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Changes in ecosystem carbon stocks in a grassland ash (*Fraxinus excelsior* L.) afforestation chronosequence in Ireland

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Abstract

Aims
Government policy in Ireland is to increase the national forest cover from the current 10% to 18% of the total land area by 2020. This represents a major land use change that is expected to impact on the national carbon (C) stocks. While the C stocks of ecosystem biomass and soils of Irish grasslands and coniferous forests have been quantified, little work has been done to assess the impact of broadleaf afforestation on C stocks.

Methods
In this study, we sampled a chronosequence of ash (*Fraxinus excelsior*) forests aged 12, 20, 27, 40 and 47 years on brown earth soils. A grassland site, representative of the pre-afforestation land use, was sampled as a control.

Important Findings
Our results show that there was a significant decline ($P < 0.05$) in the carbon density of the soil (0–30 cm) following afforestation from the grassland (90.2 Mg C ha^{-1}) to the 27-year-old forest (66.7 Mg C ha^{-1}). Subsequently, the forest soils switched from being a C source to a C sink and began to sequester C to 71.3 Mg C ha^{-1} at the 47-year-old forest. We found the amount of C stored in the above- and belowground biomass increased with age of the forest stands and offset the amount of C lost from the soil. The amount of C stored in the above- and belowground biomass increased on average by 1.83 Mg C ha^{-1} year^{-1}. The increased storage of C in the biomass led to an increase in the total ecosystem C, from 90.2 Mg C ha^{-1} at the grassland site to 162.6 Mg C ha^{-1} at the 47-year-old forest. On a national scale, projected rates of ash afforestation to the year 2020 may cause a loss of 290 752 Mg C from the soil compared to 2 525 936 Mg C sequestered into the tree biomass. The effects of harvesting and reforestation may further modify the development of ecosystem C stocks over an entire ash rotation.

Keywords: ash (*Fraxinus excelsior* L.), chronosequence, soil, biomass, carbon, ecosystem

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INTRODUCTION

At the beginning of the 20th century, forests accounted for only 1% of the total Irish land cover (Pilcher and Mac an tSaoir 1995) compared to 58% of grassland area (Rafique *et al.* 2011, 2012). However, due to the facilitating efforts of successive governments, there has been rapid afforestation since the 1960s resulting in 10.0% forest land cover as of 2007 (NFI 2007a). A large proportion of this afforestation took place after the mid-1980s and was fuelled by government grant incentive schemes targeted at private landowners. Consequently, 63% of forests are <20 years old (NFI 2007a). This specific land use change provides an opportunity for Ireland to meet in part its international obligations set forth by the United Nations Framework Convention on Climate Change (UNFCCC 1992), as 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 (Kyoto Protocol; UN 1997). Ireland was obliged to implement this article over the period of 2008–2012 (Irish EPA 2012).

To assess if Ireland can benefit from Article 3.3, the impact of afforestation on the C stocks of Ireland must be determined.

Before the 1990s, broadleaf afforestation had been low, at ~3–4% of total annual afforestation. Conifers make up the majority of afforestation, especially Sitka spruce (*Picea sitchensis* [Bong] Carr.), which are preferred due to their greater productivity. Broadleaf planting increased to 20% of total annual afforestation in 1995, but steadily decreased to 13% in 2000 (Renou and Farrell 2005). It is current policy that broadleaves should make up 30% of new plantings.

Ash (*Fraxinus excelsior* L.) is the most popular species of indigenous broadleaf in Ireland, as it has the shortest economic rotation time of 60–80 years. Ash is also used in the indigenous industry of hurley making as used in the Irish sport of hurling (Horgan *et al.* 2004; Joyce *et al.* 1998). There are currently 19 200 ha of ash forests in Ireland (NFI 2007a), and with the government's policy to increase forest cover from its current 10% (NFI 2007a) to 18% by 2020 (Department of Agriculture 1996), and that 30% of new forests should be broadleaves, the amount of land expected to be forested with ash will greatly increase.

It is important to assess the impact of afforestation on soil organic carbon (SOC) stocks as they provide a long-term store of C, which is longer than that of the C stored in the forest biomass (Black *et al.* 2009; Kumar *et al.* 2013; Vesterdal *et al.* 2002). Irish forest soils are estimated to contain ~9% of the national total soil C stock (Eaton *et al.* 2008; Tomlinson 2005).

Soil C stocks are controlled by the balance between the inputs of organic material from the biota, and losses, primarily from microbial respiration (Peng *et al.* 2008; Zerva and Mencuccini 2005). The change in soil C stocks depends on myriad factors including tree species, soil type, rotation length, age, site management, topography and climate (Dixon *et al.* 1994; Jandl *et al.* 2007; Thuille *et al.* 2000). Some studies have found no change in SOC stocks after afforestation (Davis *et al.* 2003; DeGryze *et al.* 2004; Peri *et al.* 2010; Smal and Olszewska 2008). Others have found an increase in SOC stocks (Black *et al.* 2009; Guo and Gifford 2002; Hooker and Compton 2003; Mao *et al.* 2010; Morris *et al.* 2007; Post and Kwon 2000), while some have found a decrease in SOC stocks (Alberti *et al.* 2008; Parfitt *et al.* 1997). However, many studies have shown the same trend, a loss of SOC stocks in the initial years after afforestation, but thereafter increasing with age to match pre-afforestation levels and even to surpass them (Laganière *et al.* 2010; Mao *et al.* 2010; Paul *et al.* 2002; Romanyà *et al.* 2000; Zerva *et al.* 2005).

While the effects of afforestation on soil C stocks vary between studies, there is a consensus that an increase in the C stored can occur in the above- and belowground biomass following afforestation. The C sequestered into the forest biomass increased on average by 1.18–1.53 Mg C ha^{-1} year^{-1}, whereas the C sequestered into the soil is much less and varies from −0.69 to +0.15 Mg C ha^{-1} year^{-1} (Alberti *et al.* 2008; Hooker and Compton 2003). Other studies have found large increases in the forest biomass following afforestation (Black *et al.* 2009; Taylor *et al.* 2007; Tremblay *et al.* 2006; Vesterdal *et al.* 2002). We hypothesize that the afforestation will increase the net ecosystem C storage capacity especially because of C stored in woody tissues of the trees.

This study determined the above- and belowground soil C stocks in five afforested ash chronosequence stands (12, 20, 27, 40 and 47 years) and adjacent grassland to investigate the development of ecosystem C storage following grassland afforestation. The aims of the study were (i) to estimate the changes in bulk density (g cm^{-3}), SOC concentration (%) and carbon density (CD) (Mg C ha^{-1}) of the soil and (ii) to estimate the successional changes of C stored in the tree biomass and forest floor.

MATERIALS AND METHODS

Site description

The study sites were selected from private and state owned forests located in central Ireland. Five afforested ash stands were selected for sampling, aged 12, 20 27, 40 and 47, and referred to as F12, F20, F27, F40 and F47, respectively. Prior to afforestation, each forest site was grassland. A grassland site adjacent to site F12 was sampled to provide a comparison to all sites and will be referred to as G0. The sites G0 and F12 were located on private land within County Offaly, while sites F20, F27, F40 and F47 were located within the state owned Coillte forest of Castlemorris in County Kilkenny (Fig. 1 and Table 1). The forest sites consist of similar aged stands of ash, ranging in elevations between 73 and 106 m above sea level and with flat topographies. Each site has a brown earth soil: a well-drained, mature mineral soil possessing a uniform profile (Gardiner and Radford 1980). The chronosequence technique used in this study allows for the integration of independent forest stands with different ages, into one unit, substituting space for time. The stands are as close to identical in all aspects other than stand age so as to reduce variability (Black *et al.* 2009; Hedde *et al.* 2008; Tang *et al.* 2009; Taylor *et al.* 2007).

Soil and forest floor sampling methodology

Sites G0 and F12 were sampled in February 2010, while sites F20, F27, F40 and F47 were sampled in June and July 2010. At each site, a 20 m × 20 m square plot was set out and then partitioned into four 10 m × 10 m quadrants. Within each quadrant, four points were randomly selected and sampled for bulk density (g cm^{-3}) at the depths of 0–5, 5–10, 15–20 and 25–30 cm. Horizontal spacing of 5 cm was used between samples below 10 cm to avoid the effects of compaction from previous samples. Bulk density samples were taken using stainless steel bulk density rings (Eijkenkamp Agrisearch Equipment BV, The Netherlands) of 8 cm diameter × 5 cm height.

Adjacent to the point where the bulk densities were sampled, eight holes were sampled to depths of 0–10, 10–20 and 20–30 cm for SOC using a 10-cm soil auger (Eijkenkamp Agrisearch Equipment BV, The Netherlands).

At three points within each quadrant, the forest floor litter was sampled from 0.1 m^2 square plots. Each forest floor and soil sample was placed into a labelled polythene bag in the field.

All soil samples were stored at 4°C before being 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 at each quadrant by equal volume) and then ground to a fine powder. All soil samples were tested for carbonates. Any samples that tested positive for carbonates were treated with hydrochloric acid before combustion in a C/N analyser (Elementar—Vario Max CN) to determine the SOC (%).

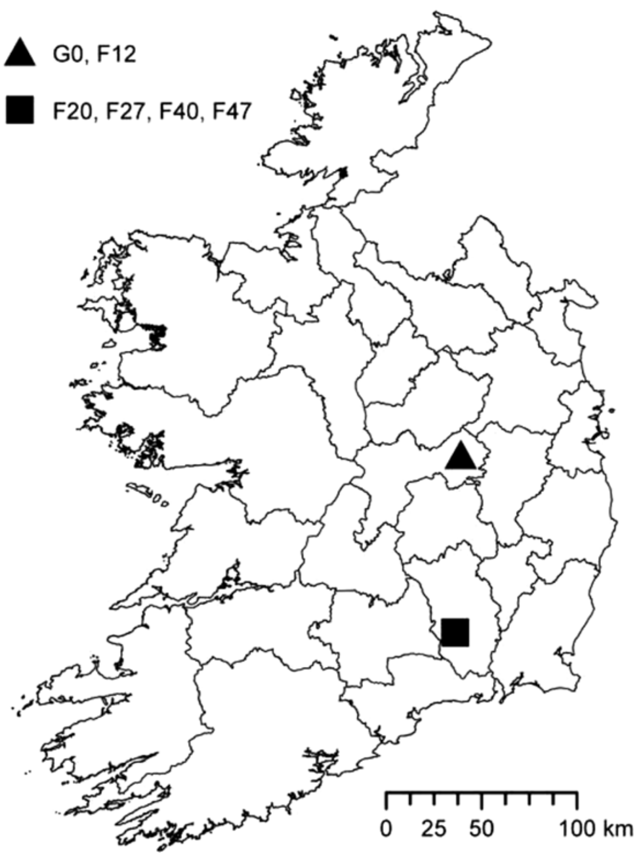

Figure 1: locations of all six sites within Ireland. F12, F20, F27, F40 and F47 are forest sites with ages of 12, 20, 27, 40 and 47, respectively. The G0 site is a grassland site used as control area.

The bulk density and CD were calculated using equations (1) and (2), respectively:

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

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

The bulk densities samples were converted to 10 cm depths to match the SOC data.

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

where CD = carbon density (Mg C ha^{-1}), SOC = soil organic carbon (%) and h = depth of soil (cm).

The soil texture was analysed at each depth for all sites from the bulked soil samples, using the hydrometer method, ASTM D422, 2002 (the soil texture data is shown in Table 2).

To summarize, at each of the six sites we obtained (i) 32 samples for SOC at each depth of 0–10, 10–20 and 20–30 cm using the soil auger that were bulked into 4 samples for each depth for analysis; (ii) 4 samples of bulk density of the depths 0–5, 5–10, 15–20 and 25–30 cm using the stainless steel rings and (iii) 12 samples of the forest floor.

Above- and belowground biomass

The methodology used to measure the aboveground biomass of the sites was adapted from the Irish National Forest Inventory (NFI) Protocol (NFI 2007b) and was non-destructive. Three random points were chosen within each forest site and a circular plot of 500 m^2 (25.24 m diameter) was set up with random points as plot centres. The diameter at breast height (cm) (DBH at 1.3 m) was recorded for each tree that had a DBH > 7 cm within each plot. Sites F40 and F47 were smaller than the other ash stands (<1500 m^2) and so the third plot was set to an area of 250 m^2. The stem and branch biomass was calculated from an allometric equation (3) of ash trees from an English study (Bunce 1968).

$$\ln(S) = -2.4598 + 2.4882 \ln(d) \quad (3)$$

Table 1: general description and stocking density, DBH and tree height at all of six sites in Ireland used to measure the ecosystem carbon dynamic after afforestation

Forest site	Stand age (years)	Elevation (m)	Georeference position	Stocking density (no. of stems ha^{-1})	DBH (cm)	Height (m)
G0	—	73	53°17′N, 7°12′W	—		
F12	12	73	53°18′N, 7°12′W	3433 ± 551	8.7 ± 0.1	9.6 ± 0.5
F20	20	87	53°27′N, 7°16′W	1400 ± 131	14.5 ± 0.4	11.4 ± 0.2
F27	27	75	53°27′N, 7°16′W	787 ± 70	17.6 ± 0.7	14.9 ± 0.2
F40	40	106	53°27′N, 7°16′W	727 ± 214	23.8 ± 3.0	20.2 ± 0.7
F47	47	102	53°27′N, 7°16′W	453 ± 153	26.6 ± 3.5	21.3 ± 1.3

Table 2: the soil texture measured as % sand, silt and clay at all six sites ($n = 4$ for each site) used to measure the ecosystem carbon dynamic after afforestation

Site	Sand (%)	Silt (%)	Clay (%)	Soil texture class
G0	43.4 ± 3.6	34.5 ± 8.2	22.1 ± 4.8	Loam
F12	39.9 ± 4.1	35.1 ± 1.6	25.0 ± 5.0	Loam
F20	40.8 ± 1.7	33.9 ± 2.0	25.3 ± 0.7	Loam
F27	39.7 ± 1.9	37.6 ± 1.7	22.7 ± 3.1	Loam
F40	45.9 ± 2.6	33.8 ± 1.1	20.3 ± 3.1	Loam
F47	43.6 ± 3.0	36.1 ± 1.6	20.4 ± 2.6	Loam

± shows the standard deviation.

where S = stem and branch biomass (kg) and d = DBH (cm).

The leaf biomass data were calculated from equation (4) of ash trees from an Italian study (Alberti *et al.* 2005).

$$L = 0.003d^{2.31} \quad (4)$$

where L = leaf biomass (kg) and d = DBH (cm).

The root biomass was calculated from Equation (5) (Cairns *et al.* 1997).

$$R = 0.26b \quad (5)$$

where R = root biomass (kg) and b = aboveground biomass (kg).

All biomass and forest floor litter were multiplied by 0.5 to estimate the mass of C (IPCC 1997).

Statistical analysis

The biomass, soil bulk density and SOC data, along with the 20–30 cm depth for CD were normally distributed and so were analysed by one-way analysis of variance to test for significant differences between all sites. The 0–10, 10–20 and 0–30 cm depths for CD and forest floor values were not normally distributed and were analysed using the non-parametric test, Kruskal–Wallis. All statistical analysis was calculated at $P < 0.05$ using SPSS (SPSS Inc., SPSS Statistics, Student Version, Release 17.0, 2008).

RESULTS

Soil texture and SOC

The soil texture class of loam was the same at all sites (Table 2). There is no difference in the soil texture along the chronosequence, confirming the suitability of the soils for sampling.

For the 0–10 cm depth, the SOC (mean ± standard deviation) decreased from its highest value of 4.5 ± 0.8% at G0 with increasing stand age to a minimum of 3.4 ± 0.5 and 3.4 ± 0.2%, at F27 and F40, respectively (Table 3). At the later stand age, the SOC was significantly lower compared to G0 and F12 ($P < 0.05$). The SOC was higher at F47 than it was at F27 and F40, but still lower than G0 and F12, although the SOC at F47 was statistically different only to the SOC at G0. The SOC of the 10–20 and 20–30 cm depths followed similar patterns as the 0–10 cm, although the magnitudes of SOC decreased with depth for sites. For example, the SOC for F12 decreased from 4.3% at 0–10 cm to 2.5% at 10–20 cm and to 1.6% at 20–30 cm giving an overall depth average of 2.8% for the 0–30 cm depth.

Soil bulk density

There were no significant differences in bulk densities between sites ($P > 0.05$) (Table 3). The bulk density of the 0–10 cm depth ranges from the lowest value of 0.85 ± 0.11 g cm^{-3} at site G0 to the highest value of 0.95 ± 0.06 g cm^{-3} at site F40. The 10–20 cm depth ranged from the lowest value of 1.03 ± 0.10 g cm^{-3} at site F20 to 1.13 ± 0.10 g cm^{-3} at site F40. The 20–30 cm bulk density values ranged from the lowest of 1.17 ± 0.06 g cm^{-3} at site F12 to the highest of 1.28 ± 0.10 g cm^{-3} at site F27. The bulk density of each site increases with depth.

Soil CD

The CD decreased with depth for all sites. The CD was highest for G0 (or F12), decreasing with age to its lowest at F27, after which CD began to increase again (Table 3 and Fig. 2). In the 0–10 cm soil depth, the largest value of CD was 40.3 ± 5.6 Mg C ha^{-1} for site F12, greater than the 38.8 ± 11.0 Mg C ha^{-1} of site G0. From site F12, there was a large decrease to 32.9 ± 3.3 Mg C ha^{-1} at site F20 and the lowest CD of 31.3 ± 2.8 Mg C ha^{-1} was at site F27. The CD began to increase with age after site F27, with values rising to 32.2 ± 3.7 and 34.5 ± 2.0 Mg C ha^{-1} for sites F40 and F47, respectively. However, there were no significant differences between the carbon densities of depth 0–10 cm of each site.

Site G0 had the highest CD of the 10–20 cm soil depth with 32.7 ± 4.9 Mg C ha^{-1}, being significantly larger than sites F20, F27 and F47 ($P < 0.05$). From site G0, there was a sustained decrease to the lowest value of 21.4 ± 3.0 Mg C ha^{-1} at site F40, before a small increase to 22.3 ± 3.0 Mg C ha^{-1} at site F47. Site F12 had the highest CD of the 20–30 cm soil depth with 18.8 ± 2.5 Mg C ha^{-1}, slightly larger than the 18.7 ± 3.6 Mg C ha^{-1} of site G0. There was a decrease in CD from site F12 to site F27 with the lowest value of 13.8 ± 1.8 Mg C ha^{-1}, before an increase with sites F40 and F47 having carbon densities of 15.0 ± 2.1 and 14.5 ± 2.5 Mg C ha^{-1}, respectively. There was no significant difference between the sites in the CD of the 20–30 cm soil depth.

For the integrated depth 0–30 cm, site G0 had the highest CD of all sites with 90.2 ± 18.0 Mg C ha^{-1}, slightly larger than

Table 3: the mean, minimum and maximum values of bulk density (BD, g cm^{-3}), soil organic carbon (SOC, %) and CD (CD, Mg C ha^{-1}) measured at soil depth of 0–10, 10–20, 20–30 and 0–30 cm for all six sites (n = 4 for each attribute) in Ireland used to measure the ecosystem carbon dynamics after afforestation

Site	Soil attributes	0–10			10–20			20–30			0–30		
		Mean ± SD	Minimum	Maximum	Mean ± SD	Minimum	Maximum	Mean ± SD	Minimum	Maximum	Mean ± SD	Minimum	Maximum
G0	BD	0.85 ± 0.11[a]	0.77	1.01	1.10 ± 0.12[a]	0.93	1.22	1.24 ± 0.09[a]	1.17	1.37	1.06 ± 0.19[a]	077	1.37
F12	BD	0.94 ± 0.11[a]	0.81	1.05	1.12 ± 0.10[a]	1.05	1.27	1.17 ± 0.06[a]	1.11	1.25	1.08 ± 0.13[a]	0.81	1.27
F20	BD	0.88 ± 0.06[a]	0.80	0.92	1.03 ± 0.10[a]	0.92	1.15	1.23 ± 0.0[a]	1.13	1.30	1.05 ± 0.17[a]	0.80	0.30
F27	BD	0.93 ± 0.06[a]	0.87	1.00	1.06 ± 0.11[a]	0.90	1.15	1.28 ± 0.10[a]	1.13	1.34	1.09 ± 0.17[a]	0.87	1.34
F40	BD	0.95 ± 0.06[a]	0.90	1.04	1.13 ± 0.10[a]	1.00	1.25	1.22 ± 0.10[a]	1.11	1.34	1.10 ± 0.14[a]	0.90	1.34
F47	BD	0.90 ± 0.07[a]	0.82	1.00	1.10 ± 0.12[a]	1.02	1.28	1.26 ± 0.09[a]	1.20	1.39	1.09 ± 0.17[a]	0.82	1.39
G0	SOC	4.50 ± 0.80[ab]	3.68	5.23	2.97 ± 0.15[c]	2.76	3.11	1.51 ± 0.29[ab]	1.21	1.89	3.0 ± 1.4[a]	1.2	5.2
F12	SOC	4.27 ± 0.24[a]	4.06	4.55	2.48 ± 0.14[b]	2.37	2.68	1.61 ± 0.15[a]	1.42	1.78	2.8 ± 1.2[a]	1.4	4.6
F20	SOC	3.75 ± 0.50[ab]	3.10	4.31	2.24 ± 0.24[ab]	1.98	2.56	1.46 ± 0.25[ab]	1.14	1.74	2.5 ± 1.0[a]	1.1	4.3
F27	SOC	3.39 ± 0.47[ab]	2.79	3.92	2.04 ± 0.08[a]	1.93	2.12	1.09 ± 0.17[b]	0.88	1.27	2.2 ± 1.0[a]	0.88	3.9
F40	SOC	3.39 ± 0.18[a]	3.20	3.61	1.89 ± 0.13[a]	1.78	2.07	1.24 ± 0.20[ab]	1.05	1.44	2.2 ± 1.0[a]	1.1	3.6
F47	SOC	3.84 ± 0.44[ab]	3.23	4.23	2.07 ± 0.45[abc]	1.53	2.45	1.17 ± 0.26[ab]	0.79	1.39	2.4 ± 1.2[a]	0.79	4.2
G0	CD	38.8 ± 11.0[a]	29.2	51.8	32.7 ± 4.9[a]	25.7	37.2	18.7 ± 3.6[a]	14.1	22.8	90.2 ± 18.0[ab]	70.1	111.8
F12	CD	40.3 ± 5.6[a]	35.5	47.8	27.7 ± 2.3[ab]	24.9	30.3	18.8 ± 2.5[a]	16.4	22.2	86.8 ± 6.7[b]	80.0	94.7
F20	CD	32.9 ± 3.3[a]	28.0	35.0	23.0 ± 2.5[bc]	19.4	25.2	17.9 ± 2.9[a]	14.8	21.7	73.7 ± 7.8[ab]	62.2	79.5
F27	CD	31.3 ± 2.8[a]	27.9	33.9	21.5 ± 2.2[c]	19.1	23.5	13.8 ± 1.8[a]	11.7	16.0	66.7 ± 3.0[a]	63.5	70.3
F40	CD	32.2 ± 3.7[a]	29.1	37.5	21.4 ± 3.0[ac]	19.1	25.9	15.0 ± 2.1[a]	13.0	17.8	68.6 ± 6.5[a]	62.4	77.4
F47	CD	34.5 ± 2.0[a]	32.3	37.0	22.3 ± 3.0[bc]	19.5	25.1	14.5 ± 2.5[a]	11.0	16.6	71.3 ± 7.1[a]	62.7	78.7

± shows the standard deviation.[abc]Means with different lowercase letters are significantly different among sites ($P < 0.05$).

the 86.8 ± 6.7 Mg C ha^{-1} of site F12. From site F12, there was a significant decline (P < 0.05) in CD to the lowest value of 66.7 ± 3.0 Mg C ha^{-1} at site F27. After site F27, there was a small increase in CD to F47, with a value of 71.3 ± 7.1 Mg C ha^{-1}, which was significantly smaller than F12 (P < 0.05). The change in the amount of C stored in the 0–30 cm soil depth with the stand age is presented in equation (6) (Fig. 3):

$$SC = 0.0162x^2 - 1.2457x + 92.839, \quad R^2 = 0.85 \qquad (6)$$

where SC = total soil, 0–30 cm (Mg C ha^{-1}); x = age of stand (years).

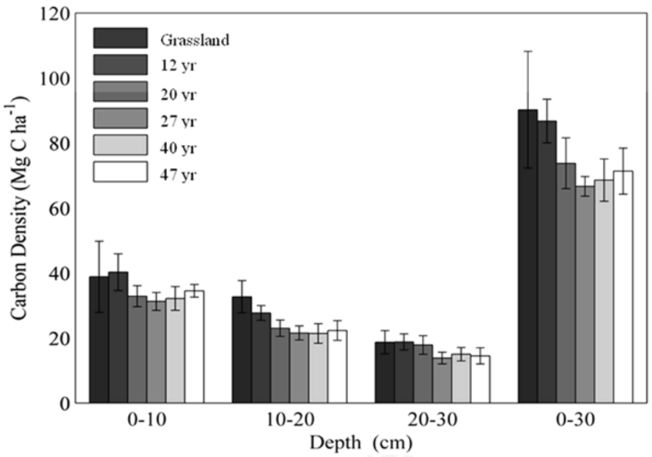

Figure 2: carbon density (Mg C ha^{-1}) versus depth for sites G0, F12, F20, F27, F40 and F47. The 12, 20, 27, 40 and 47 stand for the age of sites in years. Error bars indicate standard deviation.

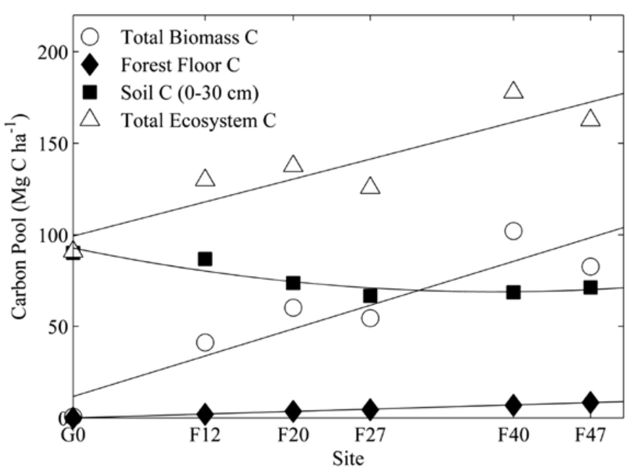

Figure 3: carbon pools (Mg C ha^{-1}) for sites G0, F12, F20, F27, F40 and F47. Equations for the carbon pools are $B = 1.826x + 12.731, R^2 = 0.85,$ $FF = 0.178x, R^2 = 0.99,$ $SC = 0.0162x^2 - 1.2457x + 92.839, R^2 = 0.85$ and $E = 1.54x + 100.207, R^2 = 0.81,$ where B = total above- and belowground biomass (Mg C ha^{-1}); FF = total forest floor (Mg C ha^{-1}); SC = total soil, 0–30 cm (Mg C ha^{-1}); E = total ecosystem (Mg C ha^{-1}); x = age of stand (years). Biomass C is total C present in living organisms.

Forest floor and above- and belowground C

The amount of C stored in the forest floor increased with the age of the ash stands (Table 4). The forest floor at site F12 had a value of 2.0 ± 0.8 Mg C ha^{-1} and increased to the largest amount of C at site F47 with 8.6 ± 4.6 Mg C ha^{-1}. The values of forest floor C were not significantly different between sites (P < 0.05). The forest floor consisted mainly of woody debris rather than decayed leaf biomass. The forest floor on average accumulated ~0.18 Mg C ha^{-1} year^{-1} (Fig. 3). The changes in the forest floor C with stand age is presented in equation (7):

$$FF = 0.178x, \quad R^2 = 0.99 \qquad (7)$$

where FF = total forest floor (Mg C ha^{-1}) and x = age of stand (years).

The DBH of the ash stands increased with age from 8.7 cm at site F12 to 26.6 cm at site F47. However, the stocking density of the ash stands decreased from 3433 stems ha^{-1} at F12 to 453 stems ha^{-1} at F47 due to thinning activities (Table 1). There was an overall increase in the live aboveground biomass C along the chronosequence (Table 4). There was a large increase in the live above- and belowground biomass C after afforestation with site F12 having accumulated 41.2 ± 6.6 Mg C ha^{-1}. There was a further increase to 59.8 ± 4.1 Mg C ha^{-1} at site F20, before a decrease in the total live above- and belowground C at site F27 with 54.5 ± 3.6 Mg C ha^{-1} as the stocking density almost halves from 1400 stems ha^{-1} at site F20 to 787 stems ha^{-1} at site F27. From site F27, there was a significant increase (P < 0.05) to 101.9 ± 5.0 Mg C ha^{-1} at site F40 before another decline to 82.7 ± 0.5 Mg C ha^{-1} again due to the stocking density decrease from 727 (stems ha^{-1}) at site F40 to 453 (stems ha^{-1}) at site F47 (Table 1). The above- and belowground C of sites F40 and F47 are significantly larger than sites F12, F20 and F27 (P < 0.05). The amount of C stored in the biomass of grasslands is much less than that stored in forests. Black *et al.* (2009) and estimate that between 2.3 and 2.4 Mg C ha^{-1} is stored in the live above- and belowground biomass of Irish grasslands.

Dead biomass was noted at only three sites, G0, F20 and F40, and is a very small fraction of the total ecosystem C representing only 0.1, 0.3 and 0.1%, respectively, of the total ecosystem C. The above- and belowground biomass accumulated on average ~1.85 Mg C ha^{-1} year^{-1} (Fig. 3). The change in the total above- and belowground C with stand age using a grassland biomass value of 2.35 Mg C ha^{-1} (Black *et al.* 2009) is presented in equation (8):

$$B = 1.826x + 12.731, \quad R^2 = 0.86 \qquad (8)$$

where B = total above- and belowground biomass (Mg C ha^{-1}) and x = age of stand (years).

Total ecosystem C

The change in total ecosystem C over the chronosequence follows the increase in tree biomass (Fig. 3). The total ecosystem C increased following afforestation, despite the loss of soil C, from 90.2 Mg C ha^{-1}

Table 4: the mean along with their ± standard deviation of each C pool (Mg C ha^{-1}) and changes along the chronosequence measured at all six sites in Ireland used to measure the ecosystem carbon dynamics

	Site					
Carbon pool stocks (Mg C ha^{-1})	G0	F12	F20	F27	F40	F47
Live stem and branch biomass	—	31.9 ± 5.1	46.5 ± 3.2	42.4 ± 2.8	79.3 ± 3.9	64.4 ± 0.4
Live leaf biomass	—	0.8 ± 0.1	1.0 ± 0.1	0.9 ± 0.1	1.6 ± 0.1	1.3 ± 0.03
Live belowground biomass	—	8.5 ± 1.4	12.3 ± 0.9	11.2 ± 0.7	21.0 ± 1.0	17.1 ± 0.1
Live above and belowground biomass	—	41.2 ± 6.6	59.8 ± 4.1	54.5 ± 3.6	101.9 ± 5.0	82.7 ± 0.5
Dead stem and branch biomass	—	—	0.3 ± 0.2	—	0.1 ± 0.2	—
Dead belowground biomass	—	—	0.1 ± 0.1	—	0.04 ± 0.06	—
Dead above and belowground biomass	—	—	0.4 ± 0.3	—	0.2 ± 0.3	—
Forest floor	—	2.0 ± 0.8	3.6 ± 1.6	4.5 ± 0.7	6.9 ± 6.0	8.4 ± 4.5
Soils (0–30 cm)	90.2 ± 18.0	86.8 ± 6.7	73.7 ± 7.8	66.7 ± 3.0	68.6 ± 6.5	71.3 ± 7.1
Ecosystem	90.9 ± 18.0	129.9 ± 9.4	137.6 ± 9.0	125.7 ± 4.7	177.8 ± 10.3	162.6 ± 8.4

at G0 to 162.6 Mg C ha^{-1} at site F47 (Table 4). The ecosystem C drops at two sites, F27 and F47, due to the reduction in the amount of C stored in the aboveground biomass (due to thinning of the stocking numbers). Over the course of the chronosequence, the portion of the total ecosystem C stored in the soil decreases from 100% of the total ecosystem C at site G0 to 43.9% of the total ecosystem C at site F47 (Fig. 4). Between sites F27 and F40, the above- and belowground biomass becomes the largest portion of the total ecosystem C, larger than the store of C within the forest soil. The change in the total ecosystem C with stand age using a grassland biomass value of 2.35 Mg C ha^{-1} (Black *et al.* 2009) is presented in equation (9):

$$E = 1.54x + 100.207, \quad R^2 = 0.81 \tag{9}$$

where E = total ecosystem (Mg C ha^{-1}) and x = age of stand (years).

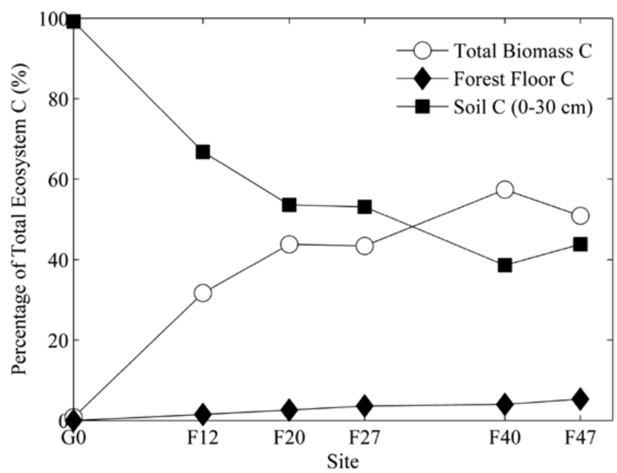

Figure 4: percentage of each carbon pool (total biomass C, forest floor C and soil C) in relation to the total ecosystem C, for sites G0, F12, F20, F27, F40 and F47. Biomass C is total C present in living organisms.

DISCUSSION

Soil organic carbon

Afforestation of grassland with ash resulted in a loss of SOC. While the 0–30 cm depth of the grassland had an SOC of 3.0%, the ash stand at age 47 had an SOC of 2.4%, corresponding to an SOC loss of 20%. This occurs as forest establishment initially reduces the SOC of soils as it disturbs soil structure and leads to an increase in the decomposition of organic matter and thus an increase in C lost to the atmosphere from soil respiration (Zerva and Mencuccini 2005). Within the first few decades, the litter input to the soil from the young forest is small and cannot match the losses of SOC, therefore becoming a source of C (Vesterdal *et al.* 2002). As the forest ages, the organic matter input from plant residues increase and along with reduced soil disturbance, the soil switches from losing C to beginning to sequester C (Mao *et al.* 2010), which occurred at about age 27 in this study.

Soil bulk density

The bulk densities of the soils show no change over the chronosequence (Table 3). Within the literature, it has been noted that the bulk density of soils decreased with age due to the incorporation of organic matter and so the bulk density decreases while the soil layer becomes thicker (Vesterdal *et al.* 2002). It is suggested that to compensate for the increasing soil depth, the SOC stocks should be calculated for a fixed mass of soil rather than a fixed volume of soil (Mao *et al.* 2010; Vesterdal *et al.* 2002). Within this study, the SOC stocks were calculated by a fixed volume as there was no detected change in bulk density with age. This was also noted in Gholz and Fisher (1982), who found no significant differences between the bulk densities in a slash pine chronosequence of 2- to 34-year-old stands in Florida, USA.

Soil CD

Soil CD follows the pattern of SOC, with a decline following afforestation. This is due to a loss of SOC from forest establishment, which outweighs the organic matter being added to the soil by the young forests. After 27 years, there was an increase in the soil C stocks of the forest with age, as the inputs of organic matter from the litterfall, woody debris and roots of the forest become greater than the loss of soil C from decomposition. The rate of increase after 27 years is slower than the rate of decline from site G0 to site F27. However, the increase in SOC after 27 years is not statistically significant. Over the chronosequence, the soil loses C and so as the ash stands reach 60 years (the age that these plantations are scheduled to be harvested), the soil CD is estimated to reach 76.4 Mg C ha^{-1}, representing a 13.8 Mg C ha^{-1} loss from the pre-afforested conditions. This is a greater loss and mitigation measures should be considered to limit these soil carbon losses. However, more work must be done to assess the C stocks of ash forests older than 47 years to verify this trend. Black *et al.* (2009), in a chronosequence of Sitka spruce stands on surface-water gley soils in Ireland, found an increase in soil C stocks, from 97.2 Mg C ha^{-1} at the grassland site to 137.3 Mg C ha^{-1} at the 16-year-old spruce stand, an annual increment of 2.2–2.5 Mg C ha^{-1} $year^{-1}$. The authors suggested that this may be due to the higher total belowground C allocation of their sites and reduced decomposition due to the anaerobic conditions associated with the water saturated soils. Tang *et al.* (2009) in a chronosequence of deciduous forests, predominantly aspen (*Populus tremuloides*) and sugar maple (*Acer saccharum*) after disturbance in Wisconsin and Michigan, USA, found an initial decrease in the soil carbon stocks at 0–60 cm depth of soil from the regenerated stand to the young stand (10 years), and thereafter the carbon stocks of the soil increased up to the mature forest (73 years) and the old growth forest (350 years).

The amount of SOC that is either lost or sequestered depends upon site management, tree species, soil type, length of rotation, age, topography, climate and management (Dixon *et al.* 1994; Jandl *et al.* 2007; Thuille *et al.* 2000). Ash has the shortest economic rotation length of any broadleaf species planted in Ireland at 60–80 years; however, ash is not as productive as the more widely grown conifers, such as Sitka spruce (*P. sitchensis*). The greater productivity of the conifers is likely to result in a large input of organic matter into the soil, leading to a quicker recovery of SOC stocks (Black *et al.* 2009) than ash, although other studies have found broadleaves to sequester more C into soil than conifers (Laganière *et al.* 2010).

Above- and belowground biomass C

The significant increase in biomass C with the age of the ash stands follows the increase in the mean DBH of the ash trees; however, there are two occasions when C falls in the above- and belowground biomass C. These are both due to the decrease in the stocking density of each stand as the sites are thinned. The cutting of trees provides more growing space for the remaining trees (NFI 2007b). The C stored in the biomass of the forests on average increased by 1.83 Mg C ha^{-1} $year^{-1}$, and at the projected time of harvesting, at 60 years, it is estimated to be 122.3 Mg C ha^{-1} for the above- and belowground biomass of the ash stands. The rate that C is sequestered into the above- and belowground biomass of the ash trees is similar to values in the literature. Alberti *et al.* (2008), in a chronosequence of mixed ash and sycamore in a natural recovery in Italy, found that the trees sequestered 1.69 Mg C ha^{-1} $year^{-1}$, while Hooker and Compton (2003), in a natural recovery white pine mixed forest in north-eastern USA, found that the aboveground biomass sequestered 1.53 Mg C ha^{-1} $year^{-1}$.

There is uncertainty in the allometric equations used to estimate the biomass of the stands due to their derivation coming from differing locations and species. Equation (3) (Bunce 1968) is an equation based on the stem and branch biomass of ash trees for England and is the most appropriate allometric equation for Irish ash trees at present, but it does not account for the biomass of the live leaves and the root biomass. Equation (4) (Alberti *et al.* 2005) is based on ash trees from Italy, from a climate different to that of the ash sites sampled within this study. Equation (5) (Cairns *et al.* 1997) is a general measure of the ratio of root biomass to aboveground biomass for a number of species, not just ash. At present, these equations represent the best method of estimating the biomass of Irish ash. Future work should focus on producing allometric equations for Irish ash trees that will allow for improved estimates of biomass and biomass C at both the stand and national level.

Total ecosystem C

While there was a loss in soil C due to afforestation, there was an increase in the aboveground biomass C along the chronosequence. As the ash stand grows, the loss of C from the soil is more than balanced by ever larger amounts of C being accumulated in the forest biomass, and the total ecosystem C follows this trend at F27 and F47, where the total ecosystem C decrease is due to thinning of the ash stands and the subsequent loss of biomass C from the ecosystem as the trees are removed from the sites. At the 40-year-old ash stand, the biomass becomes a larger store of C than the soil. Over the chronosequence, the ecosystem sequesters a mean of 1.54 Mg C ha^{-1} $year^{-1}$ from the atmosphere, and at 60 years, there is an estimated 192.6 Mg C ha^{-1} stored within the ecosystem. Black *et al.* (2009), in a chronosequence of Sitka spruce stands on surface-water gley soils in Ireland, found that after 10 years, the afforested sites become carbon sinks, due to both the increase in soil carbon stocks and the increase in C stored in the aboveground biomass increasing from 1.7 Mg C ha^{-1} at the grassland site to 176.5 Mg C ha^{-1} at its maximum at the 45-year-old forest. Vesterdal *et al.* (2002) found a loss in soil C from two separate Oak and Norway spruce forests; however, there was a much greater amount of C stored in the biomass, ~75 and 105 Mg C ha^{-1} for the Oak and Norway spruce, respectively.

It is Irish government policy to increase the current national forestry area from its current 10% to 18% by 2020, with an aim of 30% of all afforestation being broadleaf species. If ash will be planted in the same ratio as currently found (12.6% of all broadleaves), then there will approximately be an extra 21 095 ha of ash forests planted by 2020. This would cause a loss of ~290 752 Mg of SOC from the soil over the full 60-year rotation. However, we estimate that ~2 525 936 Mg C will be sequestered in the above- and belowground biomass of the trees, which is almost nine times the amount lost from the soil. However, soils store C for longer than forest biomass, and the loss of soil C in this study shows that when assessing forest C stocks, soil C should always be measured so as to assess the entire ecosystem C. As the forest biomass is normally harvested after 60–80 years, work should be undertaken to assess the changes in ecosystem C following harvesting and reforestation so as to gain insight into impacts of the full rotation of the ash forests. Studies have shown different effects of harvesting on the SOC stocks. Zerva *et al.* (2005) found a loss in soil C after clearfelling before an increase in soil C in the second rotation of a Sitka spruce chronosequence in England, while other studies have found very little or no change in soil C following harvest (Johnson and Curtis 2001; Martin *et al.* 2005; Yanai *et al.* 2003).

With the recent and continuing afforestation within Ireland, there is a unique opportunity to study the impacts of a number of different tree species on the C stocks of a number of different soil types. The chronosequence presented here could be expanded in the next few years, allowing for repetition of the younger sites, and gaining a greater insight into the losses of soil C from forest establishment. The sampling of the older sites should also be repeated in the next 10–20 years to determine the total soil C stocks of the ash sites before harvesting and postharvest.

This study examined only one soil type, brown earth, which represents approximately one-third of the total current ash area (NFI 2007a). The two other major soils that ash is grown on in Ireland are gleys and grey brown podzolics, which occupy 27 and 14%, respectively. Further work is required to study the effects of ash forests on the SOC stocks of these two soil types so as to improve the accuracy of the estimates. This is especially the case for the gley soils as soils with high clay contents, >33% (Laganière *et al.* 2010), such as gleys, have a greater capacity to accumulate SOC and so may lose less soil C over time than the brown earth soils presented here.

CONCLUSIONS

There has been very little assessment of the impact of afforestation on ecosystem C stocks in Ireland, especially the impacts of broadleaf afforestation and their effect on soil C. We present changes in the carbon pools of ash forests with age following afforestation. We found that following afforestation, the forest soil C decreased for the first three decades, before beginning to sequester C, but at a slower rate than it was initially lost. However, the soil C increase is not statistically significant. The C lost from the soil was offset by the increase in the C stored in the biomass of the ash forests resulting in the total ecosystem acting as a C sink. Given the Irish governmental policy to increase the national forest cover to 18% by the year 2020, through planting of ash on ~21 095 ha, we estimate that a 60-year rotation of these new forests may lead to ~291 111 Mg of SOC being lost from the soil. However, 2 530 155 Mg C may be simultaneously sequestered into the biomass of the trees, thus providing a substantial net ecosystem C sequestration. Future work should assess the impacts of harvesting and reforestation on the ecosystem C stocks in order to fully understand ecosystem C dynamics in afforested ash stands over multiple rotation periods.

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