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Forest Ecology and Management 255 (2008) 728–737

Forest Ecology and Management

www.elsevier.com/locate/foreco

Establishing oak woodland on cutaway peatlands: Effects of soil preparation and fertilization

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Received 10 April 2007; received in revised form 15 September 2007; accepted 21 September 2007

Abstract

This research was part of a large-scale project investigating various species and silvicultural techniques in order to improve afforestation success on cutaway peatlands in Ireland. Successful establishment, in terms of fast growth and good quality may be hampered on most cutaway peatlands by harsh environmental conditions. The effects of various soil preparation techniques and fertilization rates and methods on the survival, growth and quality of pedunculate oak (*Quercus robur* L.) were studied in two cutaway peatland sites. Survival of oak was excellent regardless of experimental treatments applied. Phosphatic fertilization had little effect on the early growth of oak but higher fertilizer rates increased foliar P concentrations and improved stem quality. Results from cultivation trials would suggest that mounding should be avoided while deep ploughing would benefit oak performance. Protection from exposure that leads to shoot die-back was found to be critical for oak development. Overall, the hypothesis that oak requires specific silvicultural management techniques adapted to various site conditions of the cutaway peatlands was confirmed.

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Keywords: Afforestation; Cutaway peatland; *Quercus robur*; Site preparation; Fertilization; Exposure

1. Introduction

Until the early 1990s, the level of broadleaf afforestation in Ireland was very low and mostly confined to the private sector (Neeson, 1991). This level subsequently increased; thanks to European and governmental financial incentives. In 1995, 20% of the afforested land was planted with broadleaf species, while the current target is to plant at least 30% of new forests with broadleaf species (Forest Service, 1996). Of the current broadleaf species, oak (*Quercus* spp.) is now the most commonly planted in this country (Forest Service, 2003). Broadleaves are generally more expensive and more difficult to establish than conifers (Joyce et al., 1998) and there are still major gaps in our knowledge of how to establish and manage many species. An increased research effort is now needed in broadleaf silviculture if we are to confidently manage the large areas of broadleaf crops over the coming years.

Industrial cutaway peatlands are those on which peat harvesting for fuel or horticulture has ceased; they form a substantial landmass in Ireland, part of which has been earmarked for future afforestation (McNally, 1997; Renou and Farrell, 2005; Renou et al., 2006). Pedunculate oak (*Quercus robur* L.) is a potential native species for afforestation on cutaway peatlands as it has a high timber value as well as a high biodiversity, heritage and landscape value but little is known about its silvicultural requirements on such sites.

The success of oak woodlands depends primarily on seedling persistence through the establishment period (i.e. 1–5 years following planting) (Kelly, 2002; Jacobs et al., 2005); survival can be very poor due to many stresses. Nursery stock quality and vegetation control have been cited as important for successful establishment (Frochot et al., 1986; Dey and Parker, 1997; McKay et al., 1999) and improvements in both areas are ongoing. The planting shock that oak seedlings undergo has also been related to moisture and nutrient stress (Jacobs et al., 2005). On cutaway peatlands, successful establishment of oak can also be hampered by severe nutrient imbalance, exposure, late spring frost and hare browsing (Renou and Farrell, 2005). It is widely acknowledged that phosphorus (P) is the most

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doi:10.1016/j.foreco.2007.09.059

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important fertilizing element on afforested peat sites (Dickson, 1971; Kaunisto and Aro, 1996). Increased fertilizer rates at planting may enhance the successful establishment of oak by increasing its water-use efficiency (Welander and Ottosson, 2000). Site cultivation has also been shown to improve wet agricultural land conditions, creating a favourable environmental for oak trees to obtain water and minerals (Patterson and Adams, 2003). In a recent study, oak growth responded positively to mounding especially where vegetation competition is a problem (Löf et al., 2006). However, soil cultivation has not always proven beneficial to the survival and early establishment of oak (Kabrick et al., 2005).

The BOGFOR research programme was established to improve the establishment success of a range of species on cutaway peatlands in Ireland (Renou and Farrell, 2005). Within the project, a special task was set up to investigate the potential of native oak as commercial forest tree species on this unique site type. The premise of this research is that oak requires specific silvicultural management techniques adapted to site conditions.

This paper examines how best to successfully establish oak woodland on cutaway peatlands, specifically investigating the effects of (1) site preparation and (2) fertilization rates and methods on the early development and survival of pedunculate oak. Pedunculate oak (referred to hereafter as oak) was chosen in preference to sessile oak (*Quercus petraea* (Matt.) Lieb.) as it has a reputation for successful establishment on a wide range of sites, including wet organic soils (Timbal and Aussenac, 1996; Joyce et al., 1998; Horgan et al., 2003).

This research was accomplished through three studies whose objectives were as follows:

Study 1 Cultivation trial to investigate the effect of deep ploughing on residual peat of two different depths.
Study 2 Cultivation trial to test three different cultivation techniques: ripping, ripping and discing and mounding.
Study 3 Fertilizer trial to examine the impact of three different rates of phosphatic fertilizer and two different methods of application.

2. Material and methods

2.1. Study areas

The three study sites were located in the Irish midlands, where annual precipitation over the last 30 years has averaged 934 mm with a mean annual temperature of 8.8 °C (Mullingar Met Station, Met Eireann, 2006). Precipitations recorded during the 5-year study are presented in Table 1. The growing season is long, extending from March to November (Keane and Collins, 2004), but frost can occur as late as June in some years. The sites are typical, low-lying industrial cutaway peatlands (60–70 m a.s.l.) but display different edaphic properties.

Table 1
Annual rainfall and average over the last 30 years (Met Eireann data from Mullingar located in the Irish midlands)

	2000	2001	2002	2003	2004	30-year mean
Precipitation (mm)	913	695	1085	707	903	934

2.2. Study 1: Cultivation trial in East Boora

East Boora is part of a large peatland complex (53°16′N 7°44′W). The site is flat and surrounded on three sides by either conifer plantations or naturally regenerated birch woodland. Within the site, two areas were identified, one of ‘shallow peat’ (average peat depth ≤100 cm), the other of ‘deep peat’ (average peat depth >100 cm). The depth threshold of 100 cm was used because in the case where average peat depth is greater than 100 cm, it is unlikely that any sub-peat mineral soil would be brought to the surface following deep ploughing. The peat was identified as *Phragmites* peat with a pH (peat/water V/V = 1/2) of 4.9 in the shallow area and slightly more acid (pH 4.3) in the deep area. The sub-peat mineral soil in both areas consisted of silty clay over an alkaline till of limestone origin with large stones. To prepare this site for forest establishment (post-peat harvesting), the area was levelled with bulldozers, effectively removing all internal ditches used for surface drainage during the peat harvesting. Additional drainage ditches were then dug in areas identified as waterlogged during high rainfall events. A block of 6 ha was deep ploughed in the autumn using a mouldboard plough (making a furrow approximately 1 m in width and 1 m in depth). An adjacent block of 6 ha remained untreated. Where the peat depth was shallow, deep ploughing allowed some mineral subsoil to be brought to the surface. Two replicated experimental plots were laid out in each cultivation treatment and peat depth was included in the analysis as a covariate. The whole site was rolled in February 2004, prior to planting with 2-year-old bareroot oak of Dutch origin (1u1, OP NLSH-C22, height ranging from 60 to 80 cm). Band fertilization with superphosphate (16% P) at a rate of 22 kg P/ha was carried out in July 2004 and the same amount applied in broadcast in July 2005. At time of planting, the site was well drained and bare of vegetation. Some physical and chemical properties of the peat were analysed in September 2004 by taking and pooling nine samples from each four treated plots (Table 2).

2.3. Study 2: Cultivation trial in Mount Lucas

The second cultivation experiment was located in Mount Lucas, a typical shallow cutaway peatland (53°16′N 7°13′W). The site was flat and exposed and consisted of a fen peat with woody remains (pH 5.4), well aerated and of light texture, ranging from 5 to 65 cm thickness. The sub-peat mineral soil is a till of limestone origin and is composed of a shallow layer of silt loam over calcareous gritty loam and gravel. The whole site was levelled off in spring 1999. The removal of fossil timber together with the digging of additional drains meant that a variable amount of the mineral subsoil became mixed with the peat. In spring 2000, further ground cultivation was carried out and four treatments were randomly applied in strips 300 m long

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Table 2
Physical and chemical characteristics of peat (0–20 cm) sampled at East Boora in September 2004, Study 1

	Mean depth (cm)	Standard deviation	Min (cm)	Max (cm)	pH	Bulk density (g cm^{-3})	M.C. (% DW)	N (%)	P (%)	K (%)
Deep peat										
Cultivated	149	25	125	203	4.37	0.1195	527	0.87	0.02	0.009
Non-cultivated	142	49	82	225	4.93	0.1237	489	0.95	0.02	0.006
Swallow peat										
Cultivated	88	17	54	113	4.87	0.1626	363	1.52	0.02	0.029
Non-cultivated	85	33	38	123	4.22	0.1474	388	0.86	0.02	0.043

M.C. = moisture content.

and 15 m wide (with two replications): (1) no cultivation; (2) excavator mounding (creating rows of mounds at *c.* 2 m spacing, using the spoil from drain construction; the drains were 5 m apart and 50 cm deep); (3) ripping (using a trailed ripper with tines 60 cm deep); (4) ripping and discing (ripping as above and discing up to 20 cm deep). This experiment followed a complete randomised design with two replications of cultivation treatment. Two-year-old pedunculate oak seedlings of Dutch origin (1u1, OP NL3-W04, height ranging from 60 to 80 cm) were planted at a density of 2 m × 1 m (5000 plants/ha) in May 2000. Due to the presence of calcareous sub-peat mineral soil close to the surface, the source of phosphatic fertilizer was superphosphate (16% P), which was broadcast manually in 2000 (21 kg P/ha) and again in 2002 (21 kg P/ha). This high-P-content fertilizer was chosen over the usual rock phosphate because of concern about P fixation due to the high pH and Ca content of the planting medium.

2.4. Study 3: Fertilizer trial in Mount Lucas

This experiment was established beside Study 2, on a similar site type. The site was deep ploughed and levelled off in spring 1999. It was later disced prior to planting with oak in May 2000 (with plants of the same origin as Study 2, height ranging from 60 to 80 cm), but at 2 m × 0.75 m intervals (6600 plants/ha). At time of planting, the site was bare of vegetation and was well drained. Each fertilizer plot was 15 m × 15 m and separated from adjoining plots either by a shallow drain or a 4 m-wide buffer zone. The experiment follows a completely randomised factorial design with 6 replications and a total of 36 plots. All plots received at planting one of three rates of phosphatic fertilizer in the form of superphosphate (16% P) in either broadcast or band application (Table 3; for clarity, the first application rate has been used as label for figures). The band application consisted of applying the fertilizer in a continuous band along the tree line (*c.* 40 cm width), while broadcast application resulted in fertilizer to be spread homogeneously across the soil surface. Two-thirds of the plots received a second application of phosphatic fertilizer, which was broadcast. All plots also received 125 kg/ha of potassium in the form of muriate of potash during the second fertilization event. Fertilizer was applied manually in all cases.

Table 3
Treatments in the fertilizer trial in Mount Lucas, Study 3

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

All the sites were fenced against hare browsing and vegetation was kept under control at all sites during the reporting period, using a combination of manual and mechanical control.

2.5. Measurements and statistical analysis

In each experimental plot, an inner block of 5 rows × 10 trees was permanently marked and the 50 trees were assessed for survival, height, diameter and shoot die-back, at regular interval after planting. Height was measured from root collar to tip of the tallest living shoot (to the nearest cm) and stem diameter (SD) was measured at 10 cm above ground (to closest 1 mm).

In Study 3, the effects of fertilization treatments on foliar nutrient contents were also investigated. Leaf samples were collected for foliar analysis in August 2003 and 2004, following the protocol described in Evans (1984). Samples were taken from the healthy crown of 20 trees per plot and dried at 70 °C for at least 48 h. Twigs were then removed and foliage was ground in an electric grinder with a 2 mm sieve. Foliar samples as well as peat samples (dried at 70 °C for 48 h, ground and mixed thoroughly) were treated with a nitric-perchloric acid digestion (Zasoski and Burau, 1977) before concentrations of P, K, Ca, Mg, Mn, Fe, Zn, B and Cu were determined by inductively coupled plasma (ICP) analysis (VARIAN LIBERTY 200 Elemental Spectroscopy). A standard Kjeldahl digestion with water distillation was used to measure N concentrations.

All percentages (survival and nutrient content) were normalized prior to analysis with the logarithmic transformation ($X' = \log(X)$) to equalize variances. Analyses were carried out using the Statistical Analysis System (SAS Institute Inc., 2002). In Study 3, the effects of rates of fertilizer application were analysed in two statistical tests using a randomised

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factorial analysis of variance. Using the GLM procedure in SAS, a linear model (Rate A versus Rate C) and a quadratic model (Rate B versus (Rate A + Rate C)/2) were analysed during the first 2 years. After the second application of fertilizer (years 3–5), 'Rate A versus Rate B' and 'Rate B versus Rate C' were logical comparisons analysed using the ESTIMATE pairwise *t*-test in SAS ($\alpha = 0.05$). Treatment effects were considered significant at $p < 0.05$. Where possible, repeated measures in a MIXED procedure in SAS were used to test the treatment effects over time.

3. Results

3.1. Response to cultivation methods

In Study 1, the oak survival was very good, with all, except one, of the oak seedlings alive after two growing seasons. There was a large variation in the height of individual seedlings (ranging from 16 to 180 cm). Where the peat layer was deep, cultivation, in the form of deep ploughing, did not have any significant effect on the height of seedlings (Table 4). Conversely, the height of trees planted in the shallow peat area was significantly decreased ($p < 0.0001$) where no deep ploughing was carried out.

In Study 2, seedling survival was above 85% after four growing seasons regardless of the site preparation method. Trees growing in the 'Rip and Disc' plots had the highest survival (95%) after four growing seasons but it did not differ significantly from the lowest survival (85%) which was recorded in the 'Rip only' plots. These plots also had the highest proportion of trees suffering from leader die-back (with 50% of the trees having a dead leader after four growing seasons, compared to 30% in other cultivated plots and 5% in the control plots.

Cultivation treatments had a significant effect on height increment over the 4-year period ($p < 0.0001$) (Fig. 1 inset). A pairwise comparison of treatments in year 4 showed that growth was significantly higher in the control plots and lower in the mounded plots ($p < 0.0001$) (Fig. 1). These results were confirmed by a repeated measures analysis (Table 5), which shows an overall cultivation effect on height growth over the 4-year period ($p = 0.04$). There was no significant interaction between treatment and age, suggesting that the response did not change over time.

3.2. Response to different fertilizer rates and methods of application

Survival after one growing season in Study 3 was excellent (>98%) across all treatments but decreased significantly ($p < 0.0001$) for all treatments after the second growing season. After 5 growing seasons, survival averaged 92% (with a minimum value per plot of 66% and a maximum of 100%). Increased fertilizer rates did not significantly affect survival nor did the method of application (Table 6). While a large number of seedlings survived, many did not have a live leader by year 5. Forty-eight percent of trees assessed in the low fertilizer rate

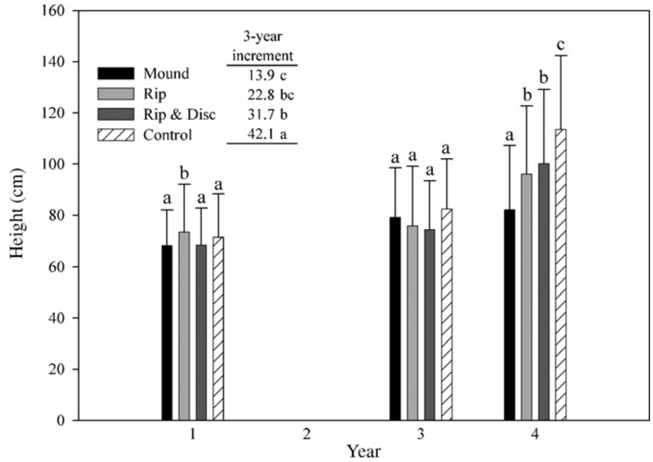

Fig. 1. Mean height of oak seedlings in the different cultivation treatments, Study 2 (bars denote ±one standard error); there was no assessment carried out in year 2. Inset: 3-year height growth increment (cm). Means having the same letter are not significantly different from each other ($p > 0.05$).

Table 4
The effects of cultivation and peat depth on the mean height ($n = 50$) in cm (+standard error) of oak seedlings after two growing seasons, Study 1

	Deep ploughed	No cultivation
Deep peat	83.9 (31)b	84.2 (25)b
Shallow peat	95.5 (34)a	63.7 (18)c

Means having the same letter are not significantly different ($p > 0.05$).
Average standard error of the difference between the means = 5.5.

plots had a dead leader compared to 33% in the high fertilizer rate plots (Fig. 2). Increasing fertilizer rate decreased the proportion of dead leader ($p = 0.03$). There was no evidence that the relationship between fertilizer rate and proportion of dead leader was other than linear ($p = 0.87$).

Rate and method of fertilization did not have any significant effect on the total height or stem diameter of the oak seedlings (Table 6 and Fig. 3). Total height decreased for the first 3 years for all treatment combinations. Examination of height and diameter increments (Fig. 4) suggests a growth response to higher fertilizer rates during the fifth growing season. While there was no significant difference between the two higher rates ($p = 0.4$), the lowest rate of fertilizer significantly decreased the diameter increment during year 5 ($p = 0.008$). Although growth was small, repeated measures analysis (Table 7) shows that over the last three growing seasons, fertilizer rates have an overall significant effect on diameter increment ($p = 0.003$) and that the response to treatments also changes with time ($p = 0.014$).

Table 5
Repeated measures analysis table showing cultivation effects on the height of oak over the 4-year period, Study 2

Effect	d.f.	*F*-value	*p*
Treatment	3	7.1	0.044
Year	1	39.43	0.003
Treatment × year	3	3.63	0.122

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Table 6
Analysis of variance table for oak after four and five growing seasons, Study 3

Year	Source of variation	*p*							
		Height	Diameter	Survival	N	P	K	Mg	Ca
4	Rate	0.939	0.825	0.447	**0.010**	0.873	0.778	0.137	0.203
	Method	0.641	0.979	0.927	0.577	0.282	0.057	0.556	0.668
	Rate × method	0.653	0.654	0.131	0.973	0.474	0.47	0.14	0.546
5	Rate	0.674	0.207	0.455	**<0.0001**	**<0.0001**	**0.062**	0.143	0.184
	Method	0.719	0.64	0.983	**0.026**	**0.024**	0.804	0.815	0.296
	Rate × method	0.41	0.346	0.119	**0.0178**	0.818	0.856	0.402	0.808

Variables include height, diameter, survival and foliar concentrations (N, P, K, Mg and Ca). Statistically significant value $p < 0.05$ are in bold.

Table 7
Effects of rate and method of fertilization on the diameter increment of oak over three growing seasons (repeated measures), Study 3

Sources	d.f.	*p*
Rate	2	0.003
Method	1	0.736
Rate × method	2	0.14
Year	1	<0.0001
Year × rate	2	0.014
Year × method	1	0.763
Year × rate × method	2	0.244

While phosphorus (P) concentrations in the foliage did not significantly differ across treatments after the fourth growing season, it showed significant differences by the fifth (Table 6 and Fig. 5). There was no rate × method interaction ($p = 0.8$) but there was a significant method effect ($p = 0.02$) and a stronger rate effect ($p < 0.0001$). Trees which received the lower fertilizer rate showed significantly lower foliar P concentrations. P concentrations were also significantly lower in the 'broadcast' plots for all fertilizer rates. There was no significant difference in foliar P concentrations between fertilizer rate A (42 kg/ha at planting) and rate B (28 + 14 kg/ha) after 5 years.

After the fourth growing season, trees which received the lowest rate of P fertilizer, displayed significantly lower

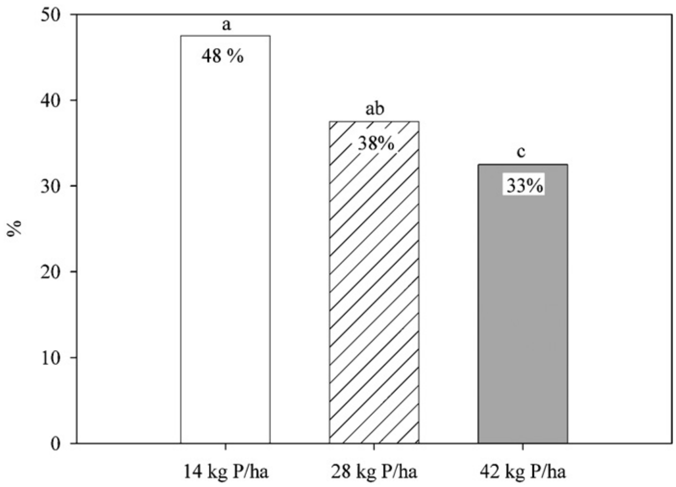

Fig. 2. Percentage shoot die-back recorded for each fertilizer rate after 4 years, Study 3. Means having the same letter are not significantly different from each other ($p > 0.05$).

($p = 0.003$) foliar N concentrations (Fig. 6). Foliar N concentrations did not differ with the method of application and there was no significant rate × method interaction (Table 6). During the fifth growing season, however, the trees which received the highest rate of P fertilizer as a broadcast application had a significantly reduced N content compared to all other treatments ($p < 0.0001$) (Fig. 6 and Table 6). That year, foliar ratios (Table 8) were found to be imbalanced for trees which received the broadcast, higher fertilizer rate with N:P:K = 10:3:13, departing from the balanced ratios of N:P:K of 10:1:5.

Potassium (K) concentrations measured in the foliage were not affected by either fertilizer rates or the method of application (Table 6) but decreased significantly ($p < 0.0001$) for all treatments between year 4 (K = 1.07%) and year 5 (K = 0.85%). Foliar K concentrations in year 5 remained above the 0.7% deficiency level (Evans, 1984).

4. Discussion

The survival rates of oak measured in our studies were encouraging being comparable to that of birch on similar site types (Renou et al., 2007), and are better than broadleaves which are non-native to Ireland such as beech (*Fagus sylvatica* L.) and sycamore (*Acer pseudoplatanus* L.) (Renou and Farrell, 2005).

4.1. Cultivation

The results from Study 1 firstly demonstrate that, in areas where the remaining peat layer was deeper than 100 cm,

Table 8
Foliar nutrient ratios (N:P:K) recorded in oak trees during the fourth and fifth growing seasons, Study 3

Fertilizer rate	Method	N:P:K	
		Year 4	Year 5
A	Broadcast	10:1:7	10:3:13
	Band	10:1:6	10:2:6
B	Broadcast	10:1:7	10:1:5
	Band	10:1:6	10:1:6
C	Broadcast	10:1:8	10:1:5
	Band	10:1:8	10:1:4

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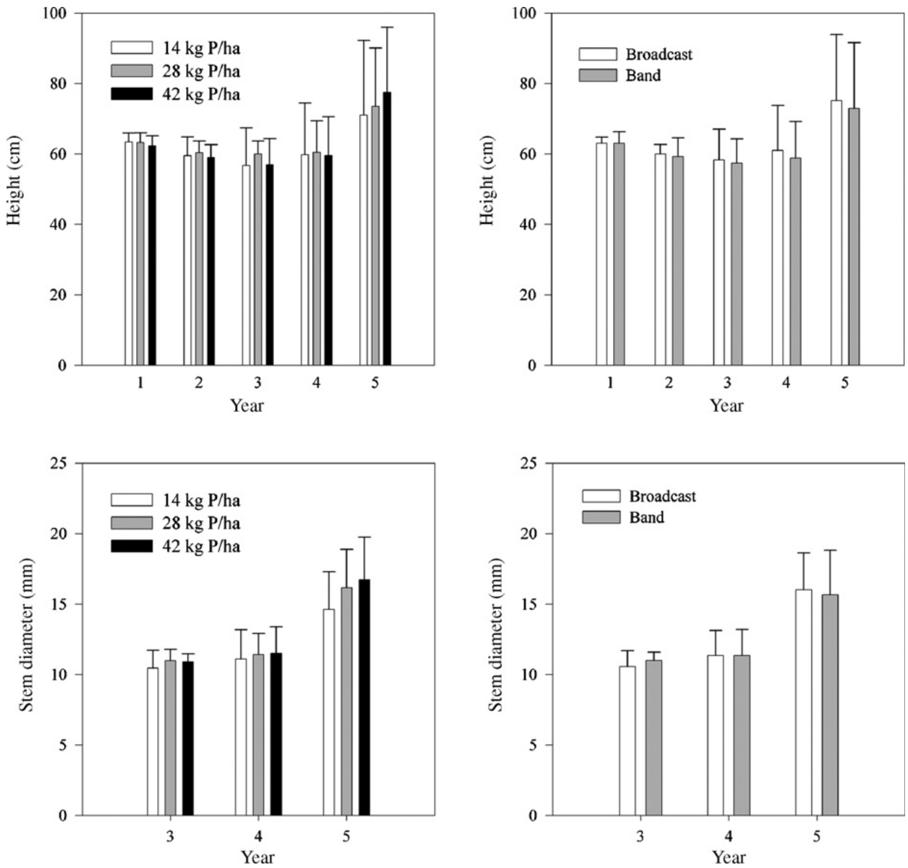

Fig. 3. Total height and stem diameter for each fertilizer rate and application method, Study 3 (bars denote ±one standard error). Means having the same letter are not significantly different from each other ($p > 0.05$).

cultivation in the form of deep ploughing did not affect the survival or early growth of oak seedlings. It is too early to make any conclusions about the long-term effects of deep ploughing on deep peat as the effect of cultivation after two growing seasons may have been limited to tree root development, without any changes to the above ground biomass. Nonetheless, the absence of cultivation effects on total height may be explained by the fact that deep ploughing was carried out in autumn prior to planting and was followed by a very wet winter. Soil analyses (Table 2) revealed that moisture contents and bulk densities did not differ between cultivated and non-cultivated deep peat areas. When compared with shallow peat, deep peat (either cultivated or not) had lower bulk density but higher soil moisture content.

Deep ploughing a shallow peat layer offered the most favourable conditions for oak seedling establishment and development. After two growing seasons, oak seedlings in the deep ploughed shallow peat reached an average height of

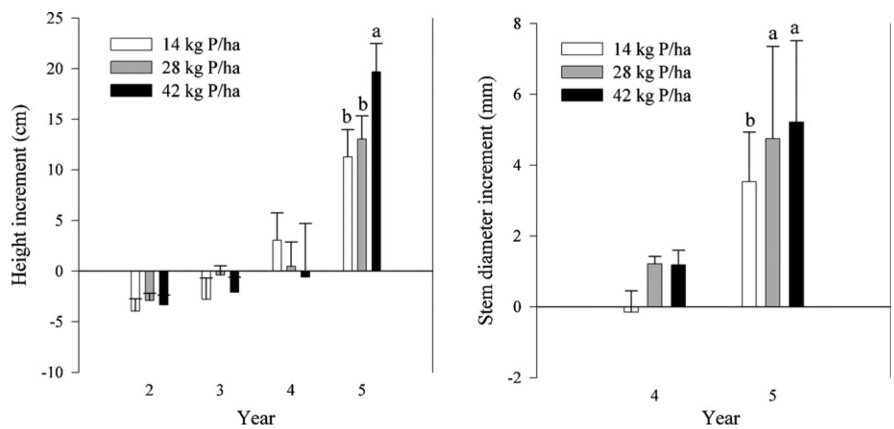

Fig. 4. Annual height and stem diameter increment in the fertilization trial, Study 3 (bars denote ±one standard error). Means having the same letter are not significantly different from each other ($p > 0.05$).

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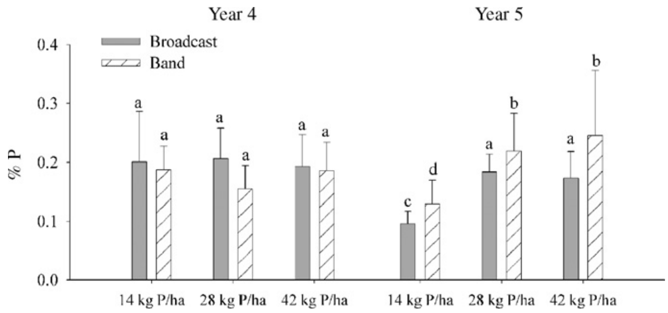

Fig. 5. Foliar P for each fertilization treatment, Study 3 (bars denote ±one standard error). Means having the same letter are not significantly different from each other ($p > 0.05$).

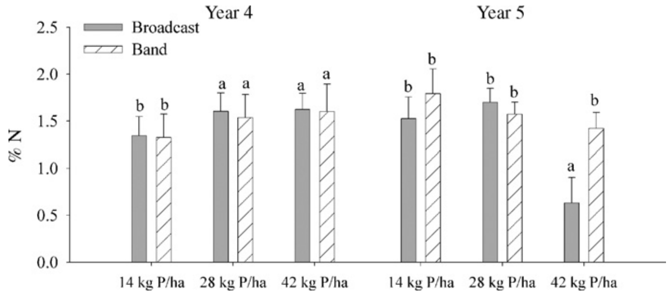

Fig. 6. Foliar N for each fertilization treatment, Study 3 (bars denote ±one standard error). Means having the same letter are not significantly different from each other ($p > 0.05$).

95.5 cm which represents a rapid establishment, reducing susceptibility to frost damage as well the need for vegetation control. While it is not possible to ascertain how much sub-peat mineral soil was mixed during this process, the end product (i.e. deep ploughed shallow peat) had a higher bulk density but more importantly a higher N content (Table 2). Cultivating shallow peat, which brought up mineral subsoil, also produced good results in Fenno-Scandinavian cutaway peatlands (Kaunisto, 1987; Åkerstrom and Hånell, 1997; Aro and Kaunisto, 1998). O'Carroll and Farrell (1989) found that Sitka spruce (*Picea sitchensis* (Bong.) Carr.) grew satisfactorily in all peat–subsoil mixtures but was significantly reduced in pure sub-peat mineral soil.

The average height of the oak (excluding the mounded plots) reached in Study 2 after four growing seasons was 103 cm and compared well with oak established on former arable land in Ireland (Bulfin and Radford, 1998). The ripping and 'ripping and discing' cultivation methods did not affect oak seedling growth. Gemmel et al. (1996) also found that site preparation methods (including mounding) did not influence the survival or growth of oak. In our study, however, mounding of shallow peat had a negative effect on height growth in this study and after four growing seasons, oak seedlings on mounded plots had reached less than seventy five percent of the height of seedlings planted in the control plots. Several factors could explain this poor performance. The seedlings may have suffered from exposure from the outset, being in an elevated position on the top of the mound. A one-third of the measured seedlings growing on mounds had leader die-back after four growing seasons. These lowland sites are subject to harsh environmental conditions including strong wind (summer gales combined with high precipitation) during the growing season. The highest percentage of trees with evidence of die-back was in the ripped plots which, due to the layout of the experiment, were located at the windward side of the plantation. Mounding also creates an elevated spot (20–40 cm high) that can contribute to the erosion of the mounds, thus exposing roots. This will depend greatly on the composition of the mounds. Many studies have found that mixed peat and mineral soil mounds provide best planting medium with respect to soil structure with increased porosity and aeration and better moisture condition (Grossnickle and Heikurinen, 1989; Sutton, 1993; Åkerstrom and Hånell, 1997). Due to the heterogeneity of soil conditions in this study, it is not possible to make any conclusions here. In some instances, the mounds were principally made of sub-peat mineral soil (containing loam and gravel and sometimes large stones) that may have acted as an impediment to the root growth in the mounds and can easily dry up. The fact that some mounds may have contained high amounts of free calcium carbonate (observed *in situ*) may also have been unfavourable. Although pedunculate oak can thrive on calcareous soils, Cogliastro et al. (2003) found that oak establishment was reduced in stony dolomitic moraines in southwestern Quebec. In the case of mixed mounds (mineral soil capping peat), oak seedlings may have suffered from moisture stress due to air pockets created by lumps of peat within the mound, thus interrupting the capillary connection (Sutton, 1993; Londo and Mroz, 2001). Inadequate water supply to the roots of young seedlings even during short dry periods can cause shoots to die-back (Hibbs and Yoder, 1993; Johnson et al., 2002), which has been attributed to stem xylem cavitation (Garriou et al., 2000; Cox and Zhu, 2003). The second growing season was particularly dry with only 695 mm compare to a 30-year average of 934 mm.

Be it due to climatic or edaphic circumstances, the susceptibility of oak to shoot die-back is of great significance as branching usually occurs after the leader has died back (Collet et al., 1997).

4.2. Fertilization

Although growing in a P deficient growing medium, the growth of oak seedlings did not increase significantly with increased amount of P fertilizer. Other studies have shown that slow-growing species such as oak are less able to respond to fertilizer addition (Chapin et al., 1986; Evans, 1986). Although Harmer (1989) noted a positive effect of fertilization on shoot length of *Quercus petraea*, oak seedlings growing under stressful environmental conditions may be less sensitive to fertilizer addition. It is also possible that resources were used primarily for root growth. In our study, percentage of shoot die-back decreased with the increase of phosphatic fertilizer. A possible reason is that increased application of P stimulates root growth (Van den Driessche, 1984; Rook, 1991). Seedlings with deeper roots would suffer less from shoot die-back as they would have access to humid soil zones. On the other hand, Larsen and Johnson (1998) argues that the repeated shoot die-back during the establishment period of oak seedlings growing

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beneath the parent stand leads to the development of large root systems, but this was not measured in this study.

Sander (1971) found that large root systems allow oaks to grow rapidly in height once favourable conditions occur. Oak seedling performance showed signs of a positive response to increased levels of phosphorus during the fifth growing season, although this was significant for stem diameter growth only. Seedling biomass was not measured, but from the average height and diameter values, it can be inferred that the higher rates of fertilizer gave a higher seedling total biomass after five growing season.

It is widely acknowledged that P and K concentrations in cutaway peats are low (Kaunisto and Aro, 1996; Andersen et al., 2006, see also Table 1) and that they are likely to be insufficient to meet growth demand, even of oak, which is known to be relatively insensitive to soil fertility (being relatively unable to obtain nutrients from intractable soil sources) (Evans, 1984; Newton and Pigott, 1991). In this study, foliar P content decreased, as was to be expected, with reduced rates of phosphatic fertilizer application. During the fifth growing season, trees which received the lower rate of surperphosphate had an average foliar P concentration of 0.11% which is substantially lower than the threshold value of 0.16% presented by Evans (1984). The fact that P concentrations were lower in the 'broadcast' plots, regardless of fertilizer rate, reflects the limited accessibility of fertilizer P to the developing root systems of the seedlings. The preference of band application is in accordance with other studies where initial spot or band fertilization near the planting hole is preferable to broadcast fertilization (Kaunisto and Päivänen, 1985; Sundström, 1997; Jacobs et al., 2005). Ballard (1984) further suggested that effectiveness of a more localized application tends to decline once the root system expands beyond the fertilized area. Because of this, it is recommended to broadcast the second application of fertilizer (after 2 years) as was done in the present studies.

Trees which received the broadcast, higher fertilizer rate displayed imbalanced foliar nutrient ratio due to a sudden reduction in foliar N concentrations. A reduction of N due to applied P may be caused by dilution as a consequence of increased photosynthesis (Leaf, 1973) and growth, as seen by the significantly higher height and diameter growth increment in year 5 (Fig. 4). This mechanism may also account for the general reduction in K concentrations between year 4 and year 5. It should be stressed that many factors, including climate, can cause variation in foliar nutrient levels from year to year, especially K which is very mobile (Mead, 1984).

4.3. Exposure and shelter effect

Despite excellent survival of oak in cutaway peatlands, negative height growths of oak have resulted from successive shoot die-back which can jeopardise future planting of oak. The establishment of a shelterwood system (by either planting or natural regeneration), in advance of planting the oak may improve environmental conditions found on the cutaways and may lead to better establishment, in terms of fast growth and good quality by reducing dead leader damage.

Oak growing under a birch shelterwood that naturally regenerated on a cutaway peatland in the Irish midlands averaged 210 cm after five growing seasons, with maxima reaching 400 cm (Renou, unpublished data). More interestingly, trees suffering from shoot die-back was limited. It can be speculated that trees were better protected from exposure and against dry periods. The micro-conditions created by the shelter wood can reduce evaporative demands, which are very high in the open, wind-swept cutaway bogs and can reduce excessive light when the photosynthesis is limited by drought. Other studies in Ireland confirmed the improved performance of broadleaf species when planted with a nurse crop, either providing side shelter or an overhead screen (Horgan et al., 2003). In Scotland, height growth of oak seedlings was improved under birch canopy but not under oak canopy (Truscott et al., 2004). In natural oak stands in Wisconsin, red oak seedlings (*Quercus rubra* L.) were found to have better height growth under a partial canopy than in the open, particularly where open sites are subject to vigorous competition and late spring frosts (Teclaw and Isebrands, 1993).

Other studies, however, have shown the negative effect of dense shelter wood on oak growth. Gemmel et al. (1996) and Gardiner et al. (2004) showed, separately, that oak seedlings growing under partial canopy had the same height after 3 years as those established in the open but root collar diameter was less than that of open-grown seedlings. It would thus be useful to measure and compare diameter growth in our studies. Furthermore, it is not known whether these under-planted seedlings will be affected by the birch canopy as both species grow taller. Oak seedlings are relatively intolerant of shade, be it overstorey or tall ground vegetation (Collet and Frochot, 1996; Johnson et al., 2002).

In practice, establishing oak seedlings under feral birch may present difficulties, due to the time required for the birch to establish naturally following peat harvesting (Curran and MacNaeidhe, 1986; Salonen and Laaksonen, 1994). Planting an overstorey of birch or alder 3–4 years ahead of the oak is a more expensive but maybe, a more secure option where density of the shelter wood can also be controlled.

5. Conclusions and management implications

Several management implications of practical significance to forest practitioners can be drawn from this work. Firstly, this paper documented good survival of oak planted on cutaway peatlands, regardless of site preparation or fertilization treatment. Secondly, that oak requires specific silvicultural management techniques adapted to site conditions was confirmed by our studies.

The type of cultivation must be tailored to site conditions, paying particular attention to the depth of peat. Results showed that deep ploughing would be beneficial especially in shallow peat. Planting oak on mounds or directly in shallow peat areas is not recommended. While fertilization may not be critical to the early establishment of oak (especially if environmental conditions are not satisfactory), the application of phosphatic

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fertilizer may be required on certain sites if the trees are to continue to grow and display good quality stems.

Successful establishment of oak, in terms of fast growth and good quality may be seriously hampered on most cutaway peatlands by harsh environmental conditions, which lead to shoot die-back. Experimental afforestation system where oak is underplanted in a shelter wood (either feral or planted) should be established if any further oak planting is to be considered on cutaway peatlands.

In conclusion, these results from the first oak plantations on industrial cutaway peatlands are a source of encouragement for the future diversity of these new forests in Ireland.

Acknowledgements

The BOGFOR research project was carried out in cooperation with Bord na Móna and Coillte and was co-funded by COFORD (the National Council for Forest Research and Development). In particular, the authors wish to thank particularly John O'Sullivan and Gerry McNally. The authors are also grateful to Joe Freeman and Donal O'Hare for technical assistance in the field and to John Connolly from the Statistical Department in University College Dublin. We also wish to thank Raija Laiho, Jukka Laine and Conor O'Reilly for reading the manuscript as well as Raquel Cabral and David Wilson for giving their valuable advice.

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