# Effects of peat depth and aeration on species performance in afforested industrial cutaway peatlands

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**Abstract**

Many of the current recommendations for afforestation of industrial cutaway peatlands in Ireland are based on findings from trials established under the BOGFOR programme. 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 various species, remained unanswered. In this study, the performance of selected species was reviewed across a range of previously established experimental trials and demonstration areas. Preliminary investigation highlighted nutritional check and dieback on Norway (*Picea abies*) and Sitka (*Picea sitchensis*) spruce crops at 6 to 20 years after establishment. To identify the causes of this, detailed peat depth/type surveys, foliar analysis and conventional mensuration assessments were carried out across selected areas in both the demonstration and experimental sites. Results suggest that peat depth and aeration is a major factor influencing the productivity of afforested species and that afforestation potential of Norway and Sitka spruce may be limited to shallow peat depths (0.5 to 1.2 m), with other species such as hybrid larch, lodgepole pine, Scots pine and birch being more suitable for planting on deeper peat sites (>1 m deep). These findings contrast with previous recommendations for afforestation of cutaway peatlands in Ireland, but agree with current afforestation practice in Finland. We also suggest that the current nutritional management of established forests may need revision and a third fertilisation may be required to ensure sustained productivity of crops on industrial cutaway peatlands.

**Keywords:** *Peat depth, species suitability, cutaway peatlands.*

## Introduction

The afforestation of industrial cutaway peatlands in this country could make a significant contribution to attaining the targets set out in the government's forest strategy. It is estimated that an area of between 16,000 and 20,000 ha of the Bord na Móna cutaway peatland resource has afforestation potential (for review see Renou-Wilson et al. 2008). Bord na Móna cutaways are extremely heterogeneous belowground, even though the landscape looks deceptively uniform in appearance

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from above. The peat varies in type, depth (because of the undulating topography of the underlying 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 the choice of future land-use programmes.

Much forest research has been carried out since the first cutaways became available for post-peat harvesting uses in the 1950s (reviewed in Renou-Wilson 2008). Since then, the emphasis has continually changed, as peat harvesting systems moved from being based partially on sod peat to exclusively milled peat, resulting in the development of new approaches to post-peat harvest utilisation, research and policies. Over the years, the main areas of investigation have included: grassland, agricultural crop production, horticulture, commercial forestry, biomass production, dry-land recolonization, 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 on the afforestation of cutaway bog, established in the mid-1950s 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. Other studies on *Phragmites* peats have suggested that their long term nutritional status may be the most limiting factor affecting successful afforestation, particularly in deeper peats (OCarroll 1966). The BOGFOR research programme made significant advances in developing guidelines for successful afforestation of cutaway peatlands (Renou-Wilson et al. 2008). The programme provided recommendations for selection of suitable peat and site types (mostly limited to *Phragmites* and woody fens), species, cultivation techniques and crop nutrition management for establishment of successful cutaway peatland forests. Many of the observations from trials established under the BOGFOR programme were limited, however, to pre-thicket stage crops (most assessments were made in crops less than six years old). 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.

The current practice of afforestation of cutaway peatlands in Ireland is based on criteria which differ to those proposed for conditions in Scandinavia. Afforestation of cutaways in Finland is generally restricted to peat depths less than 0.15 to 1 m, with Scots pine (*Pinus sylvestris* L.) being the major species of choice (Paavilainen and Päivänen 1995, Pietiläinen et al. 2005). Nutrient uptake on a very shallow (15 cm) peat layer has been suggested to increase due to root penetration through the peat layer into the nutrient richer mineral subsoil (Paavilainen and Päivänen 1995). Guidelines on peat depth for afforestation in Finland contrast the recommended practice at the time when many of the BOGFOR experiments were established, e.g. Jones and

Farrell (2000) suggested that the depth of the peat layer suitable for the afforestation of coniferous tree species should be at least 60 cm, so that the calcareous underlying tills or marls which are frequently present would not have negative impacts on the survival and growth of the trees.

Norway spruce (*Picea abies* (L.) H. Karst.) is now the preferred species for planting on cutaway peatland sites in Ireland because of its lower sensitivity to frost, compared to Sitka spruce (*Picea sitchensis* (Bong.) Carr., SS) (Renou-Wilson et al. 2008). In terms of natural regeneration, downy birch (*Betula pubescens* Ehrh.) is a pioneer species on cutaway peatlands while lodgepole pine (*Pinus contorta* Dougl.) or Scots pine will often regenerate if a suitable seed source is available locally. In Sweden, nutritionally richer peats can be colonised by Norway spruce (Svensson et al. 1998). Willow (*Salix* spp.) and birch (*Betula* spp.) 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 for commercial plantations in that country (Kaunisto and Aro 1996).

The low nutrient status of partially cutover peatland is a serious constraint for successful afforestation. This was confirmed in the BOGFOR report (Renou-Wilson et al. 2008) and by earlier studies (OCarroll 1966), the results from which showed that the absence of phosphorus (P) was the key element affecting tree growth. The availability of potassium (K), and to a lesser extent nitrogen (N), was also identified as a potential limiting factor, depending on the nature of the peat remaining after harvesting. Cutaway peatland sites are inherently low in P compared with mineral soils and, although total N levels can be reasonably high, most of this is held in an organic form unavailable for tree growth. Potassium levels also tend to be generally low, the highest levels being associated with woody fen peats compared with *Phragmites* peats which have inherently lower levels of K (OCarroll 1966, Renou-Wilson et al. 2008). The depth of peat remaining following the cessation of harvesting can therefore affect the nutritional status of the peat soil.

In this study, a selected range of experiments and demonstration areas established under the BOGFOR programme were reviewed. The demonstration areas were established as large (10 ha) blocks of Norway spruce using, what were considered at the time (in 2000), the best available techniques. During the recent (2016) preliminary assessments of demonstration crops in Blackwater, Clonsast and Tumduff, it was noted that crop performance of Norway spruce (NS) was highly variable and sections of sites were not performing well, despite previously reported good performance of these crops after four years (Renou-Wilson et al. 2008). This raised concerns because these demonstration areas had been established using best practice at the time (but before results from the BOGFOR programme had become available). Similar issues have also recently been highlighted by data from sections of more recently planted cutaway sites (planted 2010/11) in Kildare, where Norway spruce is now showing early signs of severe nutrient deficiency and dieback.

There are numerous hypotheses suggested for the dieback and/or reduction in productivity: K deficiency (OCarroll 1966, Pietiläinen et al. 2005), water deficits, peat deterioration and lack of aeration in the root zone (Aro 2000). Soil and crop assessments were subsequently carried out to determine the cause of this dieback. To this end, detailed peat depth/type characterization, foliar analysis and conventional mensuration assessments were carried out across selected areas in both the demonstration and experimental sites.

## Materials and methods

*Selected experiments and demonstration areas*
Selection of experiments or demonstration areas was confined to sites dominated by *Phragmites* or woody fen peats, based on recommended preference of these peat types for afforestation (from work by Renou-Wilson et al. 2008). Selection of species for assessment was limited to the major productive conifers planted on these site types for commercial forestry and birch, due to the prevalence of this species on cutaway peatlands (Table 1).

*Plot surveys*
Detailed survey plots were conducted to assess soil characteristics such as nutrition status, peat type, depth above the sub-soil layer, peat aeration and qualitative information relating to the performance of selected species, such as height and productivity. These data were collected using the Field Map system (IFER, Czech Republic) over the period October 2016 to February 2017. The location of survey plots was selected based on a random stratified sample of canopy height, based on a canopy height digital terrain model (DTM). Digital surface models (DSM, determine canopy height with a resolution of ±20 cm) and photo-imagery for red, green, blue and near infrared bands (Figure 1) 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 Bord na Móna. Canopy height was determined using the difference between the DSM and DTM raster values (in m, Figure 1). The areas were then classified into 6 canopy height classes using equal interval segmentation methods using ArcGIS v10.1 (ESRI). Ground survey plots (2 m radius) were selected to represent good, moderate and poor sections of the crops to provide a cross section for further field evaluation (see yellow star symbols in Figure 1). A total of 140 plots were identified across the different sites.

The IFER field mapping system was used to navigate to the centre of each plot. 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).

**Table 1:** *Details of the selected species and experimental/demonstration areas. A description of how estimated yield class (Est. YC) data were derived is given in the Materials and methods section. n.d. means not determined.*

| Exp./Site | Species | Age | Description | Est. YC ($m^3$ $ha^{-1}$ $yr^{-1}$) |
|---|---|---|---|---|
| CLE 1/99 | Norway spruce (NS) | 17 | Demonstration area | 10 |
| CLE 2/00 | Hybrid larch (HL) | 16 | Cultivation and species | 12 |
| | Norway spruce (NS) | 16 | (replicated) | 10 |
| | Scots pine (SP) | 16 | | 10 |
| | Sitka spruce (SS) | 16 | | 10 |
| Derrybrennan | Norway spruce (NS) | 5 | Demonstration area | n.d. |
| Killinagh | Lodgepole pine (LP) | 6 | Demonstration area | n.d. |
| | Norway spruce (NS) | 6 | | n.d. |
| KTY 1/99 | Norway spruce (NS) | 17 | Demonstration area | 10 |
| KTY 14/00 | Birch (BI)[a] | 16 | Mixed Species trial | 8 |
| | Sitka spruce (SS) | 16 | | 14 |
| KTY 16/00 | Hybrid larch (HL) | 16 | Cultivation and species | 8 |
| | Norway spruce (NS) | 16 | (replicated) | 12 |
| | Scots pine (SP) | 16 | | 12 |
| | Sitka spruce (SS) | 16 | | 20 |
| KTY 17/00 | Lodgepole pine (LP) | 16 | Species demo area | 8 |
| TLM 35/96 | Hybrid larch (HL) | 20 | Species trials | 12 |
| | Lodgepole pine (LP) | 20 | (duplicated) | 8 |
| | Lodgepole pine (LPS) | 20 | | 12 |
| | Improved birch[a] | 20 | | 10 |
| | Un-improved birch[a] | 20 | | 6 |
| | Norway spruce (NS) | 20 | | 18 |
| | Scots pine (SP) | 20 | | 12 |
| | Sitka spruce (SS) | 20 | | 18 |

[a]All birch (BI) species are either *Betula pubescens* (Ehrh.) or *B. pendula* (Roth).

Peat cores were sampled in the centre of each plot using a 20 mm-diameter Gouge auger. Peat depth was measured to 2 m and a description was taken of the peat layer types and the 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 to light brown or orange) due to no decomposition of organic material or a build-up of iron under anoxic conditions or a permanently water-saturated layer in the peat profile.

*Foliar analysis*

Foliar samples were collected where required in the winter of 2016/17 from some species trials and demonstration sites. Bulked foliar samples (from 4-5 trees) were collected from needles produced in 2016 from lateral branches in the top section of the canopy of

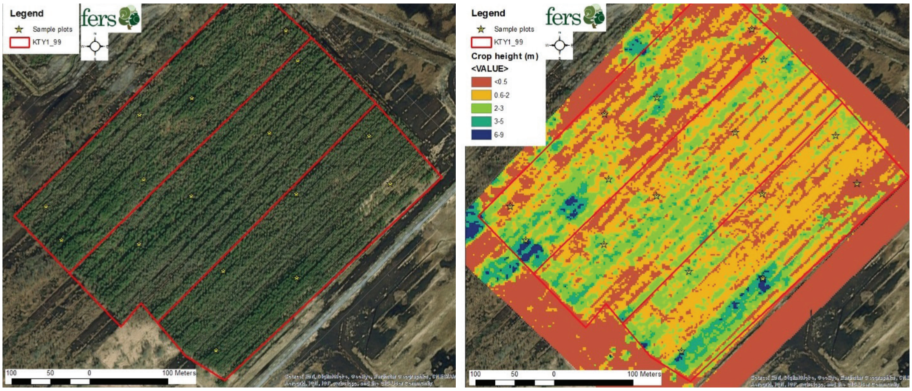


**Figure 1:** *A colour (RGB) image (left panel) and the canopy model derived from the DTM (right panel) of KTY 1/99 (NS demonstration area), showing different height classes (from brown (<0.5 m) to blue (6-9 m)) and location of selected plots (black circles).*

trees directly adjacent to the centre of the sample plot, where the peat sample was also taken. The foliar samples collected were dispatched immediately after collection to the Forestry Commission Research Laboratory in Alice Holt, Farnham, Surrey, England. The content of the following elements was determined in each: N, P and K. Foliar samples were dried at 70 °C prior to weighing to remove any residual moisture content. The combustion method for N determination was made using a Carlo Erba CN analyser (Flash1112 series) using 10 mg dried and ground needle samples. For P and K, c. 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 were 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 analyser (Thermo ICap 6500).

*Statistical analysis*

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 2006).

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

$$Normalised\ H_{16yrs} = \frac{H}{Age_{yrs}} \times 16 \qquad [1]$$

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

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

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.

<u>Pearson regression analysis</u>

Regression analysis was performed at the plot level to assess 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 statistics) using the R studio software package (https://www.rstudio.com/), if required, prior to subsequent analysis. Regression analysis of single variable sets was 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.

<u>Peat depth/aeration regression model</u>

A multiple regression model was used to develop a predictive indicator of how different species performed on different peat substrates varying in depth and aeration. The analysis was confined to hybrid larch (*Larix* × *marschlinsii* Henry, HL), Norway spruce (NS), Sitka spruce (SS), downy birch (BI), 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 of 9 different experimental or demonstration areas (see Table 1).

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

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

where, $H_{ceoff}$ is the height coefficient derived from the slope of the linear relationship between normalised H (see Eq. 1) 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 was modelled using the non-linear multiple regression function:

$$Peat_{factor(j)} = res_j + a0_j \times P_{depth}{}^{-kd(j)} \times P_{aeration}{}^{ka(j)} \quad [4]$$

where, *res* is the residual correction for the modelled dataset, *a0* is the scalar correction coefficient, *kd* and *ka* are exponential coefficient describing the decline in growth (negative) as peat depth increased (*-kd*) or increase in growth as relative aeration increased (*ka*). ($P_{aeration}$) was the depth (m) of the aerated layer relative to the total peat depth ($P_{depth}$):

$$P_{aeration} = \frac{depth\ of\ anoxic\ layer}{P_{depth}} \quad [5]$$

But if depth of the anoxic layer was deeper than the maximum sample depth core (3 m), then $P_{aeration} = 1$.

The final model formulation was derived in an iterative manner by adding the variables, such as $P_{depth}$ and $P_{aeration}$, to the model based on forward selection of variables in a stepwise multiple regression using the R-studio package. Variables and model coefficients were only included in the final model if the root mean square error (RMSE) decreased significantly and there was no significant bias in model residuals, based on the Shapiro-Wilk statistic in R studio.

## Results

### *Description of peats*

All plots were dominated by *Phragmites* or a mixture of *Phragmites* and woody fen peat types, except for two plots (one in Killinagh and one in Exp. 14/00), which had a shallow *Sphagnum* layer over deep *Phragmites* peat.

Peat depth varied within and across experimental plots. For example, in experiments KTY16/00 and TLM 35/96 (see Table 1), peat depth varied from less than 15 cm to over 2 m. Peat depth generally increased as the height of a bay increased but, in some cases, peat depth could vary by 1 m within a 5 to 10 m section of a single bay. The underlying calcareous material also varied across sites, with fine, un-weathered calcareous sediment deposits being the most prevalent underlying material. In some sites, such as TLM 35/96, weathered limestone calcareous material was present. These areas were generally well-drained and contained better crops.

Norway and Sitka spruce, in particular, did not perform well on deep peats with little or no other vegetation on site, or where *Calluna* was present on *Sphagnum*-dominated peat sites. The growth of the two spruce species appeared to slow down in the last 4 to 6 years, based on inspection of leader lengths. Birch and the two pine species seemed to perform better across the range of peat types and there was evidence of natural colonisation of these species across many of these sites. Hybrid larch was very productive, even on deep peats, but this species did not perform well in wet or poorly drained areas.

*Relationship between performance and peat depth/aeration*

The performance of all tree species investigated, in terms of normalised height, generally declined as peat depth increased (Figure 2). In addition, normalised tree height 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 to a larger extent associated with peat depth (Figure 2). There was no apparent relationship between tree height of birch and the relative aeration ratio of the peat in the plots investigated (Figure 2).

As seen from the scatter plots (Figure 2), the relationship between tree height and peat depth or aeration was best described by a second order non-linear function (Table 2). The best model fit describing these relationships suggests that c. 70% of the variation in normalised mean plot tree height across all species could be associated with variations in peat depth and aeration (see $r^2$, Table 2 and Figure 3).

When peat depth was used as the only predictor of tree height, the model described over 50% of the variation in observed tree height 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 (Eq. 4). It is also evident from the lower values of the fitted parameter for $P_{depth}$ (*kd*, Table 2) that Norway spruce and Sitka spruce displayed a greater decline in tree height as peat depth increased when compared to hybrid larch and the pines. Hybrid larch, however, appeared to be more sensitive to anoxic peat conditions, compared to the other species (see higher *ka* value for larch in Table 5). These trends are more clearly demonstrated in Figure 4.

Using the yield class thresholds defined by Ray et al. (2009), and based on the modelled scenarios presented in Figure 4 (left panel), it is evident that both Norway and Sitka spruce may only be suitable for planting on *Phragmites* or woody fen type peats 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 (yield class of less than 12 $m^3 ha^{-1} yr^{-1}$) under currently recommended management guidelines for establishment of cutaway peatlands. However, if drainage is not suitable and the aeration ratio is less than 0.5 (e.g. an anoxic layer of 0.6 m for a total peat depth of 1.2 m), then the model predicts that Sitka and Norway spruce would only be suitable for planting in peats to a depth of 0.3 m and 0.5 m, respectively (Figure 4, right panel).

The model predicts that hybrid larch can tolerate deeper peats (up to 2 m) so long

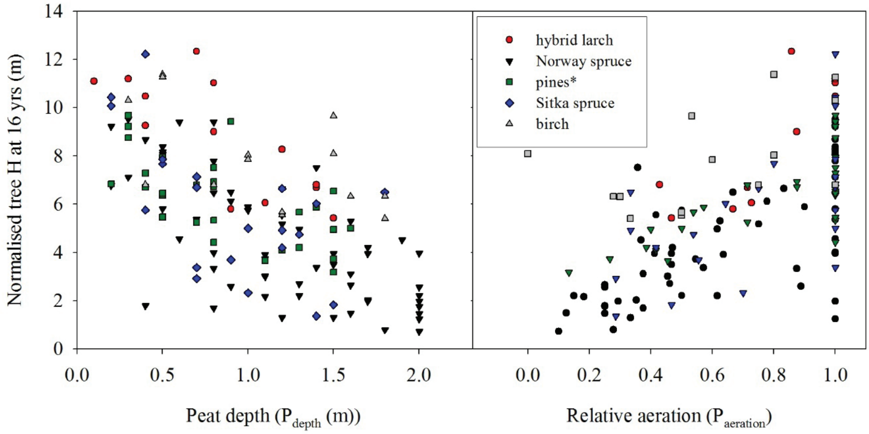


**Figure 2:** *Variation in mean plot normalised tree height at 16 years ($H_{16yrs}$) in relation to total peat depth (left panel) and relative peat aeration (right panel). See Equation 5 for description of* $P_{aeration}$ *ratio (n=140). * Pines are represented by both lodgepole and Scots pine species.*

**Table 2:** *Fitted model parameters (see Equations 3 and 4 for parameter and model description) and model goodness of fit variables for species specific functions.*

| | | Species | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | **Hybrid larch** | | **Norway spruce** | | **Pine[d]** | | **Sitka spruce** | |
| Model fit | $r^{2a}$ | | 0.75 | | 0.71 | | 0.68 | | 0.62 |
| | RMSE[b] | | 0.654 | | 0.874 | | 1.324 | | 1.161 |
| | Bias | | 0.613 | | 0.412 | | 0.364 | | 0.400 |
| Solved parameters | $H_{coeff}$ [c] | 13.66 | (0.11) | 10.7 | (0.05) | 11.7 | (0.07) | 13.4 | (0.021) |
| | res | 0.374 | | -0.129 | | 0.154 | | 0.252 | |
| | a0 | 0.423 | (0.051) | 0.723 | (0.081) | 0.534 | (0.065) | 0.223 | (0.054) |
| | kd | -0.121 | (0.022) | -0.252 | (0.038) | -0.157 | (0.062) | -0.632 | (0.084) |
| | ka | 1.874 | (0.321) | 0.408 | (0.016) | 0.542 | (0.094) | 1.302 | (0.321) |

Note: The model for birch was not significant.

[a] $r^2$ is the coefficient of determination

[b] RMSE= root mean square error

[c] Model coefficients are presented with standard error values in parenthesis.

[d] Pine included lodgepole and Scots pine.

as a site is well-drained. However, it should be noted that the maximum sampled peat depth for HL was only 1.5 m, so extrapolating predicted growth beyond that depth is not recommended. Good drainage appears to be an 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 4, right panel). The model suggests that both lodgepole and Scots pine appear to tolerate deep peats and anoxic conditions (Figure 4). The model predicts that pines would be suitable for 2 m-deep peats up to

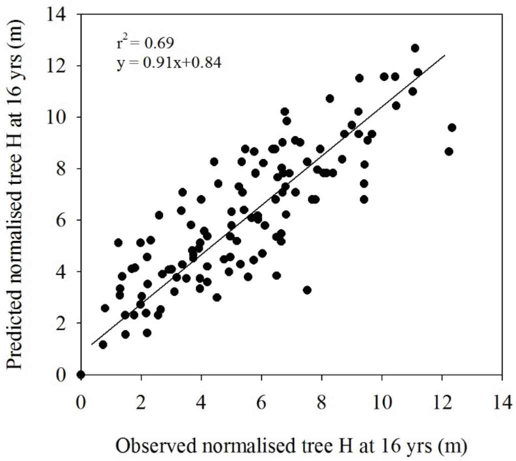


**Figure 3:** *Regression of observed versus predicted normalised tree H (n = 125) using the peat depth and aeration model (Equation 4). Note birch was excluded from regression because the model coefficients (Equation 4) were not significant.*

a $P_{aeration}$ ratio of 0.2 (data not shown). This trend was consistent with observations of extensive colonisation by pine species in deep peat areas of less well drained parts of *Phragmites* and woody fen sites, 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 2 suggest that this species can 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 were still c. 8 m high, and there was also some colonisation by willow in the same area.

*Crop nutrition*

It should be stressed that foliage samples were only collected if a crop was suspected to have nutrient deficiencies based on visual symptoms. Therefore, the results presented in Table 3 should be interpreted with caution. In addition, the site in Derrybrennan did not receive application of K as prescribed. There were also areas of the demonstration plots (CLE1/99 and KTY 1/99) which appeared to have received very little, if any fertiliser at all.

Nutrient analysis shows that P, in particular, was deficient in most samples taken (74%, Table 3). Although K deficiency was detected in only 7.7% of samples, more than half had marginal K levels. These low P and K values are mainly associated with peat depth and aeration (see Table 4), but other factors, such as the lack of appropriate timing and rates of fertilisation application or uneven application of fertiliser, may also have contributed to the poor nutrient status of the crops on some sites.

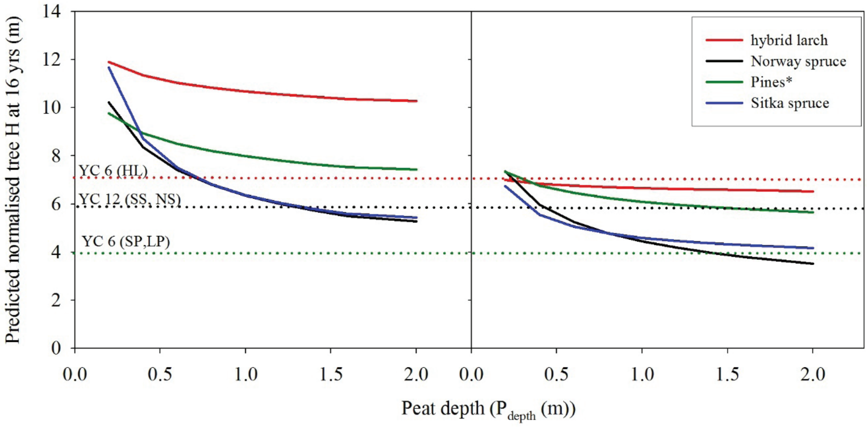


**Figure 4:** *Fitted model curves (Eq. 4) for tree H of different species over the peat depth range (solid coloured lines) under a well-drained (left panel,* $P_{aeration}$ *= 1) and poorly drained scenario (right panel,* $P_{aeration}$*= 0.5). The segmented lines represent the indicative cut-off point 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 (YC thresholds as used in the CLIMADAPT model (Ray et al. 2009)).*

Nitrogen deficiencies were detected in 12% of the samples taken. Low N in Killinagh could be associated with competition for N by *Calluna* on *Sphagnum* dominated peat plots. There were only three samples taken from this demonstration area.

Pearson's correlation analysis, presented in Table 4, provides some evidence to suggest a mechanistic reason for the poor performance of some conifer species on deeper and poorly aerated peats. The significant and 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, possibly due to a limited number of sample plots (degrees of freedom were low). The significant positive correlation between needle K and P content and relative aeration ratio ($P_{aeration}$) also suggests that P uptake was limited under anoxic conditions leading to deficiencies in K and P. This may also have been partly caused by die-back in fine roots as previously reported for spruce under very wet conditions (Coutts 1982). This relationship was, however, not significant in some cases, such as for needle P content and P aeration for Norway spruce.

## Discussion

These findings challenge the current recommendations for establishing conifer species, in particular Norway spruce, on cutaway peats of depths greater than 0.6 m (Jones and

**Table 3:** *Summary of nutrient status of crop samples from different experiments/trials, expressed as a percent of samples taken from each species in each experimental/demo nstration area that were deficient in N, P or K, based on threshold values published by Renou-Wilson et al. (2008).*

| | | % Deficient | | |
|---|---|---|---|---|
| **Experiment/Demo area** | **Species** | **N** | **P** | **K** |
| CLE 1/99 | Norway spruce | 0.0 | 90.9 | 9.1 |
| CLE 2/00 | Scots pine | 0.0 | 100.0 | 0.0 |
| | Sitka spruce | 50.0 | 50.0 | 0.0 |
| Derrybrennan | Norway spruce | 0.0 | 0.0 | 66.7 |
| Killinagh | Norway spruce | 66.7 | 0.0 | 0.0 |
| KTY 1/99 | Norway spruce | 0.0 | 100.0 | 0.0 |
| KTY 16/00 | Hybrid larch | 0.0 | 100.0 | 66.7 |
| | Norway spruce | 0.0 | 100.0 | 0.0 |
| | Scots pine | 0.0 | 0.0 | 0.0 |
| | Sitka spruce | 75.0 | 75.0 | 0.0 |
| KTY 17/00 | hybrid larch | 0.0 | 100.0 | 0.0 |
| TLM 35/96 | Scots pine | 0.0 | 100.0 | 0.0 |
| | Sitka spruce | 0.0 | 100.0 | 0.0 |
| **Total** | | **12.3** | **73.8** | **7.7** |

**Table 4:** *Pearson's regression coefficients for the relatio nships 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 indicate that the relatio nship was significant at p <0.05(a) or p <0.01(b); ns mea ns that the relatio nship was not significant, based on the Pearson's correlation coefficient and the degrees of freedom (N-1).*

| **Species** | **Peat character** | Nutrient | | | **Deg. of freedom** |
|---|---|---|---|---|---|
| | | **Ln(N)** | **Ln(P)** | **Ln(K)** | |
| Norway spruce | $P_{depth}$ | 0.08 ns | 0.22 ns | **-0.39**[a] | 36 |
| | $P_{aeration}$ | -0.12 ns | -0.12 ns | **0.41**[a] | 36 |
| Sitka spruce | $P_{depth}$ | 0.15 ns | -0.53 | -0.36 | 6 |
| | $P_{aeration}$ | -0.49 ns | **0.92**[b] | 0.59 | 6 |
| Scots pine | $P_{depth}$ | 0.55 ns | -0.62 ns | -0.44 ns | 7 |
| | $P_{aeration}$ | -0.66 ns | **0.96**[b] | **0.74**[a] | 7 |

Farrell 2000). In contrast, our results, and publications from Scandinavia (Pietiläinen et al. 2005; Paavilainen and Päivänen 1995), suggest that peats as shallow as 15 cm (Figures 2 and 4) are more suitable for afforestation so long as drainage is sufficient to ensure suitable root aeration. Although the type of underlying calcareous material did not appear to influence tree growth, trees generally grew better on weathered calcareous material than calcareous mud deposits. In addition, it should be noted that no shell marl material was detected in any of the sample plots across the experimental sites.

Preliminary results from the BOGFOR project also reported a similar relationship between peat depth and aeration and tree performance (Renou-Wilson et al. 2008), however these authors did not investigate the different response of various species.

This study demonstrates a clear difference in how the five species that were investigated responded to variations in peat depth and aeration. In general, Sitka and Norway spruce should be confined to peats of less than 1.2 m under well-drained conditions. However, if drainage is not good (i.e. aeration ratios of less than 0.5), the peat depth should not exceed 0.3 to 0.5 m for these two species. Hybrid larch is very productive on deep peats (even up to 2 m), but does not tolerate poor drainage. In addition, current phytosanitary restrictions due to the outbreak of *Phytophthora ramorum* limit the use of hybrid larch on all site types, including cutaway peatlands. Birch, Scots pine and lodgepole pine are the only species examined which are suitable for peats deeper than 1.2 m and where sufficient drainage may be difficult to maintain. However, it is generally recommended to limit afforestation to gravity drained cutaway industrial peatland sites and to exclude areas prone to flooding in the winter months (Renou-Wilson et al. 2008).

The physiological reason for the decline in tree growth associated with peat depth and aeration is not clear, but regression analysis against major macro nutrients (Table 4) suggests that this may be related to nutrient deficiencies associated with either anoxic conditions (which limit the uptake of nutrients such as P or K) or increased leaching of P or K as peat depth increases (OCarroll 1966, Pietiläinen et al. 2005, Aro 2000b). Retention of nutrients, as a function of cation exchange, is generally expected to decrease in upper levels of deep peat, compared to shallower peats and regions of the profile close to the calcareous material. There was no evidence of P or K deficiency in foliar samples taken from these sites at year 5 (Renou-Wilson et al. 2008). In addition, the observed decline in leader growth in the last 4 to 5 years, particularly on deeper or poorly aerated peats, suggested that nutrient deficiencies were only manifested in deep peats after 10-16 years. Previous studies have indicated that other factors may be influencing growth on deep peats. For example, OCarroll (1966) suggested moisture deficiencies and cracking of peat under drier condition may be a contributing factor. Some of the Norway spruce and Sitka spruce on deep, well-drained peat bays in the current study did show symptoms of stress (prolific flower production). A decline in spruce productivity under anoxic conditions has also been reported to be associated with an increase in fine root mortality (Coutts 1982) and permanent decline in photosynthesis activity of needles under prolonged waterlogged conditions (Black et al. 2005).

The fact that most crops showed a deficiency of one or more macronutrients suggests that the current recommendation for nutritional management on cutaway peatlands needs to be reconsidered. Renou-Wilson et al. (2008) recommended fertiliser application for establishment with rock phosphate (12.5% P) in a split application: 175 kg ha$^{-1}$ (21 kg P ha$^{-1}$) manually applied in bands in the year of planting and the same amount, manually broadcast, two years later, together with 250 kg ha$^{-1}$

of muriate of potash (50% K). The low level of phosphorus present in the foliage samples was 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 falloff in phosphorus levels in particular, and nitrogen and potassium, after 8 to 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 (42 kg P) and 250 kg of muriate of potash (125 kg K) at planting time. These rates are also significantly lower than those recommended in Finland. Re-fertilisation is generally carried out in Finland using PKB-fertilizer (some crops on cutaway peatlands show boron (B) deficiencies), with 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. 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 under grass for a number of years prior to afforestation and that both species responded well to re-fertilisation.

Another nutrition management issue of concern is that there was evidence of a possible lack of adherence to fertiliser recommendations ("operational drop off"), particularly in larger demonstration areas. In some cases, it was questionable if some areas received any fertiliser at all, despite how suitable industrial cutaway peatlands are for mechanised application of fertilisers. Intensive monitoring should be carried out during and after establishment to ensure even spread and correct dose of application. Furthermore, the nutritional status of the crop should be closely monitored, and a third application may be required to ensure productivity is maintained up to canopy closure of the crop.

In conclusion, it is difficult to establish what proportion of the potential Bord na Móna area (16,000 to 20,000 ha) would be suitable for productive conifer plantations based on the information provided in this study. Recent analysis on three peat production areas surrounding the Edenderry power-plant estimated that, if production were to stop in 2023, only 22 to 42% of the peat areas would have a peat depth threshold of 2 m or less (Black et al. 2017). These areas may further reduce because 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 (Black et al. 2017). Although alternative extraction methods, such as the "Haku" method[1], can be used to harvest to a more uniform peat depth, this production method is more expensive.

[1] The Peco method (from the old Russian *Peko* model) is used over large distances where peat depth may vary post-production. It involves the extraction of peat from the surface (in a horizontal plane) in the course of a number of passes, at a rate of c. 10 cm per year This method also results in a large stock pile of peat being left on a bay after production has ceased. In contrast, the Haku method can be used on smaller areas, so peat depth is more uniform post-harvest. In addition, the harvested peat is removed completely from site.

It is therefore likely that large areas of industrial cutaway peats (e.g. where peat depth is greater than 2 m and composed of *Sphagnum* peat) would not be suitable for forestry. The future configuration of industrial cutaway peatlands are likely to comprise a mosaic of wetland habitats, grasslands, short rotation coppice, peatland restoration areas, woodlands, forest plantations (for both timber and biomass) and new alternative land uses, such as windfarms or solar energy facilities. In 2016, Bord na Móna published a strategy which includes a large increase in the generation of renewable energy - through wind, solar projects and biomass supply. The company predicts an increase in biomass energy demand from 0.3 million tonnes in 2015 to 2.7 million tonnes by 2030 (Bord na Móna 2017). Forestry clearly has a role to play in meeting this demand, but the afforestation potential on cutaway peatlands appears to be much lower than was previously estimated.

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