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What is the impact of afforestation on the carbon stocks of Irish mineral soils?

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ABSTRACT

Ireland has implemented a large afforestation program in recent decades, with much of this taking place since the mid 1980s. This presents Ireland with the opportunity to offset carbon emissions through carbon sequestration in forests, as the latter are known to sequester a large amount of carbon into the tree biomass. However, the effects of afforestation on soil organic carbon in the Irish humid temperate climate are not well understood. In this study we use the paired site methodology to assess the impact of afforestation on the soil organic carbon density (SOCD) of 21 $*$ 2 sites across Ireland. We found that afforestation of Irish soils (0–30 cm depth) resulted in no significant change in SOCD. However, the low number of sites within the study is a source of uncertainty and more work must be done to assess SOCD change before any firm conclusions can be made. This work provides baseline data and future work estimating soil C changes due to land use or management changes should use the equivalent soil mass (ESM) correction method instead of the volume based method. The latter can over- or underestimate SOCD change due to variability in soil bulk density after afforestation. The large afforestation programmes to be implemented in Ireland in the next decade provides an opportunity to greatly improve estimates of Irish SOCD change. We suggest implementing a large number of resampling studies, measuring the change in SOCD following afforestation for a number of factors for a number of years.

1. Introduction

At the beginning of the twentieth century forests covered only 1% of the total Irish land area (Pilcher and Mac an tSaoir, 1995). However, due to the efforts of successive governments there has been rapid afforestation since the 1960s resulting in a 10.0% (697,730 ha) forest land cover as of 2007 (NFI, 2007a). A large proportion of this afforestation took place after the mid-1980s, encouraged by government grant incentives targeted at private landowners. Consequently, 63% of Irish forests are less than 20 years old (NFI, 2007a), providing Ireland the opportunity to contribute to meeting its international obligations set forth by the United Nations Framework Convention on Climate Change (UNFCCC, 1992). These obligations include the limitation of greenhouse gas emissions to 13% above 1990 levels. In order to promote accountability for these commitments, the UNFCCC treaty and the Kyoto Protocol (Kyoto Protocol, 1997) mandate signatories to publish greenhouse gas (GHG) emissions inventories for both greenhouse gas sources and sinks. Article 3.3 of the Kyoto Protocol allows changes in carbon (C) stocks due to afforestation, reforestation, and deforestation since 1990 to be used to offset inventory emissions. Therefore, due to the rapid rate of afforestation and the increased ecosystem (biomass, forest floor, and soil) carbon sequestration since 1990, Ireland's recent afforestation programme has the potential to significantly offset its GHG emissions.

It is well established that there is a large increase in the carbon stored in the aboveground biomass following afforestation (Morris et al., 2007; Black et al., 2009; Mendoza-Ponce and Galicia, 2010), but the effects on soil organic carbon (SOC) are still uncertain (Kirschbaum et al., 2008). Soils contain approximately two-thirds of the C stored within forest ecosystems (Dixon et al., 1994). The residence time of stable fractions of SOC can be >1000 years (von Lutzow et al., 2006) making it a much more stable sink than living plant biomass (Laganière et al., 2010). In addition to being able to estimate the carbon in tree biomass, it is therefore vital to measure the change in SOC stocks following afforestation, and to determine the mechanisms involved in controlling SOC dynamics.

Soil C stocks are determined by the balance between the inputs of C through litterfall and rhizodeposition and the loss of C mainly through soil organic matter (SOM) decomposition (Jandl et al., 2007). The change in soil C following afforestation is controlled by a number of factors, including: previous land use (grasslands, cropland, etc); tree species; soil cultivation method; soil properties (clay content, pH); stand age; site management; topography and climate (Guo and Gifford, 2002; Paul et al., 2002; Jandl et al., 2007; Laganière et al., 2010). A number of studies have been conducted to investigate afforestation induced soil C changes with different conclusions. Some studies have found no change in SOC

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stocks after afforestation (Davis, 2001; Davis et al., 2003; DeGryze et al., 2004; Smal and Olszewska, 2008; Peri et al., 2010). Others have found an increase in SOC stocks (Post and Kwon, 2000; Guo and Gifford, 2002; Del Galdo et al., 2003; Hooker and Compton, 2003; Mao et al., 2010) while some have found a decrease in SOC stocks (Perrott et al., 1999; Ross et al., 1999; Chen et al., 2004; Farley et al., 2004). However, several studies have shown a similar trend where initially there is a reduction in SOC stocks as the decomposition of soil organic matter is greater than the input of organic matter from the trees. Over time the soil organic matter input increases with the productivity of the forest stands and the soils switch from being a C source to a C sink. This can lead to an eventual recovery of soil C to the pre-afforestation levels and in some situations surpass them (Romanyà et al., 2000; Davis and Condron, 2002; Paul et al., 2002; Turner et al., 2005; Ritter, 2007; Hu et al., 2008; Laganière et al., 2010; Mao et al., 2010).

A number of reviews have been conducted to examine the effects of afforestation on soil C stocks globally (Guo and Gifford, 2002; Paul et al., 2002; Laganière et al., 2010) and for specific countries (Davis and Condron, 2002). The latter, in a review of paired plot (adjacent plots on same soils, one afforested, and one as original land use) studies of coniferous forestry in New Zealand found an initial loss of soil C, before recovery to pre-afforestation levels after 20 years. Guo and Gifford (2002) in a meta-analysis of different land use changes on soil C reported a 10% decline in SOC with afforestation of pasture land and a 13% reduction from conversion of native forest to plantation forestry. It was found that when pasture and native forests were afforested with broadleaf, there was little change; however, there was a significant loss in soil C following afforestation with pine (Guo and Gifford, 2002). Paul et al. (2002), in a review of 43 afforestation studies found, the key factors in order of importance to be: previous land use; climate; and the type of forest. Laganière et al. (2010) published a meta-analysis (synthesised from 33 publications) of the impacts of afforestation on the soil C stocks of agricultural land. They found that the main factors effecting soil C change to be, in order of importance: previous land use; tree species; soil clay content; pre-planting disturbance; and to a lesser extent, climatic zone.

Two studies have examined the impact of afforestation on the C stocks of mineral soils in Ireland, with different conclusions. Black et al. (2009) analysed a chronosequence of Sitka spruce stands on surface-water gley soils in Co. Wicklow, and found an increase in soil C stocks from the pre-afforestation grassland site to the 9 year old spruce site, and further increases with stand age. Wellock (2011) in an ash forest chronosequence located on brown earth soils in the Irish midlands, observed a continuous decline in SOC stocks from the pre-afforestation grassland sites with stand age up to the 27 years old. Thereafter, the SOC stock began to increase. Although the soil begins to sequester C (after age 27), it did not accrue C as quickly, as it was initially released from the soil, with the result that the SOC stocks of the 47 year old ash forest were only 79% of pre-afforestation grassland levels. The differing conclusions of the two Irish studies may be due to the large difference in growth rates, with the biomass of the ash forests of Wellock (2011) accumulating 1.83 Mg C ha^{-1} yr^{-1} while the Sitka spruce stands of Black et al. (2009) have a biomass uptake ranging between 5.8 and 15.1 Mg C ha^{-1} yr^{-1} over the age of the stand. However, more work must be done to fully determine the impacts of afforestation on Irish soil C stocks and the controlling factors.

The most commonly used method to determine soil C stocks is the volume-based method which multiplies the SOC concentration (%) by bulk density (g cm^{-3}) to a fixed depth. Soil bulk density varies spatially and temporally (Amador et al., 2000; Gifford and Roderick, 2003; Kulmatiski and Beard, 2004; Lee et al., 2009; Wuest, 2009) and the volume-based method does not account for variations in soil mass and this introduces uncertainty in SOC stock changes (Ellert and Bettany, 1995; Markewitz et al., 2002; Murty et al., 2002; Lee et al., 2009; Mao et al., 2010). The equivalent soil mass (ESM) correction was proposed by Ellert and Bettany (1995) as a more reliable method to determine changes in soil C stock among land use or management practices and a number of studies have used it since (Ellert and Bettany, 1995; Yang and Wander, 1999; Gifford and Roderick, 2003; VandenBygaart, 2006; VandenBygaart and Angers, 2006; Lee et al., 2009; Wuest, 2009; Mao et al., 2010). The ESM is defined as the reference soil mass per unit area chosen in a layer and the equivalent C mass (ECM) is the C stored in an ESM (Ellert et al., 2001; Mao et al., 2010).

The objectives of this paired plot study were: (1) to quantify the carbon stored in the forest floor and soil (0–30 cm depth) of 21 forest sites and their 21 adjacent non-forest site on same soils; and (2) to assess the impacts of afforestation on soil carbon stocks using the paired plot method.

2. Materials and methods

2.1. Site selection

The forest sites were selected from stands surveyed for the Irish National Forest Inventory (NFI) which systematically sampled 1742 forest plots across the Republic of Ireland (NFI, 2007b). We filtered the NFI database and rejected those sites that were inaccessible, reforested, and younger than 15 years or had soil types that were representative of less than 1% of Irish forest soils (regosols, lithosols and rendzinas). All sites with peat soils were sampled separately from the mineral soils and are presented in Wellock (2011). The remaining 98 sites were sorted into three forest categories: conifer, broadleaf and mixed. These sites were then further sub-divided by soil type; brown earth, gley, podzol and brown podzolic. Those categories with 6 or more sites were then selected for sampling. From those categories, sites were randomly chosen from each group (of soil type and forest type) for sampling. Any sites left over, were retained as replacement sites. To assess the impact of afforestation, all the selected 21 forest sites were paired with an adjacent non-forest site that had the same current land use as the forest site had prior to afforestation. The non-forest site was selected so that it had the same attributes (relief, aspect, elevation, soil type, etc) as the forest site, with the only difference being the current land use. The details and locations of sites are shown in Tables 1 and 2, Fig. 1.

2.2. Sampling

Field sampling took place between October 2007 and May 2009 and the sampling design was adapted from (Davis et al., 2004) with similar protocol sampling completed for the National Soils Database (Fay et al., 2007). At both the forest and adjacent non-forest sites, a 20 m × 20 m square plot was established and divided into four, 10 m × 10 m quadrants. Within each quadrant at a preselected random point, a soil pit was dug and sampled for soil classification and bulk density. Bulk density samples were taken at depths of 0–5, 5–10, 15–20 and 25–30 cm using stainless steel bulk density rings (Eijkenkamp Agrisearch Equipment BV, Netherlands) of 8 cm diameter by 5 cm height. Around the pit, eight points were sampled using a soil auger (Eijkenkamp Agrisearch Equipment BV, Netherlands) to depths of 0–10, 10–20 and 20–30 cm and analysed for soil organic carbon (SOC, %). The samples for bulk density and SOC were sampled separately due to the availability of sampling equipment.

At three points adjacent to the soil pit within each quadrant, the forest floor was sampled from 0.1 m^2 square plots. Each forest floor sample was separated into three separate classes: (1) fine woody

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Table 1
Characteristics of each site; F, forest site; NF, non-forest site; DMB, double mould board ploughing; SMB, single mould board ploughing; plough, agricultural ploughing.

Site	Soil type	Soil parent material	Previous land use	Elevation (F/NF) (m)	Site preparation	Precipitation (mm yr^{-1})	Georeference position
BLBE1	Brown earth	Limestone till (Carboniferous)	Pasture	97/97	Pit planting	911.9	52°54′N, 7°22′S
BLBE2	Brown earth	Sandstone till (Devonian)	Pasture	108/108	Plough	992.7	52°15′N, 8°33′S
BLBE3	Brown earth	Sandstone till (Lower Palaeozoic/ Devonian)	Pasture	44/38	DMB	1198	52°46′N, 8°25′S
CBE1	Brown earth	Limestone till (Carboniferous)	Pasture	170/169	Mounding	1083.5	53°9′N, 8°32S
CBE2	Brown earth	Granite till	Pasture	188/185	Pit planting	1154.7	52°57′N, 6°37′S
CBE3	Brown earth	Sandstone till (Devonian)	Scrub	120/100	Pit planting	1246.6	52°24′N, 7°33′S
CG1	Gley	Shales and sandstones till (Namurian)	Rough Grazing	199/207	Mounding	883.5	52°52′N, 7°11′S
CG2	Gley	Sandstone and shale till (Lower Palaeozoic)	Scrub	317/311	Plough	1073.7	52°50′N, 8°30′S
CG3	Gley	Sandstone till (Devonian)	Rough Grazing	178/180	SMB	1409.9	52°10′N, 7°47′S
CG4	Gley	Sandstone till (Devonian/ Carboniferous)	Rough Grazing	109/108	DMB	1213.3	53°47′N, 8°23′S
CP1	Podzol	Sandstone and shale till (Lower Palaeozoic)	Rough Grazing	212/192	Mounding	1183.5	52°44′N, 8°19′S
CP2	Podzol	Sandstone till (Devonian)	Rough Grazing	326/325	DMB	1555.1	52°1′N, 8°59′S
CP3	Podzol	Sandstone till (Devonian)	Rough Grazing	235/240	Pit planting	1154.7	52°15′N, 7°56′S
CP4	Podzol	Sandstone and shale till (Lower Palaeozoic)	Rough Grazing	255/279	Plough	1008.2	52°16′N, 8°31′S
CBP1	Brown Podzolic	Shales and sandstones till (Namurian)	Rough Grazing	293/307	Pit planting	1307.7	53°3′N, 7°38′S
CBP2	Brown Podzolic	Sandstone till (Devonian)	Pasture	314/304	Pit planting	996.8	52°43′N, 7°8′S
MBE1	Brown earth	Limestone till (Carboniferous)	Pasture	55/55	Pit planting	964.4	53°35′N, 8°12′S
MBE2	Brown earth	Karstified limestone bedrock at surface	Pasture	117/104	Pit planting	785.7	53°0′N, 7°6′S
MBE3	Brown earth	Sandstone and shale till (Lower Palaeozoic)	Pasture	100/108	SMB	1038.3	52°30′N, 7°1′S
MG1	Gley	Sandstone and shale till (Lower Palaeozoic)	Scrub	53/46	Plough	1084.8	52°48′N, 8°46′S
MG2	Gley	Sandstone till (Devonian)	Rough Grazing	60/57	Mounding	2301.9	51°54′N, 9°23′S

Table 2
Characteristics of each forest site.

Site	Forest type	Tree species	Tree DBH (mm)	Forest age (years)
BLBE1	Broadleaf	*Fagus sylvatica*	141–200	42
BLBE2	Broadleaf	*Acer pseudoplatanus*	31–70	20
BLBE3	Broadleaf	*Fraxinus excelsior*	71–140	17
CBE1	Conifer	*Picea sitchensis*	71–140	19
CBE2	Conifer	*Picea abies*	301–400	34
CBE3	Conifer	*Picea sitchensis*	201–300	42
CG1	Conifer	*Picea sitchensis*	71–140	17
CG2	Conifer	*Picea sitchensis*	301–400	33
CG3	Conifer	*Picea sitchensis*	201–300	29
CG4	Conifer	*Picea abies*	141–200	22
CP1	Conifer	*Larix kaempferi*	141–200	18
CP2	Conifer	*Picea sitchensis*	301–400	41
CP3	Conifer	*Pinus contorta*	401+	68
CP4	Conifer	*Larix kaempferi*	71–140	22
CBP1	Conifer	*Larix kaempferi*	301–400	68
CBP2	Conifer	*Picea sitchensis*	141–200	22
MBE1	Mixed	*Acer pseudoplatanus/Larix kaempferi*	401+	67
MBE2	Mixed	*Picea sitchensis/Fagus sylvatica*	301–400	51
MBE3	Mixed	*Larix kaempferi/Fagus sylvatica*	201–300	33
MG1	Mixed	*Picea sitchensis/Betula pendula*	301–400	37
MG2	Mixed	*Picea sitchensis/Alnus glutinosa*	31–70	17

debris (woody material with a diameter >2.5 cm and <7.5 cm); (2) litter (non-decomposed material of diameter <2.5 cm); and (3) F/H layer (decomposed material that is not mixed with the soil). Each sample from the forest floor and soil was placed into separate and labelled polythene bags.

All soil and forest floor samples were stored at 4 °C before being oven-dried at 55 °C until a constant dry weight was achieved. The augured soil samples were sieved to <2 mm (the eight soil samples were bulked for each depth for each quadrant by equal volume). All soil samples were tested for carbonates. Any samples that tested positive for carbonates were treated to remove the carbonates (Nelson and Sommers, 1996). The forest floor and sieved soil samples were ground to a fine powder before combustion in a C/N analyser (Elementar – Vario Max CN) to determine SOC. The soil texture was analysed at each depth for all sites from the bulked soil samples, using the hydrometer method, ASTM D422 (2002) and measured for pH using 1:1 soil to water using a LabFit AS-3000 pH analyser (McLean, 1982). The bulk density was sieved to 2 mm, with both the <2 mm fraction and >2 mm fractions being stored separately.

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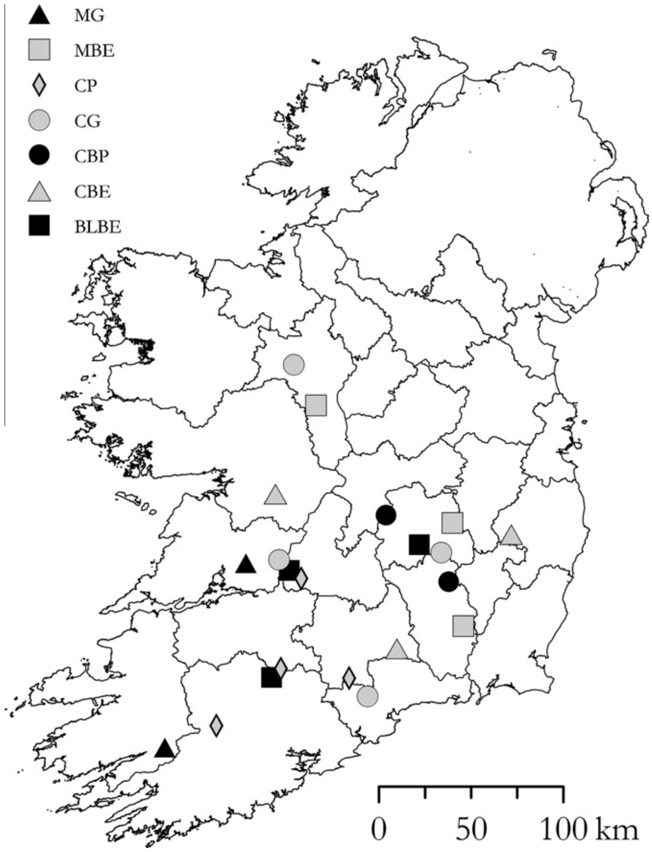

Fig. 1. Locations of all 21 sites within Ireland.

The bulk density was estimated using:

$$\rho_d = \frac{S}{RV - CFV} \tag{1}$$

where ρ_d = bulk density (g cm^{-3}); S = mass of dry sample (g); RV = ring volume (cm^3); CFV = >2 mm coarse fraction volume (cm^3).

The bulk density samples were converted to 10 cm depths to match the SOC data. The soil mass was calculated using:

$$M_i = p_d \times h \times 10^4 \tag{2}$$

where M_i = dry soil mass (Mg ha^{-1}) at the ith depth (i = 1, 2, 3 corresponding to the 0–10, 10–20 and 20–30 cm depths); h = depth of soil layer (m); 10^4 = unit conversion factor (m^2 ha^{-1}).

The carbon density of the soil to a fixed depth was calculated using:

$$C_{i,fixed} = conc_i \times M_i \tag{3}$$

where $C_{i,fixed}$ = carbon density (Mg C ha^{-1}); $conc_i$ = SOC (%).

The equivalent soil mass method uses the soil mass of each soil layer sampled at the non-forest site as the ESM for the layer, using Eq. (4), the equivalent carbon mass (ECM) can be calculated using Eq. (5) (Lee et al., 2009).

$$M_{i,add} = M_{i,equiv} - M_i \tag{4}$$

$$C_{i,equiv} = C_{i,fixed} - conc_{top} \times M_{i-1,add} + conc_{bottom} \times (M_{i,add} - M_{i-1,add}) \tag{5}$$

where $C_{i,equiv}$ = the equivalent carbon mass (Mg C ha^{-1}); $M_{i,equiv}$ = non-forest soil mass (Mg ha^{-1}); $M_{i-1,add}$ and $M_{i,add}$ = the additional soil masses that are used to estimate the ESM (Mg ha^{-1}); $conc_{top}$ = SOC concentration of 10 cm soil layer above the current layer (%); $conc_{bottom}$ = SOC concentration of 10 cm soil layer below the current layer (%). The $C_{i,equiv}$ of the 20–30 cm layer for those sites that had an increase in bulk density used the bulk density value of the non-forest 20–30 cm value. Ideally deeper soil layers should be sampled at these sites to make more accurate corrections. For more information on the ESM method see Ellert and Bettany (1995), Ellert et al., (2001) and Lee et al. (2009).

To summarise, at each of the 21 sites we obtained for both the forest and paired site: (1) 32 samples for SOC at each depth of 0–10, 10–20 and 20–30 cm using the soil auger; (2) four samples of bulk density at each depth of 0–5, 5–10, 15–20 and 25–30 cm using the stainless steel rings; and (3) 12 samples of fine woody debris, litter and F/H layer of the forest floor.

2.3. Data presentation and statistical analysis

Each of the 21 sites were analysed for seven variables that are considered to influence the soil C stocks. These include: forest type (conifer, mixed, broadleaf); pre-afforestation land-use (pasture, rough grazing, scrub); soil texture (loam, sandy loam, clay loam, silt loam); soil pH (<5, 5–7); cultivation disturbance (low-level, high/medium-level); mean annual precipitation (750–1000, 1001–1250, 1251–1500, 1501–2000, 2001–2500 mm) and the forest age (10–19, 20–29, 30–39, >40 years). Scrub was defined as unplanted broadleaf forest that is often semi-natural. The SOC, bulk density and carbon density and ECM of the forest and non-forest sites were compared along these groupings.

Multiple regression was used to assess the relative contribution of each of the seven variables to the prediction of the percentage change in soil organic carbon, bulk density and soil organic carbon density following afforestation. ANCOVA was used to test whether there was significant differences in percent change in SOCD across groups for the variables of forest type, pre-afforestation land-use, soil texture and cultivation disturbance as these four variables have been shown to exert the largest influence on soil C change following afforestation, using the covariates, age, soil pH and precipitation. The forest floor C stock was tested using ANOVA to determine differences between forest types. All statistical analysis was carried out using SPSS (SPSS Inc., SPSS Statistics, Student Version, Release 17.0, 2008).

3. Results

Among all 21 sites, the SOC (0–30 cm) of the non-forest sites had a mean value of 5.0% with a standard error of ±0.5% compared to 4.7 ± 0.6% at the forest sites (Fig. 2). This small loss of 3.8%

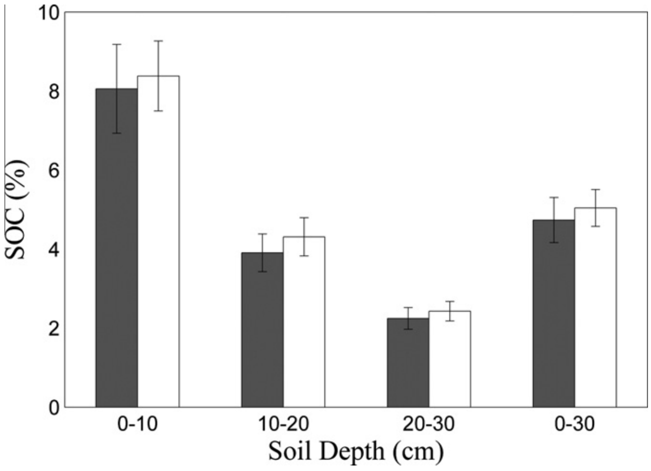

Fig. 2. The mean ± standard error SOC (%) of the forest sites (filled bars) and non-forest sites (unfilled bars) for each soil layer.

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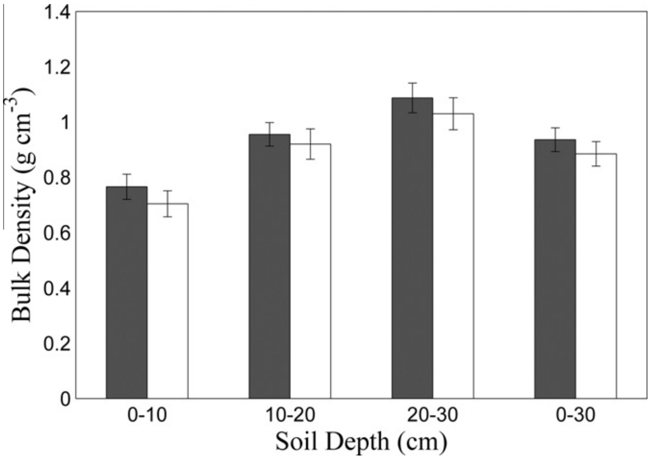

Fig. 3. The mean ± standard error bulk density (g cm^{-3}) of the forest sites (filled bars) and non-forest sites (unfilled bars) for each soil layer.

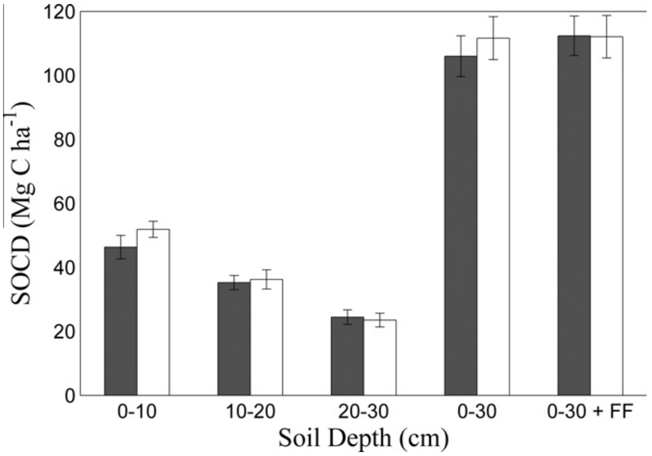

Fig. 4. The mean ± standard error carbon density (Mg C ha^{-1}) of the forest sites (filled bars) and non-forest sites (unfilled bars) for each soil layer and 0–30 cm + forest floor (FF).

following afforestation is non-significant. The soil layers 0–10, 10–20 and 20–30 cm each noted a very small loss of 2.8%, 2.7% and 2.9% respectively, but none of these represented a significant change.

The soil bulk density (0–30 cm) of the 21 sites increased following afforestation by 8.1 ± 4.8% with the non-forest having a mean value of 0.88 ± 0.20 g cm^{-3} compared to 0.94 ± 0.20 g cm^{-3} for the forest sites (Fig. 3). However, this change was not significant. Each of the soil layers 0–10, 10–20 and 20–30 cm recorded a non-significant increase in bulk density following afforestation. When sorted by forest type the bulk densities (0–30 cm) of the conifer and mixed forests increased by 10.7% and 9.5%, respectively, however, they were not significant changes. The soil bulk densities (0–30 cm) of the broadleaf forests significantly decreased after afforestation by 14.4% from the non-forest value of 1.13 ± 0.07 g cm^{-3} to the forest value of 0.97 ± 0.02 g cm^{-3}.

Amongst all sites the mean soil organic carbon density (SOCD, 0–30 cm) for the non-forest sites was 2.9% higher at 111.7 ± 30.8 Mg C ha^{-1} compared to 106.0 ± 29.2 Mg C ha^{-1} for the forest sites. The SOCD of the 0–10 cm soil decreased by 10.3 ± 6.1% following afforestation, while the 10–20 and 20–30 cm soil layers noted small increases of 3.2 ± 5.8% and 12.1 ± 7.5%, respectively. None of the changes in SOCD following afforestation were statistically significant (see Fig. 4).

The amount of C stored in the forest floor varies between the three forest types, with the 9.3 ± 5.1 Mg C ha^{-1} stored in the coniferous forest floor significantly larger ($p < 0.05$) than the 3.2 ± 2.3 Mg C ha^{-1} and 1.7 ± 1.0 Mg C ha^{-1} stored in the mixed and broadleaf forest floors, respectively (Table 3).

When the C stored in the forest floor was added to the SOCD values the mean SOCD in the forests increased to 112.8 ± 28.2 Mg C ha^{-1} very similar to the 112.1 ± 30.3 Mg C ha^{-1} in the non-forests.

The multiple regression found that none of the seven variables were significant predictors of a change in carbon density (0–10 cm, 10–20 cm, 20–30 cm, 0–30 cm and 0–30 cm plus forest floor) following afforestation. As can be seen in Fig. 5, there is no relationship between forest age and the percentage change in SOCD (0–30 cm) following afforestation. The ANCOVA analysis showed that were no significant differences across groups (forest type, pre-afforestation land-use, age, cultivation disturbance) when other variables were controlled for.

Table 3
The mean C ± standard error (Mg C ha^{-1}) stored in each forest site and non-forest site. FWD, fine woody debris.

Site	C pool (Mg C ha^{-1})							
	Litter + FWD		F/H		Soil (0–30 cm)		Total	
	Forest	Non-forest	Forest	Non-forest	Forest	Non-forest	Forest	Non-forest
BLBE1	1.6 ± 0.2	–	0.9 ± 0.1	–	98.6 ± 15.6	96.3 ± 1.1	101.1 ± 15.6	96.3 ± 1.1
BLBE2	1.0 ± 0.2	–	1.0 ± 0.1	–	111.2 ± 4.9	130.0 ± 7.1	113.1 ± 4.9	130.0 ± 7.1
BLBE3	0.3 ± 0.3	–	0.2 ± 0.1	–	136.6 ± 9.3	107.2 ± 1.3	137.1 ± 9.3	107.2 ± 1.3
CBE1	4.5 ± 0.9	–	4.2 ± 1.1	–	95.6 ± 6.2	123.9 ± 3.6	96.3 ± 6.2	123.9 ± 3.6
CBE2	4.8 ± 0.5	–	9.3 ± 1.4	–	99.1 ± 4.8	118.7 ± 7.2	113.2 ± 4.8	118.7 ± 7.2
CBE3	4.7 ± 0.7	1.6 ± 0.4	4.0 ± 0.8	2.6 ± 0.9	38.4 ± 1.1	43.1 ± 5.2	47.1 ± 1.1	47.4 ± 5.2
CG1	1.3 ± 0.4	–	1.5 ± 0.3	–	122.2 ± 9.1	117.9 ± 7.0	125.0 ± 9.1	117.9 ± 7.0
CG2	2.9 ± 0.2	0.7 ± 0.1	3.5 ± 1.2	–	112.6 ± 8.0	103.5 ± 10.9	119.0 ± 8.0	104.2 ± 10.9
CG3	2.4 ± 0.4	–	11.7 ± 0.9	–	86.6 ± 14.5	122.0 ± 7.3	100.7 ± 14.5	122.0 ± 7.3
CG4	1.7 ± 0.1	–	2.4 ± 0.4	–	164.3 ± 11.5	112.7 ± 9.8	168.4 ± 11.6	112.7 ± 9.8
CP1	2.3 ± 0.4	–	2.9 ± 0.3	–	103.0 ± 14.5	82.3 ± 10.1	108.2 ± 14.5	82.3 ± 10.2
CP2	4.5 ± 0.3	–	11.4 ± 2.2	–	148.8 ± 17.2	109.5 ± 8.1	164.7 ± 17.2	109.5 ± 8.1
CP3	5.6 ± 0.9	–	12.2 ± 4.7	–	66.7 ± 5.9	82.3 ± 24.9	84.5 ± 6.0	82.3 ± 24.9
CP4	6.1 ± 0.3	–	6.8 ± 2.0	–	116.8 ± 12.3	177.3 ± 34.7	129.8 ± 12.3	177.3 ± 34.7
CBP1	1.4 ± 0.2	–	1.3 ± 0.3	–	74.9 ± 2.8	86.1 ± 5.6	77.6 ± 2.8	86.1 ± 5.6
CBP2	2.2 ± 0.5	–	5.5 ± 1.6	–	107.1 ± 6.7	151.3 ± 5.5	114.9 ± 6.7	151.3 ± 5.5
MBE1	0.8 ± 0.1	–	1.3 ± 0.2	–	101.4 ± 6.9	112.1 ± 9.4	103.4 ± 6.9	112.1 ± 9.4
MBE2	2.6 ± 0.8	–	3.4 ± 0.7	–	88.3 ± 10.3	75.9 ± 3.2	94.4 ± 10.4	75.9 ± 3.2
MBE3	2.0 ± 0.3	–	2.8 ± 1.0	–	102.9 ± 3.0	102.2 ± 6.1	107.6 ± 3.1	102.2 ± 6.2
MG1	3.0 ± 0.5	2.4 ± 0.4	–	1.7 ± 0.5	96.9 ± 0.5	119.4 ± 4.3	99.8 ± 0.5	123.5 ± 4.3
MG2	0.2 ± 0.1	–	–	–	154.1 ± 21.0	171.1 ± 26.1	154.3 ± 21.0	171.1 ± 26.1

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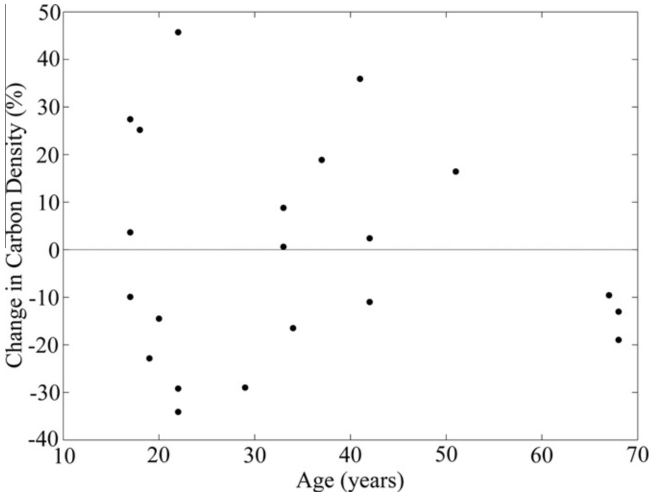

Fig. 5. The change in carbon density (%) of 0–30 cm soil for each site following afforestation.

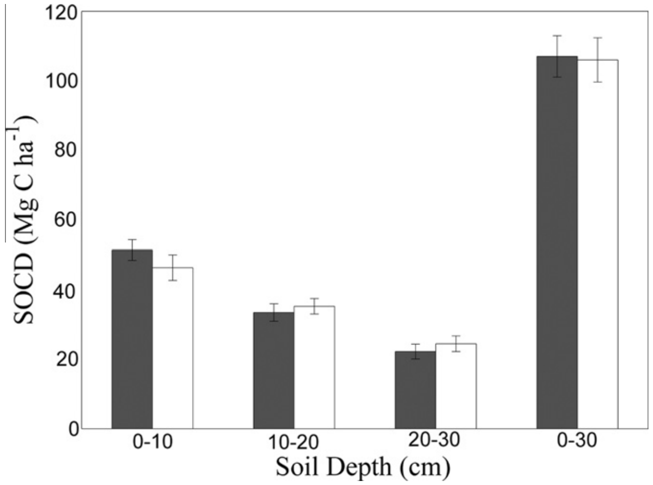

Fig. 6. The mean ± standard error carbon density (Mg C ha^{-1}) of the forest sites for each soil layer by the volume based method (filled bars) and the equivalent soil mass method (unfilled bars).

Overall there was very little change in the carbon density of the 0–30 cm soil using either the volume based method or ESM method, with a difference of less than 1% between the two methods (Fig. 6). However, there were bigger changes when looking at the individual soil layer. The SOCD of the 0–10 cm soil layer calculated using the ESM method is smaller than the respective carbon density of the same layer using the volume based method. This is due to the 8.8% increase in the bulk density of the 0–10 cm layer following afforestation. The carbon densities of the 10–20 and 20–30 cm layers calculated using the ESM method are larger than the volume based method even though the bulk density of each layer increased following afforestation. This is due to the correction of these soil layers with a larger carbon density from the 0–10 cm. There were no significant differences between the carbon densities of the forest sites using either the volume based or ESM method and the volume based method did not observe a significant effect of afforestation on SOCD.

4. Discussion

We found little differences between the SOCD (0–30 cm) of the non-forest and forest site, suggesting that there is little change in SOCD following afforestation which has been seen in the literature, with Poeplau et al. (2011) noting small but non-significant losses of SOCD following afforestation of grasslands. The same result is found when the forest floor carbon stocks are added to that of the SOCD. This finding is in contrast to the results of two chronosequence studies that have assessed the impact of afforestation on SOCD in Ireland. Wellock (2011) in a chronosequence of ash forests in central Ireland reported an overall decrease of 21% of SOCD over 47 years, while Black et al. (2009), in a chronosequence of Sitka spruce in eastern Ireland, saw a large increase in SOCD from the pre-afforestation value of 97.2–137.3 Mg C ha^{-1} at the 16 year old site. The lack of statistically significant changes in SOCD found in this study may be due to the low number of sites that were sampled as well as the variability of characteristics between sites. Large variability is a constant problem when assessing land-use change effects on SOCD and hampers a studies ability to detect changes in SOCD. A possible explanation for the two Irish chronosequences finding significant changes with afforestation is that the number of variables under investigation was limited to age as tree specie and soil type were held constant over a narrow topographical range.

Further sites must be sampled before it can be fully determined that there is no change in SOCD following afforestation in Ireland due to the high variability within sites found in this study. These sites should be selected to enhance the findings of this study. The results of the two Irish chronosequences and this study show that more work must be done to determine the role that forest type plays in determining change in SOCD following afforestation. The results found in the chronosequences are counter to what has been shown in the literature, while this study found no change associated with forest type. Future sampling efforts should sample a greater number of broadleaf stands as this forest type had the lowest number of sampled sites in this study with three sites, which is crucial as broadleaf planting is to increase to 30% of all afforestation in Ireland.

It has been noted in the literature that the clay content of a soil can impact the change in SOCD following afforestation (Paul et al., 2002). Laganière et al. (2010) notes that those sites with a clay content greater than 33% have a greater capacity to accumulate SOC than soils with a lower clay content. This present study only measured one site (CG4) with a high clay content and so more clay sites must be measured to fully determine the effects of clay content on SOCD sequestration in Ireland.

It is current Irish government policy to increase forest cover from its current 10% (NFI, 2007a) to 17% by 2030 (Department of Agriculture, 1996). This provides an opportunity to establish a large number of resampling studies, covering a number of differing forest variables, i.e. forest type, pre-afforestation land use, etc. The resampling studies should be identified prior to cultivation, so that the soil C stocks of the pre-afforestation land use can be measured to further investigate the effects of site cultivation and stand establishment on soil C stocks. Resampling studies are preferable to paired plot studies as they measure change over time, contrary to the paired plot method which only measures one point in time, and may over- or underestimate soil C changes if the selected non-forest site is not appropriate (Laganière et al., 2010).

We found that the C stored within the forest floor of the conifer stands are significantly larger than that found within the broadleaf or mixed stands. The litter of conifer species decomposes slower than broadleaf forests (Vesterdal and Raulund-Rasmussen, 1998) and so it is critical to measure the forest floor when evaluating soil C stock changes as the full sequestration potential of conifer forests following afforestation is not identified without the forest floor contribution (Laganière et al., 2010).

There was very little difference between the SOCD calculated using the volume based method and the ESM method for the 0–30 cm soil layer. However, there were greater differences in

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the 10 cm soil layers, with the 0–10 cm layer of the ESM method being lower than the volume based method. Using the ESM method the 10–20 and 20–30 cm soil layers had a higher SOCD than those calculated using the volume based method. This is further highlighted when comparing the SOCD of the 0–30 cm layer of the different forest types. The bulk density values of the broadleaf forests significantly decreased following afforestation while the bulk densities of the conifer forests increased by a small amount. Using the ESM method, the change in bulk densities with afforestation are removed from the estimation of SOCD change with afforestation. The SOCD of the broadleaf sites increased, while the SOCD of the conifer forests decreased following afforestation due to changes in SOC following afforestation. However, if the volume based method were to be used the opposite would be observed as there is a large change in bulk density with afforestation, which is overshadowing a smaller change in SOC for both forest types. The selection of a suitable non-forest site is crucial when using the ESM method for calculating the change in SOCD following afforestation. A poor choice of non-forest site may bring in variables other than land-use change that may influence the change in bulk density. We do not believe it to be an issue for this study, but future work should make certain that all non-forest sites are appropriate to sample, not only for the paired site methodology but for the ESM method also.

5. Conclusion

Afforestation had little effect on the soil organic carbon density (0–30 cm) of Irish soils with no significant change detected. This is also the case when the carbon stored within the forest floor is added to the SOCD. The number of sites and large variability presented in this study leads to uncertainty in estimating the impact of each variable on SOCD changes, and so more sampling sites are required to before it can be fully determined that there is little change in SOCD following afforestation. Further sampling should include a greater number of broadleaf stands and high clay content soils to improve the estimation of the effects of these variables on the change in SOCD following afforestation.

The methodology used to assess the change in SOCD can impact on the possible findings. The use of the equivalent soil mass method should be preferred as changes in bulk density induced by afforestation can lead to an erroneous assessment of the impact of forest type on soil C stocks. Although care must be taken in the selection of non-forest sites to make sure that no other factor is influencing the change in bulk density following afforestation other than land-use change.

The large afforestation set to take place in Ireland within the next decade represents a unique opportunity to measure the impact of afforestation on SOCD. We recommend that resampling studies should be established prior to afforestation on a large number of sites across Ireland, and periodically resampled to gain a much greater insight into changes in the soil, forest floor and biomass C following afforestation.

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