Assessment and update of species and related trials on industrial cutaway peatlands with a view to afforestation

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Executive summary

The afforestation of Bord Na Mona industrial cutaway peatlands were reviewed in the context of them making a significant contribution towards attaining the targets set out in the Government's forest strategy. It has been estimated that an area of between 16,000 and 20,000ha of the resource has afforestation potential (Renou-Wilson et al., 2008). However, the cutaways are extremely heterogeneous below ground even though the landscape looks deceptively uniform in appearance from above. The peat varies in its composition, depth, pH, nutrient status, moisture regime and in the geomorphology of the underlying (pre-bog) relict mineral soils. The adoption of a single afforestation blueprint for this land is not appropriate and future afforestation options must be based on site conditions, forestry and other landscape design options.

Although trials established on the afforestation of cutaway bog, planted in the mid 1950's at Clonsast bog in Co Offaly gave encouraging results, significantly these were carried out on sod peat cutaway which is a distinctly different medium to the milled peat situation that pertains nowadays. Subsequent afforestation of ca. 3500 ha of BNM land over the period 1980 to 2000 produced mixed results, with most establishment failures and poor productive plantations being associated with sensitivity of Sitka spruce to frost and selection of unsuitable site/peat types for afforestation. Many of the current recommendations for afforestation of industrial cutaway peatlands in Ireland are based on findings from trials established under the BOGFOR programme (1999-2008). These recommendations, however, were based mainly on observations from pre-thicket stage crops and questions, such as the long-term nutritional status of established crops and productivity of different species remain unanswered. We reviewed current recommendations for afforestation of industrial cutaway peatlands based on a re-assessment of the performance of species across a range of previously established experimental trials, demonstration areas and Bord Na Mona (BNM) land managed by Coillte since the mid 1980's.

During the preliminary assessments of "demonstration" crops in Blackwater, Clonsast and Tumduff, it was noted that long term crop performance was highly variable and sections of sites were not performing well, despite reported good performance of species, such as Norway spruce after four years (Renou-Wilson et al., 2008). Our findings show that the poor performance and die back of Sitka spruce and Norway spruce were associated with nutritional check and other factors apparently governed by peat type, peat depth and aeration.

Sphagnum dominated peats should generally not be considered as an afforestation option, with perhaps the exception of creating native woodlands, such as birch woodland (WN7-bog woodland) or wet birch woodland with Sphagnum. All other afforestation options should be restricted to *Phragmites* or woody fen dominated peats with are gravity drainage and not situated in depressed areas subject to winter flooding.

Our results suggest that peat depth and aeration is a major factor influencing the productivity of afforested species and that afforestation potential of Sitka and Norway spruce may be limited to shallow peat depths (0.15 to 1m), with other species such as hybrid larch, lodgepole pine and Scots pine being more suitable for deeper *Phragmites* or woody fen sites (<2m deep).These findings contrast with previous recommendations for afforestation of cutaway peatlands in Ireland, but are in agreement with current afforestation practice in Finland.

The range of site types suitable for Sitka spruce and Norway spruce can be expanded to depths of less than 2m if grown with birch as an intimate mixture or if existing regenerating birch is under-

planted with spruce. Productivity of Sitka spruce, in terms of top height, increased by ca. 50 % when planted with birch in alternative lines, compared to pure Sitka spruce plots. Birch appears to tolerate peat depths of more than 2 m and poorer drainage. Other species such as pedunculated oak and Corsican pine performed well on shallower peats (<1.5m).

Another striking feature of many of the BOGFOR experimental sites and more recent demonstration areas was the extent of nutritional check on virtually all the conifer crops investigated. Most crops were severely deficient in phosphorous with potassium deficiency being less prevalent. Nitrogen deficiency was not common and was more evident on *Sphagnum* dominated peats. Nutrition deficiencies were correlated with peat depth and aeration, but assessment of the long-term performance of Norway spruce nutrition trials suggest the current guidelines for nutrition management should be revised. We now recommend that a third application of phosphorous and a second application of potassium may be required from ca. 5 years onwards, in addition to initial split applications of fertiliser (Renou-Wilson et al., 2008).

The use of conventional cultivation techniques, such as mounding, ripping or disc ploughing, do not appear to have any long-term improvements to crop performance. However, the use of a Savannah bead plough to mix underlying mineral layers with peat, improve peat aeration and increase pH should be considered on shallower peats (<0.8m).

Most of the demonstration areas and experimental sites established under the BOGFOR programme have not been actively managed since the programme was terminated. This is particularly evident in the mixed species trials and underpainting trials, where timely silvicultural intervention is essential to ensure correct development of mixed species canopies. Many of the pure species blocks require thinning and or nutritional management to ensure sustained productivity of the stands. Our report provides detailed recommendations for the management of these sites. However, these recommendations should be considered in the light of specific forestry or experimental objectives. More consideration should be given to future management of stands if biomass/bioenergy production is deemed to be the primary forestry objective.

A detailed decision support system is described to aid in the selection of sites suitable for forestry, depending on landscape amenity objective (i.e. commercial timber production, forest biomass production or biodiversity forests/woodland). It is important that planning of any future afforestation on the industrial cutaway peatlands should be carried out using an integrated landscape approach using the developed decision support system and recent advances in geographic information system technology (many of which are routinely carried out by BNM). Preliminary analysis on peat production areas that are providing peat for the Edenderry plant suggest 22-42% of the future (2023) industrial cutaway in these areas would be suitable for forestry (i.e. a peat depth of less than 2m). Therefore, future configuration of industrial cutaway peatlands are likely to comprise a mosaic of wetland habitats, grasslands, short rotation coppice, peat land restoration areas, woodlands, timber and biomass forest plantations. When considering use of the landscape for biodiversity function (including woodlands), additional aspects such as, biodiversity value, habitat connectivity and the creation of key ecological ”stepping stones” should be considered. This report, and the previous BOGFOR report (Renou-Wilson et al., 2008), clearly recommends that forestry is not suitable in sections of individual peat bays or other areas. Therefore, careful design of the landscape is required to maximise forest production whilst still ensuring ecosystem services of the new peatland landscape are maintained. These functions also include social amenity and climate change mitigation actions.

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1.1 Introduction

Despite extensive traditional hand-cutting over many centuries, Irish peatlands remained largely untouched up to the establishment of the Irish Peat Board (Bord Na Móna, BNM) as a semi-state body in 1946. Of the 1.2 million ha of peatlands in the Republic of Ireland, the BNM areas classed as 'industrial' now account for about 80,000 ha or 7% of the total peatland area. These BNM areas are located mainly in the midlands and to a lesser extent on blanket bogs in the west and north west of the country. BNM harvests, on average, four million tonnes of peat annually, depending on weather conditions. Approximately three million tonnes are used for energy production, while the rest is used for horticultural peat (2/3) and briquette production (1/3).

1.2 Future uses of cutaway peatlands

About 16,000ha of the BNM peatlands have so far become 'cutaway' (this does not necessarily mean that the peat has been completely harvested). This area is increasing every year but at a variable rate and it is expected that another 60,000ha approximately of peatlands, depending on peat harvesting policy, will become 'cutaways' within the next 20-30 years (with some areas, including fringes, remaining untouched).

Much forest research has been carried out since the first cutaways became available for post peat harvesting uses in the 1950s. Since then, the emphasis has continually changed, as peat harvesting systems moved from partially cutaway sod peat to exclusively milled peat, resulting in the development of new approaches, research and policies. Over the years, the main areas of investigation have included: grassland, crop production, horticulture, commercial forestry, biomass production, dry-land recolonisation and wetland creation/restoration and recreational use. The options for post peat harvesting -use are determined to a large extent by the residual peat type and depth, hydrological constraints, geographic location and economic considerations. Although the initial trials established on the afforestation of cutaway bog, established in the mid 1950's at Clonsast bog in Co Offaly, gave encouraging results, significantly these were carried out on sod peat cutaway which is a distinctly different medium to the milled peat situation that pertains nowadays.

Bord Na Mona cutaways are extremely heterogeneous below ground even though the landscape looks deceptively uniform in appearance from above. The peat varies in type, thickness (because of the undulating topography of the bog floor and local harvesting practices), pH, nutrient status, moisture regime (drainage) and in the geomorphology of the underlying (pre-bog) relict mineral soils. All of these factors influence future land-use programmes.

1.3 Forest policy context

Forest cover currently extends to 752,231ha in this country (10.7%). This contrasts with the 35% average throughout the other EU Member-States. 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), is 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 has set a target of 1.2 million ha (17% of the total land area) to be under forest cover by 2030.

Current indications are that these are extremely stretching targets because of the reluctance of farmers to engage in afforestation, despite the presence of attractive financial incentives. In theory there are adequate lands suitable for afforestation, outside of the BNM areas to enable targets to be achieved (COFORD, 2016). However, much of the marginal lands, with good forestry potential, are currently committed to agricultural production systems, some of which are highly marginal in terms of financial return to the landowner. This highlights the urgency in determining the suitability and potential of BNM cutaway for successful and productive afforestation.

1.4 Potential contribution of cutaways to forest development

The afforestation of industrial cutaway peatlands could make a significant contribution to attaining the targets set out in the Government's forest strategy and have the benefit of being owned by one organisation (BNM). The planting and subsequent management of forestry plantations on industrial cutaways would also provide badly needed rurally-based employment and income. Plantation products including thinnings, sawnwood material from clearfells and residues could provide raw materials for the timber processing sector and an opportunity for wood energy production in locations close to existing end-use facilities. These woodland products are also suitable for co-firing in the peat-burning power stations and would extend these stations' working life, as well as providing employment in the harvesting and transport of wood fuel. The use of wood energy would also reduce fossil fuel greenhouse gas emissions and replace current imports of fuel for burning.

1.5 Land availability from cutaways

It is estimated that an area of between 16,000 and 20,000ha of BNM cutaway peatland has afforestation potential (Renou-Wilson et al., 2008). Because of the nature of peat production, the location, peat depth and when it becomes available, will all fluctuate widely across BNM lands. 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 milling surfaces on an annual basis. These factors, coupled with the fact that a depth of only 10cm is milled from the peatland surface annually, means that the bog units can be in milled peat production for up to 50 years.

The object of large scale peat harvesting is to remove as much peat as possible economically and without contamination from the underlying mineral soil. Today, all harvesting is carried out by the milling process. Milled peat production or the 'Peco' method has been adapted for Irish conditions from the old Russian 'Peko' model. In this Peco process, the surface of the peat is extracted on the horizontal plane, in a number of passes, at a rate of c.10cm per year (weather permitting). Prior to harvesting, all the vegetation is removed and fields between the ditches are made slightly convex to facilitate surface runoff. The top 1.5cm of the field is milled to crumb size by tractor-drawn rotary millers in one machine pass. 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 (15m 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 1m deep channels installed every 15m. Prior to harvesting, all the vegetation is removed and areas or "fields" between the ditches being made slightly convex to facilitate surface water runoff.

There are three main physical reasons why peat harvesting is 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); this typically occurs where there are uplifts in the bog floor.
3. The site becoming too wet (in some low lying areas, water is pumped away to keep the water table below the peat surface).

Every bog unit harvested for peat production contains a range of peat depths with a variation as great as 3m, even within bog units. Greater depths of peat are associated with depressions in the bog floor. For the first 30 years or so, the whole area of the bog area 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 for each production field. The decision to withdraw or remain 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 alternative 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, meaning that the areas withdrawn may not be available for alternative use until much later than they were previously. This emphasises further the difficulty in predicting the rate at which cutaway peatland will become available.

1.6 The BOGFOR programme and current recommendations

The BOGFOR afforestation programme made significant advances in developing guidelines for successful afforestation of cutaway peatlands (Renou-Wilson et al., 2008). The project provided recommendations for selection of suitable peat and site types, species, cultivation techniques and crop nutrition management for the establishment of successful cutaway peatland forests. Many of the observations from established trials under the BOGFOR programme were limited however to pre-thicket stage crops. In addition, many questions remained un-answered, such as the long-term nutritional status of established crops, productivity of different species and management of novel silvicultural systems (e.g. nurse crops and under-planting of birch).
In 2010-2012, BNM, in collaboration with Coillte, established additional areas on cutaway peatlands near the Lullymore in Co. Kildare area using the BOGFOR recommendations at the time. The preferred species was Norway spruce with birch and some alder planted beside the drains. The site was prepared using a Savannah plough in an effort to increase mixing of the layers and to increase peat aeration. At the time, it was considered that all Phragmites and fen peats deeper than 0.5m were suitable for growing Norway spruce successfully.

1.7 Review of national and international research

1.7.1 Peat depth and cultivation

The practice of afforestation of cutaway peatlands in Finland is based on criteria which differ to current recommendations (Renou-Wilson et a., 2008) for Irish conditions. Afforestation of cutaways in Finland is generally restricted to peat depths less than 1m, with Scots pine being the major species of choice (Pietiläinen et al., 2005). In some cases, establishment on a very shallow peat layer was carried out to enable the roots to penetrate through the peat layer and to reach the mineral subsoil where they could take up nutrients (Paavilainen and Päivänen, 1995). These approaches contrast with the recommended practice at the time when many of the BOGFOR experiments were established e.g. Jones and Farrell (2000) suggested that the peat layer for coniferous tree species should be at least 60 cm thick so that the calcareous underlying tills or marls which are frequently present would not have negative impacts on the survival and well-being of the trees.

Mixing of the residual peat with the underlying mineral soil has been suggested as a means of improving nutrient availability increasing soil pH, and soil aeration (Aro, 2000b), in studies from Finland in sites where the peat layer was 15-30 cm in depth (Aro, 2000a). Positive results were also obtained from mixing subsoil (weathered boulder drift with a decalcified layer, pH 5.5-6) at one of the earlier experiments at Trench 14, Clonsast bog in the early 1960's (unpublished). Similar results were reported in Sweden where mixing the residual peat with the underlying soil had a positive effect on seedling survival, tree growth and response to fertiliser application (Svensson et al., 1998).

1.7.2 Species

Sitka spruce (*Picea sitchensis* (Bong.) Carr.), black spruce (*Picea mariana* Britton, Sterns & Poggenb.), hybrid larch (*Larix x eurolepis*), and lodgepole pine (*Pinus contorta* Dougl.) are exotic species that have been planted with relative success in Finland, Ireland and Sweden – not all of these species in all of the countries.

Downy birch (*Betula pubescens* Ehrh.) is a natural pioneer species on cutaway peatlands. Nutritionally richer peats can also be colonised by Norway spruce (*Picea abies* (L.) Karst.) in Sweden (Svensson et al., 1998) and lodgepole pine (*Pinus contorta* Dougl.) or Scots pine (*Pinus sylvestris* L.) in Ireland.

Norway spruce is now the preferred species for planting on cutaway peatland sites in Ireland because of its lower sensitivity to frost, when compared to Sitka spruce (Renou-Wilson et al., 2008). Scots pine (*Pinus sylvestris* L.) is the species of choice for afforestation of cutaway peatlands in Finland (Pietiläinen et al., 2005). Willow and birch have also been used as short rotation coppice crops in Finland (Hytönen and Kaunisto, 1999), but establishment and maintenance costs for willow are suggested to be prohibitive (Kaunisto and Aro, 1996).

1.7.3 Nutrient status of peat sites

The low nutrient status of partially cutover peatland is a serious constraint for successful afforestation. This was confirmed by the BOGFOR report (Renou-Wilson et al., 2008), and earlier studies (Jones and Farrell, 2000), the results from which showed that phosphorus was the key element affecting tree growth. Potassium, and to a lesser extent nitrogen, were also identified as potential limiting factors, depending on the nature of the peat remaining after harvesting. Cutaway peatland sites are inherently low in phosphorus compared with mineral soils, and, although total nitrogen levels can be reasonably high, most of this is held in an organic form unavailable to tree growth. Potassium levels also tend to be generally low, highest levels being associated with woody fen peats compared with *Phragmites* peats which have inherently lower levels. The depth of peat remaining following the cessation of harvesting can therefore affect the nutritional status of the peat soil.

1.7.4 Nutrition management

For successful afforestation of cutaways, a base application of P at planting and P and K two years later are recommended in Ireland (Renou-Wilson et al., 2008). In Finland, fertilizer prescriptions are

usually based on a site type classification system and on results of fertilization experiments (Paavilainen and Päivänen, 1995).
Re-fertilisation is generally carried out in Finland using PKB-fertilizer, with phosphorus (P) in the form of apatite or wood ash (Paavilainen and Päivänen, 1995; Kaunisto and Aro, 1996). K fertilization is also recommended to be repeated about 15 years after planting (Pietiläinen et al., 2005), when broadcast fertilisation was applied at time of establishment (Aro and Kaunisto, 2003). Experiments in Finland have shown that re-fertilisation can be required earlier on deeper residual peat layers (Aro and Kaunisto, 2003 op.cit). OCarroll (1966) reported severe K deficiencies in Norway spruce and Scots pine in a drained phragmites peat site in the Irish midlands that had been in grassland for a number of years prior to afforestation. Both tree species responded well to K application. Silfverberg and Hartman (1998) suggested that K may be the most urgently deficient nutrient for re-fertilization in cutaway peatlands in Finland.
Nutrient cycling in stands on cutaway peatlands has been shown to improve, where initial tree density is high or where birch encroachment is high (Aro and Kaunisto, 2003). These factors may reduce re-fertilisation requirements.
The Irish experience with tree nutrition on cutover peatland sites mirrors in many respects that in other countries, notably Finland. Although trees respond positively to fertiliser application on such sites, issues arise in relation to duration of the growth response, the need for second, and possibly third applications, and, following on from this the possibility of fertiliser runoff, particularly from peats with little vegetation.

1.8 Project objectives:

1. Task 1: Review all and select relevant experimental and other appropriate sites for detailed field assessment and observations with the aim of addressing the project objectives:
2. Task 2: Review and update the recommendations listed in the Technical summary of the BOGFOR programme report (Renou-Wilson et al., 2008) based on results from Task 1- specifically in relation to the criteria a-j below:
    a) Site suitability
    b) Site preparation and cultivation
    c) Species performance and recommended species
    d) Tree establishment
    e) Nutrition
    f) Late spring frost
    g) Pests and disease
    h) Vegetation control
    i) Exposure
    j) The overall layout of species to account for a landscape approach. (i.e. selection of species to meet biodiversity, timber, C sequestration and other ecosystem services across the whole estate).
3. Task 3: Assess water run-off from two cutover peatland sites (Tumduff and Lullymore) in order to ascertain if phosphorous is still being lost from plots that received different cultivation and fertiliser treatments when planted in 2000 and 2011.
4. Task4: Provide a GIS database of all visited sites and selected BOGFOR experiments for future assessments.
5. Task 5: Provide guidance on the future management of trial and demo sites visited.

2. Methods

2.1 Task 1

2.1.1 Pre-assessment of relevant trials

A desk top review of the original trials and demonstration areas from the BOGFOR Programme (Renou-Wilson et al., 2008, Appendix 2) was carried out to select suitable sites for further field assessments (Task 1a). The total area covered in the original BOGFOR programme was 215.5ha, of which 194.1ha were actually planted.

The final selected sites for this current project (see Appendix A) cover three of the four basic peat types described in the BOGFOR project report. These include Sphagnum, Phragmites, Woody Fens and Menyanthes peat. Sphagnum cut-over peat sites have been excluded however due to their unsuitability for forestry and their future limited availability for afforestation (based on the BOGFOR report and our expert opinion). The experiments excluded from further assessment and analysis included:

Allen 1/00, 2/00 and 3/00: Although a wind farm has been established on part of this site in recent years, the main reason for their exclusion is because the site type no longer represents what might become available from Bord Na Mona for afforestation into the future. The site is mainly comprised of a very shallow peat over sub-peat mineral soil (alkaline silty clay and gravel).

KTY 19/00: This is a replicated experiment which compared birch species, different plant types and sizes on their establishment success. The establishment objectives of the trial have been met and the only reason to now include the trial for any further assessment might be in relation to using the data to assess biomass production or silvicultural management in birch.

CLE 4/00: This is a species demonstration area with ten plots, each of 0.74ha. All species used are coniferous with one plot comprising a mixture of sycamore and Western Red cedar. Although there was initial interest in some plots (e.g. Macedonian pine and Corsican pine grew well initially), the entire area was excluded because the site type (Sphagnum peat) is not representative of what might become available from Bord Na Mona for an afforestation programme (see above).

EB 1/00, 2/00, 3/00, 4/00 and 5/00: Although the five trials established in East Boora (EB) are named 1, 2, 3, 4 and 5/00 in the BOGFOR report, they were all actually planted in the spring of 2003. This area had establishment difficulties from early on, including hare and goat damage, site wetness and maintenance issues. The main reason, however, for excluding it from the present project was that much of the area has been subsequently invaded by large numbers of lodgepole pine regeneration from surrounding mature forests.

The final selected sites for this current project, shown in Appendix A, include additional sites (not already included under the original BOGFOR programme) so as to inform any new recommendations for the future of afforestation of cutover peatlands. Additional sites include:

1. **Areas planted under the BOGFOR Scheme (pilot) 2008 - “Afforestation of industrial cutaway peatlands”:** Two areas, each of approximately 45ha were planted under this scheme. The first area (Killinagh) was planted in spring 2010 while the second area (Derrybrennan) lies nearby to the northwest and was planted in 2011. These sites were

planted after the BOGFOR final report was published and took into account many of the recommendations from the study. Of particular interest is the fact that both areas were cultivated using the Savannah bedding plough. The BOGFOR l report recommended that this equipment be tried to enable more successful afforestation on the cutover bogs and it was subsequently purchased jointly by Bord Na Mona and Coillte and used in the preparation of these two sites for afforestation. Under the current project, we assessed the trees at both sites for growth/vigour and took samples to carry out both foliage analysis and the phosphate content of the runoff water. Results from the latter could then be compared with results from samples taken just after the areas had been originally established.

2. **Trench 14**: A half day visit to Trench 14 (Clonsast) was undertaken to make observations on earlier cutaway peat afforestation trials, some of which date back to the 1950's. Although the peat type here (sod peat cutaway) is different to that on milled peat cutaway bog, it was felt that a site visit would assist and inform the formulation of final recommendations.
3. **Existing Coillte/BNM sites**: A desktop review of all Coillte inventory data on previously afforested cutaway bog sites established in the 1980-1990s was carried out. A selection of sites was visited to investigate factors contributing to performance of species under consideration.

2.1.2 Field assessments

During the preliminary assessments of "demonstration" crops in Blackwater, Clonsast and Tumduff, it was noted that crop performance of both Norway spruce (NS) and Sitka spruce (SS) was highly variable and sections of sites were not performing well, despite reported good performance after four years (Figure 1). This raised concerns because these demonstration areas had been established using best practice at the time (but before final results from the BOGFOR programme had become available). Similar issues have also been highlighted for sections of the more recently planted Killinagh and Derrybrennan sites, where some of the Norway spruce is showing early signs of severe nutrient deficiency and dieback.

A number of hypotheses have been suggested as being the cause for the dieback and/or reduction in productivity of coniferous trees on cutaway peatlands. These include K deficiency (OCarroll, 1966, Pietiläinen et al., 2005), water deficits and peat deterioration or lack of aeration in the root zone (Aro, 2000b). Soil and crop assessments were subsequently carried out in an effort to determine the cause of this dieback. To this end, detailed peat depth/type characterization, foliage analysis and conventional mensuration assessments were carried out across selected areas in both the demo and experimental sites (see section 2.1.2.1).

Figure 1: Performance of Norway spruce in demo trials in Blackwater (KTY1/99) at 4 and 17 years after establishment.

2.1.2.1 Assessment methodology

2.1.2.1.1 Field surveys

The field assessments of selected demonstration and experimental areas (see Appendix A) and covered six broad categories:

1. **Initial Field observation**s: All of the sites originally included in the site list in Appendix A that have been visited and where initial observations have been made.
2. **Plot survey**: Detailed circular survey plots designed to assess characteristics such as, productivity (by planted species), nutrition and qualitative information relating to the performance of selected species on different peat types. These data were collected using the Field Map system (IFER, Czech Republic).

   The location of survey plots was pre-determined using information on canopy characteristics derived through using remote sensing methods (such as variation in canopy height or vegetation indices, see GIS survey below). Some survey plots were selected on the ground if there were access issues or if the team identified new areas of interest.

   Foliage samples were collected where required in the winter of 2016/17 from some species and demo sites and subsequently analysed for N, P K and trace element content. Foliage samples (4-5 tree bulked samples) were collected from the top section of the canopy of trees directly adjacent to the centre of the sample plot, where the peat sample was also taken.

   Individual tree height was determined on 4 to 5 trees immediately adjacent to the centre of the plot using a Haglof Vertex IV ultrasonic device (Haglof, Sweden). Peat cores were sampled in the centre of each plot using a 20cm diameter Gouge auger. Peat depth was measured to 2m together with a description of the peat layer types and extent of anoxic conditions in the deeper peat layers.

   The anoxic layer was defined as the region of the profile which exhibited any one of the following characteristics; a hydrogen sulphide smell, a change in colour of peat (usually brown or orange) due to no decomposition of organic material or a build-up of iron under anoxic conditions (free iron can be detected using Bipyridyl (2,2) reagent) or a permanent water saturated layer in the peat profile.

Where possible, the nature of the calcareous material below the peat layers was also described. The percentage ground cover, and occurrence of indicator species (indicative of soil nutrition or moisture regime) were also noted if present. Encroachment by birch and other pioneer species was also recorded as a percentage of plot area.

3. **Full plot inventories**: were carried out on the mixed species trial (KTY14/00) to investigate the nursing effect of planting birch with Sitka spruce. For these surveys, 0.01ha circular plots were established to measure DBH, tree height, top height, stocking and basal area of each species in the different treatments. Diameter measurements were taken from all planted trees in the plot. The height was also measured in trees representing the minimum, maximum, median, 25th and 75th percentile of the DBH distribution in the plot. Values for missing tree height were then derived from a DBH-H model for Sitka spruce and Birch using the function:

$$H = 1.3 + a(1 - Exp(b - DBH)^{(\frac{1}{c})}$$

Coefficients a, b and c were solved using non-linear curve least squares fitting procedures using R studio. All coefficients and model fits were significant at $p<0.05$. Additional statistical analysis of model residuals using the Shapiro-Wilk test was carried out to ensure all model residuals were normally distributed.

Foliage samples were also collected in KTY 14/00 to determine if nutrition of Sitka spruce is improved when grown with birch

The experiment is a block replicated 3 times trial with 6 treatments (Figure 2):

A) Pure Sitka spruce
B) Alternative lines of Sitka spruce and birch, planted at the same time (2000)
C) Alternate lines of birch and Sitka spruce, but the spruce was planted 2 years after the birch
D) Alternative line of birch and Sitka spruce, with spruce planted 4 years after birch
E) One line of birch and 2 lines of Sitka spruce planted at the same time
F) One line of birch and 3 lines of Sitka spruce planted at the same time

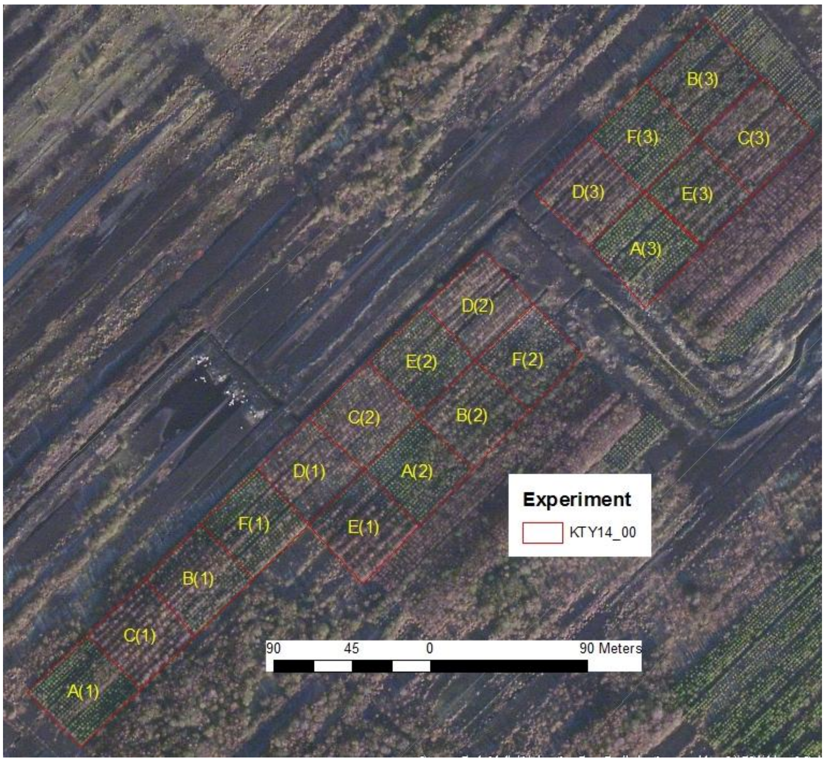

Figure 2: The layout of experiment KTY14/00 showing treatment represented by letters (see text above for description) and numbers for the 3 replicated blocks.

4. **Remote sensing assessments (GIS)**: GIS technology was used to assess stocking and productive area of selected sites (Appendix A). The technology was also used to identify sample plot locations for detailed tree and peat surveys (Appendix B). This technology significantly reduced man hour inputs and data collection costs.

   Digital surface models (DSM, height at 20cm resolution) and photo-imagery for (red, green, blue and near infrared bands, (Figure 3) were purchased from Blue Sky (imagery captured in May 2016). The height of the peat bays was determined using a Digital terrain model (DTM) provided by BNM. Experimental plot polygons were derived using information provided in the BOGFOR GIS database.

5. **Processing of GIS data:** A normalised vegetation index (NDVI) was derived from the red and infrared spectral bands. NDVI ratios are indicative of photosynthetic vigour of a crop, with high values (green in Figure 4 below) indicating good performance, compared to low values for bare soils or crops under stress (red areas shown in Figure 4).

Figure 3: An RGB image of KTY1/99 (NS demo area, left panel) and the species /cultivation trials (KTY16/00, right panel)

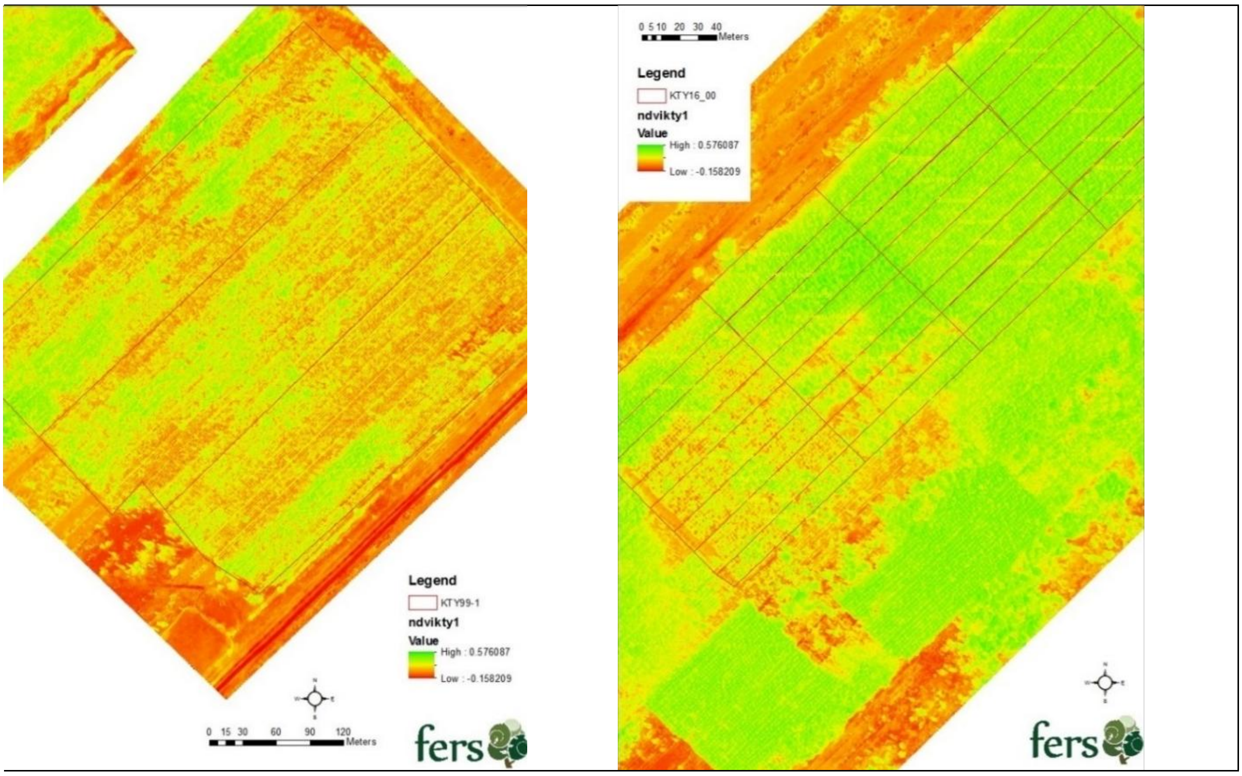

Figure 4: An NDVI image of KTY99/1 (left) and KTY16/00 (right) showing areas where crops are stressed (red or yellow) and areas where crops are performing well (green)

Canopy height was determined using the difference between the DSM and DTM raster values (in m, Figure 5). The areas were then classified into 6 canopy height classes using segmentation methods. Ground survey plots (2 m radius) were selected from the GIS to represent good, moderate and poor performing sections of the sites to provide a cross section for further field evaluation (see black circle in Figure 5). This was based on the canopy H segmentation and NDVI analysis.

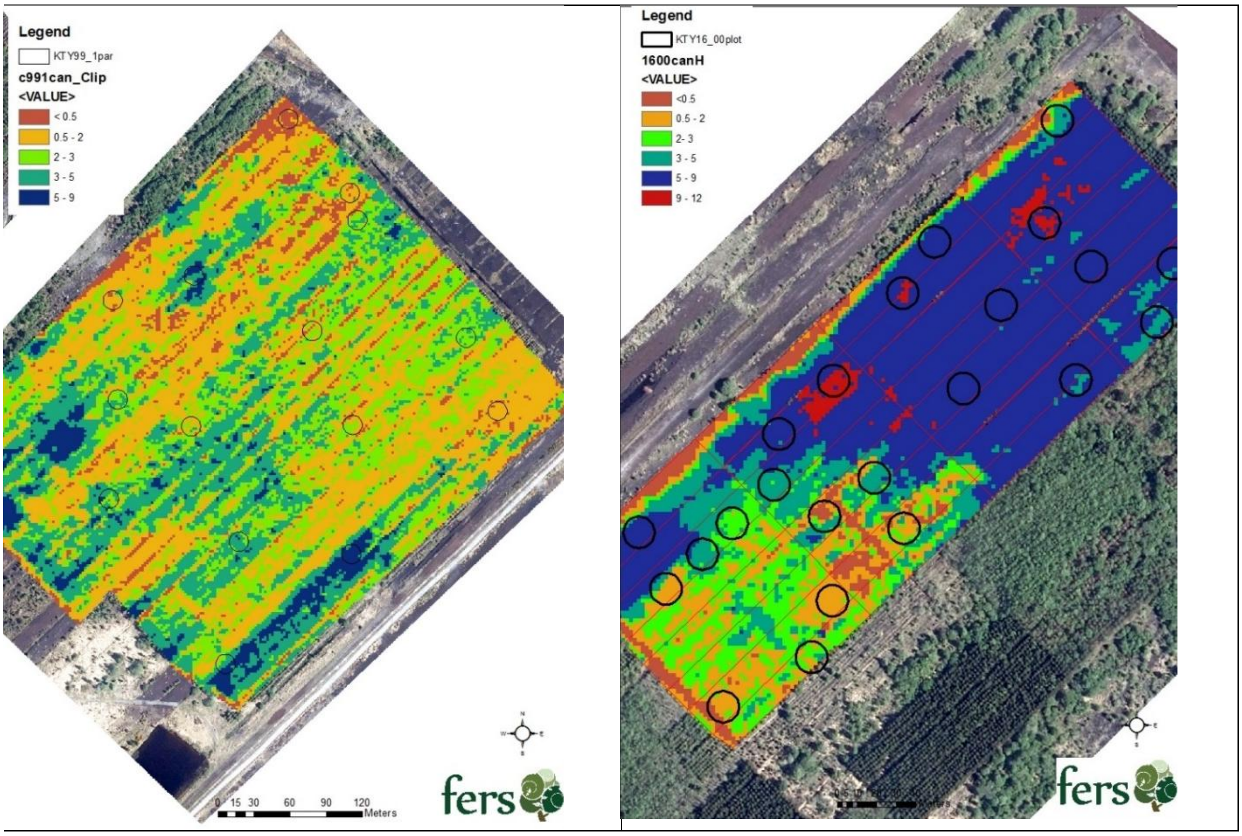

Figure 5: The distribution of canopy height classes in experiments KTY1/99 (left) and KTY16/00 (right). The black circled areas are selected plots (based on H and NDVI variability) for further ground investigation and analysis

The crown layer was then further segmented to identify individual tree crown and individual tree heights using advanced GIS methods. This information was used to derive mean height, top height and stocking per ha (Figure 6).

6. **Coillte inventory review and selected site visits:**
   Forest inventory data for all land leased from BNM were obtained from Coillte with the aim of assessing how well operational forest stands were performing on industrial cutaway peatlands. These areas were planted between 1983 and 2000. We assessed the variation in the yield class of major species (SS, NS, Birch, Oak, SP, LP and HL). This was followed by a desk review of selected sites to assess how performance related to peat characteristic. A final subset of good and poorly performing SS, NS and LP crops were assessed by the team in over the period late 2016 to early 2017. This represented 143 sub-compartments, which were assessed using the inventory data and GIS data to determine the reasons for good or bad crop performance. Some sites were visited by the team, if remote assessment did not

deliver any clear reason explaining crop performance. The age class of stands assessed was between 17 and 33 years old.

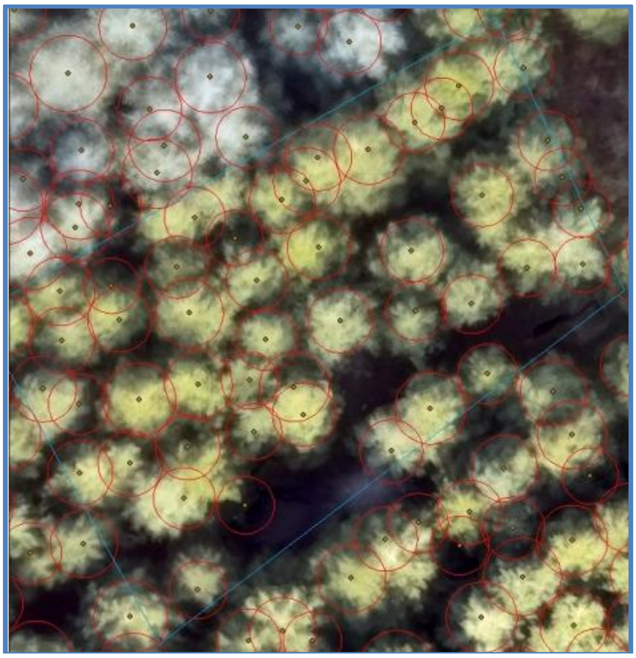

Figure 6: Image showing identified tree crowns and points where the crown is the highest.

7. **Nutrient run-off**: The possibility of nutrient runoff from fertiliser applied to forestry plantations on cutaway bog is also a potential issue and was investigated as part of the BOGFOR programme. This involved taking water samples after fertiliser application at one of the experimental sites in 2000 (CLE 1/99) in order to determine if nutrient runoff (Molybdate reactive phosphate (MRP)) was an issue. Water sampling (10 grab samples) was repeated at one of these sites (CLE1/99) in December 2016 and February 2017 in order to determine the current phosphorus status of drainage waters.

   Water sampling was also carried out by Coillte at two streams adjacent to the demonstration trials planted at Killinagh and Derrybrennan in 2011 and 2012 before and after planting/fertilising. This was repeated as part of the current project in December 2016 and February 2017. Initially it was planned to have five sampling locations but this was subsequently reduced to three.

2.1.2.1.2 Nutrient analysis

Foliage samples collected from plot surveys were dispatched to the British Forestry Commission Research laboratory at Forest Research Centre for Ecosystems, Society and Biosecurity at Alice Holt, Farnham, Surrey, England. The following elements were determined in each: Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca), Magnesium (Mg), Sodium (Na), Boron (B), Aluminium (Al), Iron (Fe), Manganese (Mn), Cadmium (Cd), Chromium (Cr), Copper (Cu), Nickel (Ni) and Zinc (Zn). Foliar samples were dried at 70 degrees prior to weighing to remove any residual moisture content. The combustion method for determination of N was done using a Carlo Erba CN analyser (Flash1112 series) using 10mg dried and ground needle samples. For all other nutrients, ca. 100 mg of dried sample was weighed into a 15 ml borosilicate (or quartz) tube. One ml of concentrated sulphuric acid was added to each sample with 0.8 ml of hydrogen peroxide (30%). The tubes are then incubated on a heating block at 335 °C for 30 min or until the digests were clear. The samples are made up to 15 ml with distilled water and then analyzed on a dual view ICP-OES (Thermo ICap 6500).

Threshold levels for each element were based on a range of published values shown in Tables 1 a and 1 b.

Table 1a: Deficient and optimum foliar macronutrient concentrations (% dw) for major conifer species[1]

Nutrient	Tree Species	Satisfactory	Marginal	Deficient
Nitrogen (N)	Sitka and Norway spruce	1.5	1.2-1.5	<1.2
	Lodgepole Pine	1.4	1.2-1.4	<1
	Western red cedar			<1.2
Phosphorus (P)	Western red cedar			<0.18
	Sitka and Norway spruce	0.18	0.13-0.18	<0.13
	Lodgepole Pine	0.14	0.11-0.14	<0.1
Potassium (K)	Western red cedar			<0.74
	Sitka and Norway spruce	>0.7	0.5-0.7	<0.5
	Lodgepole Pine	0.5	0.4-0.5	0.3
Calcium (Ca)	Sitka Spruce, Norway	0.07	0.05-0.07	0.05
Magnesium (Mg)	Sitka Spruce, Norway	0.07	0.04-0.07	0.03
	Lodgepole Pine	0.05	0.03-0.05	0.02

Table 1a: Deficient, marginal and satisfactory foliage micronutrients concentrations (ppm) during the dormant season (Renou-Wilson et al., 2008; Sypert, 2006).

Element	Species	Satisfactory	Marginal	Deficient
Iron	Sitka and Norway spruce	50	20-50	< 20
Copper	Sitka and Norway spruce	5	2.5-4	< 2.5
	Pines			<3
	Tree species generally			<2.7
Zinc	Sitka and Norway spruce	15	9-15	< 9
Manganese	Sitka and Norway spruce	25	4-25	4
Boron	Sitka and Norway spruce	25	5-20	< 5
	Broad range of species			<10

2.1.2.1.3Sample locations and nutrition management history of specific experiments

All of the experiments, and the demonstration areas (Appendix A), were fertilised at planting with non-granulated rock phosphate (12.5% P) in a split application: 175 kg/ha (21 kg P/ha) manually applied at planting in bands; the same amount was broadcast applied manually two years later,

[1] Modified from: Renou-Wilson and Farrell (2007), Savill, et al.(1997); Everard, (1973); Ballard and Carter (1986), Weetman et al (1988)

together with 250 kg/ha of muriate of potash (50% K). Fertiliser was applied along the lines of trees with no controls in place to ensure an even spread took place (this may have been the case at some sites but not all sites). The uneven growth pattern in tree growth over short distances in parts of both the experiments, and the demonstration areas, highlights the need for high standards in this regard, and the operational fall down that may occur when not complied with.

Specific sampling details for sites are:

KTY 1/99. The demonstration area planted with Norway spruce in 1999 at Blackwater. Fertilised in 2000 and in 2004. (It is assumed at the same rate as that used in the experiments). Twelve samples of Norway spruce foliage were taken for analysis.

KTY 16/00. The cultivation trial planted at Blackwater in 2000. The trial incorporated different cultivation treatments and a number of tree species. Samples taken included: four Sitka spruce; two Scots pine; three Japanese larch and four Norway spruce.

KTY 17/00. A species trial planted at Blackwater in 2000. Six foliage samples were taken including three from Western red cedar and three from lodgepole pine. The site received 175 kg/ha rock phosphate at planting; this was repeated, together with 250 kg/ha of muriate of potash just before the third growing season.

CLE 1/99. A Norway spruce demonstration area planted at Tumduff in May 1999. 25 Kg P/ha applied as ground rock phosphate in July 1999 in strips along the rows of trees; 25 Kg P/ha plus 250 Kg muriate of potash applied July 2002. Eleven foliage samples were taken October 2016.

CLE 2/00. This is a cultivation trial planted with different species at Tumduff in 2000. The site was fertilised at planting with rock phosphate (12.5% P) in a split application: 175 kg/ha (21 kg P/ha) manually applied in bands; the same amount was manually broadcast two years later, together with 250 kg/ha of muriate of potash**.** Eight foliage samples were taken, including four in Scots pine and two each in Sitka spruce and Norway spruce.

TLM 35/96. This is a species trial planted at Tumduff in 1996. Four foliage samples were taken; two from Sitka spruce, one from Scots pine and one from Western red cedar. 175 kg/ha rock phosphate was applied at planting; this was repeated together with 250 kg/ha of muriate of potash just before the third growing season.

KTY 14/00. The birch-Sitka spruce trial. Four samples were taken from four Sitka spruce trees in the middle of each full inventory sample plot. The experiment was fertilised at planting with rock phosphate (12.5% P) in a split application: 175 kg/ha (21 kg P/ha) manually applied in bands; the same amount was manually broadcast, two years later, together with 250 kg/ha of muriate of potash**.**

Killinagh (Lullymore). This is the operational area planted in 2010-2011 with Norway spruce and cultivated with the savannah plough in an effort to aerate and mix the peat and underlying calcareous layers. The area was given a broadcast application of 175 Kg/ha of granulated rock phosphate in July 2010. This treatment, together with 250 Kg/ha of muriate of potash, was repeated in 2013. Seven foliage samples taken in November 2016.

Derrybrennan (Lullymore). The area was also cultivated using the savannah plough and planted with NS in 2012. The area was given a broadcast application of 250 Kg/ha of granulated rock phosphate in 2012. Although a further application of rock phosphate and muriate of potash were planned for 2015, these treatments do not appear to have been carried out. Large parts of the area now show potash and phosphorus deficiency. Three foliage samples taken in November 2016.

Assessment of fertiliser trials

Two fertiliser trial (CLE6/00 and CLE7/00) were revisited in 2016. The BOFOR final report (Renou-Wilson et al., 2008) showed no significant effect of fertiliser treatment on the reconstitution trial CLE7/00 (located in Tumduff North). A visit to this site in November 2016 confirmed that there were no visual differences between treatment blocks, so no further assessments were carried out.

Table 2: Fertiliser treatments and plot codes used for experiment CCLE6/00

Plot Code	Application method*	First application (kgP)	Second application (kgP)
1	Broadcast	42	0
2	Band	42	0
3	Broadcast	28	14
4	Band	28	14
5	Broadcast	14	14
6	Band	14	14

*The first application (as well a standard K and N) was applied using either broadcast or band placement, but the second applications were all broadcast applied.

2.1.3 Statistical analysis

2.1.3.1 Assessment of productivity

The mean height for each plot and each experimental treatment/species was derived from survey data. Top height for each experimental treatment or plot was determined using mean height regression equations (Matthews and Mackie, 2008).

The mean height (H, m) for each plot was normalised (H at 16yrs) so that a global analysis across sites varying in age (yrs) could be performed:

$$Normalised\ H_{16yrs} = \frac{H}{Age_{yrs}} \times 16 \quad (1)$$

The growth response in different plots is then expressed as an observed normalised ratio of height potential (H_{pot}) which describes the relative decline in growth for each plot (mean plot height at 16yrs) relative to the maximum plot height for each species (*j*) from all experiments at 16yrs:

$$H_{pot(j)} = \frac{Plot\ Normanilsed\ H_{16yrs}}{Max\ Normalised\ H_{16yrs(j)}} \quad (2)$$

This ratio is indicative of the decline in growth associated with the site conditions, with 1 indicating no inhibition of growth and 0 indicating no growth. These variables were subsequently used for further statistical analysis.

Stocking of planted tree species (stems/ha) and yield class (YC, i.e. the Industry productivity index standard expressed in m^3 of timber/ha/yr) and for each experimental plot were derived from top height assessments using GIS techniques.

2.1.3.2 Replicated experiments

For the cultivation trials (KTY16/00, CLE2/00) and demonstration area (CLE1/99, KTY1/99), the long term effects of cultivation in replicated experiments was determined through analysis of variance

(ANOVA) using the R studio software package (https://www.rstudio.com/). Top height (derived from GIS analysis) was used as a measure of productivity in the ANOVA. Where there was a significant species or treatment effect, the significant difference of mean values was determined using Fishers Least Significant difference tests in R studio.

2.1.3.3 Pearson regression analysis

Regression analysis was performed when assessing relationships between site variables (e.g. peat depth or foliar nutrient concentration) and tree performance. Raw data were transformed using a natural log transformation to ensure data were normally distributed (based on Shapiro-Wilk statistic in R studio), if required, prior to subsequent analysis. Regression analysis of single variable sets were performed using the Pearson's correlation coefficient (R). R values were determined to be significant based on the probability value (p) for the returned R coefficient and the degrees of freedom (number of samples (N) -1) using the R studio package.

2.1.3.4 Regression models

Peat depth model

A multiple regression model was used to develop a predictive indicator of how different species perform on different peat substrates varying in depth and aeration. Certain species such as Western red cedar, oak and birch were excluded from the analysis because these were not represented across a sufficient range of peat depths. This is because nearly all of the BOGFOR species trials are located on shallow peat (<0.5m) sites. The analysis was, therefore, confined to hybrid larch (HL), Norway spruce (NS), Sitka spruce (SS), Birch (only 15 plots from Experiment KTY 14/00) lodgepole pine and Scots pine (Pines). The pine species were assigned to one cohort group because of limited representation of individual species across different peat depths. The model data set was derived from 140 plot assessments from 8 different experiments (CLE1/99, CLE2/006, KTY16/00, KTY1/99, TLM35/96, KTY 14/00, Killinagh, Derrybrennan)

In order to determine the relationship between peat characteristics and tree height (H), normalised H was then modelled for each species group (*j,* i.e. SS, HL, NS or Pines) using the function:

$$Normalised\ H_{16yrs(j)} = H_{coeff(j)} \times Peat_{factor(j)} \qquad 3$$

where, H_{ceoff} is the height coefficient derived from the slope of the linear relationship between normalised H (see eq1) and the ratio of tree H potential (H_{pot}, see eq. 2) for each species (j).

$Peat_{factor}$ of each species (j) is a response variable to total peat depth (P_{depth}, *m*) and relative peat aeration ($P_{aeration}$), which can be modelled using the non-linear multiple regression function:

$$Peat_{factor(j)} = res_j + a0_j \times Pdepth^{-kd(j)} \times Paeration^{ka(j)} \qquad 4$$

Where, *res* is the residual correction for the modelled dataset, *a0* is the scalar correction coefficient, k is exponential coefficients describing the decline in growth (negative) as peat depth increases (-kd) or increase in growth as relative aeration increases (ka).

($P_{aeration}$) is the depth (m) of the aerated layer relative to the total peat depth:

$$P_{aeration} = \frac{depth\ at\ anoxic\ layer}{Pdepth} \qquad 5$$

But if *depth at anoxic layer* is > P_{depth}, then $P_{aeration}$ =1

The final formulation was derived in an iterative manner by adding the variables, such as P_{depth} and $P_{aeartion}$, to the model based on forward selection of variables in a stepwise multiple regression using the R studio package. Variables and model coefficient were only included in the final model if the

root mean square error (RMSE) increased significantly and there was no significant bias in model residuals, based on the Shapiro-Wilk statistic in R studio.
The final model was also used to develop the site classification system and decision tree to aid in the site selection for species depending on different forestry objectives (see results section).

2.1.3.5 ANOVA randomised block design model

For experiment KTY14/00 the experiment was laid out in a replicated random block (n=3) design consisting of 6 treatments. In order to factor out any random block effects a random block ANOVA model was used in R studio:

$$x_{ij} = \mu + \alpha_i + \beta_j + e_{ij} \qquad 6$$

where: μ = overall mean (DBH or height), α_i = effect of treatment i (difference with μ) β_j = effect of block $_j$ (difference with μ) e_{ij} = error in measurement for treatment i and block j.
Therefore, instead of only explaining the variance through error and treatment, we also include the block as a possible source for variance in the data.
If the ANOVA model was significant and treatment and block factors were also significant based on the P-value ($p<0.05$) of the F values, then we compared the variable means (e.g. DBH, basal area, H) of treatment factor using Tukeys HSD multiple comparisons of means of the fitted ANOVA model (eq. 6). This enabled us to determine if the mean values for different treatments were significantly different to each other, whilst ensuring the block effect is factored out. Normal distribution of the final ANOVA model residuals was tested using the Shapiro-Wilk statistic (using the R studio software package).

3. Results

3.1 Coillte BNM areas

Coillte inventory data for all Bord Na Mona lands planted from 1983 to 2000 (3,594ha) where extracted from the Coillte inventory. A subset of species and yield class data was selected based on the following criteria:

- Coillte properties with the "BNM" suffix (BNM owned land).
- Primary species in sub compartment only (i.e. exclude 2 and 3rd species) and only the primary species in pure or non-intimate mixed species sub compartments. So, this does not consider intimate mixtures
- Sub compartment which were surveyed for top height and basal area in last 10 years (2006 to 2016)

Table 3a: Statistics on productivity of major species in the Coillte estate on land leased from BNM.

Species	**Mean YC**	**Min YC**	**Max YC**	**Mean age (years)**	**N***	**Coillte national mean YC****
Norway spruce	12.7	6	20	16	42	16.9
Sitka spruce	13.4	4	26	19	236	17.2
Hybrid larch	9.1	8	11	11	3	11.3
Scots pine	9.4	4	14	18	8	9.6
Lodgepole pine (LPS)	12.1	4	18	17	113	10.5
Birch	4.9	4	8	18	28	5.2
Oak	4.7	4	6	27	17	4.5
Monterey pine	15.3	10	20	23	4	14.5
Western red cedar	11.2	6	16	17	3	16.1

* N= number of stands

** The Coillte national mean YC was derived from all Coillte stands surveyed in the last 10 years, which were also planted between 1983 and 2000

Another subset of data (from the data above) was randomly selected for GIS and desk review to identify what factors might have contributed to good and poor performance of all species, based on a threshold potential YC of 14 m^3 ha^{-1} yr^{-1} within. the BNM estate (Table 3b). Selection criteria included:

- YC threshold classes of ≤14 and ≥14 m^3 ha^{-1} yr^{-1}, representing poor and good performing crops. The thresholds are based on the site and species suitability YC criteria as defined using the Ecological site classification for Ireland (Ray et al., 2009)
- Only plots in which stocking and YC was assessed in the last 5 years

Table 3b: A summary of a selected subset of data (presented in Table 3a above) productivity low (YC≤14) and high (YC>14) productivity conifers in the BNM estate

		% Area	
Species	Area	>YC14*	≤YC14*
Lodgepole pine (LPS)*	569.6	20.5	43.7
Monterey pine	16.9	25.0	75.0
Norway spruce	223.9	31.7	54.4
Sitka spruce	1895.5	28.3	60.5
Western red cedar	1.6	33.3	66.7
Total BNM Area	3594.1	20.2	42.7

* The threshold for LPS was set to a YC of 12

3.1.1 Species performance notes

3.1.1.1 Sitka spruce

The mean YC for Sitka spruce, the most common species on Coillte planted BNM cutaway peatlands, was three YCs below the national average (Table 3a). Over 60 % of crops surveyed in the land 5 years, which were planted in the period 1980 to 2000, have a YC of less than or equal to 14 m^3/ha/yr (Table 3b), which represents marginal productivity for commercial timber plantations.

Desk and field assessments

Possible reasons for the poor performance of Sitka spruce (YC <14, n = 21) in these sites include:

- Unsuitable peat types: Over 40% of sites investigated were located on unsuitable peat sites, mainly very deep *Phragmites* dominated peats (e.g. sub compartment 11352N2) or *Sphagnum dominated peat*.
- One site was located on a very shallow peat with shell marl and drainage problems (Derrybrat property).
- A total of 30% of the sites had inadequate drainage.
- Sensitivity to frost: Many crops on cutaway sites were damaged by early summer frosts (June 1989 and 1991). This resulted in growth suppression and encroachment by birch leading to reduced stocking in these sites. Of the 143 sites investigated, 10 of those previously planted with Sitka spruce (in 1989-90) were replanted with Norway spruce or lodgepole pine (in 1993-95).
- In Derryhogan, failure or poor performance of Sitka spruce was associated with the presence of a very compact *Phragmites* peat over gravel.
- Poor post-establishment maintenance and operational fall down, such as insufficient fertiliser application, uneven application of fertiliser or maintenance of drainage. It is difficult to assess the scale of this problem, but numerous sites or sections of sites visited did not appear to have been fertilised.

It should be noted that many of the poorer sites were planted before recommendations from the BOGFOR project were published (2008). In hindsight, most of these sites are now known not to be suitable for Sitka spruce. In addition, many of these sites were planted just before the occurrence of a number severe and successive frosts in the late 1980s/early 1990s.

Approximately 28 per cent of Sitka crops sampled exhibited a productivity level suitable for thinning operations and commercial timber production (YC>14 m^3/ha/yr, Table 3b). Reasons for better performance (YC>14, n=14) on these sites include:

- Better site selection, such as shallow cutaway sod peats (36% of sites investigated, e.g. Clonsast)
- 57% of sites were located on shallow (less 1m) *Phragmites* peats or woody fens. In addition, some of these crops were planted at Lullymore in 1983 and successfully established before the severe frost years of 1989-1991.

3.1.1.2 Norway spruce

The production of Norway spruce was four YCs below the national average, with 54% of the area not suitable for commercial timber production (YC<14, Table 3b).

Desk and field assessments

Possible reasons for poorer production of Norway spruce (YC<14, n=17) may include:

- Poor drainage or nutrition management, particularly confounded on deeper (1-2m) peats. These were predominantly on woody fens or *Phragmites* peats where drainage was poor.
- Selection of unsuitable peat substrates, such as high bays with a high *Sphagnum* content (30% of sites investigated).
- 31per cent of the selected dataset for Norway spruce contained sites where productivity was above the productivity threshold for commercial timber production.

Reasons for better performance on these sites (YC> 14, n=8) include:

- Suitable peat types (i.e. woody fens or *Phragmites*) all below 1 m in depth; one site was very shallow (20cm) with a weathered calcareous under layer. NOTE: a weathered layer would not normally be calcareous?
- One site was a failed reconstituted Sitka spruce sub-compartment planted with Norway spruce (less prone to frost damage than Sitka spruce).

3.1.1.3 Lodgepole pine

Lodgepole and Scots pine, performed equal to or better that the national average (Table 3a). In contrast (data for SP not presented in Table 3b), over 20% of the selected lodgepole pine crops, which were surveyed in the last 5 years, exhibited a YC >12, suggesting potential for timber production. However, the occurrence of pine shoot moth, and deterioration of timber quality as a result, should be considered. Lodgepole pine also has potential for the bioenergy market, but silvicultural systems need to be optimised for biomass production.

Desk and field assessments

The reasons for good performance of lodgepole pine (YC>12, n=25) on these site types include:

- The species appears to grow better than spruce in wetter, deeper peats. 24% of site investigated were on deep *Phragmites* peat (1-2m)
- LP is not as nutritionally demanding as many other conifers

- LP tolerates frost when other species are damaged
- LP grows quickly after planting and can outcompete other vegetation e.g. *Juncus effusus*
- Two of the investigated sites were re-constituted Sitka spruce plantations that had failed due to frost damage.
- All of the investigated sites where lodgepole pine performed well were situated on either *Phragmites* peats or woody fens.

Although 43 per cent of the LPS plantations on BNM land had a YC below 14 (Table 3b), only 1 % of the selected lodgepole pine (LPS) crops exhibited a productivity on the low range for this provenance (YC<12). Poor performance of LP (YC<12, n=12) could be associated with:

- High *Sphagnum* peat bays with poor drainage
- High levels of iron in compact *Phragmites* peats. This is evident in Mongagh, where iron deposits are present in brown veins within the peat layer.

3.2 Experimental sites

There was a large degree of variation in mean height (H), stocking and estimated yield class (m^3/ha/yr) within and across the different experimental and demo areas. Most of the intra-site variation in productivity and stocking for the conifer species was associated with peat type characteristics (see results below).

Table 4: Mensuration data for the assessed species and experimental sites.

Exp/Site	**Spp**	**Age**	**Mean H**	**Stocking***	**Est YC**
			(m)	**(stems/ha)**	**(m3/ha/yr)**
CLE 1/99	Norway spruce (NS)	17	5.1	1954	10
CLE 2/00	Hybrid larch (HL)	16	9.5	1977	12
	Norway spruce (NS)	16	5.4	1956	10
	Scots pine (SP)	16	5.2	1944	10
	Sitka spruce (SS)	16	4.4	1326	10
Derrybrennan	Norway spruce (NS)	5	0.8	n.d	n.d
Killinagh	Lodgepole pine (LPS)	6	2.1	n.d	n.d
	Norway spruce (NS)	6	1.5	n.d	n.d
KTY 1/99	Norway spruce (NS)	17	5.0	1867	10
KTY 14/00	Birch	16	8.9	n.d.	8
KTY 16/00	Hybrid larch (HL)	16	7.7	1984	8
	Norway spruce (NS)	16	5.8	2011	12
	Scots pine (SP)	16	8.4	2014	12
	Sitka spruce (SS)	16	8.7	2361	20
KTY 17/00	Lodgepole pine (LPN)	16	5.6	2106	8
	Western red cedar (WRC)	16	5.9	1362	14
TLM 35/96	Hybrid larch (HL)	20	11.8	1745	12
	Lodgepole pine (LPN)	20	6.6	2234	8
	Lodgepole pine (LPS)	20	11.2	2147	12
	Oak*	20	7.5	2897	6
	Improved Birch (Downy)*	20	12.3	2145	10
	Un-improved Birch*	20	9.8	2341	6
	Norway spruce (NS)	20	8.5	2110	18
	Scots pine (SP)	20	8.1	1987	12
	Sitka spruce (SS)	20	7.9	2214	18
	Western red cedar (WRC)	20	7.2	980	14

*derived using GIS data
n.d. not determined
LPS – south coastal provenance, LPN – north coastal provenance
All species originally planted at 2,500 trees/ha, except for oak which was planted originally at 3,333 trees/ha.

3.2.1 Site suitability

3.2.1.1 Peat type and depth

Peat depth varied greatly within and across experimental plots. For example, in experiments KTY16/00 and TLM 96/35 peat depth varied from less than 15cm to over 2m. Peat depth generally increased as height of the bay increased, but in some cases, it could vary by 1m within a 5 to 10 m section of a single bay. The intrinsic variation in peat depth across single experiments made it difficult to compare treatment or draw concrete conclusions from the analyses, particularly in un-replicated experiments. The peat types of experimental and other visited sites generally fell into five categories:

Cutover Sod peats: e.g. Clonsast: characterised by shallow (0.5m) aerated *Sphagnum* peat, transposed onto previously cutover residual peat. Results from experiments, such as Trench 14, show that most species performed well on these site. However, these peat types are atypical of industrial peatlands today arising from the milling process (with a total removal of Sphagnum).

***Sphagnum* dominated peat**: this is characterised by a dominantly *Sphagnum* peat (usually poorly drained and anoxic) such as that located on some Coillte sites planted in the 1980s to 1990s (e.g. Lullymore sub compartment (11352N2). These sites generally carry lower yielding Norway spruce, Sitka spruce (YC< 14) and lodgepole pine (YC<10).

Deeper *Phragmites* dominated peats (>2m) with some mixed *Sphagnum* peat: This was well represented in Derrybrennan, Blackwater (KTY1/99) and the deeper parts of Tumduff (CLE1/99, CLE2/00, TLM35/96) and Blackwater (KTY17/00). The organic layers are usually mixed due to previous cultivation (for forest establishment?) and the peat is generally well oxidised and drained in the shallower parts. This substrate supported good growth of lodgepole pine, hybrid larch, Scots pine and Norway spruce. Deeper *Sphagnum* dominated layers generally contained species indicative of more acidic conditions (e.g. *Calluna* and *Eriophorum*) and were not suitable for conifer growth (maybe with the exception of pines and larch in some cases).

The deeper *Phragmites* (1.5-2m) dominated peat layers appeared to initially support good growth (i.e. no check or die back) of Norway spruce, hybrid Larch, lodgepole pine and Scot pine. However, longer term growth seemed to decline in sites with deeper peat. This was particularly evident for Norway spruce which showed signs of die-back and nutrient deficiency from ca. 8 years after establishment (see Figure 1 above). The mineral soil material beneath the peat layer, if detected, was generally characterised by a non-weathered lacustrine or glacial sediment deposits. Marl layers were not detected in any of the sample plots.

In areas where the peat was deep (>1.5m) and where the anoxic zone was within 0.3 to 0.7m from the surface, tree growth always appeared to be poor and trees showed extensive dieback and nutrient deficiency symptoms. Very wet sites exhibited poor tree survival and were often dominated by *Campylopus* moss. In some cases, the *Campylopus* had died off.

Shallower *Phragmites* peats with woody fen layer: These areas (CLE1/99, KTY16/00, KTY1/99, CLE2/00, Killinagh) appeared to support more ground vegetation (e.g. *Rubus* spp, *Juncus effusus*) with encroachment by birch and even lodgepole pine and Scots pine in some cases. The peat layer was generally shallower (1-1.5m) but still contained well preserved remains of *Phragmites* or tree stems such as birch, suggesting a low degree of oxidation. The underlying calcareous material was generally un-weathered. These areas appeared to support more vigorous tree growth, but symptoms of die back and nutrient deficiency were manifested in the deeper peat areas (>1m), particularly for Sitka spruce and Norway spruce (see sections below). These sites did support a good and sustained growth of hybrid larch, lodgepole pine, Corsican pine, Scots pine, birch, alder and oak, if drainage was good. Birch spp. did appear to colonise wetter sites, even where no planting had been carried out originally because of poor drainage.

Shallow, well oxidised *Phragmites*/woody fens. This site type, characterised by a shallow (<1m) oxidised peat or fen layer with a glacial limestone till (weathered in some cases) was found in Blackwater (KTY16/00) and shallower parts of TLM35/96. Most species, including Sitka spruce, grew well on these peats, even with as little as only 15 to 20cm of peat.
Unplanted areas of the more suitable peat types were extensively covered by grasses, *Juncus* spp. and encroachment by willow, birch and naturally regenerating pines. In contrast, unplanted higher bays with deeper, less well drained substrates had little or no vegetation cover.

3.2.1.2 Peat depth and aeration

The performance of all tree species investigated, in terms of normalised height, generally declined as peat depth increased (Figure 7). In contrast, normalised tree H increased as peat aeration ratio increased, except when the peat layer was fully aerated (at a relative aeration ratio of 1), where variations in growth were associated with peat depth to a larger extent (Figure 7). There was no apparent relationship between tree H of birch and relative aeration ratio of the peat in plots investigated (Figure 7).

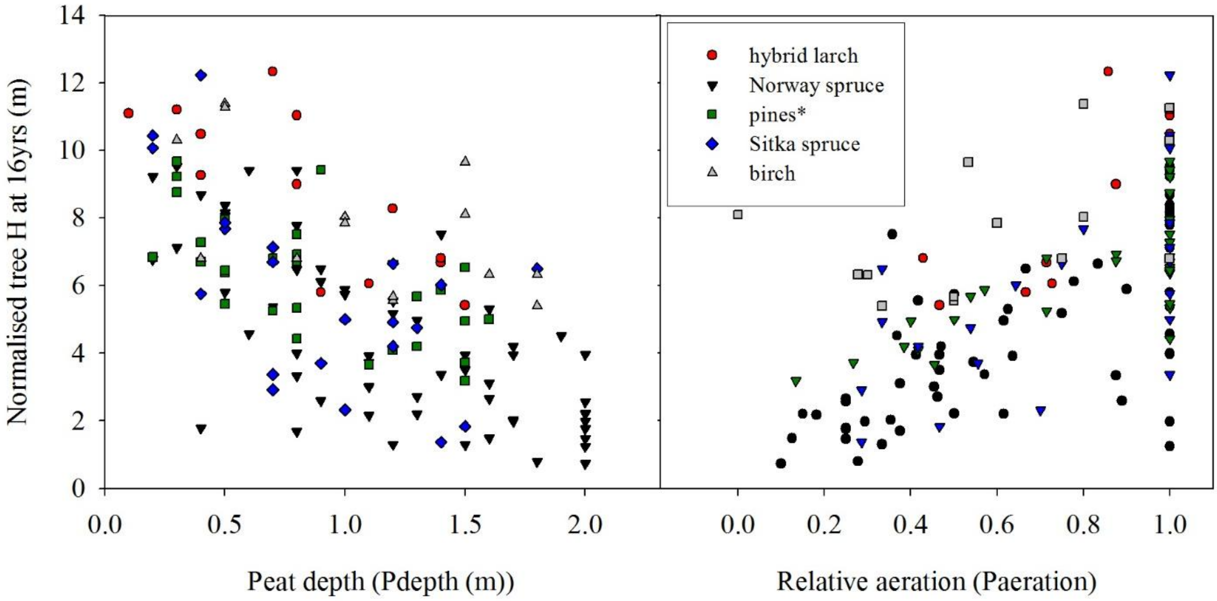

Figure 7: Variation in mean plot normalised tree height at 16yrs (H_{16yrs}) in relation to total peat depth (left panel) and relative peat aeration (right panel). See equation 5 for description of $P_{aeration}$ ratio (n=140).

As seen from the above scatter plots, shown in Figure 7, the relationship between tree H and peat depth or aeration is best described by a second order non-linear function (Table 5). The best model fit describing these relationships suggests that ca. 70 % of the variation in normalised mean plot tree H across all species can be associated with variations in peat depth and aeration (see r^2, Table 2 and Figure 8).

Table 5: Fitted model parameters (see equations 3 and 4 (Methods section) for parameter and model description) and model goodness of fit variables for species specific functions. RMSE= root mean square error, r^2 is the coefficient of determination.

		Species			
		Hybrid larch	Norway spruce	Pine*	Sitka spruce
Model fit	r^2	0.75	0.71	0.68	0.62
	RMSE	0.654	0.874	1.324	1.161
	Bias	0.813	0.512	0.864	0.500
Solved parameters	*Hcoeff*	13.66	10.7	11.7	13.4
	res	0.374	-0.129	0.154	0.252
	a0	0.423	0.723	0.534	0.223
	kd	-0.121	-0.252	-0.157	-0.632
	ka	1.874	0.408	0.542	1.302

* Pine included lodgepole and Scots pine. Note: the model for birch was not significant

When peat depth was used as the only predictor of tree height, the model described over 50% or the variation in observed tree H across all species. However, when peat aeration was included in the multiple variable regression equation, this described an additional 20 % of the observed variation in tree height (eq4). It is also evident from the lower values for fitted parameter for P_{depth} (*kd*, Table 5) that Norway spruce and Sitka spruce display a greater decline in tree H as peat depth increases, when compared to hybrid larch and pines. Hybrid larch, however, appears to be more sensitive to anoxic peat conditions, when compared to the other species (see higher *ka* value for larch in Table 5). These trends are more clearly demonstrated in Figure 9 below.

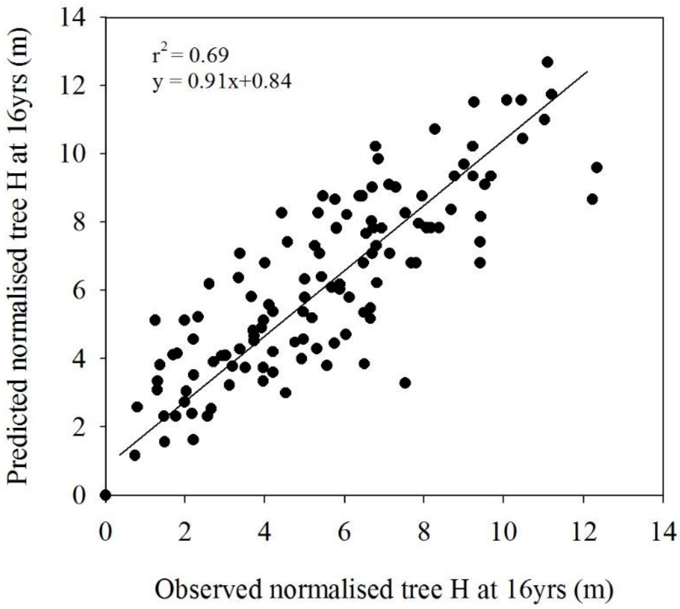

Figure 8: Regression of observed versus predicted normalised tree H (n =125) using the peat depth and aeration model (equation 4). Note Birch was excluded from regression because the model coefficients (equation 4) were not significant.

Using the yield class thresholds defined by Ray et al., 2009, and based on the modelled scenarios presented in Figure 9 (left panel), it is evident that both Norway and Sitka spruce may only be suitable for planting on *Phragmites* or woody fen type peats and when the peat depth is less than 1.2 m and sites are well drained (Relative aeration =1). Planting of these species on deeper peats would likely result in low productivity crops (less than a yield class of $12m^3$/ha/yr) under current management practices. However, if drainage is not suitable and the aeration ratio is less 0.5 (e.g. an anoxic layer of 0.6m for a total peat depth of 1.2m) then the model predicts that Sitka spruce and Norway spruce would only be suitable up to a peat depth of 0.3m and 0.5m, respectively (Figure 9, right panel).

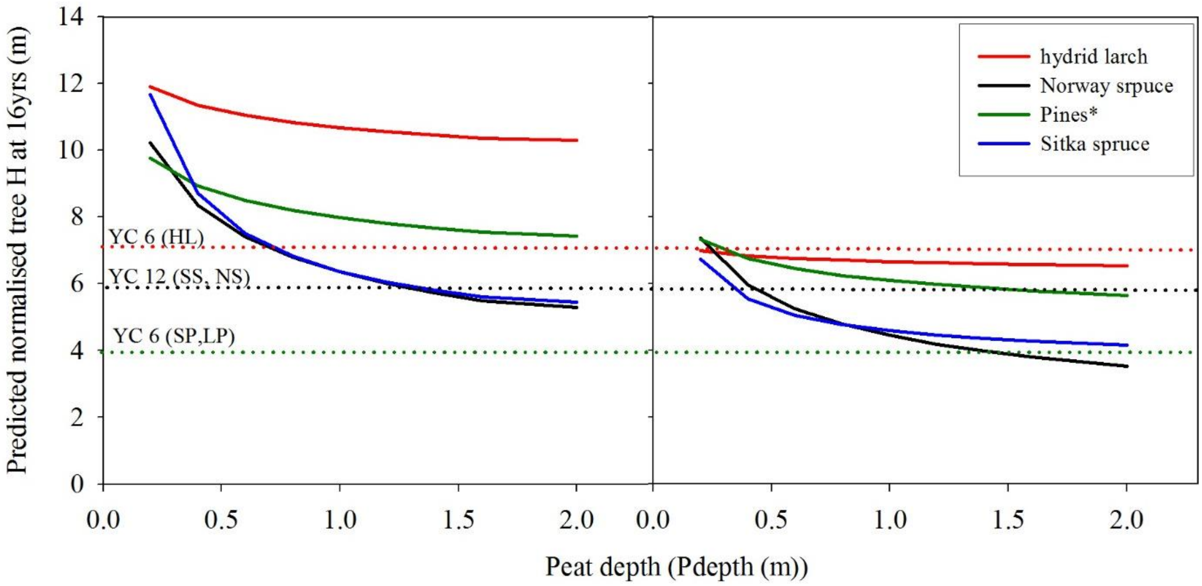

Figure 9: Fitted model curves (eq4) for tree H of different species over the peat depth range (solid coloured lines) under a well-drained (left panel, $P_{aeration}$ =1) and poorly drained scenario (right panel, $P_{aeration}$=0.5). The segmented lines represent the indicative cut off point for suitability (based on YC) of Norway spruce (NS, black), Sitka spruce (SS, black)), YC<12, hybrid larch (HL, red), lodgepole (LP, green) and Scots pine (SP, green), YC<6 (the CLIMADAPT model YC thresholds, Ray et al., 2009).

The model predicts that hybrid larch can tolerate deeper peats (up to 2m) as long as the site is well drained. However, it should be noted that the maximum sampled peat depth for HL was only 1.5m, so extrapolating predicted growth beyond 1.5m is not recommended. Good drainage appears to be a more important factor for hybrid larch. The model predicts that hybrid larch would not be suitable at any peat depth if the aeration ration is below 0.5 (Figure 9, right panel). Both lodgepole and Scots pine appear to tolerate deep peats (Figure 9) and anoxic conditions. The model predict that pines would be suitable for 2m peats up to a $P_{aeration}$ ratio of 0.35 (data not shown). This trend was consistent with observations of extensive colonisation by of pine species in deep of Phragmites and woody fen sites with poorer drainage, which generally did not support Norway or Sitka spruce. Although the model does not describe any variation in the height growth of birch, the data shown in Figure 7 suggest this species can better tolerate anoxic conditions. In experiment KTY14/00, one of the selected plots was saturated due to poor maintenance of drains in the area. However, planted birch was still ca. 8 m high, but here was also some colonisation by willow.

Pearson's correlation analysis presented in Table 6, provides additional evidence supporting the proposed mechanism for poor performance of species on deeper and poorly aerated peats. The significant negative Pearson's coefficient for the relationship between needle K content (Ln(K)) and P_{depth} for Norway spruce confirms that needle K deficiency is likely to occur in deeper peats. Although the same trend was observed for Sitka spruce and Scots pine this was not significant, possible due to a limited number of sample plots (Degrees of freedom is low). The significant positive correlation between needle K and P content and relative aeration ratio ($P_{aeration}$) also suggests that P uptake is limited under anoxic conditions leading to deficiencies in K and P. This relationship was, however not significant in some cases, such as for needle P content and P aeration for Norway spruce.

Table 6: Pearson's regression coefficients for the relationships between peat depth or relative aeration ratio and the natural log of % nutrient content for nitrogen (N), phosphorous (P) and potassium (K). Coefficients highlighted in bold with an asterisk indicate that the relationship is significant at p<0.05(*) or p<0.01(**); ns means that the relationship is not significant based on the Pearson's correlation coefficient and the degrees of freedom (N-1).

	Ln(N)	Ln(P)	Ln(K)	Deg. of Freedom
Norway spruce (NS)				
P_{depth}	0.08ns	0.22ns	**-0.39***	36
$P_{aeration}$	-0.12ns	-0.12ns	**0.41***	36
Sitka spruce (SS)				
P_{depth}	0.15ns	-0.53	-0.36	6
$P_{aeration}$	-0.49ns	**0.92****	0.59	6
Scots pine (SP)				
P_{depth}	0.55ns	-0.62ns	-0.44ns	7
$P_{aeration}$	-0.66ns	**0.96****	**0.74***	7

3.2.2 Site preparation

The 2 cultivation trials (KTY16/00, CLE2/00) and 2 demo areas (CLE1/99, KTY1/99) were replicated across 2 areas and included four species (SS, NS, SP and HL) in the cultivation trials and NS in the demo areas. This enabled the assessment of the medium-term effect of cultivation on species productivity using analysis of variance (ANOVA, Table 7). In 2005, Renou-Wilson et al., (2008) reported a significant difference in species performance in the 2 cultivation trials (KTY16/00, CLE2/00), but reported no significant effect of cultivation treatment on tree height or survival.

Table 7: Three-way ANOVA showing sources of variation (species, site and cultivation treatment) of mean tree height for CLE2/00 and KTY16/00. Treatments included control (no treatment), mounding, ripping and ripping and mounding.

Variable	Degrees of freedom	Sum of Squares	RMSE	F value	Pr(>F)
Site	1	32.56	5.62	5.62	0.004*
Species	3	20.32	4.12	4.02	0.005*
Cultivation Treatment	3	1.98	0.87	0.21	0.68 n.s.
Residual	47	26.75	1.12		

*Significant at 95 % confidence interval

The ANOVA confirmed that there was a significant site and species influence on mean tree height, but there was no significant treatment effect from the cultivation (pr(>F=0.68)). This is probably due to the variation in peat depth across the cultivation treatments, which may have masked any treatment effect on tree performance.

Similar results were seen in the demo areas (without the mounding treatment) where ANOVA showed that neither cultivation or site effects were significant (Table 8). These findings are consistent with previous assessments on the same demo areas in 2005, where cultivation treatment did not significantly influence tree height or survival of Norway spruce (Renou-Wilson et al., 2008).

Table 8: Two-way ANOVA showing sources of variation (site and cultivation treatment) of mean tree height for demo area CLE1/99 and KTY1/99. Treatments included control (no treatment), ripping and ripping and disc treatment.

Variable	Degrees of freedom	Sum of Square	RMSE	F value	Pr(>F)
Site	1	2.32	0.78	0.33	0.69
Treatment	2	2.126	0.72	0.64	0.57 n.s.
Residual	6	6.75	1.07		

3.2.2.1 Observations on Savannah plough treatments

The Lullymore demonstration areas were cultivated with the Savannah bedding plough. This plough can cultivate deeply (ca. 0.8m) and enhances increased aeration and mixture of the peat. There were no control or alternative cultivation treatments in the Lullymore demonstration, so the relative effect of the plough treatment could not be determined. Killinagh has predominantly a woody fen type of peat with some *Sphagnum* in the deeper residual areas. The underlying mineral layers varied from un-weathered glacial till in shallower regions, to calcareous mud sediments in deeper peats. The Savannah plough treatment resulted in good mixing of peat and some incorporation of the underlying mineral layers, but only in the shallower peat regions (<0.8m deep). There was evidence of some peat oxidation below the surface, suggesting that aeration was good in parts of the site. However, parts of the site were still poorly drained.

The nearby Derrybrennan area generally contained deeper *Phragmites* dominant peats (greater than 3m in some areas according to BNM peat depth surveys). All survey plots for this site, except one, had peat depths greater than 2m. Therefore, there was no obvious benefit of the plough treatment in these deep peats in terms of mixing of peat with underlying mineral material. Observations on peat cores taken from these areas suggested that the plough treatment had no obvious effect on the peat substrate aeration.

3.2.3 Tree establishment in Lullymore

Most establishment observations are related to the two demonstration areas (Killinagh and Derrybrennan) established over the period 2010 to 2012. Areas adjacent to drains and wetter areas were already colonised with birch and some regenerating lodgepole pine before establishment. These colonised areas were not disturbed in an effort to provide some shelter for Norway spruce and to assist with retention of nutrients after establishment (based on recommendations from the previous BOGFOR report, Renou-Wilson et al., 2008). Establishment and growth of Norway spruce appeared to be better in shallower peat regions and where there was more birch or lodgepole pine. In some areas, the birch has grown very tall and is starting to suppress the growth of Norway spruce.

Growth was poor in deeper, poorly drained areas and where *Sphagnum* peat was present and *Calluna* vegetation dominated. In these areas, tree growth was stunted and needles were deficient in N (see Table 9).

There was evidence of extensive natural regeneration of lodgepole pine in Killinagh and their subsequent growth was better than that of Norway spruce, despite the fact that the pine could only be one to two years older than the spruce. A section of the Killinagh site had been previously seeded with lodgepole pine but the exact details of this were not made available. However, germination and tree growth was excellent in this area (see Figure 10) and tree height of the pine was 4 to 6 times that of Norway spruce (Figure 10).

Figure 10: An image of the area directly seeded with lodgepole pine at Killinagh showing good establishment and superior growth over the planted Norway spruce crop. Note part of the Norway spruce crop appeared to have received no fertiliser

As pointed out earlier the Derrybrennan area was given a broadcast application of 250 Kg/ha of granulated rock phosphate in 2012. Although a further application of rock phosphate and muriate of potash were planned for 2015, these treatments do not appear to have been carried out. Large parts of the area now show potash and phosphorus deficiency. Ground observations suggest much of the area did not receive the initial fertilisation and/or did not receive a follow up application of K. Over 66% of trees samples were deficient in K. There was also little or no natural regeneration of birch in these areas.

3.2.4 Crop nutrition

3.2.4.1 Nutritional status

Foliar nutrient analysis showed that P in particular was deficient in most samples taken (74%). Although K deficiency was detected on only 9 % of samples taken, more than half of the samples had marginal K levels. These low P and K values are mainly associated with a greater peat depth and lower aeration (see Table 6), but other factors such as the lack of appropriate timing and rates of fertilisation application or un-even application of fertiliser also may have contributed to the poor nutrient status of the crops (see results below).

Low copper levels were also evident in many of the samples sampled, but there was no evidence of any of the other minor nutrients being an issue. Although boron deficiency has been suggested to occur in cutaway peatland sites (Pietiläinen et al., 2005), levels found in the samples tested were satisfactory.

Potential reasons for the low macro-nutrient status for these crops include:

- Limited availability of P and K in deeper and poorly drained *Phragmites* peat bays (see Table 6) due to a low soil pH, a high degree of leaching and anoxic conditions which limit K and P uptake.
- The combination of fertiliser application on completely bare peat on exposed bays which are cambered towards 1m deep drains may have resulted in much of the initial p application being lost and not available to the trees,
- All trees regardless of peat depth, showed signs of P deficiency, or had marginal P levels, at 16-20 years after establishment. Assessment of height growth suggests that most sampled trees showed sign of reduction in leader growth from ca. year 10-12 onwards.
- Insufficient initial applications of P, in particular. Experiment CLE6/00 only received a split applications of P (48kg P/ha) in total. It is recommended that higher split application rates should be considered. However, the possibility of P run-off and its potential impact water quality should be considered in this context.
- Second applications of K were not applied in some experiments or not at all in some cases (earlier recommendations from BOGFOR were for one application of K, to be applied in two years after planting). Results from studies on Scots pine in Finland show that 100kg of K/ha is required on woody fen and *Phragmites* peat sites at 8-10 years after planting to remedy potential K deficiencies and reduction in crop vigour (Pietiläinen et al., 2005).
- In some cases, inadequate delivery of fertiliser management objectives was not met due to possible uneven application of fertiliser or no application of fertiliser at all. Mechanisation of fertiliser applications and greater supervision should be considered given the nature of cutaway peatlands and to avoid potential operational fall down problems.
- Areas showing deficiencies in N (with the exception of SS in KTY16/00) were characterised by *Sphagnum* dominated peats with dominant *Calluna* vegetation cover. Copper deficiency was also detected in most of the crops (see detailed description of experimental site nutrition status below).
- N deficiency in SS is also apparent in 16 to 20-year-old crops (KTY16/00 and CLE2/00). This seemed to occur regardless of peat depth or aeration of the peat layer.

The results of the foliage analysis of samples taken from survey plots are described below on a site by site basis with reference to the appearance of the trees, their current condition and performance and the composition of the peat on which they are growing.

KTY 1/99. Norway Spruce Demonstration Area Blackwater.

The most striking feature about this area is the highly variable performance of the trees in terms of their height growth and overall appearance. At times the variation is expressed over short areas.

Some trees have grown very poorly in comparison with others that have shown excellent growth. A significant number have also died or show clear symptoms of severe decline and being likely to die in the near future (see Figure 1). Others show dieback in the mid crown following a period of reasonable growth. The response to the second application of fertiliser is evident on many trees. There is also a strong suggestion in parts of the trial that some of the variation in tree growth may relate to uneven application of the fertiliser, an issue evident in many other areas outside of this experiment on cutover and other peatland types. However, other factors, in particular peat depth, appear to have a big influence on performance (see Table 6).

The foliage analysis results show extremely low and deficient levels of phosphorus in virtually all of the samples. Even the highest level recorded is below the marginal threshold value. Although nitrogen is at a satisfactory level in all of the samples from this area, only half the samples have satisfactory potassium levels, most of the others being in the marginal category. Only one sample shows an actual deficiency level of potassium. Trace element levels are generally in the satisfactory range, apart from copper for which almost half the samples are marginal/deficient, none being satisfactory.

KTY 16/00. Cultivation and Species Trial

A cultivation/species trial planted at Blackwater in 2000. Foliar samples were taken in Norway and Sitka spruce, Scots pine and hybrid larch. The results again show extremely low levels of phosphorus in Norway spruce (the worst), Sitka spruce and hybrid larch (note that no threshold levels are available however for this latter species). Phosphorus levels in one of the two Scots pine samples are below what is considered adequate in Finland. Nitrogen is at a satisfactory level in all the samples across the four species, apart from Sitka spruce, where three out of four samples are in the deficient category. Potassium levels are marginal in three of the four Norway spruce samples and extremely low in one of the hybrid larch samples. Levels of potassium in Scots pine are well above what is considered optimal in Finland. None of the samples have satisfactory copper levels with two samples being deficient; one Norway spruce being particularly so with a result of 1.6 mg/kg. In general growth is highly variable.

KTY 17/00. Blackwater Species Demo Area

This area was planted in 2000. Sampling was confined to lodgepole pine and western red cedar (WRC). Although threshold figures for WRC are sparse (and relate to Canadian conditions), the indications from the results are that phosphorus levels are extremely low in two of the tree samples and marginal in the other. Phosphorus and potassium levels are also extremely low and deficient in the lodgepole pine. Nitrogen levels are satisfactory in the cedar but potassium levels are marginal in two of the three samples. Copper levels are low in each species apart from one of the three cedar samples that may be showing some form of contamination.

CLE 1/99. Norway Spruce Demonstration Area Tumduff.

This area was planted in May 1999. Each of the foliage samples shows extreme phosphorus deficiency, the range being in the same order of magnitude as that found at the Blackwater demo area (KTY 1/99 above). Nitrogen levels are in the marginal- satisfactory categories and in general, although somewhat higher, in the same range as those found at KTY 1/99 (above) at Blackwater.

Most of the potassium results are in the marginal category, with one sample being extremely low in this element. Over half of the samples are deficient in copper. None of the samples has what is considered a satisfactory level (5 ppm) in this regard.

CLE 2/00. Cultivation and Species Trial

This is a cultivation trial planted in 2000 at Tumduff with different species. Three of these species were sampled; Sitka spruce, Norway spruce and Scots pine. Each of the species shows extremely low phosphorus levels, apart from one of the Sitka spruce samples where the phosphorus status is satisfactory. Nitrogen levels are satisfactory in the pine but potassium levels are deficient, in contrast to the Sitka and Norway spruce where they are satisfactory. Copper levels vary between marginal and deficient with none of the samples being satisfactory.

TLM 35/96. Species Demo Area Tumduff

This area was established before The BOGFOR Programme and was planted in 1996. Three species were sampled; Sitka spruce, Scots pine and western red cedar. Each species is extremely deficient in phosphorus but nitrogen and potassium levels are generally satisfactory. Copper levels are comparable with those found in the other areas, varying between marginal to deficient with none being satisfactory.

Killinagh (Lullymore).

This is part of the operational area planted in 2010-2011 with Norway spruce. Seven foliage samples were taken in November 2016. Phosphorus levels in two of the seven samples are in the satisfactory category (just about) while the other five are marginal. This implies that phosphorus deficiency is likely to occur over the next couple of years at this site. Although potassium levels are generally satisfactory, nitrogen levels are deficient in four of the seven samples, being particularly so in three samples where *Callun*a is dominant in the vegetation. Copper levels are deficient in all the samples and generally lower in comparison to the other sites samples (above).

Derrybrennan (Lullymore).

This is the second part of the operational area (close to Killinagh above) and planted in 2012 with Norway spruce. Three foliage samples were taken in November 2016. The results show that phosphorus levels are satisfactory in each of the samples (somewhat marginal however in one instance) with nitrogen showing similar trends. Potassium levels are extremely deficient in two of the three samples. This concurs with field indications suggesting that a large part of the site did not receive muriate of potash which was scheduled for 2015. Copper levels are marginal/deficient.

3.2.4.2 Fertiliser trials

CLE 6/00 NS Fertiliser Trial

Preliminary GIS analysis shows that canopy height and crop vigour (NDVI) varied more from bay to bay than across the different experimental plot treatments (as reported by Renou-Wilson et al., 2008). This was confirmed in the subsequent field assessment, where NS generally performed better in the shallower (0.4-1.2m) peat bays (e.g. the bay on the left (L) of both panels shown in Figure 11;). Trees in this bay were taller and have a more vigorously growing canopy, as indicated by the blue areas (left panel, Figure 11) and the green areas in the right panel of Figure 11. Peat depths in plots located in the bay shown on the right (R) in both panels of Figure 11, were deeper than 2m and tree growth was very poor irrespective of previous fertiliser treatment. There was also extensive birch encroachment on this site, so the use of GIS analysis for accurate estimation of crop top height for further analysis was problematic because it is not possible to distinguish between the crop species and encroaching birch at the time of year when the imagery was taken by Blue Sky (May 2016).

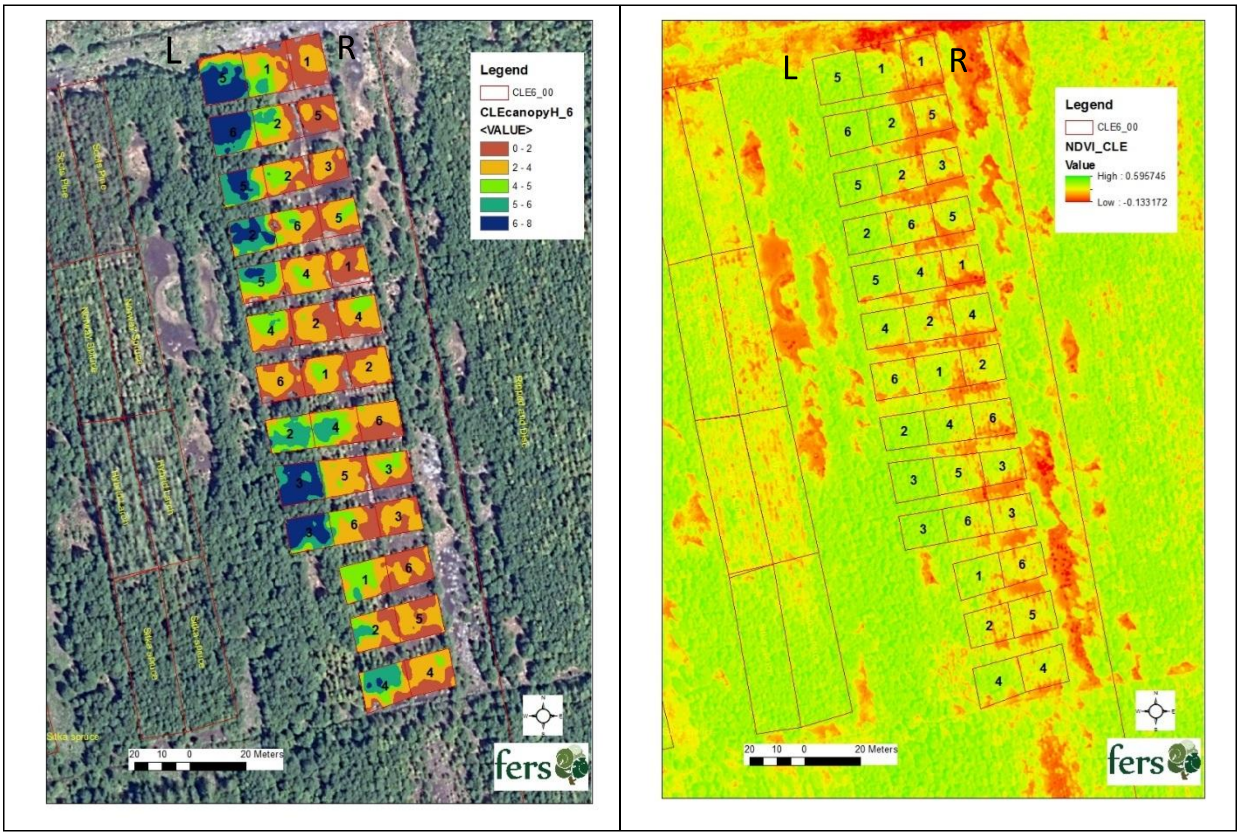

Figure 11: A RGB image overlaid with a canopy H model (left) and a NDVI image (right) of Exp. CLE6/00. Treatment codes are indicated by numbers (in black text), these relate to treatments listed in table 2 in the methods section.

Although the CLE6/00 is a replicated block experiment, the team concluded that it would not be worthwhile doing detailed nutrient or mensuration assessments. We did however, take foliage samples from each replicate of treatment 1 (42 Kg of P/ha broadcast) and treatment 3 (28 Kg of P/ha broadcast) to assess if the higher rates of P application was sufficient to maintain the long term nutritional status of the trees or if there were any differences between treatments in this regard.

In general stocking levels are highly variable and uneven across the treatments with a variable level of birch intrusion. Stocking levels are particularly low in three of the plots where the low rate of phosphorus was applied. Height growth of the spruce is also highly variable within treatments. The best plot in terms of both stocking and growth received the higher rate of phosphorus. Many of the trees in the plots that received the low rate are in check. However, most of the trees in one of the plots that received the higher rate of fertiliser are also in check and have performed poorly. This suggests strongly variable site conditions.

The results of the analysis are presented in Table 9, the data for each of the five replicates, for each of the two treatments being bulked and averaged.

Table 9: Foliage analysis Experiment CLE 6/00

Treatment	% N	% P	% K	Cu ppm
42 Kg P/ha	1.60	0.07	0.45	2.74
28 Kg P/ha	1.64	0.08	0.46	2.16

Phosphorus levels are extremely deficient in all of the samples are there are no significant differences between the two treatments in this regard. Potassium levels are also deficient but rather surprisingly the nitrogen results are satisfactory, apart from one of the samples for each of the treatments which are marginal. Although copper levels in the high phosphorus treatment are somewhat higher compared to the lower fertiliser treatment both levels are below the threshold.

In general, the results confirm that neither rate of phosphate fertiliser tested is sufficient to satisfy the needs of the crop.

3.2.4.3 Conclusions

The most striking feature of the results of the foliage analysis is the extent and severity of phosphorus deficiency across the areas sampled. The only areas not showing a deficiency of phosphorus were the two more recent developments at Lullymore (Killinagh and Derrybrennan) with parts of both areas beginning to show some evidence of impending problems in this regard. These areas are much younger (P/2011-2012) compared to the areas included in the BOGFOR programme which date back to 1999-2000.

The results clearly indicate therefore that the amounts of phosphorus applied to the areas concerned are inadequate to sustain acceptable tree growth and that a deficiency of this element is likely after about eight years (see below) depending on the amounts of fertiliser applied initially. Although the results for nitrogen and potassium may appear generally satisfactory, given the nature of the peat, it is highly likely both would have become limiting had phosphorus been maintained at a satisfactory level. Copper is at a low to marginal level in most of the samples and is likely to have become more acute had the levels of the other main nutrients, particularly phosphorus, been maintained at a satisfactory level. None of the other trace elements appear to be limiting growth.

The low level of phosphorus present in the foliage samples is indicative of the inadequacy of the rates of fertiliser phosphorus used in both the experiments and demonstration areas to sustain a satisfactory growth pattern. A significant fall off in phosphorus levels in particular, and nitrogen and potassium, after 8-10 years was also noted in the BOGFOR report (Renou-Wilson et al., 2008). These were in areas treated with either 600 Kg of 0-10-20 or 350 Kg of unground rock phosphate (42kgP) and 250 Kg of muriate of potash (125kgK) at planting time. These rates are also significantly lower than those recommended in Finland (68 Kg/ha of P). In Scandinavia, wood ash is also applied to peat soils in an effort to increase pH and nutrient levels.

The Forestry Schemes Manual for Ireland (Forest Service 2011) recommends that in the case of unenclosed land 350 Kg/ha of granulated rock phosphate (42 Kg of P) "may be necessary at establishment" and a second application of 250 Kg/ha "as required". The results in general suggest such amounts are the minimum needed to ensure successful establishment and sustained growth of forest trees on cutover peatland sites, provided excessive peat depth is not a constraint. Monitoring the crop for nutrient deficiencies at 8-10 year onwards and application of additional fertiliser is required to ensure canopy closure and sustained productivity.

3.2.5 Frost

In experiment CLE2/00, Sitka spruce growth was initially slow, possibly due to frost damage. Subsequent growth was good, particularly where there was extensive encroachment. This may be due to the nurse effect of birch on Sitka spruce (see result of EXP14/00). Large amount of birch litter did appear to improve the growth and nutrient status of Sitka spruce on deeper sites. The overall height of Sitka spruce on deep peat was lower than the other species in the same experiment (Table 4). In addition, stocking of Sitka spruce was low (Table 4), possibly due to initial mortality, possibly associated with frost and suppression by birch encroaching the site.

3.2.6 Pests and diseases

New observations:

1. There was evidence of older but severe rabbit or hare damage to beech, goat damage to western red cedar, and some more recent hare damage on pole stage hybrid larch in Tumduff North (TLM 35/96).
2. Low occurrence of mild symptoms of *Ramichloridium pini* (shoot dieback, unconfirmed) in some lodgepole pine in Tumduff North
3. Some evidence of European pine shoot moth, *Rhyacionia buoliana,* in naturally regenerating Scots pine and lodgepole pine in Tumduff CLE1/99.
4. No evidence of red band needle blight in Corsican, lodgepole or Scots pine in any of the sites visited.

3.2.7 Vegetation control

Much of the mortality in young Sitka spruce plantations on cutaways in the early 1990s was rightly attributed to the exceptional early summer frosts of 1989 and 1991. Poor performance in many of these areas, however, was enhanced by the difficulty in controlling heavy vegetation, especially rush (*Juncus spp.*). Subsequently, a lot of work was carried out (using both research and operational trials) on a suite of BOGFOR sites to ensure that vegetation was not an issue in establishing forests in those areas under the latter programme.

By the end of the BOGFOR programme, and this more recent review, our thinking on vegetation and its management has probably changed. Some vegetation is now considered an advantage and it is apparent that where herbaceous vegetation grows well, trees will also perform do well. The presence of vegetation at the establishment phase on these sites is also probably beneficial from a nutritional point of view - compared to bare peat sites (where applied nutrients may be lost). Woody vegetation (especially *Salix* and *Betula*) has also been seen only as a problem in the past. Our current thinking, however, is that working with this type of vegetation may help other crop species, particularly in relation to shelter, frost damage and nutrient recycling.

3.2.8 Exposure

The original BOGFOR report refers to the benefits of shelter on cutaway peat sites particularly prone to prevailing winds (Renou-Wilson *et al*., 2008). In situations like this, pioneer species often do best and tolerance of exposure is probably one of the reasons why lodgepole, Corsican and Scots pines and birch have done well on many cutaways. In the first 5-10 years after establishment, common alder was also reported to be tolerant of exposure on these sites. Since then, however, the species has shown die-back on some sites. It is not known whether this is related to exposure, but in CLE 3/00 (Tumduff), some sort of stress has resulted in the alder crop there showing severe die-back and profuse natural regeneration under the dying canopy.

Western red cedar established poorly, partially due to initial goat damage, but grew well in some experimental sites (Table 4) and some of the Coillte sites (Table 3a and b). There was, however, evidence of some poor growth due to exposure, particularly in plot edges and this was evident soon after establishment. Stem form displayed a high degree of taper and branching, a typical characteristic of a shade bearing species. This species may be better utilised growing under existing canopies of birch, oak or established as a mixture with hybrid larch or Sitka spruce (no trial information available but see Horgan et al., 2004).

Of the two spruces used on the cutaways, Sitka is, by far, the more tolerant to exposure. Norway spruce, on the other hand, can be very intolerant to exposure both as a young crop and even in older plantations. The condition of "top-dying" in Norway spruce has been reported in Ireland previously (Stanley *et al*., 1996) and Norway spruce crops are currently showing die-back on many cutaway sites (e.g. KTY 1/99, CLE 1/99). Unfortunately, it is very difficult to be definitive about the causes of die-back on these sites as factors such as nutrition, peat type and depth and exposure are probably all acting together on many sites.

3.2.9 Mixed species trials

The mixed birch and Sitka spruce trial (KTY14/00) was revisited in January 2017 for detailed plot assessments. The objective was to determine if birch offers any nurse effect to Sitka spruce, when planted at different configurations (see Methods section).

3.2.9.1 Tree-level assessments

Comparison of mean heights and DBH for the two species revealed that treatment planted in alternative lines at the same time produced trees with a higher mean DBH and height, for both species (Table 10). The growth of Sitka spruce in the pure stand treatment (no birch) was stunted, showing the characteristic deficiency symptoms observed on other experiment located on deep peats. In contrast, the Sitka spruce trees in the mixed species plots planted at the same time showed no signs of a decrease in growth, visual needle deficiency symptoms or suppression by birch at this stage of canopy development. When planting of spruce was delayed by 2 or 4 years after birch was planted, spruce trees showed signs of suppression by birch.

Table 10: Mean and standard error (in parenthesis) diameter and breast height (DBH) and tree height (H) of Sitka spruce and birch in the mixed species trail treatments.

Treatment	**Species**	**DBH (cm)**	**H (m)**
Pure SS	Sitka spruce	5.7(1.2)	4.4(0.9)
Alternate lines SS and BI (planted at the same time)	Birch	11.3(2.5)	7.8(1.3)
	Sitka spruce	7.7(1.7)	5.9(0.8)
1 line BI 3 lines SS (planted at the same time)	Birch	8.8(2.1)	6.3(1.3)
	Sitka spruce	5.8(1.0)	4.5(0.7)
1 line BI 2 lines SS (planted at the same time)	Birch	7.8(1.9)	6.0(0.9)
	Sitka spruce	6.2(1.0)	4.7(0.6)
Alternate lines, SS 2 years after birch	Birch	9.5(2.9)	6.6(1.4)
	Sitka spruce	4.5(0.9)	3.8(0.6)
Alternate lines, SS 4 years after birch	Birch	6.5(1.4)	5.1(0.7)
	Sitka spruce	3.3(0.9)	3.4(0.6)

3.2.9.1.1 Randomised Block ANOVA model and comparison of means.

The design of the trial allowed us to test if there was a significant block effect due to other factors which may be influencing tree performance. The random block ANOVA model was significant for both DBH and height of Sitka spruce across the treatment and blocks (Table 11). Analysis of model residuals (observed minus predicted values from ANOVA model) for normal distribution, based on the Shapiro-Wilk statistic, shows that residuals are normally distributed (i.e. the Shapiro-Wilk statistic is not significant at $p< 0.05$, Table 11). This is a particularly important goodness of model-fit check when using general linear models such as the randomised block ANOVA model described in equation 6 (see methods).

Table 11: Two-way ANOVA showing sources of variation (mixture treatment and block effect) for DBH of Sitka spruce in the mixed species trial KTY 14/00 (see methods section for treatments).

DBH (cm)					
Source of Variation	*SS*	*df*	*MS*	*F-value*	*Shapiro-Wilk*
Between Treatments	494.7	5	98.5	21.4***	
Between Blocks	104.4	2	52.2	11.2***	
Residuals	1439.2	309	4.6		0.993 n.s.
Height (m)					
Source of Variation	*SS*	*df*	*MS*	*F*	
Between Treatments	90.4	5	18.1	9.1***	
Between Blocks	40.14	2	20.5	10.6***	
Residuals	619.5	311	1.9		0.991 n.s.

The block effect was significant for both DBH and height (Table 11), which means that some other factor, presumably peat depth was also contributing to apparent differences in DBH or height across treatments. The treatment effect was also significant when block effects are factored out using the

ANOVA model (Table 10). Therefore, a valid comparison of mean DBH and height was carried out using Tukeys HSD multiple comparison test (Figure 12)

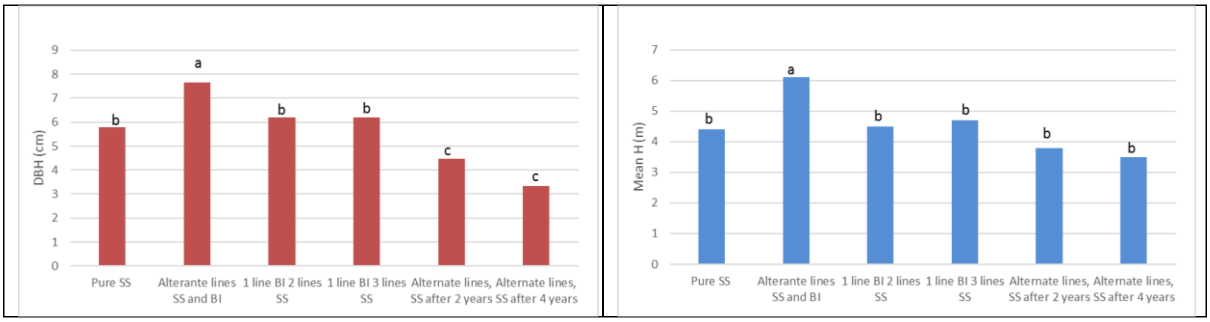

Figure 12: Comparison of mean DBH (left panel) and height (right panel) of Sitka spruce across the 6 different planting configuration treatments. Histograms with different letters indicate that mean values are significantly different (at P<0.05) based on the random block ANOVA model and Tukeys HSD test on the treatment factors.

Comparison of individual tree data across the treatments shows that Sitka spruce, planted at the same time in alternative lines with birch, had a significantly higher mean DBH (19-61%) and mean height (20-47%), compared to the other treatments (Figure 12). When compared to the pure Sitka spruce treatment, the DBH and height of Sitka spruce was ca 35% higher in the plots planted in alternative lines with birch (Figure 12). Planting Sitka spruce at higher densities than a 50:50 mix or delayed planting of Sitka spruce under birch appeared to offer no significant nurse effect, when compared to pure Sitka spruce treatments (Figure 12).

3.2.9.2 Plot -level assessments

The same randomised block ANOVA model was applied to the plot level data. The treatment effect on stocking (stems/ha) and basal area was significant (F-value, p<0.05) for the individual species within different planting configurations (see Table12). The treatment effect on top height was significant for Sitka spruce, but not for birch (Table 12). The block effect was not significant for all individual species plot variables (block F-value p>0.05). There was a significant treatment and block effect on total plot basal area, but no significant influence on stocking at both the block and treatment level (Table 12).

Table 12: Results from the random block ANOVA model showing the significance of the treatment (degrees of freedom = 4) and block effects (degrees of freedom = 2) on plot variables, such as top height, stems per hectare and basal area for individual species and for both species in the plot. F values with a probability (p-value) of greater than p>0.05 was not significant (n.s.). Effects were significant at p<0.05 (*), p<0.01 (**) and p<0.01 (***). The Shapiro-Wilk statistic is a measure of normal distribution of the model residuals, where p>0.05 is not significant (n.s.). Mean top height values for the mixed plots was not compared (NA)

Variable/Species mix	Treatment F value	Block F value	Shapiro-Wilk
Top Height (m)			
Sitka spruce	11.51**	1.57 n.s.	0.95 n.s.
Birch	0.75 n.s.	3.71 n.s	0.87 *
Plot mean	NA	NA	NA
Stems/ha			
Sitka spruce	10.67**	0.76 n.s.	0.96 n.s.
Birch	20.97***	2.71 n.s.	0.93 n.s.
Plot total	1.11 n.s.	1.64 n.s.	0.86*
Basal area (m^2/ha)			
Sitka spruce	7.97**	1.95 n.s.	0.92 n.s.
Birch	4.26 8	3.35 n.s.	0.91 n.s.
Plot total	4.76*	5.89*	0.94 n.s.

Comparison of means where, only tested for species individually. Species was not included in the model as a factor, so mean comparisons are only valid within species and for total plot data (Table 13). For example, the top height or basal area of Sitka spruce and birch was not compared, even though the letters associated with the mean values in Table 13 may be the same.

Comparison of top height across the treatments shows that Sitka spruce, planted at the same time in alternative lines with birch, had a significantly higher mean top height (by 29-51%), compared to the other treatments (Table 13). The lower top height of Sitka spruce, relative to that of birch, in the treatments where planting was delayed, suggest that spruce is being suppressed by birch. The mean top height of birch was not significantly different across the treatments.

Stocking density of planted Sitka spruce and birch varied across the treatments as expected, but there was no significant difference in total stocking density across all treatments, when mean stems per ha were compared (Table 13). Total basal area of planted trees in the treatment planted at the same time in alternate lines of Sitka spruce and birch was significantly higher (21 to 59%), when compared to all of the other treatments (Table 13). The basal area of Sitka spruce in the alternate line mixed treatment planted at the same time was not significantly different to that of the pure Sitka spruce treatment, despite double the stocking of Sitka spruce in the pure treatment (Table 13). This was associated with the much higher diameters in Sitka spruce in the mixed species treatment (Figure 12).

Table 13: Mean stand values for top height (TH) stocking (stems/ha) and basal area for birch and Sitka spruce in the different treatments. Mean values with different letters indicate that mean values are significantly different (at P<0.05) based on the random block ANOVA model and TukeysHSD test on the treatment factors. There are not valid comparisons between birch and spruce mean values

Treatment	**Species**	**TH (m)**	**Stems/ha**	**Basal area (m^2/ha)**
Pure SS	Sitka spruce	6.8b	2743a	8.3a
	Total		**2743a**	**8.3c**
Alternate lines SS and BI	Birch	9.9a	1150b	13.3a
	Sitka spruce	10.5a	1357b	7.3ab
	Total		**2507a**	**20.6a**
1 line BI 2 lines SS	Birch	8.8a	649c	4.5b
	Sitka spruce	7.1b	1386b	5.0b
	Total		**2037a**	**8.5c**
1 line BI 3 lines SS	Birch	8.0a	619c	3.6b
	Sitka spruce	7.4b	1947b	6.2ab
	Total		**2566a**	**9.8c**
Alternate lines, SS after 2 years	Birch	8.7a	1475a	13.5a
	Sitka spruce	5.9bc	1357b	2.4c
	Total		**2832a**	**15.9b**
Alternate lines, SS after 4 years	Birch	7.2a	1180ab	12.4a
	Sitka spruce	4.7c	1268b	1.4c
	Total		**2448a**	**13.8bc**

3.2.9.3 Effect of mixture treatments on nutrient status of Sitka spruce

Randomised block ANOVA analysis in the mean plot foliage concentration (N=3 per plot) of micro and macronutrients for Sitka spruce confirmed a significant treatment effect for P and Iron (Fe). There was no significant treatment effect for all other micro and macro-nutrients (Table 14 and data not shown). Comparison of plot means shows that level of P in needles of Sitka spruce sampled from the alternate line treatment (planted at the same time) was 33% higher when compared to the pure Sitka spruce treatment.

Table 14: Mean values of selected micro-and macro nutrients in Sitka spruce needles sampled from different treatments. Mean values (standard error in parenthesis) with different letters indicate that mean values are significantly different (at P<0.05) based on the random block ANOVA model and Tukeys HSD test on the treatment factors.

Treatment	**N %**	**P %**	**K %**	**Fe (ppm)**
Pure SS	1.10 (0.16)a	0.06 (0.01)b	0.60 (0.09)a	25.7 (2.4)b
Alternate lines SS and BI	1.11 (0.29)a	0.09 (0.01)a	0.78 (0.07)a	32.2 (4.2)ab
1 line BI 2 lines SS	1.2 (0.09)a	0.06 (0.01)b	0.58 (0.18)a	26.5 (4.9)a
1 line BI 3 lines SS	1.01 (0.1)a	0.06 (0.01)b	0.69 (0.13)a	23.2 (3.6)b
Alternate lines, SS after 2 years	1.12 (0.12)a	0.07 (0.005)b	0.63 (0.18)a	26.9 (5.3)b
Alternate lines, SS after 4 years	1.1 (0.09)a	0.05 (0.02)b	0.64 (0.07)a	23.5 (5.3)b

Based on the macronutrient threshold limits (Table 1a) is it clear, however, that N and P levels in Sitka spruce in all of the treatments are deficient. Although these experiments were initially at planting with a split application of 175 kg/ha rock phosphate (12.5% P) and 250 kg/ha muriate of potash after two years, a third application of P and N before canopy closure may improve productivity of Sitka spruce in all treatments.

3.2.9.4 Conclusions

The results confirm that planting Sitka spruce with birch in alternative lines results in improved growth performance of the spruce, by ca 35% for both DBH and height, compared to pure Sitka spruce stands. These findings are consistent with other studies conducted in naturally regenerating birch and Norway spruce stand in Sweden (Fahlvik et al., 2011; Johansson, 2003), who suggest that performance of Norway spruce is improved when grown with birch. Johansson (2003) highlighted the potential use of these mixtures for both biomass and timber production using the Kronoberg management approach, where birch is utilised for biomass from thinnings and the final Norway spruce crop produces valuable timber. This approach may be particularly suitable to the Bord Na Mona estate since it can fulfil both bioenergy and timber production objectives. In addition, the nurse effect of birch on spruce in deeper peat sites, means that the range of sites suitable for commercial timber production of spruce can be increased. The results suggest that pure spruce sites are only suitable on peats shallower that 0.8m, but can be planted on deeper peats (<2m) when planted in a mixture with birch. However, further research is required to assess the viability of the proposed Kronoberg silvicultural system on cutaway peats. The timing of silvicultural intervention is particularly important to ensure that the Sitka spruce crop in not suppressed whilst still preserving the birch nurse effect.

3.3 Task 3: Nutrient run-off

Water sampling was carried out at three (but only two identified below) sites as part of this study in order to gain an insight into the longevity of runoff impacts on streams following fertilisation with phosphorus fertiliser in particular.

CLE 1/99 (Tumduff)

Results from the original BOGFOR study showed that the application of phosphate fertiliser (a split application in year 1 and 2) resulted in increased levels of molybdate reactive phosphate (MRP) in local drainage waters (Renou-Wilson et al, 2008). During the first four months following fertilisation in 2000, the average MRP concentration increased from 0.014 mg/l to 0.332 mg/l with a maximum of 1.46 mg/l being recorded. Initial peaks in phosphorus concentrations occurred within one - two weeks after fertiliser application but fell off gradually and to almost pre-fertiliser application levels within a period of about 12 months.

The results of the analysis on the 10 water samples taken at this site in December 2016, and again in February 2017, show a consistent MRP concentration of 0.005 mg/l, significantly lower than any of the figures recorded in the earlier studies, including those samples taken **before** fertiliser was applied.

Killinagh and Derrybrennan

Initially it was planned to take water samples from five of the streams coming from the two sites planted at Lullymore (Killinagh and Derrybrennan) in 2011 and 2012 before and after the afforestation (including the fertilisation of same) was carried out. Subsequently the sampling points were reduced to three. Although there was some uncertainty over the location of the sampling points initially, clarification was obtained from the forestry contractor in December 2016 on their actual location. These three locations were used for taking samples in December 2016 and March 2017.

Based on data provided by Coillte, MRP levels in the drainage waters at the two Lullymore sites prior to the application of fertiliser in July 2010 were significantly higher at 6-9 mg/l compared to 0.014 mg/l found in the earlier study at CLE 1/99. There was no indication of an increase in MRP levels post fertilisation but samples taken in 2016 and 2017 showed significantly lower concentrations of 0.005 mg/l - results similar to those for CLE 1/99.

3.4 Task 4: Mapping of experiments

The BOGFOR GIS database (provided to DAFM)
GIS database will be updated to include:
Georeferenced location and the extend (polygon shape files) of all trails/demo and treatments areas.
Location of inspection paths
Experimental and treatment codes related to each area
Last date assessed

3.5 Task 5: Future management of trials

Overall comments

Within the original BOGFOR Programme, over fifty experiments, demonstration areas or monitoring sites were installed. The objectives of establishing these areas at the time were to assess various species, cultivation methods, vegetation control methods and nutrient regimes on the establishment and early growth of forest crops across a range of cutaway bog sites. Those objectives were delivered and reported on in the final BOGFOR Report (Renou et al., 2008).

Eight years after the BOGFOR report was written (and ten years after many of the trials were last assessed), this current project was initiated. This current project looked only at selected trials and demonstration areas from the original fifty. It carried out new assessments of site and crop variables and, later in this report, will report on an effort to pull many of these results together into a Decision

Support System to guide future policy makers and managers on how best to treat these areas for afforestation.

One of the other objectives outlined in this current project was to make recommendations for the future management of these trial/demonstration areas. Before outlining what these might be for individual trials, two possible difficulties should be pointed out:

Although the land under the trials is owned by BNM, the crops are owned by Coillte and should be managed by them. Because many of these crops are marked as 'experiments' within the Coillte inventory, local managers are often reluctant to carry out any operations in these areas without the 'go-ahead' from researchers within the Company. Given recent changes, there are now very few if any personnel in Coillte with the experience to give guidance on how to manage these crops.

A second issue relates to the size and scale of any operation on these trials. These crops were established at a scale which would make them completely uneconomic to thin commercially and a more 'research' based approach will have to be taken. This will cost a lot more (either /m3 or /ha) than a normal commercial thinning.

The main work now required in these areas relates to either fertilisation or thinning.

1. **Fertiliser application:** Prescriptions for application of fertiliser, based on foliar analysis results reported elsewhere in the Report, are given in Table 14 below.
2. **Operational thinning**: If we are making recommendations for an operational thinning, we should also decide whether the thinning will be "to waste" or whether the material will be removed. The latter may not be logistically or economically feasible as many of these plots are small and some are remote from transport options (road and/or rail). Some of the recommendations require a motor manual approach (for cleaning) while some will require full harvesting equipment. Modern forest harvesting equipment is expensive and a suitable package of work (a minimum volume) may have to be put together for a contractor unless a daily rate is agreed. If a more "research" approach is taken, it may be worthwhile using e.g. the Coillte harvesting/forwarding equipment with which detailed assessments can be taken of the harvested material.
3. **Biomass assessment**: Given that these crops are now 16-20 years old, it may be useful to compare species for biomass yield. This can be done for a normal thinning or it might be possible to clearfell small areas within plots to get an estimate of total biomass production/area at this stage (Kent, 2017. Personal communication). If biomass information is now required for these crops, the approach should be as follows:

    a. In plots where thinning is recommended in Table 15 below, then biomass estimates can be made from the thinned material – provided that the thinning type is a mix of systemic and selective.
    b. In plots where thinning is not yet recommended, biomass estimates can be made from selecting a relatively small number (10-20) of sample trees.

Further details on biomass sampling and the relationships between basal area and biomass are given in Kent (2009).

Table 15: Plot specific management recommendations

Expt. name	Type	Species	Area (ha)	Minimum treatment	Optimum treatment	Comment
KTY 1/99*	Demo	NS	10	Fertilise with P & K* 250 Kg/ha of granulated rock phosphate and 200 Kg/ha of muriate of potash	Fertilise and bring up to full stocking with LPS*	Although some parts of some bays are doing well, much of the crop is either dying or showing very severe nutrient deficiencies. Will the crop respond to fertilisation at this late stage**.
KTY 14/00	Mixtures trial	SS & birch	4	Thinning: remove one line of birch from centre of each bay with some selective thinning of larger birch trees. Maintain stocking of birch to ca. 600 trees/ha. Delay thinning Sitka spruce	Depends on treatment 1) **For pure SS:**- no thin at this stage 2) **For treatments planted in alternate lines**: Thinning: remove one line of birch from centre of each bay with some selective thinning of larger birch (i.e. negative selection). Maintain stocking of birch to ca. 600 trees/ha Delay thinning Sitka spruce. 3) **For SS planted in 2 or 3 lines per line of birch**: No thinning	Birch does offer significant nurse effect when planted in alternate lines at same time. Sitka spruce crop too small for a commercial thinning at this stage
KTY 15/00	Spacing trial	Birch	1.5	None	No immediate treatment required	Might have been of use for biomass assessment but birch is poor overall
KTY 16/00	Cult. trial Species	SS	1.1	250 Kg/ha of granulated rock phosphate and 200 Kg/ha of muriate of potash	Thin within 12 months*	Very good performance good stocking rate**

Expt. name	Type	Species	Area (ha)	Minimum treatment	Optimum treatment	Comment
		SP	1.1	None	Select and mark best 600 trees/ha and plan for thinning in 3-5 years*	Lightly branched crop, poorer performance in deeper peats**
		HL	1.1	None	Remove racks and crooked stems	Very mixed crop with large gaps, particularly in wet areas**
		NS	1.1	250 Kg/ha of granulated rock phosphate and 200 Kg/ha of muriate of potash	Thin better areas when next intervention happens in this area	Huge variation between bays (due to peat depth**). Useful as a demo area to show the effect of peat depth, even over a short distance
KTY 17/00	Species demo	Syc., yew, *Alnus cordata, Pinus peuce*	6.5 (total)	None	No treatment required in the next five years	The sycamore and alder are poor and will not form a crop. The pine began well but is now struggling (it is on an exposed corner of the site). Individual yew plants are doing well and show healthy colour but, again, will not form a crop.
		WRC		None	Prune best quality stems	Some areas growing well but many trees are forked**
		Oak		None	Remove willow where interfering with oak	Oak plot in western corner of this trial area not as good as the plot in north-eastern corner
		LPN		None	Re-assess in five years	Worthwhile area in which to assess biomass (very branchy)?**
		CP		None	Select and mark best 600 trees/ha and plan for thinning in 3 years	Good quality, lightly branched crop

Expt. name	Type	Species	Area (ha)	Minimum treatment	Optimum treatment	Comment
		Common alder		Assess the SS planted under some of the crop*	Thin the alder to 400-500 potential crop trees*	SS doing well under the alder. Useful demo area for future recommended scenarios. Assess the Sitka for stocking, health and height and compare with Sitka growing elsewhere in this block.
KTY 18/00	Species demo	Pedunculate oak	0.6	None	Remove naturally regenerating birch, willow and pine	Planted at 2X1m but crop generally poor with poor height growth
		Improved B. pendula	0.6	Thin approx. 40% of stems immediately	In addition to a thinning, mark approx. 600-700 trees/ha as potential crop trees*	Crop shows good potential and needs thinning immediately
		Scots pine	0.6	None	Select and mark best 600 trees/ha and plan for thinning in 3-5 years	Good stocking with mainly straight trees (some forking). Branching quite heavy. Little ground vegetation.
		Aspen	0.6	Thin approx. 40% of stems immediately	In addition to a thinning, mark approx. 600-700 trees/ha as potential crop trees*	Good stocking but large variation in diam. and quality between trees. Many trees leaning but some good individuals. Some deer damage.
		Sessile oak	0.6	None	Remove willow	Poor crop with poor height growth
		Hybrid larch	0.6	Thin heavily and immediately*	Thin heavily and immediately*	Full stocking with some individuals up to 30cm in diameter.
		Ash and yew	0.6 (each)	None	None	Two poor crops with very poor stocking, especially in yew.
KTY 19/00	Birch stock trial	*B. pendula* and *pubescens*	1.3	Thin approx. 40% of stems immediately	In addition to a thinning, mark approx. 600-700 trees/ha as potential crop trees*	Decent crop with some good potential final crop trees. Some birch regeneration appearing throughout.

Expt. name	Type	Species	Area (ha)	Minimum treatment	Optimum treatment	Comment
TLM 35/96	Shallow peat area	WRC	0.7	None	Re-visit in 2-3 years to assess whether thinning required.	Variable, with gaps from where previous goat damage occurred**
		HL	0.7	Thin heavily and immediately*	Thin heavily and immediately*	Thinning now overdue**
		SP	0.7	None	Select and mark best 600 trees/ha and plan for thinning in 3-5 years	Generally poor quality**
		JL/Beech	0.7	Thin immediately*	Thin immediately*	Beech generally all gone at this stage (mainly hare damage)
		Oak	0.7	None	Start the selection of 250-300 potential crop trees/ha	Good quality stems in the crop. Thin at ~12m top height to release potential crop trees
		JL/Sycamore	0.7	Thin immediately*	Thin immediately*	Keep some better sycamore (if straight) in the mix
		NS	0.6	None	Open up racks if thinning nearby plots	Assess need for thinning again in 2-3 years**
		SS	0.2	None	Open racks and thin lightly*	Good crop**
		LPS	0.2	Thin (rack and selection)*	Thin and mark 500-600 potential crop trees/ha*	**
		Common alder	0.2	Thin to 400-500 potential crop trees*	Thin to 400-500 potential crop trees*	Some of the alder crop has already been coppiced (WIT/BNM study)
		Ash	0.2	None	Release any trees which need it by thinning to potential crop trees.	Very poor crop, gravel and calcareous layer at surface
	Deep peat area	Poplar	0.5	None	None	Poor establishment with much of the planted crop now dead
		Oak	0.2	None	Start the selection of 250-300 potential crop trees/ha*	Note oak and sycamore plots are mapped incorrectly on the original map. Oak performing well

Expt. name	Type	Species	Area (ha)	Minimum treatment	Optimum treatment	Comment
TLM 35/96	Deep peat area	Sycamore	0.2	None	None	Note oak and sycamore plots are mapped incorrectly on the original map
		Birch (improved)	0.3	Thin approx. 40% of stems immediately	In addition to a thinning, mark approx. 600-700 trees/ha as potential crop trees*	Good growth with good stem quality, crop supressed
		LPN, SP, WRC, NS, SS X2 for each	Each plot 0.1	None	Revisit in 3 years	Consider putting in racks in harvester in the area soon
		HL	0.1	Thin heavily and immediately	Thin heavily and immediately*	Thinning overdue**
		SS (area to east of main plots)	0.6	None	Put in racks when harvester in the area	**
CLE 1/99	Demo	NS	10	Clean (brush saws?) the birch down to 1000-1500 trees/ha. Fertilise at 250 Kg/ha of granulated rock phosphate and 200 Kg/ha of muriate of potash	Clean (brush saws?) the birch down to 1000-1500 trees/ha	More encroachment by birch. Poor performance on deeper peats **. Follow the Swedish “Kronoberg” method for management of NS/Birch stands
CLE 2/00	Cult. X species	NS	1.1	Remove birch where competing. Fertilise 250 Kg/ha of granulated rock phosphate and 200 Kg/ha of muriate of potash	Remove birch where competing*	Useful to respace birch in unplanted bays – as demo?. Poor growth on deep peats**

Expt. name	Type	Species	Area (ha)	Minimum treatment	Optimum treatment	Comment
		SP	1.1	None	Select and mark best 600 trees/ha and plan for thinning in 3-5 years*	Crop growing well**
		SS	1.1	Remove birch where competing. Fertiliser at 250 Kg/ha of granulated rock phosphate and 200 Kg/ha of muriate of potash	Remove birch where competing*	Slow early growth due to frost?. Good growth after 4 to 5 years, but poorer growth on deeper peats.**
		HL	1.1	Thin immediately	Thin immediately*	Very good growth**
		Syc	0.8	None	None	
		Oak	0.8	None	Start the selection of 250-300 potential crop trees/ha	Good crop but not yet ready for thinning unless considering the selection of crop trees.
		Common alder	0.6	Thin to 400-500 potential crop trees	Thin to 400-500 potential crop trees	Some of this area has already been harvested for biomass (WIT/BNM). Note coppice performance and area under planted with NS and SS
		Oak/HL	0.6	Remove most of HL but retain good stems	Remove most of HL but retain good stems*	Oak quite good
CLE 4/00	Species demo on Sphagnum	LPN, SP, WRC, NS, HL, CP, Syc/WRC, Pinus peuce, SS, JL	7.4	None	None	May be useful if Sphagnum sites are to be included in DSS. CP and *P peuce* has not survived. Only SP and LPN remaining

Expt. name	Type	Species	Area (ha)	Minimum treatment	Optimum treatment	Comment
CLE 5/00	Under planting	Birch under planted with SS, NS and oak	8.6	Follow the Swedish “Kronoberg” method for management of NS/Birch stands	Follow the Swedish “Kronoberg” method for management of NS/Birch stands*	Badly requires treatment
CLE 6/00	Fertiliser	Fert. trial on bare peat	1	Remove birch where competing. Fertiliser at 250 Kg/ha of granulated rock phosphate and 200 Kg/ha of muriate of potash	None	Large variation within treatments due to variation in peat depth Extensive encroachment by birch**
CLE 7/00	Fertiliser	Fert. trial on recon	1	None	None	Crop growing well, but no difference between treatments
Killinagh &Derrybrennan	Best practice demo area	Mostly NS with some birch and alder	84	Fertiliser at 250 Kg/ha of granulated rock phosphate and 200 Kg/ha of muriate of potash	None	see results section**

*Indicates urgent intervention is required, ** please refer to observation for experiments in results section

4. Recommendations

The recommendation for afforestation guidelines in this report are based on the following key principles and assumptions:

1) Recommendations are based solely on suitability for forestry, defined in terms of productive potential on different cutaway peat types and characteristics.
2) No guidance is provided on any economic feasibility of different crop types or potential available land bank of peat types for future forest establishment. However, use of threshold yield class potential provides a rough guide as to the economic feasibility of different forestry option. Cost benefit analysis is not presented because of considerable variance in outcomes depending on, plantation scale, shape or location, price assumptions, grant aid assumptions and establishment costs.
3) Economy of scale is not considered when particular management guidelines are provided. For example, it may be feasible to consider lower yielding systems if large areas are afforested near a mill or energy plant because management or delivery costs would be lower. In contrast, afforestation of small, isolated areas may require the establishment of higher yielding crops to realise any economic benefit.
4) The key emphasis is on suitable species for specific site /peat types and landscape design. However, no detailed guidance can be given on spatial landscape design because this would vary from area to area.
5) Recommendations are based on available data only. It is worth noting that besides Clonsast (Trench 14), the oldest experiments or demo areas located on the most relevant peat types are only 20 years old. More recent experiments, such as Eucalyptus trials in Boora are far too young to draw any conclusions from.
6) Guidance is centred around a decision support system (DSS), which recommends different management/species options based on important site criteria. It is assumed that these management guidelines are strictly adhered to in planning, establishment and maintenance.
7) The DSS considers forestry objective options (i.e. biomass, timber production or woodland biodiversity), but does not recommend the use of one objective over another.

Findings from the current project and research in Scandinavia, indicate that more productive commercial forests may be best suited to shallower cut away peat sites with peat depths of less than ca. 1m (Figure 5, Pietiläinen et al., 2005; Paavilainen and Päivänen, 1995). Based on an analysis of production areas surrounding the Edenderry power-plant it is estimated that, if production were to stop in 2023, only 22 to 42 % of the peat areas would be 2m or less (see example site in Figure 13). It is not possible to uniformly harvest peat to a set level due to undulation of the underlying peat layer if the Peco extraction method is used. Although alternative extraction methods, such as the “Haku” method, can be used to harvest to a more uniform peat depth, this production method is more expensive. It is therefore likely that large areas of industrial cutaway peats (e.g. depth greater than 2 m and *Sphagnum* peat) would not be suitable for forestry.

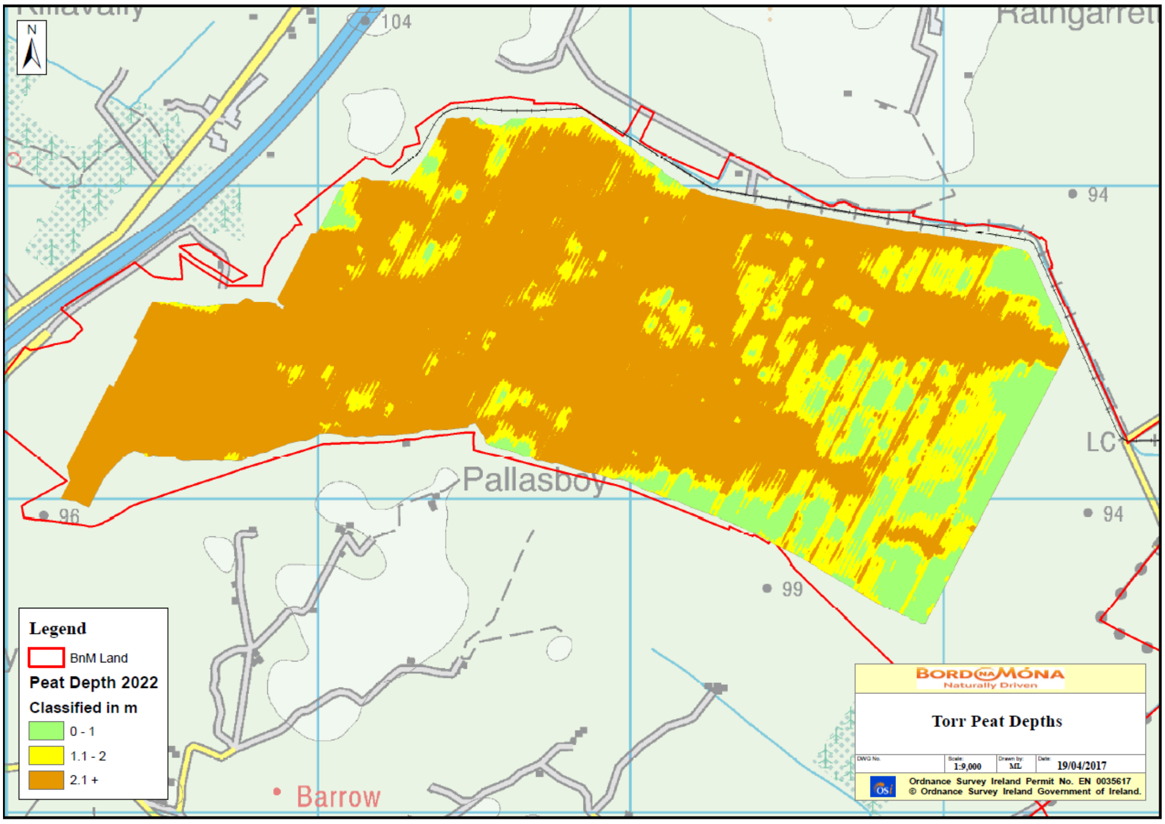

Figure 13: An example of a peat depth map of the Torr production area, near the Edenderry power plant, showing the projected peat depth categories (0-1m (green), 1.1-2m (yellow) and >2m (brown)) if production was to be stopped by 2023.

Regardless of the forestry objective, future afforestation of cutaway industrial peats should be based on selection of the correct species for specific site and peat types. This is the fundamental basis for using site classification systems to guide species selection decisions. The selected species on site types should also meet a productivity class threshold to ensure the viability of commercial forestry. For timber production, these thresholds can be based on yield class values as defined by Ray et al. (2009, see Table 16).

4.1 Establishment decision support system

The following decision support protocol (Figure 14) has been developed as a guide for selection of sites suitable for forestry depending on land scape amenity objective (i.e. commercial timber production, forest biomass production or biodiversity forests/woodland). The decision support system is based on the following criteria:

4.1.1 Site type: General classification of cutaway peats related to vegetation, topography and drainage:

- Sections of cutaway peatland areas within a productive unit that were pumped during peat production (**S1**).
- Cutaway peatlands that are located in a depression that are subject to winter flooding inundation (**S2**).
- Cutaway peatlands that have been recolonised naturally by birch, pine or willow (**S3**).
- Cutaway peatlands that have recently come out of peat production (bare brownfields) that are gravity drained with suitable drainage outlets (**S4**).

4.1.2 Peat depth and aeration ratio thresholds:

- Species thresholds can be based on the normalised H model, Table 16 below)

Table 16: The peat depth (P_{depth}), relative aeration ratios ($P_{aeration}$) and corresponding yield class thresholds of suitable species for commercial timber production

Species	P_{depth}	$P_{aeration}$	YC threshold*
Hybrid larch	0.15-2m	≥0.55	>6
Sitka spruce	0.15-1m**	≥0.6	>12
Norway spruce	0.15-1m**	≥0.6	>12
Pines (SP, LP)	0.15-2m	≥0.35	>6
Birch spruce mixtures	<2m	>0.35***	n.d.

*Yield class threshold for commercial forestry (Ray et al., 2009)

**Although section 3.2.1 provides evidence of a suitable peat depth of <0.8m for spruce, the depth threshold has been adjusted to account for shrinkage of peat after establishment.

*** The peat aeration for Birch/spruce mixtures is based on the minimum peat aeration value observed in experiment KTY14/00.

4.1.3 Peat type

- *Phragmites*
- Woody fen
- *Sphagnum*. Note: not suitable for forestry. This recommendation is based on re-evaluation of Corsican pine and Macedonian pine on sphagnum peat species trials in Tumduff (CLE4/00). Although the BOGFOR report suggested that sphagnum peat may be suitable for initial growth of these species (Renou-Wilson et al., 2008), growth has reduced considerably and both species are currently exhibiting dieback. Lodgepole pine and Scots pine are the only species in these experiments that had survived, however, their suitability for commercial forestry is doubtful on this peat type. Areas may regenerate with birch, but it also unclear if long term growth will be

maintained due to competition with heather. This aspect warrants further investigation.

4.1.4 Forest management systems:

- Commercial forestry
  - Sitka or Norway spruce (**CF1**)
  - Hybrid larch (**CF2**)
  - Lodgepole or Scots pine (**CF3**)
  - Other species mixtures such as birch-spruce mixtures (**CF4**)
  - Under planting spruce under natural regenerating birch (**CF5**)
- Biomass production*
  - Birch, or alder coppice of natural encroachment forest (**BP1**)
  - Birch, alder or lodgepole pine plantation (**BP2**)
  - Birch, alder or pine encroachment followed by commercial timber production in the second rotation (**BP3**)
  - Other species mixtures such as birch-spruce mixtures (**CF4**)

    *Note CF4 and CF5 can be included under timber and biomass objectives because these management systems may fulfil both objectives)
- Biodiversity.
  - Birch, oak, holly, rowan, alder establishment (**BD1**), to represent the birch woodland (MN 7) native woodland type (Little and Cross, 2005).
  - Natural encroachment (**BD2**) for creation of either the birch woodland (MN 7) or the wet birch woodland with sphagnum (Little and Cross, 2005).
  - Potential regeneration of birch wet woodland with sphagnum (**BD3**, see native woodland type F2; Little and Cross, 2005)

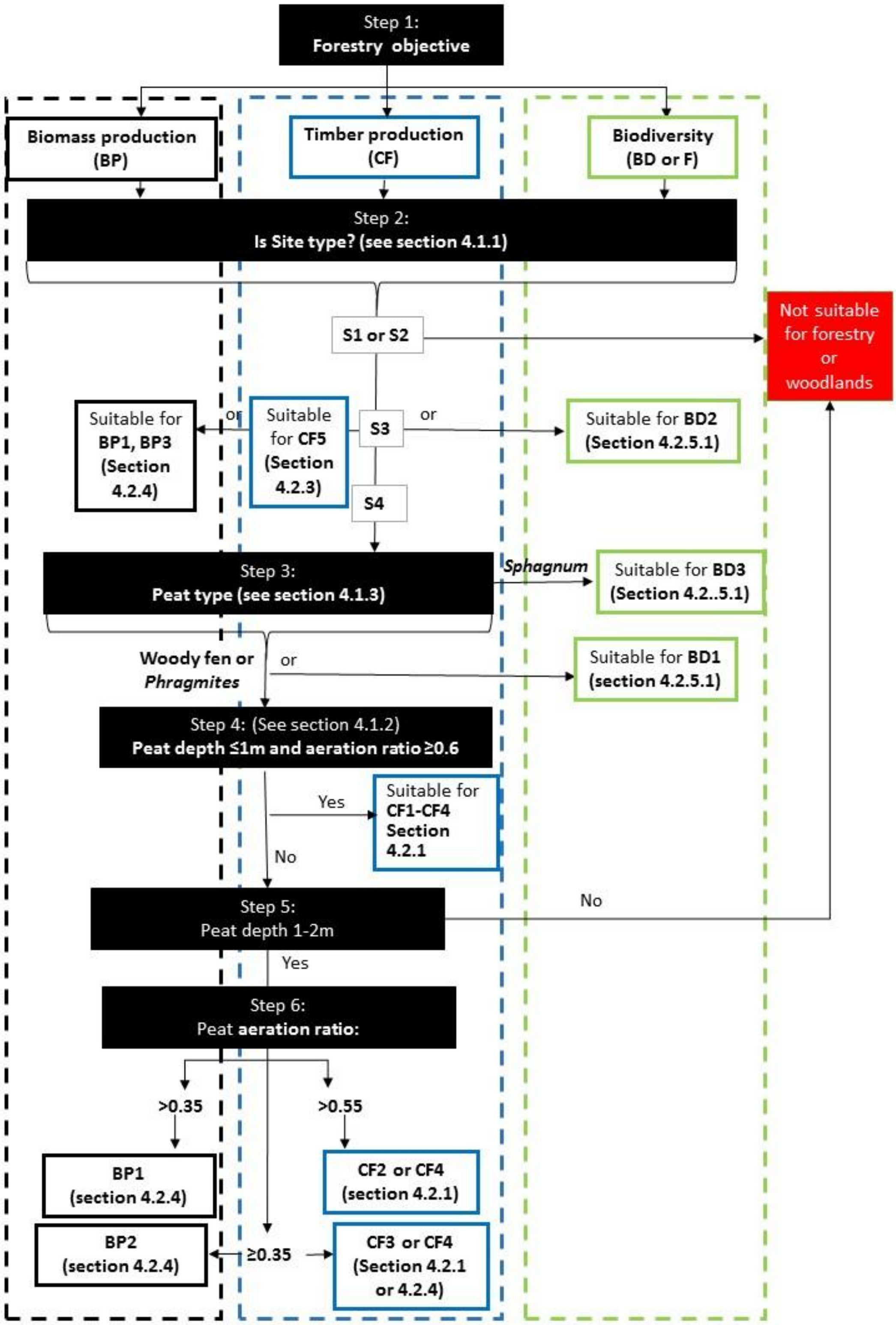

Figure 14: The decision support protocol for suitability of different forest management systems based on site and peat characteristics. (* Please refer to recommendation under forest management systems (section 4.2 below) when applying the protocol).

4.2 Description of forest management systems

The following section outlines management recommendations based on different objectives.

4.2.1 Commercial conifer plantations (CF 1-3)

4.2.1.1 Species choices for site types

CF1: Sitka spruce and Norway spruce (CF1)

A bench mark YC of 14 m^3/ha/yr is considered to suitable for commercial forestry using these species.

- Based on our results and previous recommendations, commercial forest areas are limited to *Phragmites* peat or woody fen sites with peat depths of less than 0.15-1m and a minimum relative aeration ratio (i.e. aerated peat depth over total peat depth, see Eq. 5 in section 2.1.3.4) of 0.6m for Sitka spruce and Norway spruce.

CF 2: Hybrid larch (benchmark YC 8,)

- Hybrid larch can be considered, depending on phytosanitary regulations, on *Phragmites* or woody fen peats up to 2m in depth and with a relative aeration ratio of ≥0.55.

CF 3: Lodgepole and Scots pine (benchmark YC 8)

- These pine species can be considered for establishment on *Phragmites* or fen peats up to 2m in depth and with a relative aeration ratio of 0.35 (relatively wetter sites than larch).
- Note that both species are susceptible to pine shoot moth, which could have detrimental impacts on wood quality.

4.2.1.2 Cultivation and establishment

- It is recommended that all sites should be gravity drained and areas in depressions of poorly drained areas should not be utilised for commercial forestry.
- Drainage status of potential sites should be assessed during the wet season, when rainfall is high and evaporation losses are low, e.g. December, January (Renou-Wilson et al., 2008).
- Drains should be clear of vegetation, but naturally regenerating birch or pine areas adjacent to drains should be retained to provide shelter for the establishing crop, to assist with retention of nutrients and reduce nutrient run-off (Renou-Wilson et al., 2008).
- Maintenance of drains is essential. This appears to be an issue in many of the previous BOGFOR experimental sites, where in some cases downstream drains are blocked after peat production has ceased resulting in flooding of forest areas.
- Cultivation is recommended for peat depths of 1m or less to improve nutrient availability and peat aeration (Aro, 2000b). A Savannah plough has been purchased jointly by BNM and Coillte and is available for this task.. However, it is still not clear if ploughing of deep areas prior to planting of pines or hybrid larch has any advantages (i.e. CF 2 and CF 3). More research using replicated trials with control treatments are required on deep *Phragmites* and wood fen peats (>1m).

4.2.1.3 Frost risk

- Sitka spruce should be avoided if areas are prone to the occurrence of frost, this potentially limits the species to sloped areas or regions were frost is less likely to occur

4.2.1.4 Nutrition management

- Sites should be properly drained and cultivation to mix the peat layer with underlying calcareous material or mineral soil is recommended to increase substrate cation capacity and reduce P and K leaching.
- The BOGFOR report recommended P applications to be split at half the rate (21kg P in each of the two applications) over a two-year period (Renou-Wilson et al., 2008). This is clearly not sufficient P for sustained growth of commercial forest species (see nutritional results section). It is recommended that higher rates of P need to be applied (42 kg P/ha) for each application. However, this needs to be considered in the context of increased run-off of P. More research in needed in this area.
- Crop nutrient status should be re assessed at year 8-10 followed by a repeat application of P and K, and possibly N (if required) in the case of Sitka spruce.
- The observed deficiency of copper in foliage samples did not manifest any symptoms, such as the characteristic deformity of stems and leader. The role of copper in relation to tree vigour and timber quality needs further investigation. However, at this stage, we would not recommend any treatment for copper deficiency unless symptoms are manifested in the crop.
- More research is required to determine appropriate long term nutrition management solutions, such as the use of wood ash as practiced in Finland (see Pietiläinen et al., 2005).

4.2.2 Mixed birch-spruce mixtures planted at the same time (CF4)

This management system only applies to deeper peats <2m (aeration ration >0.35) where birch offers some nursing effect on spruce, when planted in alternative lines at the same time.

4.2.2.1 Site and peat type

Based on our results, CF4 should be limited to *Phragmites* peat or woody fen sites, which are gravity drained (i.e. site type 4).

4.2.2.2 Cultivation and establishment

As for CF1 to CF3, but there may not be any advantage to using a Savannah plough on peats deeper that 1m, unless the cultivation improved peat aeration (yet to be established).

4.2.2.2 Nutrition management

As for CF1-3 above. However, the nurse effect of birch may reduce fertiliser requirement after establishment.

4.2.2.4 Long term silviculture

This silvicultural approach is novel to Ireland, but a similar system (Kronoberg system) applied to naturally generating birch and Norway spruce forests in Sweden (Johansson, 2003). This system involves the gradual removal of birch for bio-energy use and selection of spruce trees as a final timber crop at rotation age. The option provides an attractive solution for both biomass and timber production. However, further research is required to assess the viability of the proposed Kronoberg silvicultural system on cutaway peats in this country. It is recommended that the experiment KTY

14/00 should be used as a case study and more demonstration areas should be set up before this option is rolled out on an operational basis.

4.2.3 Commercial forest conversion (CF5)

This management system applies to areas encroached by birch, alder or pine (site type S3) only if:

4.2.3.1 Cultivation and establishment

- If the site has areas with a mean tree height is over 5 m with some well-formed trees (i.e. a well-developed canopy or coupe), these areas should be retained.
- If the area is covered by scrubs or trees with a height under 5m:
    - Clear corridors (approx. the bay width) but retain scrubs and trees near drains to act as shelter for establishing crop.
    - Plant at stocking of 2500 stem per ha (see species choice below)

4.2.3.2 Species choices for site types

- Sitka spruce and Norway spruce. More suitable shade tolerant species, such as western red cedar, should be considered, but further research or demonstration areas are required to establish robust silvicultural guidelines.

4.2.3.3 Stand management

- Ensure drains remain free flowing.
- Timely vegetation control or removal of birch corridors to reduce suppression of the crop and whipping is essential.
- It is recommended that the experiments KTY 20/00 and CLE5/00 should be used as a case studies and more demonstration areas should be set up before this option is rolled out on an operational basis.

4.2.3.4 Nutrition management

- As for CF1-4 above.

Other species

- Other species such as Corsican pine or western red cedar can be considered and do show good commercial forestry potential in some cases (see Table 3b). However, species specific limitations should be considered in relation to specific site conditions, such as exposure for western red cedar.
- Corsican pine is suggested to be less susceptible to pine shoot moth than Scots or lodgepole pine, but use of this species does increase the potential risk of *Dothistroma* needle blight disease (not yet documented on cutaway peat sites). There is a very encouraging crop of Corsican pine in KTY 17/00, with straight stems and very small branch size. It looks (after 16 years) superior to nearby lodgepole or Scots pine crops.
- Corsican pine or western red cedar should be limited to relatively shallow *Phragmites* or woody fen peats (<1m depth), which are well drained. These is no documentation or observation supporting the performance of these species on deeper peats.

4.2.4 Biomass production

Although both BNM and Coillte see the potential for biomass production on cutaway peats and considering there is existing infrastructure to transport biomass to BNM energy plants, considerable research is still required for this potential to be commercially realised. A small amount of work was carried out within the original BOGFOR Programme on biomass potential of a range of crops (Renou-Wilson et al., 2008). Although limited in extent, this work reported on biomass assessments from planted conifers and both planted and naturally regenerated birch. Biomass (in t DM/ha/year) ranged from 3.1 (planted birch) to 5.8 (natural regenerated birch) to 16 (planted Sitka spruce). Figures for planted lodgepole pine came in at 5.4 t DM/ha/yr.

Studies by Kent (2009) on semi mature birch dominated colonised areas in Boora suggest a yield of 777 GJ per ha^{-1} at a cost of €5.07 GJ^{-1} (including chipping, harvest and extraction, but excluding transport and handling at the power plant). Bioenergy yields from alder stands in Boora (675GJ ha^{-1}, Kent et al., 2009) were similar to birch. Although these authors suggest that "the value of energy harvested in this operation was limited, however the harvesting operation may stimulate productive coppice development on the site. If coppice development is successful then then the harvesting operation cost can be offset against site amelioration."
Bioenergy yield from 1st thinnings of the high yielding Sitka spruce (YC 24) plantations in Ireland are reported to be 163-312 Gj ha^{-1} with a roadside extraction cost of 4.1-6.2 € GJ^{-1}, depending on harvest method used (Coates et al., 2009).

Biomass production systems described here only include forest biomass systems, including naturally generating birch/alder coppices (BP1), establishment of sites using pine, alder or birch for biomass production (BP2) or harvesting of existing encroached sites for biomass, followed by under planting with species for conversion to timber production (BP3)

4.2.4.1 Species choices for site types

- Species for establishment (BP2) are limited to birch, alder or lodge pole pine.

4.2.4.2 Cultivation and establishment

- If site type is S3 and trees are less than 5m high establish, corridors and follow guideline as presented for CF5. It may be worth considering increasing establishment target stocking to ca. 4400 stems/ha (1.5 x 1.5 m spacing) to maximise biomass production but this may require more research.

4.2.4.3 Nutrition management

- For biomass conifer crops, it is recommended that the same guidelines for CF1-5, should be used. However, if there are repeated harvest from a coppice system, addition nutrients may be required.
- Monitoring crops and routine foliar analysis is recommended every 5-10 years to ensure nutritional problem do not limit productivity.

4.2.4.4 Silvicultural alternatives

Short rotation biomass forestry on cut away peatlands is not well researched, with the exception of some biomass harvesting studies carried out by WIT in Boora and Tumduff (Renou-Wilson et al., 2008; Kent, 2010). Particular emphasis for future research should be directed at developing more cost effective establishment methods for high density stands. Novel methods for direct seeding or mechanised planting methods should also be investigated. There was good evidence that direct seeding with lodgepole pine does offer a potential solution based on observations made in Killinagh (see Figure 8).

Methods should also be investigated to enhance natural regeneration capacity of sites, such a scarification, application of fertilisers and direct seeding.

4.2.5 Biodiversity

When considering use of the landscape for biodiversity function additional aspects such as, biodiversity value, value of alternative habitats, habitat connectivity and creating of key ecological ”stepping stones” (Saura et al., 2014) should be considered. The future configuration of industrial cut away peatlands are likely to be a mosaic of wetland habitats, grasslands, short rotation coppice, peat land restoration areas, woodlands for timber and biomass forest plantations. This report and the previous BOGFOR report (Renou-Wilson et al., 2008) clearly recommends that forestry is not suitable in sections of individual peat bays or other areas. Therefore, careful design of the landscape is required to maximise forest production whilst still ensuring ecosystem services of the new peatland landscape are maintained. These functions include, biodiversity (habitat preservation and connectivity), social amenity and climate change mitigation actions.

Biodiversity options presented in this report are only considered in a native woodland context. However, raised bog and fen habitat restoration should be considered in areas not suitable for woodland, such as pump drained areas or areas in depressions near the peat floor (i.e. site types S1 and S2).

4.2.5.1 Species choice and silviculture

- As mentioned previously, the potential of *Sphagnum* dominated peats to support long term tree growth is unclear, but potential regeneration of birch wet woodland with *Sphagnum* on such sites can be considered (see native woodland type F2; Little and Cross, 2005).
- Woodland options are limited to planting woodlands on deeper Phragmites and woody fen peats with species such as Scots pine birch, pedunculate oak and alder (BD1) or enhancement of biodiversity in encroached areas (BD2).
- Pedunculate oak has performed well in all species trials visited, but protection against rabbit, hare or deer damage is crucial.
- Planting of oak with birch as a nurse mixture at low overall density (4x4m for each, or 625 stem/ha) has been suggested to produce good results (Huss et al., 2016). Alternatively, planting mixed species in clumps at a spacing of 2m x 0.75m for oak and 2m x1.5m for other species is currently suggested under the native woodland scheme (Little et al., 2014). However, planting of oak at higher densities with Scots pine (or birch) in alternate lines (e.g. see experiment CLE3/00) or under planting encroached birch areas (e.g. CLE5/00) requires timely silvicultural intervention. Further demonstration areas or more detailed trials are required before this option can be considered on a large scale basis.
- If encroaching birch woodlands are utilised solely for biodiversity purposes, guidance for management is described in the DAFM native woodland scheme and publications by the Woodlands of Ireland. Birch woodland (WN7-bog woodland) and wet birch woodland with Sphagnum are recognised native woodland types (Little and Cross, 2005). These authors

suggest that up to one-third of birch woodland areas should be managed solely for conservation to include woodland edge, refuge areas, glades, buffer zones, hedgerows, rock outcrop and waterlogged depressions. In order to diversify species, the promotion of oak, holly, rowan, willow and alder should also be practised.

4.3 Mechanisation

Cut away peatlands (site type S4) are very suitable for mechanised forestry applications at establishment. Mechanised application of fertilisers during and after fertilisation should done to ensure even spread and correct dose of application. Possible solutions include:

- Initial and split applications can be done using hoppers and spreaders mounted on tractors or 4x4 all terrain vehicles (ATVs).
- For thinned or thicket stage crops aerial application should be considered, but currently aerial fertiliser licence regulations may be prohibitive. In Sweden, fertiliser application to thinned crops by a forwarder-based machine (Skogens Godslings AB, Asgaten 35, S-791 71 Falun, Sweden). at a cost of 2,500 and 3,000 SEK/ha. (9.2SEK = 1 €) These costs include the supply of fertiliser and the spreading, together with all associated costs like machine transfers, mapping, etc.

Mechanisation of seedling planting operations or direct mechanised seeding needs further investigation, but limitations of seedling size and slow initial growth of saplings may cause vegetation control problems.

4.4 Site establishments survey

Many of the DSS site criteria such as peat type, peat depth and site type are now routinely captured for productive cut away peat bays as part of the Bord Na Mona GIS database. Use of GIS methods, such as watershed segmentation methods can be used to identify areas susceptible to flooring based on analysis of DEM. Additional GIS information from surveys such as digital elevation models and peat depth surveys can be used to automatically select the above-mentioned forest management systems. However, additional on-site surveys should be done in the rainy season in order to identify:

- Poorly drained areas,
- Peat aeration using peat cores. The sampling frequency would depend on the site area in question, but a minimum of 1 core every 100 m along each bay would be recommended,
- Identification of the extent of encroachment if this cannot be done using GIS and remove sensing approaches.
- Inspection of drains to ensure good drainage from site.
- Assessment of access requirement for establishment operations.

4.5 Other ecosystem services

Although the greenhouse gas emission/removal footprints for the different scenarios are outside the scope of the current project, successful forest establishment on shallower peats could result in a lower net emission profile or a significant sink of CO_2, compared to non-vegetated degrading deep peats remaining after Peco extraction has ceased. The greenhouse gas balance of different management options, such as rewetting, renewables, forestry and biomass, habitat restoration etc. (Black and Gallagher, 2010; Wilson et al., 2015, Jordan et al., 2016), of industrial cutaway peatland requires further investigation.

Appendix A

Site name	Expt name	Type of expt	Area (ha)	Comment	Criteria (Task 2)	Assessment
Blackwater	KTY 1/99	Demo area	15	One of three demo areas, each of 15ha, looking at two cult types + control	a, b, d, h, i	Peat depth/description, nutrients, GIS
Blackwater	KTY 14/00	Nurse trial	4	Birch nursing SS where nursing may now only be starting to be evident (SS planted after birch)	c, f, i	Peat depth, nutirent full inventory plots
Blackwater	KTY 15/00	Birch spacing	1.5	not assessed just and observation note	c, j	observation
Blackwater	KTY 16/00	Cultivation	4.5	Cultivation X species (SS, NS, SP & HL). Are cultivation effects still evident?	a, b, c, d,	Peat depth/description, nutrients, GIS
Blackwater	KTY 17/00	Species	6.5	Fifteen species comparison (conifer and broadleaf)	a, c, d,	Observation
Blackwater	KTY 18/00	Species	5	Eight species comparison	a, c, d,	Observation
Blackwater	KTY 20/02	Alder/spruce	1.7	Alder cut and replaced with SS & NS. Useful to assess (location?)	a, c, d, f, i	Observation
MtLucas	Allen1/00	Demo area		Cultivation trial SS, NS, SP, OAK 34 cultivation 32 reps	a, c, d, f, i	observation
MtLucas	Allen2/00	Species		Species trial	a, c, d, f, i	observation
Tumduff	CLE 1/99	Demo area	15	One of three demo areas, each of 15ha, looking at two cult types + control	a, b, d, h, i	Peat depth/description, nutrients, GIS, water samples
Tumduff	CLE 2/00	Cultivation	4.1	Cultivation X species (SS, NS, SP & HL). Are cultivation effects still evident?	a, b, c, d,	Peat depth/description, nutrients, GIS
Tumduff	CLE 3/00	Species	4	Broadleaf trial with syc, alder and oak (pure + mixed with HL & SP). Also has plots like KTY 20/02	a, c, d,	Observation
Tumduff	CLE 5/00	Underplanting of birch	8.2	Badly needs management	a, c, d, f, i	observation
Tumduff	CLE 6/00	Fertiliser	1	Fertiliser trial on bare peat site	d, e	plots, nutrients,peat depth/description
Tumduff	CLE 7/00	Fertiliser	1	Fertiliser trial on recon site	d, e	observation
Tumduff North	TLM 35/96	Species trial	11	Older species trial	a, b, c, d, i	plots, nutrients,peat depth/description
Killinagh Derrybennan		Silviculture demo		Additional 2 sites	a, b, c, d,	Water samples, Peat depth/description, nutrients, GIS
Coilte sites		Inventory selection		Selection of LP, SS and NS sites across all BNM land managed by Coillte	a, b, d, h, i	GIS, Coillte inventory site visits to slected sites, peat depth and description

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