in 1994 in an area of the Lake District containing red and grey squirrels (Pepper, 1995). The Pesticide Safety Directorate requested a larger scale trial, which is under way on Anglesey; an island inhabited by expanding grey squirrel and declining red squirrel populations. Use of hoppers is being monitored by regular inspection of hairs caught on sticky blocks placed in the hopper entrance tunnel, monitoring of bait take, and by systematic inspection of woodlands for squirrel carcasses. More intensive monitoring of warfarin hoppers with video surveillance equipment is under way in a North Wales forest (Figure 1). In addition miniature infra-red cameras record the actions of squirrels that enter hopper entrance tunnels.

Figure 1. Closed circuit television surveillance of a grey squirrel hopper entrance in a North Wales forest.

**Cage traps and nest boxes for squirrel control**

Cage trapping is the recommended means of controlling grey squirrels in areas where the use of warfarin is not permitted. These traps, particularly single capture designs, do not select against red squirrels and there is concern that stress induced mortality of captive red squirrels can be high. A study in collaboration with Queen Mary and Westfield College (University of London) is in progress to determine if modifications to the multi-capture trap can reduce the red squirrels catch. This study will also offer specificity data for comparison with the trials of the warfarin hopper.

Nest boxes may be deployed as a means of removing grey squirrels from damage vulnerable conifer crops in which bait take from ground situated warfarin hoppers tends to be poor. A trial in collaboration with Forest Enterprise is under way in Nottinghamshire.

### Grey squirrel immuno-sterilization

The potential for the development of a grey squirrel immuno-sterilant (Pepper, 1995) is being explored by means of a contract let to the University of Sheffield. Work is focusing on grey squirrel sperm (see Figures 2 and 3) and specifically the receptor kinase involved in the sperm-egg recognition process. A cDNA squirrel testis library is being constructed in order to identify and clone the gene encoding the receptor molecule, and to test for uniqueness when compared to other species such as the red squirrel. Blocking of the receptor kinase is the most obvious route for the development of an immuno-sterilant and it is hoped to construct synthetic peptides capable of blocking the receptor so preventing fertilization. The main unknown is the degree of immune response that these peptides will invoke; a high level of immune response is required to secure a long-lasting effect. If suitably antigenic peptides are identified they will be encapsulated in an immune-stimulating-complex and the potential to deliver it orally on treated bait, without degradation in the gut, will be investigated. Work continues, but even if no major obstacles are encountered, at least five years of lab work, computer population modelling and field trials would be required before such a product becomes available to practitioners.

Figure 2. Electron micrograph of a grey squirrel sperm head showing the massive asymetrical acrosome. Acrosome intact spermatozoa displayed a mean progressive motility of 45 μm/sec.

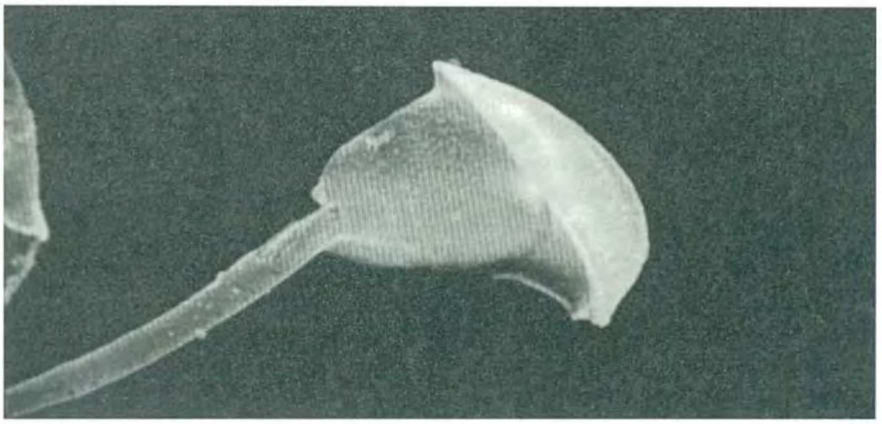

Figure 3. Electron micrograph of a squirrel sperm head after the acrosome reaction (same magnification as Figure 2). Acrosome reacted spermatozoa displayed a mean progressive motility of 15 μm/sec.

### Quantifying economic impacts of damage

There is a considerable body of case study information indicating that bark-stripping by grey squirrels is a threat to the production of high quality broadleaved timber. Furthermore, damage to conifers appears to be increasing. A comprehensive analysis is required, and is underway in the Forest of Dean, to compare the costs and benefits of control by various means. The time lag between damage and harvest, the effects of cumulative damage, and the stochasticity of infection by rot fungi are factors which complicate such an analysis.

### Damage prediction

Verification of the grey squirrel prediction index (Pepper, Dagnall and Gurnell, 1994) continues as data are required over a number of years before the relationship between index trapping and damage can be firmly established.

### Damage reduction by silvicultural adjustments

Grey squirrel damage tends to be highest on vigorous trees (Kenward *et al.*, 1996) and forest management promotes the vigorous growth of trees. This basic correlation restricts the scope of silvicultural adjustments that may reduce squirrel damage whilst not reducing stand productivity and value. Research effort will focus on stand attributes thought to be unattractive to squirrels: dense ground vegetation (Kenward *et al.*, 1996); widely spaced trees and branch-free stems.

## Forest management for red squirrels

Formulating recommendations for forest habitat management to favour red squirrels is seen as the best long-term solution to the protection of selected red squirrel populations. Red squirrels appear to have a slight competitive advantage over grey squirrels in large areas of pure conifer. Recommendations have been made by Gurnell and Pepper (1991) and Lurtz *et al.* (1995) on how to manage conifer forests to maximise the competitive advantage of red squirrels. A collaborative species recovery project established in Thetford Forest in 1985 to develop and test these recommendations in a lowland pine forest continues (Pepper, 1995).

Clocaenog Forest in North Wales is also being managed by Forest Enterprise to benefit red squirrels, and the Research Division is working with the Countryside Council for Wales to study red and grey squirrel ranging behaviour and population trends in relation to forest structure, composition and management. The research, which started in 1992 and is planned to continue to at least 1999, aims to determine whether the present species composition of Clocaenog Forest is sufficient to sustain a self-supporting red squirrel population without grey squirrel control. It is too early to establish population trends but radio tracking data indicate considerable overlap in red and grey squirrel home ranges and show that grey squirrels spend long periods of time away from broadleaved belts. Both red and grey squirrels spend much of their time in pine and Norway spruce stands over 30 years old and appear to favour Scots pine/Norway spruce mixtures, with dreys commonly built in Norway spruce trees. Lurtz *et al.* (1995) found red squirrel densities in Spadeadam Forest to be highest in lodgepole pine/Norway spruce mixtures.

In some Scottish forests, red and grey squirrels appear to be in stable coexistence at a landscape scale. It is postulated that a sharp woodland type/elevation transition (which is not found in the Clocaenog study area) could prevent grey squirrels exploiting the whole of these forests; grey squirrels tending to centre on low elevation areas of mixed woodland, whilst red squirrels survive in tracts of higher elevation conifers. A study has been initiated with Scottish Natural Heritage to test this hypothesis. The research approach allows comparison with the Clocaenog study.

## Can control of grey squirrels benefit red squirrels?

The mechanisms by which grey squirrels might interact with reds are still unclear, but the correlation between grey squirrel range expansion and red squirrel range contraction is clear. A project on Anglesey has been initiated with the Countryside Council for Wales to determine whether grey squirrel control will result in an expansion of red squirrel distribution and population both within and beyond the two conifer forest refugia. The warfarin trials described on p.40 offer the opportunity to substantially reduce the island's grey squirrel population without the prospect of significant reinvasion. Further grey squirrel control may be required if pockets remain after the 1996 control period. Systematic monitoring of squirrel activity, and deployment of several hundred hair tubes, will take place throughout the island's woodlands for the next 5 years.

## Supplementary feeding of red squirrels

Collaborative work continues on improvements to the design of the red squirrel supplementary feed hoppers (Pepper, 1993), and to determine any benefits to red squirrel population stability.

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# *Application of the Freshwater Critical Loads Approach to Forestry*

*by Tom Nisbet*

The *Forests and water guidelines* (Forestry Commission, 1993) recognise the role that forests can play in contributing to the acidification of sensitive waters. Forest canopies can significantly increase the capture or scavenging of acidifying pollutants (such as sulphur and nitrogen) from the atmosphere as a result of turbulent air mixing above forest stands (Figure 1). This factor needs to be taken into account when planning new afforestation schemes to ensure that change in land use does not lead to freshwater acidification.

Figure 1. The enhanced capture of mist, which can contain large concentrations of sulphur and nitrogen pollutants, represents an important deposition pathway to forests. This effect is greatest at high altitudes due to the increased duration of cloud cover and high windspeeds.

The critical loads concept provides a means of identifying those waters which may be at risk from forest planting. A freshwater critical load is defined as the maximum deposition of sulphur pollutants that will not cause chemical changes in stream waters or lakes leading to long-term adverse effects on salmonid fish. For new planting proposals within acid sensitive areas, critical loads assessments are required at the catchment scale (Forestry Commission, 1993). Approval of a Woodland Grant Scheme is unlikely where the additional pollutant capture is expected to contribute to critical loads exceedance.

The application, development and validation of the freshwater critical loads approach for the above task has continued to form an important activity within Environmental Research Branch. The following describes the main elements of the research and liaison work which underpin policy and advice on acidification.

Environmental Research Branch provides guidance to the Forestry Commission and to WGS applicants on the procedures and criteria to be used for undertaking catchment-based assessments. Ongoing discussions with the water regulatory authorities in Wales (Environment Agency) and Scotland (Scottish Environment Protection Agency) have resulted in a number of recent refinements to the recommended approach. A separate set of criteria based on the area of acid sensitive geology and soils and an altitude threshold of over 300 m is now in place in Wales for determining where catchment-based assessments are required. These criteria reflect the occurrence of known acid waters better than the area represented by the national critical loads map. An alternative scheme is favoured for Scotland, based on the original critical loads exceedance map in the guidelines but modified to include sites in adjacent squares, where appropriate. For England, Wales and Scotland, catchment-based assessments involve two stages, with an initial, simple, analysis being used to sift out those sites where critical loads exceedance is unlikely. Sites which fail this first stage require a more detailed assessment to be undertaken. A number of aspects of the critical loads calculation are also under discussion, such as increasing the critical chemical value in the critical loads equation in order to provide greater protection for salmonid fisheries. In the long term, the contribution of nitrogen deposition to surface water acidification and the interactions with forestry will need to be addressed.

We undertook nine catchment-based assessments for new planting applications during the year. Eight of these were in Scotland and the results indicated that the planting proposals would not result in the freshwater critical load being exceeded and so were unlikely to be damaging to the aquatic environment. In contrast, the one scheme in Wales suggested the waters would be at risk of acidification, although this situation was reversed when a subsequent, more detailed assessment (stage 2), considered the impact of forthcoming pollutant emission reductions.

Table 1. Freshwater critical loads assessments for streams draining key Welsh forest design plan sites.

| Stream | Critical load | Sulphur deposition 1986-88 | Sulphur deposition 2010 |
|---|---|---|---|
| Afon Biga | 1.32 | 1.22 | 0.49 |
| Afon Bidno | 2.11 | 1.22 | 0.47 |
| Nant yr Helyg | 1.03 | 1.66 | 0.57 |
| Nant-y-Bont | 0.51 | 0.96 | 0.49 |
| Afon Melau | 2.27 | 1.66 | 0.52 |
| Afon Wen | 5.70 | 1.41 | 0.53 |

Units in keq H $ha^{-1}$ $yr^{-1}$

Table 2. Impact of forest design plan on pollutant sulphur deposition inputs to the Nant yr Helyg and Nant-y-Bont catchments.

| Nant yr Helyg | % mature forest (>20 yrs age) | □Background sulphur deposition | *Forest sulphur deposition |
|---|---|---|---|
| 1989-1992 | 58 | 1.42 | 1.57 |
| 2002-2006 | 50 | △0.71 | △0.78 |
| 2007-2011 | 50 | +0.52 | +0.57 |
| 2017-2021 | 24 | +0.52 | +0.55 |

| Nant-y-Bont | % mature forest (>20 yrs age) | □Background sulphur deposition | *Forest sulphur deposition |
|---|---|---|---|
| 1989-1992 | 100 | 1.01 | 1.22 |
| 2002-2006 | 46 | △0.51 | △0.55 |
| 2007-2011 | 29 | +0.47 | +0.49 |
| 2017-2021 | 38 | +0.47 | +0.50 |

*Based on a 19% (N. yr H.) and 20% (N.-y-B.) forest scavenging factor modified for the proportion of mature forest within catchment.
□Assuming a complete moorland vegetation cover.
△Assuming 50% cut in 1989-1992 sulphur depostion inputs by 2005.
+Assuming predicted 54% (N.-y-B.) and 63% (N. yr H.) cut in 1989-1992 sulphur deposition inputs by 2010.
Sulphur deposit unit as in Table 1.

Recently, attention has shifted from new planting to a consideration of the impact of restocking of existing forests within acidified areas. In particular, there was a need to quantify the effect of forest restructuring on pollutant deposition following the Forestry Commission's introduction of forestry design plans in 1993. The resulting increased diversity in forest age and species structure, the opening up of stream sides and the general lowering of upper forest boundaries, were expected to bring about a significant reduction in pollutant scavenging within forested catchments. A study was therefore undertaken to investigate the impact of forest restructuring against a background of emission reductions on pollutant deposition to sensitive catchments.

Discussions with the National Rivers Authority (now the Environment Agency) led to the identification of five forest design plans within acid sensitive areas of upland Wales as candidates for exploratory catchment-based assessments. The data for six catchment streams draining the area covered by these plans are presented in Table 1. The results reveal that only in the case of the Nant yr Helyg and Nant-y-Bont streams did the 1986-88 sulphur deposition exceed the freshwater critical load. However, the substantial emission reductions that are planned to come into effect by 2010 (80% of 1980 levels) are predicted to protect all streams from further acidification. The improvement caused by forest restructuring in terms of decreased sulphur deposition inputs was found to be relatively small compared to that due to the emission reductions, the latter reducing the forest scavenging component to a very small value (Table 2). This work suggests that the restocking of forests in upland Wales is unlikely to represent a significant threat of stream water acidification. The study will now be extended to cover a number of key forest design plan sites in south-west Scotland.

Although the critical loads approach appears to provide a useful framework for assessing those sites at risk from a forest scavenging effect, the concept is relatively new and much work remains to be done in refining and validating the approach at the catchment scale. Long-term catchment studies provide an important source of data for this purpose (Forestry Commission, 1990). A recent investigation of the results from one such study at Loch Dee in south-west Scotland (Nisbet *et al.*, 1995) failed to find any evidence of a forest acidification effect (Figure 2). This was consistent with deposition model estimates which showed the additional pollutant capture by the continued growth of the forest to canopy closure to be small (<10%) at this site (Figure 3).

Recognition of the importance of long-term studies for evaluating the effects of forestry and emission reductions on surface water acidification (Department of the Environment and Forestry Commission, 1991) led to the Forestry Commission and National Rivers Authority establishing 12 new monitoring sites in upland Wales in 1991 (Figure 4). Although a fifth year of monitoring is now complete, at least ten years of data will be required before any meaningful statistical analyses can be carried out. The choice of sites, however, should provide a good basis for a thorough test of the critical loads approach (Figure 5).

Another important piece of work which should make a significant contribution to the development of the critical loads approach is the recent repeat of the original acid waters survey of upland Wales, previously carried out in 1984. This multidisciplinary study is funded by a range of organisations, including the Forestry Commission. The re-survey of 79 stream sites was completed during 1995 and the detailed analysis of the results is now underway. An assessment

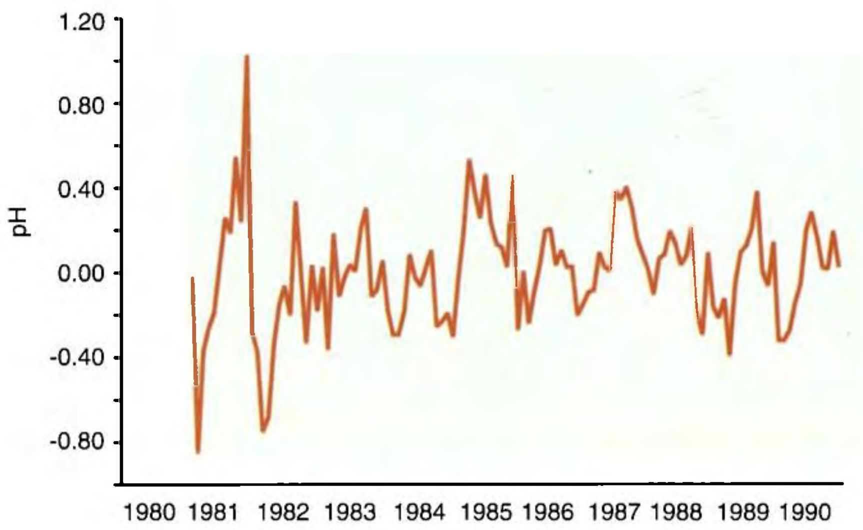



Figure 2. Trend in the mean monthly pH residuals (after correcting for the variation due to stream flow) for the forested Green Burn between 1981 and 1990. A significant increase was observed for pH (0.2 units), which contrasted with a similar decrease in pH for the adjacent moorland Dargall Lane stream.

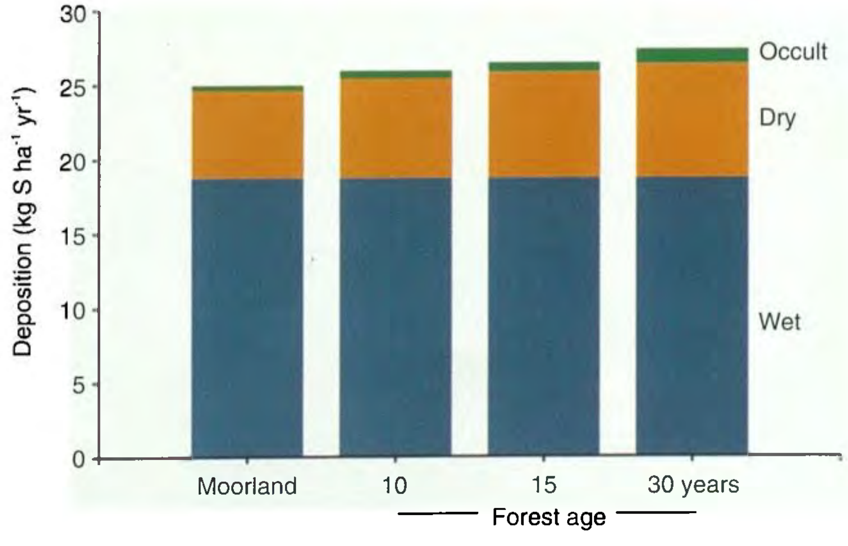
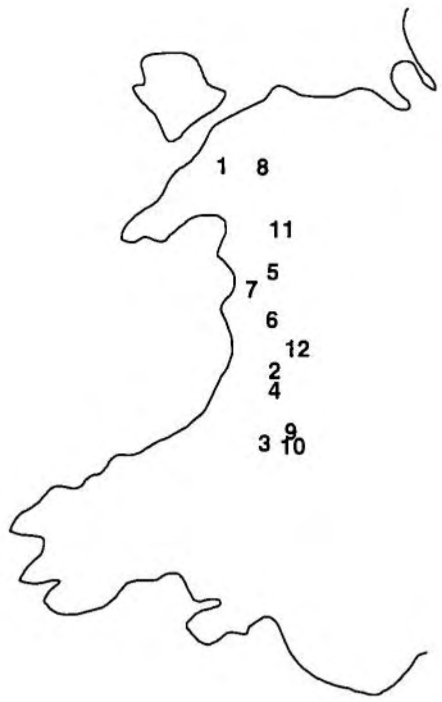



Figure 3. The effect of forest age on total pollutant sulphur depositions to the catchment of the Green Burn, assuming air pollution remains constant at 1983 levels. Calculations of critical load suggest that the planned emission reductions will result in the sustained recovery of the stream, which will be protected from further acidification by 2003.




*Moorland*

1. Afon Colwyn
2. Nant Milwyn

*Forest*

3. Tributory of Afon Cothi
4. Crugnant
5. Nant Ceiswyn
6. Llechwedd-mawr
7. Nant Iago
8. Afon Ceunant-y-Garnedd
9. River Irfon
10. Nant-y-Fedw
11. Nant-yr-Helyg
12. Cefn Hendre

Figure 4. Location of the ten forest and two moorland control, long-term monitoring sites in upland Wales. All sites are acid sensitive, with the forest catchments having greater than 50% forest cover, located above 300 m elevation, in order to maximise the forest scavenging effect.

Figure 5. Catchment view of the Cefn Hendre long-term monitoring site in mid Wales. Around 90% of the catchment is forested, with 67% planted in 1975-77.

of the change in acidification status of Welsh streams and lakes during this period, and the re-examination of forestry as a possible contributing factor, are two of the main objectives of the project.

Involvement also continued on the Plynlimon Steering Group, which oversees a major study by the Centre of Hydrology and Ecology of the impact of forest harvesting and restocking on stream water acidification. This work is now entering its third year and will address in particular, the long-term sustainability issue of whether base cation inputs from canopy scavenging are sufficient to compensate for leaching losses and their removal in harvested produce. Improved guidance on best management practice and the development of a model and guidelines for environmental impact assessment of harvesting operations, are the central objectives of this project.

The successful completion of an intensive catchment-based assessment for the Upper Halladale River in 1994 (Forestry Commission, 1994) led to the approval of four WGSs in 1995 (Figure 6). This provided a valuable opportunity to assess the sustainability of afforestation development within a sensitive highland catchment which supports an important salmonid fishery. Consequently, a multidisciplinary study was set up at the end of 1995, involving Environmental Research Branch, Macaulay Land Use Research Institute, Freshwater Fisheries Laboratory and Highland River Purification Board, with additional funding support from the EU LIFE Fund, Caithness and Sutherland Enterprise and Scottish Natural Heritage. In addition to evaluating the impact of cultivation, drainage and rock phosphate fertiliser operations on stream water acidity and the freshwater biota, this study will allow the effect of forest scavenging and emission reductions in a relatively low pollution, sea-salt dominated climate, to be determined.

The decision of the national power companies to close the catchment liming study at Loch Fleet in south-west Scotland in 1994 led to a consortium of organisations forming a steering group to continue the monitoring work (Figure 7). Most of the original liming treatments carried out in 1986/87 remain effective and it is important to determine the overall timescale of response. This information is essential to a proper cost-benefit analysis of liming as a potential ameliorative treatment to assist the recovery of acidified waters. The Environmental Research Branch and local Forest District played an active part in providing practical and scientific support for this study during 1995.

Assistance was also given to the Solway River Purification Board in evaluating the possibility of liming acid waters on a practical scale in the Galloway area of south-west Scotland. Liming is being considered as a short-term solution to the serious acid waters problem in many of the region's rivers. A working group with representatives from the Forestry Authority and Forest Enterprise has now been set up to take the matter forward at a local level.

Figure 6. Catchment view of the Bealach Burn tributary of the Upper Halldale River. Shallow ploughing was completed in April 1996.

Figure 7. View of Loch Fleet looking south from the main inflowing stream. Catchment liming resulted in the successful restoration of the brown trout fishery.

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# Genetic Diversity of Native Black Poplar

by Ian Forrest
and Joan Cottrell

Black poplar (*Populus nigra* var. *betulifolia*) is the most severely depleted and the most highly endangered of our native trees (Figure 1). It is a dioecious plant of water-meadows and river banks which very rarely reproduces sexually in Britain but readily propagates asexually by rooting from fallen trees and broken branches. As a result of habitat destruction, it has been reduced to isolated individuals and small clusters, mostly planted from cuttings, predominantly in southern England and in Wales. The total remaining population is believed to number some 2000 individuals (Rogers, 1995), many of which may be genetically identical members of unisexual clones, thus the remaining gene-pool may be very small indeed. The status of black poplar has recently attracted considerable conservation and media interest, and surveys of its distribution and diversity have been initiated both in Britain and more widely across Europe. The Forestry Commission has been actively involved in setting up clone-banks to conserve and propagate a representative collection of surviving genotypes.

The present work was undertaken in order to obtain some estimate of the population genetic diversity and of the extent to which the existing trees are clonal. The genetic traits used were RAPD DNA markers (Random Amplified Polymorphic DNA; see Forrest, 1994) obtained by amplification of arbitrary fragments of the genome, by using the polymerase chain reaction (PCR). This class of marker system had previously been successfully used to provide clonal markers for fingerprinting commercial poplar clones (Forrest and Cottrell, 1995). RAPD markers sample the greater part of the genomes of any organism on an arbitrary basis, and are independent of environmental influences. In addition, the degree of resolution achieved in the screening of distinct genotypes can be progressively and almost indefinitely increased, simply by increasing the number of the short synthetic oligonucleotide primers which are used to sample and initiate amplification of the DNA. These factors give RAPD markers significant advantages over traditional biochemical and morphological marker systems in the measurement of genetic diversity and in genetic fingerprinting applications (Figure 2).

Figure 1. Black poplar. *(41145)*

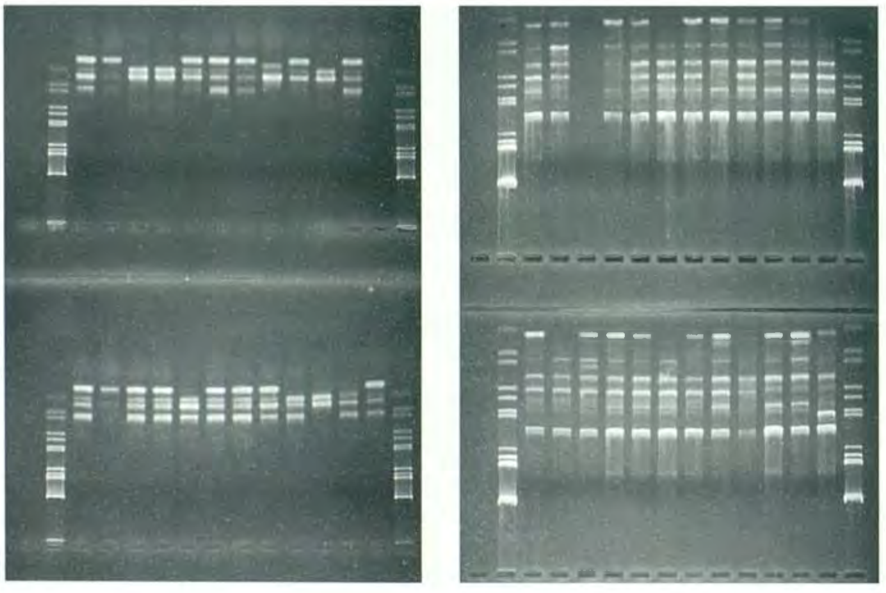


Figure 2. RAPD markers for clones of native black poplar. Stained agarose gels visualised in UV light showing electrophoretic separation of DNA fragments amplified with two different primers. Each vertical lane represents a distinct accession; the outside lanes on each gel are of a reference marker containing fragments of known molecular size. Different primers separate the accessions into different similarity groupings. Two gels are shown for each of the Operon primers G-05 (left) and C-06 (right).

Shoots with dormant or flushing buds were obtained from the native black poplar clonal collections in Norfolk and Gwent, and from mature trees sampled *in situ* in the field. DNA was successfully extracted from the buds and unfurling leaves of 36 accessions, representing a large part of the natural range and including six trees known to be female. All PCR reactions were replicated, and only those amplified fragment bands consistently visualised by agarose gel electrophoresis were recorded. Only bands of moderate to high intensity were used in the analysis. For a given primer, bands of equal mobility were assumed to be the same. From the primers screened, 12 revealed polymorphisms among accessions and so were used in the analysis. The total number of bands recorded was 43, of which 21 were monomorphic and 22 were polymorphic; however, exclusion of the data for the accession suspected to be a hybrid (Barn Elms, London) reduced the number of polymorphic bands to 11. A similarity coefficient for each pair of accessions was calculated, and a dendrogram was constructed to show the genotypic relationships between the accessions on a similarity index (Figure 3).

The 12 primers distinguished 17 distinct genotypes among the 36 accessions, implying that the number of distinct genotypes is about 50% of the total number of individuals. However, this may be an overestimate, since the accessions were in general derived from geographically distinct origins, whereas more localised clusters of trees have a greater chance of being clonal. Seven of the genotypes were clonal, and ten were unique; the largest group of a clonal genotype consisted of eight trees. It is possible that the use of additional primers would split the groups further, although 12 primers would generally be reckoned to be fully adequate to identify common genotypes with a very high degree of probability. Within most groups even the minor band patterns were identical, indicating that the accessions were indeed clonal.

Of the six accessions known to be female, five were genetically identical,

Figure 3. Dendrogram of native black poplar accessions showing percentage genetic similarity based on RAPD DNA markers.
(f) = accessions known to be female (h) = suspected hybrid

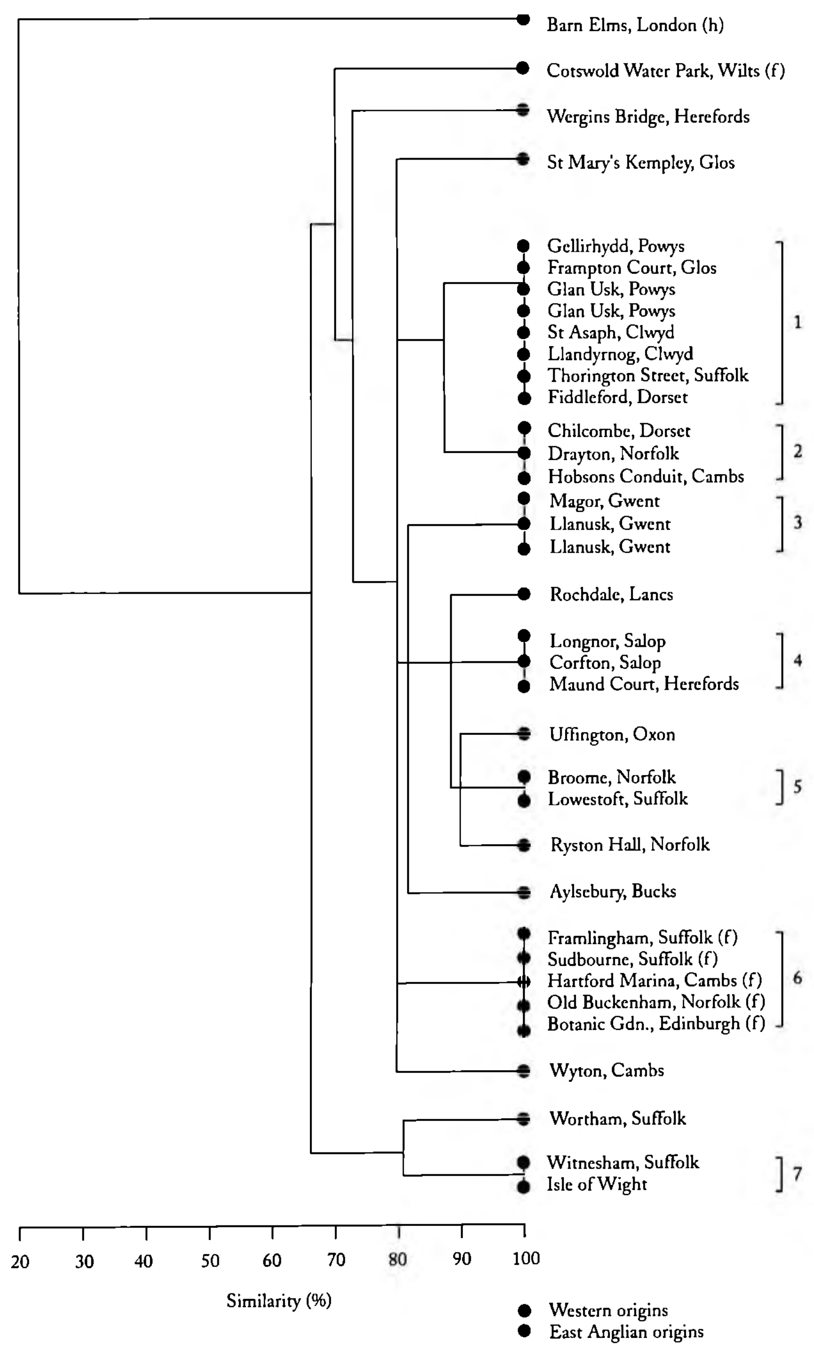
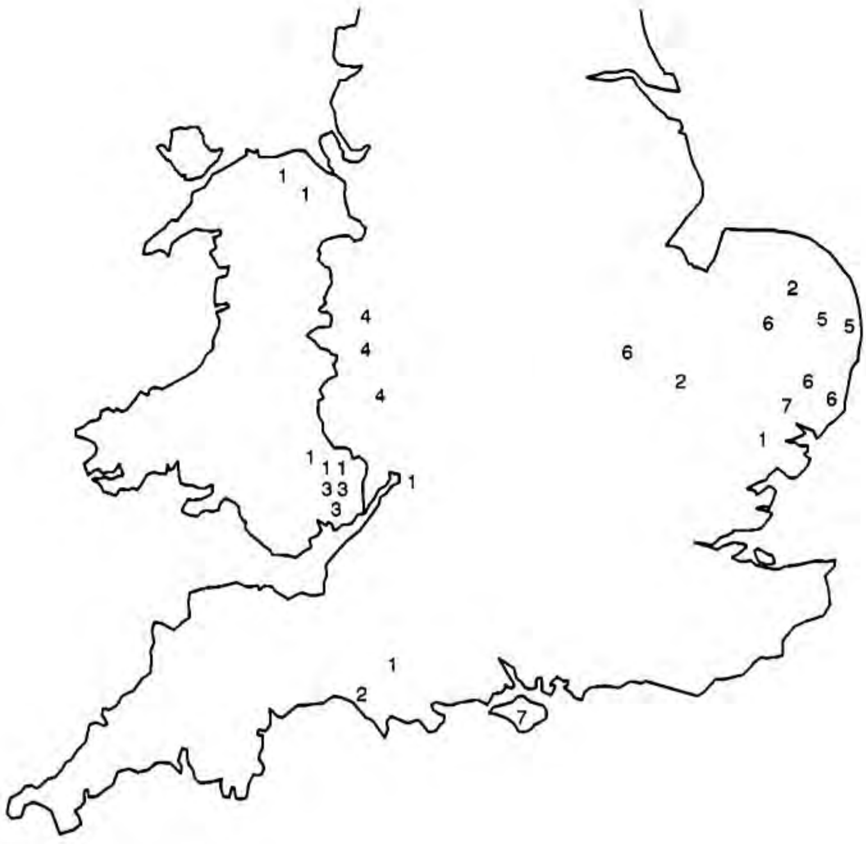


Figure 4. Location of native black poplar accessions shown to be clonal from RAPD DNA markers. Figures indicate the clonal group genotype to which the accessions belong (see dendrogram, Figure 3).




suggesting that the genetic base is dangerously low compared with that of the males, especially as there are believed to be only some 150 female trees remaining in the country (Rogers, 1995). This is probably due to the fact that propagation of females is discouraged since the seed-fluff can be a nuisance.

The dendrogram shows a moderate degree of genetic variation among genotypes. Studies on wide-ranging natural populations using RAPD markers at the species level often show variation ranging over 0.5-0.8 on a similarity index scale. Native black poplar is considered to constitute an infraspecific taxon, so that the observed variation is perhaps encouragingly high, particularly as the total population is now numerically so small and reproduction has recently been predominantly by vegetative means.

The accession from Barn Elms, London, was suspected of being a hybrid from its morphology. This genotype was outstandingly distinctive as compared with all other accessions in RAPD band pattern with the majority of the primers used, and showed the greatest genetic distance from other accessions. One of the major bands resulting from amplification with primer Operon A-01 seems from our previous work with various poplar species never to occur in *P. nigra*. Thus all the evidence points to a hybrid identity.

The individual accessions within several of the clonal groups originated wholly or predominantly from the same local area, which would result both from natural regeneration within river systems and from localised planting of selected material (Figure 4). The dendrogram similarity groupings suggest some significant correlation between genotype and geographic origin, in particular a distinction between the East Anglian origins and those clustered around the Welsh and Severn river systems. This is supported by further statistical analysis of the RAPD band patterns, and may indicate local adaptation. However, certain genotypes (most notably no. 1 in Figures 3 and 4) are represented in two or more quite distinct localities, which must reflect the wider-scale transfer and planting of ramets from selected common stock.

The implications of this work for conservation are:

- the male gene-pool is still moderately high, but that of females may be much lower;
- it is probable that the number of distinct genotypes is considerably less than 50% of the total number of individuals in the population;
- RAPD markers can be used to select a range of genotypes, representing the remaining diversity of the taxon, for conservation in clone-banks;
- the natural distribution of genotypic variation has to some extent become confused by transfer of planting material over moderate or long distances.

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# Some Examples of Computing and Statistical Techniques Used in Forestry Research

*by Ian White*

The availability of easy-to-use statistical and spreadsheet packages has reduced the amount of time that statisticians need to spend on routine analyses, such as regression and analysis of variance. However, there remains a need for advice, seminars, and short courses to teach basic statistical skills and to alert users to potential difficulties. The statistician must still ensure that experiments are properly designed and that the results are interpreted correctly. At the same time, techniques rarely used in forestry research in the past can take on increasing importance. For example, with the current emphasis on conservation and biodiversity, vegetation analysis has an increasing part to play in many experiments and surveys. As a consequence, project leaders are having to become familiar with the interpretation of results from multivariate statistical techniques such as correspondence analysis and canonical correlation analysis.

The increasing use of automatic data-loggers (e.g. at meteorological stations) results in the production of huge quantities of raw data and increasingly statisticians are concerned with validation and efficient storage as well as analysis. For example, wind and temperature data from poplar provenance trials at 42 sites are collected on memory cards and downloaded every two months. After checking and storage, Genstat is used to summarise the minimum, maximum and mean temperatures, and to display the wind directions as a rose diagram.

Computerised databases have been developed to help statisticians obtain quick and easy access to experimental data, and these have greatly increased the efficiency with which data are stored and retrieved. Computerised data entry forms, incorporating validation procedures, allow checks to be made on the accuracy of data before they are entered in the database.

Before the advent of computers, it was essential that experimental designs produced data which could conveniently be analysed by hand. Access to constantly increasing computing power and on-line data storage facilities now enables statisticians to tackle analyses that would have been impossible a few years ago. For example, the generalised lattice which was once impracticable is now relatively simple to deal with. Although many statisticians discourage their use, single tree plot designs can now be analysed comparatively easily, and the loss of trees, which would once have severely reduced the value of the experiment, can now be accommodated. However, complexity for its own sake is not desirable and many experiments will use a standard randomised block design, which is versatile, robust and easy to interpret.

The availability of increased processing power has also allowed simulations to be used to check models and provide guidance on the errors in the results. An important example of this is the estimating of deer populations using 'standing crop' counts of dung pellets. Decay times for pellet groups can be simulated using known pellet group sizes and known individual pellet decay rates.

Inferences based on small sets of data can now be made more reliably by using a package which can calculate exact tests from observations classified or ranked by one or two factors.

**The following experiments are of particular interest.**

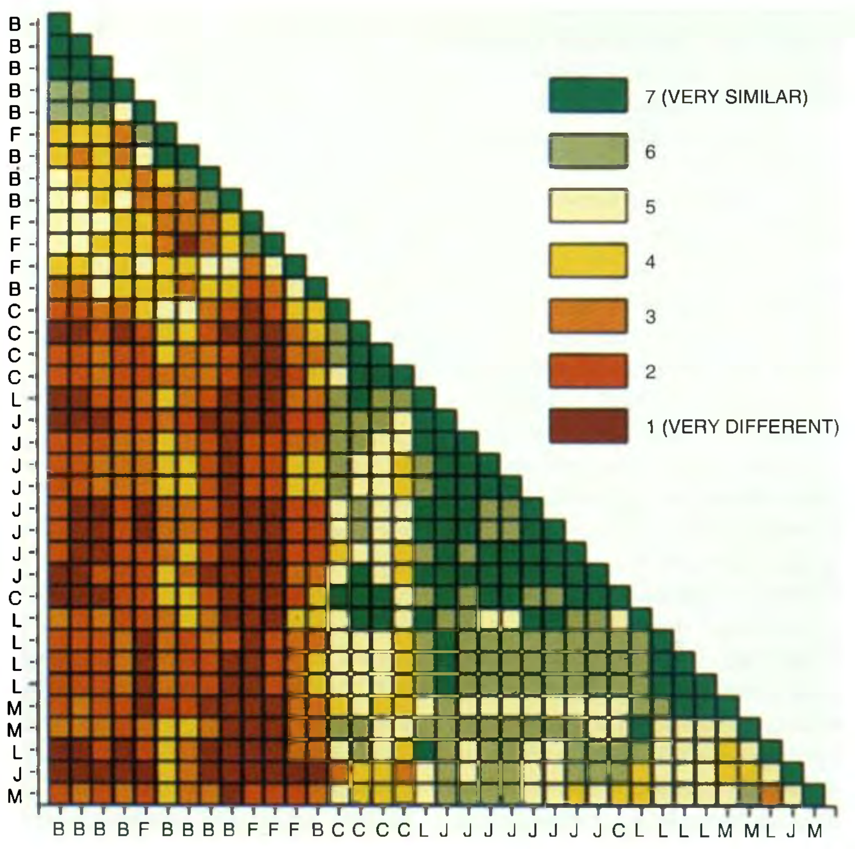
In capture-recapture experiments, each unmarked animal is marked and previously marked animals have their capture recorded. All animals are then released back into the population. At the end of the study there will be a complete capture history for every animal caught. The basic model used, for open populations, is the Jolly-Seber model. This probabilistic model allows estimation of population size and capture rate at each sampling time, as well as survival rates and recruitment numbers between sampling times. The emphasis in recent years has been on developing models where estimation of the survival and capture rates is of primary concern, rather than of population size. In the past experiments of this type have been used to estimate grey squirrel populations and at present they are being used to assist in understanding the population dynamics of the insect *Hylobius abietis*, a major pest in upland forest restocking sites.

Figure 1. RAPD analysis produced band patterns for 36 clones of poplar in six taxonomic groups: *deltoides x trichocarpa, nigra* (and *nigra* crosses), *trichocarpa, trichocarpa x deltoides,* and *trichocarpa x maximowiczii* (labelled B, C, F, J, L, and M in the diagram). The presence or absence of each of 33 bands was recorded for each clone, and a coefficient of similarity was calculated for each pair of clones as

$$S = \frac{\text{number of matching bands}}{\text{total number of bands for both clone}}$$

The structure of the 36 x 36 similarity matrix is illustrated by a system of shading. It is clear that the RAPD results agree with the established taxonomy of *Populus,* and that groups B and F (i.e. those including *nigra*) are clearly separated from the rest.

Similarity matrix for 36 clones in 6 groups




DNA analysis of plant material produces multivariate binary datasets based on the presence or absence of electrophoretic bands. These data have been analysed by calculating a matrix of similarity coefficients for each pair of samples (Figure 1). Patterns of differences between samples can be displayed as a dendrogram or a plot of principal coordinates derived from this matrix.

In hydrological studies, a simple transfer function model is now used routinely to model fluctuations in weekly borehole water levels in response to rainfall. Each of the parameters of the model has a simple interpretation in terms of physical soil properties.

Competition experiments with single tree designs allow competition between trees of contrasting species to be investigated. In these designs, the number of neighbours of each tree of opposite species is balanced throughout the experiment. Full analysis requires modelling of the interactions between individual trees.

Analyses involving repeated measures where the same unit is assessed at different times, or in the case of soil properties at different depths can be handled reasonably easily, even when the data have become unbalanced due to loss of plots or treatments over time. Such data were produced by a soil compaction experiment in which the primary measurement was the number of strikes required to drive a rod into the ground to a depth of 10, 20, ...., 100 cm. The data were unbalanced because the intensity of sampling varied from plot to plot and from year to year. The data were further complicated by missing values, produced when the rod could not be driven into the ground to the full 100 cm. The data were analysed in two stages: firstly, estimating the missing values by extrapolation from the known values, then fitting a generalized linear model to the completed data set.

An expert system for fertilizer advice is being developed. This takes data on foliar analysis and visual symptoms (e.g. needle colour and retention), applies a set of empirical rules based on past experience, and produces a recommendation on the requirement for N, P, or K fertilization and weeding.

These examples demonstrate some of the new opportunities for applying mathematics and statistics to forestry research, and show how recent advances in computing have extended the range of feasible statistical analyses.

# *Appendix 1*

The following titles were published during the year ending 31 March 1996.

**Report**

Report on forest research 1995. (£19.50)

**Bulletins**

114 Forests and wind: management to minimise damage. (£7.00)

115 Alternative silvicultural systems to clear cutting in Britain: a review. (£15.95)

116 Analysis of the changes in forest condition in Britain 1989-1992. (£9.95)

**Field Book**

8 The use of herbicides in the forest (4th edition). (£9.95)

**Handbook**

11 Creating and managing woodlands around towns. (£18.00)

**Technical Papers**

9 Decline in Sitka spruce on the South Wales coalfield. (£6.00)

11 The use of treeshelters: 1992 survey. (£3.00)

12 The native woodland resource in the Scottish Highlands. (£4.00)

15 Borates for stump protection: a literature review. (£4.00)

**Research Information Notes**

259 Management of coppice stools.

260 An ecological site classification for forestry in Great Britain.

261 The effect of whole-tree harvesting on early growth of Sitka spruce on an upland restocking site.

263 Site capability assessment for woodland creation on landfills.

264 Assessment of fence collisions by grouse species in Scotland.

265 Approved poplar clones.

266 The effect of aerial applications of urea fertiliser on stream water quality.

267 Reducing disturbance to goshawks during the breeding season.

274 Noxious weeds.

275 Natural regeneration of broadleaved trees.

276 Economic surveys of farm woodland establishment.

277 Phytophthora disease of alder: the situation in 1995.

278 Poplar and willow clones for short rotation coppice.

279 Herbicide update (spring 1996).

**Miscellaneous**

World class research for sustainable benefits. (Free booklet)

Farm woodlands research. (Free leaflet)

Silviculture South Branch. (Free leaflet)

## *Publications issued by the Technical Development Branch*

**Reports**

01/95 Second field trials of short rotation coppice harvesters.

02/95 FMG 762 grapple harvester head and Daewoo 220 LC base.

03/95 Evaluation of tractor-based wire loader forwarder.

04/95 Charcoal production: a 2 tier steel kiln case study.

05/95 Further evaluations of planting machines for short rotation coppice.

07/95 Packaging and handling of vegetatively propagated, container grown Sitka spruce.

**Technical Notes**

01/95 Ulvaforest boom modifications.

02/95 Layout of short rotation coppice for harvesting.

03/95 Initial investigation into rooting characteristics of willow clones.

04/95 RGL plant rhododendron and woody weed flail.

05/95 Temporary deer fencing.

06/95 Moisture loss after felling.

07/95 Direct seeding.

08/95 An introduction to tractor-mounted sprayers in farm woodlands.

09/95 Evaluation of Valmet 960/JS 200 LC grapple harvester.

10/95 Evaluation of the Rollmaster tractor-mounted weedwiper.

11/95 Harvested short rotation coppice transport options.

12/95 Small to medium scale comminution machinery.

13/95 Kintyre tank bund Mk II.

14/95 Machine cleaning on site.

15/95 Evaluation of applicators for Marshal/suSCon granules.

16/95 Terrain classification.

17/95 Residue production from clearfell at Kielder.

18/95 Refillable Roundup 10 litre containers.

19/95 Stump removing equipment.

20/95 Application of bunded tank systems in forestry.

21/95 Klose rotary ditch cleaner.

22/95 Lowland Ulvaforest sprayer control system.

23/95 Further trials of cartons for carrying CVPSS stock.

25/95 The adaptation of agricultural tractors for forestry.

26/95 Harvesting in undermanaged woodlands: an initial investigation.

28/95 Timber trailers for agricultural tractors.

**Information Notes**

01/95 Project areas.

02/95 Planting machines for farm woodlands.

03/95 Christmas tree planting by 2-row machine.

04/95 Register of contractors for soil loosening contracts in the East Midlands area.

05/95 Clean injection system.

06/95 Fibreglass tool shafts.

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# Appendix 3

## Entomology Branch

**Plant health**

Research into the risks from indigenous and non-indigenous forest insect species. The use of Pest Risk Analysis techniques to determine contingency options for potential pests.

**Restocking pests**

Research into effective use of chemicals for direct control of restocking pests, notably *Hylobius abietis* and develop Integrated Pest Management strategies for plant protection. IPM relies on effective monitoring linked to knowledge of population dynamics of *H. abietis*, and the use of insect parasitic nematodes for direct control of larval stages in stumps. The aim is to develop decision support systems for forest managers to avoid or reduce reliance on chemicals.

**Impact of insects on tree growth**

Investigate quantitative relationships between insect population pressure and the growth of trees attacked by those insects. An important aim is to separate the direct effects of damage from other biotic and abiotic variables that might mask the impacts of pest insects. The target species is green spruce aphid, *Elatobium abietinum*, which severely defoliates both Norway and Sitka spruces.

**Mechanisms of tree resistance to insect attack**

Investigate interactions between genetically determined tree defence mechanisms and site mediated factors. Different seed origins of Sitka spruce analysed for their physical and chemical defences when planted on different sites and when subjected to attack by insects with different feeding strategies (sucking and foliage feeding insects and bark beetles).

## Environmental Research Branch

**Soil sustainability and site studies**

Investigate the biological sustainability of current UK forest practices (i.e. the ability to grow successive crops without detriment to soil chemistry and physical properties). Specified objectives are also to improve tree growth on lowland sites, in conventional and novel silvicultural systems by establishing practices appropriate to the site factors.

**Reclamation of man-made sites for forestry**

Improve methods of establishing woodland and management practices on man-made sites, taking into account changes in forestry and land-use policy, planting opportunity, environmental impacts, mining practices, technology and advances in reclamation practice in agriculture and other land uses.

**Forest hydrology**

Catchment studies, monitoring and modelling to provide a firm basis of knowledge for the sustainable management and planning of forestry with respect to protecting the freshwater environment in both quality and quantity.

**The effects of air pollution on trees**

Experimental work in open-top chambers and at forest monitoring plots to understand the impacts of air pollution and other environmental factors on trees. Part of the work is in compliance with EU regulations and also provides data to the Longrange Transboundary Air Pollution Convention for the calculation and mapping of critical loads.

**Environmental/climate change**

Experimental work in open-top chambers and in forest stands to predict the impacts of environmental and climate change on tree growth and condition. A further objective is to identify interactions between forestry and a changing global environment (e.g. exchange of greenhouse gases).

**Environmental change network**

Monitor and understand environmental change and its impact on terrestrial ecosystems. Manage one of the national network of terrestrial sites of the ECN network.

## Mensuration Branch

**Sample plots**

Develop and maintain national reserve of periodic growth and yield data to support measurement, growth and yield studies using a network of permanent and temporary sample plots. Current focus: contemporary silvicultural practices, uneven-aged planting mixtures, modern planting and harvesting systems, long-term environmental change monitoring.

**Yield models**

Improve methods and models for forecasting growth and yield of forests. Current focus: development of interactive stand-level yield model software, site:yield relationships, biomass yield models.

**Measurement**

Investigate measurement systems and instruments for the accurate and efficient measurement of trees and timber. Current focus: European standards, revision of measurement guides, development of non-destructive methods of biomass assessment, improvement in measurement systems using field computers and laser technology.

## Pathology Branch

**Tree disease: diagnosis and the provision of advice**

Diagnose disease in trees and provide advice and information on disease identification, management and control.

**Tree health monitoring**

Monitor the health of the nation's trees, monitor the risks posed by exotic and native pathogens and raise awareness of tree health issues.

**Dutch elm disease**

Conduct research on Dutch elm disease with the aim of achieving long-term biological control. Obtain insight into the behaviour of an exotic pathogen adapting to a new environment and assist development of resistant elm cultivars.

**Fomes root and butt rot of conifers**

Manage and control Fomes root and butt rot, the most serious forest disease of conifers in the northern hemisphere, and investigate new control methods notably boron compounds.

**Phytophthora root diseases of trees**

Investigate Phytophthora diseases of trees in order to determine their impact and the possibilities of control. Monitor spread and research the new ecology of alder Phytophthora.

**Special topics in tree pathology and mycology**

To undertake a number of special studies in the field of tree pathology and mycology.

* Funding for some of these programmes is also provided by the European Union, other Government Departments, charities and commercial organisations.

## *Silviculture (North) Branch*

### Forest nutrition and sustainability

Investigate how site fertility influences tree productivity and how forest operations affect sustainability of forest site fertility, including nutrient cycling and tree growth response to fertilizer trials.

### Nurseries and establishment

Integrated studies of nursery practice, plant handling, planting methods, site preparation and maintenance of plantation establishment.

### Silvicultural effects upon timber quality

Investigate the impact of silvicultural practices on timber quality in spruce. Main emphasis is impact of site factors (e.g. exposure, fertility) on quality.

### Species and species mixtures

Research into silvicultural characteristics of candidate alternative tree species (conifer and broadleaved) in northern and western Britain, including evaluation of site requirements, sensitivity to site conditions and possible timber yields.

### Management of native woodlands

Research into the structure, dynamics and silviculture of native woodland ecosystems in northern and western Britain re support, restoration and extension for ecological and economic benefits. Current focus is Scots pine forests, birchwoods, and the Atlantic oakwoods.

### Conifer natural regeneration and silvicultural systems

Investigate natural regeneration processes in major conifer species to predict and manipulate the timing and density of natural seedling establishment. Evaluate canopy structure manipulation to provide regeneration sites within existing stands as an alternative silvicultural system to patch clearfelling.

### Stability of stands

Research to reduce wind damage to British forests using a GIS-based windthrow risk model for predicting the probability of windthrow in Sitka spruce forests.

### Farm and community woodlands

Identify optimum silvicultural practices for the establishment and management of trees on farms or as community woodlands in northern and western Britain. Research includes shelterbelts on farms, integration of grazing animals with trees, and planting on derelict land.

## *Silviculture and Seed Research Branch*

### Species

Research into silvicultural characteristics of candidate alternative tree species (conifer and broadleaved) in southern Britain, including evaluation of site requirements, sensitivity to site conditions and possible timber yields.

### Poplars

Evaluate poplar clones with potential for timber production.

### Farm woodlands

Research cost-effective vegetation management techniques, and establishment of farm woodlands such as direct sowing. Investigate the importance of side shelter and the use of high value species in the farm woodlands.

### Vegetation management

Evaluate herbicides for use in forestry to achieve cost-effective weed control regimes. Investigate alternatives to herbicides.

### Coppice

Investigate dry matter yields of willow and poplar coppice grown for renewable energy.

### Broadleaved woodland

Develop cost-effective methods for establishing and managing the main broadleaved tree species on lowland sites, research woodland processes, notably regeneration, and design planting strategies for new native woodland.

### Urban forestry and arboriculture

Research and demonstration in support of community forests and the National Forest.

### Plant production

Improve the quality and performance of tree seeds, seedlings and vegetatively propagated stock to develop more reliable and economic methods of plant production and establishment.

## *Statistics and Computing Branch*

### Process models of forest growth

Simulate biomass and structural dimensions calculated for foliage, branches, stem, coarse and fine roots using physiological processes. Modelling uses real weather data and parameters appropriate for the site and species and can predict responses to elevated $CO_2$, drought and temperature changes over 50-100 years.

## *Tree Improvement Branch*

### Selection and testing of conifers

Plus-tree selection, progeny testing. Breeding/ production populations. Demonstration of realised gain. Species: Sitka spruce, Scots pine, Corsican pine, Douglas fir, larch.

### Breeding and production of conifers

Clonal archives: conservation, advanced breeding material. Improved seed: controlled pollination, seed orchards.

### Improvement of broadleaves

Selection/testing at population, family and clonal level of oak, beech, ash, sycamore.

### Origin and provenance

Identification of suitable origins of conifer species.Key species: Sitka spruce, Douglas fir.

### Biochemical variation studies

Study of genetic variation in natural and breeding populations. Characterisation of populations, families and clones.

### Micropropagation and rejuvenation

Methods of rejuvenating Sitka spruce and hybrid larch. Tissue culture systems for multiplication.

### Flowering research

Study basis of control of flowering to increase seed production in stands and seed orchards.

## *Woodland Ecology Branch*

### Assessing biodiversity in managed forests

Determine the biodiversity status of plantation forests, develop practical assessment methodologies and identify potential biodiversity indicators.

### Forest habitat management

Understand natural ecosystem processes, and how they are modified by management, to promote characteristics of forest structure and composition that confer ecological and conservation benefits, as well as meeting other management objectives.

### Population ecology of birds and mammals in managed forests

Provide an ecological basis for the integration of the multi-purpose management of forests with the protection and enhancement of their dependent vertebrate populations.

### Landscape ecology

Provide recommendations on the landscape scale design of forests for the conservation and enhancement of biodiversity.

### Ecological site classification

Devise and promote an ecologically based site classification as a tool for sustainable forestry in Britain.

### Species action plans

Research support for the conservation of woodland species identified in the Biodiversity Action Plan.

### Squirrel management

Develop cost effective means of managing the impact of grey squirrels on timber production. To securing the future of the red squirrel as a component of the British woodland fauna.

### Deer population ecology

Provide a sustainable basis for deer management in UK woodlands using faecal pellet counts, thermal imagery techniques and other procedures to inform population dynamics, deer behaviour and herbivory.

### Tree protection

Develop techniques and materials for cost effective protection of trees and woodlands from vertebrate damage.

# *Appendix 4*

*Research Division income and expenditure (£000)*

| | 1994/95 | 1995/96 |
|---|---|---|
| Income | | |
| Non-FC clients | 1529 | 1348 |
| Non-research services to FC | 286 | 265 |
| **Total** | **1815** | **1613** |
| Expenditure | | |
| Staff costs | 6862 | 7034 |
| Accommodation | 913 | 901 |
| Materials and supplies | 1403 | 1227 |
| Services from FC | 1255 | 1302 |
| Research grants | 427 | 416 |
| **Total** | **10860** | **10880** |
| Net cost to FC of research programmes | 9045 | 9267 |

*Allocation of FC costs to Branches (£000)*

| Branch | 1994/95 | 1995/96 |
|---|---|---|
| Silviculture (North) | 1832 | 1681 |
| Silviculture (South) | 1272 | 1521 |
| Tree Improvement | 1239 | 1187 |
| Entomology | 829 | 892 |
| Woodland Ecology | 963 | 860 |
| Pathology | 894 | 820 |
| Environmental Research | 639 | 784 |
| Mensuration | 263 | 472 |
| Forest Products | 306 | 281 |
| Plant Production | 279 | 227 |
| Communications | 358 | 360 |
| Mycorrhizal Research | 61 | 98 |
| Statistics and Computing (North) | 8 | - |
| Statistics and Computing (South) | 102 | 84 |
| Total | 9045 | 9267 |

# Appendix 5

## *Contract work done by Research Division for non-FC clients*

**Brecon Beacons National Park**
Silviculture and establishment of birch

**British Coal**
Opencast coal spoil reclamation

**Countryside Commission for Wales**
Ecological design of upland woodlands in Wales
Silviculture of native woodlands in Wales

**Department of the Environment - Arb VI**
Development of plant quality index for broadleaved trees
Health monitoring in non-woodland trees
Minimising pavement damage from street trees
Production of manual on decay and safety in trees
Research and demonstration in the National Forest

**Department of the Environment**
Effects of trees on urban air quality
GM biopesticides: policy review
Potential for woodland establishment on landfill sites

**Department of Trade and Industry**
$CO_2$ fixation by native woodlands
Coppiced trees as energy crops
Initial spacing in short rotation coppice
Rooting characteristics of willow clones
Short rotation coppice planting machines
Yield models for energy coppice of poplar and willow

**Department of Transport**
Alternatives to peat
Backfill studies

**European Union**
Assessment of risks from pinewood nematode
Forest condition surveys
Long-term effects of elevated $CO_2$ and climate change on European forests
Plant vitality and dormancy
Short rotation coppice
Tree nutrition and sustainability
Tree seed dormancy

**EU/AFOCEL**
Northern conifers in fast growing conditions - a step towards an adequate wood supply for industry

**EU/Casale Monferrato**
International research for poplar improvement

**EU/Danish Forest and Landscape Research Institute**
Tree root architecture

**EU/Finnish Forest Research Institute**
Modelling risks to forests

**EU/Highland Birchwoods**
Conservation of native pinewoods

**EU/Highland Birchwoods: Life '94**
Restoration of relict pinewoods

**EU/IBN/DLO Holland**
Mixed forests

**EU/Imperial College**
Chemical control of bluestain

**EU/Institute of Virology and Environmental Microbiology**
Transgenic poplar

**EU/Macaulay Land Use Research Institute**
Agroforestry

**EU/Madaus AG**
European *Aesculus* cultivation system

**EU/University of the Algarve**
*Phytophthora* in European oak decline

**EU/University of Edinburgh**
The likely impact of rising $CO_2$ and temperature on European forests

**EU/University of Kent**
Restoration of environmental diversity by effective ecosymbiont monitoring

**EU/University of Wales, Bangor**
Poplar for farmers

**FAO**
Research design in afforestation, forestry research, planning and development in the three northern regions of the Republic of China

**Fargro Ltd**
Marshall Suscon applicator development

**Griffin (Europe) SA**
Root control in container seedlings

**Joint Nature Conservation Committee**
Red squirrel conservation

**Kemforschungszentrum (Germany)**
Spruce root stock

**Lothian Regional Council**
Transplant performance

**Macaulay Land Use Research Institute**
Bog management

**MacFarlane Smith**
Vertebrate repellents

**Ministry of Agriculture, Fisheries & Food**
Provenance testing
Yield assessments
Deterrents for lowland deer (with ITE, ADAS, CSL)
Damage caused by lowland deer (with ADAS, ITE)
Ranging behaviour of lowland deer (with ITE, ADAS)
Vertebrate repellents (with CSL, ADAS)

**National Rivers Authority**
Phytophthora disease of alder

**Niko Chemical Co Ltd**
Animal repellent studies

**ODA**
Nutritional aspects of Chinese fir
Tropical legume seed pretreatment
Virus control of teak defoliator in India

**ODA/ECTF**
China larch tree breeding project

**Pilkington Trust**
Control of *Ophiostoma novo-ulmi* by the 'd-factor'

**Private Client**
Integrated residue harvesting

**Private Client**
Residue recovery from felling coupes

**Scottish Enterprise**
Condition of large planting stock
Investigations into the stability of irregular forests

**Scottish Forestry Trust/TGA**
Physiology of native Scots pine
Soil classification

**Scottish Natural Heritage**
Bog restoration
Ecological site classification for the Cairngorms
Seed vitality in the Mar Lodge pinewoods

**Scottish Office/Scottish Crops Research Institute**
Genetic variability in native pinewoods

**Sierra UK**
Fertilization of birch

**Southern Water Service**
Short rotation coppice/sewage sludge

**Wessex Water**
Biogran dried sludge granules in land reclamation

# *Appendix 6*

## *Research contracts awarded by Research Division*

**Abertay University**
Genetic engineering of English elm

**Avon Vegetation Research**
Herbicide evaluation

**British Mycological Society**
Fungi surveys in plantation forests

**British Trust for Ornithology**
Song bird monitoring in plantation forests

**Building Research Establishment**
Application of GREENWELD technology to British timbers
Distortional stability of Sitka spruce
Improved machine grading
Modelling strength properties of Sitka spruce
Testing British grown hardwoods for British standards
Testing British grown softwoods for European standards

**S. Davey**
Lichen and bryophyte surveys in plantation forests

**Imperial College, London**
Biological control of decay in utility poles
Greenwood preservative treatments
Potential of entomopathogenic nematodes for control of restocking pests

**Institute of Hydrology**
Effects of afforestation on water resources

**Institute of Terrestrial Ecology**
Review of afforestation and predation

**London University**
Red squirrel habitat analysis

**M. Thomas**
Thermal imaging for deer census

**National Rivers Authority (Welsh Region)**
Effects of forestry on surface water acidification

**Royal Society for the Protection of Birds/ Edinburgh University**
Golden eagle ranging behaviour

**University of East Anglia**
Windspeed prediction in complex terrain

**University of East London**
Assessment of soil microbial activity in plantation forests

**University of Edinburgh**
Genetics of Scottish aspen

**University of Lancaster**
The physiological impact of long-term exposure of trees to elevated $CO_2$

**University of Nottingham**
Development of transformation systems for Sitka spruce

**University of Portsmouth**
Management of bluestain in sawn timber

**University of Sheffield**
Immunosterilisation of grey squirrels

**University of Wales, Bangor**
Crown development and timber quality
Effect of provenance and silviculture on timber quality of oak

Forestry Commission