The need to disaggregate podzols and peaty podzols when assessing forest soil carbon stocks

Michael A. Clancy[a], A. Jonay Jovani Sancho[a],
Thomas Cummins[b] and Kenneth A. Byrne[a*]

Abstract

Inventories of forest soil carbon (C) stocks are necessary to determine spatial and temporal C stock changes and support climate change mitigation policy development. Afforested podzols and peaty podzols were sampled to measure bulk density (BD) and soil organic carbon (SOC) content with the aim of improving baseline soil C stock estimates for Irish forests. Podzols are not always distinguished from peaty podzols and both qualify as mineral soil types. Distinct differences in mean BD, SOC % and soil C stock values were found between sites with podzols and peaty podzols across the four depths sampled, i.e., 0-10, 10-20, 20-30, 30-40 cm. The estimated soil C stocks for the podzol sites ranged from 129-139 Mg C ha^{-1}, while the peaty podzols had 229-385 Mg C ha^{-1}. The major disparity in the soil C stocks implies the need to disaggregate podzols and peaty podzols in conducting soil C inventories, with the need for development of carbon emission factors for peaty podzols to reduce uncertainty in soil C stock estimates.

Keywords: *Afforestation, soil organic carbon, bulk density, carbon emission factor.*

Introduction

Regional and national scale soil carbon (C) inventories are required to understand soil C dynamics and support climate change mitigation policy development (IPCC 2006, Ogle et al. 2010, Mishra et al. 2012). Sampling of a population involves taking measurements from a select subset of individuals to estimate the properties or parameters of the total population (Pennock et al. 2006). Stratified sampling (Heim et al. 2009), e.g. by soil group (e.g. peat soils, gleys, podzols) and tree species, can be used to reduce the soil organic carbon (SOC) sampling effort. Generally, precision of estimated regional or national SOC inventory values (Mg C ha^{-1}) is increased (i.e. smaller confidence ranges) with increased sampling (IPCC 2006).

Differences in definition and carbon assessment of organic and mineral soils

The Intergovernmental Panel on Climate Change (IPCC) and the Food and Agriculture Organisation (FAO) use similar criteria to distinguish between organic and mineral soils. Organic soils are also known as peatland, bog, muck soils (IPCC 2014). The IPCC mostly use the following FAO guidelines for defining organic soils, but allow

---

[a] Department of Life Sciences, University of Limerick, Limerick.
[b] UCD School of Agriculture and Food Science, University College Dublin, Dublin.
[*] Corresponding author: ken.byrne@ul.ie

greater autonomy based on country-specific historical definitions of organic soils (IPCC 2014):

i) have a minimum thickness of 10 cm where overlying rock or ice;

ii) contain at least 12% organic C (~20% soil organic matter (SOM) by weight) for 0-20 cm soil depth where the organic layer is <20 cm deep;

iii) hold >20% SOC (~35% SOM) for normally unsaturated soils; and

iv) have between 12-18% SOC with clay content varying between 0–60% (IPCC, 2014).

In contrast, most European definitions of organic soils stipulate >30% (dry mass) of SOM in layers ≥40 cm deep (Joosten and Clarke 2002, Couwenberg 2009).

The Irish Environmental Protection Agency (EPA) defines organic soils as having >20% SOC and depth >30 cm (Duffy et al. 2014). Teagasc, the Irish Agriculture and Food Development Authority, use a depth >40 cm and sub-divide organic soils with <50% SOC into sandy, loamy and peaty organic soils based on the percentage of clay and sand found (Simo et al. 2008). Northern hemisphere organic soils cover around 3% of the global land area, hold approximately one third of global SOC stocks (Gorham 1991, Turunen et al. 2002) and between 53%-62% of Irish soil's SOC (Tomlinson 2005, Eaton et al. 2008). These C rich soils occupy around 14-17% of Ireland's land area (Connolly et al. 2007, Hammond 1981) and have C stock values for their total estimated depth ranging from as low as 240 Mg C ha^{-1} for lowland blanket peats to as high as 3,070 Mg C ha^{-1} in lowland raised bogs (Tomlinson 2005). Due to their large C stock values, use of soil sampling techniques to measure relatively small changes in C stock can be adversely affected by a low signal-to-noise ratio (Baker and Griffis 2005). Therefore the C flux of organic soils is often assessed via eddy-covariance or chamber based monitoring systems from which emission inventories for carbon dioxide (CO_2) or other greenhouse gas (GHG) fluxes are derived (Alm et al. 2007, Couwenberg 2009). The measured GHG emission quantities together with activity statistics, e.g. land area and afforestation or deforestation rates form the basis of emission factors (EF's) for a studied source/GHG combination (Duffy et al. 2014). An EF of 2.6 t CO_2 ha^{-1} yr^{-1} is reported for forests on drained organic soils in temperate climate/vegetation zones (IPCC 2014), though the EPA (Duffy et al. 2014) use a much lower value based on data from Byrne and Farrell (2005) of 0.58 t CO_2 ha^{-1} yr^{-1}. The EPA also use the same soil EF as above for peaty mineral soils but adjust the EF based on the depth (cm) of the peaty layer.

Alternatively, mineral soils are defined by the EPA as having <20% SOC to a maximum depth of 30 cm and generally have much lower C stocks. For example the top 30 cm (excluding the litter and fine woody debris components) of Irish forested brown earths and gleys have estimated C stocks ranging from 42 Mg C ha^{-1} to 167 Mg C ha^{-1} respectively (Wellock et al. 2011). Tomlinson (2005) also reported Irish mineral soil C stocks ranging from 137 Mg C ha^{-1} to 343 Mg C ha^{-1} for grey-brown podzolics and podzols, respectively. Smith et al. (2006) used a cut-off point of 200 Mg C ha^{-1} to differentiate between organic and mineral soils in parameterising the Rothamsted Carbon Model (RothC; Coleman and Jenkinson 1996). Estimation of C stocks in mineral soils, to a specified depth, is typically done via stratified sampling of SOC content (%), bulk density (BD) (g cm^{-3}) and coarse fragments (such as stones and roots) mass and volume (Olsson et al. 2009, Wellock et al. 2011) Forest soil sampling methodologies for national SOC inventories vary. They include repeat standardised sampling of stock changes, which is rare (Ortiz et al. 2011): paired plots, e.g. forested and non-forested sites on similar soils (Wellock et al. 2011, Lawrence et al. 2013): and chronosequence-based studies (Reidy and Bolger 2013). These methodologies are designed to measure the net effect that temporal and spatial variables, along with climate differences and land management, have on soil C stocks within a site, region or country at a point in time. They are also intended to help forecast the impact of future land-use change (Turner and Lambert, 2000, Scott et al. 2002).

While soils are generally classified as organic or mineral soils, there is also an intermediate group of soils in the continuum (Duffy et al. 2014) of the above mentioned SOC stock ranges. These soils are listed variously in the literature as peaty, peat-topped, humus-mineral or organo-mineral soils (Duffy et al. 2014, Montanarella et al. 2006, Smith et al. 2007). These peaty mineral soils, which the EPA classify as having an organic surface layer <30 cm deep, account for over 21,000 ha of the Irish forest estate (~14%, excluding open areas) (Duffy et al. 2014). They are not as well accounted for when it comes to C stock values and sampling methodology best practice, partially due to the significant site-level spatial variability of surface organic layer thickness (Kiely et al. 2009). In their study of Irish SOC dynamics over the years 1851–2000, Eaton et al. (2008) highlighted the differences between Irish forested mineral and peat soils and the blurred distinction of soil types presented by peaty soils. They also noted that because of the prevalence of peaty soils, such as peaty podzols, Ireland's forest soils run counter to the global trends found in the study done by Guo and Gifford (2002) in that they contain greater C stocks than grasslands. They therefore warranted a focus on further disaggregation of soil classification beyond just mineral and peat soils.

Podzols and peaty podzols

The term podzol comes from the Russian words *pod* and *zola* meaning under and ash, respectively (IUSS 2014). Podzols are primarily conditioned by percolating rainwater in a temperate climate and have soil horizon profiles heavily influenced by iron (Fe) and/or aluminium (Al) chemistry (FAO 2001). In Ireland, podzols occupy an estimated 559,600 ha (8%) of the land area (Gardiner and Radford 1980, Tomlinson 2005), account for 10% of the forest estate (NFI 2013) and are most often located in hilly and mountainous areas at elevations 150 m above mean sea level (AMSL) where rainfall plays a significant part in their development (Finch and Ryan 1966). Due to their topographical location and associated issues of accessibility they are generally found under natural or semi-natural vegetation and their land-use has often been confined to rough grazing or coniferous forest plantations (Finch and Ryan 1966).

The recently developed Irish Soil Information System (SIS) identifies and describes Irish soil types. It uses soils data and a unique blend of current and traditional methods to produce a new Irish soil classification system (Creamer et al. 2014). In the Irish SIS, soil types are identified primarily by 11 soil "Great Groups", one of which is the podzol group of mineral soils. The Podzol Great Group in turn contains subgroups, e.g. "typical podzol" or "humic podzol", which further classifies together soils that share similar characteristics, which is a necessary aid to understanding the complexity of Ireland's heterogeneous soils (Creamer et al. 2014). Within the Irish SIS typical- and humic-podzol subgroups there are several soils described which have a surface peaty horizon (<40 cm-thick), underlying less decomposed organic horizons and overlying mineral horizons (Creamer et al. 2014). To keep the focus on their SOC content (%), this study uses the term "peaty podzol" when discussing these soils. They are found predominantly in mountain and hill terrain in Ireland (Gardiner and Radford 1980) and often at elevations just below upland blanket peat.

Soil C stocks in forest plantations have been a central theme of forest research in recent decades (Byrne et al. 2015). This has addressed a range of issues such as modelling the effects of land use management, changes on the SOC pool (Black et al. 2014) and estimating C stocks in Sitka spruce (*Picea sitchensis* (Bong.) Carr.) plantations (Reidy and Bolger 2013). In addition, several studies have assessed the C stock in prominent Irish forest soil types, e.g. peat soils and gleys (Tomlinson 2005, Byrne and Milne 2006, Black et al. 2009, Wellock et al. 2011). The objectives of this study were to measure BD and SOC content in afforested podzols with the aim of improving baseline mineral soil C stock estimates for Irish forests. As a result of sampling these soils, the need to disaggregate podzols (see Figure 1) and peaty podzols and the respective methodologies employed when undertaking soil C inventories of them needs to be discussed.

Methods and materials

The study sites were selected from the Irish National Forest Inventory (NFI) population of 1,827 sites, which were systematically surveyed between 2010 and 2012 (NFI 2013). The 188 sites in the NFI with a "Group Soil" classification of podzol had a sub-classification, i.e. "Principle Soil", of either podzol (37%) or peaty podzol (63%). All sites chosen for sampling were first rotation Sitka spruce stands, greater than 20 years old with a soil depth >40 cm all located in the Munster region. Following inspection of 12 sites to confirm the presence of podzol characteristics seven sites, three podzols and four peaty podzols (which approximately reflected the NFI "Principle Soil" percentage split) were selected for soil sampling (Table 1). During the site inspections four of the NFI sites were deemed unsuitable due to clear-felling, fire damage, or the presence of a dense understorey of *Rhododendron* and alternate sites were found in the general vicinity which met the selection criteria. The stand age of the alternate sites was provided by Coillte based on Global Positioning System (GPS) coordinates. The sampled sites were located in mountain or hill topographies (between latitude 52° 2' and 52° 48' N and longitude 7° 54' and 8° 51' W) at elevations between 145 and 388 m AMSL.

The soil BD and SOC% was measured starting just below the loose litter layer (L horizon) in 10 cm increments, including F, H, O organic and mineral horizons down to 40 cm, which is in line with the Teagasc test depth for organic versus mineral soils (Creamer et al. 2014). Soil augering was carried out at each site to confirm the presence of podzol soil profiles. At each site a pit of approximately 1.0 × 0.8 m was excavated to a depth of at least 40 cm. Bulk density samples were taken from three of the four pit faces using stainless steel rings with a volume of 100 cm^3 (Eijkelkamp Agrisearch Equipment BV, Netherlands). Four BD samples were taken from the centre of each 10 cm increment below the loose litter layer to 40 cm depth, giving three samples

Table 1: *General features of the podzol and peaty podzol study sites.*

Site name	**NFI / Altrn.**[a]	**Plantation age** (years)	**Elevation** (m)	**Slope** (°)	**Podzol / peaty podzol**	**Irish SIS soil type**	**Organic horizon depth** (cm)
Vee Gap	Altrn.	19	174	18	Podzol	Typical-Podzol	7
Boggeragh	NFI	21	296	15	Podzol	Typical-Podzol	7
Skeheen	Altrn.	26	294	9	Podzol	Typical-Podzol	5
Devil's Bit	Altrn.	23	339	20	Peaty podzol	Typical-Podzol	10
Glenanair	Altrn.	33	248	11	Peaty podzol	Humic-Podzol	16
Anglesborough	NFI	40	451	26	Peaty podzol	Typical-Podzol	13
Keale	NFI	44	263	11	Peaty podzol	Humic-Podzol	10

[a] Altrn: Alternative site because NFI site could not be used.

for each depth from each pit. At two points, 25 and 50 cm from the centre of each of the four pit sides, soil samples were taken to 40 cm depth using a Dutch soil auger (Eijkelkamp Agrisearch Equipment BV, Netherlands). At each site the soil profile horizons were identified using the Irish SIS horizon definitions (Simo et al. 2014), their depth and thickness measured and the stone and root size and abundance was estimated (Tables 2 and 3). At two sites, Vee Gap and Glenanair, adjacent road cuttings allowed exploration of the soil profile below 40 cm.

In the laboratory all soil samples were air dried at room-temperature for at least one week before being oven dried for 24 hours at 105 °C. The dried soil BD samples were weighed and their mass (to ±0.01 g) recorded. The samples where then broken up manually and any visible coarse fragments (i.e. >2 mm)

Table 2: *Soil profile description for podzol sampling sites.*

Site / Horizon	Thickness (cm)	Rock abundance[a] (Code: %)	Rock size class[b] (Code: mm)	Root abundance[a] (Code)	Root size class[c] (Code: mm)
Vee Gap					
L	4-0	N: 0		N	
F	0-3	V: 0-2	F: 2-6	M	FM: 0.5-5
H	3-7	F: 2-5	FM: 2-20	M	MC: 2->5
Ah	7-13	F: 2-5	FM: 2-20	M	MC: 2->5
E	13-70	C: 5-15	CS: 20-200	V	F: 0.5-2
Bf	70-72	N: 0		N	
Bs	72+	C: 5-15	CS: 20-200	N	
Boggeragh					
L	2-0	N: 0		N	
F	0-4	V: 0-2	FM: 2-20	C	MC: 2->5
H	4-7	V: 0-2	FM: 2-20	C	MC: 2->5
Ah	7-14	V: 0-2	FM: 2-20	M	FM: 0.5-5
EA	14-23	V: 0-2	C: 20-60	F	FM: 0.5-5
EB	23+	C: 5-15	CS: 20-200	V	F: 0.5-2
Skeheen					
L	3-0	N: 0		N	
F	0-3	V: 0-2	FM: 2-20	M	FM: 0.5-5
H	3-5	V: 0-2	FM: 2-20	M	FM: 0.5-5
Ah	5-9	V: 0-2	FM: 2-20	C	FM: 0.5-5
AE	9-22	C: 5-15	CS: 20-200	F	F: 0.5-2
Bs	22+	C: 5-15	CS: 20-200	N	

[a] Rock/root abundance codes: N: None, V: Very Few, F: Few, C: Common, M: Many.
[b] Rock size class codes and combinations: F: Fine gravel, M: Medium gravel, C: Coarse gravel, S: Stones, FM: Fine and medium gravel, CS: Coarse gravel and stones.
[c] Root size class codes: F: Fine, FM: Fine and medium, MC: Medium and coarse.
([a,b,c] Source: FAO 2006.)

Table 3: *Soil profile description for peaty podzol sampling sites.*

Site / Horizon	Thickness (cm)	Rock abundance[a] (Code: %)	Rock size class[b] (Code: mm)	Root abundance (Code)	Root size class[c] (Code: mm)
Devil's Bit					
L	2-0	N: 0		N	
F	0-3	V: 0-2	FM: 2-20	F	M: 2-5
Oh	3-10	V: 0-2	FM: 2-20	V	FM: 0.5-5
Ah	10-14	F: 2-5	FM: 2-20	F	M: 2-5
E/B	14-30	C: 5-15	C: 20-60	F	M: 2-5
Bs	30+	M: 15-40	CS: 20-200	F	M: 2-5
Glenanair					
L	4-0	N: 0		N	
F	0-4	V: 0-2	FM: 2-20	M	FM: 0.5-5
Oh	4-16	V: 0-2	FM: 2-20	M	FM: 0.5-5
Ah	16-23	V: 0-2	FM: 2-20	C	F: 0.5-2
E/A	23-50	F: 2-5	FM: 2-20	V	FM: 0.5-5
Bh	50-55	V: 0-2	FM: 2-20	V	F: 0.5-2
Bs	55-70	C: 5-15	C: 20-60	N	
C	70+	M: 15-40	CS: 20-200	N	
Anglesborough					
L	4-0	N: 0		N	
F	0-4	V: 0-2	FM: 2-20	C	FM: 0.5-5
Oh	4-13	V: 0-2	FM: 2-20	C	F: 0.5-2
A/E	13-26	M: 15-40	CS: 20-200	V	F: 0.5-2
Bs	26+	M: 15-40	CS: 20-200	V	F: 0.5-2
Keale					
L	2-0	N: 0		N	
F	0-8	V: 0-2	FM: 2-20	F	FM: 0.5-5
Of	8-10	V: 0-2	FM: 2-20	V	FM: 0.5-5
A/E	10-15	V: 0-2	FM: 2-20	V	MC: 2->5
Bh	15-18	F: 2-5	CS: 20-200	V	F: 0.5-2
Bs	18+	F: 2-5	CS: 20-200	N	

[a] Rock/root abundance codes: N: None, V: Very Few, F: Few, C: Common, M: Many.

[b] Rock size class codes and combinations: F: Fine gravel, M: Medium gravel, C: Coarse gravel, S: Stones, FM: Fine and medium gravel, CS: Coarse gravel and stones.

[c] Root size class codes: F: Fine, FM: Fine and medium, MC: Medium and coarse.

([a,b,c] Source: FAO 2006.)

such as gravel, stone, or roots, were removed. The samples were then sieved through a 2 mm sieve to separate the fine and coarse fractions. The mass of both the fine and coarse fraction was recorded. The volume of the coarse fraction was determined by the water displacement method. The BD of the fine earth fraction (BD_{Pfe}) of each sample was determined using the following formula from Throop et al. (2012):

$$BDPfe = \frac{Mass_{soil} - Mass_{cf}}{Volume_{soil} - Volume_{cf}} \qquad (1)$$

where:
$Mass_{soil}$ = mass of oven-dried BD soil sample
$Mass_{cf}$ = mass of coarse fragments
$Volume_{soil}$ = volume of BD ring (i.e. 100 cm^3)
$Volume_{cf}$ = volume occupied by the coarse fragments

Following drying the augured SOC samples were sieved to separate the fine (<2 mm) and coarse fractions. The SOC content (%) of 5.00-5.10 g of each sample was determined by the loss-on-ignition (LOI) method, by placing it in a muffle furnace for three hours at 550 °C and using 0.58 as the generally accepted C fraction of SOM (Guo and Gifford 2002, De Vos et al. 2005). The soil C stock in Mg C ha^{-1} was then calculated according to the following equation:

$$SCS = BD \times SOC \times Depth \times 100 \qquad (2)$$

where:
SCS = soil C stock (Mg C ha^{-1})
BD = soil bulk density (g cm^{-3})
SOC = soil organic carbon (%)
Depth = depth to which BD and SOC samples were taken (cm)

Figure 1: *Exposed profiles of a podzol at (a) the Vee Gap site and peaty podzols at (b) Keale and (c) Anglesborough sites.*

Results

The mean BD values (Table 4) for the forest podzols increased from 0.68 in the top 10 cm to 1.04 g cm^{-3} at 20–30 cm, but fell to 0.89 g cm^{-3} in the 30–40 cm soil depth. The Vee Gap soil had the highest mean BD (0–40 cm) of 1.16 g cm^{-3}, while Skeheen one had the lowest mean BD for the same depth of 0.54 g cm^{-3}. The mean SOC % decreased at each 10 cm depth from 0–40 cm at the podzol sites, from a high value of 7.8% nearest the surface to 3.0% at the deepest level. The incremental decrease in SOC in the top 30 cm was evident for the Vee Gap and Boggeragh sites, followed by a small SOC increase at those sites 30–40 cm depth, with an overall decline in SOC of 84% and 67% respectively between the top and bottom 10 cm sampled depths. The Skeheen site had the most homogenous SOC content throughout the 0–40 cm profile with a decline of 30%. There was a moderate SOC increase in the 20–30 cm layer of the Skeheen site in comparison to the over and underlying depth intervals of 11% and 13% respectively. The mean soil C stock (Mg C ha^{-1}) of the podzol sites decreased with each depth increment down to 40 cm, declining by 63% from the top to the bottom 10 cm sampled depth.

The mean BD values for the peaty podzols increased from 0.41 to 0.63 g cm^{-3} with each 10 cm increase in depth through 0–30 cm, but fell at 30–40 cm to 0.58 g cm^{-3}. The site with the lowest mean BD value (0–40 cm) of 0.51 g cm^{-3} was Anglesborough, while Glenanair had the highest mean BD at 0.60 g cm^{-3} for the full 0–40 cm depth. The mean SOC % for the peaty podzol sites also decreased with each 10 cm depth interval down to 40 cm. There was an incremental decrease in SOC% in the top 30 cm for all four sites, but two sites, Devil's Bit and Keale, showed a small increase in the 30–40 cm soil layer. The mean SOC % decreased at each depth from 0–40 cm at the peaty podzol sites, from a high value of 32% to 6% at the lowest depth. The mean soil C stock in the peaty podzol sites also decreased with each 10 cm depth interval down to the 30–40 cm level. The total soil C stock (0–40 cm) also increased by 68% across the sites from a low of 229 to a high of 385 Mg C ha^{-1}.

Discussion

The seven podzol and peaty podzols sites sampled in this study adhered to the soil classification used by Teagasc (Creamer et al. 2014) and the criteria used by the annual EPA "National Inventory Report" on GHG emissions (Duffy et al. 2014). Distinct differences were found in mean BD, SOC% and soil C stock values between podzols and peaty podzols across the four depths sampled. Even with their low mean BD of 0.55 g cm^{-3}, the C rich surface horizons of the peaty podzols had mean soil C stocks (0-40 cm depth) that are over twice that in the podzols, i.e. an estimated 304 Mg C ha^{-1} in the former versus 132 Mg C ha^{-1} in the latter. The mean BD (0-40 cm) for the podzol sites of 0.87 g cm^{-3} was 58% higher than the respective value for the peaty

Table 4: *Characteristics of the podzol and peaty podzol soils sampled. Descriptions included mean bulk density (BD), soil organic carbon (SOC), and soil carbon stock (SCS), by site code and by depth. Also mean BD and SOC for 0–40 cm, and sum of soil carbon stock for 0-40 cm.*

***BD** (g cm^{-3})*	**Podzol sites**[a]							**Peaty podzol sites**[b]							
Depth (cm)	VGP	BGH	SKE	Mean BD	S.E.	S.D.	C.V.	DVB	GLN	ANG	KEA	Mean BD	S.E.	S.D.	C.V.
0–10	0.57	0.79	0.68	0.68	0.07	0.20	86.1	0.34	0.31	0.42	0.57	0.41	0.05	0.16	97.2
10–20	1.07	1.00	0.59	0.89	0.08	0.25	88.6	0.65	0.33	0.64	0.77	0.60	0.06	0.21	93.3
20–30	1.48	1.08	0.58	1.04	0.14	0.43	96.9	0.66	0.81	0.46	0.58	0.63	0.06	0.19	135.6
30–40	1.51	0.81	0.34	0.89	0.17	0.52	109.0	0.53	0.96	0.51	0.32	0.58	0.07	0.25	114.1
Mean: 0–40	1.16	0.92	0.54	0.87				0.54	0.60	0.51	0.56	0.55			
SOC (%)	**Mean SOC**							**Mean SOC**							
0–10	8.64	6.99	7.70	7.78	0.53	2.59	33.3	31.8	39.5	35.5	22.3	32.3	1.57	8.88	27.5
10–20	3.51	3.53	5.54	4.19	0.46	2.26	53.9	8.33	39.2	19.6	7.24	18.6	2.67	15.1	81.1
20–30	1.35	1.91	6.24	3.16	0.54	2.66	84.0	5.46	11.3	9.13	6.13	8.01	1.06	5.99	74.7
30–40	1.42	2.31	5.36	3.03	0.39	1.93	63.7	5.50	4.24	7.84	7.46	6.26	0.59	3.33	53.1
Mean: 0–40	3.73	3.68	6.21	4.54	0.48	2.36	58.7	12.8	23.6	18.0	10.8	16.3	1.47	8.32	59.1
SCS *(Mg ha^{-1})*	**Mean SCS**							**Mean SCS**							
0–10	49.58	55.14	52.07	52.26				109.6	122.5	150.7	127.5	127.6			
10–20	37.55	35.33	32.56	35.15				53.90	130.0	125.4	55.51	91.20			
20–30	19.93	20.58	35.91	25.47				35.91	92.12	42.28	35.36	51.42			
30–40	21.46	18.80	18.06	19.44				29.13	40.72	39.88	24.21	33.49			
Sum: 0–40	128.5	129.8	138.6	132.3				228.5	385.4	358.2	242.6	303.7			

[a] VGP: Vee Gap, BGH: Boggeragh, SKE: Skeheen.

[b] DVB: Devil's Bit, GLN: Glenanair, ANG: Anglesborough, KEA: Keale. S.E.: standard error, S.D.: standard deviation, C.V.: coefficient of variation.

podzols sites. There are very few published sources with BD data by depth for Irish forested soils making direct comparisons with the soil types in this study impossible, therefore only comparisons with other forested mineral soils can be reported. This study's mean BD for 0-30 and 0-40 cm for the podzol sites was the same: both were 0.87 g cm^{-3}. These mean BD values are 7% lower in comparison to the mean BD (0-30 cm) of 0.94 g cm^{-3} for all 21 forested mineral soil sites assessed by Wellock et al. (2011) and 14% lower than the 1.01 g cm^{-3} for the five coniferous forest sites on surface-water gley soils studied by Black et al. (2009).

In their study of mainly humo-ferric podzol forest soils in Canada, with their typically low density organic layers, high root abundance and stony mineral layers, Perie and Ouimet (2008) found that BD was closely correlated with SOM content (r^2 =0.81). The peaty podzol sites in this study had a mean BD value (0-40 cm) of 0.55 g cm^{-3}, 37% lower than the respective value for the podzol sites, which as shown above is already low compared to other forest mineral soils. Given the direct relationship in this study between SOM and SOC content via the 0.58 conversion factor, the high estimated SOC % found in the peaty podzols at each sampled depth helps explain the low BD values found in this study. Without full soil particle and porosity analysis and more extensive measurement of the in-situ coarse fragments it is difficult to accurately assign causality for their low mean BD values. It is thought that the low BD values are attributable to a combination of the thick organic layers in the top 20 cm and the often weakly aggregated sandy texture of podzols (FAO 2001).

The coefficient of variation (CV) values of the SOC % indicates that these soils were highly heterogeneous across all sampled depths, with the podzol sites CVs ranging from 33.3 (0-10 cm) to 84.0 (20-30 cm), with a similar range of 27.5 (0-10 cm) and 81.1 (10-20 cm) in the peaty podzol sites. There was a 65% increase in the soil C stock value between the highest value for the podzol sites and the lowest value for the Peaty podzol sites, i.e. 139 Mg C ha^{-1} and 229 Mg C ha^{-1} respectively. At each sampled 10 cm depth down to 30 cm, the mean soil C stock of the peaty podzols exceeded that of the podzols by more than double. It was only in the lowest sampling depth, 30-40 cm, that this trend changed and difference between the two soil C stock values was 58%. When the combined mean soil C stock for the three podzol sites in this study are compared to the mean of the four coniferous forest podzol sites of Wellock et al. (2011), inclusive of F/H and mineral horizons to 30 cm for both studies, the results were within 5% of one another. This study estimated the soil C stock for those same horizons and sampling depths to be 113 Mg C ha^{-1}, while Wellock et al (2011) estimated it at 117 Mg C ha^{-1}. The estimated mean C stock for the peaty podzols in this study was 197 Mg C ha^{-1}, a 68% increase over the Wellock et al. (2011) podzol values to the same depth.

The soil C stock (0-40 cm) for the podzol sites ranged between 129 and

139 Mg C ha^{-1}, with a mean of 132 Mg C ha^{-1}. This mean value is 15 Mg C ha^{-1} higher than the mean of 117 Mg C ha^{-1} derived from measurements of four podzol sites sampled by Wellock et al. (2011) (0-30 cm, excluding forest litter). It should be noted that the Wellock et al. SOC values were determined using a C/N elemental analyser, in contrast to the LOI method used in this study, though De Vos et al. (2005) conclude both methods are comparable except in low organic C, non-calcareous soils where the former method is more reliable. The mean soil C stock for the podzol sites decreased from a high of 52 Mg C ha^{-1} in the top 10 cm to a low of 19 Mg C ha^{-1} in the bottom 10 cm of the sampled 40 cm soil profile, reflecting the decreasing SOC % at the same increments. The peaty podzol sites had much higher soil C stock (0-40 cm), ranging from 229 to 385 Mg C ha^{-1}, with a mean of 304 Mg C ha^{-1}. This mean is 11% lower than the 343 Mg C ha^{-1} recorded for podzol soils in the Republic of Ireland, as determined by Tomlinson (2005).

Conclusions

The disparity in the C stocks between afforested podzols and peaty podzols in this work underlines the need to disaggregate these soils and has implications for how they should be treated in soil C inventories to reduce uncertainty associated with soil C stock estimation. With their suitability for conifer plantations it is likely that these soils will be further utilised in any future expansion of the forest estate. In such cases of afforestation there may be potentially adverse implications for the stability of their inherent C stocks, e.g. via increased C emissions due to soil disturbance and drainage. Even if afforestation has only a minimal effect on soil C stocks at the regional or country level, its effect on the global C pool could be significant if large scale conversion of agricultural land to forest plantations continues (Paul et al., 2002). To establish more accurate baseline estimates against which future C stock change can be assessed and facilitate a better understanding of the impact of afforestation on their soil C stocks, the methods employed in measuring their soil C stocks and fluxes need to be adapted. Based on the findings of this study, the cut-off point of 200 Mg C ha^{-1} used by Smith et al. (2006) to differentiate between organic and mineral soils is deemed a useful threshold for determining the most appropriate method for monitoring C stock changes. For example, soil C stock sampling methodologies could be used for soils below the threshold and the development of specific C EFs for soils that are above that level.

Acknowledgements

This work was funded by the Department of Agriculture and the Marine (DAFM) CForRep project and access to forest sites was provided by Coillte. The authors are grateful for the assistance provided by John Redmond of the Forest Service, Mary Leahy of Coillte, Rachel Creamer and Brian Reidy of Teagasc and the late Otto Spaargaren.

References

Alm, J., Shurpali, N.J., Tuittila, E.-S., Laurila, T., Maljanen, M., Saarnio, S. and Minkkinen, K. 2007. Methods for determining emission factors for the use of peat and peatlands – flux measurements and modelling. *Boreal Environmental Resources* 12: 85–100.

Baker, J.M. and Griffis, T.J. 2005. Examining strategies to improve the carbon balance of corn/soybean agriculture using eddy covariance and mass balance techniques. *Agricultural and Forest Meteorology* 128: 163-177.

Black, K., Byrne, K.A., Mencuccini, M., Tobin, B., Nieuwenhuis, M., Reidy, B., Bolger, T., Saiz, G., Green, C., Farrell, E.T. and Osborne, B. 2009. Carbon stock and stock changes across a Sitka spruce chronosequence on surface-water gley soils. *Forestry* 82: 255-272.

Black, K., Creamer, R.E., Xenakis, G. and Cook, S. 2014. Improving forest soil carbon models using spatial data and geostatistical approaches. *Geoderma* 232-234: 487-499.

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.

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., Aherne, J. and Cummins. T. 2015. Current and future degradation risks to forest soils in Ireland. In *Soil Degradation Risks in Planted Forests*. Eds. González, A.A. and Bengoetxea, N.G., Eusko Jaurlaritzaren Argitalpen Zerbitzua, Servicio Central de Publicaciones del Gobierno Vasco, pp. 43-56.

Connolly, J., Holden, N.M. and Ward, S.M. 2007. Mapping peatland in Ireland using a rule based methodology and digital data. *Soil Science Society of America Journal* 71: 492–499.

Coleman, K. and Jenkinson, D.S. 1996. RothC-26.3 – A Model for the turnover of carbon in soil. In *Evaluation of soil organic matter models using existing, long-term datasets*. Eds. Powlson, D.S., Smith, P. and Smith, J.U., NATO ASI Series I, Vol.38, Springer-Verlag, Heidelberg, Germany, pp 237-246

Couwenberg, J. 2009. *Emission Factors for Managed Peat Soils – an Analysis of IPCC Default Values*. Wetlands International, Ede, Bonn.

Creamer, R.E., Reidy, B., Simo, I., Hannam, J.A., Hamilton, B., Jahns, G., Jones, R.J.A., McDonald, E., O'Connor, C., Hallett, S., Hazledon, J., Massey, P., Palmer, R.P., Sills, P. and Spaargaren, O. 2014. *Irish Soil Information System: National Soil Series Description and Classification of Representative Profiles*, Final Technical Report 9. EPA, Johnstown Castle, Co.Wexford.

De Vos, B., Vandecasteele, B., Deckers, J. and Muys, B. 2005. Capability of loss-on-ignition as a predictor of total organic carbon in non-calcareous forest soils. *Communications in Soil Science and Plant Analysis* 36(19-20): 2899-2921.

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. *Climate Change* 91: 317-334.

FAO. 2001. Lecture notes on the major soils of the world (English). In *World Soil Resources Reports (FAO),* no. 94. Eds. Driessen, P., Deckers, J., Spaargaren, O. and Nachtergaele, F., FAO, Rome (Italy).

FAO. 2006. *Guidelines for Soil Description*, 4th ed. Food and Agriculture Organization of the United Nations, Rome, Italy.

Finch, T.F. and Ryan, P. 1966. *Soil Survey Bulletin No. 16*. Soils of Co. Limerick, National Soil Survey of Ireland. An Foras Taluntais (The Agricultural Institute), 33 Merrion Road, Dublin 4.

Gardiner, M.J. and Radford, T. 1980. *Soil Associations of Ireland and Their Land Use Potential: Explanatory Bulletin to Soil Map of Ireland*. An Foras Taluntais, Dublin.

Gorham, E. 1991. Northern peatlands: role in the carbon cycle and probable responses to climatic warming. *Ecological Applications* 1: 182–195.

Guo, L.B. and Gifford, R.M. 2002. Soil carbon stocks and land use change: a meta analysis. *Global Change Biology* 8: 345-360.

Hammond, R.F. 1981. *The Peatlands of Ireland*. Soil Survey Bulletin No. 35, An Foras Talúntais, Dublin.

Heim, A., Wehrli, L., Eugster, W. and Schmidt, M.W.I. 2009. Effects of sampling design on the probability to detect soil carbon stock changes at the Swiss CarboEurope site Lägeren. *Geoderma* 149: 347-354.

IPCC. 2006. 2006 *IPCC Guidelines for National Greenhouse Gas Inventories, National Greenhouse Gas Inventories Programme*. Eds. Eggleston, H.S., Buendia, L., Miwa, K., Ngara, T. and Tanabe, K. IGES, Japan.

IPCC. 2014. 2013 *Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Eds. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. and Troxler, T.G., IPCC, Switzerland.

IUSS Working Group WRB. 2014. *World Reference Base for Soil Resources 2014. International Soil Classification System for Naming Soils and Creating Legends for Soil Maps*. World Soil Resources Reports No. 106. FAO, Rome.

Joosten, H. and Clarke, D. 2002. *Wise Use of Mires and Peatlands – Background and Principles Including a Framework for Decision-Making*. International Peat Society. International Mire Conservation Group, Finland.

Kiely, G., McGoff, N.M., Eaton, J.M., Xu, X., Leahy, P. and Carton, O.T. 2009. *Soil C-Measurement and Modelling of Soil Carbon Stocks and Stock Changes in Irish Soils*. STRIVE Report Series No. 35. Environmental Protection Agency, Johnstown Castle, Co. Wexford, Ireland.

Lawrence G.B., Fernandez, I.J., Richter, D.D., Ross, D.S., Hazlett, P.W., Bailey, S.W., Ouimet, R., Warby, R.A.F., Johnson, A.H., Lin, H., Kaste, J.M., Lapenis, A.G. and Sullivan, T.J. 2013. Measuring environmental change in forest ecosystems by repeated soil sampling: a North American perspective. *Journal of Environmental Quality* 42: 623–639.

Mishra, U., Torn, M.S., Masanet, E. and Ogle, S.M. 2012. Improving regional soil carbon inventories: Combining the IPCC carbon inventory method with regression kriging. *Geoderma* 189-190(0): 288-295.

Montanarella, L., Jones, R.J. and Hiederer, R. 2006. The distribution of peatland in Europe. *Mires and Peat*: Volume 1.

NFI. 2013. *The Second National Forest Inventory, Republic of Ireland, Main Findings, Covering the National Forest Inventory, 2009 to 2012, Results_v12 V Final*. Forest Service, DAFM, Johnstown Castle Estate, Co. Wexford.

Ogle, S.M., Breidt, F.J., Easter, M., Williams, S., Killian, K. and Paustian, K. 2010. Scale and uncertainty in modeled soil organic carbon stock changes for US croplands using a process-based model. *Global Change Biology* 16: 810-822.

Olsson, M.T., Erlandsson, M., Lundin, L., Nilsson, T., Nilsson, A. and Stendahl, J. 2009. Organic carbon stocks in Swedish podzol soils in relation to soil hydrology and other site characteristics. *Silva Fennica* 43: 209–222.

Ortiz, C.A., Liski, J. and Gärdenäs, A.I. 2013. Soil organic carbon stock changes in Swedish forest soils – a comparison of uncertainties and their sources through a national inventory and two simulation models. *Ecological Modelling* 251: 221–231.

Paul, K.I., Polglase, P.J., Nyakuengama, J.G. and Khanna, P.K. 2002. Change in soil carbon following afforestation. *Forest Ecology and Management* 168: 241-257.

Pennock, D., Yates, T. and Braidek, J. 2006. Soil sampling designs. In *Soil Sampling Designs and Methods of Analysis,* 2nd ed. Eds. Carter, M.R. and Gregorich, E.G., CRC Press, Florida.

Perie, C. and Ouimet, R. 2008. Organic carbon, organic matter and bulk density relationships in boreal forest soils. *Canadian Journal of Soil Science* 88: 315-325.

Reidy, B. and Bolger, T. 2013. Soil carbon stocks in a Sitka spruce chronosequence following afforestation. *Irish Forestry* 70: 200–219.

Simo, I., Creamer, R.E., Reidy, B., Jahns, G., Massey, P., Hamilton, B., Hannam, J.A., McDonald, E., Sills, P. and Spaargaren, O. 2008. *Soil Profile Handbook, Final Technical Report 10*. EPA, Johnstown Castle, Co.Wexford.

Scott, N.A., Tate, K.R., Giltrap, D.J., Tattersall Smith, C., Wilde, H.R., Newsome, P.J.F. and Davis, M.R. 2002. Monitoring land-use change effects on soil carbon in New Zealand: quantifying baseline soil carbon stocks. *Environmental Pollution* 116: Supplement 1: S167-S186.

Smith, P., Smith, J., Wattenbach, M., Meyer, J., Lindner, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M., Reginster, I. and Kankaanpää, S. 2006. Projected changes in mineral soil carbon of European forests, 1990-2100. *Canadian Journal of Soil Science* 86: 159-169.

Smith, P., Smith, J., Flynn, H., Killham, K., Rangel-Castro, I., Foereid, B., Aitkenhead, M., Chapman, S., Towers, W., Bell, J., Lumsdon, D., Milne, R., Thomson, A., Simmons, I., Skiba, U., Reynolds, B., Evans, C., Frogbrook, Z., Bradley, I., Whitmore, A. and Falloon, P. 2007. *ECOSSE – Estimating Carbon in Organic Soils – Sequestration and Emissions*. Scottish Executive Environment and Rural Affairs Department, Edinburgh.

Throop, H.L., Archer, S.R., Monger, H.C. and Waltman, S. 2012. When bulk density methods matter: implications for estimating soil organic carbon pools in rocky soils. *Journal of Arid Environments* 77: 66-71.

Tomlinson R.W. 2005. Soil carbon stocks and changes in the Republic of Ireland. *Journal of Environmental Management* 76: 77-93.

Turner, J. and Lambert, M. 2000. Change in organic carbon in forest plantation soils in eastern Australia. *Forest Ecology and Management* 133: 231-247.

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.

Wellock, M.L., LaPerle, C.M. and Kiely, G. 2011. What is the impact of afforestation on the carbon stocks of Irish mineral soils? *Forest Ecology and Management* 262: 1589-1596.