Forestry An International Journal of Forest Research
Institute of Chartered Foresters

Forestry, Vol. 84, No. 4, 2011. doi:10.1093/forestry/cpr046
Advance Access publication date: 2 September 2011

Soil organic carbon stocks of afforested peatlands in Ireland

MICHAEL L. WELLOCK[1]*, BRIAN REIDY[2], CHRISTINA M. LAPERLE[1], THOMAS BOLGER[2] AND GERARD KIELY[1]

[1] Centre for Hydrology, Micrometeorology and Climate Change, Department of Civil and Environmental Engineering, University College Cork, Cork, Ireland
[2] School of Biology and Environmental Science, University College Dublin, Belfield, Dublin 4, Ireland
*Corresponding author. E-mail: m.wellock@umail.ucc.ie

Summary

This paper quantified the soil organic carbon (SOC) concentration, bulk density, depth and carbon (C) stocks of 24 afforested peatlands. We found that the peat bulk density does not increase with depth, as has been previously noted in the literature. The depths of each different peat type were found to vary widely with means of 192 ± 100, 145 ± 130 and 127 ± 100 cm for raised bogs (RB), high-level blanket bog (HLB) and low-level blanket bog (LLB), respectively. Based on the full-surveyed depth, we estimated carbon densities of: 1160 ± 520 Mg C ha^{-1} for RB peat; 775 ± 590 Mg C ha^{-1} for HLB peat and 705 ± 420 Mg C ha^{-1} for LLB peat. We found peat depth and peat type to be significant predictors of peat carbon density and present pedo-transfer functions for carbon density based on these predictors that will help to improve future peat C stock estimates. We suggest that due to the similarities between the carbon densities of the HLB and LLB, they can be analysed as one group for accounting purposes and future C stock estimates.

Introduction

Although peatlands cover only ~3 per cent of the Earth's land surface, they provide a significant carbon (C) stock, with boreal and subarctic peatlands estimated to contain 270 and 370 Pg of carbon (C) (Turunen *et al.*, 2002). This is equivalent to 34–46 per cent of the total carbon (as carbon dioxide, CO_2) in the atmosphere (IPCC, 2007). An estimated 80 per cent of peatlands are in the northern hemisphere, particularly in Russia, Canada and the USA (Limpens *et al.*, 2008) with smaller areas in Ireland and Northern Europe. Between 13.8 per cent (0.95 Mha) (Connolly *et al.*, 2007) and 17 per cent (Hammond, 1981) of the Irish land area is peatland, containing an estimated soil carbon stock of between 53 and 62 per cent of the national soil carbon stocks (Tomlinson, 2005; Eaton *et al.*, 2008).

Peatlands have long been considered carbon sink ecosystems. However, with the onset of climate change, peatlands may become carbon source ecosystems with the potential to lose carbon (from their large carbon stocks) either as trace gases such as carbon dioxide (CO_2) and methane (CH_4) or fluvial dissolved organic carbon (Koehler *et al.*, 2010). One direct feedback to rising greenhouse gases in an anthropogenically warmed environment is the release of organic carbon stored in vegetation and soils. To assess this potential release of carbon and its effect on climate change, accurate estimates of the quantity and distribution of soil organic carbon (SOC) and its stock are required (Burnham and Sletten, 2010). The carbon stock is estimated as the product of bulk density (grams per cubic centimetre) and SOC concentration (per cent) over the full peat depth. Peat carbon stock studies in Scotland (Chapman *et al.*, 2009) and in Ireland (Tomlinson, 2005) have used models of peat based on either assumed values or a small sample size for peat bulk density and depth. Tomlinson (2005), Limpens *et al.* (2008) and Chapman *et al.* (2009) have identified the need for extensive data collection of bulk density and peat depth to improve the current estimates of carbon stocks. The spatial extent of peatlands (but not their depths) in Ireland has been examined by Connolly *et al.* (2007) and Hammond (1981), but there have been few studies that quantify the physical properties (e.g. bulk density, peat depth and SOC) of the major peatland types (e.g. raised bog (RB), high level blanket bog (HLB) and low level blanket bog (LLB)) (Tomlinson and Davidson, 2000; Tomlinson, 2005; Eaton *et al.*, 2008; Kiely *et al.*, 2010).

Ground-penetrating radar is becoming a useful tool for assessing the depth of peatlands (Holden *et al.*, 2002; Rosa *et al.*, 2009). However, the most commonly used method for determining peat depth is probing with connecting metal rods (Lindsay, 2010). Probing provides a cheap quick estimate of depth but is limited in that it only gives the depth of the specific location, and the peat depth can differ substantially within a few metres (Lindsay, 2010). In assessing Irish national and global peat stocks, studies often assume a mean depth value for all peat or mean values for different peat types or regions. Tomlinson (2005) in his assessment of soil C stocks, separated peat depth estimates by peat type, location and its current and past use by man. Intact midland RBs, western RBs, northwestern, HLB and LLB were assigned depths of 750, 400, 300, 120 and 300 cm, respectively. For man-modified peats, i.e. afforested peat, a loss of 66 per cent of the peat depth was assumed for all peat types except for HLBs, which assumed a 50 per cent loss. In estimating the carbon stock of peatlands, both within Ireland and globally, the lack of data on the depth of peatlands limits the accuracy of the carbon stock estimate.

SOC is the most studied property of peat, with most values reported to be around 50 per cent. Tomlinson and Davidson (2000) found a mean SOC value of 51.1 per cent for Northern Irish non-forested RBs, while Chapman *et al.* (2009) report values ranging from 50.6 to 54.6 per cent for Scottish blanket bogs.

There are very few data on peat bulk density for Ireland and Britain, especially at depths below 50 cm (Lindsay, 2010). Tomlinson and Davidson (2000) observed a mean bulk density of 0.069 g cm^{-3} for non-forested raised peats in Northern Ireland, while Lewis *et al.* (2011) observed a mean value of 0.070 g cm^{-3} for a non-forested HLB in County Kerry, Ireland. Some authors have noted that the bulk density of peat increases with depth (Clymo, 1978; Howard *et al.*, 1994; Milne and Brown, 1997; Cruickshank *et al.*, 1998). However, a number of recent studies have shown that this may not be the case, displaying either no change (Tomlinson and Davidson, 2000; Lewis *et al.*, 2011) or a slight increase with depth (Weiss *et al.*, 2002).

Over recent centuries, Ireland has been denuded of its native forests, so much so that at the beginning of the 20th century, the national forest stock was estimated at only 1 per cent of the total land cover in the Republic of Ireland (Pilcher and Mac an tSaoir, 1995; Eaton *et al.*, 2008). Since the mid–20th century, it has been Irish government policy to increase forest cover and by 2007, the national forest area had risen to 10 per cent of the total land area (National Forest Inventory (NFI), 2007a) with a projected increase to 17 per cent by 2030 (Department of Agriculture, 1996).

Large areas of peatland in the boreal and temperate zones have been commercially forested, the majority in the Nordic countries and the former Soviet Union, while large areas have also been afforested in Ireland and the UK (Byrne and Farrell, 2005; Vasander and Kettunen, 2006). In the past, afforestation of peatlands was considered an attractive option for Ireland as peatlands were considered as marginal lands unsuitable for agriculture (Renou and Farrell, 2005; Byrne and Milne, 2006). This has resulted in peat soils being the largest soil type of Irish forests; with 42.1 per cent of the total Irish forest cover (NFI, 2007a) on peat soils. The main forest species planted on peatlands were Sitka spruce (*Picea sitchensis* (Bong.) Carr.) and lodgepole pine (*Pinus contorta* Dougl.) in large monocultural non-native stands (Byrne and Farrell, 2005). Afforestation of peatlands began in the 1950s and while still continuing into the 21st century, the rate of peatland afforestation has decreased from 56 per cent of total annual afforestation in 1990 to 29 per cent in 2003 (Black *et al.*, 2009). This decrease is due to the poor economic return of forested peatland as well as the growing awareness that peatlands should be conserved not only because of the unique biodiversity of their landscapes (Foss *et al.*, 2001) which contain significant amounts of carbon but also because these ecosystems are currently known to be small carbon sinks (Sottocornola and Kiely, 2010).

Afforestation can impact the carbon balance of a peatland due to increased soil aeration which follows from lowering the water table through drainage and increased evapotranspiration. This leads to the growth of microbial aerobic decomposers (Chmielewski, 1991; Byrne and Farrell, 2005) which enhance the rate of organic matter decomposition and loss of carbon as CO_2 (Lieffers, 1988; Bridgham *et al.*, 1991) and can lead to a decrease in carbon stocks (Braekke and Finér, 1991; Sakovets and Germanova, 1992). However, there may also be an increase in the vegetative input of carbon to the peat through roots, litterfall and forest harvest residues (Anderson *et al.*, 1992; Minkkinen and Laine, 1998; Reynolds, 2007). Such uncertainties highlight the need to sample peat properties to assess the current carbon stocks of afforested peatlands.

There are two major types of peatland in Ireland: fens and bogs. Bogs are forested more frequently with 40.7 per cent of the total national forest cover occurring on them, while fens only represent 1 per cent of the total forest cover (NFI, 2007a). Bogs are ombrotrophic ecosystems, taking their water supply from the mineral-poor rainwater and are of two types: blanket bogs and RBs. Globally, blanket bogs are a small part of the total peatland area, accounting for ~3 per cent of the global peatland area (Foss *et al.*, 2001). However, blanket bogs are an important form of peatland landscape in Ireland comprising ~18 per cent of the total peatland area (Hammond, 1981). Blanket bogs are further classified into two types: LLBs have *Schoenus nigricans* as a large contributor to the vegetative cover, while HLBs do not (Hammond, 1981; Sottocornola *et al.*, 2009). Blanket bogs are located predominantly along the western seaboard and at higher altitudes and represent 0.196 Mha or 31.5 per cent of the total forest area within Ireland (NFI, 2007a). RBs are formed in areas with a high water table due to impermeable subsoil, such as in hollows, lake basins and river valleys (Gardiner and Radford, 1980). RBs are predominantly found in the midlands of Ireland and represent 0.066 Mha or 10.7 per cent of the total national forest area (NFI, 2007a). In this study, peat was classified as having a depth greater than 30 cm (excluding the thickness of the plant/litter layer) and organic matter content greater than 30 per cent (Gardiner and Radford, 1980; Hammond, 1981).

To enable improved estimates of carbon stocks in afforested peatlands, this study was designed: (1) to quantify the bulk density, SOC concentration and depth of peat soils of Irish forest soils of raised and (high level and low level) blanket bogs; (2) to estimate the current carbon stocks of Irish afforested peatland soils and (3) to determine suitable pedo-transfer type functions for carbon density.

Materials and methods

Site selection and description

In 2007, the Irish Forest Service produced a NFI with detailed field surveys of forest plots (NFI, 2007b). The NFI surveyed 1742 forest sites that were selected from a randomized systematic grid sample design. After a pilot study in Co. Wexford, a grid density of 2 × 2 km grid was placed over the total land base of Ireland (6 976 100 ha). The NFI collected data on forest biology and geography, including forest type, age and soil type. From this NFI database, we selected a subset of afforested RB, HLB and LLB sites with forest age greater than 15 years and that were accessible by foot for sampling purposes. Fen bogs were excluded from our subset as they represent a small portion (1 per cent) of the forested land cover (NFI, 2007a). We partitioned our subset into three categories: conifer forested RB; conifer forested HLB and conifer forested LLB. Twenty-four sites were randomly selected from the 315 sites of the above subset representing the three forested categories and with an age range of 18–45 years. This resulted in the following distribution of sites among groups: 11 conifer forested RB sites; 6 conifer forested HLB sites and 7 conifer forested LLB sites. Details and locations of the sites are shown in Table 1 and Figure 1.

Sampling methodology

Each NFI site was located using GPS (GPS 60; Garmin, Olathe, KS). At each site, a 20 ×20 m square plot was set out with similar protocol sampling as was done for the National Soils Database (Fay *et al.*, 2007) and then partitioned into four 10 ×10 m quadrants. Each quadrant was split into 1 × 1 m subplots and numbered. A list of randomly generated numbers was created prior to sampling and the first number of this list was sampled at the comparative point in the site. If this point was not appropriate for sampling (e.g the presence of a large tree root near the surface), the second number on the list was chosen and so on, until an appropriate sampling point was found. Within each quadrant, four points were randomly selected and the soil sampled using a Russian peat corer (Eijkenkamp Agrisearch Equipment BV, Netherlands) with sample length 50 cm, internal diameter 5.2 cm and a volume of 500 cm^3 for bulk density (grams per cubic centimetre) and SOC (per cent). The peat was sampled over its full depth from the peat surface vertically down the profile in increments of 50 cm. A second peat sample (at depth 50–100 cm) was taken at a point

Table 1: Peat type and characteristics of each site

Site ID	Elevation (m)	Slope (°)	Tree species	Forest age (years)	Tree d.b.h.	Georeference site
RB1	48	2	*Pinus contorta*	31	301–400	53° 18′ N, 8° 32′ S
RB2	50	1	*Picea sitchensis*	18	141–200	53° 26′ N, 8° 41′ S
RB3	127	2	*P. sitchensis*	25	71–140	52° 52′ N, 7° 42′ S
RB4	114	1	*Pinus sylvestris*	31	301–400	52° 4′ N, 9° 8′ S
RB5	112	9	*P. sitchensis*	31	71–140	54° 16′ N, 8° 14′ S
RB6	53	3	*P. contorta*	40	301–400	53° 27′ N, 8° 16′ S
RB7	68	2	*P. sitchensis*	24	201–300	53° 37′ N, 8° 19′ S
RB8	84	2	*P. contorta*	20	71–140	53° 29′ N, 8° 34′ S
RB9	85	1	*P. sitchensis*	20	201–300	53° 25′ N, 7° 13′ S
RB10	81	1	*Picea abies*	41	141–200	53° 28′ N, 7° 7′ S
RB11	94	2	*P. sitchensis*	30	71–140	53° 18′ N, 7° 25′ S
HLB1	219	4	*P. sitchensis*	18	31–70	54° 53′ N, 8° 0′ S
HLB2	276	2	*P. sitchensis*	39	301–400	52° 20′ N, 9° 28′ S
HLB3	270	6	*P. sitchensis*	41	141–200	51° 49′ N, 9° 23′ S
HLB4	214	3	*P. sitchensis*	18	31–70	52° 53′ N, 6° 29′ S
HLB5	142	1	*P. contorta*	21	71–140	54° 13′ N, 9° 33′ S
HLB6	286	3	*P. sitchensis*	35	141–200	54° 19′ N, 8° 7′ S
LLB1	75	2	*P. sitchensis*	24	31–70	53° 18′ N, 9° 13′ S
LLB2	56	0	*P. sitchensis*	18	31–70	52° 11′ N, 10° 18′ S
LLB3	56	1	*P. sitchensis*	35	301–400	51° 53′ N, 9° 47′ S
LLB4	121	0	*P. sitchensis*	21	71–140	52° 46′ N, 9° 7′ S
LLB5	50	0	*P. contorta*	25	201–300	53° 44′ N, 9° 49′ S
LLB6	93	1	*P. sitchensis*	45	301–400	53° 19′ N, 6° 51′ S
LLB7	136	3	*P. sitchensis*	20	71–140	54° 11′ N, 9° 35′ S

d.b.h., diameter growth at breast height.

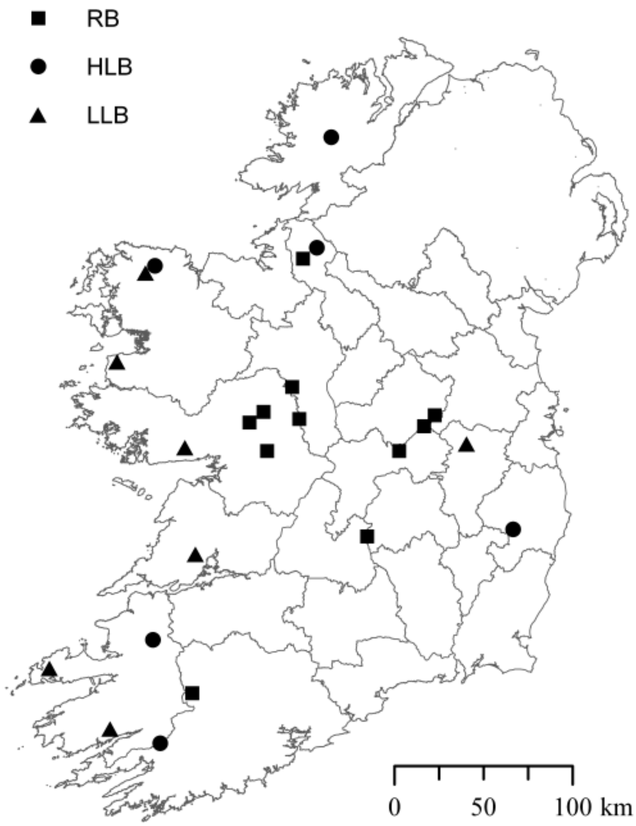

Figure 1. Locations of all 24-peat sites within Ireland arranged by peat type. RB, HLB and LLB.

10 cm west of the first sampling point to avoid the effects of compaction from the previously extracted sample and a third sample (100–150 cm) was taken 10 cm away from the second sampling point, while the fourth (150–200 cm) was from the original sampling point and so on. When the bottom of the peat was reached, indicated by the presence of a mineral layer or the presence of impenetrable rock, the final depth was recorded and the sample taken. If a sample was seen to contain a peat pipe (connected natural conduits that transport water, sediment and solute through soil systems, Holden and Burt, 2002; Holden, 2006) or cavity, its depth was recorded with the sample ID. Each sample was placed into a labelled sealable polythene bag in the field. At sites RB1-5, HLB1-4 and LLB1-5, around each sampling point, four additional points were used to determine the peat depth using the Russian peat corer. Each point was located 50 cm north, south, east or west of the initial sampling point. This was repeated for each of the four random points within the four quadrants of the site.

There were limitations to sampling using the Russian peat corer in the top layer due to the inability of the corer to cut through the roots of the forest floor vegetation, usually most prominent in the top 30 cm. To compensate for this, a random point was chosen within each 10 ×10 m quadrant where a hole was dug and samples were taken using stainless steel bulk density rings (Eijkenkamp Agrisearch Equipment BV, Netherlands) of 8 cm diameter by 5 cm height. Samples were taken with the rings to replace those that the Russian peat corer could not extract reliably. The Russian corer could not reliably sample 0–30 cm, and at each site, we used the rings to sample at depths: 0–5 cm; 5–10 cm; 15–20 cm and 25–30 cm (5 cm gaps were placed between samples after 10 cm to avoid the effects of compaction from previous samples).

To summarize, at each of the 24 sites, we obtained: (1) 16 peat profiles using the Russian peat corer for bulk density and SOC laboratory measurements; (2) 4 surface profiles (typically 0–30 cm) using stainless steel rings for bulk density and SOC and (3) 80 individual estimates of peat depth, using the Russian auger at sites RB1-5, HLB1-4, LLB1-5 and 16 individual estimates of peat depth at sites RB6-11, HLB5-6 and LLB6-7.

All samples were stored at 4°C before being dried at 55°C until a constant dry weight was achieved. The samples were then bulked by volume for each depth within each quadrant. The bulked samples were ground to a fine powder and the SOC (per cent) determined by combustion in a C/N analyzer (Elementar – Vario Max CN). The bulk density of samples were sieved to 2 mm and was determined as the dry mass per fresh volume (grams per cubic centimetre). The bulk density was estimated using equation (1):

$$\rho_d = \frac{M}{SV - CFV}, \quad (1)$$

where ρ_d = bulk density (g cm^{-3}); M = mass of dry sample <2 mm (g); SV = sampler volume (cm^3); CFV = >2 mm coarse fraction volume (cm^3).

The carbon density was estimated using equation (2):

$$C = \rho_d \times SOC \times h \times 100, \quad (2)$$

where C = carbon density (Mg C ha^{-1}); SOC = soil organic carbon concentration (per cent); h = depth of peat ≥ 30 cm.

Statistical analysis

The data for peat SOC was normally distributed and so comparisons between groups were analysed using analysis of variance at $P < 0.05$. The data for peat bulk density, depth and carbon density were not normally distributed, and so comparisons between the different peat types were analysed using the non-parametric Kruskal–Wallis test at $P < 0.05$. Analysis of covariance (ANCOVA) was used to test for significant interaction between depth and peat type when predicting total carbon density. All statistical analysis was carried out using SPSS (SPSS Statistics, Student Version, Release 17.0, 2008; SPSS Inc.).

Results

Bulk density

For the 11RB sites (RB1–RB11), the depth averaged bulk density ranged from 0.101 to 0.198 with a mean of 0.133

and standard deviation of 0.03 g cm^{-3} (Table 2). For the six HLB sites (HLB1–HLB6), the depth averaged bulk density ranged from 0.07 to 0.183 with a mean of 0.118 ± 0.04 g cm^{-3}. For the seven LLB sites (LLB1–LLB7), the depth averaged bulk density ranged from 0.088 to 0.177 with a mean of 0.125 ± 0.03 g cm^{-3}. The bulk density values reported here are within the range of values reported in the literature for non-forested peats. The bulk densities of the raised peat sites are significantly higher than the bulk densities of the low-level blanket peats.

In general, the bulk density for the upper 20 cm is higher than that at lower depths (Figures 2–4). This is most likely due to shrinkage of the upper soil layer resulting from the drainage and water table lowering at the initial afforestation stage. The bulk density of each peat type shows little change with depth with some sites showing a decrease in bulk density with depth, and some sites, e.g. RB8 (Figure 2) showing an increase of bulk density with depth.

A number of sites show an increase in bulk density at the bottom of the peat profile. RB2 (Figure 2) has a bulk density value of 0.133 g cm^{-3} at 175 cm that increases to 0.183 g cm^{-3} at 225 cm. This increase is due to the presence of humic clays and clays at the bottom of the peat profile. The bulk density profiles of Tomlinson and Davidson (2000) and Weiss *et al*. (2002) show similar trends.

Of the 913 samples that were taken for bulk density across sites, RB1–RB5, HLB1–HLB4 and LLB1–LLB5, 12 contained pipes, 3 samples at LLB1, 8 samples at HLB1 and 1 sample at RB2. The bulk density of samples with pipes was 0.07 g cm^{-3} which is significantly lower than the corresponding non-piped samples at 0.11 g cm^{-3} ($P < 0.05$). Although the bulk density of the samples containing pipes is lower than adjacent samples, pipes are found in so few samples they were not significant to the overall mean bulk density of the peats.

SOC concentration (per cent)

The mean carbon contents of the peat was 46.7 ± 5, 48.8 ± 5 and 48.8 ± 2 per cent for RB, HLB and LLB, respectively. There were no significant differences in SOC concentrations between peat types. The presence of humic clays and clays at the lowest depths affected the SOC values, typically with an SOC reduction at the bottom of the peat profile. This is shown in LLB4 (Figure 5), where the SOC drops from 54.1 per cent at 75 cm to 39.6 per cent at 125 cm.

A number of the sites, especially within the HLB and LLB showed the highest carbon contents at mid depth, with lower values near the surface and also at the bottom of the profile (Figure 5). The reduced SOC at the bottom of the peat profile is most likely due to mixing with the underlying mineral material.

Table 2: The mean ± standard deviation (SD), minimum and maximum for peat depth (cm), SOC (%) and bulk density (g cm^{-3}) for each peat site

	Depth (cm)			SOC (%)			Bulk density (g cm^{-3})		
Site	Mean ± SD	Min	Max	Mean ± SD	Min	Max	Mean ± SD	Min	Max
RB1	374 ± 20	335	409	53.6 ± 2	50.4	56.7	0.104 ± 0.01	0.095	0.13
RB2	180 ± 35	75	225	44.1 ± 11	23.9	50.8	0.128 ± 0.03	0.098	0.183
RB3	91 ± 24	42	134	43.5 ± 6	36.5	47.2	0.133 ± 0.02	0.116	0.149
RB4	87 ± 30	33	150	50.5 ± 1	49.1	51.2	0.127 ± 0.02	0.115	0.144
RB5	48 ± 15	30	84	34.6 ± 10	27.3	41.9	0.198 ± 0.001	0.199	0.198
RB6	345 ± 82	300	500	51.6 ± 2	48.0	55.3	0.101 ± 0.01	0.086	0.125
RB7	211 ± 47	115	282	43.8 ± 1	42.2	45.3	0.152 ± 0.04	0.107	0.215
RB8	129 ± 10	105	150	47.4 ± 2	45.0	49.4	0.158 ± 0.02	0.133	0.177
RB9	243 ± 12	226	267	48.5 ± 2	47.4	50.2	0.103 ± 0.02	0.086	0.148
RB10	217 ± 42	131	272	45.0 ± 3	39.6	47.7	0.148 ± 0.03	0.121	0.195
RB11	183 ± 9	164	198	51.1 ± 1	49.9	52.0	0.111 ± 0.02	0.098	0.133
RB	192 ± 100	30	500	46.7 ± 5	23.9	56.7	0.133 ± 0.03	0.086	0.215
HLB1	299 ± 65	105	419	49.8 ± 4	44.1	54.6	0.100 ± 0.01	0.087	0.114
HLB2	73 ± 20	30	100	50.7 ± 3	48.5	52.8	0.129 ± 0.01	0.12	0.139
HLB3	48 ± 14	32	89	48.9 ± 1	48.0	49.8	0.070 ± 0.01	0.065	0.075
HLB4	38 ± 6	30	50	38.3 ± 3	36.3	44.4	0.183 ± 0.03	0.123	0.208
HLB5	311 ± 42	250	375	53.8 ± 2	51.0	55.7	0.085 ± 0.01	0.071	0.109
HLB6	104 ± 21	60	130	51.4 ± 3	48.6	53.9	0.140 ± 0.01	0.126	0.151
HLB	145 ± 130	30	419	48.8 ± 5	36.3	55.7	0.118 ± 0.04	0.065	0.208
LLB1	336 ± 147	108	600	48.4 ± 3	44.3	52.3	0.088 ± 0.01	0.069	0.11
LLB2	113 ± 71	30	225	47.5 ± 2	44.4	49.8	0.122 ± 0.01	0.114	0.126
LLB3	90 ± 40	33	188	50.3 ± 2	48.5	52.2	0.096 ± 0.01	0.091	0.109
LLB4	98 ± 22	63	150	48.4 ± 8	39.6	54.1	0.131 ± 0.03	0.111	0.169
LLB5	36.7 ± 4	31	48	47.9 ± 2	45.4	49.8	0.154 ± 0.03	0.132	0.202
LLB6	60 ± 16	35	85	46.1 ± 4	43.5	48.8	0.177 ± 0.02	0.164	0.19
LLB7	158 ± 11	143	178	53.3 ± 2	50.8	55.4	0.104 ± 0.004	0.098	0.107
LLB	127 ± 100	30	600	48.8 ± 2	39.6	55.4	0.125 ± 0.03	0.069	0.202

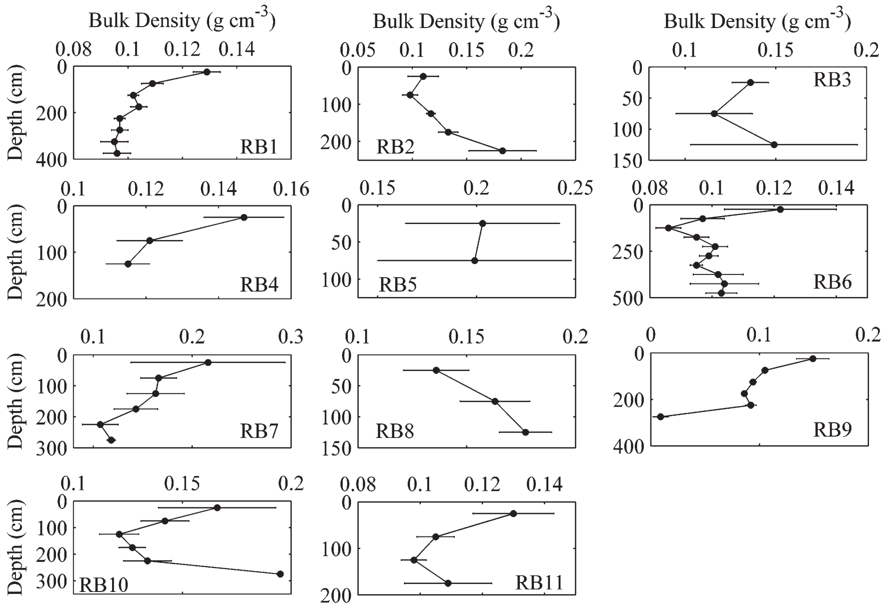

Figure 2. Bulk density (g cm^{-3}) *vs* depth for the 11 afforested RB sites, RB1; RB2; RB3; RB4; RB5; RB6: RB7; RB8; RB9; RB10 and RB11. Error bars indicate standard deviation.

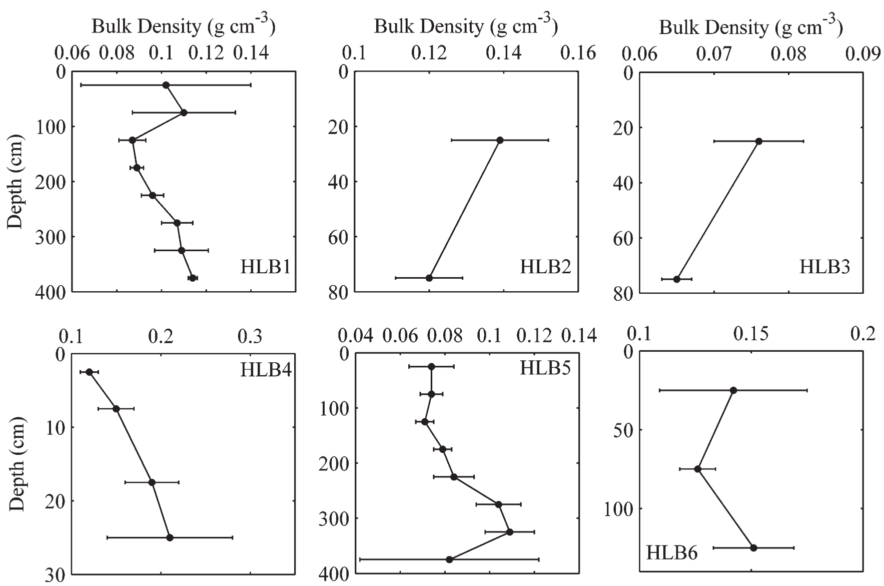

Figure 3. Bulk density (g cm^{-3}) *vs* depth for the six afforested HLB sites, HLB1; HLB2; HLB3; HLB4; HLB5 and HLB6. Error bars indicate standard deviation.

Peat depth

The mean depth varies widely, both within a site and between sites for all peat types (Table 2). For the 11 RB sites (RB1–RB11), the mean depth ranged from 48 to 374 cm with an overall mean depth of 192 ± 100 cm. For the six HLB sites (HLB1–HLB6), the mean depth ranged from 38 to 311 cm with an overall mean depth of 145 ± 130 cm. For the seven LLB sites (LLB1–LLB7), the mean depth ranges from 37 to 336 cm with an overall mean depth of 127 ± 100 cm. The depth of raised peat was significantly greater than either the high level or low level blanket peats ($P < 0.05$).

Carbon density

The carbon densities ranged from 180 Mg C ha^{-1} at site HLB3 (peat depth 48 cm) to 2090 Mg C ha^{-1} at site RB1 (peat depth 374 cm) (Table 3). Due to their greater

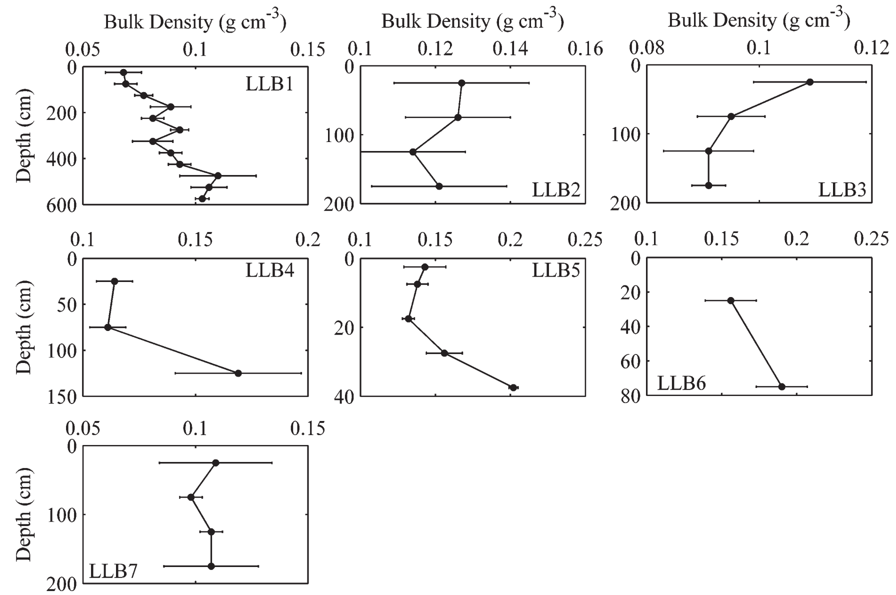

Figure 4. Bulk density (g cm^{-3}) *vs* depth for the seven afforested LLBsites LLB1; LLB2; LLB3; LLB4; LLB5; LLB6 and LLB7. Error bars indicate standard deviation.

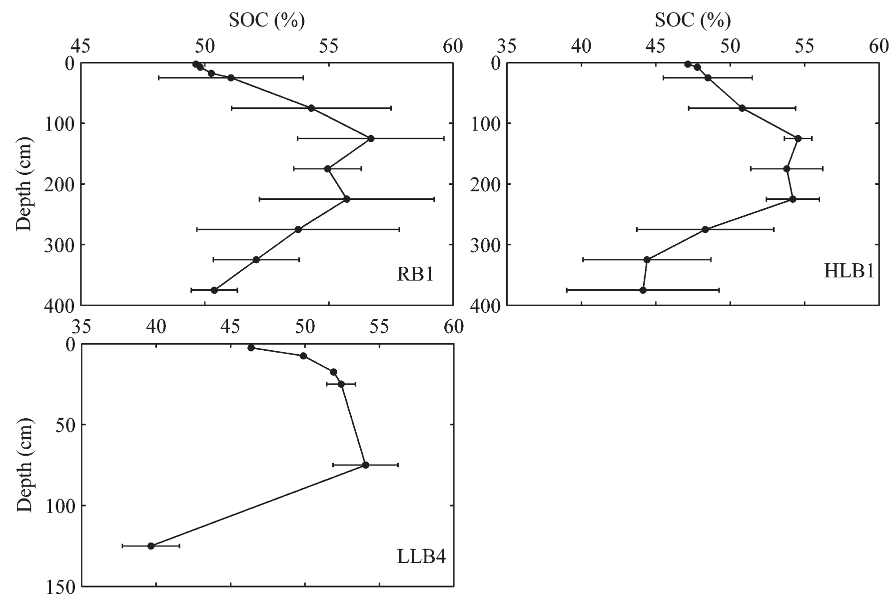

Figure 5. SOC (%) *vs* depth for sites RB1; HLB1 and LLB4. Error bars indicate standard deviation.

depth, RBs had the largest mean total carbon density of 1160 ± 520 Mg C ha^{-1}. The LLBs mean carbon density was 705 ± 420 Mg C ha^{-1}, while the HLBs mean carbon density was 775 ± 590 Mg C ha^{-1}. The total carbon densities of the RB were significantly larger than those of both the HLB and LLB ($P < 0.05$). The depth and peatland type had a significant effect on the carbon density of each site ($P < 0.05$) and were included in the following linear regression models to predict carbon density based on peat depth and peat type. The HLB and LLB were analysed together because of the similarity in total carbon density.

$$\text{RBC} = 4.878h + 228.604 \; R^2 = 0.95 \tag{3}$$

$$\text{BLC} = 4.414h + 138.399 \; R^2 = 0.96, \tag{4}$$

where RBC = raised bog carbon density (Mg C ha^{-1}); BLC = blanket bog carbon density (Mg C ha^{-1}); h = depth of peat ≥ 30 cm.

There was no significant interaction between peat type and depth on the total carbon density using ANCOVA, ($P < 0.05$).

Table 3: The mean ± standard deviation carbon density (Mg C ha^{-1}) of all peat sites down the peat profile

Site	Depth (cm)							Total
	0–50	50–100	100–200	200–300	300–400	400–500	500–600	
RB1	326 ± 15	295 ± 33	575 ± 32	531 ± 30	362 ± 94	–	–	2090 ± 140
RB2	272 ± 34	246 ± 33	559 ± 84	26 ± 50	–	–	–	1100 ± 96
RB3	314 ± 28	181 ± 150	54 ± 64	–	–	–	–	548 ± 200
RB4	358 ± 28	275 ± 110	98 ± 110	–	–	–	–	731 ± 190
RB5	368 ± 60	20 ± 44	–	–	–	–	–	388 ± 74
RB6	304 ± 44	253 ± 38	476 ± 34	547 ± 34	124 ± 160	103 ± 150	–	1800 ± 430
RB7	411 ± 93	376 ± 80	568 ± 140	128 ± 140	–	–	–	1480 ± 330
RB8	331 ± 39	387 ± 75	235 ± 110	–	–	–	–	952 ± 170
RB9	364 ± 44	262 ± 14	446 ± 20	193 ± 41	–	–	–	1270 ± 76
RB10	392 ± 67	339 ± 52	523 ± 110	144 ± 130	–	–	–	1400 ± 220
RB11	323 ± 30	274 ± 30	436 ± 69	–	–	–	–	1030 ± 100
HLB1	257 ± 85	272 ± 100	476 ± 41	480 ± 73	134 ± 120	–	–	1620 ± 250
HLB2	355 ± 47	155 ± 85	–	–	–	–	–	510 ± 100
HLB3	162 ± 22	18 ± 32	–	–	–	–	–	180 ± 49
HLB4	253 ± 73	–	–	–	–	–	–	253 ± 73
HLB5	189 ± 28	196 ± 27	400 ± 34	456 ± 130	119 ± 140	–	–	1360 ± 200
HLB6	383 ± 88	272 ± 72	72 ± 82	–	–	–	–	727 ± 170
LLB1	162 ± 19	175 ± 26	370 ± 60	329 ± 140	251 ± 140	195 ± 160	74 ± 120	1550 ± 640
LLB2	249 ± 54	200 ± 150	233 ± 190	–	–	–	–	682 ± 380
LLB3	263 ± 21	137 ± 100	61 ± 89	–	–	–	–	460 ± 170
LLB4	294 ± 21	265 ± 78	73 ± 94	–	–	–	–	632 ± 130
LLB5	255 ± 7	–	–	–	–	–	–	255 ± 7
LLB6	362 ± 27	106 ± 120	–	–	–	–	–	468 ± 130
LLB7	283 ± 56	273 ± 26	325 ± 54	–	–	–	–	881 ± 92

Discussion

Peat bulk density and SOC concentration

The values for bulk density were within the range reported in the literature for forested and non-forested peatlands. There seemed to be little difference in bulk density between non-forested and afforested peatlands below the 20 cm depth. For the near-surface depth (up to 20 cm), the afforested peatlands seem to be denser, most likely due to compaction and water table lowering caused by drainage, planting and increased evapotranspiration from the trees (Minkkinen *et al.*, 2008).

Tomlinson and Davidson (2000) observed a mean bulk density of 0.069 g cm^{-3} for non-forested RBs in Northern Ireland which is much lower than our mean value of 0.136 g cm^{-3}. Chapman *et al.* (2009) used bulk density values of basin peat at 0.112 g cm^{-3} which is lower than the values reported here. Chapman *et al.* (2009) found bulk density values of blanket peat in Scotland of 0.129 g cm^{-3} which are similar to our value of 0.121 g cm^{-3}. Burke (1978) found a mean bulk density of 0.097 g cm^{-3} for a forested blanket peat site in Ireland to 90 cm depth, which is less than our value of 0.121 g cm^{-3}. However, Shotbolt *et al.* (1998) found a mean bulk density value of 0.13 g cm^{-3} for a forested LLB site in Scotland, a value greater than our value of 0.125 g cm^{-3}. In contrast, Shotbolt *et al.* (1998) found a lower mean of 0.11 g cm^{-3} for an adjacent non-forested LLB site that is similar to the mean values of this study. The bulk densities of the RB sites were statistically greater than that of the LLBs, for the entire profile. It is unclear why this was the case but may have been due to the different processes and plant species which form each peat type.

It is widely noted in the literature that the bulk density of peat increases with depth (possibly attributed to the effect of greater humification over time) (Clymo, 1978; Howard *et al.*, 1994; Milne and Brown, 1997; Cruickshank *et al.*, 1998). However, this was not found in our study. Tomlinson and Davidson (2000) found no increase in non-forested RBs with depth in Northern Ireland. Weiss *et al.* (2002) in a bog in south east Asia, found an initial increase in bulk density in the top 150 cm of peat reflecting the transformation of living matter to poorly decomposed peat and then from 200 cm onwards, the bulk density decreased until it reached the peat/sediment interface at 840 cm. Lewis *et al.* (2011) also found no change with depth in a high level non-forested blanket bog in Glencar, Ireland. The results of Lewis *et al.* (2011) are interesting in that at the centre of the bog (where the water table never fell below 15 cm), the bulk density of 0.055 g cm^{-3} was about half of that of 0.11 g cm^{-3} at the peat margins (a narrow 20-m wide riparian strip near a stream, where the water table was generally below 30 cm) highlighting the spatial variation of bulk density within the peatland. The increase in bulk density with depth due to compression that is often assumed in peat carbon stock modelling may not be accurate and may result in an overestimate of peat carbon stocks, especially deep peats.

The values of SOC reported here are lower than those reported in the literature. Tomlinson and Davidson (2000) found an SOC concentration of 51.1 per cent for non-forested RBs in Northern Ireland. Lewis *et al.* (2011) found a mean SOC of 52.9 per cent for a non-forested pristine LLB. Our findings suggest that there may have been some minor losses in SOC (~3 per cent) in the afforested peatlands, possibly due to loss of CO_2 to the atmosphere as a result of increased aeration due to lowering of the water table in the afforestation process.

The impact of afforestation on the physical properties of peat may be better evaluated by assessing the decomposition of the peat samples as well as the bulk density. Kechavarzi *et al.* (2010) shows that the bulk density of peat increases with increasing decomposition. Analyses of peat decomposition using the von Post scale (von Post, 1924) may explain some of the variation in bulk density with depth.

Peat depth and carbon density

The measurement of peat depth varies widely between nations with some nations, i.e. Finland, having extensively measured peat depth (Virtanen *et al.*, 2003). However, globally and within Ireland, there has been very little measurement (Lindsay, 2010). Tomlinson (2005), in his estimate of soil carbon stocks in Ireland, used mean depths (taken from a number of small databases from the literature and technical reports) of 60 cm and 100 cm for high and low level, man modified (man modified encompasses a couple of land use types, including forested peatlands) blanket bogs which are lower than our results of 145 and 127 cm, respectively. Tomlinson (2005) used a depth of 150 cm for western Ireland RBs and 250 cm for midland Ireland RBs. This contrasted with our findings for western RBs of 172 cm depth for sites RB1, RB2, RB4 and RB5 and 183 cm depth for our midland RBs of sites RB3, RB9, RB10 and RB11. The values presented here represent the first comprehensive field sampling analysis of the carbon density of Irish peat soils. Tomlinson (2005) used carbon densities based on a very small sample size, using a mean of 1290 Mg C ha^{-1} for man-modified RBs, slightly bigger than the 1160 Mg C ha^{-1}, reported here. However, our estimates for the LLB and HLB, 705 and 775 Mg C ha^{-1} were higher than those of Tomlinson (2005) of 585 and 270 Mg C ha^{-1}, respectively.

HLBs are the largest forested peat type, representing 49.9 per cent of the total forested area in Ireland. The published carbon density estimates (Tomlinson, 2005) for forested HLB, at 270 Mg C ha^{-1} is much lower than our value of 772.2 Mg C ha^{-1}. Tomlinson (2005) estimated that the effect of human activities on peatlands would see a depth decrease of 66 per cent for RB and LLB and 50 per cent for the HLBs. The differences between our values and the estimates of Tomlinson (2005) suggest that to improve future peatland carbon stock estimates, afforested peat carbon stocks should be calculated separately from non-forested peatlands. By incorporating the carbon stock estimates of this study with the forest cover area from NFI (2007a) and using updated peatland maps from Connolly *et al.* (2007), the estimates of peatland carbon stocks will be much improved. Peat depth is a key property of the afforested peat carbon stocks for each peatland type (Figure 6). Depth is the simplest and quickest property to measure (but also shows large spatial variation) and the estimates based on equations (3) and (4) will allow for a much quicker assessment of peat carbon stock. However, much fieldwork is required to get a more detailed picture of the spatial variation of peat depth as we know from Lewis *et al.* (2011) that there is significant spatial variability within a few metres of the same peatland.

Equations 3 and 4 are unlikely to be appropriate for non-forested peatlands and boreal forested peatlands, where most of the global forested peatland is situated due to lower values of bulk densities found at these sites (Minkkinen and Laine, 1998; Minkkinen *et al.*, 1999; Tomlinson and Davidson, 2000; Anderson, 2002; Lewis *et al.*, 2011). Equations 3 and 4 could be used as an estimate of carbon density for other afforested peatlands in Ireland and Britain due to the similar peat types and climate. However, care must be taken in using them as in these sites, we only measured a small plot (20 ×20 m) of each forest stand and do not measure the variation within the larger peatland which would require measurements over hundreds of metres. The methodology may be used to create similar equations for other forested and non-forested peatland in other nations.

The depth and carbon density of the RBs were significantly larger than both the HLB and LLB sites as expected. For future estimates of peat carbon stocks and accounting purposes, raised and blanket bogs should be sampled and reported separately. The linear equations and carbon densities of the high and low level blanket peats are similar with 775 and 705 Mg C ha^{-1}, respectively. The HLB and LLB can be considered as the same peatland type due to similar peat carbon densities and analysed simply as blanket bogs in future work.

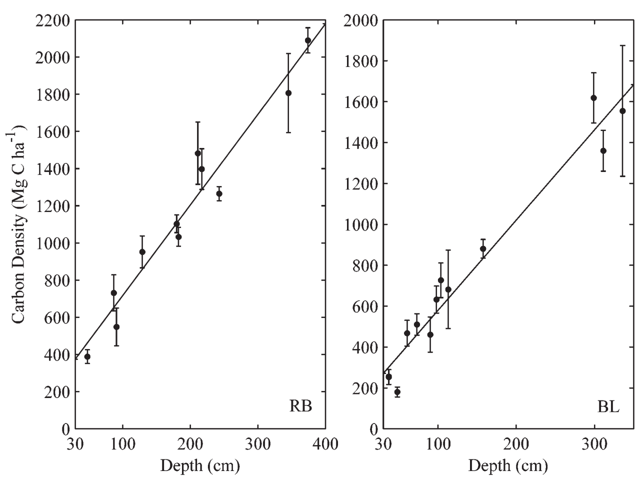

Figure 6. The total carbon density (Mg C ha^{-1}) of each peat type, RB and blanket bog (BL) (high level and low level) *vs* depth (cm). The regression equations (3) and (4) are presented for the RBs and BLs, respectively. Error bars indicate standard deviation.

The data presented in this study can be used to improve estimates of afforested peatland carbon stocks.

Conclusions

We present the depths, bulk densities SOC concentrations and carbon densities of 24 Irish afforested peatlands.

The view of peat bulk density increasing with depth is not supported by our work as each peatland type showed little change down the profile, with individual sites showing different trends. There was an increased bulk density and lower SOC in the top 20 cm of the peat, possibly due to the lowering of the water table and the subsequent increased aeration of the peat due to drainage preparations and afforestation.

The depths of peat and thus the carbon stocks of forested peatland were underestimated for Ireland in Tomlinson (2005), especially for blanket bogs where we found depths of 145 and 127 cm for high level and low level compared with Tomlinsons (2005) values of 60 and 100 cm. HLB represents 49.9 per cent of the total Irish forested peatland area; therefore, any underestimate of the carbon stocks represents a significant underestimate of the carbon stocks of the entire national forest area. The underestimate of the forested peat carbon stocks also shows that in future estimates of soil carbon stocks, forested peatlands should be analysed separately from other non-forested peatlands. The similar values of carbon density show that afforested HLB and LLB can be grouped together and analysed simply as blanket bogs. The depth and carbon densities of RB sites are significantly larger than those of the blanket bogs, and so further analysis of peat carbon stocks should focus on both the raised and blanket bogs.

The linear regression equations of carbon density with depth and peat type are simple first estimates of carbon stocks of afforested peatlands for Ireland and Britain. The linear regression equations require knowledge only of the peat type and the peat depth to estimate carbon density. The methodology presented here can be used to create similar linear regression equations for non-forested peatlands. It is important that when modelling the carbon stocks of peatlands, there should be a greater analysis of the physical properties of all peat types, especially depth, to improve the reliability of the estimates.

Funding

This work was supported by two projects 'Soil Carbon Stock Changes and Greenhouse Gas Flux in Irish Forests (ForestC)' and 'Carbon sequestration by Irish forest ecosystems (CARBiFOR II)' contributed to this study. Both are funded by the Irish Council for Forest Research and Development as part of the Department of Agriculture Fisheries and Food.

Acknowledgements

We thank Hadrien Robin, Gaelle Treut, Sylvia Dolan and Rachel Wisdom for their help with the field sampling and the laboratory analysis.

Conflict of interest statement

None declared.

References

Anderson, D. 2002 Carbon accumulation and C/N ratios of peat bogs in North-West Scotland. *Scott. Geogr. J.* **118**, 323–341.

Anderson, R., Pyatt, D., Sayers, J., Blackhall, S. and Robinson, H. 1992 Volume and mass budgets of blanket peat in the north of Scotland. *Suo*. **43**, 195–198.

Black, K., Byrne, K.A., Mencuccini, M., Tobin, B., Nieuwenhuis, M., Reidy, B. *et al.* 2009 Carbon stock and stock changes across a Sitka spruce chronosequence on surface-water gley soils. *Forestry*. **82**, 255–272.

Braekke, F. and Finér, L. 1991 Fertilization effects on surface peat of pine bogs. *Scand. J. For. Res.* **6**, 443–449.

Bridgham, S., Richardson, C., Maltby, E. and Faulkner, S. 1991 Cellulose decay in natural and disturbed peatlands in North-Carolina. *J. Environ. Qual.* **20**, 695–701.

Burke, W. 1978 Long-term effects of drainage and land use on some physical properties of blanket peat. *Ir. J. Agric. Res.* **17**, 315–322.

Burnham, J. and Sletten, R. 2010 Spatial distribution of soil organic carbon in northwest Greenland and underestimates of high Arctic carbon stores. *Glob. Biogeochem. Cycles* **24**, GB3012. doi:10.1029/2009GB003660.

Byrne, K.A. and Milne, R. 2006 Carbon stocks and sequestration in plantation forests in the Republic of Ireland. *Forestry*. **79**, 361–369.

Byrne, K.A. and Farrell, E.P. 2005 The effect of afforestation on soil carbon dioxide emissions in blanket peatland in Ireland. *Forestry*. **78**, 217–227.

Chapman, S., Bell, J., Donnelly, D. and Lilly, A. 2009 Carbon stocks in Scottish peatlands. *Soil Use Manage*. **25**, 105–112.

Chmielewski, K. 1991 The effect of habitat conditions on microbiological activity of peat soils. *Pol. Ecol. Stud.* **17**, 143–153.

Clymo, R. 1978 A model of peat bog growth. In *Production Ecology of British Moors and Montane Grasslands*. O.W. Heal and D.F. Perkins (eds). Springer, Berlin, Germany pp. 187–223.

Connolly, J., Holden, N. and Ward, S. 2007 Mapping peatlands in Ireland using a rule-based methodology and digital data. *Soil Sci. Soc. Am. J.* **71**, 492–499.

Cruickshank, M., Tomlinson, R., Devine, P. and Milne, R. 1998 Carbon in the vegetation and soils of Northern Ireland. *Biol. Environ-Proceedings of the Royal Irish Academy*. **98B**, 9–21.

Department of Agriculture. 1996 *Growing for the Future – A Strategic Plan for the Development of the Forestry Sector in Ireland*. Department of Agriculture, Food and Forestry, The Stationery Office, Dublin, Ireland.

Eaton, J.M., McGoff, N.M., Byrne, K.A., Leahy, P. and Kiely, G. 2008 Land cover change and soil organic carbon stocks in the Republic of Ireland 1851–2000. *Clim Change*. **91**, 317–334.

Fay, D., McGrath, D., Zhang, C., Carrigg, C., O'Flaherty, V., Kramers, G. *et al.* 2007 *Towards A National Soil Database (2001-CD/S2-M2) Synthesis Report*. http://www.epa.ie/downloads/pubs/research/land. EPA, Johnstown Castle, Wexford, Ireland.

Foss, P., O'Connell, C. and Crushell, P. 2001 *Bogs and Fens of Ireland Conservation Plan 2005*. Irish Peatland Conservation Council, Dublin, Ireland.

Gardiner, M. and Radford, T. 1980 *Soil associations of Ireland and their land use potential. Explanatory Bulletin to Soil Map of Ireland. Soil survey bulletin no 36*. An Foras Talu'ntais, Dublin, Ireland.

Hammond, R. 1981 *The Peatlands of Ireland*. An Foras Talu'ntais, Dublin, Ireland.

Holden, J. 2006 Sediment and particulate carbon removal by pipe erosion increase over time in blanket peatlands as a consequence of land drainage. *J. Geophys. Res.* **111**, F02010.

Holden, J. and Burt, T.P. 2002 Piping and pipeflow in a deep peat catchment. *CATENA*. **48**, 163–199.

Holden, J., Burt, T.P. and Vilas, M. 2002 Application of ground-penetrating radar to the identification of subsurface piping in blanket peat. *Earth Surf. Processes Landforms*. **27**, 235–249.

Howard, P., Loveland, P., Bradley, R., Dry, F., Howard, D. and Howard, D. 1994 The carbon content of soil and its geographical distribution in Great Britain. *Soil Use Manage*. **11**, 9–15.

IPCC. 2007 The physical science basis, Contribution of working group I to the fourth assessment report of the intergovernmental panel on climate change. In S. Solomon, D. Qin, M. Manning, Z. Chen, M. arquis, K.B. Averyt *et al.* (eds). Cambridge University Press, Cambridge, pp. 996. http://www.ipcc.ch/ipccreports/ar4-wg1.htm.

Kechavarzi, C., Dawson, Q. and Leeds-Harrison, P. 2010 Physical properties of low-lying agricultural peat soils in England. *Geoderma*. **154**, 196–202.

Kiely, G., McGoff, N., Eaton, J., Leahy, P., Xu, X. and Carton, O. 2010 *SoilC – Measuring and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils*. EPA report Strive No. 35. EPA, Dublin, Ireland. ISBN: 978-1-84995-320-6.

Koehler, A., Sottocornola, M. and Kiely, G. 2010 How strong is the current carbon sequestration of an Atlantic blanket bog? *Glob. Change Biol.* **17**, 309–319.

Lewis, C., Albertson, J., Xu, X. and Kiely, G. 2011 Spatial variability of hydraulic conductivity and bulk density along a blanket peatland hillslope. *Ecohydrology*. Unpublished.

Lieffers, V. 1988 Sphagnum and Cellulose Decomposition in Drained and Natural Areas of an Alberta Peatland. *Can. J. Soil Sci.* **68**, 755–761.

Limpens, J., Berendse, F., Blodau, C., Canadell, J.G., Freeman, C., Holden, J. *et al.* 2008 Peatlands and the carbon cycle: from local processes to global implications – a synthesis. *Biogeosciences*. **5**, 1475–1491.

Lindsay, R. 2010 *Peatbogs and Carbon: A Critical Synthesis to Inform Policy Development in Oceanic Peat Bog Conservation and Restoration in the Context of Climate Change*. RSPB, Scotland.

Milne, R. and Brown, T.A. 1997 Carbon in the vegetation and soils of Great Britain. *J. Environ. Manage.* **49**, 413–433.

Minkkinen, K., Byrne, K.A. and Trettin, C. 2008 Climate impacts of peatland forestry. In *Peatlands and Climate Change*. M. Strack (ed). International Peat Society and Saarijärven Offset Oy, Saarijärvi, Finland, pp. 98–122.

Minkkinen, K. and Laine, J. 1998 Long-term effect of forest drainage on the peat carbon stores of pine mires in Finland. *Can. J. For. Res.* **28**, 1267–1275.

Minkkinen, K., Vasander, H., Jauhiainen, S., Karsisto, M. and Laine, J. 1999 Post-drainage changes in vegetation composition and carbon balance in Lakkasuo mire, Central Finland. *Plant Soil*. **207**, 107–120.

NFI. 2007a *National Forest Inventory – Republic of Ireland – Results*. Forest Service, Department of Agriculture, Fisheries and Food, Johnstown Castle Estate, Co Wexford, Ireland.

NFI. 2007b *National Forest Inventory – Republic of Ireland – Methodology*. Forest Service, Department of Agriculture, Fisheries and Food, Johnstown Castle Estate, Co Wexford, Ireland.

Pilcher, J.R. and Mac an tSaoir, S. 1995 *Wood, Trees Forests in Ireland. Royal Irish Academy*. Dublin, Ireland.

Renou, F. and Farrell, E.P. 2005 Reclaiming peatlands for forestry: the Irish experience. In *Restoration of Boreal and Temperate Forests*. J.A. Stanturf and P.A. Madsen (eds). CRC Press, Boca Raton, FL, pp. 541–557.

Reynolds, B. 2007 Implications of changing from grazed or semi-natural vegetation to forestry for carbon stores and fluxes in upland organo-mineral soils in the UK. *Hydrol. Earth Syst. Sci.* **11**, 61–76.

Rosa, E., Larocque, M., Pellerin, S., Gagné, S. and Fournier, B. 2009 Determining the number of manual measurements required to improve peat thickness estimations by ground penetrating radar. *Earth Surf. Process. Landforms*. **34**, 377–383.

Sakovets, V. and Germanova, N. 1992 Changes in the carbon balance of forested mires due to drainage. *Suo*. **43**, 249–252.

Shotbolt, L., Anderson, A.R. and Townend, J. 1998 Changes to blanket bog adjoining forest plots at Bad a' Cheo, Rumster Forest, Caithness. *Forestry*. **71**, 311–324.

Sottocornola, M. and Kiely, G. 2010 Hydro-meteorological controls on the CO_2 exchange variation in an Irish blanket bog. *Agric. For. Meteorol.* **150**, 287–297.

Sottocornola, M., Laine, A., Kiely, G., Byrne, K. and Tuitilla, E.S. 2009 Vegetation and environmental variation in an Atlantic blanket bog in South-western Ireland. *Plant Ecol.* **203**, 69–81.

Tomlinson, R. 2005 Soil carbon stocks and changes in the Republic of Ireland. *J. Environ. Manage.* **76**, 77–93.

Tomlinson, R. and Davidson, L. 2000 Estimates of carbon stores in four Northern Irish lowland raised bogs. *Suo*. **51**, 169–179.

Turunen, J., Tomppo, E., Tolonen, K. and Reinikainen, A. 2002 Estimating carbon accumulation rates of undrained mires in Finland–application to boreal and subarctic regions. *Holocene*. **12**, 69–80.

Vasander, H. and Kettunen, A. 2006 Carbon in boreal peatlands. In *Boreal Peatland Ecosystems. Ecological Studies 188*. R.K. Wieder and D.H. Vitt (eds). Springer-Verlag, Heidelberg, Germany, pp. 165–194.

Virtanen, K., Hänninen, P., Kallinen, R.-L., Vartiainen, S., Herranen, T. and Jokisaari, R. 2003 *Suomen turvevarat 2000. Summary: The Peat Reserves of Finland in 2000*. Geologic Survey of Finland, Report of Investigation 156. Espoo, Finland.

von Post, L. 1924 Das genetische System der organogenen Bildungen Schwedens. In *Comité International de Pédologie, IVème commission (commission pour la nomenclature et la classification des sols, commission pour l'Europe, président: B. Frosterus)* (ed) Mémoires sur la Nomenclature et la Classification des Sols, Helsingfors/Helsinki, Finland, pp. 287–304.

Weiss, D., Shotyk, W., Rieley, J., Page, S., Gloor, M., Reese, S. *et al.* 2002 The geochemistry of major and selected trace elements in a forested peat bog, Kalimantan, SE Asia, and its implications for past atmospheric dust deposition. *Geochim. Cosmochim. Acta*. **66**, 2307–2323.

Received 20 January 2011