Developing a forest resource on industrial cutaway peatland

The BOGFOR programme

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First published in 2008 by COFORD, National Council for Forest Research and Development, Dublin, Ireland.

ISBN 1 902696 59 X

Title: Developing a forest resource on industrial cutaway peatland. The BOGFOR programme.
Authors: Florence Renou-Wilson, Michael Keane, Gerry McNally, John O'Sullivan and Edward P. Farrell.

Citation: Renou-Wilson, F., Keane, M., McNally, G., O'Sullivan, J. and Farrell, E.P. 2008. Developing a forest resource on industrial cutaway peatland. The BOGFOR programme. COFORD, Dublin.

Foreword

Ever since the establishment of the first afforestation trials at Trench 14 at Clonsast in Co Offaly in the mid nineteen fifties, forest establishment investigations on Bord na Móna cutaway peat sites have been a feature of national research endeavour. This has been reflected most recently in the six-year BOGFOR programme, which forms the basis of this report. Given the more than half a century of investigation, a full forest rotation, an obvious question is what has come out of it all?

What this publication shows first and foremost is that research has come up with answers, and not only where to establish tree crops, but equally important where not to. Cutaway peatlands may all look the same, but from a tree growing perspective they differ significantly, with respect to fertility, hydrology and frost risk. The ability to recognise these features, and select sites that will produce a viable commercial tree crop are very significant advances in knowledge, made possible by research. Hand in hand with these advances is the realisation that a landscape approach should underpin land use on the cutaways. What this means in practice is that part of the land is devoted to biodiversity provision, part to commercial forestry and farming, with the remainder reverting to dryland and wetland habitats.

As far as commercial forestry is concerned, Norway spruce is identified as the preferred species on cutaway peatland. Importantly, however, the report provides forestry practice recommendations for the establishment not only of Norway spruce, but for a range of species, depending on whether or not a nurse crop (alder or birch) is planted, as well as guidance on how to take into account site fertility, moisture regime and other factors before the planting decision is made.

BOGFOR was a collaborative research programme, carried out by Bord na Móna and Coillte and co-ordinated by University College Dublin, with part funding from COFORD. Its success was due to clear objectives, a well thought out programme of work, coordinated effort between the organisations involved, close interaction between managers and researchers and the ability to synthesise results from past and current research and to present them clearly in the final report.

All those involved in putting the report together are to be congratulated, as it adds significant value to the half century of national research endeavour that underpins it. A high level of scientific endeavour, involving the testing of many new ideas, is apparent from the range of experiments reported.

As the authors say in the report BOGFOR has opened the door to the future afforestation of industrial cutaway peatlands. COFORD, in agreeing with this conclusion, also emphasises the need for continued monitoring of trials and demonstration areas established under the programme of work. New areas for consideration, such as greenhouse gas emissions and sequestration, are now coming into the future cutaway land use equation.

Cutaway peatlands are a valuable land resource, let us use them wisely.

Brollach

Ó bhunú na gcéad trialacha foraoisithe i dTrinse 14 i gCluain Sosta, Co. Uíbh Failí i lár na naoi déag caogaidí, tá imscrúduithe bunú foraoiseachta ar shuímh mhóna lagphortaigh de chuid Bord na Móna tar éis a bheith mar ghné den dianiarracht taighde náisiúnta. Áit is déanaí ina bhfuil sé seo tar éis a bheith léirithe ná an clár BOGFOR sé bliana, a chruthaíonn bonn na tuarascála seo. In ainneoin an imscrúdaithe le breis agus leath chéad, rothlú foraoise iomlán, ceist soiléir ná céard atá tar éis teacht as ar fad?

Is éard a thaispeánann an foilseachán seo i dtús báire ná go bhfuil an taighde tar éis teacht ar fhreagraí, agus ní amháin an áit chun barra ó chrainn a bhunú, ach rud díreach chomh tábhachtach an áit gan iad a bhunú. D'fhéadfadh an cuma céanna a bheith ar thailte móna lagphortaigh ar fad, ach ó thaobh fás na gcrann de is mór an difríocht atá eatarthu, maidir le torthúlacht, hidreolaíocht agus baol seaca. Is suntasach an cur chun cinn i bhfeasacht, atá féideartha le cabhair an taighde, é an cumas chun na gnéithe seo a aithint, agus suímh a roghnú a tháirgfidh barr crainn tráchtála agus inmharthana. I dteannta leis an gcur chun cinn atá an fíorú gur cheart go dtacódh cur chuige an tírdhreacha le talamhúsáid ar na lagphortaigh. Is éard a chiallaíonn sé seo i gcleachtas ná go dtugtar cuid den talamh do sholáthar na bithéagsúlachta, cuid d'fheirmeoireacht agus d'fhoraoiseacht tráchtála, leis an gcuid eile ag filleadh ar ghnáthóga na dtailte tirim agus na mbogach.

Maidir leis an bhforaoiseacht tráchtála, aithnítear an sprús Lochlannach mar an speicis roghnach ar thailte móna lagphortaigh. Mar sin féin, ar bhonn tábhachtach, soláthraíonn an tuarascáil nua moltaí um chleachtas foraoiseachta le haghaidh bunú ní amháin an sprúis Lochlannach, ach le haghaidh réimse speiceas, ag brath ar cibé an gcuirtear nó nach gcuirtear barr cumhdaigh (fearnóg nó beith), mar aon le treoir ar conas aird a thabhairt ar thorthúlacht, córas taise agus fachtóirí eile an tsuímh sula ndéantar cinneadh an phlandaithe.

Clár taighde comhoibritheach ba ea BOGFOR, bainte amach ag Bord na Móna, Coillte agus Coláiste na hOllscoile, Baile Átha Cliath, le maoiniú i bpáirt ó COFORD. Bhí a rathúlacht mar thoradh ar chuspóirí soiléire, clár oibre dea-bhreathnaithe, iarrachtaí comhordaithe idir na heagraíochtaí páirteacha, idirghníomhaíocht dlúth idir bhainisteoirí agus taighdeoirí agus an cumas chun torthaí a shintéisiú ó iar-thaighde agus taighde reatha agus iad a chur i láthair go soiléir sa tuarascáil deiridh.

Caithfear comhghairdeas a rá leo siúd uile a bhí páirteach i gcur i gcrích na tuarascála, d'fhonn gur suntasach an luach a chuireann sí ar leath chéad de dhianiarracht taighde náisiúnta a thacaíonn léi. Tá ardleibhéal na dianiarrachta eolaíoch, lena mbaineann tástáil roinnt mhaith tuairimí nua, soiléir ó réimse na dturgnamh a tuairiscítear.

Mar a deireann na húdair sa tuarascáil, tá BOGFOR tar éis an doras a oscailt do thodhchaí an fhoraoisithe thailte móna lagphortaigh tionsclaíocha. I gcomhaontú leis an gconclúid seo, leagann COFORD béim freisin ar an gá atá le monatóireacht leanúnach na dtrialacha agus na réimsí taispeána bunaithe faoin gclár oibre. Tá réimsí nua le breathnú orthu, cosúil le astaíochtaí gáis ceaptha teasa agus scoitheadh, ag teacht isteach i gcothromóid talamhúsáide lagphortaigh na todhchaí anois.

Is luachmhar na n-acmhainní talún iad na tailte móna lagphortaigh, úsáidimis go heagnaí iad.

Acknowledgements

The financial support provided by the European Union, the Forest Service, COFORD (the National Council for Forestry Research and Development), Bord na Móna and Coillte is gratefully acknowledged. The achievement of the main goals of this research programme was made possible by the commitment and hard work of numerous UCD, Bord na Móna and Coillte workers. The authors would like to thank in particular Suzanne Jones for managing the programme between 1998 and 2000 and Tom Egan and Joe Freeman for their dedicated work on site. The following members of the BOGFOR team are gratefully acknowledged: Cathy Bennett, Jill Boyle, Raquel Cabral, Aoife Cassidy, Thomas Cummins, Seamus Dunne, Tom Egan, Gerhardt Gallagher, Carly Green, Pat Haranhan, Richard Jack, Mark McCorry, Donal O'Hare, Diarmuid O'Riordan, Sharon Parr, Mina Pöllänen, Jim Quinlivan and Elaine Smith. Thanks are also due to all those who have been involved in the programme:

Aro, Lasse
Bennett, Podge
Black, Kevin
Bothwell, Karen
Butler, Norman
Byrne, Kenneth
Callaghan, Annette
Carey, Michael
Casey, James
Casey, John
Cleary, John
Cody, Gerry
Collins, Tagh
Connelly, John
Connolly, Mick
Costello, Tom
Crowley, Tim
Daly, Michael
D'Arcy, Jim
Deegan, Roger
Dillon, Jim
Dooley, Pat
Downes, Sean
Farrell, Catherine
Farrelly, Niall
Fitzgerald, Andrew
Fitzpatrick, P.J.
Fogarty, Gerry
Fortune, Adie
Green, Rory
Hammilton, Billy
Hendrick, Eugene
Hipwell, George
Hutchinson, Kevin
Kaunisto, Seppo
Kelleher, Yvonne
Laine, Jukka
Lane, Michael
Little, Daragh
Lyons, John
Maudoux, Marine
McAree, Diarmuid
McCann, James
McCarthy, Richard
McEvay, Eammon
McGrath, Gillian
Meelia, Mick
Mulloy, Fergal
Molloy, Sean
Neville, Pat
O Boyle, Don
O'Carroll, Cormac
O'Carroll, Joe
O'Flannagan, Liam,
Päivänen, Juhani
Pfeifer, Alistair
Prior, John
Scallan, Una
Snell, John
Sullivan, Rae
Tobin, Brian
Traynor, David
Wilson, David

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Executive summary

The BOGFOR research programme addressed the challenges and problems of establishing forests on industrial cutaway peatlands in the Irish Midlands. The results from over 200 ha of experimental and demonstration plantations conclude that the successful afforestation of cutaway peatlands is possible but requires (a) a sound plan with specific objectives, (b) a careful selection of sites with suitable characteristics and (c) the use of specific operational methods tailored to the site conditions and species' requirements.

Although cutaway peatlands might appear to be uniform, they do, in fact, contain a great deal of heterogeneity. Small-scale variation in these site types greatly influences the establishment and growth of trees and has consequences for the choice of silvicultural practices. The adoption of a single afforestation blueprint for this land is therefore not appropriate and site preparation techniques, together with species selection and fertilisation practices, will vary depending on site conditions. Only a proportion of the total cutaway peatland area will ever be suitable for commercial forestry. The area that might be suitable has been estimated by Bord na Móna to be between 16,000 and 20,000 ha. This area will only gradually become available over the next 20 years, with the majority only becoming accessible towards the end of this time period.

Understanding how individual parcels of cutaway peatland become available is critical to developing a successful afforestation programme. Only small areas (as little as 1 ha) are released from peat production at any one time. Consequently, by the time a commercially viable block (20 ha or more) becomes available for afforestation, site conditions within it may be very variable (ranging from bare peat to areas of naturally regenerated broadleaves) - necessitating a range of site preparation techniques within the block. Part of any large cutaway peatland site will inevitably be unsuitable for commercial forestry. Some areas have been successfully planted with species such as birch, alder or Scots pine and could be managed for amenity, biodiversity or aesthetic purposes.

During the BOGFOR programme, commercial forest crops have been successfully established on certain selected site types. Lessons learned from these areas suggest that sourcing the correct machinery (such as a bedding plough, specialised vegetation cleaning equipment) that is required to carry out the necessary site preparation economically and at an operational scale, is necessary to successfully establish forests on these sites. BOGFOR has opened the door to the future afforestation of industrial cutaway peatlands. However, the initial results from the programme should be verified by continued monitoring of the trials and demonstration areas that have been established. A phased approach to the afforestation of the cutaways sites is needed, supported by an ongoing research and demonstration programme.

Technical summary and general recommendations

This report contains a large number of results and recommendations as an aid to the establishment of a sustainable forest crop on industrial cutaway peatlands in the Irish Midlands. The report does not present all the answers but attempts to lay down some key components that should be considered in afforesting cutaway peatland. During the BOGFOR programme, commercial forest crops have been successfully established on certain cutaway site types, each requiring its own establishment and silvicultural prescriptions. It is concluded that the successful afforestation of cutaway peatland requires a combination of necessary actions pertaining to:

- site assessment,
- site preparation,
- species performance,
- tree establishment,
- nutrition and fertilisation,
- late spring frost,
- pests,
- vegetation.

The following information is based on scientific results without any financial analysis or reference to the economics of the management options discussed.

Site availability and site selection

Only a proportion of the total cutaway peatland area will ever be suitable for commercial forestry. This area has been estimated by Bord na Móna to be between 16,000 and 20,000 ha. Depending on the level of peat harvesting, it is estimated that this area could become available over a period of 20 years. Understanding how and in what manner these areas are presented is critical to developing a successful afforestation programme. Only small areas (as little as 1 ha) are released from peat production at any one time. When these areas reach a commercially viable size (perhaps 20 ha in extent) and are accessible without impacting on peat production they can be considered for afforestation.

Each cutaway peatland unit investigated within the BOGFOR programme contained an area which was not suitable for forestry. Poor drainage was the most common limiting factor for tree growth. This is to be expected and it should be accepted that such areas should be managed for biodiversity or amenity or as wetland.

The variety of peat profiles found within the BOGFOR cutaway peatland sites confirms the heterogeneity of these sites and the complexity of the reclamation process for forestry. For example, the variation in peat type, peat depth and sub-peat mineral soil can cause random variations in the mineral nutrient regime of the substrate. At another level, the combination of peat type and sub-peat mineral soil can present physical difficulties with regard to drainage and this will limit site preparation options.

Woody fen and shallow/well-aerated *Phragmites* peat with good drainage were generally considered good sites for the afforestation of commercial crops (Norway spruce). Deep *Phragmites* peat with a shallow aerated peat layer have shown potential with appropriate site preparation techniques but more research should be carried out on this site type; certain methods (e.g. pre-planting with native species such as alder) may prove beneficial. Deep *Sphagnum* peat sites were found to be problematic for the growth of trees except for pine species.

Recommendations

- A successful afforestation programme requires a clear definition of objectives with due consideration to wider land-use issues.
- Proper site selection is vital if a successful forest is to be established. A detailed site survey (peat depth and peat type as well as drainage status) should be carried out, preferably in winter , to provide reliable information which will help in the choice of management options, e.g. site preparation and choice of species. Five sampling points per hectare are recommended.
- An adequate drainage system, including gradient and suitable outlet is critical. As stated, sites should be inspected in winter when conditions are at their wettest.
- Woody fen and *Phragmites* peat with a deep aerated peat layer are the most favourable site types for afforestation.
- Deep *Sphagnum* peat should be avoided for afforestation.

Site preparation

Deep ploughing created the best growing medium when it managed to lift part of the sub-peat mineral soil. Ripping, discing or mounding did not improve tree growth where trees were planted in well-aerated woody fen or *Phragmites* peat. Mounding *Phragmites* peat created an unsuitable medium for all species. Cracking of peat, which had been previously observed in uncultivated peat, was not observed in shallow uncultivated peat or deep cultivated peat.

Recommendations

- Site preparation must be selected to suit the site conditions. It is critical that a site is gravity drainable in order to carry out further site preparation as cultivation, no matter how good, will not turn a poor site into a good one.
- On the basis of present knowledge, site preparation is not considered necessary on well-aerated woody fen or shallow *Phragmites* peats, although experimental results did show a benefit from deep ploughing in tree height growth in the early years. Deep ploughing will help create a permanent aerated layer if it succeeds in bringing sub-peat mineral soil to the surface.
- Mixing peat and sub-peat mineral soil provides an excellent planting medium; the optimum mixture would be 80% peat and 20% mineral soil. Planting in pure sub-peat mineral soil should be avoided.
- Poorly drained woody fen and *Sphagnum* peat will benefit from mounding but it is not recommended to mound *Phragmites* peat or when planting oak.
- New site preparation methods such as bedding ploughs and V-shearing equipment should be tested as establishment methods on cutaway peats.

Species performance

The best performance of Norway spruce, Sitka spruce and pedunculate oak, was recorded under a naturally regenerated birch nurse crop. Where planted without a nurse crop, Sitka spruce suffered severely from repeated late spring frost. Of the two native oak species, only pedunculate oak has shown potential and only on the most fertile peats and with adequate shelter from exposure. Hybrid larch has shown potential on well drained cutaway sites while western red cedar showed little promise. Both Scots pine and lodgepole pine were damaged by pine shoot moth when measured after five years of growth.

Common alder (*Alnus glutinosa*) was the fastest growing species, performing uniformly over a variety of site types. In addition to birch, its pioneering properties make it highly suited to quickly establish forest cover. Birch also survived and grew well, with silver birch (*Betula pubescens*) showing its superiority, especially on good sites. Birch has the advantage of being an important species in vegetation succession, which can broaden options for future uses of the cutaways.

While very good growth performance was achieved for the more commercial species, large variability was encountered across sites, emphasising the need to survey site conditions prior to species selection.

Recommendations

- Norway spruce is the preferred commercial species for cutaway peatlands due to the reduced risk of damage by late spring frost.
- When a suitable nurse crop (either natural or planted) is available, Sitka spruce should be chosen instead of Norway spruce because of its higher productivity.
- Corsican and Macedonian pine should be planted on lower quality sites (acidic deep peat). Both Corsican and Macedonian pine are preferred to lodgepole pine which is not recommended as it is more likely to be damaged by pine shoot moth.
- Hybrid larch has potential as a shelter/nurse species on dry sites.
- Common alder is an excellent pioneer species for the cutaway bogs and can be planted over a variety of sites in advance of a more commercial species.

Tree establishment

Norway spruce, Sitka spruce and oak benefited from shelter and grew best under a naturally regenerated birch canopy. Oak grew better in mixture with fast-growing species such as alder and hybrid larch or where it was underplanted in natural birch woodland, compared to where it was planted alone. While large Norway spruce bare-root seedlings showed lower growth rates than container and small bare-root plants, their larger size remained an advantage, especially if vegetation was not effectively controlled. Large birch seedlings grew faster than smaller ones and bare-root silver birch grew faster than containerised seedlings.

Early results from field trials encourage the use of containerised larch for its quick establishment, leading to reduced time of vegetation control, reduced risk of late spring frost damage and its earlier use as a nurse or shelter species.

Early results from field trials showed that direct seeding of birch or alder has limited operational application; shelter and fertilisation seem to be critical to improve germination and survival.

Recommendations

- Planting of cold stored stock in April/May is recommended. Planting should not take place any later, however, so as not to delay fertilisation.
- Nurse crops of birch, alder and hybrid larch can greatly improve the performance of most species but attention must be given to subsequent management issues (e.g. timely vegetation control and pruning and thinning of the nurse crop).

- Any nurse crop (natural or planted) should reach a sufficient height (> 5 m) and density before underplanting.
- Container and small bare-root Norway spruce may be preferred where vegetation control is fully effective.
- Containerised plants should be used for hybrid larch and Corsican pine.
- Direct seeding is not yet considered a suitable option but further research with shelter system may provide better results.
- Protection of broadleaves from hares is critical; fences must be well maintained for at least three years following planting.

Nutrition and fertilisation

Initial fertilisation (at planting) with phosphatic fertiliser was found to be essential for the survival of all species on cutaway peatlands. However, increased P fertiliser rates did not necessarily lead to increased growth of Norway spruce or oak. Initial broadcast application lead to vegetation control difficulties.

Mycorrhizal infection seems to have occurred naturally in most cutaway peatland plantations. However, it is not known whether the quantity and type of mycorrhizae recorded are necessarily good enough for optimum tree growth.

The nutrient status of Norway and Sitka spruce stands established in the late 1980s has deteriorated over time, with trees suffering from P deficiencies before reaching 10 years of age, particularly on *Sphagnum* peat.

Recommendations

- A split application of fertiliser is recommended on cutaway peatlands, especially on bare peat fields: half of the conventional rate of 350 kg of rock phosphate (12.5% P) should be applied at planting and the other half two years later.
- Either superphosphate (16% P) or rock phosphate (12.5% P) can be applied (following the above recommendation) on peat mixed with calcareous sub-soil with minimal risk of P leaching (if surface runoff is reduced and timing of application is well considered).
- Fertiliser should be applied in bands at planting and broadcast for the second application, carefully avoiding drains (keeping back a minimum of 20 cm) and waterlogged areas.
- Careful consideration should be given to the timing of application in order to minimise the risk of run off immediately after application.
- Fertiliser should be applied not later than June so as to minimise the risk of P leaching; a shorter growing season and higher precipitation (August-September) increases the risk.
- The establishment of a vegetative cover would be beneficial in advance of applying fertiliser.
- Visual assessment, foliar analysis and identification of peat type are useful diagnostic tools to enable early detection of nutrient deficiencies.
- Re-fertilisation with rock phosphate should be carried out as soon as indicated by foliar analysis, so as not to delay the potential response.
- N should only be applied if foliar N concentrations indicate severe deficiency, as P application alone may promote the general nutrient status of the stand.

Late spring frost

It was confirmed that frequent late spring frosts occurred in the low-lying cutaway peatlands in the Irish Midlands, sometimes as late as June. Using late-flushing provenances did not provide an adequate remedy. A near complete overstorey shelter system was found to be the best form of protection; and the higher growth rate following underplanting also took the leading shoot above the frost layer sooner. The importance of thorough vegetation control has also been highlighted to reduce the risk of frost damage. More intensive management practice such as site levelling and cultivation were not effective, as micro-scale variations are still likely to result in local frost pockets.

Recommendations

- Late spring frosts are common in the cutaway peatland in the Irish Midlands thus limiting the choice of species.
- There is a high probability of frosts during the bud burst period of Sitka spruce in the Irish Midlands, regardless of provenance thus limiting the use of this species.
- Norway spruce is less frost-sensitive than Sitka spruce, but is more sensitive than pines.
- A near complete overstorey shelter system is the best form of protection against spring frost damage.
- Efficient vegetation control can reduce the risk of frost damage.

Pests

Lodgepole pine has suffered severely from pine shoot moth in the Midlands. The incidence of pine shoot moth in the Irish Midlands has meant that some pine species are at risk. Broadleaves have been severely damaged by hares when fencing was not adequate.

Recommendations

- Corsican and Macedonian pines are less sensitive to pine shoot moth than lodgepole or Scots pine and have also shown good growth.
- Protection against hares (either fencing or individual plastic tubes) is critical when planting broadleaves on cutaway peatlands.

Vegetation

Cutaway peatlands were found to be well suited to mechanical cleaning with purpose-built equipment such as mowers and weed-wipers (semi-chemical/semi-mechanical).

Recommendations

- It is important to reduce the colonisation of main competitors such as *Juncus* firstly by improving drainage and secondly by following a rigorous vegetation control plan.
- Timely and efficient vegetation control operations are necessary using the most appropriate machine to control the type of weeds present (mowers are most appropriate except when rush is surrounding the trees).
- The spraying of herbicides is not recommended on cutaway peatland plantations due to the poor weather conditions.
- The timely treatment of nurse species is essential to avoid excessive whipping of the main crop.

Management of poor or failed areas (reconstitution)

The reconstitution of failed Sitka spruce plantations with Norway spruce following clearance with a flail has been successful at all sites. In most cases, annual height growth of Norway spruce was greater than when planted on new cutaway peatlands.

Recommendations

- Early intervention is required when reconstituting poor or failed areas.
- The choice of management operations should be tailored to the site conditions which are best assessed prior to removal of the failed crop.
- Interplanting may be a cheaper option than total clearance but this depends on the stocking and stage of development of the existing crop.
- Control of competing vegetation is probably the most critical aspects to the successful establishment of reconstituted crop.

1: Introduction

Industrial cutaway peatlands

Definitions, historical context and background information

Peatlands are generally viewed in Ireland as a landscape unit which contains peat, i.e. a geographical area where peat soil occurs. Peat is simply accumulated partially decomposed plant material. The United States Department of Agriculture Soil Conservation Service suggested a classification of peat soils for international usage and proposed the following definition of peat:

> *"Organic soil materials that are saturated with water for prolonged periods, or artificially drained, and have 30% or more organic matter (if the mineral fraction is 50% or more clay), or 20% or more organic matter (if the mineral fraction has no clay), or proportional intermediate organic matter contents if the clay fraction is intermediate"* (Soil Survey Staff 1974).

This definition has been used in Ireland, with the provision that the organic soil material, excluding the thickness of the plant layer, must be over a depth of at least 45 cm on undrained land and 30 cm deep on drained land (Hammond 1975, 1981). The depth requirement does not apply in the event that the peat layer is over bedrock. According to the description of Irish habitats (Fossitt 2000), the term 'cutover bog (PB4)' is used in situations where part of the original mass of peat has been removed through turf cutting or other forms of peat extraction. Cutover bog can be associated with all peat-forming systems, including fens, raised bogs and blanket bogs. This category also includes areas of bog where peat is being actively worked and harvested mechanically as well as areas that are abandoned or exhausted: these areas are commonly known as industrial cutaway peatlands (referred to as cutaway peatlands or cutaways hereafter).

The practice of peat harvesting is well developed in Ireland where peat has been a source of fuel since prehistoric times. Despite traditional hand-cutting, Irish peatlands remained largely untouched up to modern times. The introduction of large-scale mechanised peat extraction in the 1940s and the establishment of the Irish Peat Board (Bord na Móna) as a semi-state body in 1946 were direct results of government policies introduced to deal with the increasing difficulties associated with importing fuel supplies. By developing Irish peatlands for electricity generation, the government not only redressed the trade imbalance, but also stimulated rural economies where the bogs were located. The introduction of a grant aid scheme under the Turf Development Act (1981) also enabled many small-scale extraction programmes to take place, either for energy production or for horticultural purposes.

Of the 1.2 million ha of peatlands in Ireland, the Bord na Móna areas classed as 'industrial' account for about 80,000 ha or 7% of the total peatland reserve. These are located mainly in the Midlands and to a lesser extent on blanket bogs in the west of Ireland. Of that area, approximately 58,000 ha is currently in production and 16,000 ha consist of former peat production fields which are now under different land-uses, including natural recolonisation.

Bord na Móna harvests, on average, four million tonnes of peat annually, depending on weather conditions (five million tonnes of peat were harvested in 2003 which was considered an exceptional year). Approximately three million tonnes of peat are used for energy production annually, while the rest is shared between horticultural peat ($^2/_3$) and briquette production ($^1/_3$). In 2003, peat contributed 21% of the total energy produced by native sources and 7.9% of the electricity used in Ireland, contributing 6% of the total primary energy requirement (McGettigan and Duffy 2003; Bord na Móna 2004). The importance of peat to the Irish energy sector has been in decline since the 1970s. After the recent closure of old power stations, three newly built, state-of-the-art power plants are now producing electricity by peat combustion with a total installed production capacity of 370 megawatts. As a result of this intensive utilisation of the peat reserves, the remaining time for peat extraction is estimated to be fifteen to twenty years (Bord na Móna 2002). This time span depends on the renewal of a harvest licence and may be shortened due to possible revised peat energy production figures in view of two drawbacks: peat costs (and necessary subsidies) and greenhouse gas emissions.

Harvesting techniques

The object of harvesting is to remove as much peat as possible economically and without contamination from mineral soil. In the past, peat was harvested by Bord na Móna from both raised and blanket bog using the sod-peat harvesting system. Today, all harvesting is carried out by the milling process. Each harvesting method leaves behind a different residue.

Machine sod-peat harvesting was the first industrial technique used by Bord na Móna and the resulting cutaways were consequently the first type of cutaway peatlands made available for other land uses, including forestry. The top *Sphagnum* peat was typically discarded and the depth of peat which could be removed was a function of the height of the peat face which a machine could handle. Bord na Móna developed the 'Bagger' method to excavate peat from a vertical trench with drains every 250 m. A 'trench' was exhausted in a single pass. In depressions, the full depth of the peat could not be fully exploited; many of these areas were subsequently re-worked using the milling process.

Milled peat production has been adapted for Irish conditions from the old Russian 'Peko' model. A similar method, called 'Haku', is used in Finland with slight variations regarding the transport of the peat. In the Peco process, the surface of the peat is extracted on the horizontal plane, in a number of passes, at a rate of c.10 cm per year (weather permitting). The top 1.5 cm of the field is milled to crumb size by tractor-drawn rotary millers. The peat is then harrowed to accelerate drying to a moisture content of c.40%, and shaped into a ridge at the centre of each field (15 m wide) by another machine called a ridger. Each ridge is then harvested 'leap frog' fashion over the drains to create a stockpile on every eleventh field. The peat is then loaded into train carriages and transported to the power station. The drainage needed for this type of extraction is intensive, with 1 m-deep channels installed every 15 m (Plate 1). Prior to harvesting, all the vegetation is removed and fields between the ditches are made slightly convex to facilitate surface runoff. Unlike sod-peat production, the milling process leaves no surface strippings of *Sphagnum* peat overlying fen peat. In addition, the amount of peat extracted could be far greater, sometimes leaving a residue as little as 20 cm deep.

There are three main physical reasons why peat harvesting would be terminated in a particular field:

1. Woody remains in the lower strata impeding the removal of the peat by the milling process;
2. The subsoil becoming exposed (fuel production allows no contamination by any mineral subsoil);
3. The site becoming too wet (in some areas, water is pumped away to keep the water table below the peat surface).

An understanding of these factors is essential for the rational selection of future land-uses for these areas once peat extraction has finished.

The method of exploitation of raised bogs in the Midlands has given rise to three distinct types, called complexes (Hammond and Brennan 2003):

1. Turbary complex (hand- or farmer-cutaway bog). Very heterogeneous in their physiography. They occur in a range of forms, either unreclaimed (exposed fen found in association with uncut turf banks) or reclaimed for agriculture (e.g. the Gortnamona Series);
2. Clonsast complex (sod-cutaway bog). Residual fen peat overlain by a layer of ombrotrophic *Sphagnum* strippings from the former bog surface. Typical drainage system is still present with a drain spacing of 250 m;
3. Boora complex (milled-cutaway bog). A complex of residual peats (mainly minerotrophic) is left exposed, with depth depending on the underlying topography. A drain spacing of 15 m separating 'fields' is typically present.

The latter two kinds are commonly known as industrial cutaway peatlands.

Future uses of cutaway peatlands

As mentioned, about 18% (16,000 ha) of Bord na Móna peatlands have so far become cutaway (this does not necessarily mean that all the peat has been harvested). This area is increasing every year, but at a variable rate, and it is expected that another 60,000 ha of peatlands will become cutaways within the next three decades (with some areas, including fringes, remaining untouched). The development of these large areas will be one of the great reclamation ventures undertaken in Europe and it has been compared in scale to the reclamation of the English fenlands or the polders in the Netherlands (Feehan and O'Donovan 1996a).

Peat extraction is licensed by the Environmental Protection Agency and Bord na Móna is required, as part of that licence, to produce a rehabilitation plan for each cutaway bog unit. The issue of the after-uses of Irish cutaway peatlands has already been the subject of several discussions at international (Healy 1980; McNally 1984, 1995, 1997), national (Healy 1978; Anon. 1979; Mollan 1989; McNally 1997), and county level (Egan 1998; Offaly County Council 2003).

Much research has been carried out since the first cutaways became available for after-uses in the 1950s and some aspects of this are on-going, mainly driven by Bord na Móna. Renou et al. (2006) reviewed over 50 years of studies in the after-use potential of industrial cutaway peatlands in Ireland. In that time, the emphasis has continually changed as new research has emerged and new policy developed, in turn directing and shaping decision-making. Over the years, the main areas of investigation have included: grassland (for silage production or grazing), crop production, horticulture (including vegetable production), commercial forestry, biomass production, dry-land recolonisation and wetland creation/restoration. The options for after-use are determined to a large extent by the residual peat type, hydrological constraints, geographic location and economic considerations (McNally 1984; Hammond 1989; McNally 1995). From above, the cutaway landscape looks deceptively uniform in appearance while, in fact, it is extremely heterogeneous. The peat varies in type, thickness (because of the undulating topography of the bog floor), pH, nutrient status, moisture regime (drainage) and in the geomorphology of the underlying (pre-bog) relict mineral soil. All of these factors will influence future land-use programmes. The phased replacement of peat exploitation by these two land-uses is likely to be of crucial importance for economic, social and environmental reasons both at local and national scale.

Cutaway peatlands forestry: opportunities and benefits

Forest policy context

By the end of 2004, forest cover had reached 680,000 ha - almost 10% of Ireland's total area.

This contrasts with the 35% average throughout the other EU Member States (Department of Agriculture and Food 2005). The overall aim of the strategic plan for the development of the forestry sector in Ireland, as stated in *Growing for the Future* (Department of Agriculture 1996), was to develop forestry to a scale and in a manner which maximises its contribution to national economic and social well-being on a sustainable basis and which would be compatible with the protection of the environment. The government set a target of 1.2 million ha (17% of the total land area) to be under forest cover by 2030. In the period 1996-2002, however, the rates were not achieved, with a deficit of 55,000 ha (c.34%). Between 2003 and 2005, this deficit increased further.

Potential contribution of cutaways to forest development

The reclamation of peatlands for forestry in Ireland has recently been reviewed by Renou and Farrell (2005). While the authors considered the important role of peatlands in the reforestation of Ireland during the twentieth century, the economic and environmental appraisal of peatlands for forestry potential revealed that further forestry development on both blanket and raised peatlands is limited. One category for which greater potential exists is the industrial cutaway peatlands. The strategic plan noted that "*afforestation of cutaway bogs was a particular case requiring a new approach to the area identified by Bord na Móna as being suitable for afforestation*".

The afforestation of industrial cutaway peatlands could make a significant contribution to attaining the targets set out in the government's forest strategy; and they have the benefit of being owned by the state. The planting and subsequent management of industrial cutaways would provide rurally-based employment and income. Thinnings and residues could also provide an opportunity for wood energy production. These two products are suitable for co-firing in the newly established peat-burning power stations, and would extend these stations' generation life, as well as providing employment in the harvesting and transport of wood fuel. The use of wood energy would also reduce carbon dioxide emissions.

In summary, the main benefits that may be generated by forestry on cutaway peatlands include: value of timber, employment opportunities and income earned, value of carbon sequestration, displacement of fossil fuels, recreational value and biodiversity value.

Prospects

It is estimated that an area of between 16,000 and 20,000 ha of Bord na Móna cutaway peatland has afforestation potential. Because of the nature of peat production, when and in what amount cutaway becomes available will fluctuate widely from year to year. In order to gain an insight into the availability of cutaway peatlands for afforestation, it is necessary to understand how peat is produced and the nature of the cutaway peatlands. Large areas of peatland are required for energy production because the harvesting of milled peat is dependent on having an extensive surface area on which to solar dry the harvested peat. Stockpiling of harvested peat also occurs on the peat surface and this necessitates a rotation of actual milling surfaces on an annual basis. These factors, coupled with the fact that a depth of only 10 cm is milled from the peatland surface annually, means that the bog units are in milled peat production for up to 50 years.

Every bog unit harvested for peat production contains a range of peat depths with a variation as great as 3 m, even within bog units. Greater depths of peat are associated with depressions in the bog floor, formed as a result of fast glacial action. This means that there is a protracted time period (up to 50 years) over which a bog unit is finally withdrawn from peat production. Each bog unit is subdivided into a series of production fields. These are a standard 15 m wide and several hundred metres long. For the first 30 years or so, the whole area of the bog remains in production. There is then a slow withdrawal from the shallowest peat depth areas, usually on an individual production field (or part thereof) basis. It is not possible to predict the exact timing of the withdrawal of each production field. The decision to withdraw or retain is taken at the beginning of each production season by experienced supervisors with local knowledge. After a period of time, a proportion of the fields may be withdrawn but their scattered locations within the bog unit render them unavailable for alternative use. When a compact block of land can be released from peat production activity, it is then withdrawn and other land uses can be considered. New mobile harvesting methods mean that as little as 10% of a bog unit, scattered throughout the whole area, may be in production, so that the areas withdrawn may not be available for alternative use until much later. This emphasises further the difficulty in predicting the rate at which cutaway peatland will become available.

Historical, political and research background

Past experience

Since the late 1950s, afforestation has been considered a feasible option for cutaway peatland areas in several countries (Mikola and Mikola 1958; Ferda 1972, 1975, 1986; Kaunisto 1986; Nilsson et al. 1987; Nilsson 1992). From the 1960s onwards, the afforestation of Irish cutaway peatlands was perceived as offering great potential, despite little research to support this (O'Carroll 1962; Ó Maoláin et al. 1979; Gallagher and Gillespie 1984). In theory, prospects were promising on the assumption that these cutaways were homogeneous in botanical origin and in character, that they were drainable, available in large, accessible units and that they ought to be productive without any requirements for cultivation. When reviewing peatland afforestation, Swan (1973) cited late spring frost as the only potential hazard, recommending a limited choice of species on susceptible areas. The early plantations on sod-peat cutaway peatlands were considered highly successful, a finding which provided much of the impetus for plans to afforest Bord na Móna cutaway peats. In 1979, the Interim Report of the Inter-Departmental Committee (Ó Maoláin et al. 1979) stated that "*… it is obvious that this type [sod peat] of cutaway bog is suitable for afforestation. Forestry research has not yet been initiated on milled peat cutaway. It should now be undertaken in co-operation with the Forest and Wildlife Service*." The report also stated that: "*The combination of peat type, peat depth and subsoil in Bord na Móna milled peat cutaway bog is extremely complex. It is clear that the varying combinations must be treated separately as they present different problems*."

Eight years later (in 1987), with over thirty years of experience in planting sod-peat cutaways and very little information on the potential of milled cutaways, the then Minister for Energy declared his intention to afforest "*…all existing Bord na Móna cutaway bogs which are suitable for this purpose*" and that this would be the responsibility of the Forest Service and not Bord na Móna. The Minister also stated that "*This will apply to any cutaway lands which are at present available for planting and also to those areas which will become available in the future as Bord na Móna bogs are exhausted for turf production purposes…*" (Minister for Energy, speaking in the Dáil in October 1987, cited in O'Flanagan 1988). This statement did not separate sod- to milled-cutaway peatlands. In 1989, Coillte took over the responsibility for this afforestation scheme and by 1992 had planted 4,000 ha of cutaway bogs leased from Bord na Móna, of which c.2,400 ha were on milled cutaway bog in the Midlands, c.1000 ha on milled cutaway blanket bog in the west of Ireland and c.570 ha on sod-peat cutaway. The main tree species planted on these sites in the Midlands were Sitka spruce (accounting for 76% of the total plantings) followed by lodgepole pine (10%). Norway spruce and oak made up 2% each, and other species 10%. Performance on these areas was mixed and it was quickly realised that previous optimistic forecasts were over-simplistic. The crop performance further emphasised that the afforestation of cutaway peatlands was a very delicate exercise that had so far yielded only mediocre results and called for an assessment (surveys) and investigations before proceeding with further planting.

Initial research

The first important survey was carried out on behalf of Coillte (Lynch and McGuire 1993). This unpublished report aimed to quantify the status of the 4,000 ha of cutaway peatlands that had been leased from Bord na Móna. A summary of the results is presented below:

Category A: Areas growing satisfactorily and established but with a stocking rate between 50% and 70% (rate as percentage of 2,500 stems/ha).

Category B: Areas not fully established.

Category C: Areas that had failed and that were beyond reconstitution, including areas that were established but were severely damaged by frost.

When taking the Sitka spruce data in isolation, the percentage in category C (failed) rose to 41% in the Midlands. This survey posed some important questions with regard to the viability of existing cutaway peatland plantations, and a more intensive survey was proposed by the Forest Ecosystem Research Group to provide a full assessment of the limitations to the successful establishment of these sites (Jones and Farrell 1997a, 1997d). The results showed that the immediate problems facing forestry on cutaway bogs were: frost; competition from weeds; nutrient deficiency; pest damage; edaphic factors (depth or compaction of the peat); and drainage. More importantly, the survey revealed that tree mortality or poor growth was not attributed to one single factor but rather to a combination of factors. For example, frost damage would enable weeds to compete with the tree much more quickly. The report concluded on the necessity to develop a complete research programme focusing on the afforestation of milled cutaway peatlands.

In 1996, the Government had already identified the potential of industrial cutaway peatlands for afforestation purposes and the need for pilot trials in the strategic plan (Department of Agriculture 1996). A Task Force was set up by the Forest Service and the first trial was established in spring 1996. Following further discussion, a research programme, aimed at investigating the potential of commercial plantation on the milled cutaway peatlands was launched in 1998, under the title BOGFOR.

2: The BOGFOR research programme

What is BOGFOR?

The primary objective of the BOGFOR research programme was to examine the forestry potential of industrial cutaway peatlands. The programme was designed to develop new approaches to the challenges and problems of establishing a tree crop on milled cutaway peatlands. The programme took a multi-pronged approach, designing individual tasks in order to address each of the specific problems encountered whilst establishing and maintaining cutaway peatland plantations. The programme was multi-disciplinary and benefited from co-operation between various organisations with different but complementary areas of expertise. A management committee ensured co-operation between the partners while a steering group guided the process over the life-span of the programme. Support and advice was also sought from scientists abroad, especially in Finland. Throughout the duration of the programme, a bottom-up approach was used, as principles were constantly revised following both positive and negative field experiences. The programme involved a combination of field trials, greenhouse experiments and full commercial-scale demonstration areas, as well as surveys and observations and last, but not least, dialogue with local practitioners, i.e. foresters and peatland workers.

The BOGFOR research programme was initiated in March 1998 under the leadership of Prof. E.P. Farrell, University College Dublin. Researchers from UCD together with collaborators from Bord na Móna, Coillte, Coford and the Forest Service formed the BOGFOR partnership. A wide range of people have been involved over the life-span of the programme (1998-2005); their names and responsibilities are in Appendix 1.

The purpose of the BOGFOR outputs was to give practitioners tools with which to better understand the complexity of cutaway peatlands and to successfully establish a forest resource on these site types. These outputs would also contribute to the international scientific community through publication.

The outputs are:

- A set of databases containing information that will serve as reference points for future research:
  - Master BOGFOR database: maps and data.
  - BOGFOR experiments database: contains information on forests, sites and experiments in tabular format.
  - *BOGFOR field log database*: record of operations and observations by site and/or experiment in a tabular format.
  - *BOGFOR photographs and films database*: a CD-Rom containing pictures and films which can be searched by site, experiment, task, theme and date.
  - *BOGFOR library endnote database*: list of full references complete with keywords.
- BOGFOR publications: list of publications and outputs with links to CD-Rom containing peer-reviewed scientific articles and other publications.
- BOGFOR folders: CD-Rom containing documents and reports pertaining to each task including reports from face-to-face discussion with practitioners.
- BOGFOR final report: includes a set of recommendations leading to guidelines to form part of a new afforestation scheme.

This report is a final report, seen mainly as a formal report to funding agencies, where the summary gives the major findings which improve our understanding of cutaway peatlands and answers many of the questions on how to grow trees successfully on these new ecosystems. It is also a work report, where results are presented in study reports and a number of appendices. Some chapters report results in detail while others are extensive summaries of original reports or published papers which are presented in electronic format only (CD-ROM). The aim of this final document is to detail the fundamental information for anybody who has an interest in cutaway peatlands and in how best to establish and maintain suitable tree species on these sites using cost-effective techniques. It also provides sufficient detail for local practitioners and managers who might be interested in the BOGFOR experiments themselves and indeed who might wish to carry on the work initiated. The report does not cover all of the familiar elements of conventional plantation forestry (to be found in COFORD and Forest Service publications), rather it looks only at the most specific aspects of relevance in the context of cutaway peatlands. It also integrates environmental aspects.

Finally, no financial analysis is included as to do so would require detailed consideration of a range of assumptions and the treatment of a large number of management options.

BOGFOR sites and experiments

Cutaway peatland sites

The sites used in this research programme are located in the Irish Midlands, mostly in Co Offaly, where peatlands represent 34.5% of the surface cover (Hammond and Brennan 2003). The complete list of study sites and their co-ordinates (both GPS and Irish grid), elevation and other relevant information can be found in the *BOGFOR experiments database*. Just over 200 ha of Bord na Móna industrial cutaway peatlands were planted during the course of the programme (see Appendix 2) and they now form part of three large Coillte forests, namely Allen, Emo and Tullamore forests.

BOGFOR experiments and databases

A total of fifty-one experiments, pilot-scale demonstration trials or monitoring sites have been established to investigate cultivation methods, species selection and vegetation control, as well as edaphic and climatic limitations. The information regarding these experiments has been collated into a database (*BOGFOR experiments*). Several experiments were used for more than one study. For example, fertiliser trials were also used for the vegetation, frost and environmental studies. Whatever study is reported, it is attached to a code that can be found in the *BOGFOR experiments database*. The same code is used in other databases, for example the *BOGFOR field log database* and the *BOGFOR photographs and films database*. The *master BOGFOR database*, developed using Geographical Information Systems (GIS), groups all the data using these codes.

Materials and methods

A number of variables of the cutaway peatland ecosystem have been systematically investigated. From these, a number of other properties have been calculated. Variables measured are presented in Table 2.1.

Experiment design and treatments

The programme was based on the establishment and maintenance of field-based trials at both experimental and demonstration scale. A greenhouse experiment was also set up to study the early growth of birch. Wherever possible, experiments were replicated and followed recommended designs for statistical analysis. This was not always possible, however, given the area of land available. It was imperative to plant on a wide range of sites and locations. For assessments, plots were used as replicates within a stand wherever possible. Where stands were too small, individual trees were used as experimental units.

Large-scale demonstration blocks were set up in parallel with small-scale experimental plots. This meant that the best establishment

Table 2.1: Variables analysed in the programme.

Tree	Soil
1. Height	1. Classification of peat type and sub-peat mineral soil
2. Leader growth	2. Peat depth
3. Diameter @1.3 m referred to as DBH	3. Depth to aeration
4. Diameter @ 10 cm referred to as ground diameter	4. Bulk density
5. Basal area	5. Moisture content
6. Shoot and root biomass	6. pH
7. Needle nutrient analysis: N, P, K, Ca, Fe, Mg, Mn, S, Na	7. Total N, P, K, Ca, Fe, Mg, Mn, S, Na
8. Photosynthetic analysis of needes	8. Ash content
	9. Carbon content
Climate	
1. Air and ground temperature	**Soil water and surface water**
2. Precipitation	1. pH
3. Soil temperature	2. Molybdenum-reactive phosphate

options based on current knowledge (at the time) and techniques were field-tested in commercial scale plots.

Measurements, sampling and analyses

Trees

Crops were measured at intervals ranging from one to six years. The diameter at breast height (1.3 m) was measured on larger trees while diameter was measured at 10 cm from the ground on smaller trees or in young stands, at ground level. The measured trees were chosen from the middle section of a field, i.e. not close to a drain or other physical barrier. Unless specified otherwise, fifty trees were measured within an experimental plot. Tree height was measured to the closest centimetre with a height rod or with a clinometer for trees greater than 2 m. Diameter was measured to the nearest millimetre with either a calliper or a measuring tape. Relative growth rate (RGR) could be calculated for each plot and for any growth period, for example:

$$RGR_{2\text{-}1} = (\ln H_2 - \ln H_1)/(t_2 - t_1)$$

where H_1 and H_2 are the height at the beginning (t_1) and end (t_2) of the sampling period and have been computed on a plot basis (Connolly and Wayne 1996). Health was also assessed during certain crop assessments. For conifers, a scale between 1 and 4 was used (1 = strong healthy plant; 2 = good; 3 = poor; 4 = very chlorotic and/or needle loss). A different health scale was used for oak: 0 = dead; 1 = alive to the tip, 2 = alive with dead leader. Visual observations have also been recorded when necessary, e.g. hare damage.

Foliar sampling was carried out during the winter months (November – January), except for oak which was sampled in August. Twenty trees per plot were chosen randomly among the dominant and co-dominant trees. Current year needles from the top third of the crown were pooled. Samples were dried to a constant weight at 70˚C. Twigs were removed and needles were ground with a Glen Creston grinder to < 2 mm size. Samples (at least 10 g) were stored in dessicators and were oven-dried at 105˚C the night before chemical analysis. Total nutrient content (phosphorus, potassium, calcium, magnesium, sodium, manganese, iron, sulphur and copper) were extracted by wet digestion with nitric-perchloric acids (Zasoski and Burau 1977) and the extracts were analysed by inductive coupled plasma optical emission spectrometry (ICP/OES). Total nitrogen was measured using a Kjeldahl distillation and digestion unit after a sulphuric acid digestion.

Soil

Soil depth was measured using either a Dutch auger (usually 1 m in depth) or extension rods. The intensity of sampling points was site-specific depending on variation in peat type and peat depth. In order to characterise the chemical status, peat samples were taken to a depth of 20 cm, unless otherwise stated, always avoiding the last 10 cm above the sub-peat mineral soil horizon. Sampling was carried out at numerous locations and bulked in order to make up a representative sample. When sub-peat mineral soil was present in the 1 m deep profile, the presence of carbonate was tested using a solution of dilute hydrochloric acid.

Bulk density was measured from volumetric soil samples collected using a box-sampler. Moisture content was also calculated using the same sampler. Dry weight of the soil samples was measured after drying at 105˚C. Percentage loss on ignition was calculated as the percentage difference in weight of soil lost in combustion at 400˚C relative to the weight of soil dried at 105˚C.

The pH of a fresh peat sample was determined in distilled water (peat/water V/V=1/2) where the solution was left to rest for thirty minutes before measuring pH using a Schott pH combination electrode. The remainder of the sample was oven-dried to constant weight at 105˚C.

Total nitrogen was measured using a Kjeldahl distillation and digestion unit after a sulphuric acid digestion. An inductively coupled plasma optical emission spectrophotometer (ICP-OES) was used to measure the other elements (P, K, Ca, Mg, Na, Mn, Fe, S, Cu) following a nitric-perchloric acid digestion (Zasoski and Burau 1977).

Water

Water level was measured within capped, perforated ABS tubes permanently inserted into the peat. Water depth measurements were made at regular time intervals and related to precipitation records from the nearest meteorological station.

Surface runoff water was collected using a specially designed collector placed on the side of the drain. Soil solution was sampled using Teflon-quartz lysimeters (Prenart Equipment Aps). Grab samples were also taken from drains.

Water was sampled weekly or every two weeks and brought back immediately to the laboratory for initial filtration through Whatman paper filter (grade 541 particle retention 20-25 μm) in order to remove organic contaminants (peat, invertebrates, vegetation, animals etc.). Approximately half of each water sample was further filtered through a 0.45 μm membrane filtration. From each sample location, a filtered and unfiltered sample was analysed. pH was measured using a Radiometer pH-meter. Total reactive phosphorus was determined colorimetrically at 880 nm using the acid antimony-molybdate method and UV-Vis spectrophotometer (Murphy and Riley 1962).

Other environmental data collection

A suite of environmental variables was measured at different sites using various equipment. An Environmental Monitoring Station (ELE International, UK) was used at two sites - East Boora and Tumduff. It recorded soil and air temperature, precipitation, wind speed, solar radiation as well as soil temperatures at 5, 10, 20 and 30 cm depths. At East Boora, two extra soil temperature data loggers were positioned in the deep ploughed area and a control area to record soil temperature at 5, 10, 20 and 30 cm. More precise air temperature measurements were also taken at several sites using Stow-Away TidbiT XT (Forestry Suppliers Ltd) data loggers which were located on a pole at 50 cm above ground level (approximately at the height of the terminal bud of newly planted seedlings).

Vegetation

Vegetation quadrats 10 m x 10 m were permanently marked at certain sites and visited at least twice (and up to four times) during the summer to enable accurate identification of all vascular plants. The cover-abundance of each plant species and the cover value of bare peat surface was recorded using the Braun-Blanquet scale (Braun-Blanquet 1964). Cover is defined as the area of ground within a quadrat which is occupied by the above-ground parts of each species when viewed from above. It is estimated visually as a percentage, but stratification or multiple layering of vegetation will often result in total cover values of well over 100%.

Plants were identified down to species, except for mosses which were identified to genus. The data collected was analysed using Canonical Correspondence Analysis (CCA) and the CANOCO® software in order to establish relationships between species distributions and the associated environmental factors.

3: Cutaway peatlands in the Irish Midlands

Above the surface

> *"To travel by helicopter from Dublin to Galway above the Irish Midlands is to fly past hard-edged tracts of chocolate-brown plain, criss-crossed with drains…"* (Viney 2003).

History of a new landscape

Industrial cutaway peatlands are relatively new in the Irish landscape and as such they have not been included in many classic Irish landscape studies. In order to understand cutaway peatlands, one has to look back at the formation of peatlands, particularly, the raised bogs. In geological time, peat formations are of recent origin. They are biogenic formations which have developed in the post-glacial period (Holocene) after the recession of the ice sheets some 14,000-11,000 years ago. As the ice retreated, the Midlands of Ireland were irregularly covered with glacial deposits (moraines and eskers) which impounded melted water creating a maze of large, shallow lakes extending over as much as 5% of the country. It is in these basins and flood plains that raised bogs have developed over the last 9,000 years. Profiles through such bogs indicate that the peat was first laid down in calcium-rich lakes with clays and/or marls at the base. Most of these lakes became overgrown, swamped and infilled in a burst of aquatic growth; this process is called terrestrialisation and has been discussed by Malmer (1975) and Tallis (1983). Feehan (2000) gave a description of the pre-bog landscape and discussed several factors that may have triggered the onset of peat accumulation in the Irish Midlands. As there was insufficient oxygen in the lake water, plant litter remained partly decomposed and accumulated to form the peat deposit. If the flushing water is relatively rich in nutrients, the peat is called a fen and is identifiable by the presence of macrofossils of the common reed (*Phragmites australis*) and the saw sedge (*Cladium mariscus*). Given the right climate, hydrology and physiography, this basal peat and the living mosses growing on it act as water reservoirs, leading to an increasingly high water table. After considerable time, the peat accumulates into a dome shape. The deposit rises above the influence of the inflowing mineral water and is supplied only by rain water. A raised bog is thus formed, dominated by *Sphagnum* moss. The domed part of a raised bog typically shows a two-fold division in profile. The surface layers are fibrous with a reddish-brown colour and comprise slightly humified *Sphagnum* mosses. The lower stratum displays a more highly humified peat with various proportions of *Calluna* and *Eriophorum* residues. Initially, ombrotrophic peat development was confined to swamp and fen areas, but in time it extended beyond the confines of the enclosed basins and onto the surrounding moraine. This encroachment of forming peat is a self-perpetuating process called paludification (von Post 1937). The term paludification refers to the swamping of a landscape. The process is a lateral overgrowth of mosses and deposition of peat, which smothers the surrounding vegetation. Generally, these bogs are shallower than raised bogs and the sub-peat mineral soil does not have any glacial characteristics as it had time to develop before peat was deposited on top.

Bog development in Ireland was not continuous and during periods of milder, drier weather conditions, bog growth slowed down and allowed birch invasion followed by pine, sometimes interspersed with oak and yew. The remnants of these forests (occasionally whole trunks) can often be seen on harvested peatlands. Dendrochronological and radiocarbon dating have shown that this forest resource existed for a period sometime between 2300 and 1800 BC. With time and a deteriorating climate, bog grew and engulfed these ancient forests under several metres of peat. The layer of peat where woody debris are found is typically called a woody fen peat.

Because of the way in which the ice retreated, the sub-peat mineral soil (referred to as mineral soil hereafter) present at the bottom of the peat layer undulates. The horizontal removal (through milling) of peat formed over a rolling terrain means that the remaining peat depth can vary greatly over short distances. A cutaway peatland will also display different kinds of peat depending on the original development of the bog and where the milling stopped. In a typical cutaway peat profile in the Irish Midlands, the layer of ombrotrophic peat (*Sphagnum* or *Calluna* dominant) is either absent or very shallow, and it overlays minerotrophic peat (*Phragmites* peat or woody fen peat).

Present landscape and climate

The first impression one gets of a cutaway peatland is often a bleak one: a flat, bare, windswept, dark desolate area lacking macrotopography. Not without reason, these boggy areas have often been called 'wet deserts'. The topography of Ireland is likened to that of a saucer or basin and the cutaway peatlands are to be found mostly at its centre, sometimes lying lower than the river beds.

Temperatures recorded in the Irish Midlands over the period 1969-90 show that January is the coldest month with an average of 4.1ºC. July and August are the warmest months, being on average 14.5ºC (Met Éireann, Mullingar meteorological station).

Industrial cutaway peatlands located in the Irish Midlands are prone to late spring frosts due to the low-lying nature of the topography (creating frost traps) and the absence of coastal influences (Keane and Collins 2004). Late spring frosts, which can occur repeatedly in May and as late as the end of June, are radiative in nature. Also, under clear and calm weather conditions, frost tends to develop in areas where cold air accumulates, such as depressions or on flat areas (Lindkvist and Lindqvist 1997). Temperatures as low as -3ºC have been measured regularly during May and June on the BOGFOR sites, and frosts of -5°C have been recorded as late as the end of June. Freezing temperatures at flushing and early shoot growth are a major barrier to the successful establishment of sensitive species such as Sitka spruce; 50% of trees planted in the 1980s suffered severe frost damage in the form of lateral or leading shoot die-back (Jones and Farrell 1997a).

Another characteristic of cutaway peatlands is exposure. While their low-lying position provides protection against high-speed wind, their topography is conducive to persistent exposure and this is an important ecological factor. While wind can be desirable from a colonisation point of view (dissemination of pollen and seeds), it can have adverse effects at plant level (desiccation of young seedlings, uprooting) and at soil level where erosion and crust-forming processes are common features due to the aerodynamically smooth surface of cutaway peatlands (Campbell et al. 2002). Rain will also act as an erosion factor. Between 1970 and 2000, annual precipitation averaged 934 mm in the Midlands. Summer gales, combined with high precipitation events are also common in these parts (Keane and Sheridan 2004).

Flora and fauna

Vegetation communities on cutaway peatlands vary as a function of prevailing physical and ecological factors (Wheeler and Shaw 1995) and time elapsed since harvesting ceased. Most recent non-rehabilitated cutaway peatlands are still essentially bare. Spontaneous revegetation following the cessation of peat harvesting can be a slow process (Salonen and Laaksonen 1994) and is often limited due to the almost total absence of typical peatland plant species on the surface and in the seed bank (Curran and MacNaeidhe 1986; Jauhiainen 1998), and the extreme abiotic conditions left after peat mining (Quinty and Rochefort 1997; Campbell and Rochefort 2003; Lanta et al. 2004). Colonisation will be affected by hydrological conditions (Price 1997; Tuittila et al. 2000), the characteristics of the remaining peat (Wind-Mulder et al. 1996) and the instability of the peat surface (Campbell et al. 2002). Its tendency for irreversible drying during short periods of high temperature is probably one of the greatest impediments to seedling survival (Salonen 1987). The principal factor influencing colonisation, however, is the surrounding land use, as this land acts as a seed bank (Campbell and Rochefort 2003; Campbell and Hawkins 2004).

The initial vegetation communities are rarely bog communities and are in a state of rapid change in their succession to more stable plant communities. Where environmental conditions are suitable, regeneration of the vegetation is possible through germination from blown-in seeds but principally through vegetative expansion from adventitious roots. As seen in Finnish mires (Jauhiainen 1998), some seeds buried in peat deposits can also survive over centuries and germinate in the right conditions. Depending on the characteristics of the remaining peat layer and sub-peat mineral soil, numerous vegetation communities can evolve to maturity and several studies have now been carried out describing different plant communities (O'Connell and Foss 1999; Rowlands and Feehan 2000a,b; Wilson 2005). A proportion of cutaway peatland will be colonised by pioneer species such as vigorous birch (*Betula* spp.) and willow (*Salix* spp.), just as these species colonised the land in the wake of the last Ice Age. Common rush (*Juncus effusus*) can also exclusively colonise some of the wetter parts of the cutaway peatlands, where the water table fluctuates and minerotrophic conditions prevail (McCorry and Renou 2003). Overall, it is believed that a diversity of ecosystems can spontaneously develop (Feehan 2004). This natural colonisation, together with the creation of other open ecosystems such as grassland and plantation forestry, provide a rich and diverse mosaic of habitats (both wetland and terrestrial) which is conducive to a rich fauna. For example, cutaway peatland is a new landscape for bird-life. Kavanagh (1998) argued that, apart from the Irish red grouse (*Lagopus lagopus scoticus*) which is wholly dependant on heather moorland, all the other species typically found on lowland raised peatland can be found adapted to the new cutaway areas. Some, such as the meadow pipit (*Anthus pratensis*) survive at even higher densities than on raised bogs.

In addition to the peatland species, a suite of breeding birds can be seen in the spring and summer months: skylark (*Alauda arvensis*) and reed bunting (*Emberiza schoeniclus*) above the grassy areas, lapwing (*Vanellus vanellus*) and snipe (*Gallinago gallinago*) on the bare peat areas in the wetter parts, mallard (*Anas platyrhynchos*) and water hens around the drainage channels. Some more notable species, grey partridge (*Perdrix perdrix*), merlin (*Falco columbarius*) and nightjar (*Caprimulgus europaeus*), which are listed on the Irish Red Data Book of threatened birds in Ireland, have all been found on cutaway bogs (Whilde 1993). Grey partridge has been reintroduced successfully in Ireland due to the presence of cutaway peatlands. Young forestry plantations on cutaway peatlands have been found to be suitable habitat for the nightjar (Kavanagh 1998). Flocks of whooper swans (*Cygnus cygnus*) and golden plover (*Pluvialis apricaria*) are also present in the winter. Finally, two species - grey heron (*Ardea cinerea*) and curlew (*Numenius arquata*) - regularly use cutaway habitats.

The frog (*Rana temporaria*) is the most commonly encountered vertebrate inhabitant of cutaway peatlands. Cutaway peatlands are also a favourite habitat of the Irish hare (*Lepus timidus* Limnaeus) which is a protected species, and considered the only mammal that truly belongs to the bog (Feehan and O'Donovan 1996a). Where it is present, broadleaves need to be fenced.

Below the surface

Peat depth

Cutaway peatlands investigated in this programme have a peat thickness varying from 0 to over 2 m. The GIS map (Appendix 3) showing the peat depth distribution at East Boora, Co Offaly, reveals the variation in depths over very short distances. As expected, the thickness of the remaining peat layer varied widely and its distribution was not predictable. Shallower and more homogeneous peat depths are found where the sub-peat mineral soil is clay, silt or sand. This is because the surface of glacio-fluvial clay, silt and sand deposits is more even and allows peat to be harvested closer to the surface of the sub-peat mineral soil. On the other hand, glacial drift can contain boulders of varying shape and size which can prevent further milling when exposed at the surface. The peat layer between two glacial knolls can be as deep as 2 m. In addition, the remaining peat layer varies due to the peat harvesting system and the production method used; the need for stockpile fields and for turning points for machinery means that these areas are ultimately much deeper. From a subsequent site preparation point of view, this means that homogenisation of the remaining peat depth is not feasible.

Peat type

Three peat types were encountered while surveying the BOGFOR sites. They are described here according to the botanical composition of the peat. The type most commonly found was reed peat, also called *Phragmites* peat, as it was formed when the bog was dominated by *Phragmites australis*. It is easily recognisable, as intact *Phragmites* leaves can be found in the peat, even in well-humified material. Sometimes *Phragmites* rhizomes are also present. It is often distinctly laminated in a horizontal plane. It is a black (or orange in a very wet environment), dense peat, having been consolidated for thousands of years under several metres of peat and then for many seasons under heavy machinery.

In some instances, the *Phragmites* peat was overlain by a shallower layer of highly humified *Sphagnum* peat, which is the second most common peat type. These cutaway peatlands were usually very deep and located in areas where peat harvesting ceased earlier than usual.

In localised areas (usually shallow peatland), a third type was encountered: woody fen peat. Woody fen peat consists essentially of a mixture of birch wood and non-*Sphagnum* wetland and woodland mosses, together with the remains of other hydrophilous plants. A fourth type was only found at Lullymore and is called a *Menyanthes* peat due to the presence of black seeds which are the remains of the bog bean plant (*Menyanthes trifoliata*).

Sub-peat mineral soils

The mineral soils found underneath the peat layer derived primarily from two main types of parent material: (i) glacial drift (deposited during the last glaciation); and (ii) surface materials such as glacial clays and marls deposited on the drift in the lower areas soon after the ice-sheets retreated and before peat accumulation began. Depending on the relief, these soils show different degrees of development. The presence of limestone bedrock has resulted in much free calcium carbonate occurring in the mineral soil. Unlike in other European countries (e.g. Finland and Germany), where most bogs overlie acidic soils (Kaunisto 1997; Aro 1998), the substrata on which the raised bogs of the Irish Midlands developed are thus generally alkaline, varying greatly from pH 7 (silty clay) to pH 9 (marl) (Barry et al. 1973). Some cutaway peatlands are so deep that the influence of the calcareous mineral soil is absent. In other cases, a thick, decalcified layer of silty clay of lacustrine origin acts as a buffer between the peat and the calcareous soil parent material. In Tumduff, the buffering effect was provided by a layer of sapropel (a soft black layer of decaying organic matter) beneath the peat. Chemical characteristics of the sub-peat mineral soil found at Tumduff can be found in Table 3.1.

Table 3.1: Chemical properties of the sub-peat mineral soil at Tumduff.

pH	P	Al	Fe
		(mg/kg)	
7.8	2.9	3.3	0.4

Chemical composition

A summary of chemical analyses (pH and nutrient concentrations) carried out on the different peat types encountered on the BOGFOR sites is presented in Table 3.2. The pH values show that a large difference exists between peat types found in the cutaway peatlands investigated. As expected, *Sphagnum* peat was the most acid and woody fen peat the most alkaline. Variation was found within the *Phragmites* peat category ranging from pH 3.9 to 5.1. It is clear that the pH varies depending on the position of these peat types within the profile: the closer to the mineral soil, the higher the pH of the peat. As found in previous studies (Barry et al. 1973), this trend was often associated with an increasing calcium content, but not always. Total calcium levels measured in *Phragmites* peat varied from 0.16 to 2.16%; these extremes being found in a shallow and deep peat respectively.

The nutrient status of the peats surveyed across the BOGFOR sites was in accordance with previous analysis carried out various sites (Table 3.3). The total nitrogen content of the sampled peats varied from 0.91 to 2.18%, but most of the nitrogen is in an organic form and is unavailable to plants. It has been suggested that peats containing less than 1.3% N require nitrogen fertilisation to sustain tree growth (Kaunisto 1982). Nutrient addition is, however, more likely to be required to raise phosphorus levels. Total phosphorus levels were low and comparable across all the peat types (ranging from 170 to 440 mg/kg). These values are much lower than for mineral soils found in Ireland. It is also interesting to note that these levels were lower than concentrations found on Finnish (Aro 2003) and Canadian (Andersen et al. 2006) cutaway peatlands. Peats were found to be low in potassium, but concentrations varied greatly between and within peat type: the poorest being *Phragmites* peat (ranging from 80 to 300 mg/kg) and the richest being woody fen peat (ranging from 240 to 870 mg/kg). The same observation was valid for magnesium where levels were extremely low in the *Phragmites* peat and may raise questions in terms of availability to plants. Total sulphur content varied from 0.25 to 0.56%. In deep anaerobic conditions, most of the sulphur is likely to be

Table 3.2: Chemical compositions of peat (0-20 cm) sampled across the BOGFOR sites.

Sites	n*	pH	N (%)	P (%)	K (%)	Ca (%)	Fe (%)	Mg (%)	S (%)	Mn (%)
Highly humidified *Sphagnum* peat										
Tumduff R	15	3.89 (0.1)	1.32 (0.31)	0.024 (0.0067)	0.021 (0.0052)	0.67 (0.185)	0.201 (0.11)	0.012 (0.0020)	0.25 (0.027)	0.005 (0.003)
Clonast	24	3.70 (0.1)	1.33 (0.17)	0.025 (0.0066)	0.033 (0.0143)	-	-	-	-	-
15-year-old forests	18	3.60 (0.2)	1.15 (0.05)	0.022 (0.007)	0.007 (0.002)	0.93 (0.49)	0.45 (0.4)	0109 (0.066)	0.34 (0.17)	0.003 (0.005)
Phragmites peat										
East Boora - shallow	18	4.90 (0.52)	1.19 (0.65)	0.017 (0.002)	0.036 (0.035)	2.01 (1.00)	0.51 (0.17)	0.107 (0.036)	0.352 (0.17)	0.008 (0.005)
East Boora - deep	18	4.29 (0.26)	0.91 (0.26)	0.017 (0.002)	0.008 (0.008)	0.57 (0.28)	0.18 (0.09)	0.117 (0.030)	0.229 (0.026)	0.003 (0.001)
Tumduff F - deep	36	4.63 (0.22)	2.17 (0.23)	0.017 (0.002)	0.01 (0.009)	0.16 (0.02)	0.86 (0.34)	0.064 (0.015)	0.53 (0.19)	0.035 (0.013)
Tumduff R - deep	8	3.96 (0.15)	1.76 (0.27)	0.027 (0.008)	0.030 (0.012)	0.94 (0.16)	0.45 (0.16)	0.009 (0.001)	0.30 (0.03)	0.01 (0.003)
Blackwater - deep	24	5.00 (0.6)	2.03 (0.19)	0.033 (0.008)	0.022 (0.021)	-	-	-	-	-
15-year-old forests	14	5.1 (0.1)	1.7 (0.48)	0.029 (0.009)	0.012 (0.009)	1.5 (0.83)	1.14 (0.73)	0.07 (0.04)	0.51 (0.14)	0.0018 (0.02)
Woody fen peat										
Noggus	1	5.8	1.44	0.022	0.087	2.16	0.98	0.041	0.56	0.002
Derrybrat	1	5.2	1.53	0.044	0.064	0.68	0.62	0.073	0.27	0.003
Derryrobinson	1	5.3	2.18	0.022	0.024	0.42	1.21	0.084	0.51	0.028

* number of samples analysed

Table 3.3: Properties of some peats found in cutaway peatlands in Ireland (adapted from Walsh and Barry 1958; Barry et al. 1973; Hammond 1984; Jelley and Burke 1984).Table 3.3: Properties of some peats found in cutaway peatlands in Ireland (adapted from Walsh and Barry 1958; Barry et al. 1973; Hammond 1984; Jelley and Burke 1984).

Peat type and location	Reference	Bulk density (g/cm³)	Ash content (% DM)	Field moisture (% DM)	pH	N (%)	P (g/kg)	K (g/kg)	Ca (g/kg)	Ca/Mg ratio
Woody fen	Hammond 1984	0.112	11.6	76.5	5.3	2.1	-	-	-	-
Woody fen	Jelley and Burke 1984	0.11	-	-	-	-	-	-	-	-
Woody fen	Jelley and Burke 1984	0.23	-	-	-	-	-	-	-	-
Sphagnum peat	Hammond 1984	0.116	9.8	95.5	5.9	1.86	-	-	-	8
Sphagnum peat	Jelley and Burke 1984	0.255	-	-	-	-	-	-	-	-
Sphagnum peat	Walsh 1958	-	0.05	94.3	5.8	1.44	0.05	0.038	-	-
Woody fen	Walsh 1958	0.78	0.04	91.2	5	1.64	0.05	0.022	-	-
Woody fen	Barry et al. 1973	0.083	0.09	90.3	5.4	1.38	0.04	0.07	1.59	26.5
Sphagnum peat	Barry et al. 1973	0.106	0.08	88.5	6	1.58	0.03	0.05	2.9	29
Sphagnum peat	Barry et al. 1973	0.099	0.07	88.9	5.7	1.71	0.04	0.07	1.84	20.44

in sulphide form (H_2S) which gives a distinctive smell. Upon drainage and oxidation, peat containing high amounts of sulphur may become more acid due to the formation of sulphuric acid (H_2SO_4). The total amount of iron varies greatly between and within peat types, suggesting site-related conditions. This is of importance with regard to phosphorus absorption during fertilisation and will be dealt with in Chapter 5. It is believed that the chemical characteristics of the basal peat correlate well with the type of sub-peat mineral soil (Carey 1969; Carey and Hammond 1970; Barry et al. 1973).

Hydro-physical characteristics

Hydrological characteristics of soil, such as water storage and rate of water movement, depend to a large extent on the porosity and pore-size distribution of the material. These are in turn related to the particle size distribution and structure of the soil. In peat materials, the particle size, structure and resulting porosity are determined by the state of decomposition. As organic matter decomposition increases with increasing peat depth, the well-decomposed peat (sapric material) found lower in the profile has water-holding properties strikingly different from those in the upper layers (fibric material). Generally, peat found in the bottom layers is well-decomposed, largely gelatinous and colloidal. Both macroporosity and hydraulic conductivity decreases with increasing peat depth (Mulqueen 1975). Conversely, bulk density increases with depth, primarily due to the burden of the overlying peat layers. The peat materials found across the BOGFOR sites had bulk densities ranging between 110 and 246 kg/m³ and contained between 62 and 87% water by volume. These well-decomposed bottom-layer peats are constituted primarily of small pores which are not easily drained at low suction (Boelter 1969). An increased water retention capacity with increasing depth means that lowering the water table in a well-decomposed peat would drain only a very small part of the water compared to peat found higher in the profile. It is thus very important to know the peat type and the peat depth before planning drainage. The type of sub-peat mineral soil can also exacerbate drainage problems. Boulder till soils are more easily drainable than glacial clay which forms an impermeable layer, which can lead to surface ponding during high precipitation events.

Cutaway peat is characterised by denser soil and smaller pores that cause exaggerated variability in water table depth (Schouwenaars and Vink 1992; Price 1996). Periodic high water table levels are inevitable. Excess moisture is itself not detrimental to plant growth but the concomitant effect of very limited aeration adversely affects root metabolism (Boggie 1972) and inhibits the activity of micro-organisms which play such an important role in the nutrient cycle (Bowen 1984). In effect, drainage is also a technical means to improve the availability and uptake of nutrients (Lauhanen and Kaunisto 1999). A fluctuating water table can also retard tree growth dramatically, favouring competitors such as *Juncus* that thrive under these partially anaerobic conditions (thanks to its aerenchyma which allows the transport of oxygen from the leaves to the roots). In anoxic peat, trees may also stop growing or suffer dieback due to the presence of reduced compounds such as H_2S which poison the roots (Lyr and Hoffmann 1967).

This variability in water table depths also means that the water table level does not coincide with the aerobic-anaerobic boundary in the peat profile. This indicates that when the water table drops lower in the profile in the summer, the aerobic zone can remain very shallow and *vice versa* in the winter (Boggie 1972). The ground water table is considerably more sensitive, responding more quickly to changes in the condition prevailing than the aerobic boundary and thus the latter should be used as a more reliable factor in the determination of the water and oxygen conditions of the soil.

In conclusion, the most important objective of drainage is to remove excess moisture, as well as to adjust the water content of the soil to a level that ensures sufficient aeration. Additional or deeper ditches are usually required to lower the water table and increase the anaerobic layer but, because local conditions are so variable, no precise drainage method can be applied. Paavilainen and Päiviänen (1995) give a generalised synthesis which suggests lowering the water table to a depth lower than 35-55 cm below the soil surface depending on nutrient status and peat characteristics.

Overall, it is better to aim to aerate and improve the surface layer than to try to lower the water table on the whole site. Once the trees are established they will significantly affect the water regime of the site, initiating a positive feedback as their growth further lowers the water table due to increased evapotranspiration. Some experiments have reported water table responses to depth and spacing of drains (Pyatt 1990), but on most peatlands the effect of the crop itself, once the canopy has closed, becomes even greater.

Other edaphic features

Peat 'wastage'

With water contents ranging from 75 to 98% by volume, peat is an extremely compressible material (Hobbs 1986). The term 'wastage' has been used in relation to drained peatlands (Barry et al. 1973) and may be said to cover the combined effects of shrinkage, subsidence, compaction, decomposition, biochemical changes and breakdown, frost-action, physical damage due to traffic, wind and water erosion. Subsidence of peat soils is caused by loss of buoyancy upon drainage (i.e. load and shrinkage of upper peat layers). In the long run, moisture reduction produces the decomposition of the organic matter by microbial oxidation. Peat subsidence rates are lower in deeper peat layers where bulk density is higher and where water does not move easily to the drains (Ilnicki 2003). The intensity of peat decay depends also on climatic conditions, land use and management. A peat depth study was carried out on sod-peat cutaway peatland planted with different tree species in 1955 at Clonsast Bog (Trench 14). Peat depth measurements were taken at the time of planting (see Carey and Barry 1975) and again in 2004. All plots had been fertilised with ground rock phosphate. Peat depth means were not significantly different after almost fifty years ($p = 0.24$) and correlated significantly (Figure 3.1). Peat subsidence varied from plot to plot, however, and subsidence was more marked in plots where the remaining peat layer was

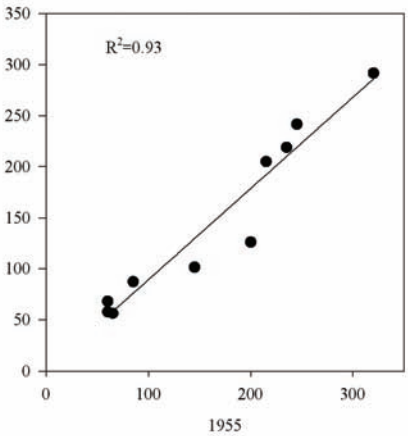


Figure 3.1: Peat thickness measured in the year 1955 and again in 2004 in Trench 14, Clonsast.

deep. Similar results were found in Finnish cutaway peatlands twenty years after afforestation (Aro 2003).

Peat cracking

Phragmites peat cracks upon compaction and drying. The only way compacted blocks of peat can accommodate horizontal strains is by cracking. This has been known in Ireland since the 1960s when cutaway peatlands were reclaimed for agriculture and horticultural uses (Healy 1978). It is still a poorly understood phenomenon, however. Different peat types exhibit different rates and amounts of shrinkage. Generally, the more decomposed the peat is, the greater the degree of shrinkage on dewatering (Graham and Hicks 1980; Päivänen 1982). It is thus not surprising that cracking has been recorded mainly on *Phragmites* peat, in both its natural state and following reclamation procedures such as afforestation. It is still difficult to find explanations for the occurrence of cracking and whether it has the potential to become a serious problem for future forestry plantations on cutaway peatlands. Where cracking has been observed in older uncultivated cutaway peatland forests, the cracks lead to the isolation of trees on a monolith of peat.

A small study carried out under the BOGFOR programme revealed that, unlike the cracking pattern in clay soils, peat tends to crack into roughly rectangular blocks (Boyle 1999). The author concluded, however, that this study did not permit the drawing of any conclusions about the occurrence of cracking in *Phragmites* peat, nor the conditions under which cracks form. The direct effect of peat cracking on tree growth, health and stability was not addressed either. Following observations in several older cutaway peatland forests, roots were found to cross the cracks in some cases, while, in other cases, the roots followed the walls of the cracks. The wider the cracks, the fewer roots will cross the void (Whiteley and Dexter 1984) although Pyatt and Craven (1978) found that tree roots did cross furrows when a carpet of needles had accumulated, usually around the time of canopy closure. In some circumstances, cracks will control the water table, usually drying the site. While this may put the trees under pressure by reducing the moisture content of the peat, it can also help regulating the excess moisture at certain sites.

Bord na Móna has succeeded in reclaiming such peat for grassland without any cracking effect by using intensive cultivation, sometimes mixing the peat with sub-peat mineral soil. Once the peat is in a more granular form, it allows for peat crumbs to slide over one another and so accommodate horizontal strains without cracking. It is thus projected that planting trees on cultivated *Phragmites* peat would alleviate the occurrence of cracking. Cracking will not occur if the peat is mixed with sub-peat mineral soil. Where deep peat is present, it is crucial that the peat is not levelled or recompacted straight after cultivation. If *Phragmites* peat is deep ploughed, disced, and levelled within one season, cracks will inevitably develop as seen in Mongagh bog. This means that sufficient time should be left between cultivation and planting.

Conclusion

The variety of peat profiles found within the BOGFOR sites confirms the heterogeneity of these sites and the complexity of the reclamation process for forestry. For example, the variation in peat type, peat depth and sub-peat mineral soil can cause random variations in the mineral nutrient regime of the substrate. At another level, the combination of peat type and sub-peat mineral soil can present physical difficulties with regard to drainage and this will affect in turn the type of site preparation the cutaway can undergo.

4: Planning an afforestation scheme

Objectives and frameworks

The idea of planting a forest on bare land may seem simple, but for a tree planting programme to succeed it requires planning, including first and foremost a clear definition of objectives. Afforesting industrial cutaway peatlands (approximately 20,000 ha) would make a significant contribution to attaining the planting targets set out in the government's forest strategy (Department of Agriculture 1996). These new plantations would be able to satisfy most of the roles that forests play, particularly the provision of industrial wood products. These crops could primarily be used for sawn timber but could also supply wood biomass for energy production. While wood production may be a priority, it does not necessitate exclusivity. Establishing a forest on industrial cutaway peatlands can yield a wider range of products, and silvicultural practices can be developed that reconcile timber production with other benefits of the forest, especially landscape, biodiversity and recreation.

While this report is devoted primarily to the scientific and technical aspects of planting trees on cutaway peatlands, it is essential to consider tree planting on cutaways in the context of economic, environmental and social frameworks. Because of the magnitude, location and ownership of these future forests, there is a great need to ensure that the balance between the economic, environmental and social needs of the local communities is met. Within the sustainable forest management framework, it is imperative that these objectives are specified at the planning stage so that appropriate sites, species and practices can be proposed and evaluated.

Site availability and selection

While Bord na Móna owns approximately 80,000 ha of peatland, 25% of this area is already in after-use. The remaining 60,000 ha are mainly located in the Midlands, in some 150 separate units. A prerequisite for growing trees on cutaway peatland is adequate drainage. Only areas which are drainable by gravity (as opposed to pumping) are suitable for forestry. Approximately 50% (30,000 ha) of Bord na Móna industrial peatlands have or will have pumped drainage to facilitate peat production and are thus deemed unsuitable for forestry. Within the areas deemed drainable, there are depressions where additional remedial drainage with deeper drains will be necessary. The intensity of this will be site-specific and may or may not be economically justified.

Only a proportion of the total cutaway peatland area will ever be suitable for commercial forestry. This total area has been estimated by Bord na Móna to be between 16,000 and 20,000 ha. Depending on the level of peat harvesting, it is estimated that this area could become available over a period of 20 years. Understanding how and in what manner these areas are presented is critical to developing a successful afforestation programme.

Only small areas (as low as 1 ha) are released from peat production at any one time and it may take up to 20 years for a block of 20 ha (minimum commercial plantation) to be released in total for after-use. By then, however, a significant portion of this block may have been colonised with pioneering vegetation and certain areas may not be suitable for immediate planting.

The next step in planning an afforestation scheme is the identification of suitable sites where plantation establishment is an economically viable and environmentally acceptable proposition. This involves the identification of areas where features which would prevent successful afforestation or would have a negative impact on the environment. Environmental impacts are typically identified and evaluated through the preparation of an environmental impact statement (EIS). Because industrial cutaway peatlands are mostly in single ownership (Bord na Móna) and are located in regional clusters, appropriate impact assessment methodologies should be developed.

In order to select management practices best adapted to specific site conditions, an evaluation protocol was created to assess and classify cutaway peatlands for forestry purposes. Table 4.1 shows a list of site factors that can be used to assess the forestry potential of a cutaway peatland. Poor quality sites are highly unsuitable for commercial forestry without intensive site preparation operations. Good quality sites have good forestry potential requiring minimum inputs.

A typical site classification using soil or botanical systems cannot be used for cutaway peatlands due the absence of vegetation and the importance of micro-climatic conditions. A more structured classification is required and a three-step site evaluation protocol is proposed (Table 4.2). This will assist in the choice of optimum forest management options (G1-G4) for a given site. To use this classification, a peat survey has to be carried out across the site at a minimum intensity of one measurement per 0.25 ha.

Table 4.1: Quality factors used to assess cutaway peatlands for forestry potential.

Factor	Quality scale	
	Poor	Good
Drainage system	High water table with waterlogged areas	Low water table and drains cut into mineral soil
Aeration of peat	Orange/brown, aerobic peat with H_2S smell	Dark brown aerated peat
Peat structure	Massive, dense	Granular
Exposure	Open, windswept	Presence of wind barrier (e.g. older plantation)
Vegetation	Bare	Grass and shrubs

Table 4.2: Three-step process to determine suitability for afforestation.

Step 1: General classification of cutaway peats.			
1	Cutaway peatlands that were pumped during peat production	→	No commercial planting
2	Cutaway peatlands that are located in a depression, close to the bottom contour of the bog floor	→	No commercial planting
3	Cutaway peatlands that have been recolonised naturally by birch and willow	→	G1
4	Cutaway peatmands that have recently come out of peat production (bare brown fields); gravity drainable, suitable outlet	→	Step 2
Step 2: Peat depth			
1	Very shallow peat(<50 cm) over undeveloped mineral soils* or marl	→	No commercial planting
2	Very shallow peat (<50 cm) over weathered mineral soil	→	G2
3	Shallow peat (50-100 cm)	→	G2
4	Deep peat (>100 cm)	→	Step 3
Step 3: Peat type			
1	*Phragmites* peat	→	G3
2	*Sphagnum* peat	→	G4

*Undeveloped sub-peat mineral soils display typically greyish colours and can be either sandy-loam or silty-clay (glacial 'blue clay'). They all have massive compact structure with free carbonates usually present throughout the profile.

Site survey

It is clear from the site evaluation protocol that a successful afforestation project will depend on information describing the site and its biophysical properties such as soil description (e.g. peat type, peat depth, sub-peat deposits, permeability), hydrology (e.g. presence of outfall drains), climatic characteristics (e.g. risk of late spring frost) and ecological features (e.g. vegetation). Because both tree growth and composition of the vegetation are determined by the same basic variables of light, temperature, water table levels, soil aeration and fertility, indicator plants (when present on site) can be a valuable guide for site and species selection. Where there is enough natural vegetation, it can be a remarkably sensitive indicator of site variability, especially micro-topography. This is assuming that there is enough natural vegetation, which may not be the case on many post-harvesting cutaway peatland sites. While a site may be selected as suitable for forestry purposes, it will inevitably have areas that are not suitable for planting, which a site survey should adequately identify.

The collection and analysis of biophysical data through a site survey is essential and should be presented using a GIS mapping system to facilitate the decision-making process. A typical example of the significance of these data is in relation to the drainage system. As mentioned earlier, any consideration of drainage must take into account various hydrological and related factors of a site. It is important that this database is dynamic, due to the difficulties with the phased timing of the peat fields becoming abandoned within a bog unit. While part of a cutaway may be withdrawn from milled peat production, it may not be available for afforestation for five years or more due to its location within the bog unit. During this time, natural vegetation may start colonising and drain infrastructure may start breaking down, creating waterlogged areas which then become unsuitable for afforestation.

Site access and shape also need to be taken into consideration in afforestation plans. The scale and remoteness of most peatlands may appear to be a disadvantage but midland cutaway bogs have had some road or rail system already developed for harvesting and transport of peat. With some improvement, these systems should suffice for the establishment of a plantation and no further development should be contemplated until thinning is due. However, these vast areas may give a mistaken idea that large tracts of land can be planted. The issue of scale is of principal significance in terms of site selection, site preparation and overall management of the plantations (especially vegetation control logistics). On the other hand, assuming a roughly square/rectangular shape, the cutaways offer much larger tracts of land in one block than most other afforestation projects (the current average block size being planted under the afforestation scheme is < 10 ha). This would lead to efficiencies of scale.

Landscape integration

In the final stage of the planning and designing of plantation forests, integration with the surrounding landscape must be considered. The future of industrial cutaway peatlands will be a mosaic of wetland, grassland, naturally colonised areas and plantation forestry. Where forests are established, they should be within an integrated landscape. It is important to acknowledge that each bog unit will contain areas that are not suitable for forestry. These should be targeted for restoration of native ecosystems or maintained as open spaces as the pre-industrial landscape was once open. Afforestation of cutaway peatlands is an integrated venture that does not end at the boundary of the forest. These forests should be designed, planted and managed in recognition of legal requirements, customary rights and local demands.

SUMMARY POINTS: PLANNING AN AFFORESTATION SCHEME

- *A successful afforestation programme on cutaway peatlands requires a clear definition of objectives and considerations must be given to wider land use issues.*
- *Understanding how and in what manner cutaway peatlands are presented after harvesting is critical to developing an afforestation programme.*
- *Small areas (as low as 1 ha) are released from peat production at any one time.*
- *A site survey will provide reliable information which will help in the choice of management options.*
- *The afforestation of cutaway peatlands requires total integration with the wider 'cutaway peatland' landscape to create a successful multipurpose area where yields of timber are set alongside many other products and benefits.*

5: Management guidelines

The requirement for management guidelines comes as a direct consequence of the problems encountered in the past while afforesting cutaway peatlands. Since most of the trials and experiments on cutaways were initiated as recently as the late 1990s, these guidelines should be considered preliminary in nature. Results and experiences from future plantings (following these practical recommendations) should provide opportunities to refine these guidelines. The guidelines are addressed under the following headings:

- Site preparation;
- Species performance;
- Tree establishment;
- Nutrition and fertilisation;
- Late spring frost;
- Pests;
- Vegetation;
- Management of poor or failed older plantations;
- Biomass production potential.

Site preparation

While site preparation methods have been practised with good results on blanket bogs (OCarroll et al. 1981), plantations on cutaway peatlands have mostly been established without site preparation, the trees being planted directly into the peat without cultivation or additional drainage.

Site preparation is often necessary for the establishment of a new forest. Numerous experiments have now shown that site preparation is an important silvicultural tool through which unfavourable growing conditions can be ameliorated in order to make a site suitable for tree growth (Sutton 1993; Savill et al. 1997; Ryans and Sutherland 2001). Each seedling has the potential to grow into a mature, merchantable tree, given the right environmental and soil conditions. Micro-site growth factors such as soil temperature, drainage, aeration and nutrient status can be ameliorated through specific site preparation techniques (Dobbs and McMinn 1973; Sutton 1993). While the principal objective of site preparation is to enhance the establishment of a tree crop, the specific aims of site preparation can vary according to site, climate, history and the ambitions of the forest owner. Any form of mechanical site preparation can have effects on water movement, soil moisture content, soil aeration, soil temperature, soil texture, soil compaction, nutrient availability (especially nitrogen) and competing natural vegetation. The cost of the whole afforestation project will be greatly affected by the decision and choice of site preparation. In order to make the right decision, a sound knowledge of site-specific conditions and operational constraints is required.

Soil conditions

Peat moisture regime

Excess soil moisture is the biggest constraint during the establishment of tree seedlings on cutaway peatlands. Cutaway peat soils following cessation of peat harvesting still have a very high water content, requiring some sort of drainage to lower the water table. The major reason for drainage is to increase the oxygen content of the peat, thereby improving tree growth, depth of rooting and soil decomposition. Successful drainage on cutaway peatland will allow quicker tree establishment, thus increasing interception of precipitation and evapotranspiration by the trees.

During peat production, bogs are drained either by using deep main drains or by pumping. In the latter case, reflooding is the only sustainable after-use, requiring only the discontinuation of pumping. Several sites have now been re-flooded by Bord na Móna after peat harvesting ceased and the new lakes and bird habitats are now valuable ecosystems for amenity and wildlife (Rowlands and Feehan 2000a; Higgins and Colleran 2004, 2005). Gravity-drained cutaway areas cannot be completely flooded without substantial re-engineering due to the complexities of the drainage pathways and the relative levels of water table and the surrounding regional hydrology. The installation of ditches for peat harvesting lowers the water table and reduces the moisture content of the surface peat layer from c.95 to c.80%. The significance of this *in situ* drainage system has yet to be evaluated for forestry.

In general terms, the problems of wet land can be divided into those created by high groundwater levels, by groundwater seepage and those caused by the inability of the soil to transmit surplus surface precipitation to the regional water table. The latter is particularly noticeable on cutaway bogs where precipitation can greatly exceed evapotranspiration and where glacial tills are locally impervious.

Peat aeration

In peat soils, aeration is often reduced by an excess of water at the surface, due to capillary rise. Excess water can result in anaerobic conditions, causing decreased root respiration and ultimately reduced growth or plant death. Anaerobic conditions cause the plant to produce toxic compounds (e.g. ethanol and ethylene), while it also causes the soil to produce substances that are harmful to plant roots (e.g. sulphides). Soils must be aerated for tree roots to grow satisfactorily. The greater the aerated mass of peat, the greater the volume the tree roots can exploit for nutrients and the stability of the growing tree. In general, broadleaves show greater tolerance to waterlogging than conifers (Gill 1970). Among conifer species, pines will suffer less than spruce species (Coutts and Philipson 1978). Damage to trees caused by excess water generally occurs when land becomes temporarily waterlogged because of flooding or blockage of drains. Whether the tree is tolerant of flooding or not, the root system will typically be restricted to the surface layer, thus causing poor anchorage and susceptibility to windthrow. In cutaway peatlands, the water table can drop rapidly during summer months. At East Boora, the water table was measured monthly over a year and results revealed a variation of 60 cm between winter and summer levels, regardless of cultivation treatment (Figure 5.1). While the water table can fluctuate rapidly, it may not affect the total depth of aerated peat. At East Boora, the depth to the anoxic layer was measured using steel rods inserted into the peat (c.f. Carnell and Anderson 1986 for methodology). Figure 5.2 shows that while the water table fluctuated between December and May 2004, the anaerobic limit remained relatively shallow between 10 and 30 cm deep.

Drainage of cutaway peats

Waterlogging difficulties will occur in most cutaway peatlands. In considering the necessity of taking action to lower the water table, two questions arise: what level is required to ensure the establishment of a particular tree species, and for how long is the drain maintenance required before the trees naturally lower the water table by themselves?

Peat soils vary greatly in hydraulic conductivity and permeability, and these properties will affect the efficiency of the drainage system. The high proportion of very small pores in many peat soils requires close spacing of drains if they are to be effective.

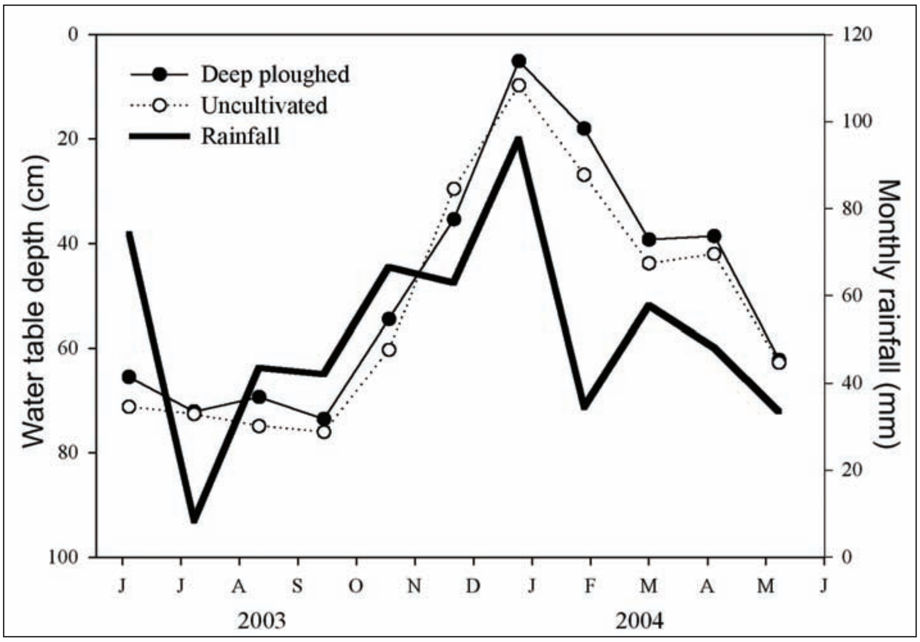
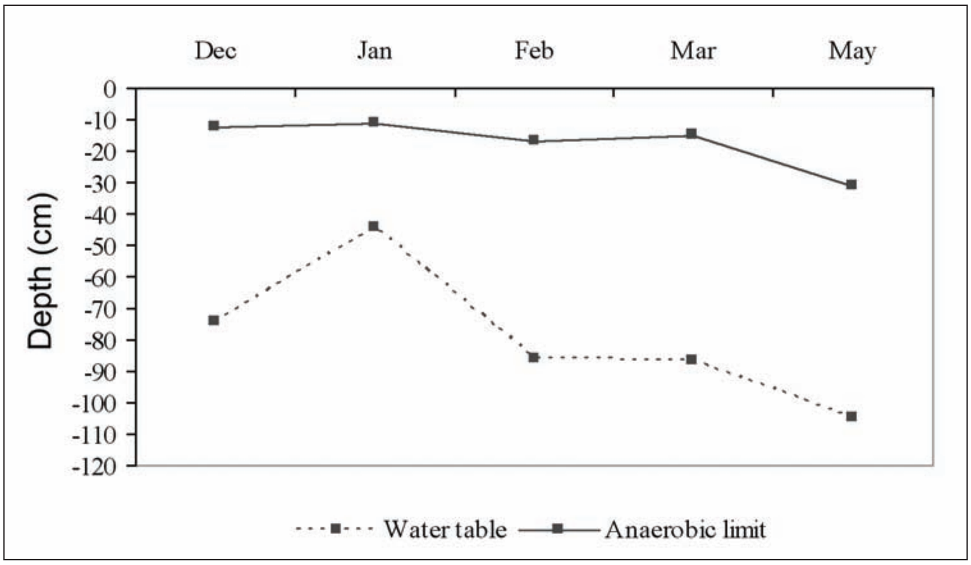


Figure 5.1: Monthly mean rainfall and water table depths in the deep ploughed and uncultivated cutaway area at East Boora.

Figure 5.2: Relationships between water table levels and anaerobic layer (measured by rusting of steel rods) at East Boora in 2003/2004.



Woody fen peat, on the other hand, has a better pore size distribution, a higher non-capillary pore content and therefore higher conductivity. *Sphagnum* peat, particularly humified *Sphagnum* which is found in cutaway peatlands, and deep *Phragmites* peat are more likely to show drainage difficulties. Observations using test pits in cutaway peatland plantations on *Phragmites* peat showed that drains were only effective in lowering the water table close to the edge of the drains (Mulqueen and Rodgers 2002). For this reason, attempts at reducing the water table over large areas of cutaway peatland can be very difficult and some areas may be better left unplanted.

Any consideration of drainage must also take into account various hydrological and related factors that vary from one cutaway site to another. As local drainage conditions typically vary within one site, depending on the bottom contour of the cutaway peatland, test pit observations may be used to measure the state and movement of the water at different points. The identification of a suitable outlet and the presence of a gradient (to allow gravity drainage) is of critical importance. Site assessment is best carried out in late autumn or early winter when precipitation is highest. Before planning any drainage system, local experience and knowledge should be sought.

Excavating deep drains in most waterlogged areas can usually alleviate localised drainage problems. In the case where the sub-peat mineral soil is glacial till or clay, spreading the spoil over the cutaway surface can also help the aeration of the surface layer where the trees are planted. Drain slope should be kept even and gentle to reduce erosion and silting. Generally, operations must follow the Forest Service guidelines on water quality (Forest Service 2000a) which specify maximum drain slopes, drain layout and the use of silt traps.

From observations, cutaway peatlands without vegetation show the poorest drainage. The impact of raindrops may break down the surface structure to form a seal thus promoting surface flow. Conversely, a vegetative cover protects the surface from such deterioration and also increases percolation through the aeration of the peat by the root system. Woody vegetation, in particular, can greatly improve the moisture regime of cutaway sites by increasing evapotranspiration and reducing the water table level. This also has the advantage of creating a better aerated and better structured surface layer. The lack of oxygen can also be overcome by planting trees which transport it from shoots to roots, e.g. some species of alder, birch and willow (Lyr and Hoffmann 1967).

Having lain for thousands of years under several metres of peat and then, under heavy machinery for many seasons, the peat layers found in cutaway bogs are considerably compacted. Drainage alone cannot resolve this. Site cultivation that disturbs the peat mass can also improve drainage by increasing the rate of removal of surface water.

Site preparation techniques

Past experiments

Most cutaway peatland plantations established in the late 1980s and early 1990s were carried out without any site preparation. Sites were accepted for planting in an essentially unreclaimed condition, probably because of the relative ease of planting and the apparent absence of competing vegetation. In a review of the potential for plantation forestry on cutaway raised bogs, Carey et al. (1985) reported that 'some kind of surface cultivation may be desirable'. Consideration was given to the fact that *Phragmites* peat and woody fen peat layers are relatively compact due to the *in situ* consolidation from the overlying peat layers and from peat harvesting machinery. Cultivation trials were subsequently established at Lullymore in 1988.

The Donadea 32/88 Coillte trial was planted with Scots pine and Sitka spruce in 1988 and various cultivation techniques were tested: deep ploughing at 50 and 100 cm; rotavating at 15 cm, ripping at 200 cm spacing to 90 cm depth and cambering (COFORD 2006). The Sitka spruce suffered heavy frost damage and had disappeared by year nine. Results with Scots pine showed that, after nine years, cultivation did not have any beneficial effects on growth (Anon. 1997). When this site was visited in 2002, cultivation treatments were still visible on the ground and it was apparent that some sub-peat mineral materials had been brought to the surface. There seemed to be some link between soil conditions and needle retention, but this was not studied. Again, site factors seem to have counteracted treatment effects.

The Donadea 44/89 Coillte trial tested the effect of mounding on Sitka spruce and Norway spruce (COFORD 2006). Because of the severe damage caused by late spring frosts in the first year, there were clear treatment effects on survival (Table 5.1). The positive effects of mounding could be associated with the raised planting position that helps lift the tree above the frost level.

O'Carroll and Farrell (1993) developed a site productivity model for Norway spruce on fen peat in central Ireland and found that the yield class of the species was correlated with the physical properties of the peat (mainly soil C/N ratio, soil air space and pH). This was

Table 5.1: Survival percentage for each treatment and each species after one year (Donadea 44/89), adapted from Coillte.

Treatment	Sitka spruce	Norway spruce
Mounding	90%	90%
Control	30%	60%

further confirmed by a greenhouse experiment which tested the effect of mixing peat and sub-peat mineral soil. Satisfactory growth was recorded on all soil mixtures except pure mineral soil. In addition, significant responses to both N and P fertilisation were obtained over all soil mixture levels.

While it was recognised that the peat depth remaining after harvest and the influence of sub-mineral soil were important for tree nutrition (especially in the case of unweathered and highly calcareous soils), no critical peat depth was indicated. McCarthy (1991) ventured a minimum required depth of 75 cm but added that deeper peat would be required where the subsoil is highly calcareous, e.g. marl. Recently, the same author investigated several sites where Norway spruce (planted in 1954) is growing successfully (Yield Class 12-14) on a cutaway fen peat site (20 cm deep) underlain by shell-marl of pH 8.2. It was concluded that free drainage, presence of an outfall and presence of a reasonable amount of organic matter in the soil profile made such sites suitable for planting, although they are currently not deemed to be so by the Forest Service (Forest Service 1996; Horgan et al. 2003).

BOGFOR cultivation experiments

Conventional site preparation for tree planting on poorly drained soils has relied on ploughing or mounding. However, cheaper options exist that needed to be tested on cutaway peatlands. The overall objective of the BOGFOR cultivation experiments was to determine the effects of site preparation treatments on early survival and growth of different species that have good growth potential on cutaway peatland. A series of experiments was established at various sites to investigate whether site preparation could improve the growth of a range of tree species on different cutaway peatlands.

Technical aspects of site cultivation methods

Each site preparation method differs in the way soil is manipulated to create enhanced planting medium and positions. These are described below. Most of the cultivation operations were carried out using Bord na Móna equipment that was available at the time. The machines are especially adapted for cutaway peat sites where bearing capacity and soil strength are low. On cutaway peatlands, cultivation should be carried out in dry periods in early autumn avoiding the winter period when soil water levels are high.

1999 Norway spruce demonstration areas

Norway spruce commercial demonstration areas were established on bare peat areas at Blackwater (KTY 1/99), Clonsast (Emo 1/99) and Tumduff (CLE 1/99) to test current site preparation techniques. The three sites were approximately 15 ha in size and divided into three treatment areas:

1) no cultivation;
2) ripping only and
3) ripping and discing.

Drains were cleaned and additional ditches excavated where necessary. The sites were rolled prior to planting with bare-root Norway spruce of Danish provenance (2+1 transplants; DKTVIL-TO3) at 2 x 2 m interval in May 1999.

2000 cultivation trials at Tumduff, Blackwater and Mount Lucas

Site cultivation treatments tested at Tumduff (CLE2/00), Blackwater (KTY16/00) and Mount Lucas (Allen1/00), included four different treatments:

1) no cultivation;
2) excavator mounding;
3) ripping;
4) ripping and discing.

Cultivation treatments were carried out in autumn 1999 and were applied to peat fields using a randomised design. The cultivation treatment areas were 300 m long and 15 m wide, while the species treatment blocks were c.0.12 ha in size. Drains were left intact at all sites. Norway spruce, Sitka spruce, Scots pine and hybrid larch were planted in 2000 across the three sites, except at Mount Lucas where hybrid larch was replaced by pedunculate oak. Provenances were similar across sites (Appendix 5).

2003 cultivation trial at East Boora

One experiment was established at East Boora (EB1/00) to examine the effect of deep ploughing in conjunction with peat depth. The site was levelled with bulldozers in September 2003, effectively removing all internal ditches used for surface drainage during peat harvesting. Additional drainage ditches were then dug in areas identified as waterlogged during high rainfall events. A block of 6 ha was deep ploughed in the autumn using a mouldboard plough (making a furrow approximately 1 m wide and 1 m deep). An adjacent block of 6 ha was left untreated. Where the peat depth was shallow (<80 cm), deep ploughing allowed some of the mineral subsoil to be brought to the surface. The trial was laid out as a crossed strip design where seedlings were planted in four blocks as follows:

A1: Deep ploughed - deep peat

A2: Deep ploughed - shallow peat

B1: Not cultivated - deep peat

B2: Not cultivated - shallow peat

The whole site was rolled in February 2003, prior to planting with Norway spruce, Sitka spruce, oak in blocks averaging 0.2 ha.

All the experiments were fertilised at planting with rock phosphate (12.5% P) in a split application: 175 kg/ha (21 kg P/ha) manually applied at planting in bands; and the same amount, manually broadcast, two years later, together with 250 kg/ha of muriate of potash (50% K). Due to the presence of mineral soil close to the surface, the source of phosphatic fertiliser chosen for Mount Lucas was superphosphate (16% P) which was broadcast manually at the same rate as the other sites (21 kg P/ha). All cultivation trials were fenced against hares. Vegetation was kept under control during the reporting period, using a combination of manual and mechanical methods (mowers).

Mounding

Nowadays, mounding is the principal ground-preparation technique used in afforestation in Ireland. It provides elevated planting positions and has been shown to increase survival and growth of trees on several site types (Dobbs and McMinn 1973; Sutton 1975; Haywood 1987). Bucket mounding uses a tracked excavator to create mounds, rather than equipment towed behind or attached to a skidder or bulldozer. It can thus be used in wet areas. Typically, on cutaway peatlands, the excavator moves across the site using spoil from excavated drains to create drains that are roughly 5 m apart and 50 cm deep. Mounding creates a raised planting position, resulting in more aerated soil above the water table, warmer soil temperatures during the growing season, greater nutrient availability, and a degree of vegetation control (Haywood 1987; Orlander et al. 1996; Londo and Mroz 2001).

Deep ploughing

Spaced double and single mouldboard ploughing, used for many years on oligotrophic peat (Savill 1976; Thompson 1978), have now fallen out of favour, and these methods have never been used on cutaway peatlands. Complete deep ploughing is the most intensive form of site preparation that has been tested on cutaway peatlands and the most expensive (€400-500/ha). It has been used primarily to reclaim industrial cutaway peatlands for grassland production (McNally 1984). Deep ploughing was particularly suitable where the maximum amount of peat had been removed so that it allowed the remaining peat to be mixed with subsoil. Destroying the contact horizon (between the peat and sub-peat mineral soil) by roto-tilling or ploughing has been found to be crucial to improve the physical and chemical quality of cutaway for agricultural production (Drennan et al. 1984). The same ploughing technique was used by Bord na Móna for agricultural reclamation to prepare some of the cutaways for forestry. It makes a furrow approximately one metre wide and one metre deep and produces an upturned furrow slice that provides a drier site for the tree and encourages root growth. Due to the linear nature of the plough furrows, rooting is sometimes confined to the furrow slice rather than the surrounding soil; this may have consequences for stand stability. Depending on the peat depth remaining, deep ploughing may or may not bring sub-peat mineral soil to the surface (Plate 2).

Ripping

Ripping is typically carried out using a trailed ripper with 60 cm long tines at 1 m spacing (Plate 3). When the peat is very compact, ripping can loosen the soil structure. Ideally, ripping should take place when the soil is dry so that the effect is a 'shattering' of the soil structure instead of a narrow fracture. Ripping can provide water channels, helping in the removal of surface water. In most cases however, the rip lines tend to fill up with peat debris. Ripping is often followed by discing to flatten and regroup the ripped soil. This site preparation method requires lighter equipment than ploughing or mounding, rendering it more suitable to the cutaway peatland conditions and also less expensive (€300/ha).

Discing

Discing is often used in conjunction with deep ploughing or ripping. Discing disturbs the soil and the top layers to a depth of 20 cm. The result is a more homogenous medium for planting. In dry conditions, discing may not be advisable as it pulverizes the peat into powder. In addition, vegetation is largely removed during the operation.

Levelling

Industrial milled cutaway peatlands typically have a drainage system consisting of parallel drains every 15 m. Levelling consists of bulldozing to fill in all the drains, thereby disturbing the surface of the peat field. Additional drains can then be excavated where necessary (so as to alleviate waterlogging). This operation also leaves a clean field, as it removes much of the vegetation.

Effects of site cultivation methods on the early growth of Norway spruce

1999 demonstration areas

After five growing seasons, survival rates were high at both Clonsast and Blackwater (97% and 95% respectively). Survival rates at Tumduff consistently decreased during the establishment period and ranged between 73 and 89% after five growing seasons. Cultivation treatments did not affect survival rates or total height after five growing seasons (Figure 5.3). Tree growth varied greatly, however, between and among the three commercial plantations. When analysing all the data across sites, it appears that site

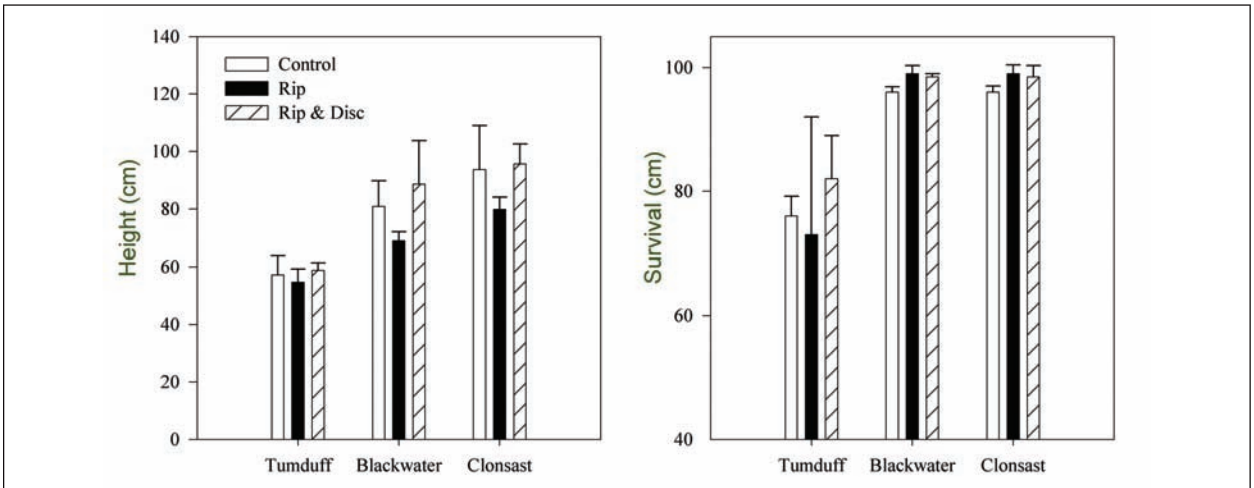


Figure 5.3: The effect of cultivation treatment on the total height and survival of Norway spruce after five growing seasons across three demonstration areas (vertical bars denote ± one standard error).

significantly affects survival, height and RGR_{1-5} (Table 5.2). Tumduff is the poorest site with significantly lower survival rates and height growth than the other two commercial plantations (Figure 5.4).

A special assessment was carried out by Renou and O'Hare (2005) after six growing seasons at Blackwater and Clonsast. Despite good growth (5% of the trees failed to grow properly in Blackwater and 10% in Clonsast), there was great variation in growth rate. The analysis of relationships between morphological characteristics of Norway spruce and soil and nutritional properties produced different results in the two plantations under examination. At both sites, height and leader growth were negatively correlated with peat depth and positively correlated with the percentage of aerated peat (Table 5.3). The relationship between soil quality in terms of nutrient concentrations and tree performance varied between the sites. In Blackwater, tree height was positively correlated with the concentrations of P and K in the peat. In turn, P and K concentrations in the peat correlated positively with depth of aeration and negatively with peat depth. No relationship was found between morphological parameters and peat nutrient concentrations in Clonsast. On the other hand, tree height and leader growth were positively correlated with foliar N (Table 5.3).

2000 cultivation trials

Regardless of cultivation treatment, Norway spruce established very well at all of the cultivation trials. There was no significant cultivation effect on survival rates after four growing seasons and average survival rates ranged from 84 to 100% across all the sites. Analysis of variance (ANOVA) revealed that cultivation treatment did not significantly affect the height or the relative growth rate between years 1 and 4 (RGR_{1-4}). When combining all the data, the repeated measure analysis revealed a significant site effect over time on both RGR_{1-4} (Table 5.4) and height (Figure 5.5). Mount Lucas had the tallest trees as well as the best growth rate. Height increment during the fourth growing season was almost double that of Tumduff where tree height and growth rates were the lowest of the three sites (Figure 5.5 inset).

Table 5.2: Effects of site on height and survival after five growing seasons as well as the relative growth rate between year 1 and year five (RGR_{1-5}) at three demonstration Norway spruce plantations.

Site	Height (cm)	s.e.	Survival (%)	RGR_{1-5}	s.e.
Blackwater	77.3a	4.3	95.7a	0.16a	0.011
Clonsast	90.7a	5.6	97.8a	0.14ab	0.017
Tumduff	57.2b	4.9	73.5b	0.11b	0.014
p value	<0.0001		<0.0001	0.02	

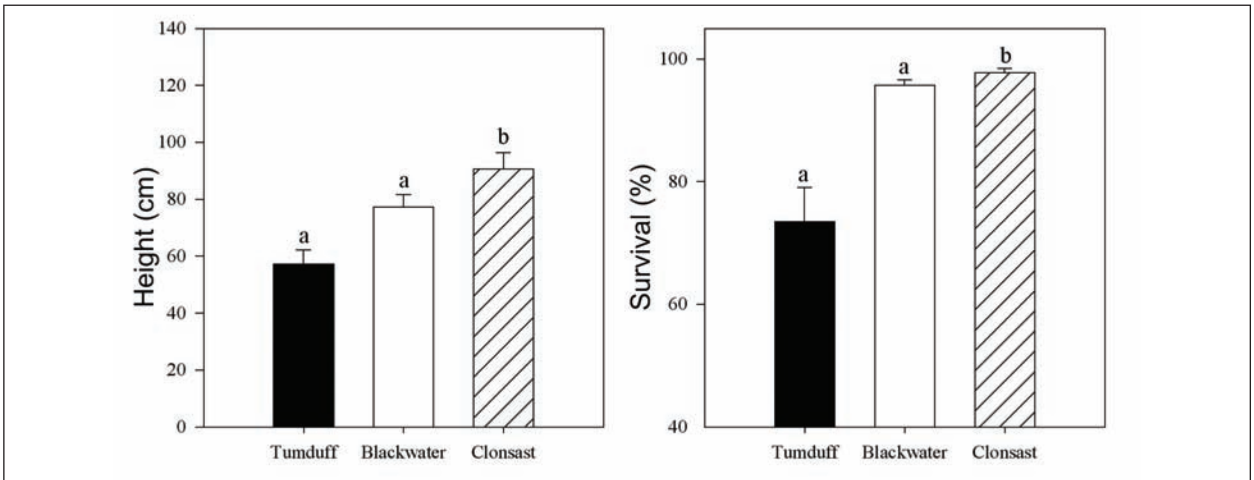


Figure 5.4: The effect of 'site' on the total height and survival of Norway spruce after five growing seasons (vertical bars denote ± one standard error).

Table 5.3: Pearson correlation coefficients between some soil parameters, foliar nutrient concentrations and morphological characteristics of two Norway spruce stands (Blackwater and Clonsast) five growing seasons after planting: * p<0.05, ** p<0.01, *** p<0.001.

	Site	Total height	Leader growth	Peat depth	Aeration
Foliar P	Clonsast	-0.07	-0.06		-0.36
	Blackwater	-0.03	0.18		
Foliar N	Clonsast	0.78***	0.77***	0.52*	0.80***
	Blackwater	-0.23	-0.18	-0.24	
Foliar K	Clonsast	0.30	0.26		-0.26
	Blackwater	0.48*	0.60*		
Peat depth	Clonsast	-0.76***	-0.74***		0.40
	Blackwater	-0.51**	-0.54**		
Aeration	Clonsast	0.60**	0.63**		
	Blackwater	0.59**	0.50*		
Peat P	Clonsast	0.24	0.19	0.02	
	Blackwater	0.52***	0.55**	-0.79***	0.52***
Peat N	Clonsast	0.29	0.27	-0.11	
	Blackwater	0.39	0.28	-0.33	0.40*
Peat K	Clonsast	0.07	0.01	0.25	
	Blackwater	0.40*	0.55**	-0.74***	0.50***

Table 5.4: Summary of ANOVA results showing the effects of site on RGR_{1-4} across all the cultivation trials.

Source	df	SS	F	p
Treatment	3	0.004	0.92	0.4500
Site	2	0.046	15.03	0.0002
Treat x site	6	0.006	0.71	0.6400
Error	16	0.024		

Site	RGR_{1-4}	s.e.
Tumduff	0.15	0.010
Blackwater	0.20	0.012
Mount Lucas	0.25	0.015
p value	0.0002	

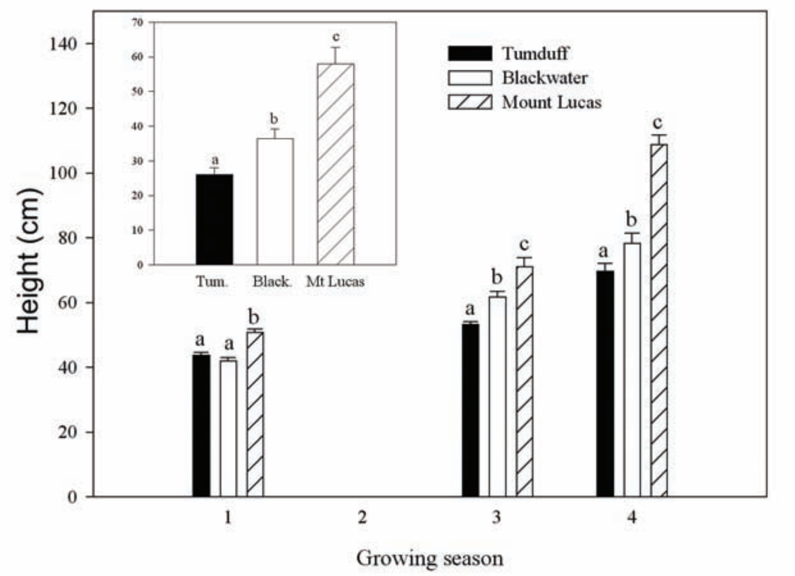


Figure 5.5: Effect of site x time on Norway spruce height (bars denote least square means ± one standard error). There was no measurement in year 2. Inset shows site effect on height increment. Means having the same letter are not significantly different (p>0.05).

2003 cultivation trials

Survival of Norway spruce after three growing seasons was very good, ranging from 98 to 100%, and was not affected by cultivation treatments or peat depth. ANOVA of height growth showed a significant interaction between cultivation treatment and peat depth ($p = 0.0002$). After three growing seasons, trees were significantly taller in the deep peat area that was deep ploughed while cultivation did not affect growth significantly in the shallow peat (Figure 5.6). Overall, Norway spruce grew better on shallow peat.

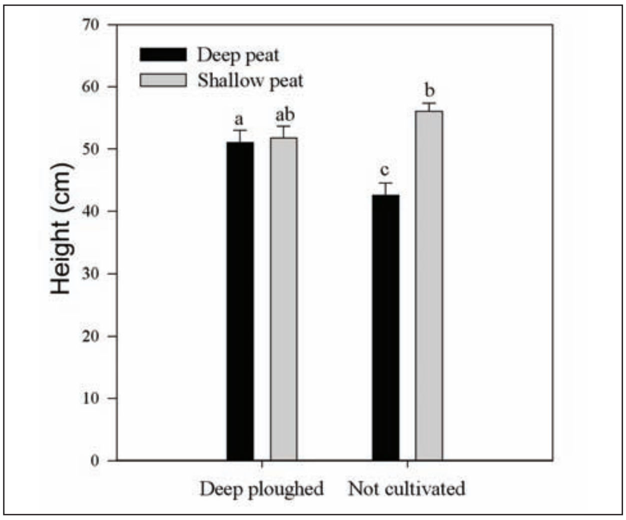


Figure 5.6: Cultivation x peat depth interaction in Norway spruce height growth at East Boora after three growing seasons (vertical bars denote ± one standard error). Means having the same letter are not significantly different (p>0.05).

Effects of site cultivation methods on the early growth of Sitka spruce

2000 cultivation trials

Regardless of cultivation treatments, Sitka spruce established very well at all three cultivation trials. Cultivation treatment did not affect tree height, except at Mount Lucas where, after four years, trees growing on mounds were significantly taller than in the other treatments (Figure 5.7).

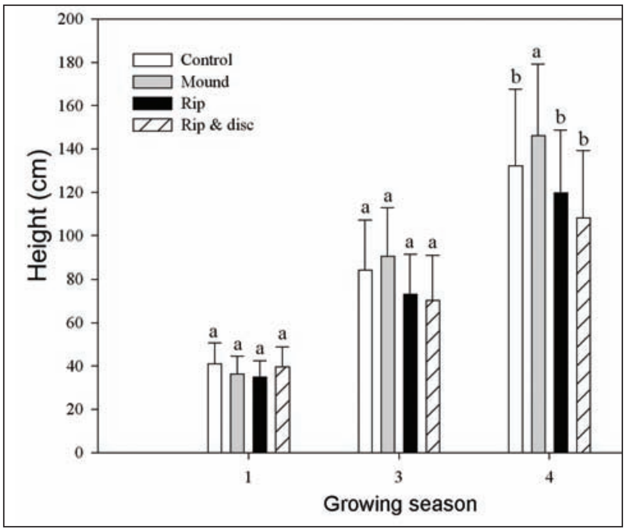


Figure 5.7: Effect of cultivation treatments on Sitka spruce height at Mount Lucas (shallow peat) (vertical bars denote ± one standard error). Means having the same letter are not significantly different (p>0.05).

No growth difference due to cultivation treatments was detected at the other two sites during the 4-year period. Interestingly, trees planted on mounds at Tumduff and Blackwater did not fare as well as the other treatments. These conflicting results may be explained by the composition of the mounds. At Mount Lucas, the shallow depth of the peat (< 60 cm on average) resulted in the mounds being composed of sub-peat mineral soil (in various proportions) mixed with woody fen peat. This allowed the mounds to hold together better than where they were comprised of pure *Phragmites* peat (Tumduff and Blackwater). At the latter sites, the mounds broke apart due to irreversible drying and cracking of the peat. As with Norway spruce, it can be concluded that the effects of cultivation on the growth of Sitka spruce can vary with site type. When the cultivation trial data are amalgamated across treatments and presented by site only (Figure 5.8), it becomes clear that tree growth is affected by site conditions, with growth being the poorest at Tumduff.

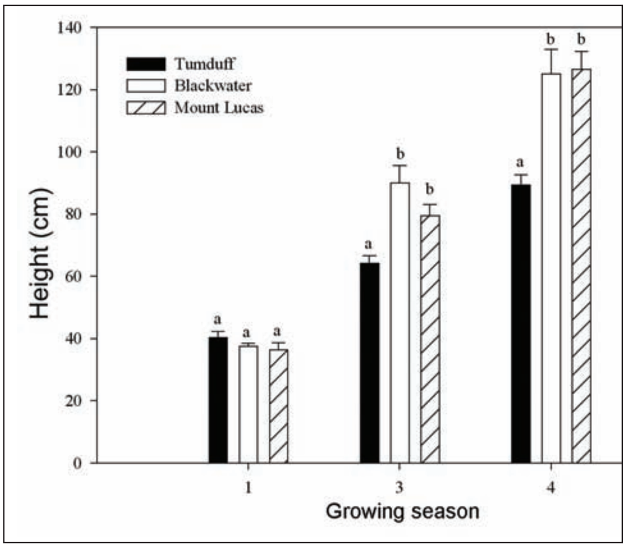


Figure 5.8: Effect of site on Sitka spruce height growth (vertical bars denote ± one standard error). Means having the same letter are not significantly different (p>0.05).

2003 cultivation trials

At East Boora, Sitka spruce survival ranged from 80 to 98% after three growing seasons. Similar to the Norway spruce results, the deep ploughing treatment improved height growth in the deep peat area only (Figure 5.9).

Effects of site cultivation methods on the early growth of Scots pine

2000 cultivation trials

Cultivation did not affect the height of Scots pine at any of the sites. However, trees growing on mounds had the lowest heights across all sites (Figure 5.10).

As with Norway spruce and Sitka spruce, the growth of Scots pine varied between sites with Tumduff showing the poorest growth (Figure 5.11). At Blackwater and Mount Lucas, total height after four years ranged from 75 to 122 cm and at both sites the trees were very healthy with no sign of damage (including absence of pine shoot moth).

Effects of site cultivation methods on the early growth of hybrid larch

2000 cultivation trials at Tumduff and Blackwater

Cultivation treatments did not affect the height growth of hybrid larch at either site (Figure 5.12) but growth differences were significant between the two (Figure 5.13).

Effects of site cultivation methods on the early growth of oak

2000 cultivation trial at Mount Lucas

At Mount Lucas, the survival of oak seedlings was high after four growing seasons regardless of the cultivation method (ranging from 85 to 91%). Cultivation reduced tree height growth in year four (Figure 5.14). Oak growing in the control plots was taller than in the other treatments, while mounding produced the smallest trees.

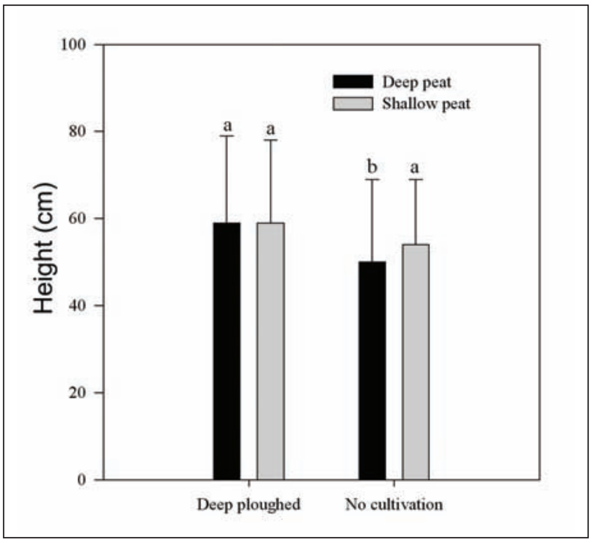


Figure 5.9: Effect of cultivation and peat depth on Sitka spruce height at East Boora after three growing seasons (vertical bars denote ± one standard deviation). Means having the same letter are not significantly different (p>0.05).

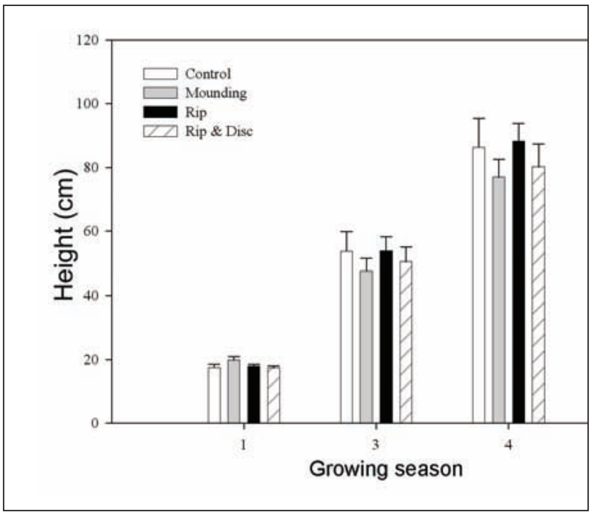


Figure 5.10: Effect of cultivation treatment on Scots pine height across all sites (vertical bars denote ± one standard error).

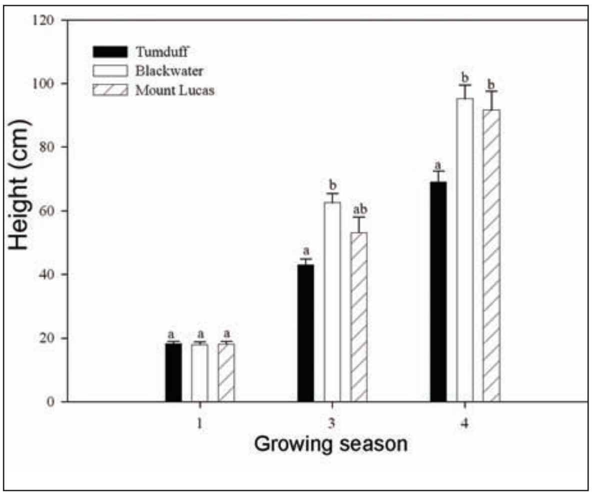


Figure 5.11: Effect of site on Scots pine height growth (vertical bars denote ± one standard error). Height means having the same letter are not significantly different (p<0.05).

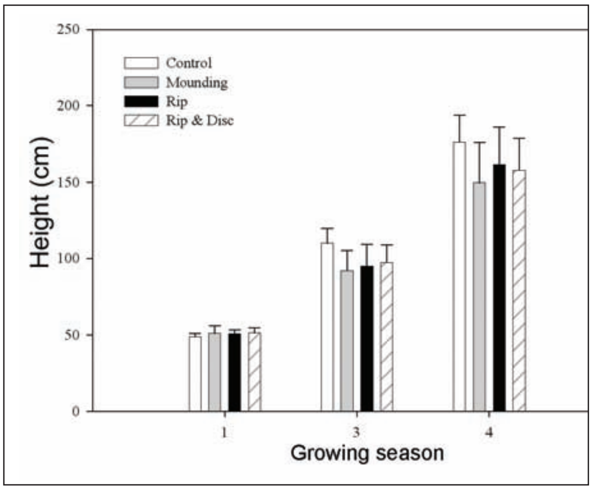


Figure 5.12: Effect of cultivation treatment on hybrid larch height growth (vertical bars denote ± one standard error). Height means were not significantly different (p<0.05).

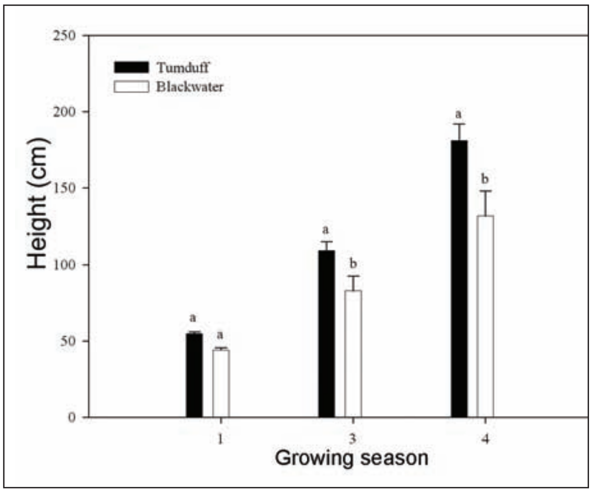


Figure 5.13: Effect of site on hybrid larch height growth (vertical bars denote ± one standard error). Height means having the same letter are not significantly different (p<0.05).

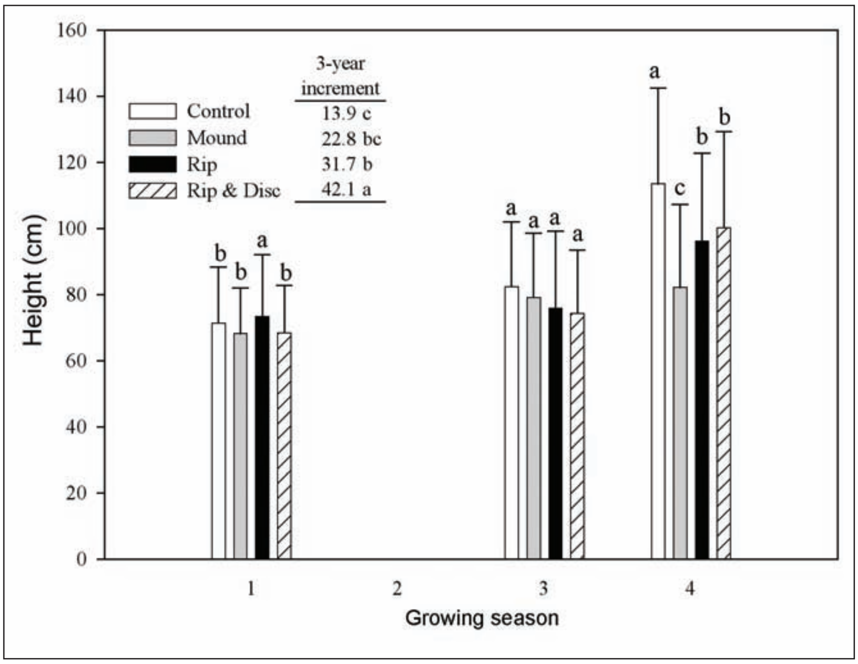


Figure 5.14: Mean height of oak seedlings in the different cultivation treatments (vertical bars denote ± one standard error). Height means having the same letter are not significantly different (p<0.05). No measurements were carried out in year 2.

2003 cultivation trial at East Boora

At East Boora, oak establishment was extremely successful, with all except one of the 200 oak seedlings in the assessment plots alive after two growing seasons. There was, however, a large variation in the height of individual seedlings (ranging from 16 to 180 cm). Where the peat layer was deep, cultivation in the form of deep ploughing did not have a significant effect on the height of seedlings (Figure 5.15). Conversely, trees planted on the shallow peat area were significantly smaller where no deep ploughing was carried out.

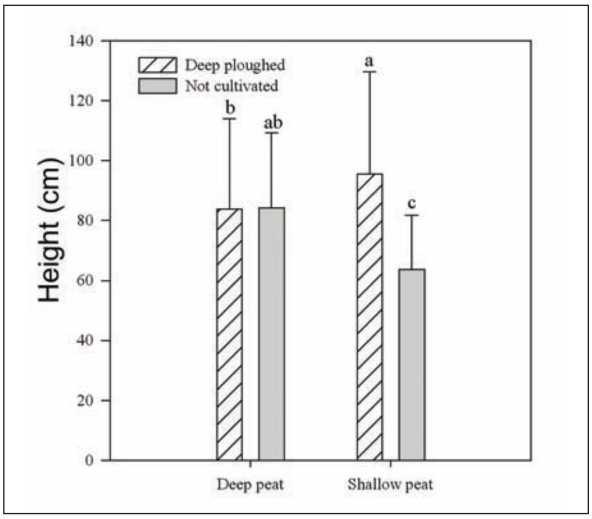


Figure 5.15: Mean height of oaks after two growing seasons (vertical bars denote ± one standard deviation). Height means having the same letter are not significantly different (p<0.05).

Conclusions and management implications

Site preparation can be expensive and needs to be economically justified through improved survival and growth of trees. The expense can sometimes be offset by savings in other respects, e.g. vegetation control may not be necessary on mounded sites.

The results from the BOGFOR cultivation trials revealed that conventional treatments such as ripping, ripping and discing and mounding were ineffective in increasing seedling survival or height growth of trees. The results confirm the importance of site conditions and their interaction with silvicultural treatments.

In general, conifers grew better on shallow or well-aerated peat. In the case of Sitka spruce, mounding has been successful on woody fen peat but it is not recommended on *Phragmites* peat, where the mounds disintegrated as the peat dried. Deep ploughing treatment positively affected the height of both Norway spruce and Sitka spruce in the deep peat and the height of oak in the shallow peat only. Peat analyses from East Boora (Table 5.5) revealed that N content was higher in the deep ploughed area where the depth of aerated peat was also the greatest.

Alternative mechanical site preparation techniques

Investigations through literature review and contact with experts in forest soil preparation have shown that other techniques might be suitable on cutaway peatlands. Two pieces of equipment - the Donaren trailed mounder and the Savannah bedding plough - have been identified for their potential use on bare peat cutaways, combining drainage and aeration effects. V-shearing is another site preparation technique that could be used specifically on re-vegetated cutaway peatlands, along with other methods such as corridor cleaning.

Donaren mounder (Plate 4)

The Swedish Donaren mounder (now manufactured by Bräcke) consists of two sets of hydraulically operated tri-spade wheels pulled behind a prime mover. The tri-spade wheel rotates and scalps the peat surface, forming a depression. It rotates the collected material onto the surface peat as intermittent mounds. The composition, shape, position and size of the mounds will vary depending on the soil type and surface vegetation. The machine was tested in a cutaway peatland site in the Irish Midlands and a report is available (Renou et al. 2005). This machine is clearly not suited for bare, wet peat. It was able to work best on different kinds of vegetated bog surface as long as the vegetation was not too high (or cut prior to mounding).

Savannah bedding plough (Plate 5)

Savannah bedding ploughs are used in many parts of the world to cultivate (disc) the soil before forming it into a continuous raised bed. Although this equipment has never been tested in Ireland, it is felt that the bedding plough could be employed for the preparation of bare brown peat fields, coming out of peat production with very little vegetation colonisation. In these conditions, the bedding plough could be suitable for creating a continuous, elevated aerated medium. The mounted bedding plough would be suitable for most cutaway peatland sites with either deep or shallow peat. The large disks can provide well cultivated beds, above the water

Table 5.5: Physical and chemical characteristics of peat (0-20 cm) at East Boora, Study 1.

		N		P		K		Bulk density		Depth		Aeration		pH	
Treatment	n	g/kg	s.e.	g/kg	s.e.	g/kg	s.e.	g/cm^3	s.e.	cm	s.e.	cm	s.e.		s.e.
No cultivation	18	9.10	0.8	0.18	0.01	0.25	0.06	0.141	0.035	113	11	39.7	2	4.57	0.14
Deep plough	18	12.00	1.4	0.17	0.01	0.19	0.08	0.136	0.038	118	8	56.4	3	4.61	0.10
t-test (p value)		0.08		0.75		0.78		0.55		0.47		<0.0001		0.71	

table all year around. As a continuous bed is formed, *Phragmites* peat would be less likely to dry and disintegrate (Renou et al. 2005). It also a relatively cheap option at €150/ha.

V-shearing (Plate 6)

V-shear equipment is placed on the front of a dozer and shears woody vegetation off at ground level, while pushing it to either side of the machine as it moves forward. V-shearing could be employed where cutaway peatlands have been naturally recolonised by woody growth (birch and willow mainly) or where a thicket has formed (from either planting or sowing). V-shearing cuts through woody material and sweeps aside the debris.

There are several advantages to this method of site preparation. First, the peat medium has already been improved due to the vegetation and tree growth aerating the peat. Second, rows of standing trees can be left at regular intervals, thus providing shelter to the newly-planted tree crop (Renou et al. 2005). The cost of this treatment is estimated at around €300/ha.

A similar method called 'corridor cleaning' has been developed in Sweden and Canada and which involves the removal by machine of all the trees in a corridors 2 m wide.

In conclusion, although neither the bedding plough nor the V-shearing methods have been field tested under Irish conditions, it is felt that both could play a role in the preparation of cutaways for planting. Until they are both successfully tested here, however, neither can be recommended.

SUMMARY POINTS: SITE PREPARATION

- *It is critically important to correctly select adequate sites (particularly in terms of peat properties and hydrological regimes) before any site preparation method is contemplated as cultivation, no matter how good, will not turn a poor site into a good one.*
- *Part of any cutaway peatland site will inevitably be unsuitable for forestry; these should not be planted.*
- *The need for an adequate drainage system, including suitable gradient and outlet is critical to the success of plantations on cutaway peatlands.*
- *Peat type and depth are important factor to assess before any site preparation is prescribed.*
- *Woody fen and Sphagnum peat will benefit from mounding but avoid mounding on Phragmites peat or when planting oak.*
- *Deep ploughing has been found to be the most successful site preparation method.*
- *Mixing peat and sub-peat mineral soil provides an excellent medium but planting in pure sub-peat mineral soil should be avoided.*
- *Avoid discing peat in dry conditions.*

Species performance

Sitka spruce and lodgepole pine have been the main species planted on milled cutaway peatlands, but experience of their survival and performance is very limited as the first plantings took place as recently as 1988. Horgan et al. (2003) give some general guidelines for the selection of species for planting in different site types, including cutaway bogs, but detailed knowledge of species performance on this site type is lacking. Within the BOGFOR research programme, over 150 ha of species trials were established between 1996 and 2003 in order to identify which species are likely to thrive on cutaway peatlands. Biological considerations (i.e. matching species to soil and climate) have been given priority in order to give the forester a range of species from which to choose, be it for biodiversity or commercial objectives. Species selection should take into account the main functions of a sustainable forest, namely economic, environmental and social, all of which provide a framework within which species selection should be decided.

BOGFOR species trials

Different approaches exist for the selection of species. The research approach chosen carefully examined species performance under different site and environmental conditions in order to provide site-specific species guidelines. This requires an environmental classification of the sites under study which can only be done by carrying out a detailed pre-planting site survey to match species to site characteristics. The BOGFOR species trials were established on four large cutaway peatland areas and tested ten conifer species and twelve broadleaved species (Table 5.6). Correct provenance choice is essential for successful establishment and growth; wherever possible the same provenance of each species was used. Within some sites, however, different provenances of certain species, such as lodgepole pine, were planted. The list of provenances of all the species planted in BOGFOR are listed in Appendix 5. Genetically improved sources were also used for certain species where available. Large-scale demonstration plantings were limited to certain species only. All the sites were

Table 5.6: List of species planted across the BOGFOR trials.

Broadleaves	English name	Abbreviation	Latin name	
Alder	Common alder	C. al	*Alnus glutinosa*	Native
	Italian alder	I. al	*Alnus cordata*	
Ash	Common ash	Ash	*Fraxinus excelsior*	Native
Aspen	Aspen	Asp	*Populus tremula*	Native
Beech	European beech	Be	*Fagus sylvatica*	
Birch	Downy birch	D. bir	*Betula pubescens*	Native
	Silver birch	S. bir	*Betula pendula*	Native
Oak	Pedunculate oak	P. oak	*Quercus robur*	Native
	Sessile oak	S. oak	*Quercus petraea*	Native
Poplar	Poplar	Pop	*Populus Beaupré*	
Maple	Norway maple	Map	*Acer platanoides*	
Sycamore	Sycamore	Syc	*Acer pseudoplatanus*	
Conifers				
Larch	Hybrid larch	HL	*Larix x eurolepis*	
	Japanese larch	JL	*Larix kaempferi*	
Pine	Corsican pine	CP	*Pinus nigra* var. *maritima*	
	Lodgepole pine	LP	*Pinus contorta*	
	Macedonian pine	PP	*Pinus peuce*	
	Scots pine	SP	*Pinus sylvestris*	Native
Spruce	Norway spruce	NS	*Picea abies*	
	Sitka spruce	SS	*Picea sitchensis*	
Cedar	Western red cedar	WRC	*Thuja plicata*	
Yew	Irish yew	Y	*Taxus baccata*	Native

prepared using the best available techniques suited for each site and received similar fertiliser application: 175 kg/ha rock phosphate at planting, repeated +250 kg/ha of muriate of potash just before the third growing season. Filling-in was carried out on all the sites (where required) at the beginning of the second growing season, and survival results are shown for year one as well as for the year the crop was last assessed.

Results

Since site conditions greatly affected tree growth, it was not possible to regroup the crop assessment data by species only. Results are thus presented by sites as follows:

- Site type 1: *Sphagnum* over *Phragmites* peat, mostly deep peat, good surface drainage but limited aeration.
- Site type 2: *Phragmites* peat, both deep and shallow, poor drainage conditions and poor aeration.
- Site type 3: *Phragmites* peat, both deep and shallow, good gravity drainage.
- Site type 4: Woody fen peat, both deep and shallow, good drainage and aeration.

Most sites are heterogeneous and display certain characteristics of more than one site type (e.g. where drainage system broke down)

Site type 1

Tumduff: CLE4/00

All species, except Japanese larch, had average survival rates above 75% after year one (Figure 5.16). Japanese larch failed on this site (less than 20% survival), probably due to wet ground conditions. Sitka spruce height growth was double that of Norway spruce but not as good as most pines (Figure 5.17). All four pines looked healthy, while Corsican pine was the tallest and had the greatest annual relative growth rate (RGR). Western red cedar was severely damaged by hares as well as winter blasting and was prone to disease. Severe leader loss meant that most trees of this species were smaller after four growing seasons than after the first year, hence a negative RGR. Many trees, especially the spruce species were also suffering from heather check.

Site type 2

Tumduff: CLE3/00

Broadleaves were established on this site either as pure stands or in mixture. The survival of all the broadleaved species was good (over 80% after four years with some filling-in occurring in year 2) (Figure 5.18). Alder had both the greatest height and relative growth rate over the monitoring period (Figure 5.19). Oak and sycamore had particularly poor growth.

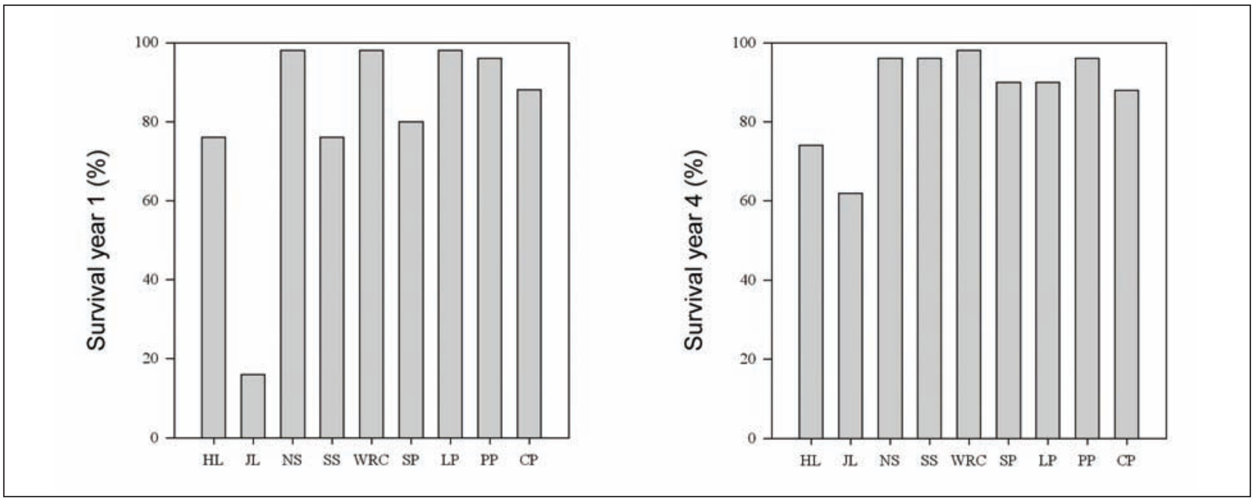


Figure 5.16: Survival of species planted at Tumduff CLE4/00 after one and four growing seasons after filling-in before the second growing season.

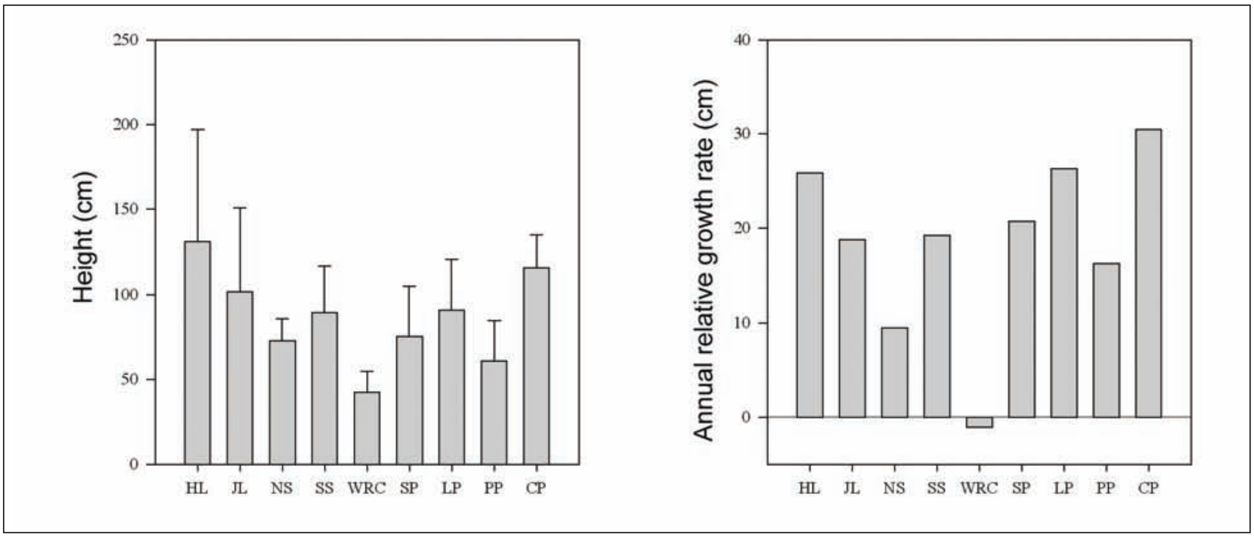


Figure 5.17: Height of species planted at Tumduff CLE4/00 after four growing seasons and annual relative growth rate between year 1 and year 4.

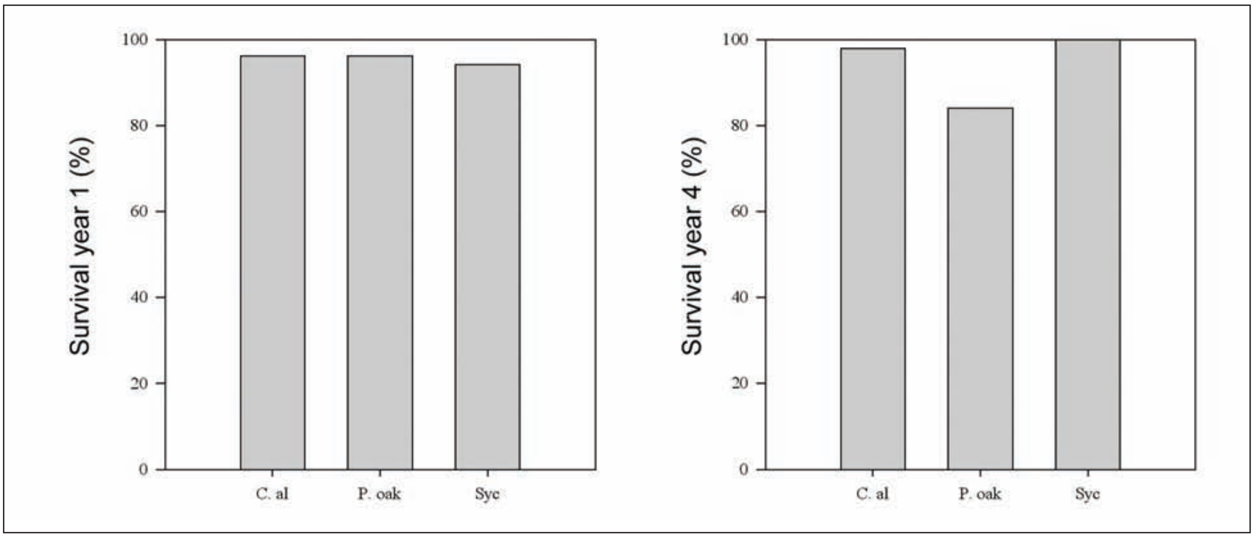


Figure 5.18: Survival of broadleaves at Tumduff CLE3/00.

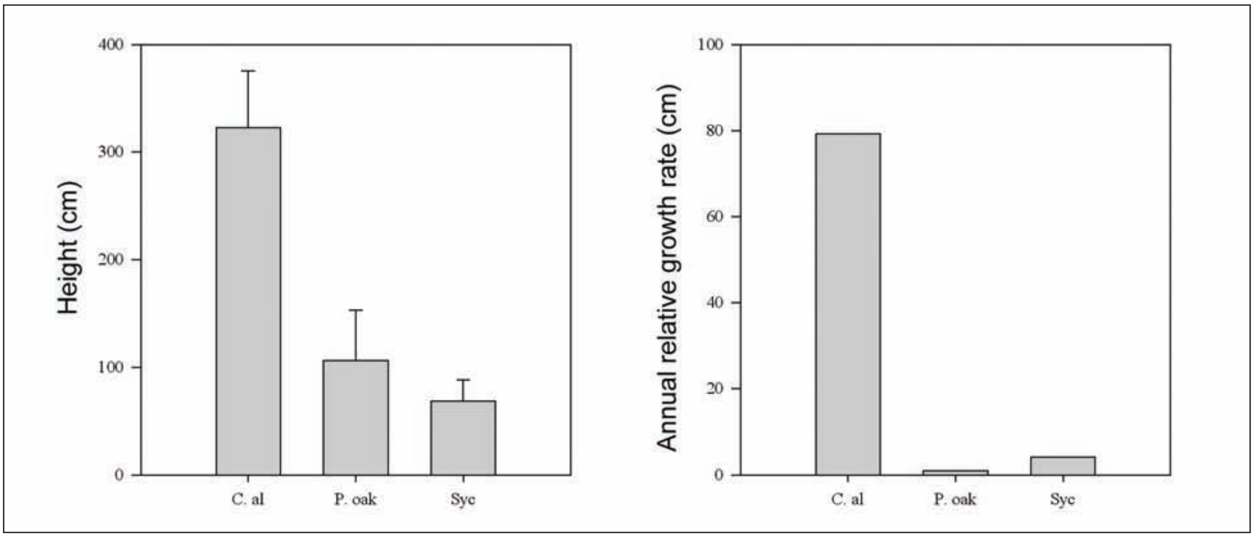


Figure 5.19: Height of broadleaves at Tumduff CLE3/00 after four growing seasons and annual RGR between year 1 and year 4.

Site type 3

Blackwater: KTY17/00 and KTY18/00

Broadleaves

The survival of all the broadleaved species was excellent after the first (>90%) and fourth years (100%) (Figure 5.20). Silver birch and common alder were the tallest trees after four years and had the greatest growth rate (Figure 5.21). Silver birch performed better than downy birch on this site. Sessile oak suffered from leader die-back and, like sycamore and ash, growth was disappointing. Aspen was the third fastest growing species after alder and silver birch. All the alder, aspen and birch were very healthy.

Conifers

The survival of all conifer species in this trial was very good after one (>80%) and four years (95%) after filling-in before the second growing season (Figure 5.22). Hybrid larch and western red cedar were the tallest conifers (Figure 5.23) after four years. Of the pines, Corsican and Scots pine displayed remarkable growth and were very healthy. Yew survived well, is still growing, but all trees are in a poor condition.

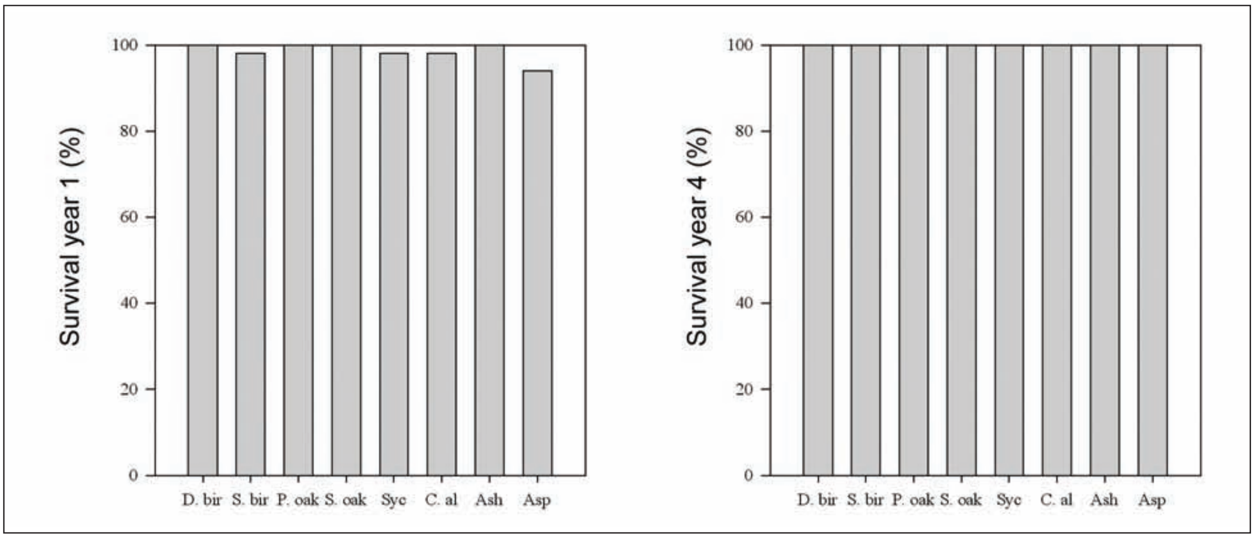


Figure 5.20: Survival of broadleaves at Blackwater (KTY 17/00 and KTY18/00).

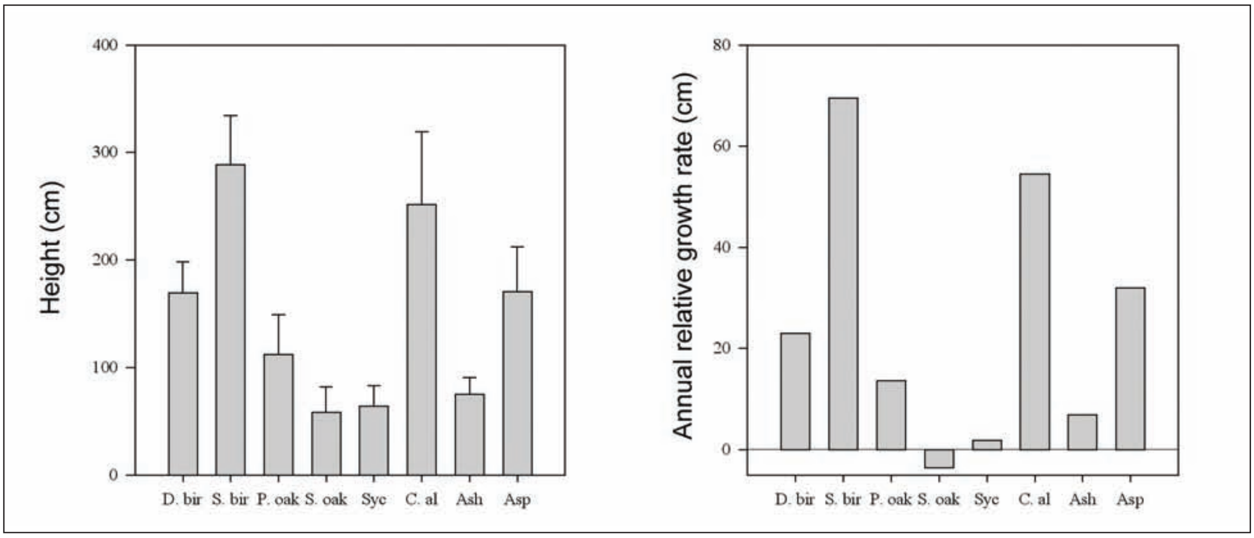


Figure 5.21: Height after four growing seasons and annual RGR of broadleaves at Blackwater (KTY17/00 and KTY18/00).

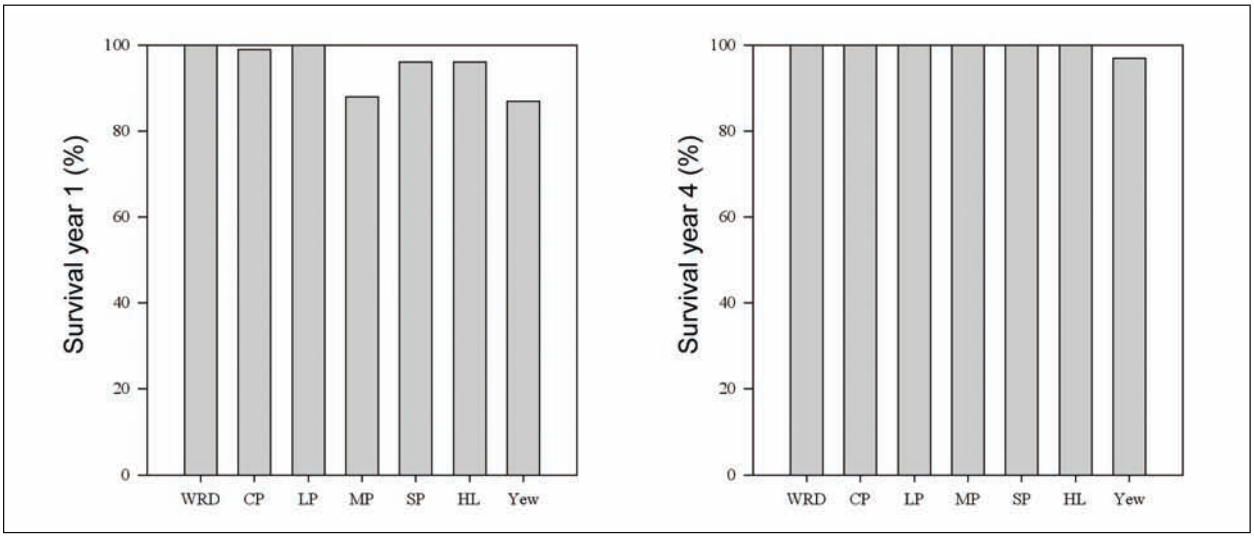


Figure 5.22: Survival of conifers at Blackwater (KTY 17/00 and KTY18/00).

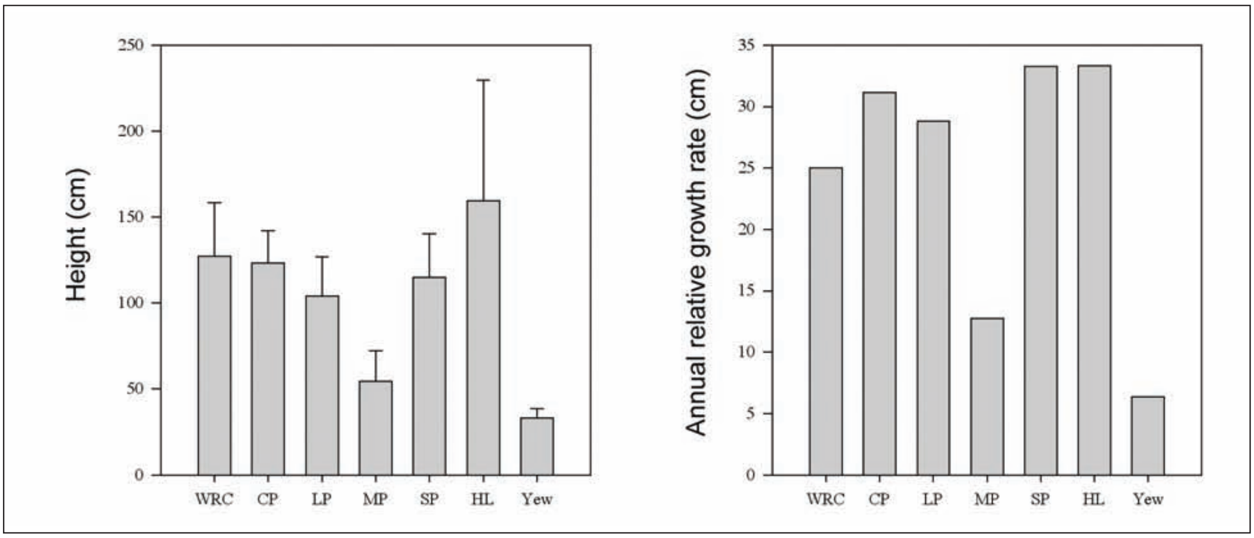


Figure 5.23: Height after four growing seasons and annual RGR of conifers at Blackwater (KTY17/00 and KTY18/00).

Site type 4

Mount Lucas (Allen2/00)

Broadleaves

Survival rates of all broadleaved species were good after one year (>90%) but decreased subsequently, especially beech (Figure 5.24), and despite filling-in after one growing season. Sessile oak, beech and sycamore suffered severely from leader die-back and although many trees were alive, almost all had lost their leaders. Norway maple growth was also mediocre. Poplar and common alder were the tallest broadleaves by far (Figure 5.25). Common alder had almost double the RGR of the Italian alder.

Conifers

All conifers species survived well at Mount Lucas (>90%), except for hybrid larch which had very poor levels at 18% after one year (Figure 5.26). Subsequently, one plot was replanted with alder and the second plot filled-in with hybrid larch, which had 65% survival after three growing seasons and grew reasonably well. Corsican pine and Scots pine had the highest growth rate over the recording period and were very healthy (Figure 5.27). Western red cedar also had good growth. Yew had good survival but grew poorly.

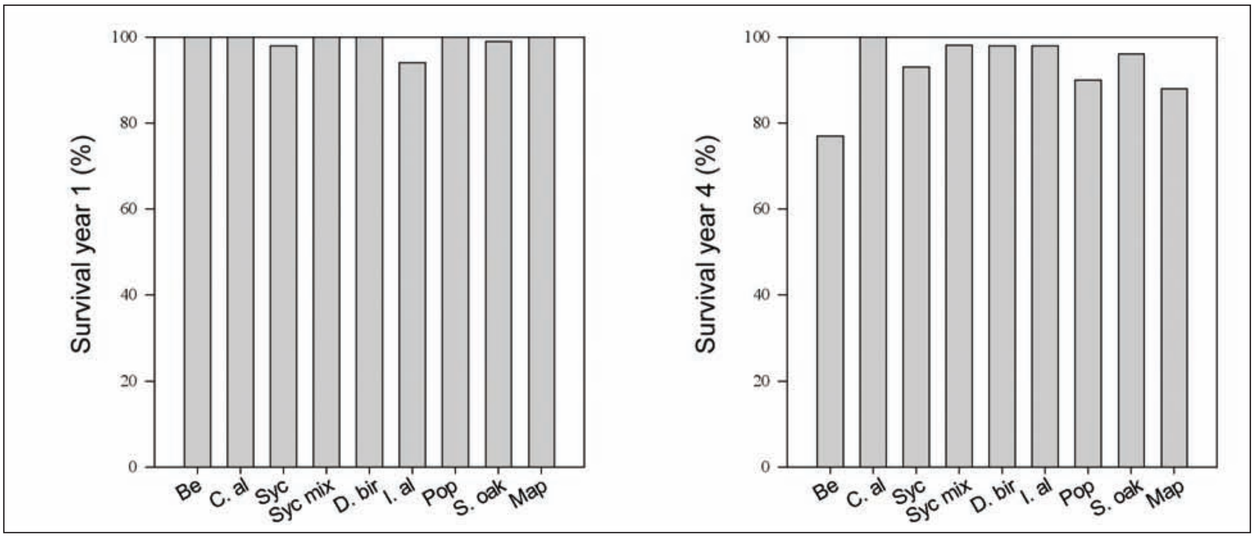


Figure 5.24: Survival of broadleaves at Mount Lucas (Allen 2/00).

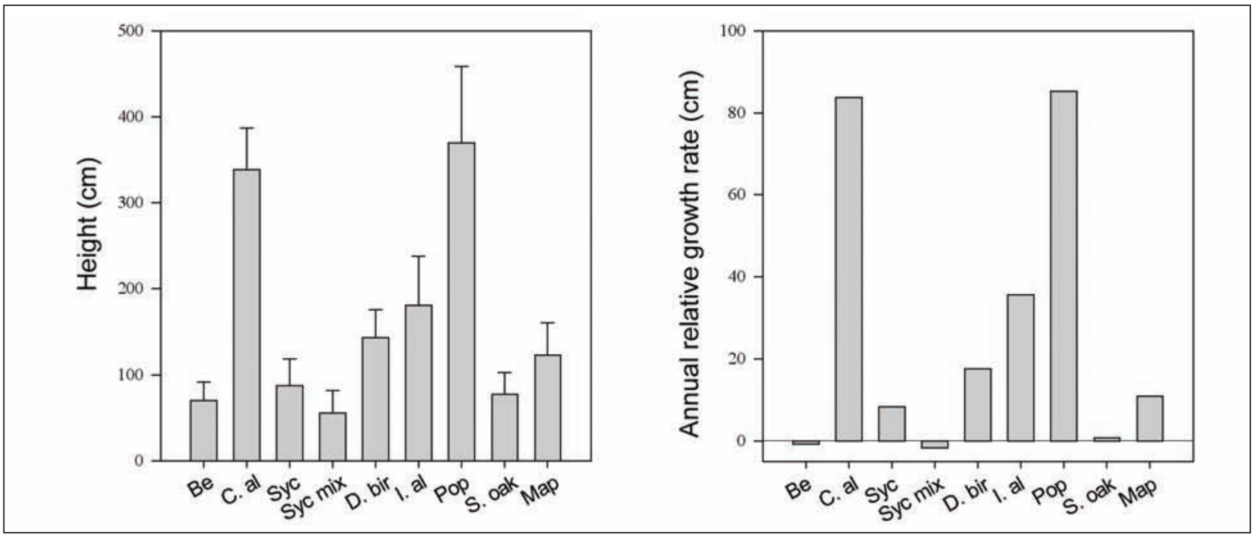


Figure 5.25: Height after four growing seasons and annual RGR of broadleaves at Mount Lucas (Allen 2/00).

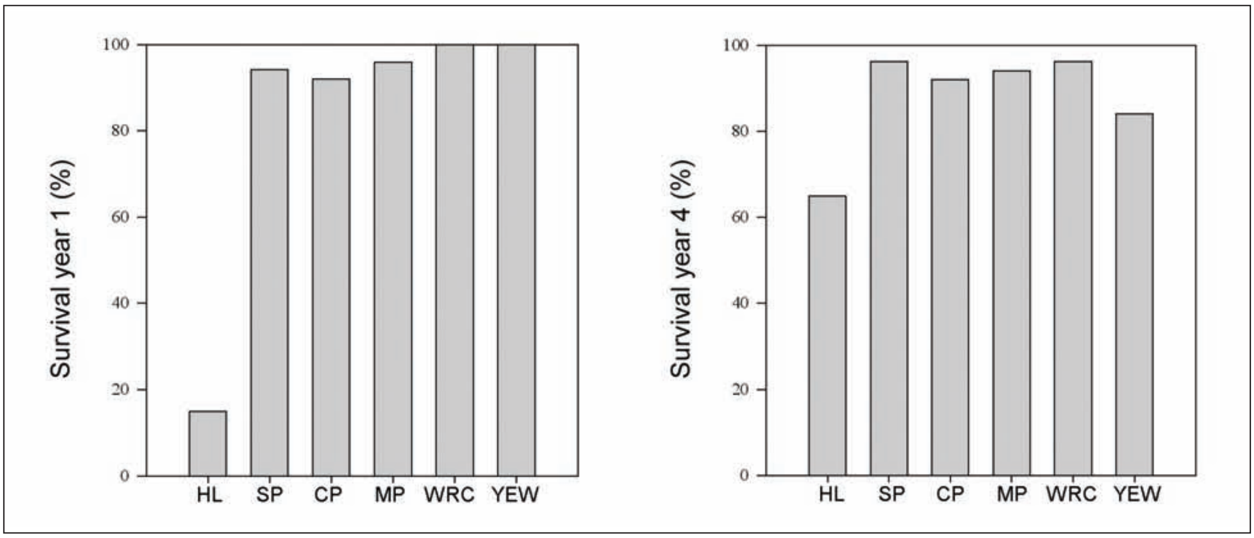


Figure 5.26: Survival of conifers at Mount Lucas (Allen 2/00).

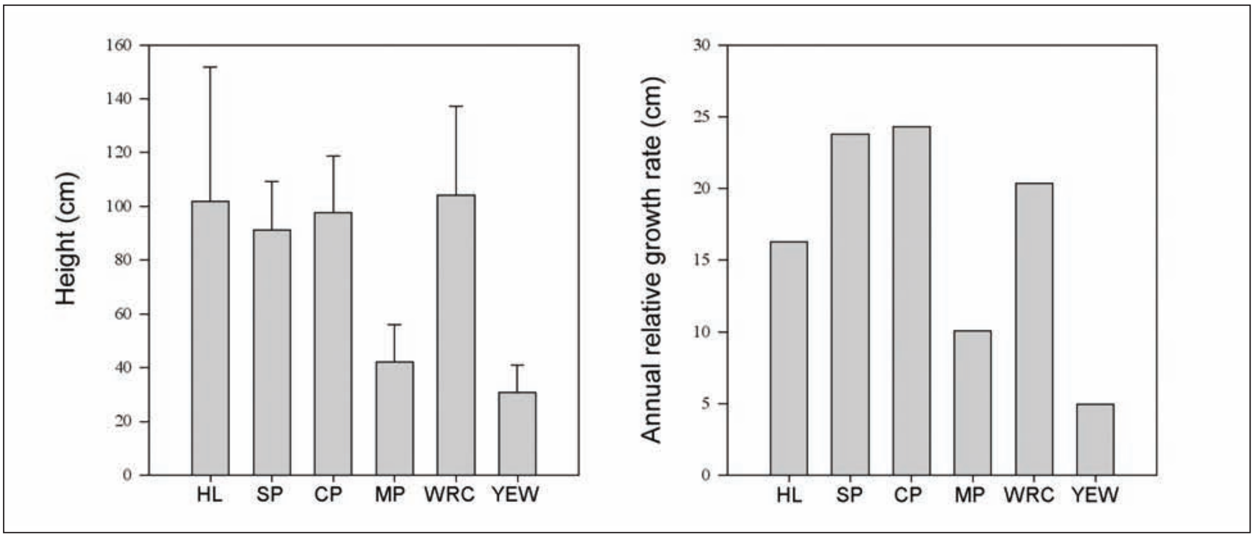


Figure 5.27: Height after 4 years and annual RGR of conifers at Mount Lucas (Allen 2/00).

Tumduff: TLM35/96

Survival of all species was above 80% except hybrid larch, which fell to 60% after six growing seasons. Improved larch had better survival and greater height but hybrid larch had the larger DBH after 10 years (Figure 5.28). Of all conifer species, Scots pine displayed the best growth rate and outgrew all the other pines and spruce species in terms of height and DBH (Figure 5.29 and 5.30). While Sitka spruce was slightly taller than Norway spruce, the latter displayed a higher growth rate and better survival. Lodgepole pine (south coastal provenance) displayed better growth than the north coastal provenance, but both have been attacked by pine shoot moth in recent years. Common alder and silver birch appear to be the best

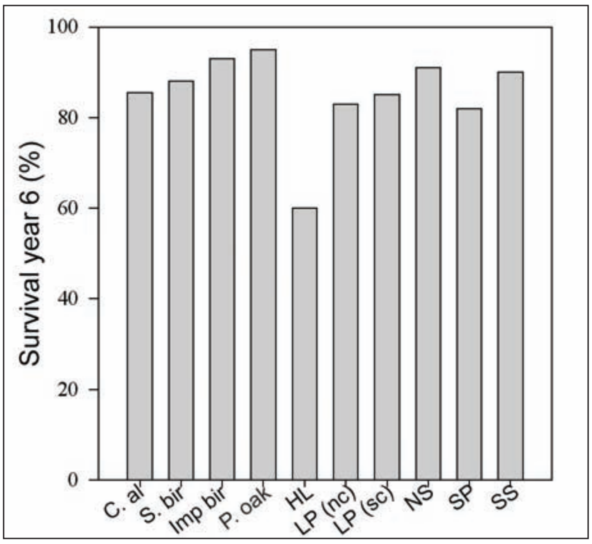


Figure 5.28: Survival after six years of all species at Tumduff (TLM35/96).

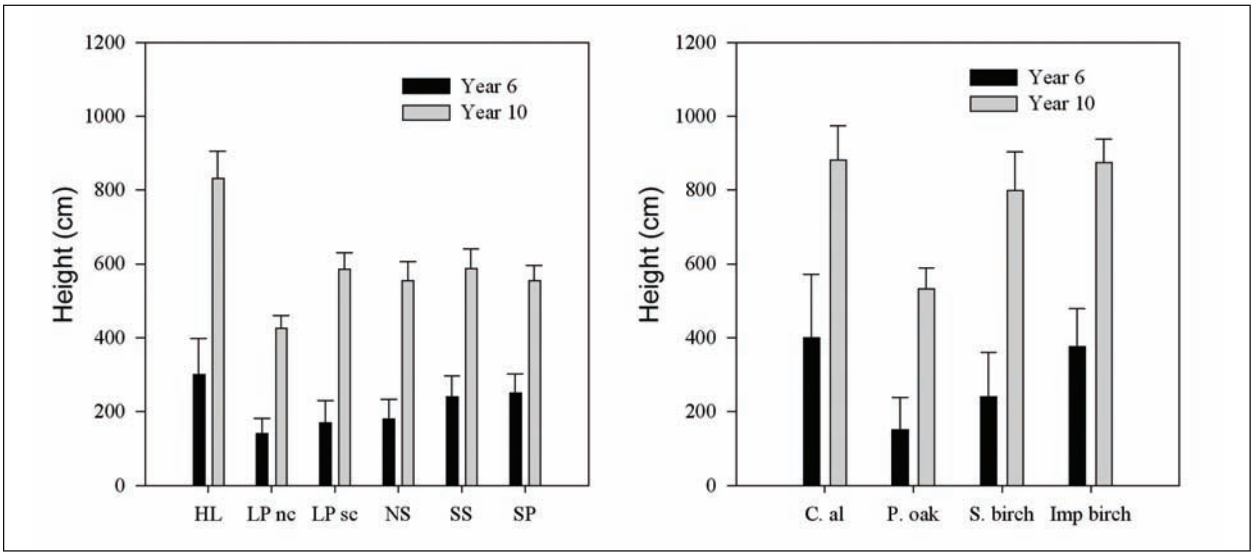


Figure 5.29: Height of conifers and broadleaves after 6 and 10 years at Tumduff (TLM35/96).

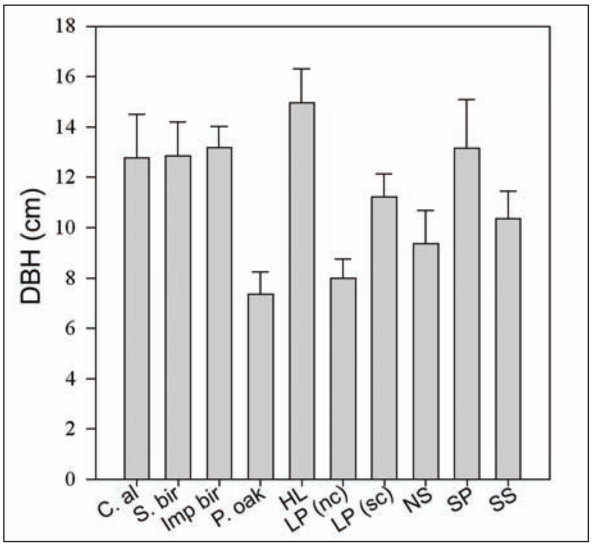


Figure 5.30: DBH of conifers and broadleaves after 10 years at Tumduff (TLM35/96).

broadleaved species on this site. The common alder is taller than the birch, but has a similar DBH, while pedunculate oak remained the smallest but shows good growth.

Matching species to objectives

The way in which the results are presented here by site, in the form of survival, total height, DBH and relative growth rate, aims to present the biological potential of the species (i.e. if they are ecologically well adapted to the range of cutaway peatland site characteristics). Selecting a species based on biological considerations is not sufficient, however. Tree performance should be compared in terms of functions or objectives that the species should fulfil.

For commercial plantations, desirable features of a species include good survival and growth rate as well as the economic value of the wood. A commercial species should achieve an acceptable level of productivity as well as produce timber which has a wide range of uses. Using top height/age curves for 0-20 years produced by Everard (1974), yield class was estimated for the main species showing potential across each site (Table 5.7). The average yield classes recorded in Coillte's forests for each species is given for comparison in Table 5.8. Yield class estimates at this age are indicative only. As such, these predicted yield classes should only be used as a measure of relative performance. While very good predicted yield classes were achieved, large variability was encountered across sites, emphasising the need to survey site conditions prior to species selection.

At Tumduff species trial (TLM35/96), tree performance was assessed at year 6 and 10, thus allowing a comparison of predicted yield classes at different ages (Table 5.9). For Sitka spruce, Scots pine and oak, predicted yield classes were similar at both assessments. In the case of Norway spruce, hybrid larch and silver birch, predicted values noticeably increased, showing an increased growth rate over the reporting period.

While oak showed good growth performance, it is relatively slow growing compared to most species and, as such, may not be attractive as a commercial species. The fact that it survived and grew well in certain site conditions, especially under shelterwood means that this species could be planted successfully and, in addition, greatly add to the biodiversity of these new forests.

The species that grew fastest on the cutaway peatlands (common alder, downy and silver birch, Corsican pine and Scots pine) may not be as commercially attractive as the spruces (at least in the present market) but might have potential because they are species that are tolerant of exposure and not too demanding nutritionally. Such characteristics are those associated with pioneer species, which should be favoured on difficult sites in particular (exposed brown peat field). The main objective in choosing a pioneer species is to quickly establish forest conditions and initiate forest processes. Although they may not be commercially attractive in terms of productivity, these species display important characteristics such as ease of establishment, rapid early growth, and soil improvement characteristics (Gardiner 1968). In addition, four of the five are native species. They could eventually provide shelter for future underplanting with more commercial species while in the meantime adding value to the cutaway peatland forest in terms of biodiversity, recreation and amenity.

Table 5.7: Predicted yield class by species and site.

Species	Site	Expt.	Treatment	Planting year	Age	Mean height	Predicted yield class
NS	Tumduff	TLM35/96	Deep ploughing	1996	10	556	>22
	Tumduff	CLE5/00	Under natural regen. birch	2000	5	128	12-14
	Tumduff	CLE1/99	Rip and disc	1999	5	59	6-8
	Blackwater	JTY1/99	Rip and disc	1999	5	88	10-12
	Clonsast	Emo1/00	Rip and disc	1999	5	95	10-12
	Tumduff	CLE2/00	Rip and disc	2000	4	74	10-12
	Blackwater	KTY16/00	Rip	2000	4	83	10-12
	Mount Lucas	Allen1/00	Control	2000	4	115	14-16
	Tumduff	CLE4/00	Rip and disc	2000	4	73	8-10
SS	Tumduff	TLM35/96	Deep ploughing	1996	10	588	>24
	Tumduff	CLE5/00	Under natural regen. birch	2000	5	171	18-20
	Tumduff	CLE2/00	Rip and disc	2000	4	99	12-14
	Blackwater	KTY16/00	Rip	2000	4	141	22-24
	Mount Lucas	Allen1/00	Mound	2000	4	146	22-24
	Mount Lucas	Allen1/00	Control	2000	4	127	18-20
	Blackwater	KTY16/00	Rip and disc	2000	4	125	18-20
	Tumduff	CLE4/00	Rip and disc	2000	4	89	12
SP	Tumduff	TLM35/96	Deep ploughing	1996	10	554	>14
	Tumduff	CLE2/00	Rip	2000	4	77	6-8
	Blackwater	KTY16/00	Control	2000	4	102	8-10
	Mount Lucas	Allen1/00	Rip	2000	4	100	8-10
	Mount Lucas	Allen2/00	Deep ploughing	2000	4	91	6-8
	Tumduff	CLE4/00	Rip and disc	2000	4	75	6-8
	Blackwater	KTY17/00	Rip and disc	2000	4	115	8-10
CP	Blackwater	KTY17/00	Rip and disc	2000	4	128	8-10
	Tumduff	CLE4/00	Rip and disc	2000	4	115	8-10
	Mount Lucas	Allen2/00	Deep ploughing	2000	4	98	8-10
HL	Tumduff	TLM35/96	Deep ploughing	1996	10	831	>14
	Tumduff	CLE2/00	Rip	2000	4	200	8-10
	Blackwater	KTY16/00	Control	2000	4	151	6-8
	Tumduff	CLE4/00	Rip and disc	2000	4	131	4-6
	Mount Lucas	Allen2/00	Deep ploughing	2000	4	102	2-4
WRC	Blackwater	KTY17/00	Rip and disc	2000	4	127	16-18
	Tumduff	TLM35/96	Deep ploughing	1996	6	140	12-14
	Tumduff	CLE4/00	Rip and disc	2000	4	42	<12
	Mount Lucas	Allen2/00	Deep ploughing	2000	4	104	12-14
Oak	Tumduff	CLE5/00	Under natural regen. birch	2000	5	214	8
	Tumduff	TLM35/96	Deep ploughing	1996	10	533	6
	Mount Lucas	Allen	Control	2000	4	113	4-6
S. bir	Tumduff	TLM35/96	Deep ploughing	1996	10	799	>12
Alder	Tumduff	CLE3/00	Rip and disc	2000	4	323	10-12
	Tumduff	TLM35/96	Deep ploughing	1996	6	401	10-12

Table 5.8: Average yield class for main species in Coillte's forests (adapted from Figure 3.2 in Coillte 1999).

Species	Average yield class (Coillte)
Norway spruce	15
Sitka spruce	16
Scots pine	9-10
Larch	8-9
Western red cedar	16
Oak	4

Table 5.9: Mean height and predicted yield class by species in the 1996 Tumduff species experiment (TLM35/96).

Species	Mean height (cm)	Predicted yield class	Mean height (cm)	Predicted yield class
	Age 6		Age 10	
SS	240	>24	588	>24
SP	250	>14	554	>14
NS	180	>16	556	>22
HL	300	6-8	831	>14
Oak	150	4-6	533	6
S. birch	240	>8	799	>12

Species notes

The following species notes have been compiled by collating the results and experience from the species trials together with other BOGFOR field experiments (fertiliser trials and cultivation trials) replicated across several sites in the Irish Midlands. These research data, together with associated literature and local silvicultural knowledge from programme participants, provided the background information used to compile the following notes on suitable species for cutaway peatland forests.

Sitka spruce

Sitka spruce can thrive on cutaway peatlands but it carries a high risk of being hit by late spring frost (Plate 7). For that reason alone it should not be planted on cutaway peatlands without shelter from a nurse crop. There is little inherent difference between provenances of Sitka spruce in frost resistance (Thompson et al. 2005). In the BOGFOR trials, the best Sitka spruce growth was recorded under naturally regenerated birch. The key to the success of this system, however, is the punctual and effective removal of the whipping birch once its sheltering effect is no longer required. Sitka spruce grew well on most other cutaway sites (Plate 8), as there were no major frost occurrences during the programme, except on the most acidic sites (deep *Sphagnum* peat) where it suffered nutrient deficiency and heather check.

Norway spruce

The resilience and tolerance of Norway spruce, as well as its potential to produce reasonable yields, mark it out as a promising candidate on cutaway peatlands (Plate 9). Although it has a lower potential yield class than Sitka, Norway spruce should be favoured on cutaway peatlands as it is not as susceptible as Sitka to late spring frost. Variable flushing time results in more trees escaping damage. Nevertheless, it can suffer considerable damage during severe frost. The fact that it grows slowly for the first few years after planting also increases the risk of frost damage and means that it may require vegetation control for longer than Sitka spruce. Survival rates for Norway spruce can be reduced on very exposed sites, but a shelterbelt can greatly enhance growth during the establishment phase. Older plots of Norway spruce growing on cutaway peatlands have developed healthy, well-formed canopies and are fairly uniform.

Lodgepole pine

In the 1980s and early 1990s, lodgepole pine was the second most commonly planted species on the cutaways. Although considered a low risk choice, the incidence of pine shoot moth on many Irish Midlands sites has moved t down the list of suitable species. Trees will form a crop but probably only of pulpwood quality. Some older crops of south coastal provenance escaped major damage from pine shoot moth but growth can be patchy. Its susceptibility to basal sweep (curving at the base of the tree) also suggests that its use is questionable.

Scots pine

Scots pine is a good pioneer species for cutaway peatlands, especially on the poorest acidic sites. It is very frost-hardy and could be used as a nurse species. It suffers, however, on very exposed sites where form and health deteriorate quickly. In better conditions, however, it can produce higher growth rates than spruce and other pine species. As best results are achieved using small plants and because Scots pine is a strong light-demander, efficient vegetation control is required with this species. Scots pine is less susceptible to pine shoot moth than lodgepole pine, but will become infested if the area is prone to the pest. Careful monitoring of established plantations is also required as several older plantations on cutaway peatlands have suffered from unexpected die-off for no obvious reason.

Corsican pine

As well as having all the advantages of Scots pine described above, Corsican pine has the added attribute of tolerating exposure quite well (Plate 10). It also tends to produce straighter stems than Scots pines. It is less liable to be attacked by hares and rabbits and also shows resistance to damage from pine shoot moth. In order to ensure satisfactory survival, it is recommended that containerised stock be planted during late spring/early summer. Corsican pine has its place on cutaway peatlands but long-term monitoring is required as there are few mature crops in Ireland.

Macedonian pine

Macedonian pine survived very well on cutaway peatlands but displayed slower growth than Scots and Corsican pine. Vegetation control may be required for up to four years after planting. However, it has two major advantages: first, it is a good pioneer species with a well-developed deep root system. This means that it can, in effect, improve raw deep peat soils. Second, Macedonian pine appears to be attacked by fewer insects than other pines. Growth rate usually increases after 6-10 years, making this species particularly promising for cutaways.

Larch

Both hybrid and Japanese larch displayed the lowest survival rates of all the planted species, but variation was encountered across sites. Contradictory results have also been found on similar site. As it flushes very early, hot-planting (planting the seedlings immediately after being lifted from the nursery beds) should be completed by early March. However, planting directly in cold, wet conditions has resulted in high plant mortality. Larch has also suffered from late spring frost damage. The use of containerised larch may provide a solution to delay the planting season and has the potential to allow the plant to grow out of the frost damage zone quicker.

Generally, waterlogged areas and frost hollows are unsuitable for larch. It should also be avoided on shallow peats. Where it survived, both larch species grew very fast but, as expected, hybrid larch was the more productive. This rapid early growth makes it very useful as a nurse species. Larch has the added advantage of shedding its needles, which helps to control surface vegetation, while improving nutrient recycling. While its use may be limited, its growth is sufficiently promising to justify further planting on appropriate sites.

Western red cedar

Large variations in growth were encountered with this species across different sites. Western red cedar suffered from wind exposure as well as browsing, which renders it unsuitable for most cutaway peatlands. On more sheltered sites, best development is expected to be on shallower peats.

Oak

Of the two native oak species, sessile oak is the less suitable for cutaway peatlands. Pedunculate oak has shown potential on some areas, particularly those which are relatively fertile and sheltered from late spring frost and exposure (Plate 11). On most typical open cutaway peatland sites, oak suffered from severe leader die back (Renou-Wilson et al. 2008). Due to its propensity to coppice (i.e. to regrow after cutting near ground level), oak often grew back quite well once other species had established around it. It is thus preferable to grow oak in mixture with a fast-growing species, but considerations should be given to the mixture species and spacing. Oak is not suitable on exposed sites, frost hollows, poorly drained peat, very infertile peat and very shallow peat where the sub-peat mineral soil is essentially unweathered. In addition to the above factors, a hare-proof fence is essential if the species is to grow well on cutaway peatlands.

Birch

Birch gave high survival and quick establishment on cutaway peatlands. Of the two native species, *B. pendula* is the superior species displaying both quick growth and reasonable form (Plate 12). In all cases, browsing and vegetation competition will need to be controlled, especially if small seedlings are planted. Birch is a pioneer and, as such, a key species in ecosystem development, which can broaden options for wood utilisation, such as biomass. Birch can also be used as a nurse species but requires sufficient time to develop an adequate cover.

Alder

Of all species planted on cutaway peatlands, common alder has been the most productive. Unlike all other species, it also demonstrated a relatively uniform growth over different site types (Plate 13). Alder grew well in acidic peat but also in the more shallow woody fens. It did not suffer from exposure and because of its fast early growth, very little vegetation control was required. As with all broadleaves, it requires adequate protection against hares. Alder is probably the best species with which to establish forest cover or shelter quickly on cutaway peatlands. It has soil-improving attributes due to its vigorous fibrous root system and its capacity to fix atmospheric nitrogen. This makes alder a particularly useful nurse species for growing in mixture with more commercial species such as spruce (Schaible 1992). Because of its coppicing ability, alder could also play a role in biomass production.

Other species tested on cutaways

Aspen and ash showed relatively good (but slow) growth rates and neither can be excluded from the range of suitable species. Both sycamore and beech are unsuited to cutaway peatlands where they suffered high levels of mortality due to late spring frosts and exposure. In particular, they performed poorly on very acidic *Sphagnum* peat. Beech is also very susceptible to browsing by hares. Yew survived on all sites but its growth rate is too low for commercial planting. It may, however, have a role to play in planting for native woodland or biodiversity.

Dawn redwood (*Metasequoia glyptostroboides*) is an exotic species originating from China which can withstand long periods of time with its roots submerged in water. Very little is known about its requirements in Ireland. The fact that it is a deciduous conifer means that it may not be subject to the same stresses of winter exposure as a non-deciduous species. It may be considered for testing in future planting of cutaway peatlands.

Monterey pine (*Pinus radiata*) has grown successfully on sod-peat cutaway bogs (Swan 1973) but its survival was poor, giving a patchy and irregular crop.

Conclusions

The process of species selection requires knowledge of the silvicultural characteristics of a particular species, an understanding of the environment into which the species will be placed and the likely response of the species to silvicultural treatment. The correct choice of tree species is crucially important and investment in other preparatory measures will be worthless if care is not taken in matching species to the exacting conditions that cutaways represent.

While there is still little knowledge of the long-term performance of different species on cutaway peatlands, there seems to be a range of species from which the forester will be able to choose. Taking into account that a site assessment is necessary prior to selecting a species and that certain site preparation and management practices will be required, the following species can be generally regarded as being suitable for the afforestation of cutaway peatlands: Norway spruce, Sitka spruce (under a nurse crop), Scots pine, Corsican pine, hybrid larch, pedunculate oak, silver birch and common alder.

This range of suitable conifer and broadleaved species affords the forester the opportunity to create interesting landscapes that will later provide options for a range of markets, as well as being ecologically suitable. The variation in site conditions encountered in any given cutaway peatland means that not one but several species might flourish within a given area. This would inevitably enhance the sustainability of these new forests.

SUMMARY POINTS: SPECIES PERFORMANCE

- *Norway spruce is the preferred commercial species for cutaway peatlands.*
- *When a suitable nurse crop (either natural or planted) is available, Sitka spruce should be chosen instead of Norway spruce because of the higher yield.*
- *The best performance of Norway spruce, Sitka spruce and pedunculate oak was recorded under a naturally regenerated birch nurse crop.*
- *Corsican and Scots pine should be planted on lower quality sites (acidic deep peat) and should have their place in most commercial plantations. Both Corsican and Scots pine are preferred to lodgepole pine which is not recommended as it is most likely to be attacked by pine shoot moth.*
- *Hybrid larch and western red cedar have limited opportunities on these sites.*
- *Of the two native oak species, only pedunculate oak has shown potential on the most fertile peats and only in combination with shelter from late spring frost and exposure.*
- *Alder was the fastest growing species, performing uniformly over a variety of site types. Its pioneer properties make it most suitable to quickly establish forest cover.*
- *Birch also survived and grew well and has the advantage of being a key species in ecosystem development which can broaden options for future use of the cutaways.*
- *While very good growth performance was achieved for the more commercial species, large variability was encountered across sites, emphasising the necessity to survey site conditions prior to species selection.*
- *Protection of broadleaves from hares is critical.*

Tree establishment

Planting stock and size

Certain planting stock types are more suited to particular environments than others. While the use of a particular type and size of planting stock can greatly increase establishment success, it is sometimes difficult to balance the advantages and disadvantages of different stock, for example bare-root and container, with site requirements. The plants must be robust enough not to suffer damage when handled, not to desiccate too quickly, have adequate reserves to make new growth, have root systems which will rapidly become established, and be able to withstand transplanting and environmental stress.

While the use of containerised seedlings is on the increase in Ireland, most seedlings currently planted are bare-root stock (O'Reilly et al. 2001); it is easier and less expensive to grow plants this way. In operational terms, however, the choice of stock sometimes depends on availability at the time of planting.

Published information on the outplanting performance of different stock type is limited in Ireland (O'Reilly et al. 2003) and non-existent for cutaway sites. Results from stock size research carried out by Coillte on mineral soil indicated that Sitka spruce greater than 40 cm in height generally performed better in the field than smaller seedlings, but initial height had little effect in Japanese larch or Douglas fir (Thompson and Lowe 1999). In the southern United States, height growth of longleaf pine (*Pinus palustris* Mill.) appears to be positively related to stock size, regardless of site conditions (South et al. 2005). In other studies, larger seedlings performed even better on favourable sites, for example with soil cultivation treatment and intense vegetation control (Dobbs 1976; South et al. 2001).

Three field experiments were carried out within the BOGFOR programme in order to gain information about the best planting stock for Norway spruce, hybrid larch and birch.

Norway spruce

A field trial was established at East Boora (EB 4/03) in 2003 to assess the field performance of three Norway spruce stock types: container (NS plug), bare-root small (NS2) and bare-root large (NS1) (Plate 14). Stock characteristics are presented in Table 5.10 and layout of the experiment is shown in Figure 5.31 and more information can be found in Renou-Wilson et al. (submitted).

After two growing seasons, survival rates were above 98% for small bare-root and containerised seedlings, but were significantly lower (91%) for large bare-root seedlings (Figure 5.31).

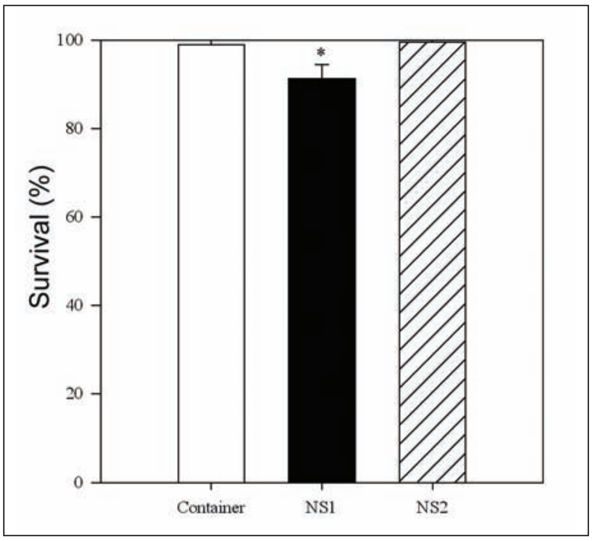


Figure 5.31: Mean survival after one year of Norway spruce stock types (vertical bars denote ± one standard error). Mean survival with a star is significantly different ($p<0.05$).

Table 5.10: Norway spruce stock types and their characteristics planted at the East Boora stock trial.

Stock type	Code	Provenance	Seed source	Age	Size	Nursery	Planting time
Large bare-root	NS1	IE-2212-V88A	Irish	2+2	30-60 cm	Ballintemple (Coillte) cold storage	May 2003
Small bare-root	NS2	DK-LUN-X78	Danish	2+1	20-40 cm	Ballintemple (Coillte) cold storage	May 2003
Container	NSc	NS-DE-CP33	German	2+2	30-40 cm	Ballintemple (Coillte)	May 2003

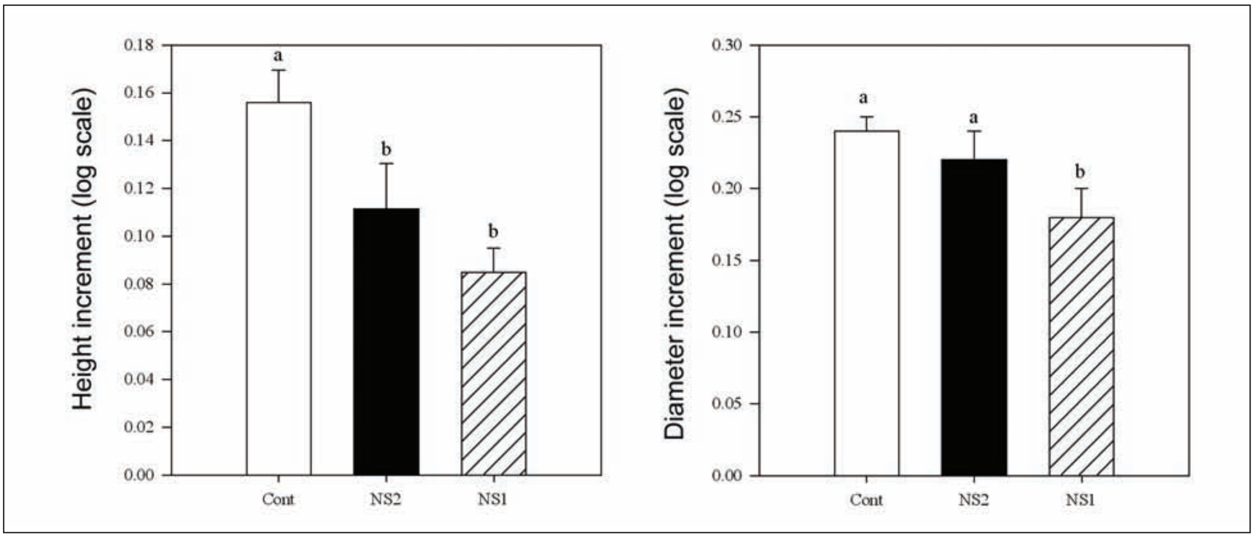


Figure 5.32: Mean height and diameter increment after three growing seasons for different Norway spruce stock types (vertical bars denote ± one standard error). Means with the same letter are not significantly different (p<0.05).

The effect of planting stock type on growth of Norway spruce was estimated by calculating mean height increments over the first two growing seasons. Containerised stock had significantly better growth than either of the bare-root stocks (Figure 5.32).

Despite having the largest initial diameter, the large bare-root (NS1) had a lower diameter growth compared to both the container and small bare-root seedlings.

Large bare-root stock had greater height and diameter at the time of planting compared to containerised and small bare-root stock. Small bare-root stock seedlings were approximately half the height and diameter of the large stock at planting, but at the end of the second growing season, mean height was 73% and mean diameter 86% that of large bare-root stock, demonstrating the superior growth rate of the small bare-root stock (Figure 5.33a). The growth of containerised stock more than doubled between the first and second growing season. While initial height was a good predictor of height after two years for bare-root stock, this was not the case for containerised stock. Diameter at planting was a good indicator of total height for container and small bare-root stocks but not large bare-root. It appears that for small seedlings (< 40 cm initial height), it is important to have a large diameter to enhance good height growth. This is also confirmed by an examination of the height:diameter (H:D) ratios, which showed a large decrease over two years in the case of container and large bare-roots seedlings, but not for the small bare-root stock type (Figure 5.33b). At planting the H:D ratio of the container stock was 60 and by the end of the second season it had fallen to 48. By contrast the H:D ratio of small bare-root stock type slightly increased from 37 to 39. In taller seedlings with small diameter, dry matter was mostly diverted to growth in stem diameter. In this study, container stock increased their diameter range from 4-6.5 cm to 6-13 cm. For more rapid early height growth, planting stock with a low H:D ratio (i.e. avoiding thin, tall trees) should be used.

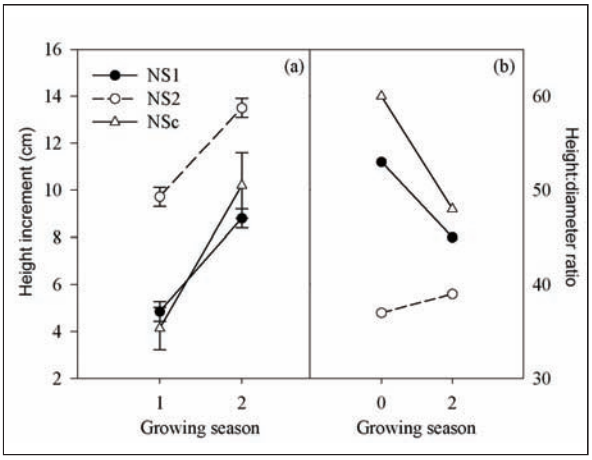


Figure 5.33: (a) Height increment and (b) height:diameter ratio for each stock type.

Hybrid larch

Containerised and bare-root stock hybrid larch were planted at East Boora (EB 2/03) in 2003 and seedlings characteristics are given in Table 5.11.

All seedlings survived well on this site (>85%) but containerised larch had better survival rate than bare-root (Figure 5.34). Although initial height was not recorded, the initial size range was similar, allowing total height comparisons. After three growing seasons, containerised larch grew significantly more than bare-root (Figure 5.34). Following a severe frost in May 2005, bare-root seedlings lost all their needles, but damage was less severe for the containerised seedlings. This may have been caused by a difference in provenance.

While containerised larch may be more expensive to produce, its superior growth rate is advantageous for several reasons: reduced duration of vegetation control; reduced risk of late spring frost damage; earlier use as nurse or shelter species. However, further trials need to be carried out comparing stock type from the same seed source.

Birch

An experiment was established to evaluate differences (in terms of survival, growth attributes and form) between bare-root and containerised stock, and between small and medium size seedlings for both silver (*B. pendula*) and downy birch (*B. pubescens*). The trial was established in Blackwater (KTY 19/00) in 2000. Further information can be found in Renou et al. (2007).

Survival rates were high for both species, with plot means ranging from 92 to 100% and effects of stock types and size were small. Survival after one year was higher for bare-root *B. pubescens*, showing that it is adapted to the cutaway conditions which resemble its native environment - *B. pubescens* is often called bog-birch and is the species that naturally regenerates on cutaway peatlands (Pöllänen et al. 2004). While initial planting size did not have any effect on survival after one year, small seedlings had lower survival rates than larger seedlings after five years. This was probably due to the absence of vegetation control after three years. Containerised stock survived better on deep peat compared with shallow peat, whereas

Table 5.11: Hybrid larch seedling characteristics planted at East Boora.

Stock type	Provenance	Size	Nursery	Planting time
Containerised	HL-DE-CP28	30-60 cm	Ballintemple (Coillte)	May 2003
Large bare-root	HL-UKNT21J46	30-60 cm	Ballintemple (Coillte) cold storage	May 2003

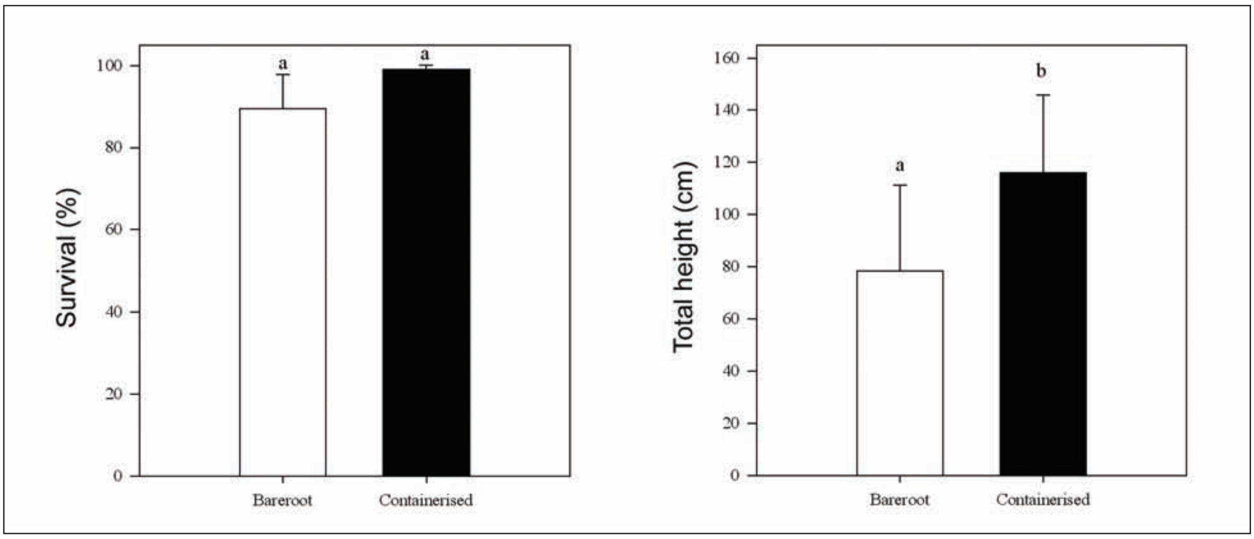


Figure 5.34: Means for survival and height after three growing seasons for different hybrid larch stock types (vertical bars denote ± one standard error). Means with the same letter are not significantly different (p<0.05).

the opposite was true for bare-root stock (Figure 5.35).

After five growing seasons, bare-root *B. pendula* had the higher growth rate but the converse was the case for *B. pubescens* (Figure 5.36).

Regardless of size and species, peat depth affected the growth of stock types differently. On shallow peat, bare-root stock grew faster than containerised stock (Figure 5.37). Containerised stock grew faster on deep peat than on shallow peat.

The results also show that both birch species can be successfully established on cutaways. *B. pendula* had superior growth. On well drained and shallow peat sites, bare-root *B. pendula* will grow quickly with reasonable form. Together with results from BOGFOR species trials, the growth rate of silver birch shows promising results compared to studies on different site types in the UK (Brodie 1991; Brown 1991) or on peat in Finland (Kaunisto 1987; Aro and Kaunisto 1998a).

In conclusion, birch can be established on cutaway peatland by planting. This can have many advantageous results; restoring native woodlands and their associated biodiversity, restoration of soil structure and function, the nursing of more sensitive and commercially attractive species and the production of biomass for energy production.

Conclusions

These studies showed that the choice of stock type and size must be tailored to the species and site conditions. Long-term monitoring and further planting on different sites should be carried out in order to assess stock type and size for different species suited to the cutaway peatlands. While containerised seedlings may be more productive in the early years, large bare-root Norway spruce seedlings still have the advantage in terms of competition with vegetation and root development. Early results favour the use of containerised larch, for quick early growth, which reduces the need for vegetation control, reduced risk of late spring frost damage and earlier use as a nurse species.

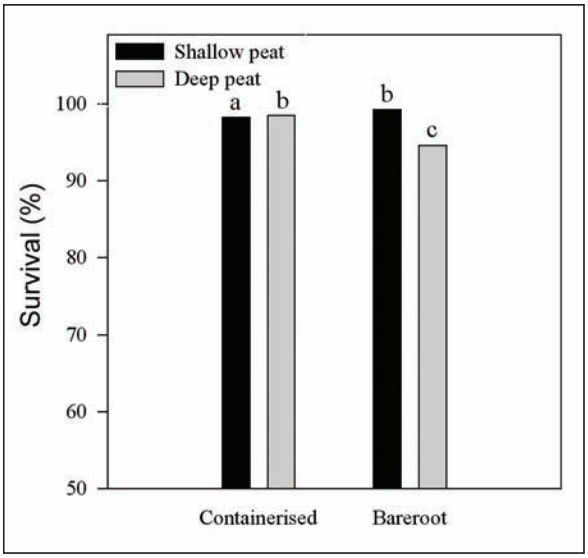


Figure 5.35: The interaction of stock x peat depth (p<0.001) in survival after five growing seasons. Means with the same letter are not significantly different (p<0.05).

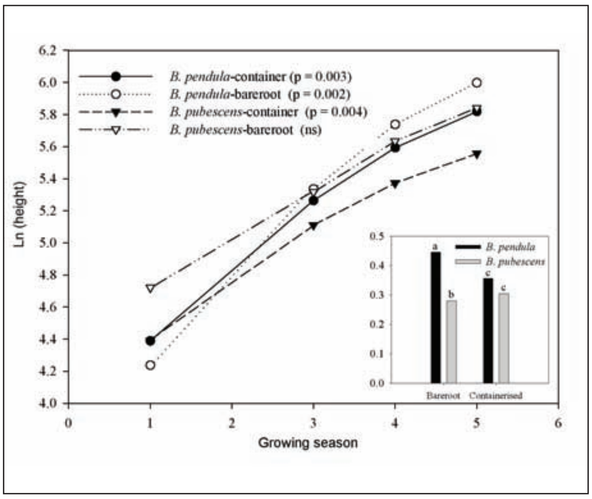


Figure 5.36: The species x stock type interaction in height growth of birch. Inset: The species x stock type interaction in relative growth rate between year one and year three. RGR means with the same letter are not significantly different (p<0.05).

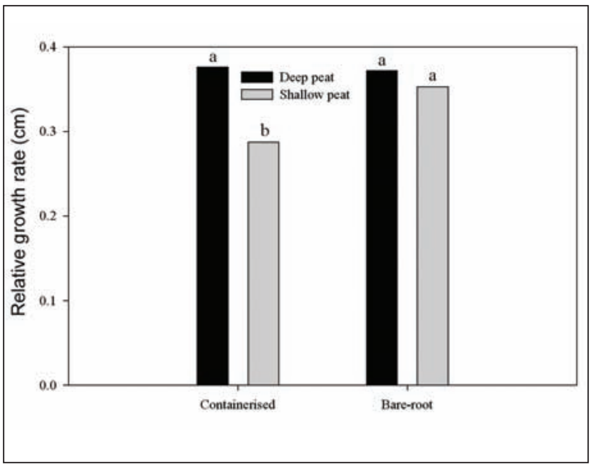


Figure 5.37: The planting stock type x peat depth interaction in relative growth rate. Means with the same letter are not significantly different (p<0.05).

Finally, regardless of the stock type, it is essential that seedlings planted on cutaway peatlands should be healthy and of good quality at time of planting.

Planting method, timing and density

Planting method

A range of planting methods can be used on cutaway peatlands. The simplest and most common method of planting bare-root stock is slit notching: a single vertical cut is made in the peat with a spade and after the tree is inserted it is firmed in by foot. The same technique is generally used for container stock. Whatever the tools used, the important part of this process is that the tree is firmly inserted into the soil without too much compaction. This is important on cutaway peatlands because of the high risk of erosion of the peat surface and frost-heave, all of which tend to destabilise the newly planted seedling.

Depending on the cultivation treatment, the planting position changes. If the site is mounded, for example, it is important that the seedling is properly inserted in the middle of the mound to avoid later root distortion.

Planting timing

It is well known that the chances of successful establishment are greatly improved if bare-rooted stock is planted when it is dormant (O'Reilly et al. 2000). Because cutaway peatlands are typically very wet during this period, however, it may be preferable to use cold-stored plants which can extend the planting date until late spring or early summer - as long as the conditions are favourable (not too hot or dry). Containerised seedlings can be planted throughout the growing season. In all cases, planting from April to May should be adequate to allow time for new roots to develop and not to delay the fertiliser application.

Planting density

Plantations should be established using regular spacings which vary according to species, site and management objectives and are detailed in the Forestry Schemes Manual (Forest Service 2003). The current recommendations for pure crops are to plant all conifers at 2 x 2 m (2,500 plants/ha) and all broadleaves at 2 x1.5 m (3,300 plants/ha), except oak and beech which should be planted at a higher density (2 x 0.75 m). Aro (2003) found that growing trees on cutaway peatlands at higher densities than normal may improve nutrient cycling in stands and hence decrease leaching of nutrients from the site. Closer spacings are also preferred to reduce branchiness and improve tree form, especially for broadleaves. However, a minimum of 2 m spacing between lines is required on cutaway peatland to facilitate the passage of quad bikes and trailed flail mowers or weed-wipes for efficient vegetation control.

A trial was established at Blackwater (KTY 15/00) to investigate the effect of different spacings on the growth of downy birch (*B. pubescens*) (Table 5.12). The total height of the birch after five growing seasons ranged from 180 to 210 cm (Figure 5.38). Spacing did not affect height growth rate but, after five growing seasons, diameter growth may be starting to respond positively to the widest spacing.

Nursing and sheltering effect

The principal objective of a nurse is to protect tender species from frost and exposure during their early years. Nurse species can perform other functions such as suppressing competing vegetation rapidly (using fast-growing species which shed their leaves or needles) or improving the nutritional regime (with nitrogen-fixing species such as alder).

Certain species can also grow better when mixed initially with a faster growing nurse

Table 5.12: Treatments in the *B. pubescens* spacing trials at Blackwater.

Spacing	Density (trees/ha)
2 x 1 m	5,000
2 x 2 m	2,500
2 x 3 m	1,666

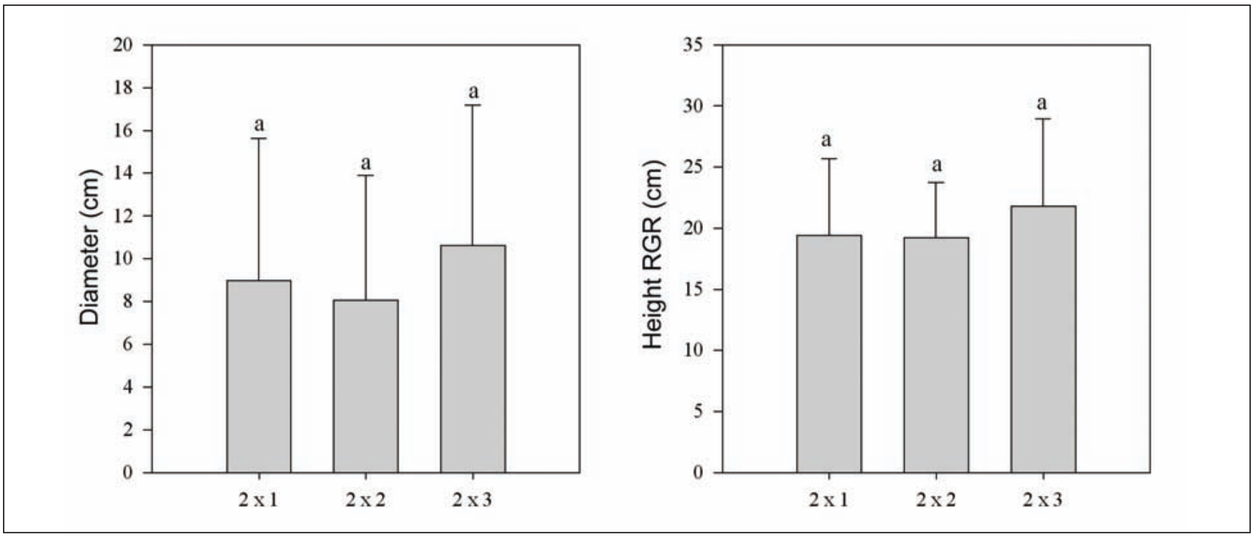


Figure 5.38: Downy birch mean diameter after five growing seasons and relative height growth rate over four growing seasons for each spacing treatment (vertical bars denote ± one standard error). Means having the same letter are not significantly different (p>0.05).

species or if planted under the canopy of a near-mature crop. OCarroll (1978) found that on a peaty podzol, Sitka spruce intimately mixed with Japanese larch or lodgepole pine grew significantly better than Sitka spruce alone. This was considered to be mainly due to improved nitrogen nutrition caused by the larch or pine. Other studies have shown that the growth of broadleaves is improved when planted in mixture with conifers (Evans 1984; Horgan et al. 2003).

Within the BOGFOR research programme, different mixed species plantations were established to investigate nursing and sheltering effects:

a) Oak and conifer mixtures.

b) Sitka spruce and birch mixtures.

c) Sycamore and western red cedar mixtures.

d) Sitka spruce, Norway spruce and oak in near-mature naturally regenerated birch woodland.

Oak and conifer mixtures

Pedunculate oak was planted at Tumduff (CLE 3/00) in 2000 in large blocks either pure or in mixture with hybrid larch or Scots pine. Oak survival rates were excellent when planted in mixture (Figure 5.39) and grew significantly better when in mixture with hybrid larch compared to pure or in mixture with Scots pine (Figure 5.40). In the later plots, recurrent leader die-back was observed, explaining the negative relative growth rate. It is suggested that the quick-growing larch provided a better environment for the growth of oak on these sites. Such a mixture may be even more productive if the nurse species is planted 2 or 3 years in advance of the sensitive species. Care must be taken in later management, however, to ensure that the nurse does not overgrow the oak completely.

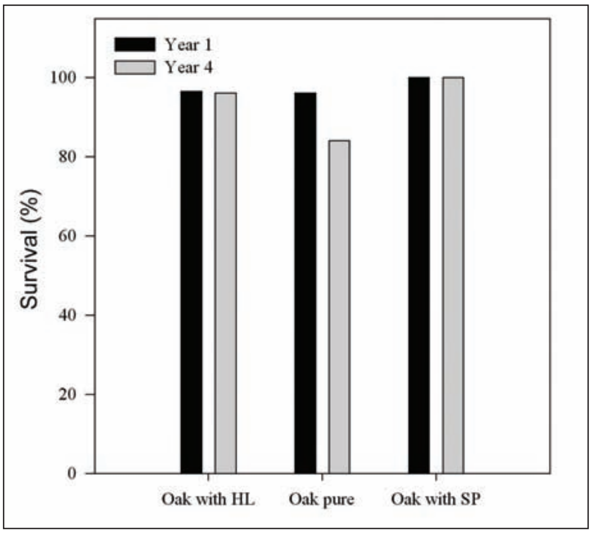


Figure 5.39: Survival in pure stand and mixture crops of oak at Tumduff after 1 and 4 years (CLE 2/00).

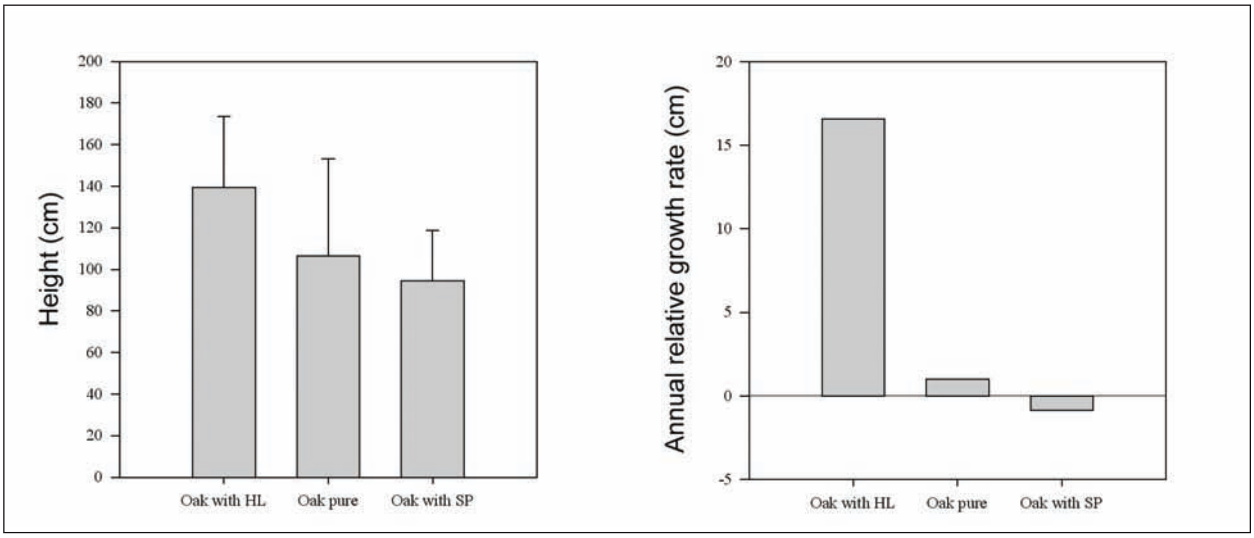


Figure 5.40: Height after four growing seasons and annual RGR of oak in pure and mixed crops at Tumduff (CLE 2/00) (vertical bars denote ± one standard error).

Sitka spruce and birch mixtures

A trial was established at Blackwater (KTY 14/00) to investigate the nursing effect of downy birch on the growth and survival of Sitka spruce. Different nursing densities were examined (Table 5.13).

While *B. pubescens* grew well in this experiment, with an average height of 214 cm after four growing seasons, its effect on the growth of Sitka spruce planted at the same time was not significant when compared to the control plots of pure Sitka spruce (Figure 5.41). Long-term monitoring is required to establish the effect of the nursing birch when the Sitka spruce is planted two and four years later. Horgan et al. (2003) suggests that unless already present, birch (or alder) needs to be planted well in advance of the main species and reach a height of about 6 m before opening up and underplanting the main target species.

Experiments were established at Blackwater (KTY 20/02) and Tumduff (CLE 3/00) in which 2-year-old planted alder trees was cut and replanted with Norway and Sitka spruce (see thinning design in Appendix 6). After three growing seasons, survival of both spruce species was excellent with the growth of the

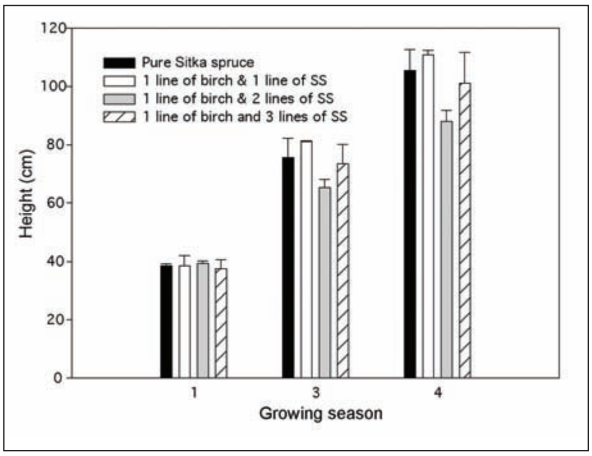


Figure 5.41: Total height of Sitka spruce after four years growing with a same-age nurse crop of downy birch at Blackwater (KTY 14/00) (vertical bars denote ± one standard error).

Table 5.13: Mixture configurations and dates of planting examined in the Sitka spruce/birch mixture trial at Blackwater.

Mixture configuration	Year planted	
	Birch	Sitka spruce
Pure	2000	2000
Alternate birch and Sitka spruce	2000	2000
Alternate birch and Sitka spruce	2000	2002
Alternate birch and Sitka spruce	2000	2004
1 line of birch and 2 lines of Sitka spruce	2000	2000
1 line of birch and 3 lines of Sitka spruce	2000	2000

Sitka spruce better than Norway spruce (Table 5.14). Long-term monitoring of this trial should be carried out in order to assess the effect of the alder planted in advance of the sensitive crop. The problem of strong coppice growth in the alder may need to be further addressed.

Table 5.14: Height and survival after three growing seasons of Norway and Sitka spruce underplanted in a 3-year-old crop of alder (KTY 17/00).

Height (cm)	NS	SS	Survival (%)	NS	SS
Plot 1	56.9	81.9	Plot 1	88	100
Plot 2	48.5	84.3	Plot 2	88	94
Plot 3	50.1	84.2	Plot 3	96	100
Plot 4	48.4	84.9	Plot 4	86	100

Other mixtures

Sycamore was planted in mixture with western red cedar at Mount Lucas (Allen2/00) and Tumduff (CLE2/00). In both plots, sycamore had a lower survival and growth rate and were smaller than those planted in pure plots.

Sitka spruce, Norway spruce and oak in near-mature naturally regenerated birch woodland

A species trial was established at Tumduff (CLE 5/00) under naturally regenerated birch (*B. pubescens*) on a woody fen peat, ranging from 0 to 100 cm in depth. From both ground and aerial surveys, the higher density of naturally regenerated birch seemed to coincide with shallow peat areas and old ditches. Stem height varied (up to 10 m) but the form of the birch was very poor. Selective felling took place in strips, leaving either only rows of birch along old drain channels ('side-shelter' plots) or side rows plus individual large trees within the plot ('under canopy' plots). Oak, Norway spruce and Sitka spruce were planted in 2000. At the same time as the underplanting, the same species were also planted on an open, exposed area of the cutaway, some 500 m away from the birch woodland. This 'open' site displayed different soil characteristics than the birch woodland. The peat was over a metre deep on average, mainly consisting of *Phragmites* peat. Vegetation was kept under control at all sites during the reporting period, using a combination of herbicides and manual control.

Norway spruce and Sitka spruce

Norway and Sitka spruce growing in the open were smaller than under shelter from year one onwards (Figures 5.42 and 5.43). Both species were also affected by the type of shelter as, from year one, trees were significantly taller when growing directly under the birch canopy compared to those growing in the 'side shelter' plots. The birch canopy benefited

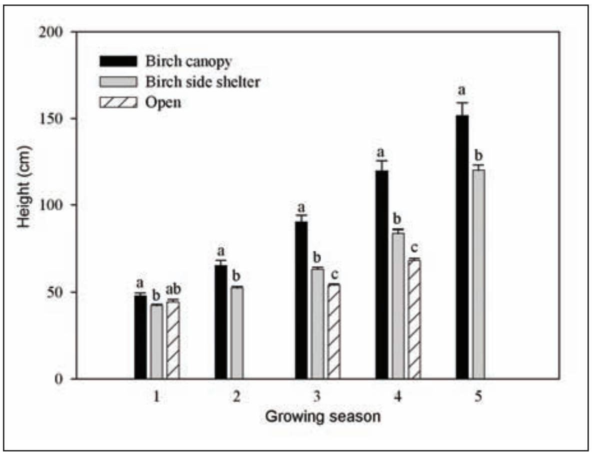


Figure 5.42: Growth of Norway spruce under birch shelter and in the open (vertical bars denote ± standard error). There was no measurement in the open area at the end of the fifth growing season. Means within year with the same letter are not significantly different (p<0.05).

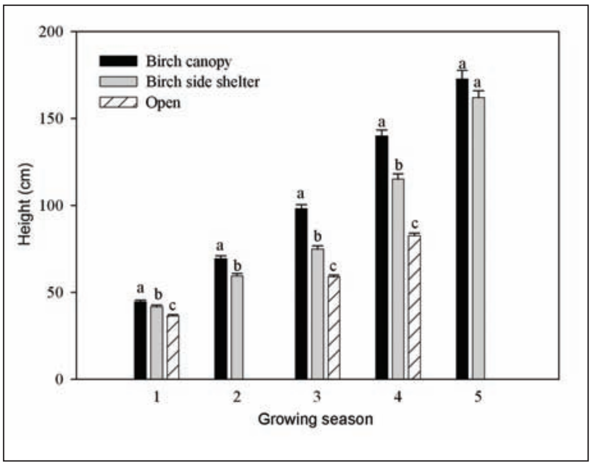


Figure 5.43: Height growth of Sitka spruce under birch shelter and in the open (vertical bars denote ± standard error). There was no measurement in the open area at the end of the fifth growing season. Means within year with the same letter are not significantly different (p<0.05).

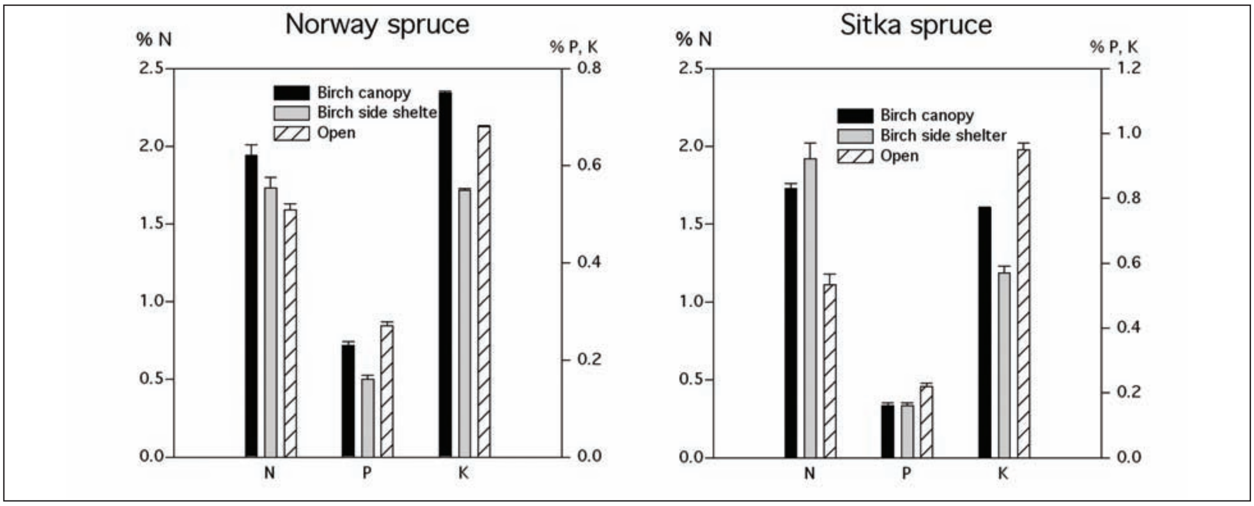


Figure 5.44: N, P and K foliar nutrient contents in Norway and Sitka spruce growing under birch shelter and in the open.

the trees in the early years but it is possible that this trend will be reversed as the trees grow taller, unless the birch is carefully thinned. Among all the BOGFOR trials, Sitka spruce grew best under the naturally regenerated birch. The influence of shelter on the early growth of Sitka spruce has been reported in other studies (Thompson 1984; Strand et al. 2006).

Norway spruce did not suffer from frost damage under birch, while damage to Sitka spruce was reduced under the birch canopy compared to the open areas. Some Sitka spruce trees were damaged by frost where the canopy was sparse, which is in agreement with Carlson and Groot (1997) who found that intact canopies provided near-complete frost protection.

As well as protecting against frost and exposure, shelterwood planting may be beneficial for nutrition. Foliar nutrient concentrations of spruce growing under birch shelterwood had significantly higher foliar N contents (Figure 5.44). How this improved nutrition was brought about is not clear, but it may be by the mobilisation and rapid turnover of nitrogen by the deciduous birch or improved mycorrhizal associations. Foliar P and K did not seem to be affected by sheltering.

Oak

Survival of oak was not significantly different between trees grown under shelter and those grown in the open (average survival for each treatment varied between 84% and 86% after four growing seasons). Oak growing in the open, however, were significantly smaller than under birch, from the second growing season onwards (Figure 5.45). There was no significant difference between the height of oaks growing directly under the birch canopy compared to growing with birch side shelter. Height increment under birch was greater than in any other oak plantations on cutaway peatlands. It was also observed that frost damage was absent in oak growing under birch shelter while trees suffered severe leader die-back in the open.

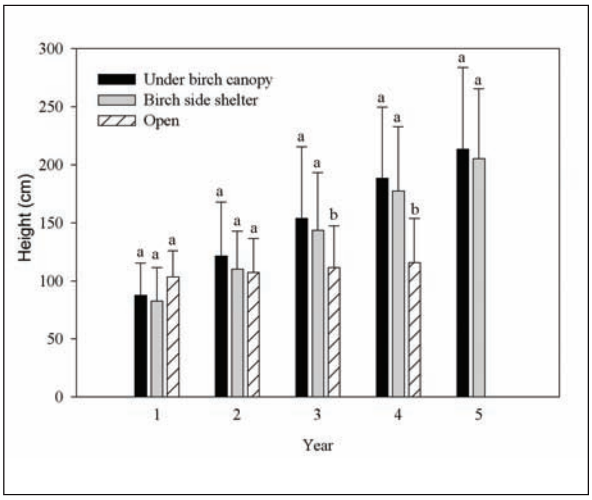


Figure 5.45: Height growth of oak under birch shelter and in the open (vertical bars denote ± standard error). There was no measurement of the oak in the open area in the fifth growing season. Means within year with the same letter are not significantly different ($p<0.05$).

Conclusions

In conclusion, there are several components to the successful establishment of tree plantations on cutaway peatlands. However, the use of nurse species, either planted or natural, is most likely to improve the successful establishment and development of potential species such as Norway spruce, Sitka spruce and oak. Most importantly, the use of natural birch woodlands as a 'nurse' for more commercial species should be encouraged wherever possible. Natural expansion of birch on Irish cutaway peatlands has occurred over the last forty years or so, with birch regenerating in the vicinity of established birch woods or as shelter belts, especially in areas protected from prevailing wind. These older woodlands are of limited distribution, and the consequent lack of seed limits colonisation by birch over large areas. Seed sources could be encouraged by establishing islands of birch (*B. pendula* preferably) at strategic locations across the cutaway peatlands.

Once birch has established itself, it should reach an adequate height (c. 6 m) before it can produce a suitable environment for underplanting with a more sensitive species such as Sitka spruce. This could be done by felling strips of natural birch woods using V-shearing equipment or alternatively, by chipping the felled birch for energy.

Practically, establishing any species under naturally regenerated birch may present some difficulties, due both to the time required for the birch to establish naturally following peat harvesting (Curran and MacNaeidhe 1986; Salonen and Laaksonen 1994) and the cost of controlling the birch between the lines of the planted nursed crop. It is worth considering, however, the establishment of birch or alder a number of growing seasons in advance of planting a main crop species. Results of planting under birch and especially under alder are encouraging in this sense. These mixture types need to be managed carefully, however, and timely intervention will be required to ensure the nursed crop is given enough light. Direct seeding is another option available to the forester.

Direct seeding of birch

Planting of seedlings is the most common method used for afforestation in this country. Another regeneration option is direct seeding, i.e. sowing of seeds by manual or mechanical means. This has been successful in France (Kroth et al. 1976) where 10% of afforestation is done by seeding. It is also quite common in Feno-Scandinavia, Scotland and Iceland (McVean 1966; Kroth et al. 1976; Brown 1984; Aro and Kaunisto 1998a; Karlsson et al. 1998; Aradottir and Eysteinsson 2002). The results of trials in the UK have been variable (Savill et al. 1997).

Since birch naturally colonises cutaway peatlands, sowing with birch or a similar pioneer species such as alder may be an alternative, cheaper option to planting to quickly establish a ground cover on these sites. A study was carried out within the BOGFOR programme to assess whether this method is appropriate for certain cutaway sites and certain species. The experiment looked at the emergence and survival of birch (*B. pubescens*) and alder (*A. glutinosa*) in relation to seed treatment, sowing date, fertiliser application, cultivation and artificial shelter.

Seed treatment is usually recommended by nursery practitioners to increase germination (Aldhous and Mason 1994). The treatment for birch and alder included increasing the seed moisture content and chilling for 12 weeks. For the purpose of this study both were used: treated and non-treated seed. Sowing time is also an important factor in the establishment of seedlings. As a rule of the thumb, in areas that do not suffer from winter frosts, but tend to be dry in early summer, autumn sowing may be advisable. Alternatively, areas that are prone to frost but have relatively high water carrying capacity may be more suitable for spring sowing (Anon. 2002). Due to their susceptibility to frost and exposure and having a tendency to surface drought in springtime, cutaway peatlands in Irish Midlands are highly unpredictable in this sense. This study investigated sowing early in the year (February) without the chilling treatment and later (April and May) with treated and non-treated seeds. Sowing was done partly by hand and partly by machine. The cultivation method varied from site to site.

Initial analysis of the number of birch seedlings at the end of the first growing season showed that seedling emergence was significantly affected by many factors (Table 5.15). Time since cessation of harvesting is the principal factor influencing seedling emergence; germination at the two older sites was almost double that on the new, less weathered sites. The non-treated seed sown during the winter performed better than the treated seed sown in spring.

In comparison, the alder seedlings seemed to prefer newer sites and treated seed sown at spring gave best results (Table 5.16).

The number of both birch and alder seedlings decreased considerably over the first year and this change was consistent across all sites (Figure 5.46).

Fertilisation (115 kg/ha of rock phosphate) had a significant positive effect on the number of emerging birch seedlings: on average three times more birch seedlings were counted in the fertilised areas compared to the unfertilised areas (Table 5.17). There was no fertilisation effect when alder was sown alone or in mixture with birch. Low, more sheltered bays resulted in increased seedling survival.

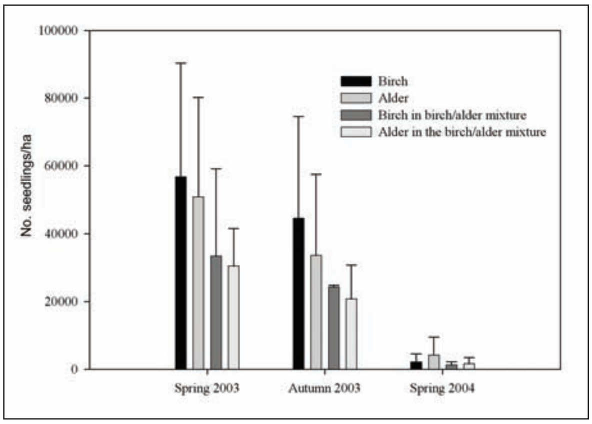


Figure 5.46: Average number of birch and alder seedlings per ha recorded during each survey across all experiments.

This was significant for alder and birch/alder mix (Table 5.17).

The use of artificial shelter significantly increased the emergence of seedlings (Figure 5.47). This artificial shelter consisted of a green polypropylene fabric of 50% mesh gauges located to protect seedlings from the prevailing wind and mid-day sunshine. An average of 226 seedlings/m^2 was recorded in the sheltered plots compared to 26 seedlings/m^2 in the non-sheltered plots.

Early results from these trials show that the emergence and survival of birch and alder seedlings are limited by environmental conditions. While birch is a coloniser of many cutaway peatlands, the majority of sites appear to be too harsh and sterile for satisfactory germination and survival of

Table 5.15: Effect of site age, seed treatment, sowing date, sowing method and cultivation on the emergence and survival of birch seedlings on cutaway peat after one growing season.

Treatment	p value	Factor	Average no. of birch seedlings per 1 m^2 plot	s.e.
Harvesting ceased	<0.0001	Old	7.4	0.36
		New	3.4	0.33
Seed treatment	<0.0003	Treatment	3.7	0.50
		No treatment	5.8	0.29
Sowing date	<0.0001	February	5.8	0.29
		April	4.7	0.57
		May	0.6	1.02
Sowing method	<0.0001	Hand	5.6	0.26
		Machine	0.6	1.02
Cultivation	<0.0001	Levelled	7.5	0.40
		Levelled and harrowed	7.3	0.80
		Ploughed, disced, levelled	2.8	0.39
		Ploughed, disced, levelled and harrowed	4.8	0.60

Table 5.16: Effect of site age, seed treatment, sowing date and cultivation on the emergence and survival of alder seedlings on cutaway peat after one growing season.

Factor	p value	Treatment	Average no. of alder seedlings per 1 m^2 plot	s.e.
Age	0.1807	Old	1.9	0.25
		New	2.2	0.15
Seed treatment	<0.0001	Treatment	3.5	0.22
		No treatment	1.5	0.15
Sowing date	<0.0001	February	1.5	0.15
		April	3.5	0.22
Cultivation	<0.0001	Levelled	1.4	0.33
		Levelled and harrowed	2.3	0.33
		Ploughed, disced, levelled	1.6	0.18
		Ploughed, disced, levelled and harrowed	3.5	0.24

Table 5.17: Effect of fertilisation in combination with bay height on the emergence of birch and alder seedlings.

Variable	Factor	Value	Average no. of seedlings per m^2	s.e.	p value
B. pubescens	Bay height	Low	81	18.7	0.2647
		High	51		
	Fertilisation	No fertilisation	33	11.2	<0.0001
		Fertilised	133	15.8	
B. pubescens	Bay height	Low	36	10.1	0.7869
		High	32		
	Fertilisation	No fertilisation	21	6.62	0.003
		Fertilised	63	10.1	
A. glutinosa	Bay height	Low	18	3.76	0.0078
		High	2		
	Fertilisation	No fertilisation	12	3.71	0.2473
		Fertilised	4	5.72	
Mixture: *B. pubescens + A. glutinosa*	Bay height	Low	65	6.17	<0.0001
		High	8		
	Fertilisation	No fertilisation	30	9.13	0.2206
		Fertilised	51	13.9	

artificially sown seed. There is strong evidence that shelter promotes the emergence and survival of birch and alder sown directly on cutaway peatlands. Fertilisation is also critical as the seedlings will not survive the first growing season without it. Direct seeding of birch or alder as a mean to afforest cutaway peat sites requires further research before this method can be applied and used operationally. The increasing interest in using birch or alder for energy crops may lead to research in this area.

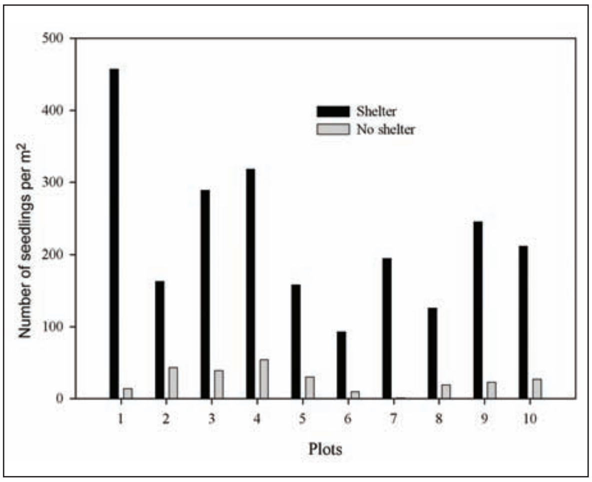


Figure 5.47: Effect of shelter on birch and alder seedling density after the first summer.

SUMMARY POINTS: TREE ESTABLISHMENT

- *Containerised seedling stock should be used for planting of hybrid larch and Corsican pine on cutaway peatlands.*
- *While large Norway spruce seedlings show lower growth rates after out-planting than containerised or small bare-root plants, their larger size remained an advantage, especially where vegetation was not effectively controlled.*
- *Planting of cold stored stock in April/May is recommended. Planting should not take place later on to avoid delay in fertilisation.*
- *Nurse crops can greatly improve the performance of most species.*
- *Oak performed better in mixture with fast-growing species such as alder and hybrid larch or underplanted in a natural birch woodland, compared to where it was planted in the open.*
- *Norway spruce benefited from shelter and grew best under a naturally regenerated birch canopy.*
- *Nurse crops (natural or planted) should reach a sufficient height and density before underplanting with the final crop species.*
- *Early results from field trials showed that direct seeding of birch or alder has limited operational application; shelter and fertilisation seem to be critical to improve seed germination and subsequent seedling survival.*

Nutrition and fertilisation

Initial fertilisation

Fertilisation requirements on peatlands

The analyses of the nutrient content of peat found at various BOGFOR sites confirmed that total phosphorus levels were low across all peat types (ranging from 170 to 440 mg/kg). The values are much lower than those for mineral soils in Ireland and are also lower than levels recorded on Finnish cutaway peatlands (Aro 2003). On the cutaways, peats were also found to be generally low in potassium, but concentrations varied greatly between and within peat types: the lowest being *Phragmites* peat (ranging from 80 to 300 mg/kg) and the highest being woody fen peat (ranging from 240 to 870 mg/kg). Total nitrogen content of the sampled peats varied from 0.91 to 2.18%. It should be noted, however, that most of the nitrogen is in organic form and is unavailable to plants. The variation in peat depth, peat type and sub-peat mineral soil quality is also likely to cause random variation in the nutrient regime of the peat.

Holmen (1969) suggested that Swedish peats required fertilisation unless they contained at least 1.3 to 1.5% N, 0.6 g/kg P and 0.4 g/kg K in the surface layer (upper 20 cm). Dickson (1971) showed that trees on peat become checked, growing very little within one to three years of planting on peat without P fertiliser. Tree seedlings planted on Finnish cutaway peatlands soon die without fertilisation because of shortages of P and K; spot fertilisation with P (as apatite) and K is necessary especially if there is no sub-peat mineral soil within the root zone (Mikola 1972; Kaunisto 1987; Kaunisto and Aro 1996; Aro 2003).

In Scotland, 50 kg P/ha was recommended in order to grow Scots pine, Sitka spruce and

Norway spruce on deep blanket peatlands (McIntosh 1981). Experimental work on blanket bogs (oligotrophic peat) in Northern Ireland has shown that Sitka spruce grew reasonably well for the first eight years with applications of 90 kg P/ha and 100 kg K/ha (Dickson and Savill 1974). Application of N at planting did not increase growth in this experiment. The only other element recommended for application on peat soil is potassium, at the rate of 125 kg K/ha (equal to 250 kg/ha of muriate of potash).

In summary, therefore, phosphorus and potassium are the two main elements that are likely to be required at planting on cutaways, with perhaps nitrogen at a later stage on very poor sites.

Fertiliser application to cutaway peatlands

Rate of fertiliser

The current recommendation in Ireland for unenclosed land (such as cutaway peatland but also blanket bogs) is to apply 350 kg/ha of rock phosphate (42 kg P/ha) at planting (Forest Service 2000b). Other research has suggested that there is no economic advantage in applying more than 500 kg of rock phosphate (14.5% P) (Farrell and McAleese 1972). The Forestry Schemes Manual (Forest Service 2003) specifies that 'phosphorus application on peat soils should be kept to a minimum in any single application and careful consideration should be given to splitting the application on these soils'. The current phosphorus application recommended here is smaller than that recommended in Finland for cutaway peatlands (68 kg P/ha with 127 kg K/ha) (Aro 2000).

Form of fertiliser

While ground rock phosphate has been used in the past, granulated rock phosphate (Granuphos or GranRP) has been recommended by the Forest Service since 2000, especially where there is a risk of P-loss from newly planted forests. Where peat is mixed with calcareous mineral soil (with high P-binding capacity), superphosphate (16% P) is acceptable for initial application. Wood ash or peat ash, the use of which is limited in Ireland, have shown good results on Finnish and Swedish cutaway peatlands, with longer responses than with normal fertiliser (Silfverberg and Issakainen 1987; Hytönen and Kaunisto 1999).

Method of fertiliser application

Of the methods tested to date, broadcast application (i.e. to the whole site rather than just to the crop trees) is generally the most effective means of applying fertiliser to seedlings at time of planting. The Forest Service guidelines suggest that fertiliser should be applied evenly and in broadcast fashion (Forest Service 2003). However, broadcast application of fertiliser may stimulate the growth of competing vegetation and thus partially negate the effect of the fertiliser on planted seedlings. Band application may thus be more beneficial in the first years but it has been suggested that spot application on peatlands does not encourage the plant roots to spread, leading to crop instability (Swan 1973). Swan argues, however, that the effects might have been confounded with cultivation treatment (ribbon ploughing). According to the Code of Best Practice (Forest Service 2000b), aerial fertilisation as a method of initial fertiliser application is unlikely to be approved on any site type.

BOGFOR fertiliser trials

The objectives of the BOGFOR fertiliser trials were to identify appropriate fertilisation regimes for the establishment of two species on three typical cutaway peatland sites. The experiments were set up to investigate the effects of different rates of fertiliser application, as well as the timing and method of application on the development (survival, growth and foliar nutrient content) of Norway spruce and oak. The fertiliser rates to be tested were chosen for environmental rather than silvicultural considerations, concurring with the recommendations of the Forest Service that fertiliser application should be 'kept to a minimum in a single application' on such sites (Forest Service 2003). Thus, the highest application rate tested was 350 kg/ha rock phosphate.

In 2000, two trials (Norway spruce) were established at Tumduff (CLE6/00 and CLE7/00) and one (pedunculate oak) at Mount Lucas (Allen3/00). One of the Norway spruce trials was established on a reconstitution site (where the previous crop had failed), while the other spruce trial and the oak trial were established on bare peat sites. Diameter (at 10 cm above ground level) and height were measured after each growing season. At each site, treatment plots were 15 x 15 m in size, separated by a 15 x 6 m buffer zone. Since the effects on ground vegetation were also studied in the newly afforested sites, no vegetation control was carried out except at the reconstituted site where manual control was used for four years due to competing vegetation that was present from establishment.

Results from a Norway spruce fertiliser trial on bare cutaway peatlands at Tumduff (CLE 6/00)

Background information

This fertiliser trial was established on a bare cutaway peatland site that was ripped and disced in spring 2000 prior to planting with Norway spruce in May 2000. The treatments are shown in Table 5.18. The experiment design was a randomized block. Trees were planted on three different peat fields. Field elevation was used as a covariate (two peat fields being elevated (high) in comparison to the third one (low)).

The soil characteristics of this site are typical of a deep cutaway peatland, composed mainly of *Phragmites* peat (Table 5.19). Concentrations of P and K are generally quite low in this type of peat and necessitate fertiliser application at planting.

Response to different fertiliser rates and methods of application

This experiment had the poorest survival results but displayed a wide variation, with mean survival rates per plot varying from 8 to 92%. The repeated measures analysis showed only one significant interaction effect on survival: method*peat field ($p = 0.0004$). Over the five year period, survival was the highest in plots where fertiliser was band applied and on high peat fields. The lowest survival (< 40%) was recorded at plots that were located on the low field and where fertiliser was broadcast. Survival during the fifth growing season also decreased significantly for all treatments.

Table 5.18: Experimental treatments applied at the Norway spruce fertiliser trial at Tumduff (CLE 6/00). Broadcast: the fertiliser is spread over the ground surface; Band: the fertiliser is applied in a 30-40 cm band along the line of trees.

Treatments		First application June 2000	Second application June 2002
Rate of rock phosphate	A	42 kg P/ha	0 kg P/ha
	B	28 kg P/ha	14 kg P/ha
	C	14 kg P/ha	14 kg P/ha
Methods of application	1	Broadcast	Broadcast only
	2	Band	

Table 5.19: Soil characteristics of peat found at the Tumduff CLE 6/00 trial.

Site: Tumduff F-CLE6/00	n*	pH	N (%)	P (%)	K (%)	Ca (%)	Fe (%)	Mg (%)	S (%)	Mn (%)
Deep *Phragmites* peat	36	4.63	2.17	0.017	0.01	0.16	0.86	0.06	0.53	0.035

* number of samples analysed.

The repeated measure analysis, which modelled the effect of fertiliser rates and method of application with peat field as a covariate (high or low field) on tree height, diameter and relative growth rate between year 5 and year 1 (RGR_{1-5}) did not detect any significant factor or interaction. After five growing seasons, trees which received the recommended rate (42 kg P/ha) in a split application) were taller and had larger stem diameter than the other two treatments, but differences were not statistically significant. Annual height increment was significantly higher in the low field compared to the high fields from the fourth growing season onwards (Figure 5.48). Diameter increment was also higher in the low field during the fifth growing season (Figure 5.48).

No relationship was found between soil parameters measured in each plot (pH and soil nutrient concentrations) and growth parameters. Foliar nutrient concentrations measured after the third, fourth and fifth growing seasons were not affected by treatment (Table 5.20). Foliar N consistently decreased over the monitoring period ($p \leq 0.001$) for all treatments but remained above deficiency thresholds. Foliar P also significantly changed over time and was below critical values after four growing

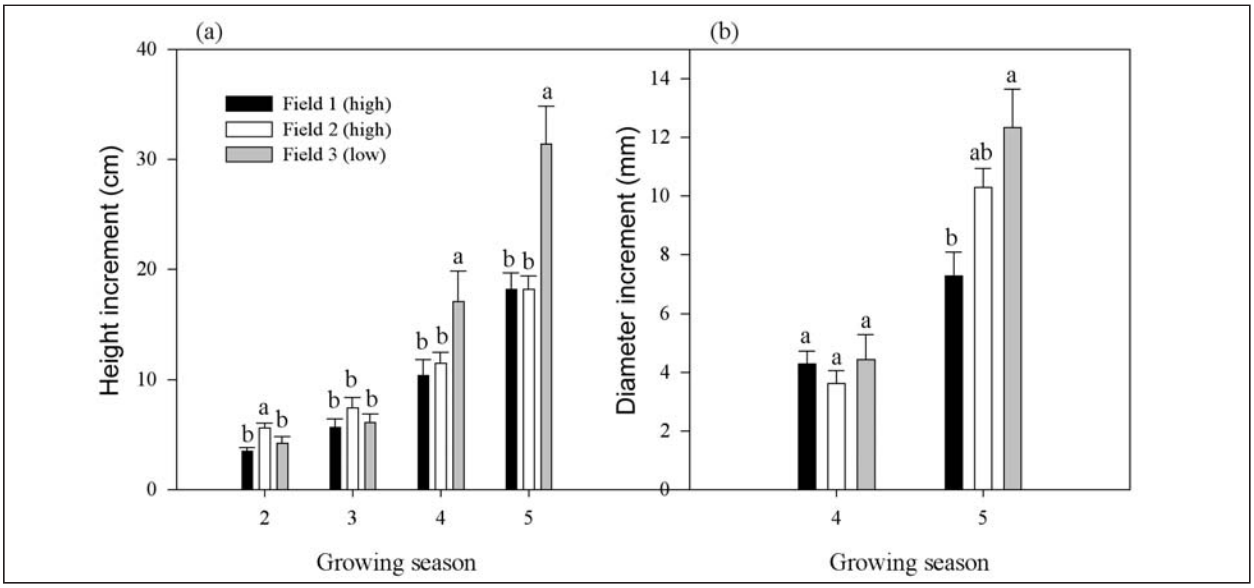


Figure 5.48: Effect of peat field elevation on (a) height and (b) diameter increment at the Tumduff fertiliser trial. Vertical bars denote means ± standard deviation. Means with the same letter were not significantly different ($p > 0.05$).

Table 5.20: Foliar nutrient concentrations of Norway spruce for each fertiliser treatment after the third (2002), fourth (2003) and fifth (2004) growing seasons (see Table 5.4.1 for treatment legend).

Treatment	N	P	K	Ca	Mg	Mn	Fe	Zn	Cu
	g/kg	g/kg	g/kg	g/kg	g/kg	g/kg	mg/kg	mg/kg	mg/kg
2002									
A	21.90	2.11	5.06	9.52	1.30	5.68	109.77	41.21	3.18
B	21.97	2.08	5.18	8.73	1.18	5.50	89.80	36.64	2.95
C	22.35	2.00	4.97	8.96	1.21	5.14	101.83	42.73	3.02
2003									
A	17.53	0.81	3.30	11.07	1.29	3.63	94.89	34.45	4.69
B	14.89	0.66	2.94	9.72	0.98	3.44	76.41	27.24	3.56
C	16.54	0.76	3.01	12.24	1.96	3.26	61.71	33.29	11.67
2004									
A	16.01	1.84	4.58	8.25	0.89	5.21	54.55	35.85	8.23
B	14.70	1.91	4.68	8.54	0.87	5.16	51.21	31.77	7.88
C	14.48	1.82	4.40	9.39	0.87	5.59	51.04	31.70	8.08

seasons but increased again during the fifth year. Foliar K decreased consistently and dropped below the deficiency threshold after five growing seasons. Foliar concentrations of micro-nutrients (Fe, Cu, B and Mn) remained above the deficiency thresholds during the monitoring period, but Fe and Mg concentrations decreased over time. Overall, foliar nutrient concentrations were independent of fertiliser rates and methods of application and were not related to soil nutrient concentrations or growth parameters.

Results from this trial demonstrated that the rates of fertiliser tested did not affect tree growth or nutritional status. Survival improved where fertiliser was band applied rather than broadcast, in low bays. However, tree growth was not improved following either broadcast or band fertiliser application. On Finnish cutaway plantations, the duration of the fertilisation effect has been shown to be shorter if the spot-fertilised trees are growing on shallow peat over coarse-textured soils such as boulder till, typically requiring second fertilisation after 4-5 years, while broadcast-fertilised trees on deep peat should be second fertilised after 10-15 years (Aro and Kaunisto 1998b, c).

It is doubtful if higher fertiliser rates would have induced a positive tree growth response in this study. The fact that higher growth increments were found in the low field from year three suggests that other environmental factors, for example exposure, may have had a greater effect on the tree growth than the treatments tested. The rapid colonisation of the low peat field with *Juncus effusus* and shrubs (*Betula* and *Salix* spp.) reaching over 1 m tall by year three would have provided shelter for the surviving Norway spruce trees. On the other hand, high peat fields became only slowly colonized with *Eriophorum angustifolium, Triglochin palustris, Campylopus introflexus* and *Epilobium angustifolium*.

Results from Norway spruce fertiliser trials on reconstituted cutaway peatland at Tumduff (CLE7/00)

Background information

This site was initially planted in 1989 with Sitka spruce and was replanted with Norway spruce in May 1999. No site preparation was carried out except herbicide spraying prior to planting. The treatments (Table 5.21) were established using a randomized block design (see GIS map). In addition, all plots (including the controls) received an application of muriate of potash (250 kg/ha) at planting.

Both *Phragmites* and *Sphagnum* peat were present at the site and had different chemical composition. The *Phragmites* peat had, on average, significantly higher pH and N, P and K concentrations than the *Sphagnum* peat, but both these levels were very low. When added to the growth model, peat type did not have any significant effect on the height, diameter or foliar nutrient content of the trees. Although not measured at this site, bulk density is usually higher in *Phragmites* peat

Table 5.21: Experimental treatments applied at the Norway spruce reconstituted site (CLE 7/00).

Treatments		
Rate of rock phosphate	A	0 kg P/ha
	B	17 kg P/ha
	C	34 kg P/ha
	D	51 kg P/ha
Method of application	1	Broadcast
	2	Band

Table 5.22: Soil characteristics on peats found at the Tumduff reconstituted trial (CLE 7/00).

Site: Tumduff R-CLE7/00	n*	pH	N (%)	P (%)	K (%)	Ca (%)	Fe (%)	Mg (%)	S (%)	Mn (%)
deep *Sphagnum* peat	15	3.89	1.32	0.024	0.021	0.67	0.2	0.01	0.25	0.005
deep *Phragmites* peat	8	3.96	1.76	0.027	0.03	0.94	0.45	0.009	0.30	0.01

* number of samples analysed.

than in *Sphagnum* peat and consequently the former also has a higher nutrient concentration per unit volume.

Results

All plots had a mean survival rate between 80% and 90% after six growing seasons. There was no treatment effect on survival rate. The repeated measures analysis which modelled the effect of rate of fertiliser, application method, peat type and their interactions on ln(height) detected one significant factor: Fertiliser rate*time ($p < 0.0001$) (Figure 5.49). Similar results were found when modelling ln (DBH) ($p < 0.0001$). The relative growth rate between year 2 and 6 (RGR_{2-6}) was significantly smaller in the control plots compared to all the fertilised plots but there was no difference between the three rates of fertiliser (Figure 5.49 inset).

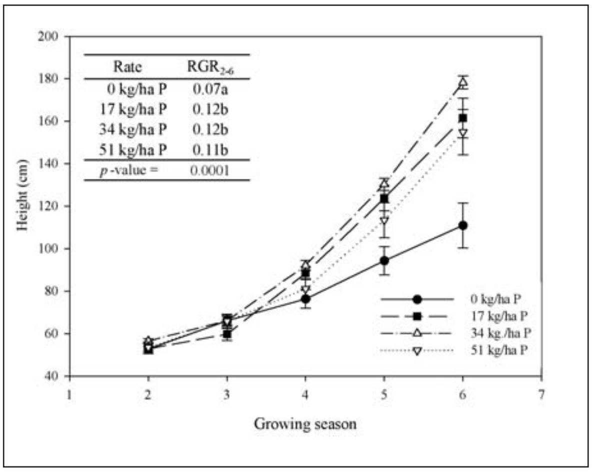


Figure 5.49: Effect of P fertiliser rate x time on Norway spruce height (vertical bars denote least square means ± one standard error) in the fertiliser trial A. Inset shows fertiliser rate effect on relative growth rate between year 2 and year 6 (RGR_{2-6}). Means having the same letter are not significantly different ($p > 0.05$).

Foliar P concentrations measured after the fifth growing season were positively related to RGR_{2-6} (Figure 5.50). There was also a linear relationship between foliar P concentrations and rates of fertiliser (Figure 5.51). Increased rates of fertiliser application led to increased P concentrations in the needles, suggesting increased uptake by the trees. Trees growing on the control plots had an average foliar P concentration below the deficiency threshold (< 0.12%). Foliar K was also positively correlated with rates of phosphatic fertiliser (Figure 5.50). Trees growing in the control plots also suffered from K deficiency (< 0.5%). There was no significant relationship found between P fertiliser rate and foliar N concentrations, which were adequate across all treatments (> 1.2 %). Micro-nutrient concentrations (Fe, Mn, Cu and B) in the foliage were also all above deficiency thresholds.

Results from this fertiliser trial showed that growth was not affected by the different rates of fertiliser application or the method of application during the six years after planting. It confirmed, however, that the growth of Norway spruce is limited when no fertiliser is applied on reconstituted cutaway peatland.

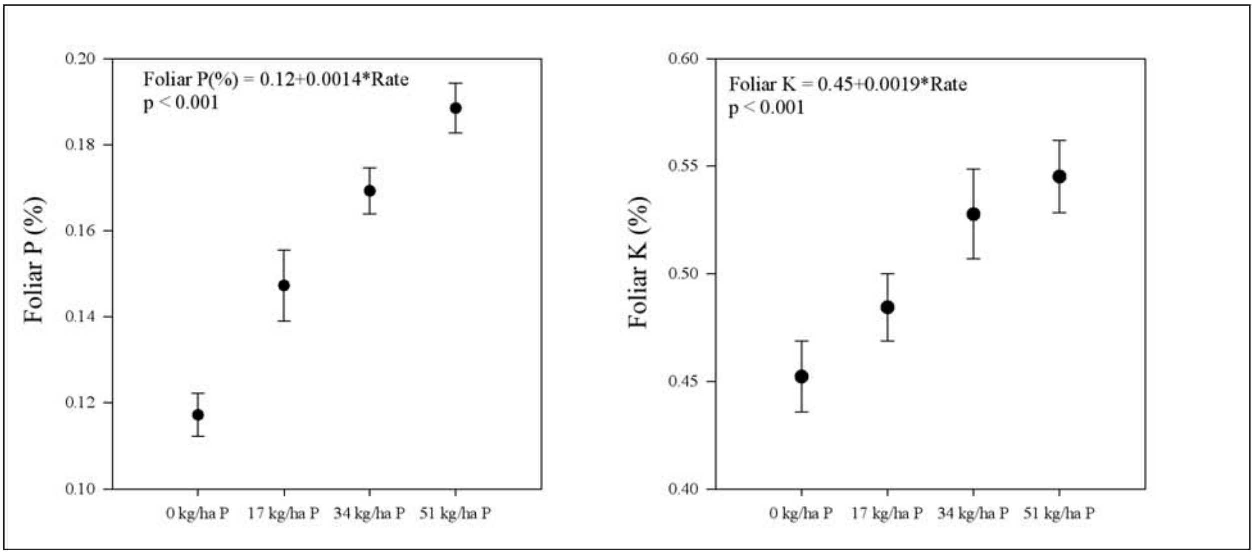


Figure 5.50: Relationship between fertiliser rates and (a) foliar P concentrations and (b) foliar K concentrations in the fertiliser trial A (vertical bars denote standard error).

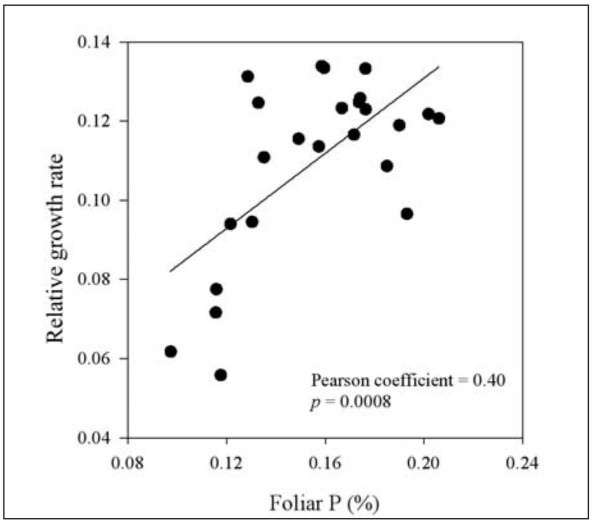


Figure 5.51: Correlation between relative growth rate (RGR_{2-6}) and foliar P concentrations measured after the fifth growing season.

Results from the oak P fertiliser trial at Mount Lucas (Allen 3/00)

Background information

This fertiliser trial was established on a bare cutaway peatland that was deep ploughed and levelled. The treatments are shown in Table 5.23. The treatments were in a randomized block design.

Response to different fertiliser rates and methods of application

Survival after one growing season was excellent across all treatments, decreased significantly ($p < 0.0001$) for all treatments after the second growing season, but remained above 90% throughout (Figure 5.52). The increased survival rates in the following years are because some oak regrew from ground level where the main shoot had died. After five growing seasons, survival averaged 92% (with a range 66-100%). Increased fertiliser rate did not significantly affect survival, nor did the method of application (Table 5.24). While a large number of seedlings survived, many did not have a live leader by year 5. Forty eight percent of trees assessed in the low fertiliser rate plots had a dead leader compared to 33% in the high fertiliser rate plots ($p \leq 0.01$) (Figure 5.53).

Rate and method of fertilisation did not have any significant effect on the total height or stem diameter of the oak. Total height decreased for the first three years for all treatment combinations. Examination of

Table 5.23: Treatments applied in the pedunculate oak P fertiliser trial at Mount Lucas (Allen 3/00).

Treatments		First application June 2000	Second application June 2002
Rate of rock phosphate	A	42 kg P/ha	0 kg P/ha
	B	28 kg P/ha	14 kg P/ha
	C	14 kg P/ha	14 kg P/ha
Methods of application	1	Broadcast	Broadcast only
	2	Band	

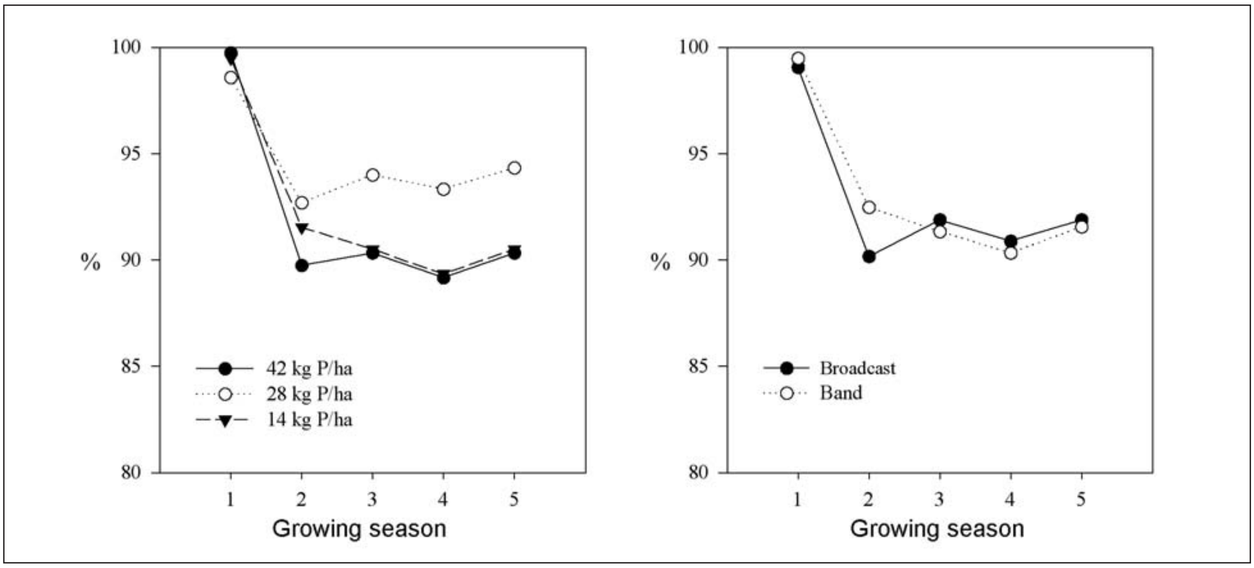


Figure 5.52: Percentage survival over five growing seasons for each fertiliser rate and method of application, Study 3. Standard errors of the means = 3.9%.

Table 5.24: Analysis of variance table (probability of greater F-values) for oak after four and five growing seasons. Variables include height, stem diameter, survival and foliar concentrations (N, P, K, Mg and Ca).

		p > F							
Year	Source of variation	Height	Diameter	Survival	N	P	K	Mg	Ca
4	Rate	0.939	0.825	0.447	0.010	0.873	0.778	0.137	0.203
	Method	0.641	0.979	0.927	0.577	0.282	0.057	0.556	0.688
	Rate x method	0.653	0.654	0.131	0.973	0.474	0.47	0.14	0.546
5	Rate	0.674	0.207	0.455	<.0001	<.0001	0.062	0.143	0.184
	Method	0.719	0.64	0.983	0.026	0.024	0.804	0.815	0.296
	Rate x method	0.41	0.346	0.119	0.0178	0.818	0.856	0.402	0.808

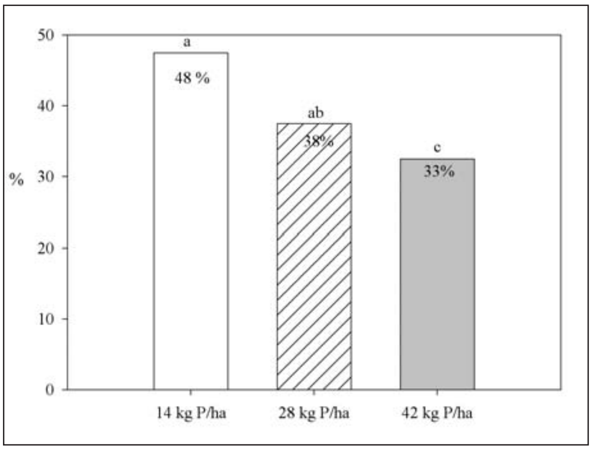


Figure 5.53: Percentage shoot die-back recorded for each fertiliser rate after four growing seasons, Study 3. Means with the same letter are not significantly different ($p > 0.05$).

height and diameter increments (Figure 5.54) suggests a growth response to higher fertiliser rates during the fifth growing season. Repeated measures analysis shows that over the last three growing seasons, fertiliser rates had an overall significant effect on diameter increment ($p = 0.003$) and that the response to treatments also changed with time ($p < 0.014$).

While P concentrations in the foliage did not significantly differ across treatments in the fourth growing season, there were significant differences by the fifth (Table 5.24 and Figure 5.55). Trees that received the lower fertiliser rate showed significantly lower foliar P concentration. P concentrations were also significantly lower in the 'broadcast' plots for all fertiliser rates.

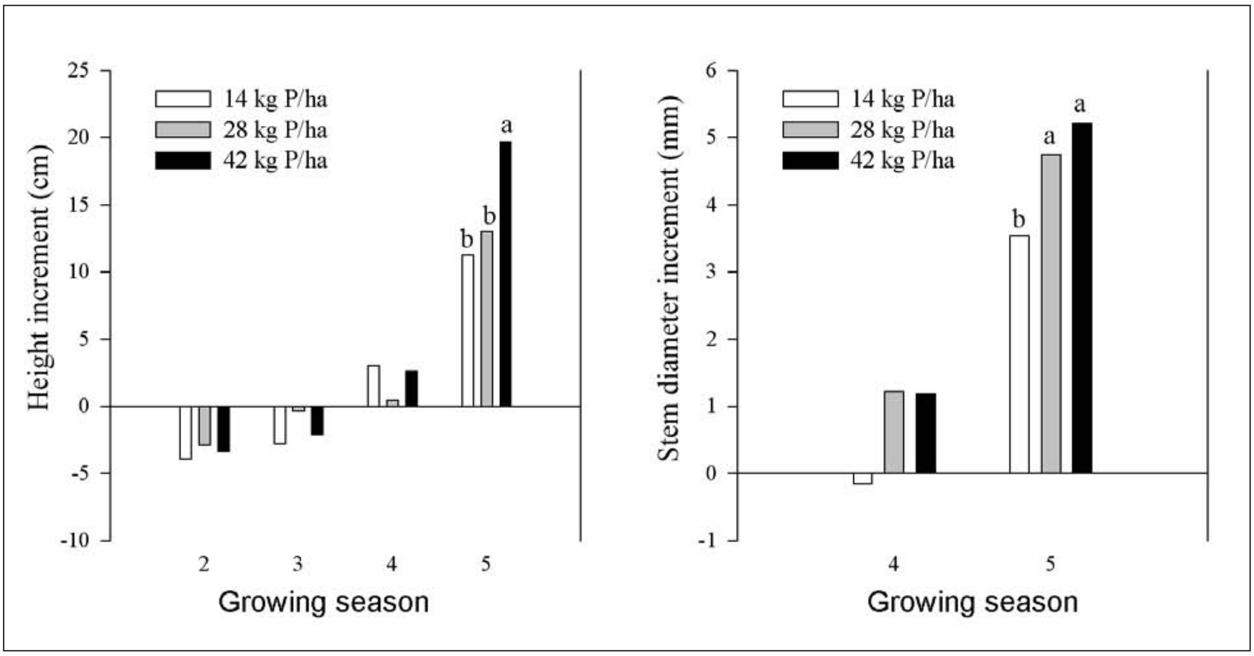


Figure 5.54: Annual height and stem diameter increment of oak. Means within year having the same letter are not significantly different ($p > 0.05$).

The foliar nitrogen (N) concentrations suggest that, during the fourth growing season, trees which received the lowest rate of phosphatic fertiliser displayed significantly lower foliar N concentrations (Figure 5.56). Foliar N content did not differ with the method of application and there was no significant rate x method interaction (Table 5.24). During the fifth growing season however, the trees which received the highest rate of P fertiliser as a broadcast application had a significantly reduced N content compared to all other treatments.

Potassium (K) concentrations measured in the foliage were not affected by fertiliser rate or the method of application but decreased significantly ($p < 0.0001$) for all treatments between year 4 (K = 1.07%) and year 5 (K = 0.85%).

Neither the range of fertiliser rates tested nor the methods of application had an effect on tree survival or growth over five growing seasons. In year 5, greater height and diameter were associated with higher rates of fertiliser. Foliar P concentrations decreased with reduced rates of phosphatic fertiliser application and were lower where fertiliser was broadcast. Oak trees suffered from leader die-back across the whole site, probably due to exposure.

Conclusions and management implications

Initial fertilisation with rock phosphate can improve the growth of young Norway spruce and oak on cutaways in the establishment years, but the effects can vary considerably depending on site factors. While P is needed

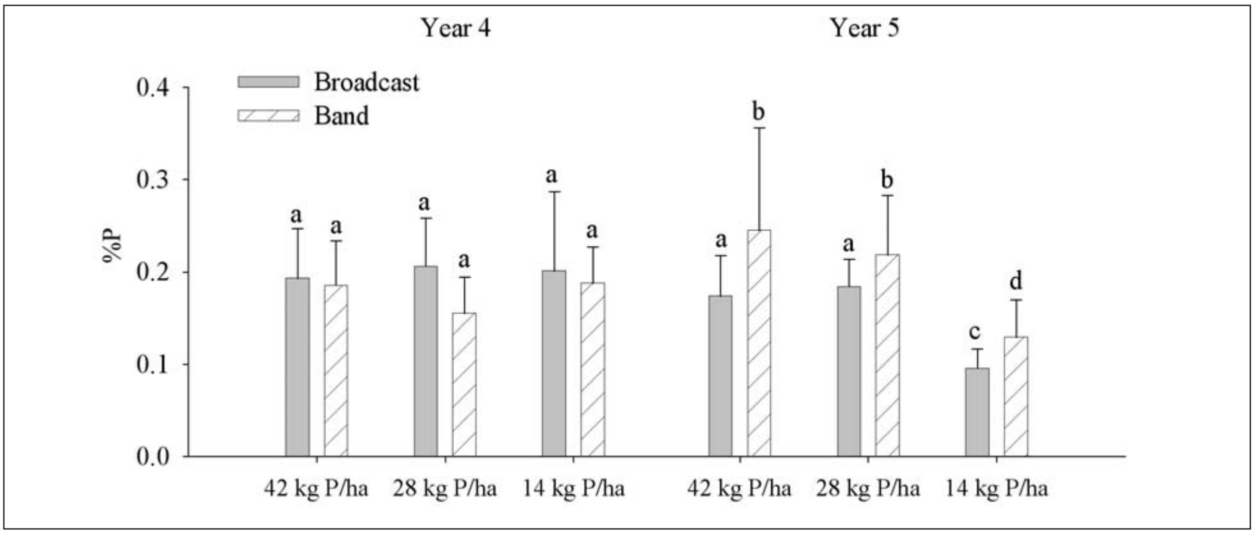


Figure 5.55: Foliar P for each treatment, Study 3 (vertical bars denote ± one standard error). Means within treatment and year having the same letter are not significantly different (p > 0.05).

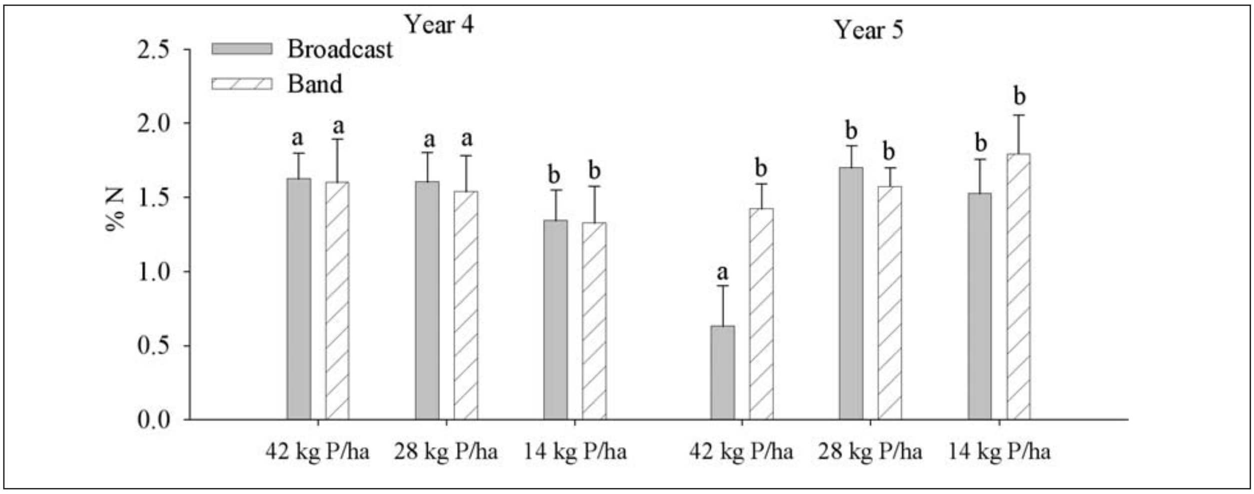


Figure 5.56: Foliar N for each treatment, Study 3 (vertical bars denote ± one standard error). Means within treatment and year having the same letter are not significantly different (p > 0.05).

at planting, increased application rates may not necessarily lead to increased growth, if other growth-limiting factors (such as exposure, competition with vegetation and poor site quality) are present.

The recommendation for initial fertilisation on bare peat fields is to split the application between planting time and two or three years later. Fertiliser should be applied in bands at planting and broadcast for the second application, carefully avoiding drains and waterlogged areas. Band application is particularly recommended in low peat fields that will typically require effective vegetation control from the outset in order to avoid high mortality. If there is only one application, such as in the case of reconstitution, a broadcast method is preferred.

Nutrient deficiency in cutaway peatland plantations

Diagnosis of nutrient deficiencies: chronosequence study

The success of Sitka spruce on most sites in Ireland led to it being planted on three quarters of all industrial cutaway peatlands that came out of production in the 1980s. Lodgepole pine (10%) was the second most commonly planted species, while Norway spruce was also used, albeit on a much smaller scale (2%). These plantations generally received 350 kg/ha of 0-10-20 (N:P:K) compound fertiliser at planting. While late spring frost and vegetation competition seriously jeopardized their establishment, it became apparent, as the plantations progressed, that nutrient deficiency was also a limiting factor. Many of the plantations sampled, which had escaped spring frost damage, displayed large variations in terms of productivity, with some trees showing symptoms of nutrient deficiency ranging from chlorotic foliage to near cessation of growth. Complete failure of some plantations and the absence of natural birch on such sites are also indications of phosphate deficiency.

There may have been several causes of crop failure due to nutritional deficiencies, including:

- Inadequate or wrongly prescribed fertiliser application.
- Incorrectly timed fertilisation.
- Application of fertiliser during unsuitable weather.
- Application of fertiliser on areas with high risk of leaching (e.g. bare cambered surfaces).
- Site quality inherently poor (e.g. due to poor drainage).

Nutritional requirements are greatest between about 5 and 15 years of age when all nutrients are employed in the development of a tree crown and root system (Miller 1981). At this stage of the rotation (pre-canopy closure), nutrient reserves from the nursery have been depleted and plantations are dependent on the availability of soil nutrients in order to build a canopy. This is the period when nutrient deficiencies are most likely to occur. As discussed previously, the reserves of P and K in cutaway peat are inadequate to sustain a healthy tree crop, and fertilisation at planting is required. The duration of the effect from this initial fertilisation is not yet known, although several authors have reported that plantations on cutaway peatlands frequently experience P, K and also N and Cu deficiencies before canopy closure (Paavilainen and Päivänen 1995; Kaunisto and Aro 1996; Jones and Farrell 1997c). The correct identification of nutrient deficiencies and the appropriate refertilisation regime are critical during this period.

The BOGFOR research programme set out to examine growth, as well as the nutritional and health status of young spruce stands. The chronosequence study (Renou-Wilson and Farrell 2007b) first allowed the determination of the duration of initial fertilisation effects, the extent of the deficiencies and the variation of nutrient concentrations over time. The study also examined how the growth and health (i.e. productivity) of Sitka and Norway spruce related to their nutrient status by identifying the nutrients that limit tree growth and how in turn the nutrient status of the trees is influenced by soil fertility.

Monitoring the nutritional status of cutaway peatland plantations

The objectives of this long-term monitoring study were to examine the growth as well as the nutritional and health status of young Sitka and Norway spruce plantations planted on cutaway peatlands in the late 1980s. Thirty stands, located across eleven Coillte forest properties, were visited over 10 years. This facilitated an analysis of variations over space and time. A description of each site can be found in Appendix 7.

Very little site preparation had been carried out for the establishment of these plantations. No cultivation was undertaken and the seedlings were slit planted straight into the peat. Soon after planting, all areas received either 600 kg/ha of 0-10-20 or a mixture of 350 kg/ha of unground rock phosphate with 250 kg/ha of muriate of potash. Foliar sampling was carried out during the dormant season in 1994, 1998, 1999, 2001 and 2004.

Foliar analysis results should be read in the context of nutritional status, which is usually categorized as: satisfactory, marginal and deficient. Nutrient concentrations are a function of factors such as species, age, sampling material, time of sampling and geographical location (Van den Driessche 1974; Raitio 1995). Concentration values were compiled from a number of publications and are presented in Table 5.25.

In assessing nutritional status, the use of absolute values is useful, as are nutrient ratios. Everard (1973) postulated that the occurrence of nutrient imbalance tends to be frequently associated with peat soil. An N:P ratio of >16 usually indicates an excess of N relative to P. Table 5.26 summarizes optimum ratios where each nutrient concentration is expressed as a proportion of the N concentration. Values greater or less than those quoted are indicative of a nutrient imbalance.

Under conditions of moderate-to-severe deficiency, growth restriction may be accompanied by observable symptoms. Symptoms associated with individual nutrient deficiencies are presented in Table 5.27. Within the programme, such symptoms were also recorded while taking foliar samples. These included needle length, needle loss, discoloration, evidence of pest or disease attack and tree forking. These supplemented an assessment of crop height, diameter and leader growth.

Table 5.25: Deficient, marginal and satisfactory foliar nutrient concentrations for young stands of Sitka and Norway spruce during the dormant season, as unit oven-dry weight. Modified from Everard (1973), Leaf (1973), Binns et al. (1980), Taylor (1991) and Savill et al. (1997).

Element	Unit	Deficient	Marginal	Satisfactory
N	g/kg	<12	12-15	>15
P	g/kg	<1.2	1.2-1.8	>1.8
K	g/kg	3-5	5-7	>7
Ca	g/kg	0.5	0.7	1-2
Mg	g/kg	<0.6	0.6-1.2	>1.2
S	g/kg	0.9	0.9-1.5	>1.5
Fe	mg/kg	<20	20-50	50
Cu	mg/kg	<2.5	2.5-4	5
Zn	mg/kg	<9	9.15	15
Mn	mg/kg	4	4.25	25
B	mg/kg	<5	5-20	25

Table 5.26: Proportions of mineral nutrient (N=100) in spruce seedlings considered optimum for growth, modified from Ingestad (1979).

Foliar ratio	Optimum
N:P	16
N:K	50
N:Ca	5
N:Fe	0.70

Table 5.27: Visual symptoms in conifer species associated with individual nutrient deficiencies, modified from Binns et al. (1980) and Timmer (1991).

Element	Visual symptom
N	Needles short, stiff, yellow-green or even yellow in severe cases. Discolouration uniform over the entire length of needle and whole live crown.
P	Much reduced needle length and weight. Youngest needle green or yellow-green with older needles purple-tinged. Extreme deficiency causes the needles to become closely adpressed to the stem giving rise to a scaly or lizard-like appearance. Loss of older foliage.
K	On young trees, yellowing confined to the needles at the tips of the current shoots. On older trees, yellowing confined to older needles on the lower branches. Individual needles show a gradual chlorosis from the green base to the tip. Loss of apical dominance.
Ca	General chlorosis followed by necrosis of the needles especially at branch tips. In severe cases, death of the terminal bud and top dieback; resin exudation.
Mg	Yellow tipping of the current needles (more vividly than K deficiency); followed in severe cases by tip necrosis.
S	General chlorosis of foliage followed in severe cases by necrosis.
Fe	More or less diffuse chlorosis confined to new needles. In more severe cases, bright yellow discolouration occurs with no bud development.
Mn	Needles slightly chlorotic, in severe cases, some necrosis of needles can occur.
B	Tip dieback late in the growing season with associated chlorotic foliage and characteristic crooking of the leading shoot.
Zn	Extreme stunting of the tree with shortening of branches. Needles are yellow, short, crowded together on twigs and sometimes bronze-tipped.
Cu	Needles twisted spirally, yellowed or bronzed. Leading shoots twisted or bent.

Results: Foliar nutrient concentrations and ratios

Variations in foliar nutrient concentrations (N, P, K, Ca, Mg, and Fe) between 1994 and 2004 are presented in Figure 5.57. All nutrients were above the deficiency threshold in 1994. Foliar N and P decreased during the following 10 years to reach values below the deficiency threshold by 2004. While foliar Fe also decreased over time, it did not fall below the critical threshold value. On the other hand, Mg and Ca concentrations increased with time while K remained steady except in 2001 when it fell below the deficiency threshold.

Overall, foliar nutrient concentrations showed significant changes between 1994 and 2004; these are summarised in Table 5.28. Analysing the data by species, N concentrations decreased by 40% in Norway spruce plots and 32% in Sitka spruce plots. Decreases in P concentrations were the greatest of all macro nutrients and were 60% for Norway spruce compared to 36% for Sitka spruce (Table 5.28a). While K concentrations decreased by 32% in the Norway spruce plots, the 9% decrease in the Sitka spruce plots was not significant. Concentrations of foliar cations (Ca and Mg) increased for all plots but increases were higher in the Norway spruce plots. Among the micro-elements, there were large decreases in Fe concentrations, 63% for Norway spruce and 64% for Sitka spruce. Levels remained, however, above deficiency thresholds. No other micro-elements varied in the Norway spruce while a significant increase in boron concentration occurred in Sitka spruce over time (62%).

Examining the foliar concentrations by peat type showed that decreases in N and P were significant for both peat types but greater for trees growing on *Sphagnum* peat compared to *Phragmites* peat (Table 5.28b). The increase of foliar cations (Mg and Ca) was significant in *Phragmites* peat plots but not in *Sphagnum* peat plots.

When examining the percentage of plots within each foliar nutrient category over time (Table 5.29a), it was observed that all Norway spruce plots had satisfactory foliar N concentrations in 1994 compared to only 66% of the Sitka spruce plots. However, by 2004 Sitka and Norway spruce plots suffered from N deficiency in the same proportion (50%). Fewer than 20% of the Sitka spruce plots showed critical P deficiency in 1994 while

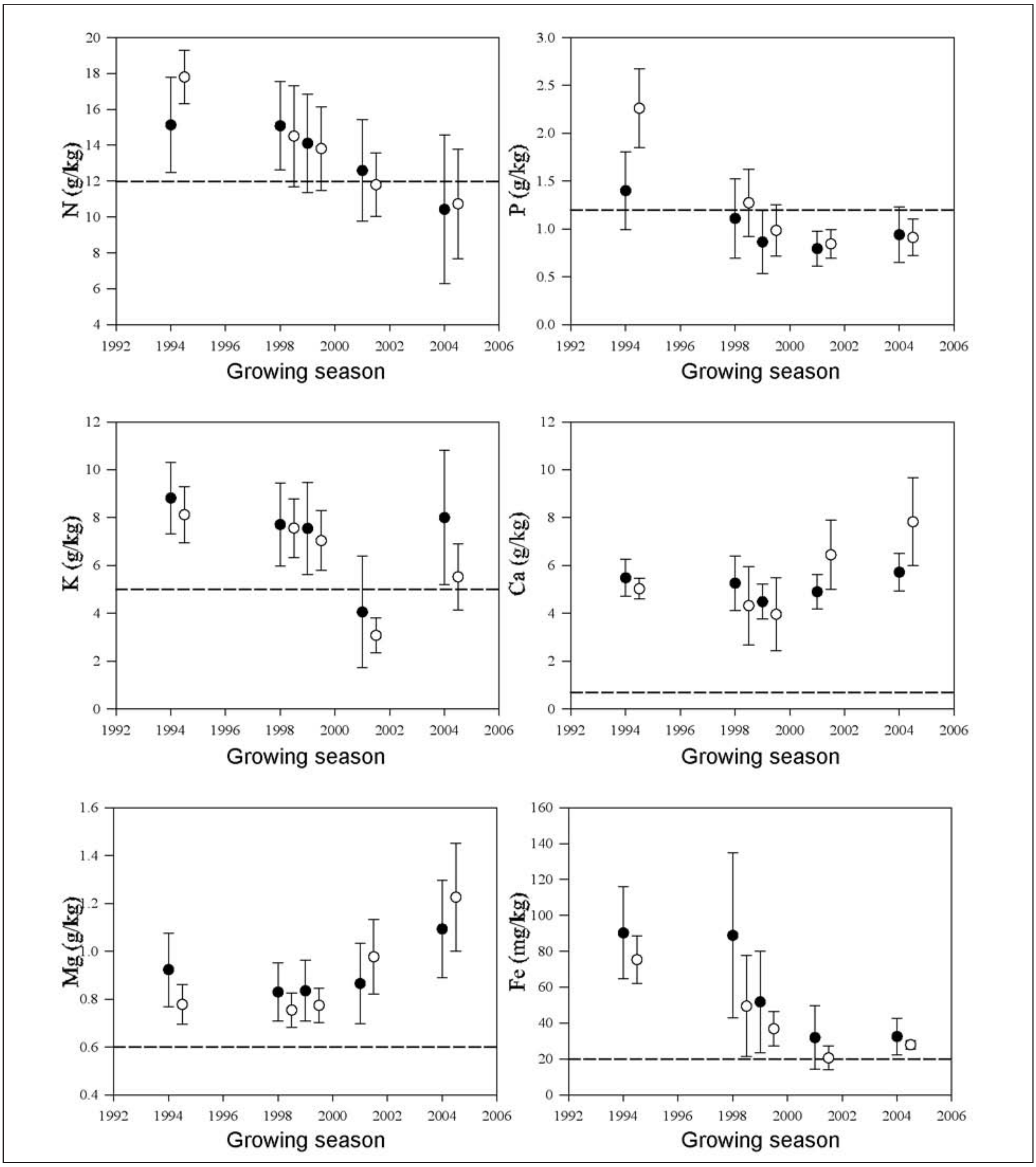


Figure 5.57: Foliar concentrations (N,P, K, Ca, Mg and Fe) measured in 1994, 1999, 2001 and 2004. For each year, means of 16 Sitka spruce stands (●) and 12 Norway spruce stands (○). Vertical bars denote ± standard deviation; dashed line denotes deficiency threshold.

none of the Norway spruce plots fell below the critical level. However, in 1999 (8-10 years after planting), all the crops suffered from either marginal or severe P deficiency. While no plots showed strong N:P imbalance in 1994, about 20% of all plots showed critically high N:P ratio (>16) by 2004, irrespective of tree species. K deficiencies occurred sooner in the Sitka spruce plots, but by 2004, 67% of the Norway spruce plots were marginal or deficient compared to 19% of the Sitka spruce plots. 45% of Norway spruce plots showed K:N imbalance compared to 25% in Sitka spruce.

Trees growing on *Sphagnum* peat entered the N deficiency sooner, all were severely deficient by 2004 compared to only 22% of the trees growing on *Phragmites* peat (Table 5.29b).

Table 5.28: Foliar nutrient concentrations over time by (a) species and (b) peat type: ranges, means, coefficients of variation (CV), percentage changes relative to 1994 values and paired t-test values: * = p < 0.05, ** p < 0.01, *** = p < 0.001 and ns = not significant.

a) By species

Norway spruce

Foliar nutrient	1994			2004			Difference 2004-1994	Relative difference (% of initial value)	Paired t- test
	Range	Mean	CV	Range	Mean	CV			
N (g/kg)	15.1-19.6	17.8	0.08	4.3-15.4	10.7	0.28	-7.10	-40	5.83***
P (g/kg)	1.8-3.1	2.3	0.18	0.7-1.3	0.9	0.21	-1.35	-60	12.35***
K (g/kg)	6.8-10.47	8.1	0.15	3.7-8.5	5.5	0.25	-2.60	-32	5.13**
Ca (g/kg)	4.5-6.0	5.0	0.09	5.3-10.9	7.8	0.23	2.77	55	-3.32*
Mg (g/kg)	0.6-0.9	0.8	0.11	0.9-1.5	1.2	0.18	0.45	58	-7.41***
S (g/kg)	1.1-1.6	1.3	0.10	0.7-1.2	0.9	0.16	-0.40	-31	6.31***
Fe (mg/kg)	53-100	75.3	0.18	24.1-31.2	27.8	0.09	-47.50	-63	8.97***
Cu (mg/kg)	1.8-4.8	3.3	0.30	2.2-6.6	4.1	0.36	0.80	24	-1.92ns
B (mg/kg)	16.6-27.3	21.5	0.17	9.9-35.6	20.0	0.52	-1.50	-7	2.07ns
Zn (mg/kg)	24.6-37.2	29.5	0.13	14.2-50.0	30.1	0.37	0.60	2	-0.8ns

Sitka spruce

Foliar nutrient	1994			2004			Difference 2004-1994	Relative difference (% of initial value)	Paired t- test
	Range	Mean	CV	Range	Mean	CV			
N (g/kg)	11.8-20.3	15.3	0.17	2.1-16.2	10.4	0.40	-4.90	-32	3.06*
P (g/kg)	0.9-2.0	1.4	0.29	0.6-1.7	0.9	0.31	-0.50	-36	3.93**
K (g/kg)	6.0-10.8	8.8	0.17	2.3-10.7	8.0	0.35	-0.81	-9	0.69ns
Ca (g/kg)	4.1-7.1	5.4	0.14	4.4-7.0	5.7	0.14	0.30	6	-0.48ns
Mg (g/kg)	0.7-1.2	0.9	0.17	0.7-1.3	1.1	0.19	0.19	21	-2.5*
S (g/kg)	1.2-1.8	1.5	0.12	0.8-1.5	1.2	0.14	-0.25	-17	3.05*
Fe (mg/kg)	53.0-146.7	90.2	0.28	19.5-55.1	32.4	0.31	-57.80	-64	11.06***
Cu (mg/kg)	2.4-4.9	3.5	0.18	1.7-6.9	4.4	0.38	0.93	27	-1.65ns
B (mg/kg)	18.5-26	22.9	0.12	22.4-57.7	37.2	0.27	14.30	62	-5.9***
Zn (mg/kg)	22.2-44.65	28.7	0.23	19.3-50.1	29.4	0.29	0.70	2	-0.11ns

b) By peat type

Phragmites peat

Foliar nutrient	1994			2004			Difference 2004-1994	Relative difference (% of initial value)	Paired t- test
Macro (g/Kg)	Range	Mean	CV	Range	Mean	CV			
N (g/kg)	11.8-19.4	16.3	0.15	7.9-16.2	12.5	0.19	-3.80	-23	3.7**
P (g/kg)	0.9-2.4	1.7	0.28	0.6-2.6	1.02	0.49	-0.68	-40	4.2**
K (g/kg)	6.8-8.9	7.8	0.08	2.4-9.5	6.5	0.35	-1.30	-17	1.98ns
Ca (g/kg)	4.1-6.5	5.1	0.13	3-8.4	5.9	0.21	0.80	16	-2.31*
Mg (g/kg)	0.7-0.9	0.8	0.11	0.7-1.5	1.1	0.21	0.32	40	-4.7**

Sphagnum peat

Foliar nutrient	1994			2004			Difference 2004-1994	Relative difference (% of initial value)	Paired t- test
	Range	Mean	CV	Range	Mean	CV			
N (g/kg)	12.7-19.6	16.5	0.13	4.06-12	9.04	0.32	-7.46	-45	5.3**
P (g/kg)	1.1-2.6	1.7	0.30	0.6-1.7	0.9	0.33	-0.80	-47	4.84**
K (g/kg)	6.02-10.8	8.8	0.21	2.3-10.7	7.2	0.41	-1.60	-18	1.07ns
Ca (g/kg)	4.9-7.1	5.5	0.14	4.5-10.5	6.4	0.27	0.90	16	-0.13ns
Mg (g/kg)	0.7-1.1	0.9	0.15	1-1.4	1.2	0.13	0.30	33	-1.8ns

Table 5.29: Percentage of plots within each foliar nutrient category over time for each element: N, P and K.

a) By species

		Norway spruce					Sitka spruce		
		Deficient	Marginal	Satisfactory			Deficient	Marginal	Satisfactory
	1994	0	0	100		1994	0	34	66
N	1999	8	59	34	N	1999	13	44	44
	2004	50	42	8		2004	50	25	25
	1994	0	0	100		1994	19	25	56
P	1999	83	17	0	P	1999	88	13	0
	2004	92	8	0		2004	100	0	0
	1994	0	8	92		1994	0	6	94
K	1999	0	50	50	K	1999	13	19	69
	2004	25	42	33		2004	13	6	81

b) By peat type

		Phragmites					*Sphagnum*		
		Deficient	Marginal	Satisfactory			Deficient	Marginal	Satisfactory
	1994	9	18	73		1994	0	14	86
N	1999	9	62	29	N	1999	33	56	11
	2004	22	67	11		2004	100	0	0
	1994	20	20	60		1994	14	29	57
P	1999	100	0	0	P	1999	89	11	0
	2004	100	0	0		2004	78	22	0
	1994	0	10	90		1994	0	14	86
K	1999	8	46	46	K	1999	11	22	67
	2004	27	27	46		2004	22	22	56

However, trees growing on *Phragmites* peat were all severely P deficient by 1999. While there was no K deficiency recorded in any of the plots in 1994, 27% of the *Phragmites* plots were severely K deficient compared to 22% of the *Sphagnum* plots in 2004.

Ratios

All stands showed low N:P ratios after 5 and 15 years. N:P ratios dropped in Norway spruce plots over time, reflecting the significant decrease in P concentrations in these crops, compared to N (Table 5.30). N:K ratios were around the optimum value.

Relationships between foliar concentrations and visual symptoms

Visual symptoms of deficiency appeared ten years after planting, chiefly in the form of short discoloured needles. This was closely related to deficiencies recorded during foliar analyses, but it was difficult to relate a specific symptom to the deficiency of a specific nutrient. This is mainly because chlorosis and stunted growth are common features in crops suffering from both N and P deficiency.

Relationships between foliar nutrients, soil nutrients and stand characteristics

The study sites were allocated to three peat types. Average pH and nutrient concentrations are presented in Table 5.31. Highly humified *Sphagnum* peat contains less nutrients (except Mn and Mg) than *Phragmites* and woody fen peat.

Foliar N concentrations were significantly correlated with the availability of nitrogen in the soil (Pearson coeff. = 0.63, p = 0.007, Figure 5.58). This positive association between foliar

Table 5.30: Nutrient ratios calculated for each species, five and fifteen years after planting.

		1994		2004	
Ratio	Optimum	Norway spruce	Sitka spruce	Norway spruce	Sitka spruce
N:P	16	13	9	8	9
N:K	50	46	58	51	77

Table 5.31: Chemical composition of the peat in the foliar plots by peat type.

		Total nutrient concentration (mg/g)									
Peat type	n	pH	N	P	K	Ca	Fe	Mn	Mg	S
Highly humified *Sphagnum*	18	3.60	11.50	0.22	0.07	9.30	4.50	0.03	1.09	3.40
Phragmites	14	5.10	17.00	0.29	0.12	15.00	9.40	0.02	0.70	5.10
Woody fen	4	5.80	17.20	0.29	0.32	23.00	9.40	0.10	0.60	4.40

and soil N concentrations held for both *Sphagnum* and *Phragmites* peat. Foliar and soil levels of P were poorly correlated, although the lowest foliar concentrations coincided with low levels of available P in acid *Sphagnum* peat plots. There was no relationship between foliar K and its availability in the soil. Overall, no correlations were found between the foliar nutrient concentrations.

Stand growth characteristics did not correlate with any nutrient variables (foliar or soil). Height and diameter growths were very variable among the studied plots, especially as the trees grew older. In 1994 (5-7 years after planting), mean heights of Norway and Sitka spruce were similar: 154 cm (CV = 0.14) and 156 cm (CV = 0.16) respectively. In 2004, mean height of Norway spruce averaged 614 cm (CV = 0.22; range: 267 to 793 cm) while Sitka spruce averaged 515 cm (CV = 0.40; range: 240 to 954 cm). Between 1994 and 2004, average annual leader growth dropped by 50% for both Sitka and Norway spruce.

Conclusions and management implications

The nutrient status of both Norway and Sitka spruce crops established in the late 1980s has declined over time. In most plots, phosphorus deficiency occurred before the trees reached 10 years of age. Nutrient deficiencies occurred sooner in Sitka spruce than in Norway spruce. It is suggested that in these plantations the effect of initial P fertilisation did not last more than eight years. Both species also suffered from N deficiencies after ten years. Foliar N deficiency occurred sooner with *Sphagnum* peat than with *Phragmites* peat. K deficiencies were not widespread but may be more difficult to assess due to inter-annual variations, probably caused by climatic conditions.

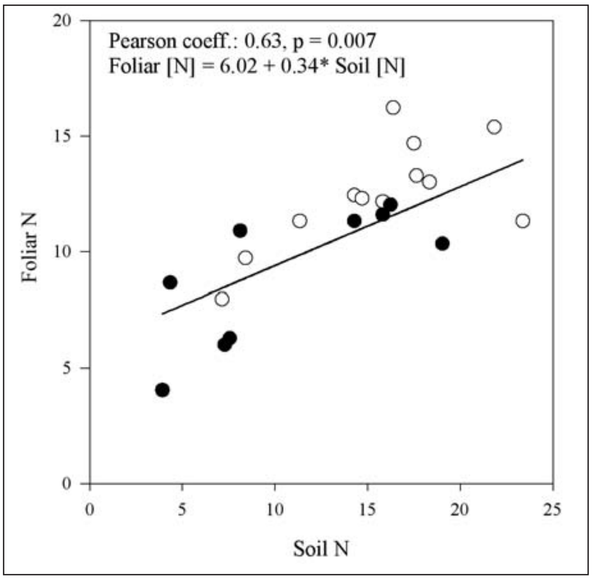


Figure 5.58: Linear association between foliar and soil N concentrations in different peat types: (●) *Sphagnum* peat (○) *Phragmites* peat.

Visual assessment of nutrient status depends on the forester's skill in detecting deficiencies as an aid to deciding the timing and type of fertiliser application required. It is recommended that visual diagnosis be supplemented with foliar analysis, in order to objectively identify the specific nutrient(s) which are deficient.

While new plantations were treated according to best fertilisation practice, the risk of nutrient deficiency should not be ignored in the pre-canopy stage in cutaway peatland plantations. It is suggested that foliar analyses be carried out in all plantations on cutaway peatlands prior to canopy closure to compile base-line information and develop a more accurate range of critical concentrations for a range of nutrients.

Second fertilisation prior to canopy closure

Background to study

Since nutrient deficiency causes tree growth to fall below the site optimum level, fertilisation is used to bring nutrient levels back up to a level where they will maintain an optimum rate of growth. During the years prior to canopy closure, tree growth is very dependent on soil nutrient concentrations, since litter fall and nutrient cycling have not fully developed and nutrient input from rainfall and canopy interception are small. During this phase, the foliage forms a considerable proportion of the stand biomass, requiring large amounts of nutrients. As seen in the foliar nutrient monitoring study, severe nutrient deficiencies can occur early in the life of cutaway peatland plantations, preventing canopy closure. Appropriate fertilisation during this phase will stimulate growth, resulting in earlier canopy closure, which reduces susceptibility to various influences such as vegetation competition and exposure. This should positively influence the subsequent development of the stand.

The effective use of fertiliser depends upon proper nutritional diagnosis of the stand using foliar analysis, but also proper diagnosis of site and stand conditions in general: soil type, species, current tree growth rate and appearance, proximity to canopy closure, past fertiliser treatment and local experience. Fertiliser application should take place where the plantation is able to respond and can achieve its growth potential. Several factors can potentially reduce response to fertilisation, e.g. drainage impediments, inadequate weed control, presence of growth inhibitors (either chemical or physical) or absence of mycorrhizal fungi. Very poor stocking, heavy loss of foliage or damaged root systems can also jeopardize the economic benefits of second fertilisation. As nutrient retention is limited on peat soils, any nutrient application will benefit the trees rather than the site itself. Applications should thus be timed to maximize both the rate of uptake and the storage within the trees. It is not recommended to apply fertiliser to a crop that has very sparse crowns as much of the nutrient storage occurs in the foliage. Also application early in the growing season is recommended to reduce losses of added nutrients.

A study was set up to examine the effect of aerial second fertilisation on the growth, foliar nutrient concentrations and health of three nutrient-deficient Sitka spruce stands established in the 1980s. The working hypothesis was that nutrient deficiencies would be 'cured' after second fertilisation. Several factors, however, may influence the level of tree response to second fertilisation, including edaphic conditions (soil nutrition, soil moisture) and existing foliar nutrient status.

The study included three representative cutaway peatland sites in the Irish Midlands (Table 5.32). The sites were planted in 1989 with Sitka spruce of the same provenance and received fertiliser (0-10-20) at planting. As part of the foliar monitoring study, the sites have been monitored regularly. A survey of mycorrhizae occurrence was also carried out at each site (Table 5.33). Clongawney had the lowest amount of ectomycorrhizal species. Each species recorded was, however, found in relatively high abundance in Clongawney as well as the other two sites. In July 2001, aerial second fertilisation was carried out following the rates recommended by Coillte in the case of nutrient deficiencies: 350 kg/ha of

Table 5.32: Sites where monitoring of growth response to second fertilisation was carried out.

Plot code	Property	Forest	Species	P/Y	Initial fertilisation 1989	Second fertilisation 2001	Surface peat type	Peat depth average (cm)	Soil pH	Dominant vegetation 2001
SSF7	Clongawney	Tullamore	Sitka spruce	1989	350kg/ha of 0-10-20	300 kg/ha urea + 350 kg/ha GRP	*Phragmites*	80	4.9	*Polytrichum, Campylopus*
SSA223	Clonsast	Emo	Sitka spruce	1989	350kg/ha of 0-10-20	300 kg/ha urea + 350 kg/ha GRP	*Phragmites*	65	3.6	*Polytrichum, Juncus*
SSA75	Noggus	Tullamore	Sitka spruce	1989	350kg/ha of 0-10-20	300 kg/ha urea + 350 kg/ha GRP	Woody fen/ *Phragmites*	68	5.8	*Juncus, Calluna, Betula*

Table 5.33: Ectomycorrhizal species found in the three Sitka spruce stands in 1999.

Ectomycorrhizal species	Clongawney	Clonsast	Noggus
Boletus piperatus			x
Laccaria laccata	x	x	x
Lactariss deterrimus		x	x
Leccinum variicolor			x
Hebeloma crustuliniforme		x	
Latarius rufus	x	x	
Lactarius glyciosmus		x	
Thelephor terrestris	x		
Total	3	5	4

granulated rock phosphate and 300 kg/ha urea. Tree crop assessment and foliar analysis were carried out annually for four years after second fertilisation.

Effects of second fertilisation in three Sitka spruce stands

As with the other Sitka spruce stands monitored in this study, the nutrient status of the trees at Clongawney, Clonsast and Noggus declined with time (Figure 5.59). Prior to second fertilisation in July 2001, the three stands suffered from severe P deficiency, and either severe or critical N deficiency. Following aerial fertilisation in July 2001, trees growing in Clonsast and Noggus showed immediate positive response in foliar P, reversing the trend observed over the previous three years (Figure 5.59). In Clongawney, however, there was no immediate P uptake and P concentrations continued to decline when sampled the first winter after second fertilisation (2002). However, foliar P concentrations increased during the second year. Foliar P continued to increase for three years at all sites with the greatest increase occurring at Clongawney. Second fertilisation increased foliar N content immediately at Clongawney and Noggus but not in Clonsast where foliar N concentration was only in the critical range prior to second fertilisation (Figure 5.59). Foliar N dropped subsequently at all sites to reach values below the critical level after four years. The foliar N:P ratio was excessively high in Clongawney the first winter following second fertilisation but dropped subsequently for the following 3 years, in the same fashion as in the other two sites (Figure 5.59). Following P and N second fertilisation, foliar K levels also increased except at the superior site in Noggus where K concentrations consistently decreased following second fertilisation and fell below critical level after four years (Figure 5.59). The foliar N:K ratio increased at all sites following second fertilisation and decreased subsequently to reach just above 1. Other elements measured remained above critical threshold following second fertilisation. Boron remained in the critical range during two years following second fertilisation but increased to optimum levels thereafter.

Foliar nutrients did not correlate with tree growth prior to second fertilisation and the stands displayed a gradient from very poor, mediocre to superior for Clongawney, Clonsast and Noggus respectively. A comparison of growth for the three stands (Table 5.34) illustrates that in 2001 the trees at Noggus were on average 261% taller and 264% larger in diameter than the trees at Clongawney. Differences between the three stands were more pronounced in basal area, with Noggus having the best growth. Following second fertilisation, annual height increment increased at the three sites for three consecutive years (Figure 5.60). It slightly increased at Clonsast during the fourth growing season but decreased at the two other sites. The highest annual height increment was recorded at the superior site (Noggus) for the first two years but Clongawney, the poor site produced the highest height increment for the following two years. On average, over the four years following second fertilisation, the poorest site (Clongawney) had the highest annual height increment with 50 cm/yr compared to 42 cm/yr for Noggus and 31

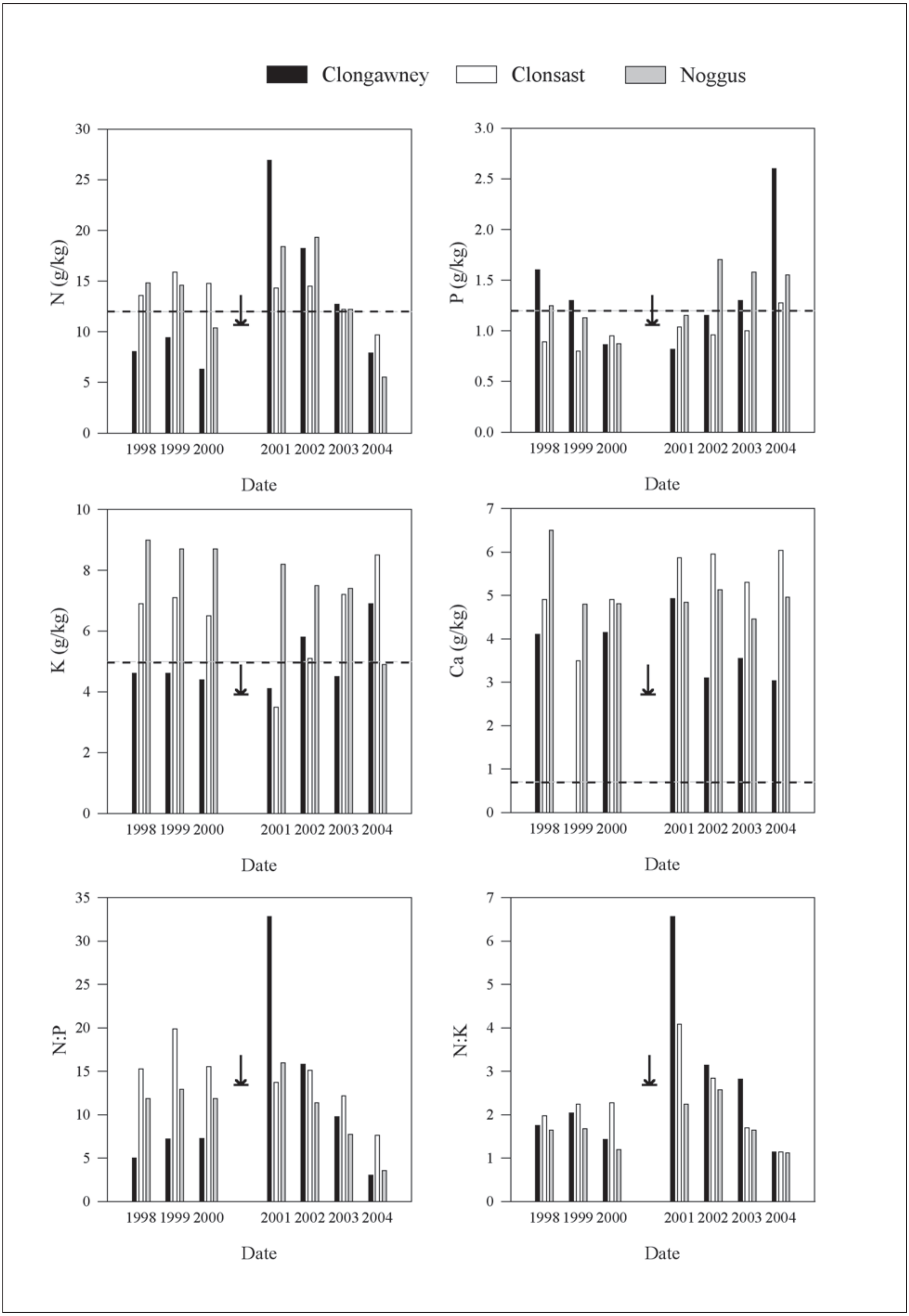


Figure 5.59: Foliar concentrations (N, P, K, Ca) and ratios (N :P and N:K) measured in three Sitka spruce stands re-fertilised in July 2001 with P and N. Dashed line denotes deficiency thresholds.

Table 5.34: Summary of growth (means with standard deviation in bracket) of three typical Sitka spruce stands planted in 1989 and re-fertilised in 2001.

	2001			2004			Growth increment		
	Height (m)	DBH (cm)	Basal area (m^2/ha)	Height (m)	DBH (cm)	Basal area (m^2/ha)	Height (m/yr)	DBH (cm/yr)	Basal area (m^2/ha/yr)
Clongawney	2.22 (0.55)	2.76 (0.9)	1.26	3.71 (0.71)	5.16 (1.5)	4.39	0.50	0.80	1.05
Clonsast	3.15 (0.82)	4.22 (0.39)	2.73	4.07 (1.18)	4.71 (0.8)	3.40	0.31	0.16	0.22
Noggus	5.80 (1.2)	7.28 (2.3)	8.53	7.05 (1.8)	9.88 (3.1)	15.46	0.42	0.84	2.31
Percent [(b/a) .100]	141	153	217	110	91	77			
Percent [(c/b) .100]	184	173	312	173	208	455			
Percent [(c/a) .100]	261	264	679	190	190	352			

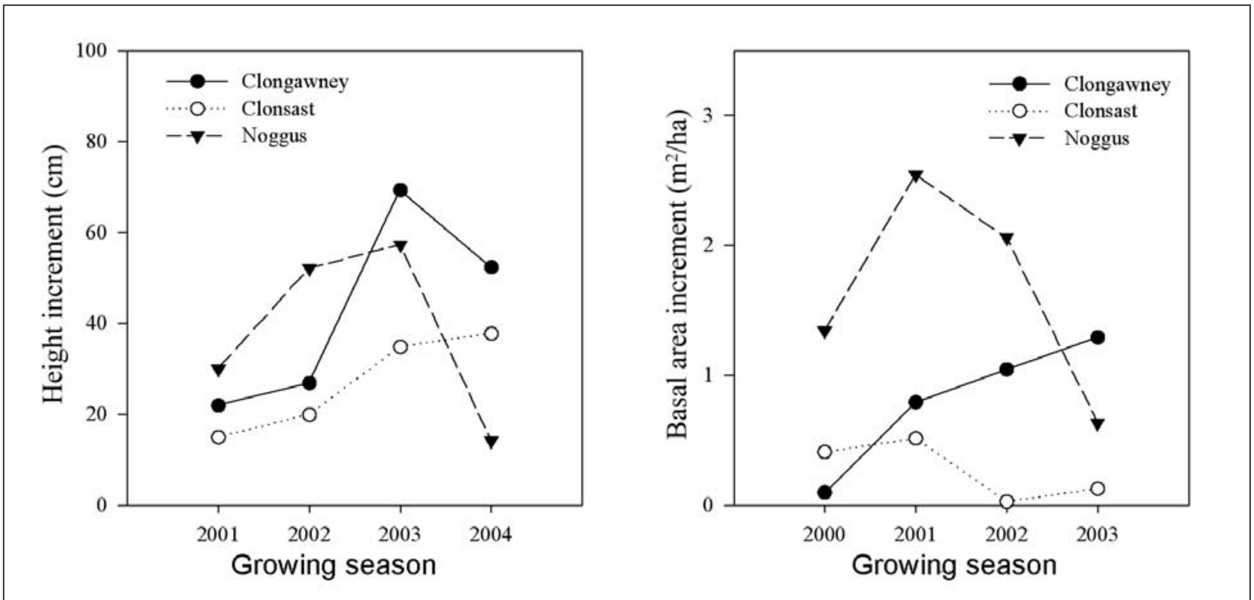


Figure 5.60: Mean height and basal area increment in three Sitka spruce stands re-fertilised in July 2001.

cm/yr for Clonsast (Table 5.34). Basal area increment was the greatest at the superior site in Noggus with 2.31 m^2/ha/yr, compared to 1.05 m^2/ha/yr at Clongawney and 2.31 m^2/ha/yr at Clonsast. However, Clongawney was the only site at which steadily increased basal area increment was shown for four years after second fertilisation (Figure 5.60). In effect, second fertilisation trebled the basal area increment at Clongawney, doubled at Noggus while increase was limited at Clonsast.

N, P, Ca and Fe concentrations measured in the peat at the three sites mirrored the growth gradient: in the increasing order Clongawney > Clonsast > Noggus (Table 5.35). With N concentrations of 6.4 g/kg and 10.7 g/kg respectively, Clongawney and Clonsast were very nitrogen-poor sites. On the other hand, Noggus, the superior site, had a concentration of 16.3 g/kg. P concentrations at Noggus were also double that found in Clongawney and Clonsast. Peat nutrient concentrations measured in 2004 where not significantly different to that of 2001.

Conclusions and management implications

Nutritional problems can usually be rectified by appropriate fertiliser application. The applications recommended by Coillte (Table 5.36) have produced good responses from deficient stands monitored in this study. Three years after second fertilisation, phosphorus was no longer a growth limiting factor at the studied sites. Application of P should be

Table 5.35: Site characteristics of the three re-fertilised Sitka spruce stands in 2001.

	Clongawney	Clonsast	Noggus
Growth characteristic:	Very poor	Mediocre	Superior
Peat characteristic:	*Phragmites*	*Phragmites*	*Phragmites*
Average depth (cm)	100	100	80
Aerated layer (%)	55	50	75
pH	4.9	3.6	5.8
OM (%)	98.0	97.6	92.3
Soil nutrients:			
N (g/kg)	6.40	10.70	16.30
P (g/kg)	0.16	0.19	0.41
K (g/kg)	0.10	0.09	0.10
Ca (g/kg)	2.15	5.70	16.10
Mg (g/kg)	2.06	0.95	0.56
S (g/kg)	2.5	2.2	3.8
Fe (mg/kg)	0.32	2.40	6.68

Table 5.36: Recommended (from Coillte) fertiliser application for re-fertilisation of plantations prior canopy closure.

N	150-400 kg urea/ha
P	350 kg GRP/ha
K	250 kg muriate/ha

carried out immediately following detection of deficiencies. This emphasises the need for monitoring of newly established plantations up to canopy closure. The growth response to N application seems to be more complex. N application is not recommended unless crops show severe deficiencies from foliar analysis, P application alone may suffice to bring the nutrient status of the stand to a satisfactory level.

Mycorrhizae and cutaway peatland plantations

What are mycorrhizae?

The word 'mycorrhizae' was coined from two classical Greek words meaning fungus and root. Hence the term is used for a root with which a fungus is associated (Trofymow and van den Driessche 1991), leading to a symbiotic relationship that exists between the plant and the fungus. The fungi transfer different nutrients (mainly nitrogen and phosphorus) from the soil to the plants and the plants in turn supply the fungi with carbon fixed via photosynthesis (Read and Perez-Moreno 2003).

Ectomycorrhizae, or sheathing mycorrhizae, form one of the most common forms of mycorrhizal association. Mycorrhizae have long been recognised as having important functions in tree nutrition (Harley and Smith 1983; Bowen 1984). In northern temperate countries, ectomycorrhizal associations occur in the majority of trees, e.g. pine, spruce, larch, fir, poplar, willow, lime, and oak (Dix and Webster 1995; Smith and Read 1997). Many sheathing mycorrhizae are formed by fungi with conspicuous fruiting bodies, e.g. toadstools and earthballs. These fruiting bodies make it easier to confirm the presence of the associations below ground.

Ectomycorrhizae facilitate growth, nutrient uptake and survival of young seedlings, mainly through the enhanced uptake of nitrogen and phosphorus (Melin and Nilsson 1953). Mycorrhizae have been known to affect the P nutrition of host plants by accessing soil P beyond the zones created by the plant roots, as well as by increasing the uptake of mineralised P (Harvey and Smith 1983; Safir 1987). In addition to N and P, mycorrhizal fungi take up and translocate almost all elements required for plant growth, while also enhancing the transport of water from soil to plant (Allen 1991). It has been shown that mycorrhizal development is most vigorous on soils where there is a deficiency of available minerals such as nitrogen and phosphorus, and where there is an accumulation of raw humus. High levels of phosphorus and nitrogen suppress mycorrhizal infection (Dix and Webster 1995).

Mycorrhizal associations in terms of forestry practice

Fungi that establish themselves on seedling roots usually do not persist as the tree ages, but are displaced by a succession of mycorrhizal partners. Some mycorrhizal species colonise only the roots of young seedlings, while others colonise later stages of tree growth. Early and late stage mycorrhizae-formers on tree roots have been distinguished (Deacon and Donaldson 1983). Common early stage species include *Hebeloma* spp., *Laccaria* spp., and *Thelephora terrestris*. Late stage species include *Cortinarius* spp., and *Russula* spp.

Changing the site characteristics will cause a change in the succession and development of the mycorrhizal community. For example, draining a peat bog will induce changes in the structure and distribution of mycorrhizae (Paavilainen 1966). Mikola (1973) points out that prolonged agricultural use or absence of trees does not exterminate all ectomycorrhizal fungi. Controlled burning of slash will kill those fungi in the top few centimetres of the soil but fungi below these depths are left unharmed. Herbicides or other pesticides have been found not to exert a harmful influence on mycorrhizal fungi (Allen 1991).

Ectomycorrhizal infection has been shown to be necessary for the successful establishment of genera such as *Pinus* (Carlile and Watkinson 1994; Baar and Elferink 1996). Melin (cited in Marks and Kozlowski 1973) indicated as early as 1917, the importance of ectomycorrhizae to the afforestation of drained peat bogs. He found that as long as the fungal partner was absent, *Pinus sylvestris* and *Picea abies* remained stunted. As the fungi spread into the drained habitat, the trees resumed growth. Bjorkman (1941) stated that on the same bog substrate, moderate fertilisation with wood ash stimulated tree growth and mycorrhizal formation.

BOGFOR mycorrhizal study and results

A study of mycorrhizal fungus occurrence was carried out in October 1998 and October 1999 on thirty plots taken from a number of cutaway peatland plantations established across the Irish Midlands in the late 1980s and early 1990s. Fungal specimens were identified using keys developed by Courtecuisse and Duhem (1995) and Phillips (1985). The site description together with the mycorrhizal species observed in each plot are presented in Cassidy (2000).

Results from the 1998 and 1999 surveys show a significant presence of fruiting ectomycorrhizal species at all sites visited, with only one site (Mongagh) where only two species were found. Ectomycorrhizal species of *Laccaria, Lactarius, Thelephora, Hebeloma, Inocybe, Hygrocybe* and *Cortinarius* were found in abundance. Less frequently observed species included *Collybia, Leccinum, Lycoperdon, Russula, Boletus* and *Suillus*. Overall, out of twenty-six observed genera, fifteen were mycorrhizal. It is worth noting that mycorrhizae were observed with conifers exhibiting particularly poor growth characteristics.

Fewer species were observed in the 1999 survey and this may be attributable to the slightly later sampling period, together with the presence of increased ground vegetation at several sites. Sites with extensive vegetation growth also showed the lowest mycorrhizal species diversity. This may be due to the fact that (a) it was difficult to see fruiting bodies, or (b) conditions such as these were unfavourable for certain species.

Having observed thirty-five different species of ectomycorrhizal fungi at the sites visited, it can be concluded that mycorrhizal associations are present in plantations on industrial cutaway peatlands in the Irish Midlands.

Conclusions

Mycorrhizae infection seems to have occurred naturally on most cutaway peatland plantations. However, it is not known whether the quantity and type of mycorrhizae recorded are sufficient for optimum tree growth. More research remains to be done to identify the potential to manage mycorrhizae at plantation level.

Environmental implications of initial fertilisation

Background

The capacity of peat soils to sorb phosphorus (P) is low as they contain very small concentrations of clay and iron and aluminium oxides, all of which reduce the solubility of phosphates (Nieminen and Jarva 1996). Once phosphorus is applied as fertiliser, it can be taken up by trees and vegetation or leached out of the soil. The possibility of loss of applied phosphorus from peat soils to drainage water is an important factor in determining the efficient use of fertiliser, the overall economics of afforestation and the potentially deleterious effect that the fertiliser may have on the ecology of downstream water bodies. Anthropogenically-induced eutrophication has been identified as the greatest threat to the quality of rivers and lakes in Ireland and elsewhere (Lucey et al. 1999; Mainstone and Parr 2002). The negative impact of P entering aquatic ecosystems has been demonstrated through its contribution to eutrophication of surface waters and the subsequent degradation of water quality. P transfers from forest systems are usually considerably lower than those from the managed agricultural landscape (Heathwaite et al. 1996). The leaching of P to water bodies from peatlands has been investigated widely in relation to forestry operations such as cultivation and fertilisation (Gibson 1976; Kenttamies 1981; Ahti 1983; Malcolm and Cuttle 1983; Nieminen and Ahti 1993; Joensuu et al. 1998; Nieminen 1999; Renou and Cummins 2002; Cummins and Farrell 2003).

P loss from drained and mined peatlands has also received attention (Sallantaus 1992; Kløve and Bengtsson 1999; Kløve 2000, 2001). These studies have shown that fertilisation carries a risk of the P leaching with a duration that may exceed 10 years. The low Fe and Al content of peat is a critical factor in P leaching (Nieminen and Jarva 1996; Nieminen 2003). In addition to their low capacity to sorb phosphorus, cutaway peatlands present a high risk of nutrient leaching due to their physiography. The intensity of the drainage system, together with the fact that cutaway peatlands are often devoid of vegetation at cessation of peat harvesting, makes surface runoff an important pathway for applied P loss. The risk of runoff and erosion is also accentuated by the fact that the remaining peat is often dense, with a very low hydraulic conductivity; the water table fluctuates readily, remaining close to the surface for long periods; and finally the cutaway peat fields are often cambered, sloping towards the drains as a result of the milled-peat harvesting process.

Within the BOGFOR programme, a large-scale environmental monitoring study was set up to estimate the nature and magnitude of the leaching of fertiliser phosphorus on afforested cutaway peatlands. The study aimed to assess the fate of phosphorus applied to different cutaways, and examines spatial and temporal trends in the concentration of phosphorus in surface runoff water and soil water by means of regular monitoring over a number of years and under different management practices. The experiments are summarized here and general results presented below. Results from the entire study can be found in Renou-Wilson et al. (2007a).

Material and methods

In experiment 1, surface runoff samples were analyzed to test the effect of splitting the recommended rate of phosphatic fertiliser into two applications (at planting and three years later). The division of the site into two comparable plots (A and B) also permitted the investigation of the potential impact of cultivation on phosphorus movement (Figure 5.61). Area A was left intact while area B was cultivated (ripped and disced up to 40 cm deep followed by levelling). Both areas were planted on the flat with Norway spruce in May 1999. Initial fertilisation took place in July 1999 with 25 kg P/ha of unground rock phosphate applied manually in strips along the rows of trees. This is half of the current recommended rate of application for afforestation of cutaway peatland. In July 2002 a further 25 kg P/ha of granulated rock phosphate was applied, together with 250 kg K/ha. A total of fourteen surface runoff water collectors had been positioned randomly across the site (Figure 5.62) and measurements started immediately after planting (May 1999). This was ten weeks before fertiliser was applied, thus creating a baseline dataset of water quality for the site. Phosphorus concentration in each sample was measured as Molybdate Reactive Phosphate (MRP).

Experiment 2 consists of a 1 ha fertiliser trial adjacent to Experiment 1 and planted with Norway spruce in 2000. It consists of deep *Phragmites* peat. The site was cultivated (ripped and disced up to 40 cm deep followed by leveling) and was bare of vegetation when planted. Similar surface runoff collectors, as described for Experiment 1, were positioned in the drain at the side of each experimental plot. It was a fully randomized replicated experiment with unfertilised buffer zones (15 x 6 m) present between each 15 x 15 m fertilised plot. Initial fertilisation took place in mid-June 2000 with different rates of rock phosphate and methods of application (Table 5.37). A second fertilisation with 14 kg P/ha took place in June 2002 on plots B and C only in addition to all plots receiving K fertiliser (250 kg/ha of muriate of potash at that time.

Experiment 3 consists of a 1 ha fertiliser trial established in a woody-fen cutaway peatland that was deep ploughed and levelled and planted with pedunculate oak (*Quercus robur*)

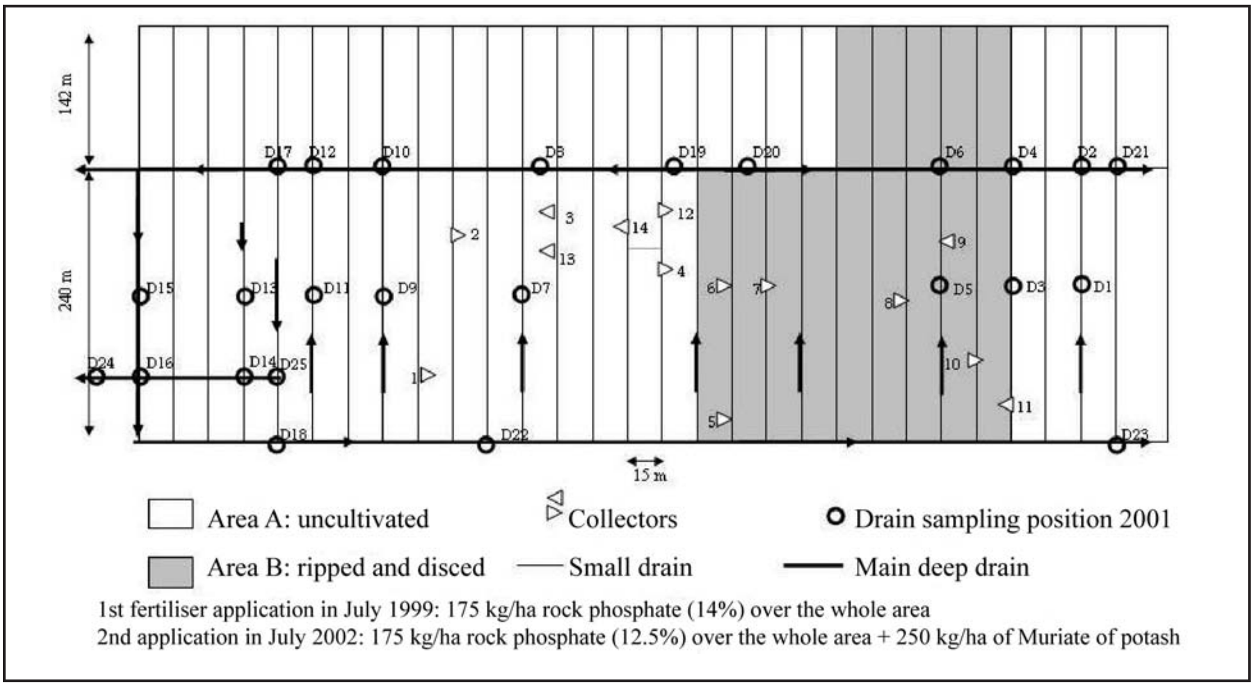


Figure 5.61: Map of Tumduff Norway spruce demonstration area showing treatments and sampling points.

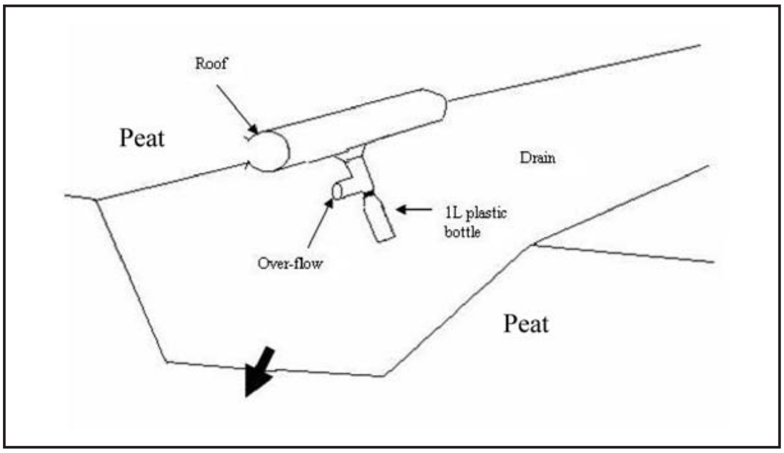


Figure 5.62: Surface runoff water collector.

in 2000. Due to the shallow residual peat layer, varying amounts of sub-peat mineral soil (alkaline silty clay and gravel) were brought to the surface and mixed with the peat. The levelling of the site removed all the drains. Therefore leaching of P through the soil profile was monitored by analyzing soil water below the root zone. After a period of calibration, phosphatic fertiliser (superphosphate containing 16% P) was applied using similar rates of phosphorus and methods of application as in Experiment 2 (Table 5.37).

Table 5.37: Rates and methods of fertiliser application for Experiments 2 and 3.

Treatments		First application June 2000	Second application June 2002
Rate of rock phosphate	A	42 kg P/ha	0 kg P/ha
	B	28 kg P/ha	14 kg P/ha
Methods of application	1	Broadcast	Broadcast only
	2	Band	

Effect of P application rate and method, and soil cultivation on P contentration in surface runoff

MRP concentrations measured in the filtered surface runoff water before fertiliser was applied averaged 0.014 mg/l in Experiment 1 and 0.036 mg/l in Experiment 2. The source is probably leaching of native soil phosphorus previously immobilised in partly decomposed plants (Laiho and Laine 1994). Concentrations measured were of the same order of magnitude as values reported from unfertilised old-drainage peatland water: about 0.020 mg/l (Kenttamies 1981; Paavilainen and Päivänen 1995). Higher values measured in Experiment 2 may be due to a better drainage system shown by the lower mean water table (40 cm) than in Experiment 1 (31 cm). The drainage of peatlands usually aerates large volumes of peat thereby increasing the potential for mineralization of organically-bound elements and leading to higher P concentrations compared to undrained bogs (e.g. Malcolm and Cuttle 1983; Wind-Mulder et al. 1996).

In Experiment 1, the first application of rock phosphate at the end of July 1999 led to increased MRP concentrations at all sampling points. During the first four months (autumn) following fertilisation, the average MRP concentration across all 14 sampling points increased from 0.014 mg/l to 0.332 mg/l (maximum recorded at a sampling point was 1.46 mg/l) (Figure 5.63). Similar values occurred during the winter period (mean = 0.347 mg/l). However, MRP concentrations increased again during events recorded in spring and summer 2000. The highest concentration recorded during the whole monitoring period (5 years) was observed in May 2000 (maximum of 3.01 mg/l).

In Experiment 2, the application of rock phosphate also led to an immediate increase at all sampling points (Figure 5.64). Regardless of treatments, the maxima recorded over the whole sampling period (4 years) occurred during the three months following fertilisation (autumn 2000). After this period, there was a clear decrease in concentrations for all treatments.

In Experiments 1 and 2, initial peaks in P concentration occurred within one to two weeks of fertiliser application. This immediate leaching corresponds to easily-dissolved water-soluble P, the amount of which should be limited in a slow-release fertiliser such as rock phosphate. However, Nieminen (1997) argued that materials with citric acid-soluble P content over 30% are usually regarded as possible alternatives to water-soluble phosphatic fertilisers for direct application.

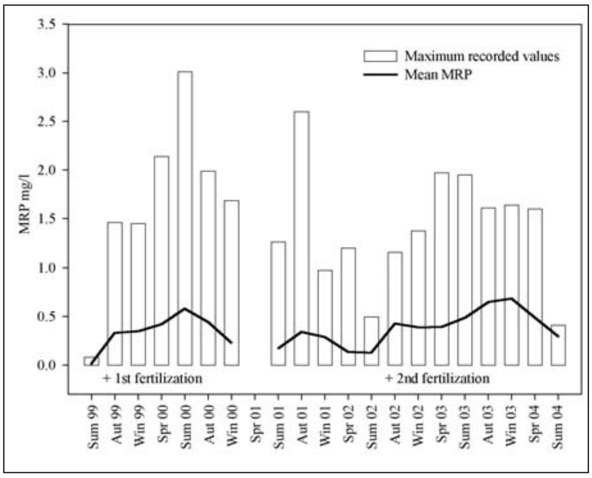
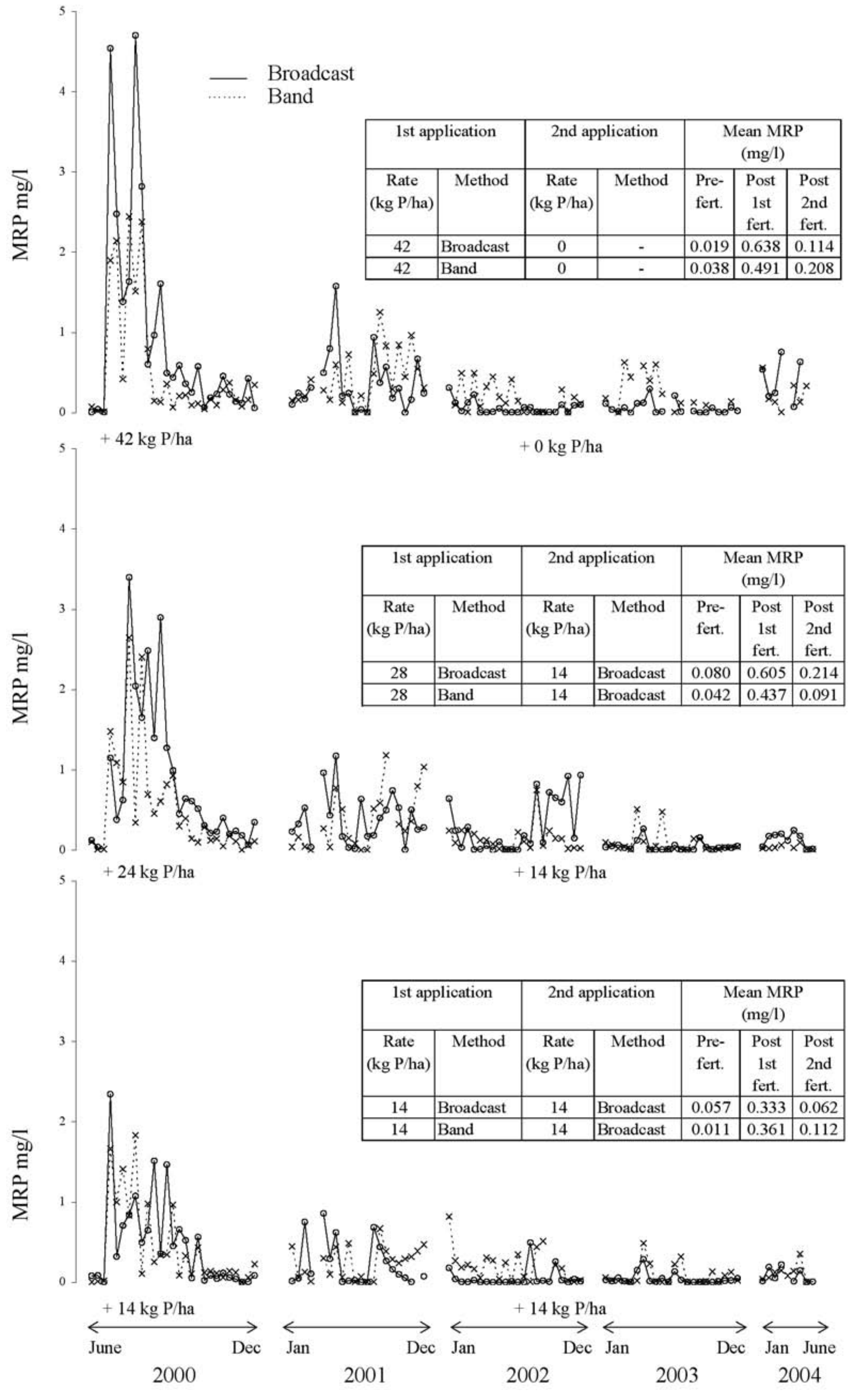


Figure 5.63: Seasonal means and maximum values of MRP concentrations measured in the surface runoff in Experiment 1.



1st application		2nd application		Mean MRP (mg/l)		
Rate (kg P/ha)	Method	Rate (kg P/ha)	Method	Pre-fert.	Post 1st fert.	Post 2nd fert.
42	Broadcast	0	-	0.019	0.638	0.114
42	Band	0	-	0.038	0.491	0.208

1st application		2nd application		Mean MRP (mg/l)		
Rate (kg P/ha)	Method	Rate (kg P/ha)	Method	Pre-fert.	Post 1st fert.	Post 2nd fert.
28	Broadcast	14	Broadcast	0.080	0.605	0.214
28	Band	14	Broadcast	0.042	0.437	0.091

1st application		2nd application		Mean MRP (mg/l)		
Rate (kg P/ha)	Method	Rate (kg P/ha)	Method	Pre-fert.	Post 1st fert.	Post 2nd fert.
14	Broadcast	14	Broadcast	0.057	0.333	0.062
14	Band	14	Broadcast	0.011	0.361	0.112

Figure 5.64: MRP concentrations in surface runoff sampled in Experiment 2 during the 5-year monitoring study for each fertilisation treatment combination.

Based on Boland et al. (1993), the rock phosphate used in Experiments 1 and 2 can be classified in the 'most reactive' group (Table 5.38).

Climatic and surface conditions may also have contributed to the immediate leaching of P via increased surface runoff. This process is spatially limited and temporarily confined to high magnitude, high intensity rainfall events (Heathwaite and Dils 2000). High precipitation following fertiliser application on bare peat can enhance both the movement of phosphatic fertiliser and its dissolution. While it was found that dissolution can be hampered by limited moisture supply, as seen in studies in Australia (Boland and Gilkes 1995), or sub-zero temperatures as in Finland (Nieminen 1997), high precipitation following fertilisation will promote the rapid removal of the released phosphate ions away from the surfaces of fertiliser particles. As the concentrations of $H_2PO_4^-$ remains low, more fertiliser is being dissolved.

The absence of vegetation was probably a critical factor explaining the magnitude of the leaching events observed. Following on this hypothesis, lower magnitude leaching events should be recorded following the second application of fertiliser a couple of years after planting, assuming development of vegetation and tree cover. In Experiment 2, peaks following the second application were much lower than after applying the same amount at planting (Figure 5.64). However, in Experiment 1, MRP concentrations increased in a similar fashion (max 1.16 mg/l) after second fertilisation as after the first (Figure 5.63). In contrast to Experiment 1 (which was slowly recolonised by vegetation and suffered high tree mortality) Experiment 2 was colonized rapidly by willow, birch and sedge, which together with good tree survival and growth, may have prevented some erosion and surface runoff, while at the same time increasing P uptake.

In both Experiments 1 and 2, initial peaks were followed by a general decrease in P concentration while displaying temporal variation. When examining monthly MRP concentrations in Experiment 1 against monthly precipitation at the area (Boora meteorological station, Bord na Móna), there is a general trend showing peaks (i.e. high P concentrations in the surface runoff) when precipitation was low (Figure 5.65). This is in agreement with observations by Sallantaus (1983) and Kløve (2001) who reported a negative correlation between phosphorus concentrations and runoff in mined peatlands. P concentrations in leachates from a drained and fertilised raised bog were also higher during summer (Malcolm and Cuttle 1983).

Table 5.38: Some chemical properties of the fertilisers used in the experiments.

	Total P	P soluble in: Water	2% citric acid	2% formic acid
Type of fertiliser	%	(% of total P)		
Unground rock phosphate*	14.5	<0.1	40	70
Granulated rock phosphate*	12	0.53	33	8
Superphosphate	16	14.74	na	na

*Moroccan origin; na = not analysed

Effects of cultivation (Experiment 1)

In Experiment 1, MRP concentrations during the pre-fertilisation period were similar for both the cultivated and non-cultivated areas (0.014 mg/l). High MRP concentrations (max 0.740 mg/l) were recorded immediately after fertiliser application in all uncultivated sampling points while MRP concentrations of similar magnitude (max 0.791 mg/l) occurred in the cultivated area a week later. Overall, while higher MRP concentration peaks were recorded in the uncultivated area (Figure 5.65), there was no significant difference between the two areas when the weekly means were analysed with repeated measures over time or as period-averaged means (Figure 5.66).

Effects of fertiliser rates and methods of application (Experiment 2)

Examination of the peaks during the eighteen months following initial fertilisation (Figure 5.63) and the means over the same period (Figure 5.67) indicates that MRP concentrations were related to the rate of fertiliser applied and the method of

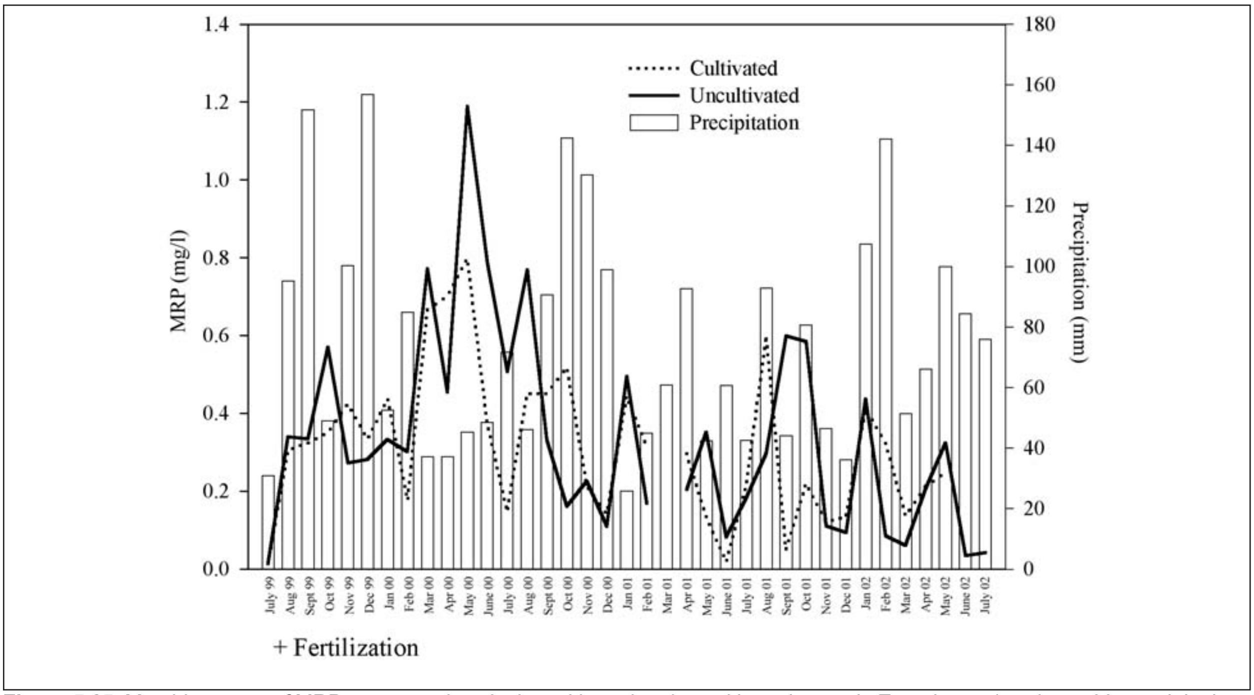


Figure 5.65: Monthly means of MRP concentrations in the cultivated and uncultivated areas in Experiment 1 and monthly precipitations during the same period.

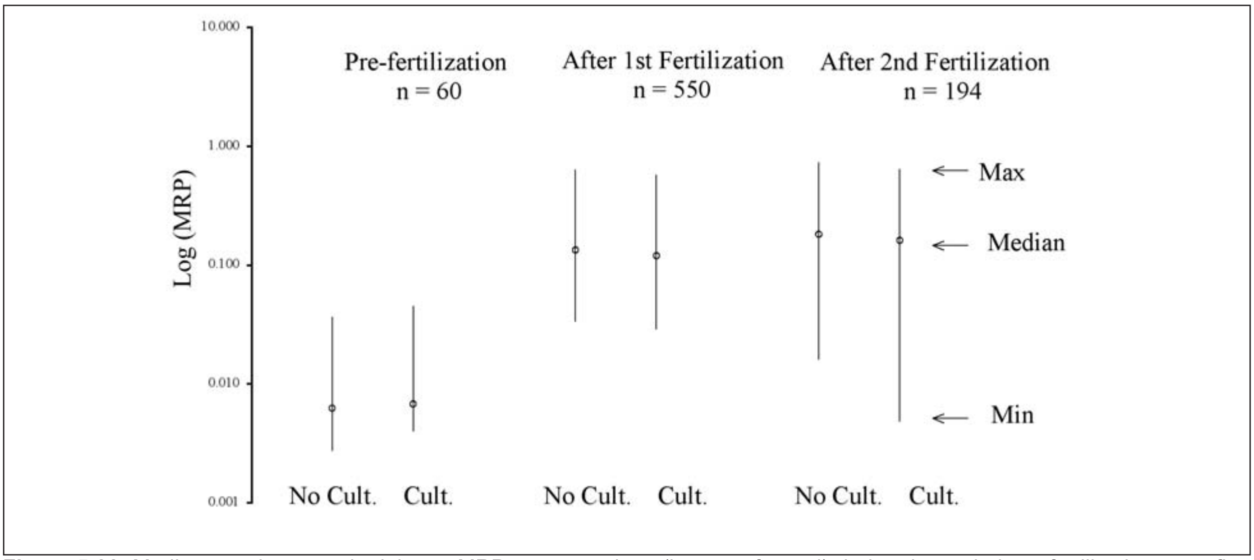


Figure 5.66: Median, maximum and minimum MRP concentrations (log transformed) during the period pre-fertilisation, post first fertilisation and post second fertilisation for both cultivated and non-cultivated areas in Experiment 1.

application. Repeated measures analysis confirmed that P concentrations were significantly affected by the rate of application ($p = 0.0233$) and the method of application ($p = 0.0051$); the interaction between the two factors was not significant. Both maxima and period means recorded after initial fertilisation were higher for broadcast application than for band application, regardless of the rate applied (Figure 5.63). The fact that band application may reduce the occurrence of very high MRP leaching events in surface runoff may be simply explained by

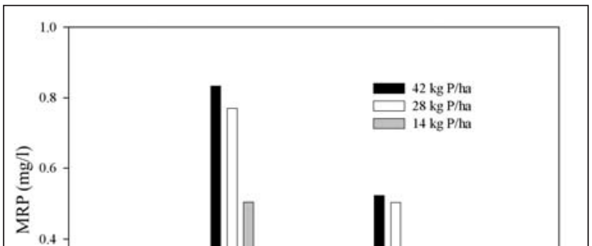


Figure 5.67: Period-averaged MRP concentrations for each fertiliser rate treatment in Experiment 2.

a reduced risk of transport into the adjacent ditches. Since peat soils have low sorption capacity there is no advantage in broadcasting fertiliser for the purpose of increasing the bulk soil P to adequate levels. On the other hand, band application will increase P in specific zones around the trees thus maximizing short-term P efficiency.

As expected, the rate of fertiliser also affected MRP concentrations in the surface runoff water. The highest P concentration (4.7 mg/l) was recorded with the highest rate of fertiliser and was twice as great as with the lowest rate (Figure 5.64). Concentrations of this magnitude did not, however, recur during the four-year monitoring period. Cummins and Farrell (2003) reported a maximum P concentration of 2.3 mg/l in water collected from a drain in a replanted blanket peatland fertilised with 70 kg P/ha. An exceptional concentration of 4.9 mg/l was also found in the leachates four months after application of 50 kg P/ha of rock phosphate on a drained raised bog (Malcolm and Cuttle 1983). Despite producing higher leaching maxima, the higher rate application had a mean P concentrations similar to that of the medium rate application while average MRP concentration were reduced by almost 50% for the lower rate (Figure 5.64 inset and Figure 5.67).

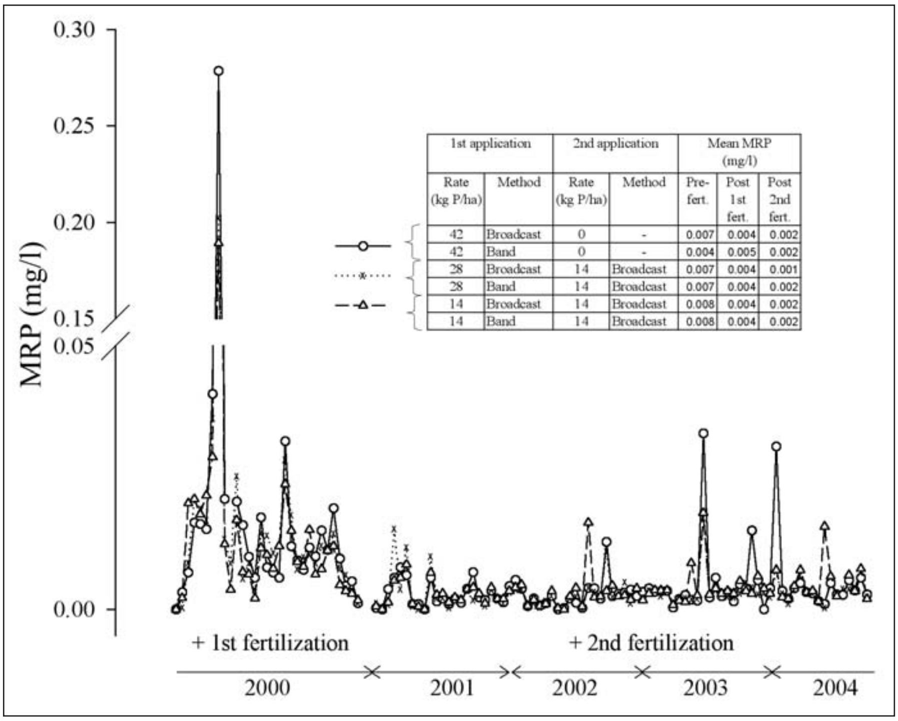
In summary, several factors can contribute to the immediate high leaching events recorded following fertilisation on newly afforested deep cutaway peatlands. Best practice to avoid high P concentrations events should include band application of the lowest possible rate of fertiliser at planting, followed by broadcast application of higher rates a couple of years later, this second application should not be made until there is good vegetation growth and the trees are growing satisfactorily.

Magnitude of P concentrations increase in soil water following fertilisation on a mixed peat and sub-peat mineral soil matrix and the impact of rate of fertiliser and method of application

Surface runoff is one pathway of P leaching that can be considered at a 'site' or 'slope' scale. This lateral surface movement of water is significant in a cambered peat field with regular ditches. Another hydrological pathway associated with P leaching can occur at the 'soil' scale via percolation of water through the soil. Soil water is the first stage in the hydrochemical transfer process and is perhaps more significant than surface runoff in sites that have been ploughed, ditches filled in and surface levelled. In Experiment 3, MRP concentrations measured in the soil water during the pre-fertilisation period averaged 0.012 mg/l ranging from 'not-detectable' to 0.049 mg/l. Mean MRP concentrations did not increase following the first or second fertiliser application (Figure 5.68, inset). There was no significant difference between the treatments when MRP concentrations were analysed with repeated measures over time or as period-averaged means.

The retention of P in any soil matrix is closely connected with levels of Fe and Al oxides as well as calcium carbonate. In peat soils, any Al and Fe is tightly bound with the organic matter and reaction with P fertiliser is thus quite limited, leading to any added soluble P remaining mobile in the peat matrix. In Experiment 3, the presence of sub-peat calcareous soil within the soil matrix permitted the excess soluble P applied as superphosphate to be retained. Where the remaining peat depth does not exceed 50 cm, ploughing the sub-peat mineral soil into the peat layer can have a liming effect, thus creating a P-retentive soil matrix. Rannikko and Hartikainen (1980) found that liming *Sphagnum* peat significantly decreased the amount of fertiliser-P in the water fraction. It is also likely that the increase of pH improved microbiological fixation, thus decreasing the amount of soluble P (Ghoshal and Jansson 1975). In Experiment 3, pH of the soil water averaged 7.3 before fertilisation and increased to 7.7 at the end of the monitoring period. This is in contrast with values recorded in the soil water from the peat-only sites that ranged from 4.1 to 5.6 (data not shown).

The retentive capacity of a peat/mineral soil matrix is limited, however, when water-soil interaction is minimized such as during high intensity rainfall events as observed during



1st application		2nd application		Mean MRP (mg/l)		
Rate (kg P/ha)	Method	Rate (kg P/ha)	Method	Pre-fert.	Post 1st fert.	Post 2nd fert.
42	Broadcast	0	-	0.007	0.004	0.002
42	Band	0	-	0.004	0.005	0.002
28	Broadcast	14	Broadcast	0.007	0.004	0.001
28	Band	14	Broadcast	0.007	0.004	0.002
14	Broadcast	14	Broadcast	0.008	0.004	0.002
14	Band	14	Broadcast	0.008	0.004	0.002

Figure 5.68: Soil water MRP concentrations during the 5-year study in Experiment 3. Inset: period-averaged concentrations for each treatment.

the week following initial application (Figure 5.68). This phenomenon was captured because water moving through the soil at a rapid rate may not allow nutrient concentrations in the soil solution to reach their equilibrium level (Wolt 1994). Peaks were recorded only once, MRP concentrations returned to pre-fertilisation levels the following week and remained below 0.050 mg/l for the remaining monitoring period regardless of the fertiliser rate and method of application.

In conclusion, application of superphosphate using current recommended practice (42 kg P/ha) does not affect the quality of the soil water when the peat is mixed with sub-peat calcareous mineral soil.

Environmental implications of aerial second fertilisation

Background

Studies reported here have demonstrated that second fertilisation of cutaway peatland plantations with N, P and sometimes K may be required before canopy closure, if a satisfactory rate of growth is to be maintained. Access disfavours manual application and thus fertiliser is applied by helicopter.

A limited amount of research has been carried out to monitor the fate of fertiliser following aerial application. The main concern is to minimize the loss of fertiliser to water bodies. This is a key environmental issue since enhanced levels of nutrients, particularly phosphorus, could render water bodies unsuitable for drinking-water or could lead to eutrophication.

The impact of Coillte's fertilisation regimes have been studied at twenty-two forest properties across Ireland (Coillte 1999). Results indicate that the impact of aerial fertilisation on water quality was minimal where the Forestry and Aerial Fertilisation Guidelines were followed. Overall, the risk of eutrophication from aerial P fertilisation is likely to be minimal due to:

(1) the infrequent nature of the operation, with at most two treatments per forest rotation;

(2) the small proportion of a catchment that is usually treated in any one year;

(3) the dilution occurring between the fertilised area and any sensitive water bodies;

(4) other limiting factors on algal growth (light, nitrogen and silica levels).

The aerial application of fertiliser to forest plantations can be an integral part of Sustainable Forest Management ensuring that optimum yield is achieved and where terrestrial and aquatic surrounding ecosystems are protected. All fertilisation operations in Ireland should be carried out in accordance with the Forest Service guidelines. The Forest Service published the 'Forestry and Aerial Fertilisation Guidelines' (Forest Service 2001) which contain detailed methods and procedures. These complement the 'Forestry and Water Quality Guidelines' (Forest Service 2000a) which address the main water quality and quantity issues. They provide advice to forest managers on working methods, and those measures that should be taken to ensure that water draining from forests and surrounding areas reaches a satisfactory standard. Compliance with the guidelines is a condition of Forest Service approval of forestry operations on all lands and for grant approval.

A BOGFOR monitoring study was set up to measure the risk of negative impact by assessing different operations involved in the aerial fertilisation process and their role in controlling the risk of pollution. These operations fell under three main headings:

- Assessment of the forest site (prior to fertilisation)
- Monitoring of the distribution of fertiliser (during fertilisation)
- Assessment of water quality (both before and after fertilisation)

Three cutaway peatland forests were identified as nutrient deficient and requiring aerial second fertilisation and were closely monitored before, during and after the operation. The three sites were described previously in this report.

Site assessment

Nutritional diagnosis

A site assessment was carried out as part of the second fertilisation study. The symptoms of nutrient deficiency (short needles, chlorosis etc.) were easily recognisable. These visual symptoms are, however, not always specific. Foliar nutrient analyses confirmed that the nutrient status of the three sites was deteriorating, requiring P and N fertiliser application. Soil analyses confirmed the poor nutrient status of the sites, especially in relation to P concentrations.

Site condition diagnosis

A site assessment was carried out to verify that the site warranted aerial fertilisation and that the trees were likely to respond to the addition of nutrients. At this stage, all sites were deemed to require aerial fertilisation as they displayed adequate drainage, adequate weed control, absence of any growth inhibitor (e.g. marl or very low pH) and sufficient stocking. Finally, before fertilisation could be carried out, there were a number of operational measures to take into account such as weather, fertiliser storage, handling, security, aircraft equipment, supervision etc. All are important factors to consider in preventing fertiliser loss.

Monitoring of fertiliser distribution

Two of the three sites (Clonsast and Clongawney) were monitored during the fertiliser application. The accuracy of distribution was measured by checking the presence/absence of fertiliser in the exclusion zones or buffer strips and by measuring the amount of fertiliser, following a transect, in the targeted area. The protocol was adapted from a procedure previously used in Ireland (O'Dea and McCarthy, 1999, unpubl.).

The variables used to assess the fertiliser distribution are defined below:

- Uniformity quotient: the data from collection buckets were ranked in ascending order according to the weight collected in each bucket; the uniformity quotient is the sum of the weights of the highest 50% divided by the sum of the weights of the lowest 50%. Values below 3 are regarded as acceptable.
- Mean: average rate of applied fertiliser (kg/ha) as determined from the weight of fertiliser collected in the buckets left in a transect during the application.
- Coefficient of variation: the standard deviation divided by the sample mean.

- Half value: percentage of points which received less than half the designated rate of application. Values of 10% or below are taken to be acceptable.
- Variation of target rate:
  <u>(Target application rate (kg/ha) –</u>
  <u>Mean rate measured (kg/ha)</u>/ *100
  Target application rate (kg/ha)

At Clonsast, the notable feature (Table 5.39) was over-fertilisation by 38%. However, both the uniformity quotient and half value were acceptable. In total, seven buckets were place in the exclusion zone around the plantation and two buckets contained some fertiliser granules, but at a very low rate (11 kg/ha).

At Clongawney, the notable feature of the assessment was under-fertilisation by 22% (Table 5.40). This is also illustrated by a half value greater than 10%. The uniformity quotient was acceptable. While the wind speed was very low (6.3 knots), difficulty arose with the small size of the plantation (~ 25 ha). The pilot had difficulties attaining the correct ground speed when reaching the boundary of the property. Since not all the fertiliser had been applied in the first pass, the pilot applied the remaining fertiliser in a subsequent pass at a much lower rate. No fertiliser was found in any of the buckets placed in the exclusion zone. The distribution of the granulated rock phosphate was considered to be uniform.

Table 5.39: Fertiliser distribution assessment at Clonsast.

Forest:	Emo		
Property:	BNM Clonsast		
Compartment no:	77568W - 77576D		
Crop:	Sitka spruce planted in 1999		
Weather conditions during application:	Showery and windy		
Fertiliser type:	Granulated rock phosphate: 300 kg/ha		
Date of application:	11 July 2001		
Type of collector:	Bucket (diameter: 31cm, depth: 35 cm)		
Number of collectors:	30		
Distance between collectors:	25 m		
Location of first collector on transect:	25 m		
Angle to flight path:	10 degrees		
Targeted area results		**Exclusion zone results:**	
Target (kg/ha)	300	Total collectors	7
Mean (kg/ha)	416	Collector with fertiliser	2
Variation from target rate (%)	38	Mean (kg/ha)	11 kg/ha K
Uniformity quotient:	2.06		
Half value:	5		
Coefficient of variation (%)	43		

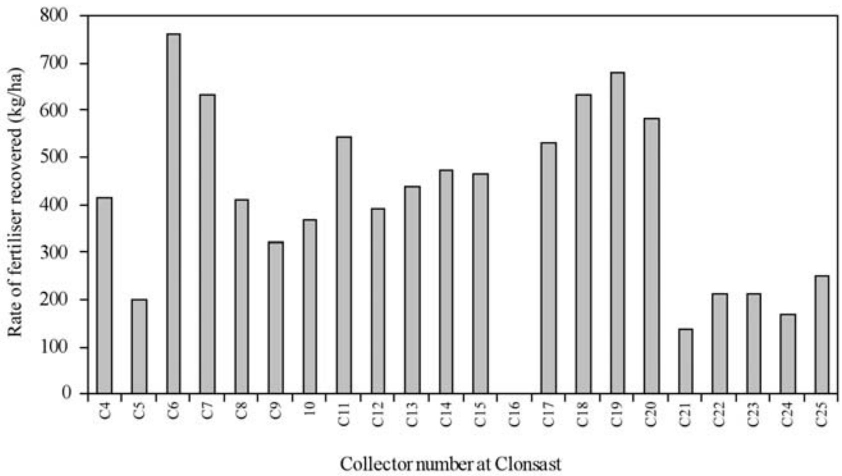
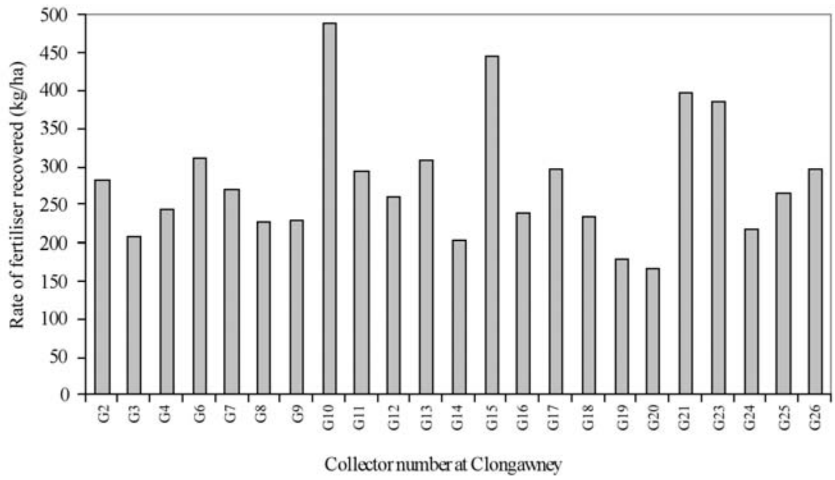


Table 5.40: Fertiliser distribution at Clongawney.

Forest:	Kinnity		
Property:	BNM Clongawney		
Compartment no:	74107A-75156N		
Crop:	Sitka spruce planted in 1999		
Weather conditions:	Dry and calm		
Fertiliser type:	Granulated rock phosphate: 350kg/ha		
Date of application:	19-Jul-01		
Type of collector:	Bucket (diameter: 31cm, depth: 35 cm)		
Number of collectors:	30		
Distance between collectors:	25 m		
Location of first collector:	25 m		
Angle to flight path:	45 degrees		
		Exclusion zone results:	
Target (kg/ha)	350	Total collectors	7
Mean (kg/ha)	272	Collector with fertiliser	0
Variation from target rate (%)	22	Mean (kg/ha)	0
Uniformity quotient:	1.9		
Half value:	12		
Coefficient of variation (%)	36		



Inadvertent fertiliser application to adjacent water bodies presents a potential problem in aerial fertilisation. Results from both areas show that this risk was limited due to the accuracy of the placement of the fertiliser. Recent technical developments include the use of on-board GPS together with a 'Light Bar', the latter enables the pilot to provide an accurate coverage of the area by maintaining a line of flight that is determined by the desired swath width and boundary line entered into the guidance system. The pilot can then produce a map of the flight line which can be used to check the accuracy of the flight path taken.

The results confirm the difficulty of this operation when weather conditions are not optimum. Uniformity of the application depends on a uniform speed of travel. This is difficult to achieve in windy conditions and where targeted areas are small (where the helicopter has to make frequent turns). A system is being developed with which the pilot could adjust the hopper aperture according to ground speed.

Water quality control

In order to assess the potential negative effect of aerial fertiliser on cutaway peatlands, analyses of both surface and soil water were carried out at each site. Drains were sampled both above and below the plantations as well as before and after aerial fertilisation. In Clongawney, drains were dry before aerial application and could not be sampled. The results (Table 5.41) show that water quality was good at all sample point for the water flow conditions prevailing at the time of sampling. In particular, the results indicate that there was little or no evidence of increased ammonia or soluble molybate reactive phosphate (MRP) in the analysed samples. MRP concentrations remained below the critical threshold of 0.03 mg/l at all times. A relatively high concentration of ammonia was detected in the 'below' sample point at Noggus but there is no certainty that this result was related to the fertilisation, which had been carried out three months previously, because of the lack of water quality data before the operation.

Soil lysimeters were also installed prior to second fertilisation at each site (two replicates per site) and soil water was sampled on a regular basis. Soil water pathway was considered more significant than surface runoff given the presence of a thicket-stage tree crop and vegetation which would reduce direct fall of fertiliser into drains. The range of MRP concentrations measured in the soil water prior to second fertilisation was low at all sites (average 0.003 mg/l) (Figure 5.69). This demonstrated that phosphorus was not being leached via soil water percolating below the root zone ten years after the initial broadcast fertilisation with rock phosphate. An examination of different aged Sitka spruce needles at the three sites showed that the stands became P deficient between six and ten years after planting.

During the four months following aerial second fertilisation, MRP concentrations did not vary in the soil water (Figure 5.69). In two

Table 5.41: Water chemical analysis from surface bodies.

	Clonsast				Noggus		Clongawney
	Pre-fertilisation		Post-fertilisation		Post-fertilisation		Post-fertilisation
Parameters	Above	Below	Above	Below	Above	Below	Below
pH	8.08	8.08	7.98	7.5	8.04	7.9	4.47
MRP (µg/L P)	<10	<10	<10	<10	<10	<10	<10
Total phosphorus (µg/L P)	14	<10	10	26	32	<10	<10
Ammonia (mg/L N-NH_3)	<0.02	<0.02	0.03	0.06	<0.02	0.56	0.18
Nitrate (mg/L N-NO_3)	0.6	0.39	0.76	0.71	0.75	2.13	0.12
Potassium (mg/L K)	1.18	0.66	11.11	2.6	2.3	1.1	0.2

Data courtesy of Philip O'Dea and Richard McCarthy, Coillte.

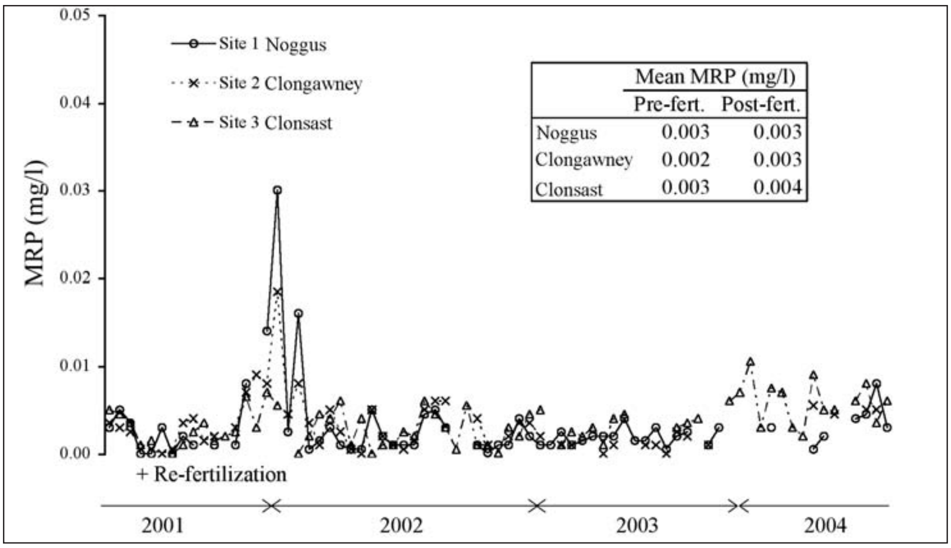


Figure 5.69: MRP concentrations measured in the soil water from three re-fertilised sites (Experiment 4). Inset: Averaged MRP concentrations at the three sites over the pre-fertilisation period and post-fertilisation period.

of the three monitored sites, small short peaks occurred in winter 2001, but remained below 0.030 mg/l. For the duration of the monitoring period, values remained comparable to psecond fertilisation levels (means = 0.003 ranging between 'non-detectable' to 0.020 mg/l). The highest concentrations were recorded during winter 2003 which coincided with the fragmentation of *Campylopus introflexus*, the main ground species. This phenomenon is known to occur when the moss carpet reaches a certain thickness and when fertiliser is applied (van der Meulen et al. 1987). The following spring, the moss gave way to *Calluna vulgaris, Betula pubescens* and *Salix* spp.

Overall, the quality (in terms of MRP concentrations) of the soil water leaving the root zone of a deep peat Sitka spruce plantation was good ten years after initial application and aerial second fertilisation did not lead to a significant increase of MRP concentrations in the soil water below the root zone. These results suggest that aerial fertilisation would have minimal deleterious impact on water chemistry within a cutaway peatland catchment, providing that the fertiliser is not applied directly to open water surfaces and that the operation is carried out following the Forest Service guidelines and procedures required. Risks can be greatly reduced by proper fertiliser storage, handling, aircraft GPS equipment, choosing suitable weather, and monitoring of distribution.

Scientists in the UK have recently completed an assessment of the efficacy of their 'Forest and Water Guidelines' in practice (Nisbet 2001). On the particular subject of aerial fertilisation, they found that technological improvements have allowed better targeting of aerial fertiliser application and when combined with protective measures such as riparian buffer strips, have helped to reduce the threat of nutrient enrichment. Finally, in areas where there is concern about phosphate levels in receiving water bodies, manual application or phasing aerial application over several years should be considered.

Conclusions on the environmental implications of fertilisation

The hydrochemistry of runoff from cutaway peatland forests is influenced by a variety of natural and anthropogenic factors and is therefore complex. Results from these studies showed that initial fertilisation on bare peat automatically led to an increase in P in surface runoff. The occurrence and magnitude of P loss events depends on a) transport factors, b) soil characteristics and c) fertilisation variables (rates and methods).

- risk of transport of P was high due to the cambered surface, the absence of vegetation cover and the presence of drains every 15 m. In addition, high precipitation following P fertilisation on cutaways increased the physical movement of particles of fertiliser.
- soil characteristics of cutaway peatlands play crucial role in the occurrence of P leaching. The P-retention capacity of one site was increased by mixing the peat with calcareous sub-soil thus increasing the P-binding ability of the medium.
- application of full recommended rate of fertiliser at planting led to the maximum P concentrations in surface runoff. Splitting the application (at planting and 2 years later) resulted in lower peaks in P concentration leaving the system and allowed increased uptake by trees and vegetation.

The management implications of these results are:

- Half of the recommended rate of rock phosphate should be applied at planting, the other half two years later.
- Fertiliser should not be applied during heavy rainfall or when it is forecast.
- Planting should take place early in the year so that fertiliser is not applied too late (shorter growing seasons and higher precipitation (August-September) lead to greater risks of P leaching). Ideally fertiliser should be applied between April and June.

- Vegetation cover is beneficial in advance of applying the fertiliser.
- Superphosphate and rock phosphate can be applied on peat mixed with calcareous sub-soil with minimal risk of P leaching.
- Fertiliser application should follow existing 'Forestry and Water Quality Guidelines' (Forest Service 2000a) and 'Forestry and Aerial Fertilisation Guidelines' (Forest Service 2001).

If loss of phosphorus to drainage water is accepted as a natural consequence of fertilisation, considerations must be given to its environmental implications. While concentrations recorded may look very high, the surface water drains where the runoff took place are not permanent water courses. Thus, phosphorus limits defined in Water Quality Standards for Phosphorus Regulations (Lucey et al. 1999) are not relevant to the results of this study. While P is leaving the root zone and entering drains, the ultimate fate of this element is not determined. Results from the snapshot study of drain water are encouraging, as MRP concentrations were very low and comparable to unfertilised cutaway peatlands. It can be speculated that some of the leached MRP is likely to be adsorbed as the water moves into ditches that contain a high cation concentration, especially calcium, due to the proximity of the calcareous sub-peat mineral soil. The presence of vegetation growing at the bottom of the drains (macrophytes and microphytes, including filamentous algae) is proof that phosphorus input has occurred but they too can play an important role in the sorption of the soluble leached phosphorus. Drain water from afforested cutaway peatland would also be expected to be diluted with water from unfertilised parts of a catchment before reaching a substantial water body. A study in Finnish cutaway peatlands showed that biological and physical processes occurring in the ditch network can considerably reduce the nutrient load to watercourses (Kløve 2000).

Future directions

Alternatives to fertiliser application on this kind of site type exist and may merit further investigation. Trials in Irish nurseries have shown that the use of biostimulants may improve growth while reducing fertiliser requirements (Thompson 2004). Spraying the seedlings prior to outplanting may reduce stressful conditions and allow the seedlings to establish successfully without fertilisation at planting but this has not been tested on sites such as cutaways. Using the approaches outlined would entail fertiliser being applied after two years, at which stage uptake should be maximised due to tree root development and vegetation cover.

Incorporation of slow-release fertiliser pellets (teabags) into the planting hole is used in afforestation of cutaway peatland in Canada to limit vegetation growth and contamination of nearby peat production fields. Technically, this method should allow minimum leaching via surface runoff and should be definitely tried on cutaways.

The use of specially formulated fertiliser containing Fe and Al has shown to effectively reduce leaching from peat soils by increasing the adsorption of soluble MRP (Larsen et al. 1959; Fox and Kamprath 1971; Scheffer and Kuntze 1989; Nieminen 2002).

Another solution is to restore part of the cutaway peatland or create a wetland and use it as a biofilter. The restoration of a drained peatland in Finland has been shown to be a successful 'buffer' where the vegetation was the main factor in nutrient retention (Laine et al. 2004; Silvan 2004; Silvan et al. 2004). A recent study showed that some restored Irish cutaway areas can have either strong or low nutrient barrier capacities depending on soil characteristics and the extent of re-vegetation (Higgins and Colleran 2004; Higgins 2005). Further research is required to develop appropriate protective measures to be adopted for local stream ecosystems and to determine the efficacy of these measures at both micro- and sub-catchment scales.

SUMMARY POINTS: NUTRITION AND FERTILISATION

- *A split application of fertiliser is recommended on cutaway peatlands, especially on bare peat fields: half of the recommended rate of rock phosphate should be applied at planting and the other half two years later.*
- *Superphosphate and rock phosphate can be applied on peat mixed with calcareous sub-soil with minimal risk of P leaching (if surface runoff is reduced and timing is considered).*
- *Fertiliser should be applied in bands at planting and broadcast for the second application, carefully avoiding drains and waterlogged areas.*
- *Fertiliser should not be applied during heavy rainfall or when it is forecast.*
- *Planting should be completed and fertiliser applied between April and June so as to minimise the risk of P leaching; a shorter growing season and higher precipitation (August-September) increases the risk.*
- *The establishment of a vegetation cover is beneficial in advance of applying fertiliser.*
- *The risk of occurrence of nutrient deficiency should not be ignored in pre-canopy cover stage on cutaway peatland plantations.*
- *Visual assessment, foliar analysis and identification of peat type are useful tools to enable early detection of nutrient deficiencies.*
- *Second fertilisation with rock phosphate should be carried out as soon as indicated by foliar analysis, so as not to delay the potential response.*
- *N should only be applied if foliar N concentrations indicate severe deficiency, as P application alone may improve the overall nutrient status of the stand.*

Late spring frost

Background

Up to the 1960s it was considered inadvisable to plant low-lying areas, particularly in the Irish Midlands, with Sitka spruce. As a result of low levels of frost damage between the early 1970s and the late 1980s, however, the use of Sitka spruce on such sites increased. When the afforestation of the cutaway peatlands began in the late 1980s, the risk of serious frost damage was perceived to be low. Several surveys (Jones and Farrell 1997b, c) subsequently revealed that late spring frost was recorded as a widespread contributing factor to crop failure within young Sitka spruce plantations in the Irish Midlands in the late 1980s and early 1990s.

Industrial cutaway peatlands in the Midlands are prone to late spring frosts due to the low-lying nature of the topography and the absence of coastal influence (Keane and Collins 2004). Under clear and calm weather conditions, frost tends to develop in areas where cold air stagnates, such as in depressions or on flat areas (Lindkvist and Lindqvist 1997). Late spring frosts, which can occur repeatedly in May and as late as the end of June, are radiative in nature. Sitka spruce is most susceptible to frost damage at the time of budburst and when temperatures fall below -3°C (Cannell and Smith 1983). Visible frost damage can be observed following nights of severe frost (Lundmark and Hallgren 1987) and may be indicated by the collapse of buds, discoloration of needles or failure of the next season's leader growth

(Malcom and Freezaillah 1975). Shoots from ground level up to about 2 m or more are likely to suffer damage, leading to retarded growth, forking and mortality if other factors such as vegetation growth are not under control.

Factors

An understanding of conditions that influence the occurrence of frost damage is essential in order to achieve the best fit of species to site in plantation establishment. The coincidence of budburst with late spring frost, the impact of site preparation techniques on minimum temperature development and the influence of particular site conditions, at both macro- and micro-scale, are all relevant to the successful development of plantation forestry on the post-cutaway peatlands of the Midlands.

Extrapolation from Murray et al. (1989) indicates that Sitka spruce budburst in the Irish Midlands could occur in early May, with leading lateral shoots flushing until late May. Sitka spruce provenance trials in the UK (Lines and Mitchell 1965) and Ireland (Thompson et al. 2005) indicate dates of budburst between 27 April and 5 May, and that newly flushed buds are susceptible to frost damage within ±7 days of budburst. Applying these ranges of dates to annual minimum temperatures in order to determine an annual recurrence interval (ARI) of damaging temperatures provides an indication of the risk of frost damage at a regional level.

Frost damage of newly flushed shoots can be caused by a combination of conditions other than minimum temperature, such as direct solar radiation on mornings following frost (Lundmark and Hallgren 1987; Strand and Lundmark 1987), the duration of freezing and thawing (Orlander 1993), wind exposure, and humidity and soil conditions (Day and Peace 1937). These factors can be influenced by various site preparation and silvicultural techniques such as vegetation control, soil cultivation and side shelter.

Newly established forest crops are particularly susceptible to heat loss on peat soils. This is due to the large diurnal temperature range associated with the peat surface (high temperature by day and cool by night), which results in increased risk of frost development (Connaughton 1969; Geiger 1971). Peat is a relatively poor conductor of heat, even when wet, due to the relatively low conductivity of organic matter compared to common soil minerals.

Newly established cutaway peatlands are often completely bare of vegetation for a year or two after planting. As vegetated surfaces tend to have higher maximum and lower minimum temperatures compared to bare soil (Geiger 1971), the lack of vegetation can be expected to confer an advantage on the young seedlings (Hendrick 1991).

Soil cultivation can have a negative effect on temperature development near the ground. Geiger (1971) reports that minimum night temperatures may be reduced by 2°C where the upper 2 cm of a wet soil is loosened. Oke (1992) found, however, that cultivation may be beneficial with respect to minimum temperature development where it serves to break up poorly conducting soil layers and causes mixing with underlying soil layers of higher conductivity.

Side shelter has been suggested as the most effective method of reducing the extent of frost damage during late spring and early summer (Ottosson-Lofvenius 1987; Groot and Carlson 1996). The shelter influences the irradiance and precipitation reaching the ground and also affects humidity, wind, and air and soil temperature (Ottosson-Lofvenius 1987) resulting in less diurnal variation (Geiger 1971) and higher minimum temperatures (Orlander and Langvall 1993). Topography is also an important site factor in the determination of frost risk to young seedlings (Lindkvist and Lindqvist 1997; Blennow 1998). Cold air tends to flow down slopes and even small topographical variations can have a significant influence on temperature development (Geiger 1971; Bjor and Sandvik 1984; Raitio 1987), with elevation impacting on minimum temperature development (Hocevar and Martsolf 1971; Laughlin and Kalma 1987).

Finally, nutritional status is believed to influence the susceptibility of trees to frost damage (Butin 1995). It is generally accepted that nutrition affects the level of frost hardiness (Jalkanen et al. 1998; Colombo et al. 2001) but it is more difficult to attribute nutritional causes to spring frost damage except that nutrition may play a secondary role in the ability of trees to recover from frost damage. Trees with optimal or balanced nutrition demonstrate the best ability to recover to normal rates of photosynthesis after freezing (Hawkins et al. 1995).

BOGFOR frost studies

A series of temperature assessments and field experiments was undertaken between 1998 and 2002 across seven cutaway peatlands located in the Irish Midlands. The objectives of this research were to:

- Examine the occurrence of late spring frost in the Midlands;
- Determine the annual risk of a frost below –3°C at a regional scale using frost frequency analysis;
- Investigate the effects of various establishment practices on the severity of late spring frost;
- Examine the influence of local site topography on minimum temperature development.

Details on the methodology used in this research can be found in Smith (2000), Green and Renou (2002) and Renou-Wilson et al. (in prep a).

The occurrence of late spring frosts in the Irish Midlands: frost frequency analysis

Air temperature records covering 34 years were obtained from Met Éireann from four national stations located within and bounding the Irish Midlands, namely Casement, Birr, Kilkenny and Mullingar. Research into vertical temperature gradients identified in field research (Cannell 1984) suggests that an air temperature (measured at 1.25 m above ground level) of -0.5ºC is likely to yield ground frost temperatures below -3°C .

The risk of frost was assessed for three potential periods of bud burst:

± 7 days from 27 April (20 April - 4 May)

± 7days from 5 May (28 April - 12 May)

± 7 days from 15 May (8 - 22 May)

The analysis of the annual recurrence interval (or the expected return time of frost events below -3ºC) at each Met station for each of the mean dates of budburst is listed in Table 5.42. The annual recurrence interval is based on the occurrence of at least one frost below the critical -3ºC at 0.5 m within seven days of the mean date listed in the table. For example, at the Mullingar station, there is a risk of a severe frost occurring seven days either side of 27 April in one out of four years.

Frequency analysis identified minimum temperatures recorded during the potential periods of budburst for Sitka spruce and the risk of damaging frost occurring at a regional scale during the period identified. Frequency analysis modelling of regional meteorological data is quite simplistic, ignoring the complex interactions between the tree and its immediate environment; it does not give an indication of the potential damage to individual trees. Due to the location of the regional meteorological recording stations and variable surrounding lan-use practises, frost recurrence values should be used as a guide only.

The frost frequency analysis, however, shows reasonably consistent results between the stations investigated. The first two budburst

Table 5.42: Recurrence interval of spring frost for three mean periods of budburst.

	Met Station				
	Casement	Mullingar	Birr	Kilkenny	Average
Mean period	Recurrence interval of spring frost				
20 April - 4 May	2.0	4.0	2.5	3.0	2.9
28 April - 12 May	3.7	5.0	4.0	5.0	4.4
8 - 22 May	6.7	50.0	10.0	20.0	21.7

periods experienced frost occurrences that are consistent with field observations (Jones and Farrell 1997b, c), supporting work suggesting that budburst dates in the Irish Midlands may be earlier than 15 May (Thompson et al. 2005). Although provenances of Sitka spruce differ in their date of bud break (Lines and Mitchell 1965), differences are not sufficiently large to exclude the risk of frost damage on these sites. Furthermore, the most northerly origins, which flush latest, are too slow-growing in Irish conditions to have a role in commercial forestry (Thompson et al. 2005). The conclusion is that using different Sitka spruce provenances provides no protection against late spring frost on cutaway peatlands in the Midlands. If the risk of frost damage to Sitka spruce is considered acceptable, it would be judicious to plant the more productive provenances (such as Washington in preference to Queen Charlotte Island), irrespective of the fact that they will break bud earlier, so that the Sitka spruce may outgrow the risk of frost damage more quickly. In other words, the best strategy is to minimise the risk of experiencing a significant spring-frost occurrence, rather than to hope to avoid it by using a late-flushing provenance. The more conservative strategy is to select a more frost-tolerant species, accepting a lower growth rate.

Management practices (site preparation) to reduce late spring frost damage

Temperatures during two late spring frost events (2000 and 2001) were compared at four sites where different methods of forest establishment have been used.

Site 1: Tumduff - Bare peat versus vegetation.

Site 2: Clonsast - Established side shelter versus cleared area.

Site 3: Mongagh - Scrub vegetation versus deep ploughed.

Site 4: Lullymore - Temperature monitoring.

Temperatures at all sites were monitored using StowAway TidbiT XT (Forestry Suppliers Ltd) dataloggers located on a pole at 0.5 m above ground level (the approximate height of the terminal bud of newly planted seedlings) and also at 1.25 m (standard air temperature recording height). A visual frost survey was also undertaken in June 2001 to assess the season's frost damage.

Bare peat versus vegetation at Tumduff

The minimum ground temperatures experienced were found to be significantly lower over the vegetated surface (-1.49ºC) compared to the bare peat area (0.83ºC) (Table 5.43). No significant difference in temperature was recorded at the 1.25 m level between the two areas (data on file). The colonisation of vegetation post fertilisation created an environment conducive to colder temperatures during frost events compared with the bare peat surface. Results from this experiment support earlier conclusions (Geiger 1971) that vegetated surfaces generally tend to experience cooler minimum temperatures when compared to bare peat surfaces in the near ground microclimate. These lower temperatures result in an increased risk of frost damage to seedlings associated with vegetated surfaces compared with adjacent bare ground (Gardner et al. 1991). The vegetation in this environment absorbs heat, and as air is a poor conductor of heat (Oke 1992) this leads to lower temperatures. Cutaway peatlands should therefore be planted as soon as possible after peat harvesting has ceased and fertiliser should be applied initially at reduced rates

Table 5.43: Temperature comparison between site preparation techniques on three cutaway peatlands.

Site	Treatment	Average temperature (ºC)	s.e.	n	p value
Tumduff	Vegetation	-1.49	0.87	27	< 0.001
	Bare	0.83	1.07		
Clonsast	Cleared	-2.1	1.05	70	< 0.001
	Side Shelter	-1.3	1.21		
Mongagh	Scrub (older) vegetation	-1.11	0.83	32	< 0.001
	Ploughed	-0.08	0.96		

and, as far as possible, targeted on the young trees through spot or band application. This practice will also minimise leaching losses.

Sparse scrub vegetation versus deep ploughed at Mongagh

The area where trees were planted within a scrub-type vegetation recorded significantly lower mean temperatures than the deep ploughed area during frost events. The frost damage line was higher in the vegetated area, suggesting that the scrub vegetation was too sparse to provide any kind of shelter and instead trapped the cold air. Analysis of preliminary data collected from the site in 1999 (Smith 2000) found that the difference in minimum temperature recorded between the two areas was 2 to 3ºC. This study showed this difference was reduced to approximately 1ºC in 2000 and further to 0.5ºC in 2001. It appears that ploughing (and thus bare ground) may initially provide a favourable microclimate but the benefits are almost lost within three years, possibly due to vegetation colonisation following fertilisation. If vegetation control is correctly applied for at least three years, this may be sufficient to allow the trees to reach heights above the potential damage of leaders.

Side shelter versus cleared area at Clonsast

Frequent and severe frosts were recorded at the shelter experiment at Clonsast throughout the study period. On several occasions, temperatures dropped below –3ºC, and consecutive nights of frost were common. The average minimum temperature recorded in the cleared area was significantly lower than that experienced in the side shelter area during nights of radiative frost as has been found in other studies (Ottosson-Lofvenius 1987; Orlander 1993; Ottosson-Lofvenius 1993).

Various factors are involved in the development of a successful shelter system to minimise frost damage, and these include the number of stems per hectare (Ottosson-Lofvenius 1993) and the extent of the overhead sheltering effect (Odin et al. 1984). Carlson and Groot (1997) found that intact canopies provided near-complete frost protection. On average, the minimum near ground temperature recorded on nights of ground frost was 0.8ºC warmer in the side shelter area compared with the cleared area. In a similar environment, Odin et al. (1984) found that minimum temperatures were 1ºC warmer with birch side shelter (2-4 m tall with 1 m spacing). Reducing the spacing to 0.5 m resulted in a 2ºC increase in the minimum temperature. The difference between the minimum temperatures recorded at 1.25 m was reduced to 0.3ºC on average.

Another BOGFOR study has shown that birch shelterwood can provide protection against frost in susceptible areas (see Chapter 5.3 Tree establishment). It is believed that the thawing effect after nights of frost occurs at a much slower rate than in cleared areas (Odin et al. 1984). Rapid freezing and thawing increases frost injury (Day and Peace 1937). In this study, the rate of freezing was faster in the cleared area (Figure 5.70a). The near ground

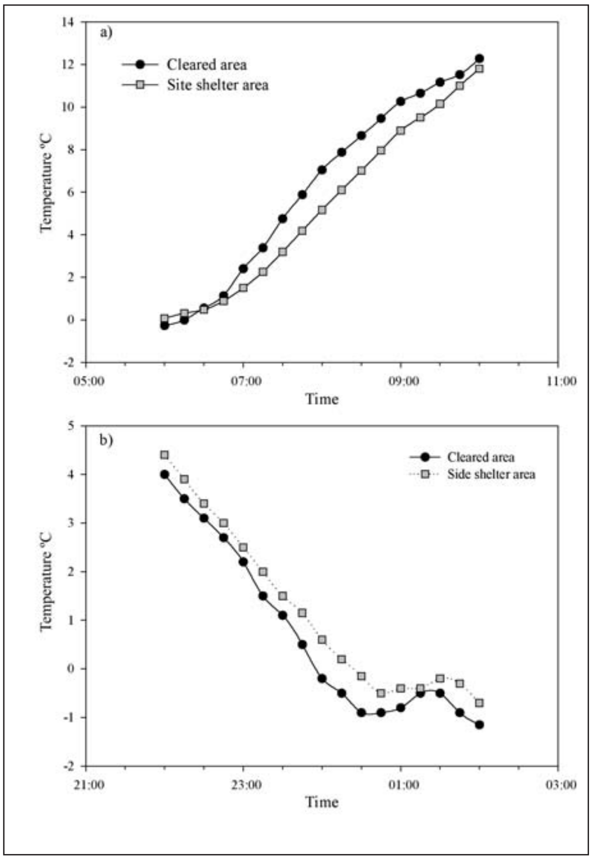


Figure 5.70: a) Freezing rate comparison with cleared area temperatures dropping on average 0.2ºC/hr more than experienced in the side shelter area. b) Thawing rates were on average 0.8ºC/hr slower in the cleared area compared with the side shelter area.

rate of thawing was found to be on average 0.8ºC/hr slower in the side shelter compared to the cleared area (Figure 5.70b). Variation in thawing rates between nights of frost seemed to correspond to the minimum temperature experienced, suggesting a correlation between minimum temperature and rate of thawing. On the coldest frost event (–4.3ºC) the difference in thawing rate between the side shelter area and the cleared area was 1.5ºC/hr. In comparison, on nights which experienced relatively slight frost (-0.8ºC), the difference between thawing rates was 0.7ºC/hr. The limited number of nights of severe frost did not allow for further confirmation of this correlation in this study.

Additionally, the higher minimum temperatures experienced in the side shelter areas can delay the bud burst date (Langvall and Ottosson-Lofvenius 2002). This would reduce the frost susceptible period and subsequently the risk of damage, depending on when the frost occurred.

Frost date and temperature comparison between sites

In relation to minimum temperatures and potential frost damage, the worst conditions over the two-year study were experienced at Clonsast and Lullymore (Table 5.44). More favourable conditions were found at Tumduff

Table 5.44: Date of minimum temperature recorded between 20 April and 30 June at each experimental trial location over two seasons. Shaded area identifies possible frost risk period. Figures in bold are at or below critical temperatures.

Year	Date	Lullymore	Clonast	Monagh	Tumduff
2000	29 April	-0.97	-1.17		
	30 April	-2.49	**-2.92**	-0.17	
	1 May	-1.88	**-3.16**	-1.24	
	2 May	-2.18	-2.03	-1.24	
	3 May	-1.88	-2.5		
	4 May	-0.667	-2.66		-0.16
	5 May	**-3.11**	**-4.06**		
	9 May		-1.13		
	10 May		-0.82		
	19 May		-0.82		
	20 May	-1.88	-1.88		
	22 May	**-3.42**	-1.73	-1.85	-1.37
	25 May	-0.67			
	26 May	-0.67	-0.98	-2.62	-0.46
	27 May	-1.57	-2.35		
	28 May	-2.18	-2.81		
	29 May	-2.49	-1.13	-0.78	-0.61
	30 May	-2.8	-2.19	-1.54	-1.98
	31 May	**-4.09**	**-4.22**	-1.46	-2.29
	9 June	-1.54	-1.58		
	25 June	-2.49	-2.5		
	26 June	-1.88	-1.88		
2001	24 April	-1.43	-1.32		
	25 April	-2.01	-1.57	-0.82	-0.64
	30 April	-0.69	-1.04		
	1 May	-1.12	-1.36	-0.98	-0.29
	2 May	-2.01	-1.87	-1.23	-0.47
	9 May		-2.62		
	10 May		**-2.93**	-0.64	
	13 May		-0.64		
	14 May		-1.24		
	21 May		-0.79		
	22 May		-0.65		
	23 May	-1.88	**-2.98**	-0.63	-1.39
	24 May	-0.36	-1.39		
	2 June		-1.85		
	3 June	-2.49	**-3.71**		-2.71
	4 June		-0.18		
	6 June		-1.55		
	7June	-0.97	-2.31		-0.68
	8 June	**-4.69**	**-3.24**	-0.48	-1.49
	10 June	-2.18	-4.33		-2.4
	21 June	-0.97		-0.18	
	22 June	-2.18	-1.85	-0.78	

and Mongagh, which experienced significantly fewer days of frost and higher minimum temperatures. Consecutive nights of frost were recorded on occasions during the study period at all sites, and frosts were experienced late into June in both seasons.

Frost damage assessment

The results of the visual frost survey are outlined in Table 5.45. As expected with the mild temperatures recorded in the area, trees at Tumduff experienced a low level of damage. Frost damage was more prominent at the cleared area than the side shelter at the Clonsast site, which had the minimum temperatures recorded. Lullymore experienced the highest levels of moderate and severe frost damage.

Microtopography and development of minimum temperature

In 1999, a small-scale study was carried out at Tumduff to investigate the influence of topography (high and low fields) on the development of low temperatures. Results suggested that topographical variation influenced the spatial distribution of temperatures during radiation frosts. However, the absence of severe frosts during the period of the study limited the value of these results.

The experiment was replicated in 2002. In the latter study, eighteen temperature recorders were positioned throughout the site, covering the range of topography. The elevation difference between the data loggers was a maximum of 1.59 m. Temperatures were recorded every fifteen minutes for one year, during which a total of 93 frost events were identified. The minimum temperature recorded on each frost event at each logger as well as the duration of the frost event was used in the analysis. Each logged temperature was then ranked from coldest to warmest. The probability of each logger recording the minimum temperature was then calculated and a 'minimum temperature rank' applied to each logger with 1 representing the coldest temperature and 18 the warmest. A relationship between logger height and minimum temperature rank was examined to assess the effect of topography on the occurrence of minimum temperature. The relationship shown in Figure 5.71 indicates that 30% of the variation in minimum temperature development at the 18 locations

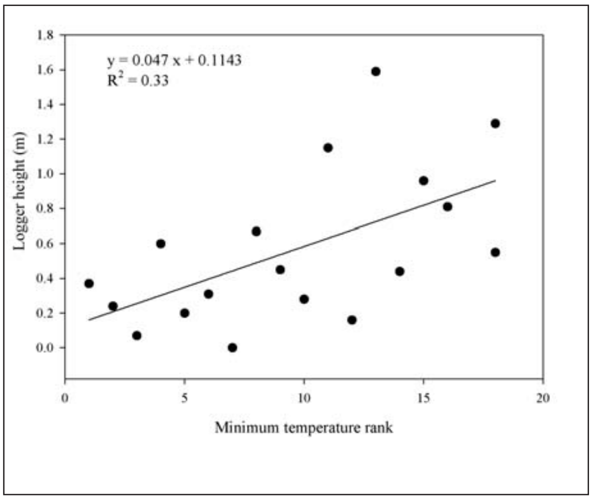


Figure 5.71: Relationship between relative minimum temperature rank (index between 1 (coldest) and 18 (warmest) depending on the probability of each logger recording the minimum temperature) and topographical height.

Table 5.45: Frost damage recorded by site and treatment.

			Extent of damage			
Site	Treatment	Average tree height (m)	None	Slight[a]	Moderate[b]	Severe[c]
Tumduff	Vegetation	0.6	69%	25%	4%	2%
Clonsast	Cleared	1.2	15%	39%	30%	16%
	Sheltered	1.3	75%	19%	5%	1%
Lullymore	None	1.2	3%	14%	48%	35%

[a] Some buds damaged on lower branches

[b] Majority of buds damaged; leader not hit

[c] Leader damage

could be associated with variations in topographical height. A strong relationship was also found between frost duration (time below 0 ºC) and the minimum temperature recorded (Figure 5.72).

Topography was found to have an influence on the development of minimum temperatures as well as the duration of frost events. Given the low R^2 value, however, the model is not adequate to be used for prediction purposes. Conditions other than elevation are having an influence on the development of minimum temperatures. Certain areas were repeatedly found to experience colder temperatures even though they were not the lowest lying areas. The presence and abundance of vegetation is most likely to have been the other major factor at this site. Thus, removing the topographical variation by levelling the site, without consideration to vegetation management is unlikely to equalise the risk of frost across a site, as any area where cold air can stagnate and accumulate is predisposed to frost.

Conclusions

Following large-scale peat harvesting of the midland raised bogs, low lying cutaway peatlands can be subject to frequent late spring frosts. The date of the last spring air-frost varies from one year to the next. The high probability of frosts occurring during the Sitka spruce bud burst period renders this species at risk. The occurrence of frosts as late as June also shows that avoiding late spring frost by delaying bud burst (e.g. by using late flushing provenances) is not an option.

Management practices have been found to alleviate the risk of frost damage. A near complete overstorey shelter system is probably the best form of protection, and it also has the advantage of increasing the early growth of trees, thus bringing the leading shoot above the frost line sooner. The importance of thorough vegetation control has also been highlighted to reduce the risk of frost damage, as well as improving tree growth. More intensive management practices such as site levelling and cultivation were not effective, as micro-scale variations are likely to promote local frost pockets, and these are not amenable to change.

Further questions can be raised regarding late spring frosts from a climate change perspective. An increase in average winter temperature in Ireland, as predicted by Sweeney (1997), could results in bud break occurring at a slightly later date. This would reduce the probability of damage by late spring frosts but would also reduce the length of the growing season (Murray et al. 1989; Leinonen and Hanninen 2002). In the meantime, the use of a less frost-sensitive species is to be preferred, leaving the option to plant Sitka spruce at a later stage under a shelter system. Species such as Norway spruce have a much wider range of bud break, thus reducing the risk of late spring frost damage. On sites where frequency and severity of late spring frosts is a problem (such as Lullymore), pine species should be planted; these could subsequently be used as a shelter for more productive spruce species.

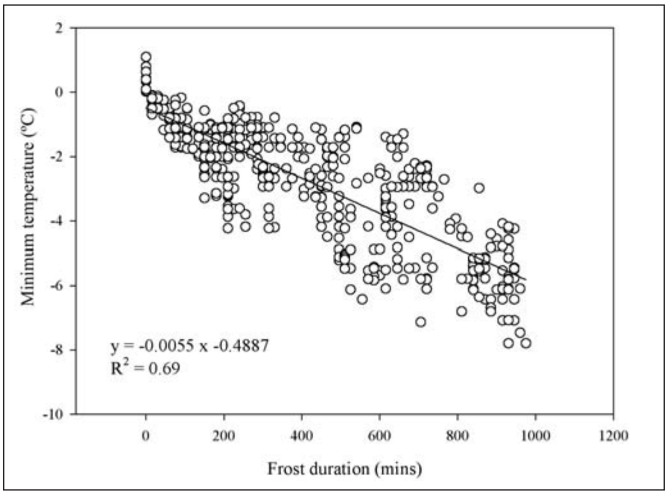


Figure 5.72: Relationship between frost duration and minimum temperature developed.

SUMMARY POINTS: LATE SPRING FROST

- *Late spring frosts are common on the cutaway peatland in the Irish Midlands, thus limiting the choice of species for these areas.*
- *There is a high probability of frosts during the bud burst period of Sitka spruce, regardless of provenance.*
- *Norway spruce is a less frost-sensitive species but it is not totally frost-resistant like pines and occasional late frost will damage Norway spruce.*
- *A near complete overstorey shelter system is the best form of protection against spring frost damage.*
- *Effective vegetation control can reduce the risk of frost damage.*

Pest damage

Plantations in temperate regions are less likely to be seriously damaged by pests, often because protection is possible (Savill et al. 1997). Although pest damage on cutaway peatland plantations can be unpredictable and variable in its severity, only pine shoot moth and hares cause severe widespread damage.

Pine shoot moth

The European pine shoot moth, *Rhyacionia buoliana* (PSM), is distributed throughout Ireland (Quirke 1945). Damaging infestations over the years have been associated with lodgepole pine and Scots pine. In the mid-1990s concern was raised with respect to the intensity of attacks on lodgepole pine growing on cutaway bog at Boora, Co Offaly. A survey carried out at the time by Coillte established that, across the cutaway areas in the Midlands, the most damaging infestation occurred at Boora (planted in 1989) with over 50% main stem damage. The distinctive feature of this plantation is that it was established at close spacing (1 x 1 m) for Christmas tree production, but was never harvested.

Since 1998, PSM has been noted in lodgepole pine and Scots pine plantations at Mongagh and at Tumduff, but no attack has yet been recorded at Lullymore or Blackwater. Control of PSM is extremely difficult, mainly due to the protected nature of its life cycle: the insect spends most of its life as a larva and pupa within tree buds. The use of insecticides, under such circumstances, is ineffective. There are few, if any, natural enemies of PSM and the development of biological control agents would be extremely costly. Internationally, the development of a pheromone mating disruption technique has failed to live up to its early promise (Sukovata et al. 2002).

The survival of PSM larvae is related to the amount of resin encountered during the initial attack on the bud (Harris 1960), the larvae being unable to establish themselves in very resinous buds. Resin canals in the buds are developed in response to short days at the end of summer, while the development of the moth is associated with high summer temperature. Thus more larvae survive in a warm summer than in a cool one, as they attack the buds before resin protection is well developed. Fewer larvae survive on the very resinous Corsican pine (*Pinus nigra* var. *maritima*) than on Scots pine.

In Canada, Haynes and Butcher (1962) found that red pine, *P. resinosa*, supported the highest population of larvae with lower populations on Scots, ponderosa (*P. ponderosa*), Austrian (*P. nigra* var *nigra*), Jack (*P. banksiana*) and Weymouth pine (*P. strobus*), in that order. In addition, Holst and

Heimburger (1955) presented a scale of resistance to PSM for a range of species in their native habitat and for North America. Japanese black pine (*P. thunbergii*) is the most resistant in North America, followed by Austrian and Corsican pine as highly resistant in their native habitat and resistant in North America. However, results are tempered by several observations of species not necessarily retaining the same level of resistance when planted in other locations, for example, coastal lodgepole pine was highly susceptible when grown in Europe due to lower precipitation in the regions in which it was introduced.

It was suggested by Ward (2002) that while a move to a less susceptible species of pine, such as Corsican or Macedonian (*P. peuce*) may prevent attack, the slower growth of these species might not justify it. Results from the BOGFOR trials at Tumduff (Clonaslee 4/00) show that after five growing seasons Corsican pine displayed the best growth of all pines with strong healthy plants while other pines showed PSM attack as well as damage due to hare browsing and basal sweep.

It can be concluded that lodgepole and Scots pine are not suitable for sawlog production at locations identified as being at risk from PSM, viz. Boora and Clonsast and their surroundings. The risk seems to be lower when moving away from the Midlands.

Hare

The Irish mountain hare (*Lepus timidus* L.) is one of the country's few native mammals, enjoying the status of a unique sub-species. Mountain hares and rabbits are unique in Ireland in that they are sympatric, i.e. they live alongside each other in similar habitats (Rooney and Hayden 2002). Cutaway peatlands are also the favoured habitat of the Irish hare (Plate 15), which is considered the only mammal that truly belongs in the bog (Feehan and O'Donovan 1996a). While hares are more solitary than rabbits, they are often seen feeding in large groups. As more cutaway peatlands come out of peat production, the hare population density is likely to increase in areas already heavily populated, thus having implications for future plantations.

At the East Boora plantation, one hare entered the 12 ha fenced area and browsed 100% of the birch and 98% of the oak. Significantly, alder escaped damage. Browsing by hares is most severe on young trees in winter and early spring but may occur all year around. The cut ends have a characteristic clean angle with the cut tips lying by the side of the tree. Hares systematically move along a line of trees, browsing each one in turn. Trees need to be replaced to avoid forking. A well-maintained fence is necessary if broadleaves are to be planted on cutaway peatlands. The presence of ditches and pipe drains makes the task more difficult as these areas provide possible access points for the animal. Individual plant protection, in the form of one metre or taller plastic tubes offer very good protection and have become more common recently, although they remain expensive.

SUMMARY POINTS: PEST SUSCEPTIBILITY

- *The incidence of pine shoot moth in the Irish Midlands has meant that pine species are at risk.*
- *Corsican and Macedonian pine are less sensitive than lodgepole and Scots pine, and are considered to be suitable species on cutaway sites.*
- *Protection against hares (either fencing or individual plastic tubes) is critical when planting broadleaves on cutaway peatland*

Vegetation and cutaway peatland plantations

Scientific and common names of plants referred to in the text can be found in Appendix 8.

Introduction

As discussed in Chapter 3, the spontaneous re-vegetation of cutaway peatland after peat harvesting is limited by harsh environmental conditions. Seed source, drainage, characteristics of the remaining peat and the type of subsoil heavily influence the nature of re-colonisation. Following the planting of tree seedlings on cutaway peatlands and, more importantly, the application of fertiliser, the natural succession changes its course, together with species assemblages and the rate of colonisation. The plentiful availability of light, water and nutrients is conducive to an explosive development of herbaceous and woody vegetation.

Non-crop vegetation competition can have a very significant effect on the successful establishment, development and ultimately productivity of a forest plantation (Davies 1987). Several studies in different conifer species have demonstrated that diameter growth and wood volume gains are proportional to the number of years of vegetation control (Lauer et al. 1993; Wagner et al. 1996). Vegetation competes with the trees not only underground (for nutrients and water) but also aboveground; some species (e.g. *Juncus effusus*) can quickly smother the young seedlings (Plate 16). Other species such as *Calluna vulgaris* can have negative effects on certain tree species such as Sitka spruce, which can suffer from heather-check (Handley 1954; Leyton 1955; Brosnan 1980; Griffin et al. 1984).

The importance of rigorous ground vegetation control has already been highlighted on cutaway peatlands, especially to reduce the risk of late spring frost damage. On the other hand, it has also been found that taller woody vegetation can offer protection against late spring frosts. Not all plants which spontaneously invade cutaway peatland plantations are unwanted, as some can have beneficial effects. Ground flora increases the percolation of water and reduces soil erosion; it has other benefits through the uptake, storage and recycling of nutrients that might otherwise be lost from the ecosystem; and it can shelter the trees from exposure as well as protecting them from browsing.

Controlling competing vegetation is a major component of any afforestation programme and requires labour and financial resources. Forest certification also means that there is an increasing trend towards the use of more environmentally friendly herbicides or non-pesticide methods for vegetation control. This chapter firstly describes various vegetation communities found on young cutaway peatland plantations following a chronosequence from planting to pre-canopy closure, indicating which factors can most affect the occurrence of competition. It describes the main characteristics of the most important competing weeds and finally indicates, from field observations and early results, the appropriate strategies for vegetation control on these site types.

Throughout the BOGFOR research programme, four vegetation surveys have been conducted on over 100 quadrats, covering 15 different sites (Parr 1999; Pöllänen and Renou 2002; Bennett et al. 2003). Studies on genera such as *Juncus* (McCorry and Renou 2003) and *Betula* (Pöllänen et al. 2004), and other work has been summarised here.

Chronosequence of vegetation colonisation of different cutaway peatland plantations

The methods used to survey the vegetation and measured variables can be found in Chapter 2. A subjective assessment of presence or absence of above-ground competition between the trees and the ground flora was given for each plot, based on species present in the plot, the number of plants, height and location (around the tree seedlings or in between). A plant was deemed a competitor when it was growing very close to or in contact with the trees (competing for light). Severe above-ground competition arises when the tree is surrounded by taller vegetation.

Newly afforested sites

Twenty-two quadrats laid down at the Tumduff Norway spruce demonstration area, planted in May 1999, were first assessed in early August of that year. The plots were very sparsely vegetated (8% cover value for ground vegetation) and 40 vascular plant species were recorded. The four most frequently recorded were *Juncus bulbosus, Juncus articulatus, Triglochin palustris* and *Juncus effusus*. Two years later (August 2001), 50 species were found in the same quadrats, showing little change in terms of species richness. Rather, changes in cover-abundance occurred with the main species: mosses (mainly *Campylopus introflexus*), *Juncus effusus, Juncus bulbosus, Holcus lanatus* and *Epilobium angustifolium*. Competition was recorded as being present in over 50% of the plots. A third survey, carried out in August 2002, on the same quadrats revealed a total of 43 species with *Juncus effusus* the most abundant, representing almost 50% of the total species cover and being present in all plots examined. Mosses (mainly *Campylopus introflexus*) were also present in all plots with a high percentage cover of over 30%. *Holcus lanatus* and *Hypochaeris radicata* also increased their cover values. Competition was recorded in 82% of the plots with *Juncus effusus* and *Holcus lanatus* being the main competitors. While *Calluna vulgaris* and *Typha latifolia* were no longer recorded, grass species such as *Anthoxanthum odoratum* and *Lolium perenne* occurred for the first time. Overall, while species richness remained the same over the three-year period, abundance values increased significantly for *Campylopus introflexus, Juncus effusus* and *Holcus lanatus*, the latter two becoming the main competitor species for the trees during the third growing season (Figure 5.73).

In 2002, twenty-one quadrats were examined in a Norway spruce demonstration area at Blackwater that had been planted in 2000. The area had received similar treatment to the Tumduff site. In terms of species richness and level of competition, results were comparable to Tumduff (Table 5.46), showing a similar pattern of colonisation.

Reconstituted plantations

Thirty-five quadrats were laid out in three reconstituted plantations immediately after the planting of Norway spruce in 1999. The study sites were visited in 1999, 2001 and 2002. Results in Table 5.47 shows that, along with an increase in species number from 48 in 1999 to 54 in 2001, there was more than a

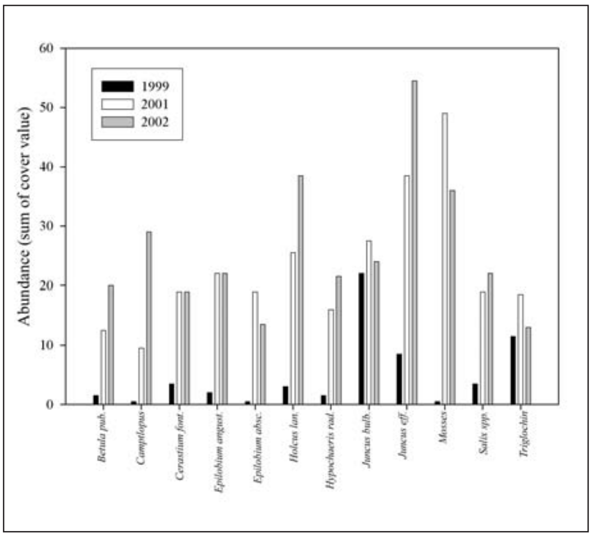


Figure 5.73: Annual abundance (Braun-Blanquet scale) of the main vegetation species at the Tumduff Norway spruce peatland plantation from 1999 to 2002.

Table 5.46: Vegetation comparison between two Norway spruce demonstration areas

	Tumduff	Blackwater
Number of species	43	49
Total abundance (cover value)	453	518
Incidence of competition (% plots)	81%	82%
Incidence of severe competition (% plots)	27%	24%
Main competitor species	*Campylopus introflexus* *Juncus effusus* *Holcus lanatus*	*Campylopus introflexus* *Juncus effusus* *Holcus lanatus*

Table 5.47: Comparison over time of number of species, species abundance and percentage of plots with competition from different cutaway peatland plantations.

		1999	2001	2002
No species	New afforested sites	41	50	43
	Reconstituted plantations	48	54	49
	Older plantations	77	55	46
Sum of cover values	New afforested sites	126.5	437	453
	Reconstituted plantations	356.5	732	817
	Older plantations	242	265	297
% plots with competition	New afforested sites	0	55	82
	Reconstituted plantations	51	75	77
	Older plantations	54	77	50
Main competitor species	New afforested sites	*Campylopus introflexus, Juncus effusus, Holcus lanatus*		
	Reconstituted plantations	*Juncus effusus, Epilobium angustifolium, mosses*		
	Older plantations	*Mosses, Agrostis capillaris, Juncus effusus, Salix spp.*		

doubling in species abundance over the same period, with a further increase in 2002. The surveys identified *Juncus effusus,* various mosses, *Epilobium angustifolium* and the grasses *Holcus lanatus* and *Agrostis capillaris* as the main competitors showing a continued increase in abundance over the survey period (Figure 5.74). With a smaller, but increasing cover value, *Betula pubescens* was also seen to compete with the trees. The incidence of competition was already high in 1999 (51%) and continued to increase over the period, reaching 81% in 2002. The increase in competition levels and the corresponding decrease in species in 2002 suggest competition between the ground flora species. All three surveys identified competition as a major problem in reconstituted areas. This was mainly because of the established seedbank and surrounding vegetation that was a source for rapid colonisation, together with a richer site due to two applications of fertiliser over a relatively short period of time.

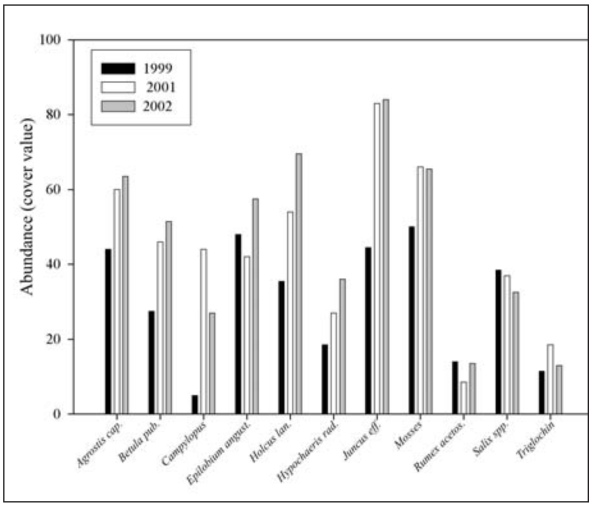


Figure 5.74: Change in abundance of the main vegetation species on the Norway spruce reconstituted cutaway peatland plantations from 1999 to 2002.

Existing cutaway peatland forests

The existing forests investigated were planted at the end of the 1980s and had generally performed poorly. A sequence of vegetation changes could be identified in the early development stages. Results showed a gradual decline in the total number of species recorded from 60 in 1999 to 46 in 2002. The main competitors remained the same over the survey period: mosses, *Agrostis capillaris, Juncus effusus, Salix* spp. and *Betula pubescens* (Figure 5.75). After an initial increase in competition levels from 1999 to 2001 (mainly from *Juncus effusus* and *Calluna vulgaris*), they subsequently remained either the same or decreased after 2001 (Table 5.47). With increasing crop age, vegetation cover changed until canopy closure when it was shaded out. With Sitka spruce, which generates heavy shade, vascular plants are largely eliminated during the thicket stage. Norway spruce casts slightly less dense shade than Sitka spruce (Hill 1978) and should tolerate more competition. However, this hypothesis was not substantiated in this study.

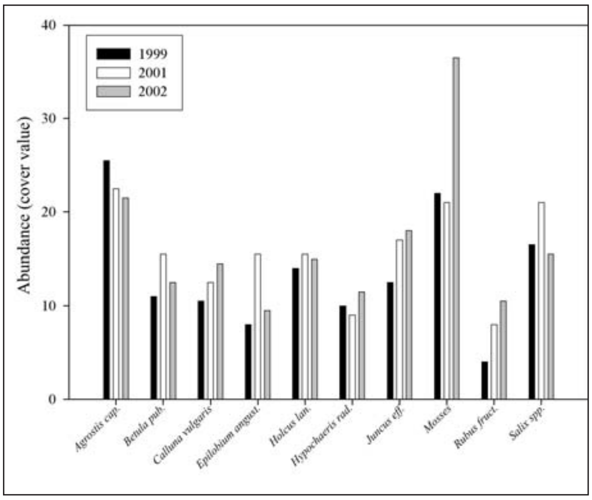


Figure 5.75: Change in abundance of the main vegetation species on existing Sitka spruce cutaway peatland plantations from 1999 to 2002.

The spread of Sitka spruce crowns was narrowed by the severity of the frost damage and may explain the fact that competition was actually more common in Sitka spruce than in Norway spruce plots.

The chronosequence study of the different cutaway peatland plantations of various age and types provided an insight into the dynamics of vegetation colonisation and potential competition. Vegetation colonisation was rapid, as shown by the considerable increase in total vegetation cover value at all sites. Species richness increased rapidly in the first three years of the life of the plantation but thereafter competition set in and it eventually decreased as the canopy was closing. The same species were present during the pre-canopy closure period - *Juncus effusus, Epilobium angustifolium, Holcus lanatus, Agrostis capillaris, Salix* spp. and *Betula pubescens*. The dominant species and level of competition is influenced by several factors.

Factors affecting vegetation colonisation, species composition and competition

The importance of the presence or absence of a seed bank has been confirmed by comparing reconstituted sites to recently planted cutaway peatlands. The very high cover values found on reconstituted sites suggest the influence of a well-established seed bank and existing vegetation, both leading to rapid colonisation. *Juncus effusus* and *Epilobium angustifolium* (to a lesser extent) will compete aggressively with the trees and require well-timed and effective control.

Nutrient status is a main factor delaying the revegetation of cutaway peatlands. Surveys carried out in the BOGFOR fertiliser trials showed that the number of species and cover values were positively correlated with increasing rates of fertiliser application. Higher fertiliser rates also meant that the trees grew faster, however, and shaded out the ground vegetation sooner. The nature of the residual peat was also found to influence the colonisation process. Less acidic peats were found to support more competitive species than acid soils. Peat type was found to be less conducive to competition in the following order: *Sphagnum* < *Phragmites* < woody fen peat.

The effects of cultivation on the extent of colonisation by weeds were not sufficiently clear at any of the BOGFOR sites studied. This is probably due to the fact that cultivation was only possible on relatively drier areas. At Tumduff, cultivation reduced the extent of the colonisation, leaving more surfaces bare after two years than in the non-cultivated areas. The opposite was true at Blackwater where vegetation competition was greater in cultivated areas.

Microtopography was also an important factor influencing the initial colonisation by weeds, and the condition of the tree crop. The microtopography of cutaway peatlands is related to the presence or absence of shelter as well as hydrological conditions. Low-lying areas may be engulfed sooner by rushes and scrub species while higher, more exposed fields often have lichens and mosses as ground vegetation. In the latter case, the Norway spruce did not suffer from competition but did not grow as well as the trees in lower bays that initially suffered from competition from *Juncus* spp., *Carex* spp. or *Betula* spp.

Characteristics of certain weeds and their use in assessing site potential

Unlike on many mineral soils, the major competitive plants on cutaway peatlands are not grasses but *Juncus* spp. and to a lesser extent *Epilobium* spp. As time goes by, grasses such as *Agrostis* spp. and woody species (*Salix* and *Betula* spp.) become major competitors in their turn. Most of these can be considered as pioneers and have certain features in common. They are difficult to control because they are competitive, adaptable and tend to form extensive populations. Further characteristics of these species are described below.

Juncus effusus

- *J. effusus* is well adapted to growing and spreading on bare cutaway sites due to: (1) its broad tolerance of wet, acidic, nutrient-poor conditions; (2) its good reproductive potential with substantial seed production, persistent seed bank and clonal growth of tussocks; and (3) the availability of bare peat surfaces with no other plant competition, making it a rapid coloniser and competitor.
- *J. effusus* is frequently found on disturbed cutaway raised and blanket bogs that have a fluctuating water table (the surface is not flooded all year) and slightly enriched nutrient conditions.
- *J. effusus* was not particularly associated with any one peat type or peat depth at the BOGFOR sites studied.
- *J. effusus* was one of the most frequently found species in the BOGFOR vegetation surveys but was often found at low to moderate cover values (low abundance). Only a few sites had high cover values (high abundance), where *J. effusus* was a particular problem.
- In agricultural situations, *J. effusus* is relatively easy to control using a variety of mowing and herbicide applications, along with land improvement such as drainage (Lazenby 1955).
- *J. effusus* has a seasonal growth cycle, with highest growth rates and shoot production rates in the summer.
- *J. effusus* has been difficult to control in cutaway peatland forests in the past using herbicides due to adverse climatic conditions (few calm days suitable for spraying).
- The lifecycle of *J. effusus* has few weak points that are easily exploited to enhance control efficiency (Agnew 1961). The optimal time for control is in early-mid summer when growth rates of *J. effusus* are highest.
- Effective control of *J. effusus* on cutaway peatland sites requires more intensive control (several herbicide/mowing applications per year).
- Several cuttings of *J. effusus* may reduce moisture and decrease water table levels rendering the environment less favourable to *J. effusus* growth.

Other *Juncus* species, e.g. *J. bulbosus* and *J. articulatus*, are present on afforested cutaway bogs but they are not considered as competitors due to their relative smaller size.

Epilobium angustifolium

Another common species found on cutaway peatland is rosebay willowherb. It grows on a variety of habitats but favours sites that have been disturbed (Shamsi and Whitehead 1974; Curran and MacNaeidhe 1984). It occurs on acidic peat only where nutrients have been added. It is capable of vegetative reproduction with new shoots arising from buds on the roots. A lateral spread of approximately 1 m per year in a single direction has been recorded in a colony and the roots may be long-lived, some having been determined to be up to 27 years old. Plants are capable of flowering in the first year and then in each subsequent year. The seeds (from 250 to 500 per capsule) are plumed and thus wind-dispersed. Their viability is about eighteen months in dry storage. Seedlings establish most successfully on open, moist sites of at least moderate fertility where there are few competitors. Fertiliser application improves their establishment. Unlike *Juncus*, *Epilobium* dies back during the winter.

Campylopus introflexus

Campylopus was prevalent in many cutaway peatland areas but it is not thought to be a major competitor to trees. Its presence indicates poor quality peat. It was dominant on very poor areas and its extensive carpet tended to reduce the germination rate and establishment of species such as *Calluna vulgaris* and *Salix* spp. (Equihua and Usher 1993). On some sites, it declined following the application of fertiliser. This could also be associated with its ecological cycle (van der Meulen et al. 1987).

Strategies for weed control

Given that all the other factors are suitable, trees will eventually suppress most of the competition from herbaceous vegetation once the crowns begin to close. Vegetation control is, however, required on cutaway peatland where survival of the tree crop is at risk. Complete weed control is costly and unrealistic.

Chemical herbicides

Neither residual nor sprayed foliar herbicides can be effectively used on cutaway peatlands, the former being efficiently adsorbed on organic matter, while the latter should not be applied to wet foliage when rain is imminent or when there is a danger of drift. In open, windy peatland areas, there are usually few days in the early growing season when ideal spraying conditions occur.

Machine control

Mowing has been tested at different frequencies and over a number of years on BOGFOR sites. The mower (Plate 17), which has a purpose-built flail, can be pulled by a small all-terrain vehicle (quad bike) and cuts the vegetation between tree rows. Vegetation within the tree line is not affected. Evidence suggests that the time of mowing is important. If there is to be only one mowing per year, the optimum time is in mid-summer when growth is at its fastest. However, other observations indicate that for good control, repeated control (up to four times a year) is necessary, especially when the site is fully colonised by rushes. On some sites, *Juncus effusus* had already swamped the trees. These could only be mowed to about half their height, and thus mowing had no noticeable effect.

Another method tested was a weed-wiper (Plate 18). This consists of a carpeted roller wetted with contact herbicide (glyphosate) and manually controlled by a 12V pump. The vegetation is wiped twice, the second time in reverse direction. While the rushes died off in most plots treated in this way, vegetation cover did not decrease as much as with mowing methods. In the context of reducing herbicide use both mowing and weed-wiping are appropriate systems. Weed-wiping should only be used in cases where mowing is not feasible. More field trials are required, however, in order to identify the most cost-effective control method. In some difficult sites, manual cleaning with hooks will be the preferred option, especially if the vegetation is smothering the trees.

Crop competition

The establishment of ground cover that does not compete with the tree crop can delay competition from natural vegetation and help retain nutrients which will later become available to the trees. Some studies on this subject have recently been reviewed by McCarthy and McCarthy (2005) but this technique was not evaluated within the BOGFOR programme. Further research is required in this area especially using nitrogen-fixing legumes (e.g. *Lupin* spp.).

Mulching

Mulching or spreading material around the trees has been used successfully in forestry although it is expensive (McCarthy and McCarthy 2005). Although not scientifically tested on cutaways, this method is unlikely to be suitable for this site type due to difficulties with installation together with low durability of the mulching material due to climatic conditions and damage by hares.

SUMMARY POINTS: VEGETATION CONTROL

- *It is important to reduce the colonisation of main competitors such as Juncus by improving drainage and by following a vegetation control plan.*
- *Timely and efficient vegetation control operations are necessary.*
- *The spraying of herbicide is not recommended on cutaway peatland plantations due to the difficulty of getting wind-free days.*
- *Crops on cutaway peatland are suited to mechanical cleaning with purpose-built equipment such as mowers, and with weed-wipers.*

Management of poor or failed existing plantations

Assessments of existing plantations

The pre-1996 plantations on industrial milled cutaway peatlands have been assessed extensively. The first investigation was carried out by Coillte (Lynch and McGuire 1993). This unpublished report aimed to quantify the status of the c.4,000 ha of cutaway peatlands that Coillte had leased from Bord na Móna for forestry. Results from this survey have been discussed in this report. The poor results posed questions with regard to the viability of cutaway peatland plantations. A more intensive survey was later carried out by the Forest Ecosystem Research Group (UCD) to provide a fuller assessment of limitations to the successful establishment of tree crops on these sites (Jones and Farrell 1997a; Jones and Farrell 1997d). The results of the latter surveys showed that the problems were: frost; competition from weeds; nutrient deficiency; pest damage; edaphic factors (depth or compaction of the peat); and drainage. The survey revealed that poor growth was not due to a single factor but rather to a combination of factors. For example, growth retardation as a result of frost damage gave weeds a competitive advantage.

In 1999, Coillte carried out another survey of all the plantations leased from Bord na Móna in order to identify areas for reconstitution, fertilisation, drainage and vegetation control, and to identify problem areas unsuitable for forestry. In the meantime, the BOGFOR research group earmarked 60 ha of such areas to be reconstituted for intensive monitoring.

Categories of poor or failed plantations

Due to the heterogeneity of cutaway peatlands (see Chapter 3), it is expected that a proportion of any land parcel is inherently unsuitable for forestry (e.g. small, isolated wet basins). Where large cutaway peatland sites have been 'blanket' planted in the past, some poor quality areas inevitably failed. There is little point in now attempting to reconstitute them. Unmanaged, they will contribute to landscape and biodiversity. If birch and willow colonise these sites, they could undergo both drainage and nutrient amelioration.

If drainage, drain maintenance or fertiliser inputs have been inadequate, competing vegetation has not been controlled or the species has been badly damaged by frost, pine shoot moth or other factors, the use of any remedial and/or replanting should be carefully considered. If stocking is adequate, restoring productivity may be feasible using re-fertilisation, for example. If stocking is not adequate, the decision whether or not to reconstitute (i.e. replant) should be based on a thorough survey of the whole area according to specific criteria.

Management of mixed stands of spruce and wild birch

Until recently, naturally regenerated birch was removed from coniferous plantations. There is now an inclination to manage birch/conifer mixtures without removing the birch. In general, these stands all have the following characteristics, albeit in variable proportions:

- Presence of individual trees with reasonable growth rate;
- Variable stocking rates across the site;
- Presence of naturally regenerated birch (of variable quality) and woody shrubs;
- Dense ground vegetation, especially in clearings.

Two main management options might be considered, depending on conditions in individual plantations:

a) *Do nothing or use minimal intervention at low cost:* Increment of the remaining conifers may be sufficient and may be improved by a thin-to-waste operation. However, if stocking of the spruce is low, it would be important to keep the stocking of the birch relatively high in order to keep the branch size small in the spruce. The management approach could be best described as 'getting the most of the present poor crop while minimising the costs wherever possible'. Premature clearfell could then be carried out and a more suitable crop established on these ameliorated forest sites. However, management would be required due to the large number of birch seedlings likely to emerge.

b) *Intensive intervention:* This requires a careful diagnosis to assess the potential of the crop, and will also depend on the relative markets for spruce and birch wood. If adequate, respacing should be carried out to free up the conifer crop. This means removing any birch trees where they are interfering with the growth of the spruce. At the same time, efforts should be made to use any good quality birch stems. A study in Sweden has shown that it is possible to manage a mixture of Norway spruce and birch, with a large number of competing birch at the time of first commercial thinning, without volume loss in the spruce compared to a pure spruce crop at the same density (Fahlvik et al. 2005). However, management of conifer and birch mixtures often encounters two problems: the difficulty in assessing each individual tree while cleaning the site and the lack of good quality birch stems (multi-stem birch mostly present). New machines (like the feller-buncher or specially designed Scandinavian 'cleaning machines') may be better equipped to deal with these sites. Another option is to create a mosaic pattern with separate birch-only and conifer-only areas. Aerial photographs are now relatively cheaply available and would be useful in assessing these sites to ascertain their potential and choose the best option.

The following points are suggested to guide future research on mixed-stand management:

- Birch is a pioneer species which will help to lower the water table of cutaway sites and provide shelter from exposure and late spring frosts. Given certain conditions, it can improve site quality through rapid rates of leaf breakdown and root biomass growth and sequestration of nutrients (Saramäki and Hytönen 2004).
- Although it is a forest biomass producer, birch has not been managed in Ireland long enough to show whether repeated coppicing is a way to sustain birch biomass production rates.
- Birch is a native broadleaved species which adds to the biodiversity (microfauna and flora) of the plantation and mixed birch-spruce stands may provide a new option for sustainable forest management.

In conclusion, managing mixed stands of spruce and birch will have the advantage of giving a commercial return while promoting the growth and use of native birch for roundwood production.

Management options for reconstituted plantations

Background

The objective of reconstitution is to restore a forest crop that has either partially or fully failed by filling in or replanting to bring the stocking up to an acceptable level. The decision on whether to replant must be based on an assessment of the possibility of restoring the forest and the cost of doing so; the alternative being to leave the stand to follow its natural course. It is important to assess the site conditions, as the intensity and cost of intervention should match site potential. Depending on what caused the failures in the first crop, reconstitution may be carried out by replanting with a different species, better suited to the site conditions. Where drainage is a problem, the site should be assessed (preferably in winter) in terms of cost and feasibility of installing a drainage system. If invasion by birch is the principal concern, this is best assessed when the birch is in leaf.

Herb and shrub species can act as indicators of the physical and biological environment. The presence of *Eriophorum* spp. or *Carex* spp. usually indicates a high water table. Grasses and shrubs grow better on aerated soils. Older plantations being considered for reconstitution usually have the added difficulty of no longer being in the establishment phase. Any treatment then will inevitably cost more than at an earlier stage in the forest cycle. In some cases, the removal of the entire old crop and woody shrub could substantially increase the cost of replanting and exceed the reconstitution grant currently available. It may also be silviculturally questionable to plant small transplants within a mosaic of existing trees that may be already 6 – 8 m tall. In addition, the removal of this type of vegetation may cause the water table to rise. Existing shrub vegetation could also be used as shelter for replanting other species.

BOGFOR reconstitution areas: Results

The 60 ha of cutaway peatland plantations that were reconstituted under the BOGFOR programme were distributed over five Coillte properties and divided into nine areas. These sites were originally planted in the late 1980s or early 1990s with Sitka spruce which failed, mainly due to late spring frost damage and subsequent vegetation competition, but also due to poor drainage conditions. Different management options for reconstitution were examined in these demonstration areas including different methods of vegetation control and the use of existing woody vegetation as shelterwood (Table 5.48). A description of each area and its silvicultural prescription can be found in Jones and Farrell (2000).

Table 5.48: Summary information regarding the BOGFOR reconstituted demonstration areas.

Area	Compartment	Site	Species*	Treatment	Original crop present
1	74087F	Tumduff	NS	Flail machine and excavator mounted with a circular saw	No
2	74103U	Tumduff	NS	Excavator mounted circular saw	No
3	74084U	Boora	NS	Original crop left in situ	Yes
4a	74084U(LP)	Boora	NS	Excavator mounted circular saw + windrow	No
4b	74084U(LP)	Boora	NS	Same as 4a but one line of LP left in the middle of each bay	Yes
5	77572A	Clonsast 2	NS	Excavator mounted circular saw + windrow + mounding	No
6	75570K	Clonsast 3	NS	Excavator mounted circular saw + windrow	No
7a	77576D	Clonsast 3	NS	3 m strips cleared by flail machine within older crop	Yes
7b	77576D	Clonsast 3	SS	3 m strips cleared by flail machine within older crop	Yes
8	73475B	Mongagh	NS^	Original crop (SS) left in situ	Yes
8	73475B	Mongagh	NS	Deep ploughed and levelled	No
9	77577V	Derryounce	HL^	Excavator mounted circular saw	Some

* species is the species used for reconstitution

^ some of the original crop of SS were left standing

NS = Norway spruce, SS = Sitka spruce, HL = Hybrid larch

Survival

Area 9 (Derryounce) is the only site that failed following reconstitution. After two growing seasons, the survival of hybrid larch was very low at 11%, and this fell to 6% after the third growing season, despite filling in. The site is very heterogeneous and the hybrid larch suffered from poor site conditions (waterlogging) as well as late spring frost. Interestingly, the frost-damaged Sitka spruce, together with some good naturally regenerated birch may eventually form a crop.

In the remaining areas (Figure 5.76), the survival of the Norway spruce was greater than 70% after two growing seasons at all sites except Mongagh, where mortality was high due to very wet soil conditions. Over time, however, the site improved and survival after the third growing season (following filling in) was satisfactory (88%).

Height

The mean height of Norway spruce after four growing seasons ranged from 1.4 to 2.4 m. During the fourth growing season, all sites displayed particularly good growth (Figure 5.77). The tallest mean height was achieved at Boora but this is somewhat misleading due to the presence of a small number of Norway spruce trees planted in 1995 which were included in the assessment. The next best growth was at Clonsast, the highest average height being on the mounded site where the reconstituted tree crop has grown particularly well from the outset. This was a woody fen peat and mounding this peat type has been successful at other afforested sites (e.g. Mount Lucas). The inverted mound and elevated microsite can also help the trees to compete with the vegetation. The smallest trees have consistently been found at the Mongagh reconstituted area, where the Norway spruce growing within the original crop of Sitka spruce is doing much better than those growing on the ploughed area.

Except for Derryounce, all the reconstituted areas are now well established and growth continues to improve. After three to four years, they have overcome any problems of ground vegetation competition. Competition with naturally regenerated trees (lodgepole pine, oak) and re-coppicing of spruce may be a problem on certain sites requiring a longer maintenance programme.

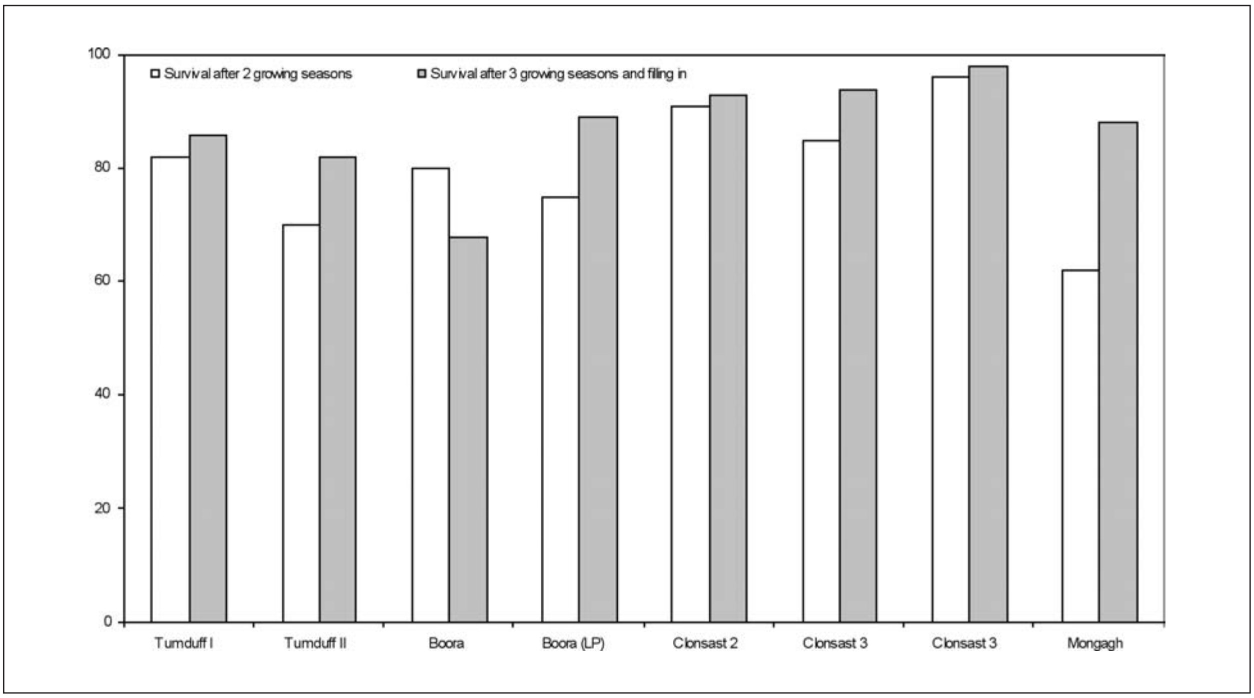


Figure 5.76: Survival after 2 and 3 growing seasons in Norway spruce reconstituted areas.

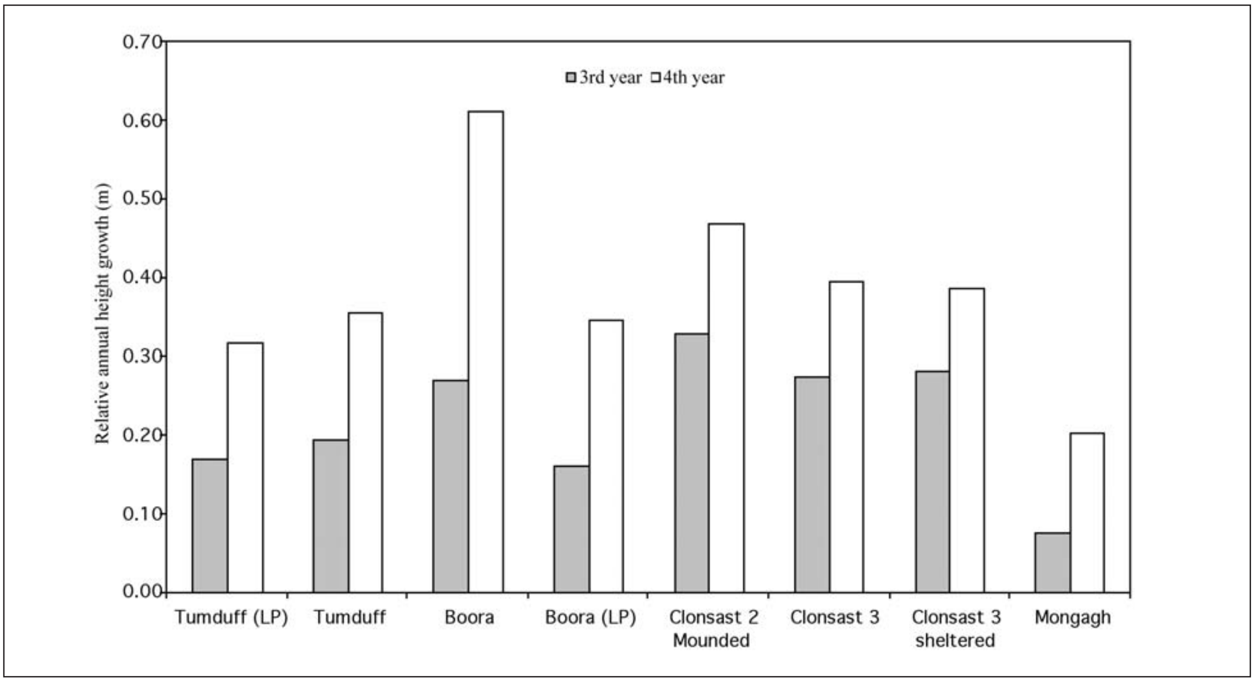


Figure 5.77: Annual height growth during the third and fourth year in the Norway spruce reconstituted areas.

Main problems encountered during reconstitution

- **Drains**: The drains already present on these areas may need to be dug deeper if the site requires further drainage. In most cases however, these drains have already been colonised with shrubs (birch and willow) which can act as shelter for the young planted crop as well as biological drainage. Some small basins may remain waterlogged and it is not worth replanting these areas, except perhaps with alder.
- **Vegetation**: Most of the sites chosen for reconstitution carry a dense ground cover (mainly *Juncus* spp.) together with taller shrubs (birch and willow). It was quickly recognised that spraying herbicide was difficult on these areas due to windy conditions. Weed-wiping the whole site prior to planting is advised in the summertime only and mechanical cleaning is necessary once the trees are planted. Resprouting of older crops (SS or LP) and the growth of naturally regenerated birch may also need vegetation control.
- **Equipment**: The flail machine was found to be suitable with small-sized trees/shrubs only (i.e. less than 5 cm DBH). An excavator-mounted clearing saw is more suitable for the removal of larger trees. The added difficulty of clearing large material is that brash needs to be windrowed using a dozer. Harvesting with a head/feller-buncher would be a better option. Weather conditions should always dictate work with equipment and timing is crucial for its success. V-shearing has been identified as a potential technique that could be used on sites where naturally regenerated birch and dense ground vegetation prevail.
- **Late spring frost**: In Norway spruce reconstituted sites where the original Sitka spruce regrew, it was often observed that the Sitka spruce was damaged again by another late spring frost, while the Norway spruce did not suffer damage as severely. This emphasised the point that it is not worth leaving the recoppiced Sitka spruce (often forked) on these sites and it is preferable to favour the Norway spruce in any cleaning operations.
- **Marl**: The current position of the Forest Service is that "soils where marl occurs within 70 cm of the soil surface are not plantable"(Forest Service 2003). While it is believed that marl may cause growth stagnation of plantations, there have been

cases of successful plantations growing on peat with marl within 70 cm of the soil surface (McCarthy 2001). Results from these sites concluded that, under favourable conditions (such as good drainage and the presence of a reasonable amount of organic matter in the soil profile), marl sites may be suitable for planting. It has often been mistakenly thought that subsoil (be in marl or other) may be the cause of poor growth, while poor drainage may in fact have been the limiting factor. Where marl is present, it inevitably means that the land was, at some point, impeded by drainage and usually localised in depressions or dammed between drumlins (Feehan and O'Donovan 1996b). When the peat has been removed, these areas can again become waterlogged. Consequently, drainage problems need to be properly assessed and remedied first if planting (either afforestation or reconstitution) is to be carried out on such soils.

Conclusions and management implications

No ‘blanket’ treatment may be applied on older failed or poor cutaway plantations, as these sites are typically non-uniform and the reasons for failure may vary across sites. Some areas may be left unplanted and eventually add to the diversity of the plantation. In some cases, an option may be to retain and interplant the older crop, thereby providing shelter to the newly planted crop from exposure and frosts. Consideration might also be given to harvesting the older trees for energy generation (especially in the case of pine for example).

When removing the previous poor crop for reconstitution, suitable equipment should be chosen: the flail for light material or feller-buncher for larger trees. It is best to carry out any site preparation work during the summer, ideally July to September, but weather and subsequent ground conditions should dictate progress. Windrowing or biomass removal for fuel may be options where the volume of brash is significant. Care should be taken to ensure that drains are not damaged by machinery. Mounding is advisable on peat types other than *Phragmites* and loose consolidated *Sphagnum*, of residual depth is greater than 50 cm.

The principles of reconstituting failed areas do not differ much from initial afforestation. As mentioned earlier, the application of phosphatic fertiliser is necessary after reconstitution and prescriptions are the same as for initial afforestation. It is even more important to have a vegetation management plan. Cleaning in advance of planting is crucial but because the seed bank is already present, effective vegetation control is required soon after planting. Three years of vegetation control should suffice as the trees usually grow faster than in an open bare peatland situation.

SUMMARY POINTS: RECONSTITUTION

- *The choice of management operations should be tailored to the site conditions which should be assessed prior to removal of the failed crop in order to choose the best methods.*
- *Interplanting may be a cheaper option than total clearance but this depends on the stocking of the existing crop.*
- *The reconstitution of failed Sitka spruce plantations with Norway spruce following clearance with a flail has been successful.*
- *Mounding is also appropriate in certain conditions.*
- *The choice of species and the control of competing vegetation are probably the most critical aspects to successful establishment of reconstituted crop.*

Biomass production potential

As part of the BOGFOR research programme, the biomass potential of both naturally regenerated and planted tree crops was assessed by measuring the different tree components (only above-ground biomass data are presented here).

Potential biomass production from a lodgepole pine plantation

In March 2006, biomass production in a lodgepole pine plantation located in Boora, Co Offaly, was estimated.

The site consists of deep *Sphagnum* peat. It was not cultivated prior to planting with lodgepole pine (2500 stems/ha) in 1993 but received 350 kg/ha of 0-10-20 (N:P:K fertiliser) at planting. The form of the pine was very poor and suffered from PSM damage. In 2006 (age 13), stocking was estimated to be 2180 stems/ha with a mean height of 3.7 m. Five sample trees were selected from a stratified height assessment and subsequently felled and measured (Figure 5.78). The total above-ground biomass for the site was estimated at 70 t DM/ha which equates to growth of 5.4 t DM/ha/year.

Potential biomass production from a silver birch plantation

Biomaas production in a birch species plot at Tumduff, TLM35/96, was also assessed in March 2006. The site consists of a shallow woody fen peat that was not cultivated prior to planting with silver birch (2500 stems/ha) in 1996 but received 350 kg/ha of rock phosphate at planting. In 2006 (age 10), stocking was estimated to be 2120 stems/ha and mean height was 6.6 m with an average DBH of 8.2 cm. Five sample trees were selected from a stratified height assessment and measured (Figure 5.79). The total above-ground (leafless) biomass was estimated at 30.5 t DM/ha which was compartmented as follows: 22.8 t DM/ha from the stem and 8.3 t DM/ha from the branches. This equates to growth of 3.05 t DM/ha/year.

Potential biomass production from naturally regenerated birch

An alternative option to the proposed afforestation programme is the natural colonisation of cutaway peatlands by broadleaved species such as birch. Natural expansion of birch on Irish cutaway peatlands has occurred across the Irish Midlands and elsewhere. Like most natural birch woodland in Ireland, few, if any, of these natural stands

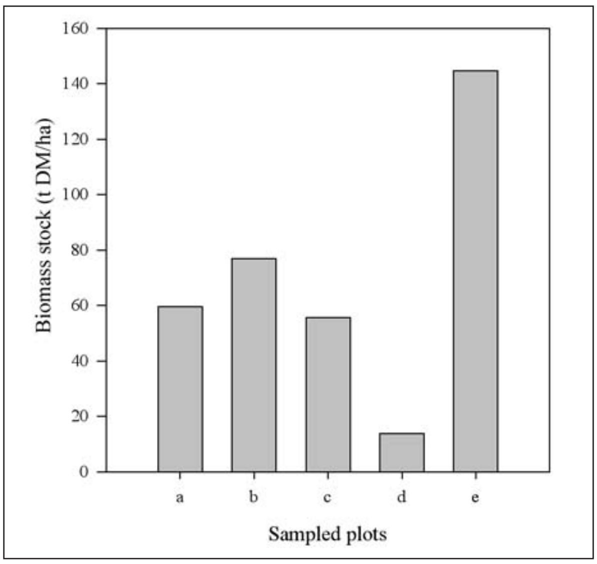


Figure 5.78: Total biomass stock estimated in each sampled plot within a 13-year-old lodgepole pine plantation.

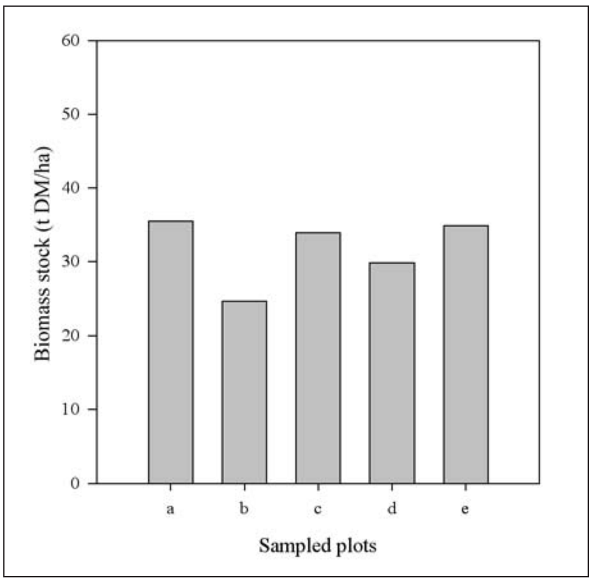


Figure 5.79: Total biomass stock estimated in each sampled plot within a 10-year-old silver birch plantation.

were managed for timber. Nonetheless, Nieuwenhuis and Barrett (2002) found that the potential productivity of naturally regenerated downy birch on a peatland site was the highest of the six sites studied (including mineral site types) with a top height/age curve representative of Yield Class 8. Although conditions seem favourable for the natural establishment of birch seedlings on some cutaway peatlands, their continued development is more questionable. Results in Finland are promising and show that management of naturally regenerated birch on cutaway peatlands is an attractive option regardless of the desired final product, pulpwood, veneer logs or wood for energy (Kinnaird 1974; Hytönen and Aro 2004). One of the main features of these woodlands is that they have been established without management inputs and therefore at little or no cost.

Two sites located in the Irish Midlands were investigated to estimate the biomass potential of birch growing naturally on cutaway peatlands.

Turraun

At Turraun, a site survey was undertaken to investigate the stocking density and the species composition of this naturally re-colonised cutaway in 2003 and 2004. The average birch height was 5.5 m with an average DBH of 5.8 cm and an average density of 4867 stems/ha. Based on the analysis of 10 trees, the total above-ground leafless biomass was estimated at 47.1 t DM/ha and as with the planted birch, most of this biomass was contained in the stemwood (29 t DM/ha).

Based on tree ring analysis, the Turraun stand ranged from 10 to 20 years old. Taking an average of 15 years, an estimate of biomass production was calculated as an average annual biomass increment of 3.3 t DM/ha/yr. This is lower than results from research in Finland (Hytönen and Kaunisto 1999; Hytönen and Aro 2004) where a yield of 4.5 tonnes of dry biomass per ha per annum was measured on a cutaway peatland. However, the density was almost double that of Turraun reaching 11,000 stems/ha. A second naturally regenerated birch woodland was thus sampled at Boora in order to get another estimation of potential biomass from naturally regenerated birch on cutaway peatlands.

Boora

This small naturally regenerated birch woodland is located at Boora and estimated to be around 20 years of age. The average height of the birch was 8.2 m with an average DBH of 7 cm with 9300 stems/ha. Based on the analysis of 10 trees, the total above-ground (leafless) biomass was estimated at 115 t DM/ha. This is equivalent to an average annual biomass increment of 5.8 t DM/ha/yr.

Conclusion

These studies highlighted variations between naturally regenerated birch stands existing on industrial cutaway peatlands (Table 5.49). It should be emphasised that these stands did not receive any inputs. The study also shows some potential for planted birch if the density was appropriately increased (densities up to 10,000 stems/ha should be tested). The highest biomass figures came from naturally

Table 5.49: Summary of biomass production of different crops.

	Average height (m)	Estimated age	Stems/ha	Biomass* t DM/ha/year
Naturally regenerated birch (Boora)	8.2	20	9300	5.8
Naturally regenerated birch (Turraun)	5.5	15	4867	3.1
Planted silver birch (Tumduff)	6.6	10	2120	3.1
Planted lodgepole pine (Boora)	3.7	13	2180	5.4
Planted Sitka spruce (Lullymore)	12	19	1367	16

*Above-ground leafless biomass

regenerated birch at Boora simply due to the higher number of stems. The lodgepole pine plantation also showed good biomass production.

Energy wood production may end up playing a significant role in the national energy strategies in the future. Further research and development is needed in this area to ensure its eventual success.

6: Draft guidelines and concluding remarks

Summary of major findings

This report presents a large number of results and recommendations as an aid to the establishment of a sustainable forest crop on industrial cutaway peatlands in the Irish Midlands. It does not present all the answers but attempts to outline key issues that should be considered in afforesting cutaway peatlands. Although cutaway peatlands might appear to be uniform, they do in fact contain a great deal of heterogeneity. The adoption of a single afforestation blueprint for this land is therefore not appropriate.

Only a proportion of the total cutaway peatland area will ever be suitable for commercial forestry. This area has been estimated by Bord na Móna to be between 16,000 and 20,000 ha. However, due to the nature of peat production, the rate at which this land becomes available is uncertain and subject to considerable year-to-year fluctuation.

It was concluded from the early results of over 200 ha of experimental and demonstration cutaway peatland forests that the successful afforestation of cutaway peatland requires (a) a sound afforestation plan with specific objectives, (b) a careful selection of sites with suitable characteristics and (c) specific operational methods (e.g. deep ploughing and provision of shelter), tailored to the site conditions and species requirement.

The land released after harvesting is not immediately suitable for commercial afforestation. It is first necessary to alter the physical and biochemical properties of the peat in order to provide a suitable growing medium. However, with careful site selection, good drainage, site preparation, species selection and fertilisation practices, a range of species can be established on cutaway peatland sites. Based on experience and knowledge to date, guidelines have been drafted for the successful establishment of forest crops on specific cutaway site types.

Draft guidelines based on experience and knowledge to date

a) General guidelines

Site selection

Proper site selection is vital if a successful forest is to be established and a detailed site survey (drainage status as well as peat depth and peat type sampled every 0.25 ha) is required to provide reliable information which will help in the choice of management options, e.g. site preparation and choice of species (see site-adapted guidelines). The need for an adequate drainage system, including gradient and suitable outlet, is critical but it should be noted that part of any large cutaway peatland site will inevitably be unsuitable for commercial forestry and could be managed as wetland or to enhance biodiversity.

Woody fen and shallow/well-aerated *Phragmites* peats with good drainage are generally considered good sites for forestry. Site preparation will be required if the permanent layer of aerated peat is not deep enough. Deep *Sphagnum* peat sites can be problematic for the growth of trees other than pine species.

Site preparation

The site preparation method must be selected to suit the site conditions (see below site-adapted guidelines). It is critical that a site is gravity drainable in order to carry out further site preparation as cultivation, no matter how good, will not turn a poor site into a good one.

On the basis of present knowledge, no site preparation is considered necessary on well-aerated woody fen or shallow *Phragmites* peats, although experimental results did show a benefit from deep ploughing in height growth in the early years. Deep ploughing will help in creating a permanent aerated layer if it succeeds in bringing sub-peat mineral soil to the surface. Mixing peat and sub-peat mineral soil provides an excellent medium; the optimum mixture would be 80% peat and 20% mineral soil. Planting in pure sub-peat mineral soil should be avoided.

Poorly drained woody fen and *Sphagnum* peats will benefit from mounding but it is not recommended to mound *Phragmites* peat.

Species

The high probability of frosts occurring on cutaway peatlands during the Sitka spruce bud burst period renders this species at risk and differences due to provenance are not sufficiently large to remove this risk. Norway spruce is the preferred commercial species for cutaway peatlands due to the reduced risk of damage by late spring frost. Alternatively, a nurse crop will have the advantage of offering protection against last spring frosts, thus allowing the choice of a wider range of species, including a higher yielding species such as Sitka spruce.

The occurrence of pine shoot moth in certain areas in the Midlands precludes the use of lodgepole and Scots pines near infested plantations. Corsican and Macedonian pine are less sensitive to pine shoot moth and can be used instead, especially on lower quality sites such as acidic (*Sphagnum*) deep peat. Hybrid larch has potential as a shelter/nurse species on dry sites.

Common alder is an excellent pioneer species for the cutaway bogs and can be planted over a variety of sites in advance of a more commercial species.

Fencing (or individual plastic tube shelter) is required wherever broadleaves are planted to avoid browsing by hares.

Stock types

While large bare-root Norway spruce seedlings may be a better immediate choice if vegetation control is not ideal, smaller bare-root or containerised seedlings may be more productive in the long run. It is preferable to use containerised seedlings for hybrid larch and Corsican pine.

Fertilisation regime

A split fertiliser application is recommended on cutaway peatlands, especially on bare peat fields:

- 175 kg/ha rock phosphate applied in bands at planting;
- 175 kg/ha rock phosphate broadcast two years later together with 250 kg/ha of muriate of potash.

The same regime is recommended when underplanting in a nurse crop.

Vegetation control

Timely and effective vegetation control is necessary and it is important to monitor plantations for competition from the onset.

Cutaway peatlands are suited to mechanical or semi-mechanical cleaning with purpose-built equipment such as mowers or weed-wipers. It is not recommended to spray herbicides.

b) Site-adapted guidelines

Following the three-step evaluation protocol proposed below, four typical cutaway peatland site conditions (G1-G4) can be identified which would require further specific management options.

G1: Cutaway peatlands which have been naturally recolonised by birch

Site preparation:

- If birch height is over 5 m with some well-formed trees, selective felling of birch in blocks.

Three-step site evaluation

Step 1: General identification of cutaway peatlands			
1	Cutaway peatlands that were pumped during peat production	→	No commercial planting
2	Cutaway peatlands that are locatd in a depression, close to the bottom contour of the bog floor	→	No commercial planting
3	Cutaway peatlands that have been recolonised naturally by birch and willow	→	G1
4	Cutaway peatlands that have recently come out of peat production (bare brown fields); gravity drainable, suitable outlet	→	Step 2
Step 2: Peat depth			
1	Very shallow peat (<50 cm) over undeveloped mineral soils or marl	→	No commercial planting
2	Very shallow peat (<50 cm) over weathered mineral soil	→	G2
3	Shallow peat (50-100 cm)	→	G2
4	Deep peat (>100 cm)	→	Step 3
Step 3: Peat type			
1	*Phragmites* peat	→	G3
2	*Sphagnum* peat	→	G4

- If birch height is below 5 m, clean corridors leaving rows of shrubs as shelter.
- Ensure drainage outlet allows free flow of water from site.

Species choice:

- Sitka spruce, Norway spruce, pedunculate oak.

Other management practices:

- Timely vegetation control to whipping.

G2: Cutaway peatlands which are gravity drainable with suitable outlet and which have <100 cm remaining peat

Site preparation:

- Ensure drainage outlet allows free flow of water from site.
- Clean existing drainage system.
- Create a permanent aerated layer (most economical technique still to be developed).

Species choice:

- Norway spruce, Corsican pine, Macedonian pine, hybrid larch, western red cedar.
- Alder or silver birch can be planted with a view to underplanting after 5 years or so with Norway spruce, Sitka spruce or pedunculate oak.

G3: Cutaway peatlands which are gravity drainable with suitable outlet and which have a deep (>100 cm) *Phragmites* peat layer.

Site preparation:

- Additional drainage system required with deep drains in most affected areas.
- Create a permanent aerated layer (most economical technique still to be developed).

Species choice:

- Norway spruce (if site not too exposed), Corsican pine, Scots pine.
- Preferred option: plant alder or silver birch with a view to underplanting with Norway spruce, Sitka spruce or pedunculate oak after five years or so.

G4: Cutaway peatlands which are gravity drainable with suitable outlet and which have a deep (>100 cm) *Sphagnum* peat layer

Site preparation:

- Additional drainage system required with deep drains in most affected areas.
- Create a permanent aerated layer (most economical technique still to be developed).

Species choice:

- Corsican pine, Macedonian pine.

Future directions

BOGFOR has opened the door to the potential for industrial cutaway peatlands to grow successful forest crops. The results from the programme should, however, be treated with caution as most of the conclusions are based on the performance of young plantations. These results can only be verified by continued monitoring of growth. Further work is also needed to reach a sufficient scientific base for finalising best management options for different sites. Future research is also necessary to obtain better predictions of productivity, potential wood production and overall performance in relation to species and site. A phased approach to the afforestation of these sites is needed, backed up by an ongoing research programme.

The most immediate information gap highlighted in this report is the need to test new site preparation methods such as the bedding plough and the V-shearing equipment under Irish conditions. Another important area is the monitoring of foliar nutrients in order to create baseline records for stands of different quality on cutaway peatlands. Further fertiliser trials should also be established to get a better understanding of the optimum nutrient levels for both the medium and long-term. The possibility of using wood ash or sludge should be integrated in future trials, as well as manufactured fertiliser with P-holding capacity. The possibility to restore part of cutaway peatland and create a wetland to be used as a biofilter should also be explored. The use of container seedlings especially for Norway spruce, Corsican pine and larch should also be further investigated for these site types.

Policy related issues

The afforestation of cutaway peatlands is a long-term investment where the income benefits typically lag behind the initial capital costs of establishment. As such, it cannot be expected to take place without capital support. At present, no grant aid is available for afforestation of cutaway but this situation may now be changed as a result of the draft EC Rural Development Regulation. The recommendation is that a scheme be introduced post-2006 to enable afforestation of cutaways to be phased in over the period of the new regulation. This new afforestation scheme should be subject to an independent review of performance and growth after five years.

Outlook

The afforestation programme of the cutaway peatlands could become one of the largest reclamation projects in Ireland and as such will be critically evaluated in a wider environmental context. The capacity of forests to influence the greenhouse gas balance has recently come into sharp focus, especially in the context of Ireland's significant current economic growth and accompanying increases in emissions. The role of peatland forests and especially cutaway peatland forests in sequestering atmospheric CO_2 remains uncertain. Little is known of the long term effects of forestry on cutaway peat, but from evidence in the literature and work carried out in BOGFOR, once the trees are established, decomposition of the peat will accelerate. Once the depth of the aerobic layer in peat increases, methane emissions cease, but decomposition rates and soil CO_2 emissions increase (Byrne and Farrell 1997, 2000; Waddington et al. 2002). However, these losses may be offset by CO_2 sequestration in the forest crop (Byrne and Farrell 2000). Afforested peatlands in Scotland have been shown to accumulate more carbon in litter, soil, and forest products than is lost from the peat for 90-190 years (Hargreaves et al. 2003). However, future management options on cutaway peatland forests, such as rotation lengths, clearfelling, reforestation, and site preparation will impact upon carbon storage and the greenhouse gas balance.

The planting of substantial forests in proximity to the new peat power stations could provide an opportunity for co-firing the stations with peat and forest biomass (such as thinnings and forest residues) thus mitigating CO_2 emission levels.

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BOGFOR PUBLICATIONS AND OUTPUTS

Publications submitted to/ in preparation for peer-reviewed journals

Renou-Wilson, F., Keane, M. and Farrell, E.P. Submitted. Effect of stocktype and cultivation treatment on the survival, morphology and physiology of Norway spruce on cutaway peatlands. *New Forests.*

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2006-2008

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Workshops

29 September 1999: Workshop in Boora led by Pat Hanrahan, Coillte. The aim was to engage the discussion with very experienced foresters, both in active service and retired with particular experience of the establishment of Coillte plantation on Bord na Móna cutaway peatlands during the 1980s and early 1990s.

5 November 1999: Workshop in Tullamore Court Hotel, led by Prof. E. P. Farrell with presentations by personnel involved in the BOGFOR project followed by discussion with foresters, stakeholders and consultants.

20 October 2002: Workshop at UCD lead by Florence Renou with presentation on: What is the optimum depth of peat required for growing trees on industrial cutaway peatlands?

8 June 2004: Worshop during the 12th International Peat Congress in Tampere, Finland. Florence Renou and Lasse Aro, Finnish Forest Research Institute (METLA), organised a round-table discussion on the specific theme of afforestation of cutaway peatlands. The goals of this meeting were to exchange information and ideas concerning the afforestation of cutaway peatlands, to review current research in Finland, Ireland and Canada and to address a range of other topics. Following this workshop, Commission V (After-use of Peatlands, chaired by Line Rochefort) and Commission VII agreed at the IPS chair meeting in Amsterdam in 2004, to create a joint working group on the subject of forest plantations on cutover peatlands. The goal of this working group is to organise the exchange of information and field workshops on how to grow trees on cutover and cutaway peatlands. This can be aimed at timber production or habitat creation to improve biodiversity.

Outreach material

22-27 September 2003: Invited by Line Rochefort, Professeur titulaire, Groupe de Recherche en Écologie des Tourbières (GRET) et Département. Phytologie, Université Laval, Québec, Canada, to give a talk and provide expertise during a week-long international workshop in Québec and New Brunswick, Canada, on the afforestation of cutaway peatlands; Duration of assignment: 22-27

September 2003.Talk title: ‘Presentation des projets de plantations forestières sur tourbières résiduelles en Irlande’ (Presentation of research work in relation to the afforestation of cutaway peatlands in Ireland).

5 September 2003: Field day presentation to the Society of Irish Foresters.

3 March 2003: Field day presentation to a group of forest researchers from Alice Holt Research Station, Forestry Commission, UK (Drs Andy Moffat, Mark Broadmeadow and Tom Nisbet).

24 September 2002: Field day presentation to a group of scientists in genetics and tree improvement (lead by David Thompson (Coillte).

2001-2004: Annual field day presentation to forestry students from Waterford Institute Technology (Dr Nick McCarthy) and 4th year AES and Masters students from University College Dublin (Dr John Feehan).

Appendix 1: BOGFOR research team and responsibilities

BOGFOR Senior Committee:

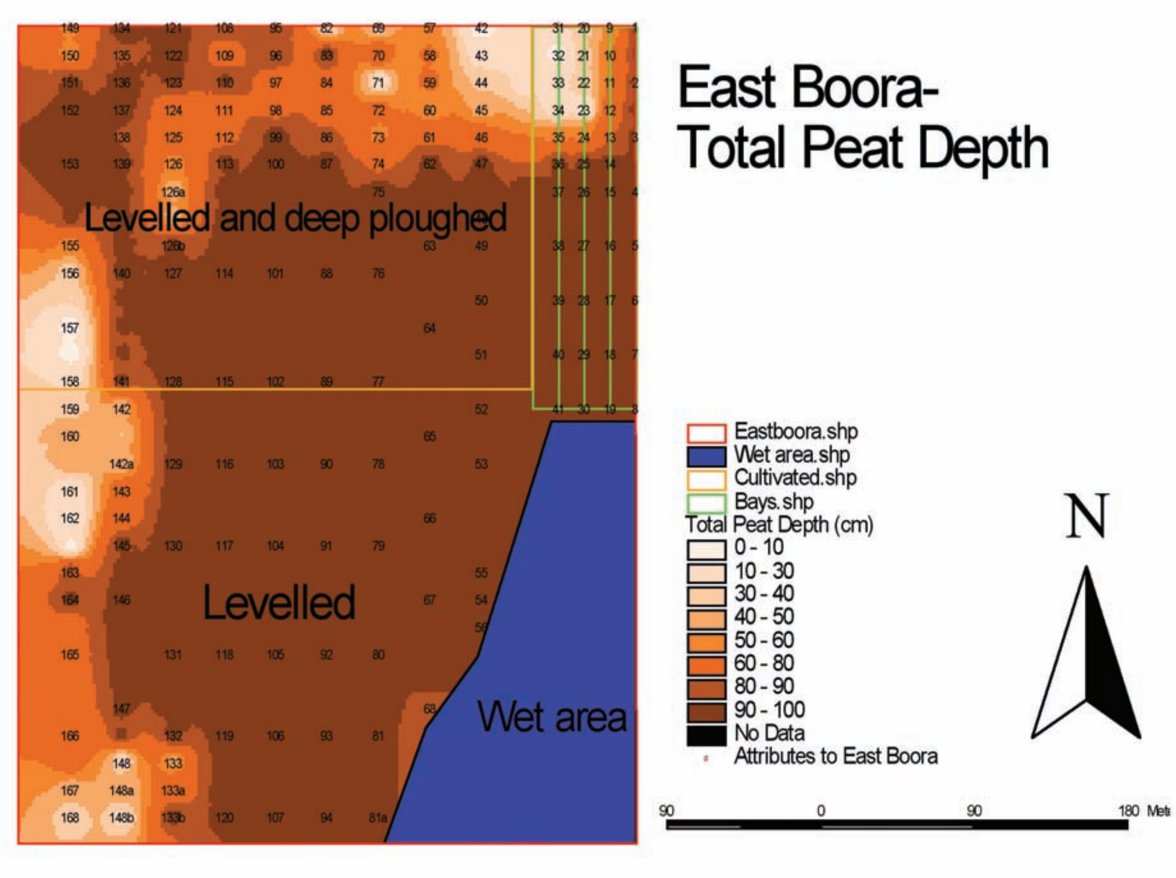
Name	Organisation	Responsibility
Ted Farrell	UCD	Programme leader
Florence Renou-Wilson	UCD	Programme manager
Gerry McNally	Bord na Móna	Sourcing land, site preparation
John O’Sullivan	Coillte	Management
Mick Keane	Coillte	Species and cultivation trials

Tom Egan	Bord na Móna	Site preparation and sourcing
Joe Freeman	Coillte	Species and cultivation trials
Pat Hanrahan	Coillte	Demonstration areas
Dick McCarthy	Coillte	Older trials
Diarmuid Ò’Riordan	Coillte	Demonstration areas
Declan Ward	Coillte	Pine shoot moth
Gerhardt Gallagher	Consultant	Assessment and reporting
Fergal Mulloy	Consultant	Advisory role
Donal O’Hare	Consultant	Assessment
Seamus Dunne	Forest Service	Advisory role
Diarmuid McAree	Forest Service	Advisory role
Jim Quinlivan	Forest Service	Advisory role
Eugene Hendrick	COFORD	Advisory role
Cathy Bennett	UCD	Vegetation study reporting
Jill Boyle	UCD	Cracking study, management 1999
Norman Butler	UCD	Field technician
Raquel Cabral	UCD	GIS mapping
Aoife Cassidy	UCD	Mycorrhizae study
Thomas Cummins	UCD	Collation of data
Carly Green	UCD	Frost study
Suzanne Jones	UCD	UCD programme manager 1998 to 2000
James McCann	UCD	Peat characteristics study
Mark McCorry	UCD	Vegetation study
Gillian McGrath	UCD	Lab technician
Sharon Parr	UCD	Vegetation study
Minna Pöllänen	UCD	Vegetation and birch PhD study
Elaine Smith	UCD	Frost study, foliar sampling
Rae Sullivan	UCD	Lab technician

Appendix 2: BOGFOR study sites

Experiment name	Type of experiment	Site name	Area (ha) (planted)	Area (ha) on map (fenced)
Allen 1/00	Cultivation trial	Mount Lucas	4	
Allen 2/00	Species trial	Mount Lucas	11	
Allen 3/00	Fertiliser trial	Mount Lucas	1	
		Mount Lucas	**16**	**Mount Lucas 17.7**
Emo 1/00	Demonstration area	Clonsast	**15**	**Clonsast 15.2**
KTY 1/99	Demonstration area	Blackwater	15	
KTY 14/00	Nurse species trial	Blackwater	4	
KTY 15/00	Spacing trial	Blackwater	1.5	
KTY16100	Cultivation trial	Blackwater	4.5	
KTY 17/00	Species trial	Blackwater	6.5	
KTY18/00	Species trial	Blackwater	5	
KTY 19/00	Birch stock trial	Blackwater	1.2	
KTY 20102	Stock trial	Blackwater	1.7	
		Blackwater	**39.4**	**Blackwater 40**
CLE 1/99	Demonstration area	Tumduff	15	
CLE2/00	Cultivation trial	Tumduff	4.1	
CLE3/00	Species trial	Tumduff	4	
CLE 4/00	Species trial	Tumduff	7.4	
CLE5100	Species trial	Tumduff	8.2	
CLE6100	Fertiliser trial	Tumduff	1	
CLE 7/00	Fertiliser trial	Tumduff	1	
		Tumduff	**40.7**	**Tumduff 57.1**
TLM35196	Species trial	Tumduff North	**11**	**Tumduff North 12**
EB 1/00	Species trial	East Boora	4	
EB 2/00	Larch stock trial	East Boora	1	
EB 3/00	Nurse species trial	East Boora	2	
EB 4/00	Stock trial	East Boora	0.5	
EB 5/00	Fertiliser trial	East Boora	4.5	
		East Boora	**12**	**East Boora 13.5**
TOTAL NEWLY PLANTED BOGFORSITES			**134.1**	**155.4**
74087F	Reconstituted	Tumduff West	10	10
74103U	Reconstituted	Tumduff West	5	5
74084U	Reconstituted	Boora	5	5
74084U (LP)	Reconstituted	Boora 5	5	
77572A	Reconstituted	Clonsast 2	10	10
75570K	Reconstituted	Clonsast 3	5	5
77576D	Reconstituted	Clonsast 3	5	5
73475B	Reconstituted	Mongagh	5	5
TOTAL RECONSTITUTED SITES			**60**	**60**
TOTAL BOGFOR SITES			**194.1**	**215.5**

Appendix 3: Example of GIS map showing peat depth variation at a cutaway peatland site (East Boora)



Appendix 4:
Characteristics of peat at the BOGFOR sites

Sites	n*	pH	N (%)	P (%)	K (%)	Ca (%)	Fe (%)	Mg (%)	S (%)	Mn (%)
Highly humified *Sphagnum* peat										
Tumduff R	15	3.89 (0.1)	1.32 (0.31)	0.024 (0.0067)	0.021 (0.0052)	0.67 (0.185)	0.201 (0.11)	0.012 (0.0020)	0.25 (0.027)	0.005 (0.003)
Clonsast	24	3.70 (0.1)	1.33 (0.17)	0.025 (0.0066)	0.033 (0.0143)	-	-	-	-	-
15 year old forests	18	3.60 (0.2)	1.15 (0.05)	0.022 (0.007)	0.007 (0.002)	0.93 (0.49)	0.45 (0.4)	0.109 (0.066)	0.34 (0.17)	0.003 (0.005)
Phragmites peat										
East Boora - shallow	18	4.90 (0.52)	1.19 (0.65)	0.017 (0.002)	0.036 (0.035)	2.01 (1.00)	0.51 (0.17)	0.107 (0.036)	0.352 (0.17)	0.008 (0.005)
East Boora - deep	18	4.29 (0.26	0.91 (0.26)	0.017 (0.002)	0.008 (0.008)	0.57 (0.28)	0.18 (0.09)	0.117 (0.030)	0.229 (0.026)	0.003 (0.001)
Tumduff F - deep	36	4.63 (0.22)	2.17 (0.23)	0.017 (0.007)	0.01 (0.009)	0.16 (0.02)	0.86 (0.34)	0.064 (0.015)	0.53 (0.19)	0.035 (0.013)
Rumduff R - deep	8	3.96 (0.15)	1.76 (0.27)	0.037 (0.008)	0.030 (0.012)	0.94 (0.16)	0.45 (0.16)	0.009 (0.001)	0.30 (0.03)	0.01 (0.003)
Blackwater - deep	24	5.00 (0.6)	2.03 (0.19)	0.033 (0.008)	0.22 (0.021)	-	-	-	-	-
15 year old forests	14	5.1 (0.1)	1.7 (0.48)	0.029 (0.009)	0.012 (0.009)	1.5 (0.83)	1.14 (0.73)	0.07 (0.04)	0.51 (0.14)	0.0018 (0.02)
Woody fen peat										
Noggus	1	5.8	1.44	0.022	0.087	2.16	0.98	0.041	0.56	0.002
Derrybrat	1	5.2	1.53	0.044	0.064	0.68	0.62	0.073	0.27	0.003
Derryrobinson	1	5.3	2.18	0.022	0.024	0.42	1.21	0.084	0.51	0.028

* number of samples analysed

Appendix 5: List of provenances of species used in the BOGFOR programme

Area	Experiment	Species	Code	Origin
Blackwater (Area 1)	Kinnitty 14/00 (SS nursing trial)	*Betula pubescens*	Plots 1-6	BC UK106 ZP20
			Plots 7-18	BC UK Scot W43
		Picea sitchensis	SQ1 - 2+1	SQ UK Scot V12
	Kinnitty 15/00 (birch spacing trial)	*Betula pubescens*	All plots	BC UK106 ZP20
Blackwater (Area 2)	Kinnitty 16/00 (cultivation trial)	*Picea sitchensis*	SQ1 - 2+1	SQ UK Scot V12
		Pinus sylvestris	SP2 - 1u1	SP IE 1405 V91
		Larix x eurolepis	2+2	HL IE 1111 V111
		Picea abies	NS1	NS DKT V1L T03
	Kinnitty 17/00 (demonstration area)	*Thuja plicata*	WR4 - 3yr.	WR USA (Van) ZP11
		Pinus contorta	LN1 1u1	LN-UK QCI V44
		Pinus nigra var. maritima	Rootrainers	Corsica
			20-40cm	94 (44) 04F
		Pinus peuce		
		Taxus baccata	Rootrainers	Shropshire
			10-20cm	96 (40) F
		Quercus robur	OP3 1u1	OP-NL3-W04
		Alnus glutinosa	AC3 1u1	AC-UKDURH-W68
		Acer pseudoplatanus	SY3 1u1	SY-NL3-W63
		Alnus cordata		AL – PVM – ZP16
Blackwater (area 3, shallow peat)	Kinnitty 18/00 (demonstration area – shallow peat)	*Pinus sylvestris*	SP 1u1	SP IE 1405 – V91
		Larix x eurolepis	HL 1u1	UKENG – W28
		Taxus baccata	Rootrainers	Shropshire
			10-20cm	96 (40) F
		Quercus robur	OP3 1u1	OP-NL3-W04
		Quercus petraea	OS3 2+0	FR ZP75
		Fraxinus excelsior	AS4 1u1	AS-IE V108
		Populus tremula	Rootrainers	Hungary
			40-60cm	99 (439)
		Betula pendula	Rootrainers	Newstyle select
			40-60cm	93 (20) F
	Kinnitty 19/00 (birch stock trial)	*Betula pendula*	Rootrainers	Perthshire
		111	20-40cm	96 (20) Scottish
		Betula pendula	Rootrainers	Perthshire
		112	40-60cm	96 (20) Scottish
		Betula pendula	Bareroot	BS-HEDE - ZP59
		121	20-40cm	Danish
		Betula pendula	Bareroot	BC UK105 - ZP02
		122	40-60cm	Scottish
		Betula pubescens	Rootrainers	Bad an Scalaig
		211	20-40cm	98 (105) Scottish
		Betula pubescens	Rootrainers	Bad an Scalaig
		212	40-60cm	98 (105) Scottish
		Betula pubescens	Bareroot	BC UKSCOT
		221	20-40cm	W43 Scottish
		Betula pubescens	Bareroot	BC UKSCOT
		222	40-60cm	W43 Scottish

Area	Experiment	Species	Code	Origin
Tumduff (Area 1)	Clonaslee 2/00 (cultivation trial)	*Picea sitchensis*	SQ1 2+1	SQ – UKSCOT -V12
		Picea abies	NS1 2+2	NS DKTV1L T03
		Larix x eurolepis	HL1 1+1	HL – UKENG V42
		Pinus sylvestris	SP2 1u1	SP – IE1405 V91
	Clonaslee 3/00 (demonstration area)	*Pinus sylvestris*	SP2 1u1	SP – IE1405 V91
		Larix x eurolepis	HL1 1+1	HL – UKENG W28
		Quercus robur	OP 1u1	OP – NL3 WOD
		Alnus glutinosa	AC 1u1	UKDURH – W68
		Acer pseudoplatanus	SY 1u1	NL3 W63
Tumduff (Area 2)	Clonaslee 4/00 (demonstration area)	*Picea sitchensis*	SQ1 2+1	SQ – UKSCOT V12
		Picea abies	NS1 2+2	NS DKTV1L T03
		Pinus sylvestris	SP2 1u1	SP – IE1405 V91
		Larix x eurolepis	HL1 1+1	HL – UKENG W28
		Larix kaempferi	JL1 1+1	JL UKENG V99
		Thuja plicata	WR4 - 3yr.	WR USA (Van) ZP11
		Pinus contorta	LN1 1u1	LN-UK QCI V44
		Pinus nigra var. maritima	Containerised	Corsica
			20-40 cm	94 (44) 04F
		Acer pseudoplatanus	SY 1u1	NL3 W63
Tumduff (Area 3)	Clonaslee 5/00 (birch regeneration area)	*Picea sitchensis*	SQ1 2+1	SQ – UKSCOT V12
		Picea abies	NS1 2+2	NS DE840 S22
		Quercus robur	OP3 1u1	OP-NL3-W04
Mount Lucas	Allen 1/00 (cultivation trial)	*Picea sitchensis*	SQ1 2+1	SQ – UKSCOT
				V12
		Picea abies	NS1 2+2	NS DKTV1L
				T03
		Pinus sylvestris	SP2 1u1	SP – IE1405
				V91
		Quercus robur	OP3 1u1	OP-NL3-W04
	Allen 2/00 (demonstration area)	*Pinus sylvestris*	SP2 1u1	SP – IE1405
				V91
		Pinus nigra var. maritima	Rootrainers	Corsica
			20-40cm	94 (44) 04F
		Larix x eurolepis	HL1 1+1	HL – UKENG
				W28
		Taxus baccata	Rootrainers	Shropshire
			10-20cm	96 (40) F
		Thuja plicata	WR4 - 3yr.	WR USA (Van) ZP11
		Pinus peuce		
		Alnus glutinosa	AC3	AC UK203 ZP04
		Acer pseudoplatanus	SY 1u1	NL3 W63
		Quercus robur	OP3 1u1	OP-NL3-W04
		Quercus petraea	OS3 2+0	FR ZP75
		Betula pubescens	BC3	BC UK106 ZP20
		Fagus sylvatica	BE3	BE UKENG ZP08
		Alnus cordata		AL – PVM – ZP 16
		Acer platanoides		NM – MAPLE – ZP72
		Populus beaupré	90-120cm	No details available

Area	Experiment	Species	Code: grade and stock type	Origin
Tumduff	TLM35/96	*Fraxinus excelsior*	AS3 -1u1	23/I/95
Tumduff	TLM35/96	*Quercus robur*	OP3 -1u1	104/I/94
Tumduff	TLM35/96	*Fagus sylvatica*	BE4 - 1u1	96/I/93
Tumduff	TLM35/96	*Alnus glutinosa*	AC2 - 3	20/09/1992
Tumduff	TLM35/96	*Acer pseudoplatanus*	SY2 - 2	20/09/1993
Tumduff	TLM35/96	*Picea sitchensis*	SW1 - 2+1	94/R/91
Tumduff	TLM35/96	*Picea abies*	NS1 - 2+2	104/L/92
Tumduff	TLM35/96	*Pinus contorta (S. C)*	LS2- 1u1	HC/1409/92
Tumduff	TLM35/96	*Pinus contort (N.C.)*	LN1- 1u1	23/01/1993
Tumduff	TLM35/96	*Pinus sylvestris*	na	92(2010)F
Tumduff	TLM35/96	*Thuja plicata*	na	96/122256
Tumduff	TLM35/96	*Larix kaempferi*	JL1- 1+1	20M/94
Tumduff	TLM35/96	*Larix x eurolepis*	HL1- 1+1	112F/93
Tumduff	TLM35/96	*Populus*		Beaupré
Tumduff	TLM35/96	*Improved birch (Elite birch)*	1U1	Black Isle Nursery seed orchard

Area	Species	Grade	Stock type	Provenance
East Boora 2003	*Quercus robur (area A)*	OP3		OP NL3 A50
	Quercus robur (area A)	OP3		OP NL3 A50
	Quercus robur (area B)	OP4		OP NL5 A51
	Alnus glutinosa	SQ1		AC-UK403-CP38
	Alnus cordata		1+1	AI-IEROSC-A127
	Picea sitchensis	AC1	2+1	SQ-IE115-V87A
	Picea abies	NS1	2+2	NS-IE2212-V88A
	Picea abies	NS2	2+1	NS-DKLUN-X78
	Picea abies	NS 1	Containerised	NS-DE-CP33
	Pinus sylvestris	SP1	Very small	SP IE00C Z153
	Larix X eurolepis	HL1 (2)	Containerised	HL-DE-CP28
	Larix X eurolepis	HL2(C)	Bareroot	HL-UKNT21J x46
	Betula pubescens	BC3		BC-UK-Z55
East boora Filling in January 2004	*Quercus robur*	OP3	1u1	OP NLSH-C22
	Picea abies	NS1	2+2	NS-DEWEST-x67
	Betula pubescens	BC3	1U1	BC-IECORK-A62
East Boora interplanting May 23005	*Picea sitchensis*	AC1	2+1	SQ-IE115-V87A
	Picea abies	NS1	2+2	NS-IE2212-V88A

Appendix 6: Thinning design in planted alder used for underplanting of spruce

Alder thinning design in Blackwater

A = Alder
S = Spruce

Before

A		A		A		A		A
	S		S		S		S	
A		A		A		A		A
	S		S		S		S	
A		A		A		A		A
	S		S		S		S	
A		A		A		A		A
	S		S		S		S	
A		A		A		A		A
	S		S		S		S	
A		A		A		A		A
	S		S		S		S	
A		A		A		A		A
	S		S		S		S	
A		A		A		A		A
	S		S		S		S	
A		A		A		A		A

After
25% alder removed

A		A		A		A		A
	S		S		S		S	
A				A				A
	S		S		S		S	
A				A				A
	S		S		S		S	
A		A		A		A		A
	S		S		S		S	
A		A		A		A		A
	S		S		S		S	
A				A				A
	S		S		S		S	
A				A				A
	S		S		S		S	
A		A		A		A		A
	S		S		S		S	
A		A		A		A		A

Alder thinning in Mount Lucas and Tumduff

A = Alder
S = Spruce

Before

```
A       A       A       A       A
    S       S       S       S
A       A       A       A       A
    S       S       S       S
A       A       A       A       A
    S       S       S       S
A       A       A       A       A
    S       S       S       S
A       A       A       A       A
    S       S       S       S
A       A       A       A       A
    S       S       S       S
A       A       A       A       A
    S       S       S       S
A       A       A       A       A
    S       S       S       S
A       A       A       A       A
```

After
18% alder removed

```
A       A       A       A       A
    S       S       S       S
A               A               A
    S       S       S       S
A       A       A       A       A
    S       S       S       S
A               A               A
    S       S       S       S
A       A       A       A       A
    S       S       S       S
A               A               A
    S       S       S       S
A       A       A       A       A
    S       S       S       S
A               A               A
    S       S       S       S
A       A       A       A       A
```

Appendix 7: Permanent foliar sampling sites within the BOGFOR programme

Plot number	Property	Compart-ment	Species	Planting year	Survey year	Survival %	Mean height[1] (m)	Health class[2]	Surface peat type	Peat depth (cm)
SSB60	Boora	74085P	Sitka spruce	1990	1997	99	2.0	C	*Phragmites*	100+
NSA58		74089S	Norway spruce	1989	1994	90	0.9	B	*Sphagnum*	100+
SSF4		74099M	Sitka spruce	1991	1998	80	2.3	B	Woody fen	40
SSA45		74097W	Sitka spruce	1990	1997	84	2.5	C	*Phragmites*	100+
SSA98	Boora West	74090L	Sitka spruce	1989	1997	88	2.5	C	*Sphagnum*	100+
SSA157	Clonsast	77573S	Sitka spruce	1989	1994	98	1.3	B	*Sphagnum*	100+
SSC127		77573S	Sitka spruce	1989	1994	90	2.0	B	*Phragmites*	100+
SSA223		77568W	Sitka spruce	1989	1994	78	1.5	C	*Phragmites*	65
SSB101	Clongawney	75155S	Sitka spruce	1989	1997	92	2.3	C	*Phragmites*	100+
SSB102		75155S	Sitka spruce	1989	1997	100	2.7	B	*Phragmites*	100+
SSB103		75155S	Sitka spruce	1989	1994	84	1.7	B	Woody fen	100+
SSC62	Derrybrat	74091G	Sitka spruce	1989	1994	78	1.8	B	Woody fen	50
NSD88		77573S	Norway spruce	1989	1994	58	1.5	C	*Sphagnum*	100+
NSD89		77573S	Norway spruce	1989	1994	85	1.7	B	Woody fen	15
NSD191	Derryhogan	43540S	Norway spruce	1989	1994	72	1.6	B	Mixed	60
NSA254		43539C	Norway spruce	1989	1994	78	1.2	B	*Phragmites*	48
NSD198		43539C	Norway spruce	1989	1994	76	1.8	B	*Phragmites*	100+
NSD199		43539C	Norway spruce	1989	1994	82	1.6	B	*Phragmites*	100+
NSD204		43539C	Norway spruce	1989	1997	92	2.3	C	*Sphagnum*	100+
NSD206		43539C	Norway spruce	1989	1994	71	1.8	B	*Phragmites*	72
SSB113	Derryrobinson	11469L	Sitka spruce	1989	1997	100	1.8	C	Mixed	100+
NSF2		11469L	Norway spruce	1989	1998	100	4.2	A	Woody fen	60
NSF3		11469L	Norway spruce	1989	1998	100	3.9	A	*Phragmites*	100+
SSA81	Drinagh West	74093T	Sitka spruce	1989	1997	98	2.7	B	*Sphagnum*	100+
SSA82		74093T	Sitka spruce	1989	1994	90	1.3	C	*Sphagnum*	100+
SSD132	Mongagh	73474G	Sitka spruce	1988	1994	92	2.2	B	*Phragmites*	35
SSF5		73474G	Sitka spruce	1988	1998	80	2.9	B	*Phragmites*	100+
SSA75	Noggus	73044G	Sitka spruce	1989	1994	82	1.6	B	Woody fen	68
NSA34	Tumduff	74088A	Norway spruce	1989	1997	56	2.2	C	Woody fen	100+
SSF1		74087F	Sitka spruce	1989	1998	100	2.4	C	*Sphagnum*	100+

[1] Mean height = the height of the "average tree" in the circular plot

[2] Health class: a plot-wide ocular assessment was made of the following criteria: crop health, needle length, chlorosis, tree form, forking, needle loss, pest damage. Taking all the criteria, including stocking, into account one of four health classes (A =best, B =satisfactory, C =in need of remedial management and F =failed) was assigned to each plot.

Appendix 8: Latin and common name of vegetation found on cutaway peatlands

Latin name	English common name
Agrostis capillaris	Common bent
Anthoxanthum odoratum	Sweet vernal grass
Betula pendula	Silver birch
Betula pubescens	Downy birch
Calluna vulgaris	Heather
Campylopus introflexus	Moss
Carex spp.	Sedge
Epilobium angustifolium	Willow herb
Eriophorum angustifolium	Cotton grass
Holcus lanatus	Yorkshire fog
Hypochaeris radicata	Cat’s ear
Juncus articulatus	Jointed ruch
Juncus bulbosus	Bulbous rush
Juncus effusus	Common rush
Loliumperenne	Ryegrass
Molinia caerulea	Purple moor grass
Phragmites australis	Common reed
Sphagnum spp.	*Sphagnum* moss
Salix spp.	Willow
Triglochin palustris	Marsh arrowgrass
Typha latifolia	Bulrush

List of tree species

Alder	Common alder*	*Alnus glutinosa* (L.) Gaertn.
	Italian alder	*Alnus cordata* (Loisel.) Duby
Ash		*Fraxinus excelsior* L.
Aspen		*Populus tremula* L.
Beech		*Fagus sylvatica* L.
Birch	Downy birch	*Betula pubescens* Ehrh.
	Silver birch	*Betula pendula* Roth
Douglas fir		*Pseudotsuga menziesii* (Mirbel) Franco
Grand fir		*Abies grandis* Lindl.
Larch	European larch	*Larix deciduas* Mill.
	Hybrid larch	*Larix* x *eurolepis*
	Japanese larch	*Larix kaempferi* (Lamb.) Carr.
Norway maple		*Acer platanoides* L.
Oak	English oak	*Quercus robur* L.
	Sessile oak	*Quercus petraea* (Matt.) Lieblein
Pine	Corsican pine	*Pinus nigra* var. *maritima* (Ait.) Melville
	Lodgepole pine	*Pinus contorta* var. *latifolia* S. Wats.
	Macedonian pine	*Pinus peuce* Griseb.
	Scots pine	*Pinus sylvestris* L.
Spruce	Norway spruce	*Picea abies* (L.) Karst.
	Sitka spruce	*Picea sitchensis* (Bong.) Carr.
Sycamore		*Acer pseudoplatanus* L.
Western hemlock		*Tsuga heterophylla* (Raf.) Sarg.
Western red cedar		*Thuja plicata* Donn ex D. Don
Yew		*Taxus baccata* L.

Glossary

Afforestation:	Conversion of land that has not been forested for a period of at least 50 years to forested land through planting, seeding and/or the human-induced promotion of natural seed sources.
Anaerobic/anoxic:	process/condition lacking oxygen.
Autecology:	term referring to the study of the ecology of a single species, including its requirements, tolerances, adaptations to its environment and responses to environmental changes.
Bare-root stock:	the seed is sown directly into the nursery seedbed soil and the seedlings are mechanically lifted and despatched to the planting sites with their roots bare of soil.
Bog:	general term for *ombrotrophic* peatland.
Bulk density:	the amount of solid material per unit volume.
Canopy:	the mass of foliage and branches formed collectively by the crowns of trees.
CO_2:	carbon dioxide.
Cleaning:	a treatment in young stands that eliminates or suppresses undesirable vegetation.
Cold-stored:	seedlings placed in cold storage (+1 - +2°C) for a short period prior to outplanting.
Competition:	refers to the competition by vegetation for resources – moisture, nutrients and light. Especially used in relation to the unfavourable influences of other vegetation on planted crop tree species.
Container seedling/containerised stock:	a seedling grown in a receptacle containing the soil, etc., in which it has developed either from seed or as transplant.
DBH - diameter breast height:	diameter of the stem measured at 1.3 m above ground level.
Discing:	a cultivation technique using disks to break up the organic layer and vegetation while loosening and incorporating these into the soil.
Dominant tree:	a tree of the upper layer of the canopy.
Ecophysiology:	the study of the interrelationship between an organism's functioning and its environment.
Introduced species:	non-native species, such as Sitka and Norway spruce.
Fen:	general term of minerotrophic peatland; formed under the influence of mineral soil water; vegetation dominated by sedges, brown mosses and *Sphagnum* moss, sometimes shrubs.

Filling in: the replacement of trees which die or fail to develop after planting.

Foliar nutrient concentration thresholds:

Deficient: concentrations associated with the occurrence of visual symptoms of deficiency and poor growth.

Marginal: concentrations that are higher than the threshold value of visual deficiency but are nevertheless associated with poor or insufficient growth. Fertilisation would be expected to increase growth.

Satisfactory: Concentrations that are associated with the maximum attainable yield. Increased foliar concentration does not lead to better growth.

Hot-lifted: seedlings that have been freshly lifted from the nursery.

Leaching: the removal of chemical constituents from rocks and soil by water.

Levelling: a treatment using bulldozers to even-out the surface of the peat (consists mainly of filling the ditches).

Mean height or diameter: the mean of the heights or diameters recorded for all the trees within an experimental plot.

Milling: method of peat extraction in which the bare peat surface is milled to a depth of 15-50 mm and harrowed to promote drying, prior to collection.

Minerotrophic: regime within which nutrients are derived directly from underlying mineral soil or flowing into the site by flooding or sub-surface water movement.

MRP: Molybdate reactive phosphate.

Mounding: creation of elevated mounds on which seedlings are planted.

Ontogeny: the origin and development of an individual organism from embryo to adult.

Ombrotrophic: regime within which nutrients are derived only from rainfall and dust.

Optimal management practices: practices that represent the best methods to achieve specific management objectives.

Paludification: the development of wetland directly over mineral ground due to waterlogging through impeded drainage and/or increase in water supply.

Peat fields: term used for the areas between the open drains in the milling system of peat extraction (usually 15 m wide and could be up to 1000 m long).

Peat: sedentarily accumulated material consisting of at least 30% (dry mass) of dead organic material.

Peat soil: organic soil materials which have sedentarily accumulated and have at least 30% (dry mass) organic matter over a depth of at least 45 cm on undrained land and 30 cm deep on drained land; the depth requirement does not apply in the event that the peat layer is over bedrock.

Peatland: a geographical area with or without vegetation where peat soil occurs.

Photosynthesis: the process by which green plants use light to synthesise organic compounds from carbon dioxide and water.

Provenance: the original geographic source of a lot of seed.

Pulpwood: logs suitable for processing into fibreboard, chipboard etc. and generally too small for economic sawing. In Ireland, pulpwood is defined as logs from 7-14 cm top diameter.

Ripping: the mechanical loosening of soil with tines up to 50 cm deep.

Runoff: the amount of water leaving a peatland and entering drains or water courses due to gravity.

Sawlog: logs, usually of at least 10 cm top diameter which are intended for conversion in a sawmill.

Seedling: the term seedling is used in the broadest generic sense in this thesis to include all phases of growth from nursery to transplanted seedlings in the field and during the first years of establishment (usually four years).

Shelterwood: a stand of trees which can be partially felled in order to underplant and thus act as a shelter, protecting the young plants.

Soil solution: strictly considered, the moisture that is in intimate contact with the soil particles, although the term is sometimes more loosely applied to all forms of soil water.

Sorption: the bonding of elements (e.g. phosphorus) to soil particles.

Spacing: the distance between trees in a plantation.

Top height: the average height of the 100 trees of largest diameter per hectare.

Water table: the upper surface of groundwater.

Yield Class: a classification of rate of growth in terms of the potential maximum mean annual increment per hectare of volume to 7 cm top diameter (m^3/ha/annum).

Tree species index

General index

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