Original article

Carbon stock changes in a peaty gley soil profile after afforestation with Sitka spruce (*Picea sitchensis*)

Argyro ZERVA, Maurizio MENCUCCINI*

School of GeoSciences (IERM), Edinburgh University, Darwin Building, Mayfield Rd, Edinburgh EH9 3JU, United Kingdom

Abstract – We investigated the changes of carbon (C_{org}) stocks in the litter (O_L), organic (O_H) and mineral (A) layer after afforestation and at different stages after clearfelling of the first rotation, in a forest chronosequence of Sitka spruce (*Picea sitchensis*) on peaty gley soil, in Harwood Forest (N.E. England). The sites chosen were: unplanted natural grassland, 40-yr-old first rotation, 18 months-old clearfelled, and 12, 20 and a 30 yr-old second rotation. A further comparison was carried out in three 40-yr-old stands between unplanted stripes of land (rides) and adjacent forest. Measurements of soil C_{org} were conducted with two methods, i.e., weight loss on ignition (L.O.I.) and dry combustion by C/N analysis. The results from two methods were linearly related. Afforestation changed both the total amounts and the distribution of the C_{org} stocks from the unplanted natural grassland. The total stocks of C_{org} decreased during first rotation and increased during second rotation to values similar to those found in the unplanted grassland. The vertical distribution of C_{org} also changed, with proportionally more carbon stored in the O_L and inside the A layer and less in the organic layer after afforestation and two rotations.

soil carbon stocks / bulk density / C concentration / Sitka spruce / forest management / peaty gley soil

Résumé – Changement des stocks de carbone dans le profil des sols tourbeux à gley après boisement avec l'épicéa de Sitka (*Picea sitchensis* (Bong.) Carr). Les variations de stocks de carbone (C_{org}) dans la litière (O_L), dans l'horizon organique (O_H) et l'horizon minéral (A) ont été étudiées après boisement et à différents stades après coupe rase de la première rotation, dans une chronoséquence forestière de l'Epicéa de Sitka (*Picea sitchensis*) sur des sols tourbeux à gley en Forêt d'Hardwood (N.E. Angleterre). Les sites choisis étaient les suivants : prairie naturelle, première rotation âgée de 40 ans, coupe rase depuis 18 mois, et 12, 20 et 30 ans de deuxième rotation. Une comparaison supplémentaire a été faite dans trois peuplements âgés de 40 ans entre des bandes de terre non plantées et dans une forêt adjacente. Les mesures de C_{org} ont été menées en utilisant deux méthodes : pertes de poids par ignition (L.O.I.) et combustion sèche par analyse du C/N. Les résultats des deux méthodes étaient linéairement liés. Le boisement change à la fois l'importance et la distribution des stocks de C_{org} des prairies naturelles. Les stocks totaux de C_{org} décroissent pendant la première rotation et s'accroissent pendant la seconde rotation vers des valeurs similaires à celles trouvées dans les prairies non plantées. La distribution verticale de C_{org} change aussi avec proportionnellement plus de carbone stocké dans la litière (OL) et dans l'horizon A et moins dans l'horizon organique après le boisement et deux rotations.

stocks de carbone dans le sol / densité volumique / concentration en C / épicéa de Sitka / aménagement forestier / sol tourbeux à gley

1. INTRODUCTION

Soils constitute a significant reservoir of carbon (C) in both organic and mineral forms and can play an important global role, by mitigating or contributing carbon to the atmosphere. Globally, soils contain more than two thirds of the total C stored in vegetation [9, 22] and almost twice the amount in the atmosphere [22], while forest soils (including peaty soils) contain approximately 69% of the total forest C pool [4]. The soil C in temperate forests is estimated to vary from 104 to 142 Pg [22, 30], while in Europe approximately 35% of the total C in the soils is held within high organic matter soils ($\geq$ 8% organic matter) [24].

The amount of C stored in the soil is the balance between inputs of organic material from the biota, which depends on the type of vegetation and its productivity at a particular site, and losses, primarily through soil microbial respiration [18]. Forests continuously recycle C through photosynthesis and respiration; however, the net sequestration of C in vegetation and especially in soil can range over time periods from years to centuries, depending on the species, site conditions, disturbances regime and management practices [4].

Currently, forest plantations globally occupy an area of 187×10^6 ha; however, they account for less than 5% of the global forest cover [5]. Recent trends towards harvesting younger stands raise concerns about how such forest management will impact on soil processes and global carbon sequestration [15]. Forest plantations are often planted in areas that did not have forest cover before (at least in temperate regions), such as grasslands or abandoned agricultural land. At establishment, site

* Corresponding author: m.mencuccini@ed.ac.uk

preparation may involve disturbing the soil, e.g. by the creation of drainage ditches or ploughing. These practices may accelerate organic matter decomposition by disturbing soil structure and breaking soil aggregates, leading to a loss of soil C [14, 31].

Substantial losses of C from vegetation and soils can also be caused by harvesting [10]. Soil carbon storage is likely to initially decline after clear cutting, because C inputs from plant production are too low to counteract losses by soil respiration. Furthermore, intensive forest management may also lead to long-term decreases in soil organic matter content [9]. On the other hand, regenerating forests and plantations may represent important carbon sinks as a result of carbon storage in both plant biomass and soils [12]. Carbon accumulation rates during afforestation depend on tree species, soil type and the length of the rotation [29].

In Britain, about 315 000 ha of shallow peatlands (mainly peaty gleys) have been planted with coniferous forests, mostly Sitka spruce (*Picea sitchensis* (Bong.) Carr) [3]. Afforestation on peaty soils may cause an increase in the rates of oxidation of the peat due to improved aeration by the drainage and the lowered water table under a maturing tree stand [16]. Growing trees can sequester carbon in the aboveground biomass as well as in the litter layer and soil; however, whether or not afforestation will give a net benefit of C sequestration depends on the rate of peat oxidation.

Two commonly used methods for measuring soil C are: (a) the weight by loss on ignition (L.O.I.) which measures organic C (C_{org}) content by measuring mass loss following high temperature combustion at approximately 500 °C and (b) dry combustion by C/N analysers where samples are oxidised at high temperature (approximately 1 000 °C) and then the CO_2 gas evolved is measured by infrared gas absorption analysis (IRGA) or gas chromatography (GC). The use of C/N analysers is expensive and the high temperature oxidation also liberates C from carbonate minerals, thus a separate analysis for the separation of carbonate-C (C_{min}) is sometimes required. The ignition temperature used for L.O.I. is below that at which C_{min} decomposes [11] and the use of L.O.I. has been suggested, as long as it is checked against a dry-combustion method [25].

Soil carbon storage is an important factor for ecosystem stability in the long-term, but small changes in a large pool are difficult to detect, although even small changes in the soil carbon pool can result in relatively large changes in fluxes of CO_2 to the atmosphere. The vital role of soils as a sink or source for C at the global scale in offsetting atmospheric CO_2 concentrations [13] makes it important to accurately evaluate the effects of forest management on soil C storage.

The objective of the study was to examine the effects of afforestation on peaty gley soils with Sitka spruce and forest management on soil C stocks within the soil profile. The overall aim was to gain some insight into the long-term effects of afforestation, forest harvesting and reforestation on soil C stocks.

2. MATERIALS AND METHODS

2.1. Site description

Measurements were made in various stands within Harwood forest (55° 10' N, 2° 3' W), in Northamberland, England. Harwood forest mostly consists of even aged stands of pure Sitka spruce (*Picea sitch-*

ensis (Bong.) Carr.). The area rises from 200 m in the South-East to 400 m in the North-West. Average annual precipitation is 950 mm, mean annual temperature is 7.6 °C. The dominant soil type is peaty gley, i.e., a seasonally waterlogged soil with a superficial organic-rich layer [19].

The establishment of the forest started in the 1930s with the planting of ericaceous moorland. The trees were planted on top of small ridges following ploughing, i.e., a process that resulted in a peculiar structure of the soil profile. In the furrows the organic horizon is often absent. On the ridges there is often an inversion of the usual horizon arrangement (O_L, O_H, A), with the A horizon above the O_H, and the O_L horizon in deeper layers.

The forest is managed with rotations of about 40 years. At this age a whole stand is clearfelled and the planting of trees takes place after two or three years. Tree harvesting is conducted by mechanical harvesters with a mechanically operated harvesting head that fells a tree, de-limbs it, and transfers the logs to a special extended rear frame and carries them out of the forest. The slash is left on site to create the bed over which the harvester moves. Subsequently, the brash is accumulated into large heaps to make room for planting. Based on visual observations, these processes created a surface layer of mixed organic material, logging slash, twigs and roots.

2.2. Soil sampling

The detailed methodology for soil C sampling and analysis is described in [31] and will only be outlined here. Soil sampling took place during the summers of 2000 and 2001. The research was undertaken in stands of different ages to represent the continuum of stand development since initial afforestation, an area where a mature stand had been clearfelled, and areas under natural moorland that were representative of the land cover prior to forest establishment. All stands were on peaty gley soils. The following stands were sampled: three first-rotation 40-yr-old, three 30-yr-old, three 20-yr-old, and four 12-yr-old stands, all of which during second rotation. Two unplanted (grassland) areas were also used, together with a single clearfelled area (CF), for which no comparable replicate was available. The two unplanted grassland sites were chosen inside the forest in areas left unplanted for conservation reasons, but still on the same soil type.

For each stand, we sampled between 1 and 5 plots, with between 8 and 9 soil cores taken from each plot. In the summer 2000, five plots were sampled from each stand, to determine the within- as well as the among-plot variability. In 2001, given that most of the variability was within, not among, plots, number of plots/stand was reduced to one. Soil samples were taken using a manually driven soil corer with a slide hammer attachment (Giddings Machine Company, Inc., USA) (5.5 cm diameter) or a soil auger (2.5 cm diameter), to a depth of about 45 cm. Tests were also carried out to compare the estimates obtained with the auger with those obtained with the corer. Twenty-eight individual cores were taken adjacent to one another with both corers in several different plots. The cores were separated into three layers (see below) and a *t*-test conducted to test whether significant differences existed in the estimation of soil C stocks by the two instruments. The values given by the two methods were not significantly different ($P > 0.05$) and the data were pooled.

An additional study was conducted in three 40-yr-old stands to compare soil C stocks inside the forest with soil C stocks in the unplanted rides in between forest stands. Rides are unplanted stripes of land (8 to 10 m wide) that separate blocks of forest 200 m wide. In a ride, litterfall is largely reduced, but depth of the water table may be as low as inside a block of forest, as two ditches border the ride on both sides. In three separate areas, we selected three paired plots (one in a ride, and one alongside in the forest) located as close to each other as possible and nine samples were taken for each plot.

All samples were transferred to the lab, where the depth of the total core was measured and then separated into three layers: the litter layer (O_L), organic layer (O_H) and mineral layer (A). In the case of forest

stands and the clearfelled site, the O_F layer was included with the O_H layer. In the unplanted grassland the O_L layer was considered as the layer consisting of dead plant material and the layer of partly decomposed material (i.e., mostly O_F).

The samples were kept in polythene bags in a freezer (–4 °C) till further analyses. The samples were then oven-dried at 105 °C for 24 h to constant weight [1]. Stone content was negligible. Any stones present and coarse fragments were removed by hand and the soil was ground to pass a 0.5 mm mesh [25].

2.3. Determination of C concentration

Thirty per cent of all samples from all layers were analysed both in a C/N analyser (Carlo-Erba, NA 2500) and by loss on ignition (L.O.I.). Finely ground sub-samples of about 4 mg for the litter and the organic layer and 10 mg for the mineral layer were combusted in the C/N analyser, and their C concentration (g kg^{-1}) was determined. Total C was assumed to equal organic C, as the samples did not come from a calcareous soil. Other sub-samples of approximately 1 g [1] were weighed and then ignited in a furnace at 500 °C, for 5 h (L.O.I.). After burning the samples were weighed again and the percentage mass loss (L%) was calculated, to determine the relationship between C and L%.

2.4. Soil bulk density

Soil bulk density was calculated for the samples from the 2001 study only, because no layer depths had been measured during the 2000 study. Bulk density was calculated with the following formula:

$$P_b = M/V \qquad (1)$$

where P_b is the bulk density (g cm^{-3}), M is the dry mass of a given soil sample (g) and V its fresh volume (cm^3). Only few small stones were found in the cores.

2.5. Statistical analysis

The slopes of the regression equations for the relationship between the C (g kg^{-1}) obtained from C/N analyser and the % mass loss from L.O.I. methods for each of three layers (O_L, O_H, A) was tested by ANCOVA (Analysis of Covariance) in SPSS [26].

The data from both study years were first analysed separately to determine whether significantly different patterns emerged as a result of the different methodologies employed. Because the patterns were similar, the data were combined and the mean was used as the soil C stock for each site. Differences among age classes were tested using one-way ANOVA (Analysis of Variance), using plot averages as the unit for analysis. Because of the lack of site replication in the case of the CF, the site was not included in the ANOVA analysis.

A Mann-Whitney test was employed for the comparison between the 40-yr stands and the ride plots, as the ride values did not follow a normal distribution. One-way ANOVA was performed using SAS [20] and equations were fitted using Sigma Plot. All the probabilities were tested at the 5% significance level.

3. RESULTS

3.1. Equation for predicting soil C using the L.O.I. method

When the mass loss (%) by L.O.I was plotted against the C concentration (%) obtained by the C/N analyser, a significant linear relationship was obtained ($R^2 = 0.98$, Fig. 1). ANCOVA revealed significant differences in the slopes of the regression equations among the 3 layers ($P < 0.05$). Thus, separate regression equations were fitted for each layer [31]:

$$C \text{ (g kg}^{-1}) = 0.513 \text{ L}(\%) - 0.092 \text{ , } R^2 = 0.99 \text{ for } O_L \qquad (2)$$

$$C \text{ (g kg}^{-1}) = 0.542 \text{ L}(\%) + 0.184, R^2 = 0.99 \text{ for } O_H \qquad (3)$$

$$C \text{ (g kg}^{-1}) = 0.533 \text{ L}(\%) - 0.700, R^2 = 0.99 \text{ for A.} \qquad (4)$$

3.2. Soil C stocks in the litter, organic and mineral layers along the chronosequence

Soil C_{org} stocks in litter, organic and mineral layer down to 45 cm depth at each site are presented in Figure 2. The change of total soil C stocks along the chronosequence can be found in Zerva et al. [31]. C_{org} in the O_L layer in the UN site (also inclusive of O_F) was 18.2 ± 4.5 t C ha^{-1}, i.e., significantly lower than 29.5 ± 6.3 t C ha^{-1} in the O_L in the 40-yr stands in first rotation ($P < 0.05$). The O_L in the CF site contained 7.4 ± 1.8 t C ha^{-1}, i.e., considerably less than the 40-yr stand, although this could not be tested statistically because of lack of inter-stand replication (the standard error given above refers to intra-stand variability). In second-rotation stands, C_{org} in the O_L significantly increased from 16.4 ± 0.8 t C ha^{-1} in the 12-yr stands to 20.4 ± 1.8 t C ha^{-1} in the 20-yr stands and 27.7 ± 1.5 t C ha^{-1} in the 30-yr stands ($P < 0.05$). The changes in C_{org} in the O_L were accompanied by changes in the thickness of the O_L as well (Tab. I). The depth of the litter layer in the UN site was similar to the 40-yr stands. The O_L layer in the single CF site was much thinner than the 40-yr, while during the second rotation O_L thickness significantly increased with age from the 12-yr to the 30-yr stands. The thickness data refer to the 2001 sampling only.

C_{org} in the O_H layer in the UN site was 243.2 ± 60.3 t C ha^{-1}, i.e., significantly higher than the 65.8 ± 9.3 t C ha^{-1} in the 40-yr stands at the end of the first rotation ($P < 0.001$). The single CF site had considerably lower C_{org} than the 40-yr stands, although again this could not be tested. Soil C started increasing again as the stands grew in second rotation, from 108.6 ± 34.3 t C ha^{-1} in the 12-yr stands to 115.1 ± 6.1 t C ha^{-1} in the 20-yr stands (although $P > 0.05$), but the increase became significant in the 30-yr stands, with values of 173.3 ± 26.3 t C ha^{-1} ($P < 0.05$). The thickness of the O_H was reduced after the planting of trees (compare UN with the 40-yr stands), despite O_F being bulked with O_L for UN and with O_H for 40-yr. The 12-yr and 20-yr stands were not significantly different for the thickness of their O_H, although the 30-yr stands had significantly deeper O_H than the 12-yr stands.

The UN site contained 20.3 ± 1.1 t C ha^{-1} in the A layer, while significantly higher amounts were found in the same layer of the 40-yr stands (44.8 ± 8.1 t C ha^{-1}, $P < 0.0001$). The A layer in the single CF site contained 64.4 ± 15 t C ha^{-1}. In the 12-yr in second rotation, soil C_{org} in the A layer was 22 ± 15.5 t C ha^{-1}, in the 20-yr stands in 45.3 ± 16.9 t C ha^{-1} and 48.4 ± 11.9 t C ha^{-1} in the 30-yr stands, i.e., the values showed an increasing trend, although the differences were not significant ($P > 0.05$).

The average total soil C_{org} stocks in the rides next to 40-yr stands were 129.7 ± 14 t C ha^{-1}, while the average for the
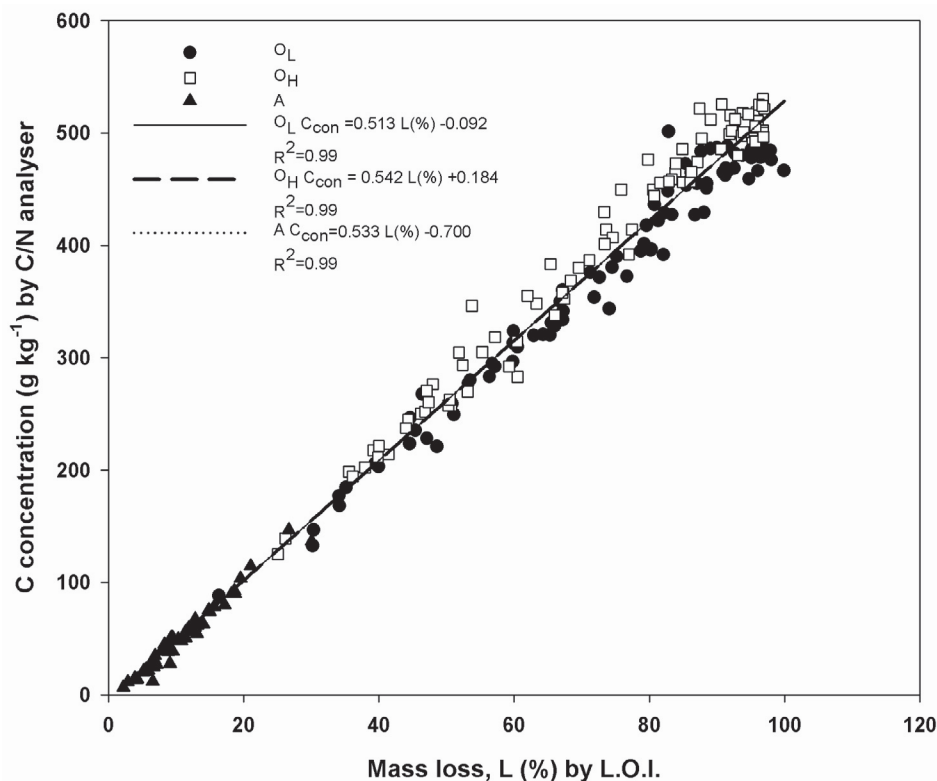
Figure 1. Linear regressions between mass loss L (%) from L.O.I and C (g kg^{-1}) by C/N analyser for 230 samples from O_L, O_H and A layers and from different sites within Harwood forest.
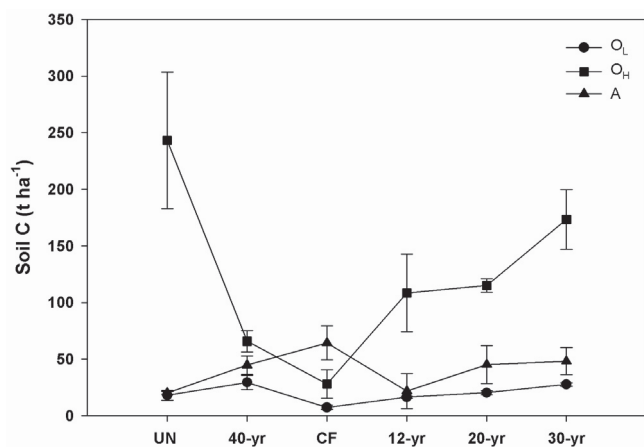

Figure 2. Soil C stocks (t ha^{-1}) along the Sitka spruce chronosequence in O_L, O_H and A layers. The vertical bars indicate the standard error of the mean across stands, except for CF where they indicate the standard error of the mean across plots.

40-yr forest plots was 127.0 ± 17 t C ha^{-1}. Figure 3 shows the three pairs of study plots in rides and adjacent 40-yr stands. Although no significant difference ($P > 0.05$) was found for total C_{org} between rides and 40-yr stands, there were different patterns in the vertical distribution of C. The C in the litter layer

of the 40-yr stand was significantly higher than the C contained in the litter layer of the ride (19.6 ± 3.6 and 6.7 ± 1.1 t C ha^{-1} respectively, $P < 0.001$), while soil C stocks in the organic layer of the 40-yr stands were lower but not significantly different (73.4 ± 5.8 vs. 92.1 ± 10.8 t C ha^{-1}, in the 40-yr stands and rides respectively, $P > 0.05$). No significant differences were observed for the mineral layer (38 ± 3.3 and 31.8 ± 6.0 t C ha^{-1}, respectively, $P > 0.05$).

Bulk densities and C concentration for each soil layer are shown in Table I for the 2001 samples. Bulk density in the O_L had varied between 0.1 and 0.2 g cm^{-3} at all sites, whereas the bulk density in the O_H ranged between 0.34 and 0.86 g cm^{-3}. Afforestation increased bulk density in the O_H from UN to 40-yr stands. For the stands growing in second rotation, bulk density in the O_H decreased from the 12-yr stand to the 30-yr stand ($P < 0.05$). The bulk density in the mineral layer was very similar at all sites, with values ranging between 1.30 and 1.52 g cm^{-3}.

C concentration in the O_L did not significantly vary across the chronosequence and ranged between 339 and 453 g kg^{-1}, increasing slightly in the second-rotation stands. UN had a high C concentration in the O_H, while afforestation resulted in a significantly lower C concentration in the first-rotation 40-yr stands ($P < 0.001$). C concentration increased significantly with stand age in the second rotation ($P < 0.001$). The C concentration in the mineral layer ranged from 18 to 29 g kg^{-1} and there were no significant differences between sites ($P > 0.05$).

Table I. Bulk density (g cm^{-3}), thickness (cm) and C$_{org}$ concentration (g kg^{-1}) for each layer of the chronosequence. Numbers in brackets indicate the standard error of the mean (across stands), except for CF, where it indicates the standard error of the mean (across plots); n. d.: not determined. Different letters for each site indicate significant differences (at least $P < 0.05$): capital letters refer to O$_L$, smaller letters to O$_H$. None of the differences among mineral layers were significant ($P > 0.05$).

Site	Layer	Bulk density (g cm^{-3})	Thickness (cm)	C concentration (g k^{-1})
UN	O$_L$	0.11 (0.01)^A	3.8 (0.9)^A	453 (12)^{ns}
	O$_H$	0.55 (0.1)^a	20.3 (1.3)^A	399 (34)^A
	A	1.42 (0.04)^{ns}	n. d.	16 (5) ^{A}
40-yr	O$_L$	0.15 (0.02)^A	4.6 (0.5)^A	339 (32)^{ns}
	O$_H$	0.86 (0.2)^b	12.8 (0.7)^C	155 (29)^B
	A	1.52 (0.03)^{ns}	n. d.	17 (4)^A
Rides	O$_L$	0.18 (0.03)	1.8 (0.3)	311 (76)
	O$_H$	0.75 (0.05)	16.1 (0.8)	98 (17)
	A	1.48 (0.04)	n. d.	18 (4.4)
CF	O$_L$	0.14 (0.03)	2.7 (0.4)	337 (08)
	O$_H$	0.49 (0.04)	6.3 (1.4)	138 (21)
	A	1.35 (0.08)	n. d.	25 (7)
12-yr	O$_L$	0.16 (0.01)^B	3.6 (0.2)^A	339 (38)^{ns}
	O$_H$	0.62 (0.06)^a	16.9 (1.8)^B	152 (51)^B
	A	1.39 (0.05)^{ns}	n. d.	18 (0.4)^A
20-yr	O$_L$	0.14 (0.02)^A	4.7 (0.6)^A	368 (14)^{ns}
	O$_H$	0.40 (0.04)^c	16.4 (1.8)^{BC}	306 (19)^A
	A	1.36 (0.05) ^{ns}	n. d.	17 (0.2)^A
30-yr	O$_L$	0.11 (0.01)^A	7.0 (0.3)^B	402 (35)^{ns}
	O$_H$	0.34 (0.03)^c	20.9 (1.4)^A	413 (13)^A
	A	1.30 (0.04) ^{ns}	n. d.	29 (2)^B

4. DISCUSSION

4.1. Equation for predicting soil C using the L.O.I. method

The strong linear relationships between the mass loss obtained by L.O.I. and the C (%) by C/N analyser for the three layers, O$_L$, O$_H$ and A, indicates that L.O.I can be used as a precise method for estimating organic C from peaty gley soils, with the significant advantage of the low cost of the method. We found significantly different slopes for each layer, probably because of the different amounts of organic matter present in each layer, with the litter and organic layers containing more C per unit of mass loss than the mineral layer. Additionally, clay content and clay mineralogy have also been reported as significant factors in affecting these relationships. Konen et al. [17] developed equations for predicting organic C content (as deter-

mined by C/N analyser) from L.O.I for 255 non-calcareous samples from selected major land resource areas in the North Central USA. They found significant differences in the slopes of equations among each major land resource area. The strong predictive equations found here indicate that L.O.I can be a precise method that can be used successfully to predict accurately C (g kg^{-1}) in peaty gley soils in the Harwood forest area. L.O.I. may not be a true measure of organic matter, because at the temperature of ashing some bound water is lost from the clay minerals. This error is more serious in soils low in organic matter [1].

4.2. Soil C stocks in the litter, organic and mineral layers

Afforestation on previous grasslands on peaty gley soil caused changes in the C content in the O$_L$, O$_H$ and A. Soil C$_{org}$ in the O$_L$ layer of UN was not significantly different from the
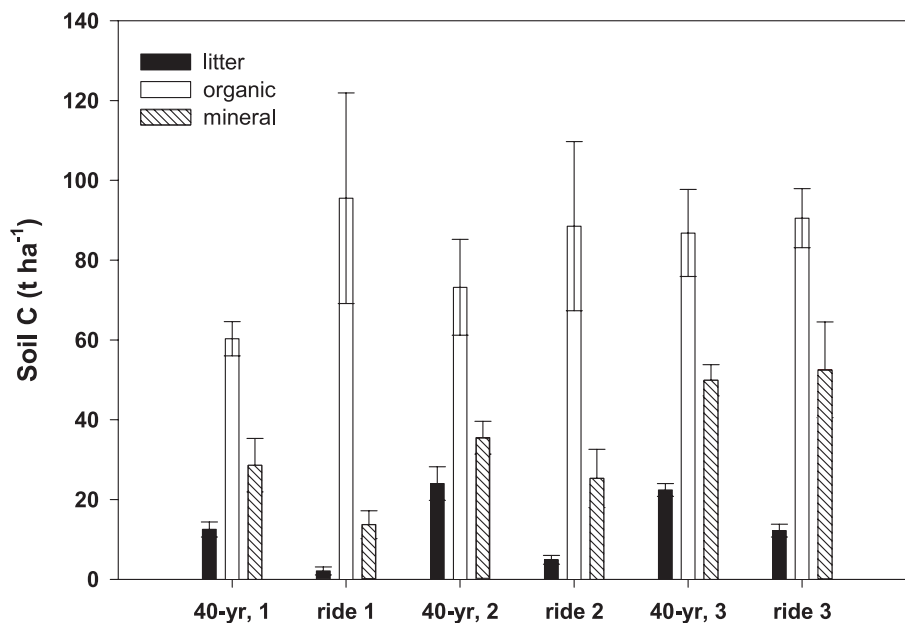
Figure 3. Soil C (t ha^{-1}) in litter, organic and mineral layers of three paired plots in 40-yr stands and rides. The vertical bars represent the standard error of the mean.

40-yr stands, but the C stock in the O_H layer was considerably higher in UN. This decrease could be due to the accelerated decomposition caused by the site preparation for drainage and for the planting of trees [3].

When soil C_{org} in the 40-yr stands was compared with the C stocks in adjacent unplanted rides, no significant difference was found, though one may have expected that the ride would resemble the unplanted grassland, since no site preparation or tree planting took place there (although each 8-m ride is bordered with one ditch on either side). The O_L layer had significantly less C content in the rides. The extra C_{org} in the O_L in the forest is a characteristic feature of this system. The decrease in C_{org} in the O_H layer in the forest was not significant at the 5% significance level, although the trend was in the same direction as for the comparison between the UN sites and the 40-yr stands.

The considerably lower C_{org} content in the O_L layer of the single CF compared to the 40-yr stands could be attributed to the cessation of litter input from harvested trees. The O_H layer had also considerably lower C than the 40-yr stands, probably as a result of increased losses through organic matter decomposition, but the A layer had considerably higher amount of C. That could be attributed to the re-distribution of organic material after harvesting operation and the incorporation of slash in the soil. Johnson et al. [14] investigated the effects of clearfelling on soil carbon dynamics in a northern hardwood forest. A decrease of 20 t C ha^{-1}, eight years after logging, was estimated, as well as a redistribution of carbon within the mineral soil, with an increase in C in the A and E horizons. Gholz et al. [7] found that the A horizon of a 2 yr-old stand of slash pine contained approximately twice as much soil C as the other stands of the chronosequence (up to the age of 34). This was attributed to

bedded slash. The effect of slash was short lived, so by the age of 5 years, the soil C decreased to 50% of pre-harvest levels. In the CF slash was left behind, however the extent to which slash contributed C to the soil and prevented a greater loss of C from the site is not known.

In second-rotation stands, the amount of C_{org} in the O_L, as well as the thickness of O_L and O_H layers, increased as the amount of litterfall increased [31]. A linear accumulation of organic matter with stand age in the forest floor (O_L and O_{F+H} layers) was found in slash pine plantations in Florida [7].

In the 30-yr stands, the amount of C_{org} in the O_L was significantly higher than in the grassland and the amount of C_{org} in the O_H layer was not significantly different than the one in UN.

Changes in the soil C_{org} stocks across the chronosequence were accompanied by changes in the concentration of C_{org} in the soil. C concentration in the litter layer was not significant different across the chronosequence ($P = 0.5$). Schiffman et al. [21] also found no significant differences in the C concentrations with stand age in the O_L layer in a chronosequence of lobolly pine plantations, between 1 and 47 years old and established on previous agricultural land or cleared land.

However, afforestation caused a significant decrease in C concentration in the O_H in the 40-yr stands at the end of the first rotation compared to UN, while C concentration significantly increased again with stand age during the second rotation. The same pattern was observed in red pine plantations in Wisconsin [30] where, soil organic matter concentration (%) increased linearly with stand age (13 to 48 years). However, [8] found no significant differences in the C concentration down to a soil depth of 10 cm in harvested stands of 5-yr, 15-yr, 40-yr old and old-growth Douglas fir stands in Canada. Smethurst et al. [23]

observed that clearfelling decreased C concentration in the 0–15 cm depth from an initial value of 2.7% to 1.9%, 3 years after replanting a *Pinus radiata* plantation, in South Australia.

C concentrations in the mineral layer were not significantly different across the chronosequence in Harwood; however, the C concentration in the mineral layer of the single CF site was slightly higher, compared with the corresponding one of the 40-yr stands, indicating that mixing of the soil during/after clearfelling may result in some transfer of organic material deeper into the soil. Gholz et al. [7] also found no significant differences (or trend) in the organic matter concentrations in the mineral horizons of a slash pine chronosequence (stand ages between 2 and 34 years old) in Florida.

Afforestation on natural grassland, clearfelling and replanting also caused changes in the soil bulk densities, mainly in the organic layer. Bulk densities in the litter layer of all sites ranged between 0.1 and 0.2 g cm^{-3} and increased with increasing depth. Afforestation increased bulk density in the O_H of the 40-yr stand at the end of the first rotation ($P < 0.001$), which was accompanied by a decrease in total soil C. Soil bulk density is strongly inversely related to organic matter concentration [28] and decreases in organic matter result in increases in bulk density. The O_L in the 40-yr stand did not differ in bulk density from the O_L of the ride, but appeared to have higher bulk density than the single CF, although the opposite would be expected. Bock and Van Rees [2] studied the effects of clearfelling on soil physical properties in white spruce forests in Canada. They found that, three years after harvesting, soil bulk densities in the LFH and the mineral layers were higher by 12 and 7%, respectively compared with the bulk density in the respective layers of an uncut stand. This was due to the accelerated decomposition of organic matter. Johnson et al. [14] also found that clearfelling of hardwood and spruce forests in USA caused an increase of between 5 and 14% in bulk density in the top 20 cm of mineral soil. The increase depended on the severity of the disturbance. In our clearfelled site, the low bulk density was either a result of lack of replication or represented a small effect of the harvesting practices on soil compaction, or recovery since clearfelling (which had taken place 18 months before). Frazer et al. [6] also found similar bulk densities between clearfelled and uncut mixed conifer stands (0.8 and 0.9 t m^{-3} respectively) in Sierra Nevada. They attributed it to cumulative action of frost and incorporation of residues into the soil, which was indicated by higher C concentration at the clearfelled site.

Soil bulk density in the organic layer decreased with stand age during second rotation reflecting increases in the soil C. Switzer et al. [27] also found that soil bulk density decreased with stand age and organic matter concentration increased in oak-hickory-pine forest growing on abandoned agricultural land, in the South-eastern USA.

As mentioned before, bulk density increased with increasing depth, and the mineral layers had the highest bulk densities. These values were similar across stands indicating that the mineral layer was not directly affected by land use changes and stand growth. Bulk density also reflects the distribution of organic matter with depth as well as soil compaction [28]. Tamminen et al. [28] also found that soil bulk density increased with depth and remained uniform at depths of more than 20 cm. Bock and Van Rees [2] found no significant differences in soil bulk

densities of mineral layers between the clearfelled and uncut white spruce stands in Canada. Gholz et al. [7] also observed no significant differences in soil bulk densities in a slash pine chronosequence (stand ages between 2 and 34 years old) in Florida.

5. CONCLUSIONS

The establishment of Sitka spruce (*Picea sitchensis*) forests on previous grasslands on peaty gley soils have changed soil C_{org} content, concentration and bulk density. During the first rotation after afforestation C_{org} in the O_H layer declined and the vertical distribution of the stocks changed, with more C_{org} stored in the O_L and A layers. Clearfelling seemed to cause a further decline in C_{org} in the O_L and O_H but increased C_{org} in the A layer. Because of lack of replication, this finding will need to be confirmed. During second rotation, C_{org} progressively accumulated in O_L and O_H. It is estimated that by the age of clearfelling of second rotation stands soil C_{org} stocks will have equalled those of the former unplanted grassland [31].

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