Chapter 5

The effects of forest management on the soil carbon balance in a Sitka spruce chronosequence on peaty gley soil

5.1 Introduction

Trees allocate carbon belowground in order to produce roots (coarse and fine), for root respiration, exudates and mycorrhizae (Raich and Nadelhoffer, 1989). Although a significant amount of the carbon that is assimilated annually is allocated to fine roots (Gower *et al*., 1996); the process is still poorly understood and estimated (Raich and Nadelhoffer, 1989; Nadelhoffer and Raich, 1992; Lauenroth, 2000), as how much carbon is allocated belowground is the most difficult C flux to measure (Vogt *et al*., 1986). Helmisaari *et al*. (2002) found that 62% of net primary production was allocated for the production of fine (58.6%) and coarse roots (3.4%) in 35‑years‑old Scots pine (*Pinus sylvestris* L.) stands in Finland, while Vogt (1991) reported that fine root production accounted from 7 up to 76% of net primary production (NPP) over a range of forest ecosystems.

Accurate measurements of fine roots and mycorrhizae turnover are essential for understanding and quantifying belowground carbon allocation (Nadelhoffer and Raich, 1992; Ryan *et al*., 1997; McDowell *et al*., 2001). For the estimation of coarse root biomass, allometric equations have been commonly used (Helmisaari *et al*., 2002; Giardina and Ryan, 2002); while for the measurement of the fine root biomass different methods have been used: soil coring (Helmisaari *et al*., 2002; Giardina and Ryan, 2002), in‑growth cores (Neill, 1992), minirhizotrons (Hendrick and Pregitzer, 1992), isotopes (Milchunas and Laueronth, 1992), the nitrogen balance approach (Nadelhoffer *et al*., 1985) and the carbon balance approach (Raich and Nadelhoffer,

1989; Giardina and Ryan, 2002). However, the estimates depend on the methods used (Nadelhoffer and Raich, 1992; Publicover and Vogt, 1993, Laueronth, 2000)

Raich and Nadelhoffer (1989), used the conservation of mass approach in order to estimate the belowground carbon allocation for forest ecosystems globally. Total belowground carbon allocation (*TBCA*) is the sum of mycorrhizae and root (fine and coarse) production, respiration and exudates. All C that enters the soil must either leave the soil or increase soil C stocks. Raich and Nadelhoffer (1989) assumed that if the forest is near steady-state, the change in soil carbon stock will be near zero and thus the main regulators of *TBCA* can be estimated from measurements of annual rates of soil respiration and aboveground litterfall. Many have followed their example (e.g. Ryan, 1991; Smith and Resh, 1999); however, this simple approach cannot be applied to aggrading or disturbed forests (Gower *et al*., 1996). A few studies have examined the *TBCA* patterns with age and the findings are not consistent (see Chapter 1).

Peatlands on their natural state accumulate C in the soil and afforestation can alter their C balance. Increased aeration after drainage will increase the decomposition rates of peat and, consequently the emissions of soil CO_2 to the atmosphere. Also, it will cause shifts in biomass production from the field and bottom layers grasses to the tree layer (Laine and Minkkinen, 1996). As trees grow, accumulation of C takes place both aboveground, in the woody tissues of the trees and belowground in the forest soil, with the inputs of litterfall and roots. Litterfall is the largest natural flow of C to the forest floor (Berg and Meentemeyer, 2001). Since, roots play an important role in soil C cycling; stand age and disturbances due to forest management can affect the mass of roots present in the soil (Grier *et al*., 1991; Vogt *et al*., 1983).

The vital role of soils as a sink or source for C at the global scale and in offsetting atmospheric CO_2 concentrations (Johnson and Curtis, 2001) makes it important to evaluate accurately the effects of forest management on soil C storage.

The objective of this study was to determine how stand age and management practices affect the soil C balance along a Sitka spuce (*Picea sitchensis*) chronosequence, from natural unplanted grassland to second rotation growth stands.

5.2 Materials and Methods

5.2.1. Site description

A full site description can be found in Chapter 1.

5.2.2 Litterfall

To measure litterfall, four circular traps (0.2 m^2) were randomly placed within a 2 m radius, for each cardinal point, from the centre of five random plots within each stand. Traps were constructed by using water permeable, reusable acetate lining bags within the frame of a 25 l plastic container and mounted on wooden pegs, so that the height of the trap opening was ca. 80 cm above ground level. The traps were installed in the 12, 20, 30 and 40-yr-old stands during May and June 2000. Litter was collected for the first time in October 2000, and then every two months from January 2001 until the end of September 2001. After collection, all litter was dried at 80° C for 48 hours and weighed. Average annual litterfall was calculated from the sum of the bimonthly litterfall values, by using the average values for the measurement period July-September from both years 2000 and 2001. A C content of 50% was assumed for the litter. Aboveground litterfall was measured as part of the CARBO-AGE project. The data are provided courtesy of Dr. M. Mencuccini.

5.2.3 Soil C stocks

The soil sampling scheme as well the soil analysis for C determination are fully described in Chapter 2.

5.2.4 Soil respiration measurements

Soil respiration was measured weekly or biweekly, from July 2001 to October 2002, in the 40-yr-old stand, while in the CF_{old}, 20-yr-old and 30-yr-old stands measurements were taken biweekly or once a month. In the 40-yr-old stand and in a recently clearfelled site soil respiration was measured using two methods: the dynamic closed chamber (DC) and the static closed chamber (SC) technique. Full description of the methods and the experimental design is provided in Chapter 3.

Soil respiration at the other sites was measured with the SC method on 8-16 chambers (of 20 or 40 cm diameter). To allow a comparison between C stocks and CO_2 efflux measurements at all sites, the annual respiration flux at the 12-yr-old stand was also estimated from a relationship obtained between annual litterfall and annual soil respiration (R^2=0.93, n=4).

The soil respiration data from the CF_{old}, 20-yr and 30-yr stand are provided courtesy of Dr. T. Ball.

5.2.5 Root biomass

Fine root biomass, M_{FR}, (t ha^{-1}) was estimated from the equation:

$$M_{FR} = -0.12 \; age + 7.23, \tag{4}$$

(R^2=0.94), from Dimitriadis (2000) who used a C balance approach to estimate the amount of carbon allocated to fine roots.

Coarse root biomass was estimated from empirical allometric equations (Dimitriadis, 2000):

$$M_{CR} = 0.0149 \text{ x } d_0^{2.3302}, \tag{5}$$

where M_{CR} is the coarse root biomass,

$$d_0 = \text{-}2.4 + 6.9 \text{ x } 0.85^{DBH} + 1.4 DBH \tag{6}$$

and *DBH* is the tree diameter at breast height (1.33 m). These allometric equations were provided courtesy of Robert Matthews (Southern Research Station, Forestry Commission).

Annual changes in fine and coarse root biomass were estimated from the same allometric equations, while the change in *DBH* was estimated from measured annual mean growth data for each age class (Van Der Eb, 2002). Root biomass (fine and coarse) was assumed to be 50% C.

5.2.6 Total belowground carbon allocation

Total belowground allocation (*TBCA*) was estimated by using a conservation of mass approach as in Ryan and Giardina (2002), where outputs from the belowground system must equal inputs minus any change in storage over a defined time period:

$$F_S + F_E = TBCA + F_A - (\Delta C_S + \Delta C_R)/\Delta t \tag{7}$$

Where F_S = soil respiration, F_E = export of C (CH_4 flux or erosion or leaching), *TBCA* = the total of root respiration (carbohydrates used for mycorrhizae or exudates and production of fine roots, F_A = aboveground litterfall, ΔC_S = the change in soil C stock, ΔC_R = the change in C stored in roots (fine and coarse) and Δt = 1 year for this study. All the components are expressed in t C ha^{-1} y^{-1}.

Thereafter, *TBCA* can be expressed by difference by measuring fluxes out of the soil (F_S and F_E), into the soil (F_A) and any change in the C storage (($\Delta C_S + \Delta C_R$)/Δt):

$$TBCA = F_S + F_E - F_A + (\Delta C_S + \Delta C_R)/\Delta t \qquad (8)$$

The fluxes of C in leaching, runoff and erosion were ignored, but these are probably minor in most closed canopy forests (Raich and Naderlhoffer, 1989). The annual soil CH_4 flux in the 40-yr-old stand was 0.05 ± 0.03 t C ha^{-1} y^{-1}, and because it was so low it was assumed to be zero in the estimation of *TBCA*. For the first rotation, ΔC_S was estimated by the difference in C stocks between the first rotation 40-yr-old stand and the unplanted grassland site, divided by the period length, while for the second rotation ΔC_S was estimated by the difference in C stocks between different age classes divided by the period length.

The variance in the *TBCA* was estimated from the sum of the variances of the other components, with the exception of ΔC_R, since this term was estimated from an allometric equation. However, compared to the other fluxes, ΔC_R is a very small component in the *TBCA* equation therefore variance was assumed to be negligible and was ignored.

5.2.7 Statistical analysis

The plot level means were used for the comparison of soil C stocks and litterfall. The Kruskal-Wallis test was used to test for differences in litterfall across age classes. The statistical tests were performed in SAS (SAS Institute, 1988). An α=0.05 level was used to detect statistically significant differences in all analyses.

5.3 Results

## 5.3.1 Components of the TBCA budget

5.3.1a Litterfall

Mean annual litterfall mass ranged from 1.1 to 1.9 t C ha^{-1} y^{-1} (Table 1). The litterfall was the same in the 12-yr-old and 20-yr-old stands (1.1 $\pm$ 0.1 and 1.1 $\pm$ 0.2 t C ha^{-1} y^{-1} respectively) and it increased as the stands grew older to 1.7 $\pm$ 0.3 t C ha^{-1} y^{-1} in the 30-yr and 1.9 $\pm$ 0.2 t C ha^{-1} y^{-1} in the 40-yr-old stand. Litterfall was not significantly different between the 12-yr-old, 20-yr-old and 30-yr-old stands (P=0.3) or between the 20-yr-old, 30-yr-old and 40-yr-old stands (P=0.6).

Table 1: Total Belowground Carbon Allocation and its components, where F_S is the soil respiration, F_A is litterfall, M_{FR} is fine root biomass, M_{CR} is the coarse root biomass, $\Delta C_{R(F+C)}$ is the change in root biomass (fine plus coarse) over a year and ΔC_S is the change in soil C stocks over a year. The numbers in the brackets represent the standard error of the mean.

Stand age	F_S	F_A	M_{FR}	M_{CR}	$\mathbf{D}C_{R(F+C)}$	$\mathbf{D}C_S$
(y)	(t C ha^{-1} y^{-1})	(t C ha^{-1} y^{-1})	t C ha^{-1}	t C ha^{-1}	(t C ha^{-1} y^{-1})	(t C ha^{-1} y^{-1})
UN	14.2 (3.1)	-	-	-	-	-
40, first rotation	5 (0.4)	1.9 (0.2)	2.4	56.3	1.2	-2.4 (0.7)
12	2.3 (0.9)	1.1 (0.2)	5.8	11.1	0.5	4.0 (1.3)
20	2.2 (0.7)	1.1 (0.3)	4.8	24.0	0.9	5.9 (0.9)
30	5.4 (0.7)	1.7 (0.3)	3.6	27.1	0.8	1.6 (0.9)

5.3.1b Soil C stocks

Soil C stocks across the chronosequence are shown in Figure 1. Soil C stocks along the chrnosequence are described in details in Chapter 2. In brief: The planting of trees led to a significant decrease in soil C stocks from unplanted site to the first rotation 40-yr-old stand. Clearfelling at the end of the first rotation led to a further significant decrease in soil C. Soil started accumulating C again during the second rotation (Figure 2). The soil C stocks in the 30-yr stand, second rotation, were not significantly different from the UN site. The equation from Figure 2 (y= 98.61 +((376.61* x)/(66.85 + x)), R^2=0.98 where y is the soil C stock at a certain stand age and x the years since clearfelling) was used to estimate the soil C stock in a 40-yr-old stand at the end second rotation and gave a value of 238 ± 19 t C ha^{-1}.
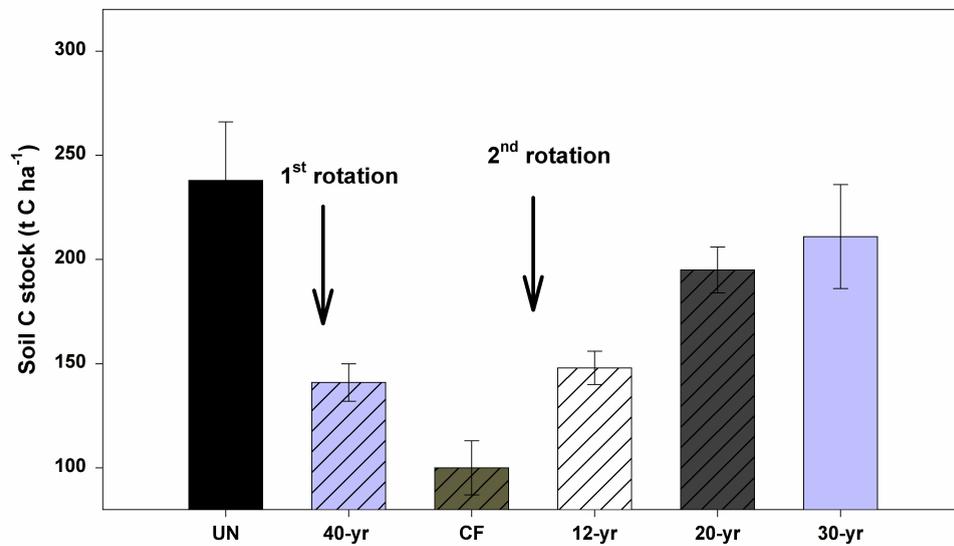
Figure 1: Soil C stocks (t ha^{-1}) along the Sitka spruce chronosequence. The planting of the trees on natural grassland (UN) leads to a decrease on soil C, which is further enhanced by clearfelling of the trees (CF). Soil C starts accumulating again when trees grow in a second rotation. The vertical bars represent the standard error of the mean.
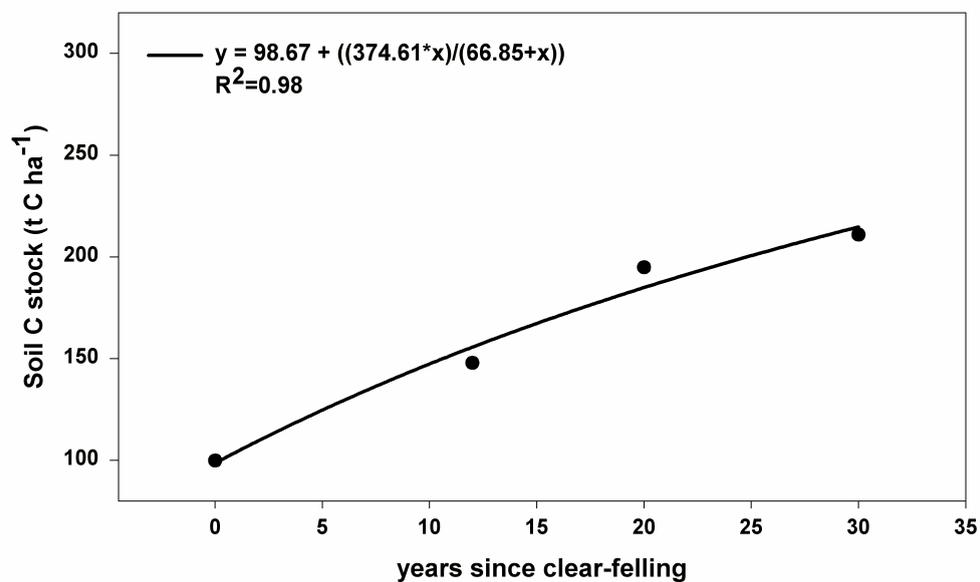
Figure 2: Increase in soil C stocks ± 1 standard error (t ha^{-1}) in stands growing in a second rotation after clearfelling. Year 0 refers to the CF site.
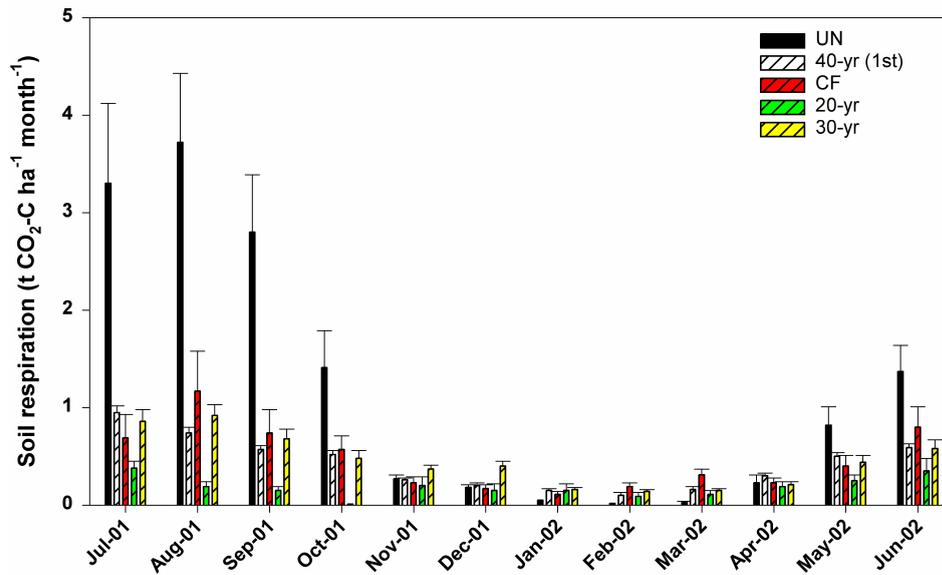
5.3.1c Soil respiration

Since soil respiration was measured both by SC and CD methods, the empirical regression reported in Figure 2 in Chapter 7, was used to convert all values for all age clases to those for the DC method.

Annual soil respiration ranged from 2.2 ± 0.7 to 14.2 ± 3.1 t C ha^{-1} y^{-1}, with the lowest value in the 20-yr stand and the highest in the UN. The CF$_{old}$ had higher soil respiration rates than the mature (40-yr-old) stand although the difference was not significant (5.6 ± 1.6 t C ha^{-1} y^{-1} and 5.0 ± 0.4 t C ha^{-1} y^{-1} respectively, P>0.05). Soil respiration was 2.3 ± 0.9 in the 12-yr-old and 2.2 ± 0.7 in the 20-yr-old, increasing to 5.4 ± 0.7 in the 30-yr-old and 5.0 ± 0.4 t C ha^{-1} y^{-1} in the 40-yr-old stand. Soil respiration showed a strong seasonal trend at all sites, with higher fluxes during the summer and low fluxes during the winter (Figure 3).

Soil respiration data combined for all forest stands was strongly related to soil temperature, with an exponential relationship:

$R_S = 0.50 \, e^{0.25T5}$ (R^2=0.56, Q$_{10}$=13.3),

where R_S is soil respiration (g CO$_2$ m^{-2} d^{-1}) and T_5 is soil temperature (°C).

Figure 3: Monthly soil respiration (t C ha^{-1} month^{-1}) in the chronosequence. Soil respiration follows the same seasonal trend at all sites. Values calculated using the dynamic closed chamber method. The vertical bars represent the standard error of the mean.

5.3.1d Root biomass

Fine-root biomass decreased from 5.6 t ha^{-1} in the 12- yr to 2.2 t ha^{-1} in the 40-yr stand (Table 1). In contrast coarse root mass increased from 11.1 t ha^{-1} at the 12-yr to 56.3 t ha^{-1} in the 40- yr (Table 1).

5.3.2 Total belowground carbon allocation (*TBCA*)

Figure 4 gives all the values employed to calculate *TBCA* for the four studied age classes. The values of some additional parameters are listed in Table 1. *TBCA* was found to range from 2.0 ± 1.0 t C ha^{-1} y^{-1}, in the 40-yr-old stand in the first rotation to 6.1 ± 1.0 t C ha^{-1} y^{-1}, in the 30-yr-old second rotation stand.

Soil respiration was the largest flux contributing to *TBCA*, for the 30 and 40-yr-old stands, while $\Delta C_S/\Delta t$ was the largest flux for the younger, 12 and 20-yr-old stands (Figure 4).
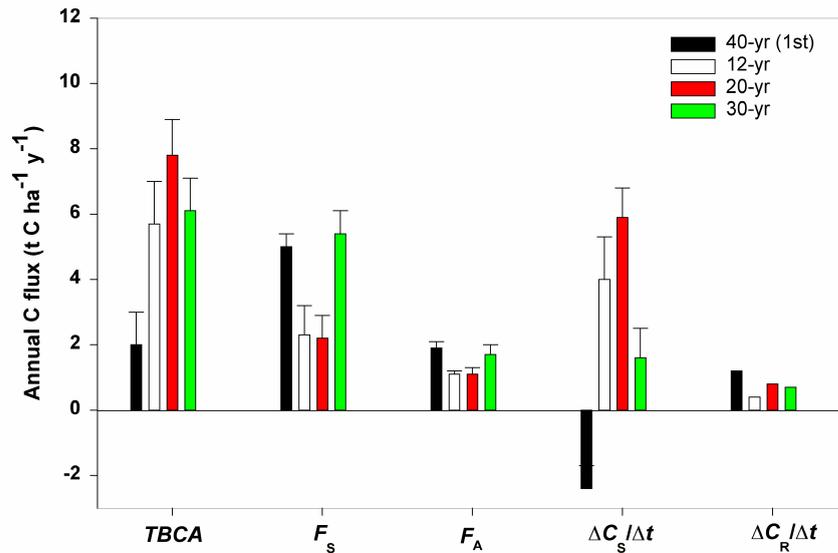
Figure 4: Total belowground C allocation and its components in the forest stands of first and second rotations. The vertical bar represent the standard error of the mean.

5.4. Discussion

5.4.1 Components of the TBCA budget

5.4.1a Litterfall

The aboveground litterfall values in this study (1.1–1.9 t C ha^{-1} y^{-1}) are within the range of 0.57-3.48 t C ha^{-1} y^{-1} increasing with age for temperate forests, referred to

by Gower *et al*. (1996). Litterfall values are also similar to those measured by Pedersen and Bille-Hansen (1999), in 35-years-old Sitka spruce and Norway spruce on poor soil in Denmark, over six years. In the first year of measurements (age 35 years) they found that the litterfall was 1.2 t C ha^{-1} y^{-1} in the Sitka spruce, while after six years (age 41 years) it was 2.4 t C ha^{-1} y^{-1}. Litterfall was similar for the Norway spruce stands, however there was large variation from year to year.

5.4.1b Soil C stocks

The description and interpretation of the trends in soil C stocks over the chonosequence have been presented in Chapter 2.

5.4.1c Soil respiration

The annual F_S (14.2 ± 3 t C ha^{-1} y^{-1}) in the UN site was far higher than the F_S from forest stands (5.0 ± 0.4 t C ha^{-1} y^{-1} in the 40-yr-old first rotation) or the CF site (5.6 ± 1.6 t C ha^{-1} y^{-1}). This is in agreement with Raich and Tufekcioglu (2000) who reported consistently greater soil respiration rates in grasslands than in forests under similar conditions, world-wide. That is because grasses, with virtually no allocation of C to wood production, may have more photosynthate available to allocate below ground than trees do (Raich and Tufekcioglu, 2000).

The annual F_S fluxes in the forest stands (2.2 ± 0.7 to 5.0 ± 0.4 t C ha^{-1} y^{-1}) are lower than the mean rates for temperate coniferous forests of 6.81 ± 0.95 t C ha^{-1} y^{-1}, reported by Raich and Schlesinger (1992). Wingate (2003) also estimated a rather low soil CO_2 flux of 4.7 t C ha^{-1} y^{-1} for a 20-yr-old Sitka spruce plantation in Scotland. However, no other published studies on soil respiration under Sitka spruce on peaty gley soils were found to compare with the results of this study. Law *et al*.

(1999) estimated an annual soil respiration of 6.83 t C ha^{-1} y^{-1} in a mixed age stand of ponderosa pine in Oregon.

Clearfelling of the forest led to slightly higher F_S (5.0 ± 0.4 t C ha^{-1} y^{-1} and 5.6 ± 1.6 t C ha^{-1} y^{-1} in the 40-yr and CF$_{old}$ respectively). Londo *et al.* (1999) reported significantly higher soil respiration in a clearfelled bottomland hardwood forest in Texas between 6 and 22 months after clearfelling. They also reported vigorous vegetation recovery in the first growing season following harvesting from rapid invasion of herbaceous species. However, Striegl and Wickland (1998) found that clearfelling of a boreal jack pine (*Pinus banksiana* Lamb.) forest in Canada reduced soil respiration to about 40% of that in an uncut stand of similar age (60-90 yr old), in the first season following harvest. They attributed the major part of this reduction to destruction of near-surface soil autotrophic and heterotrophic respiration and to tree-root die-off. In Harwood Forest, colonisation by grasses and shrubs is generally vigorous after about one or two years since harvesting. The data reported here are for three years after clearfelling (cf., Chapter 3, for data for a newly clearfelled stand).

Temperature has been found to explain much of the variability in F_S in temperate forests. In our sites it explained 56% of the variation, when all data were combined. Much more of the noise around the regression line was due to significant differences among the various age classes. Much higher proportions of the total variance could be explained by separating the stands out (cf., Chapter 3).

5.4.1d Root biomass

The estimations of fine root biomass in the chronosequence (except for the 40-yr-old stand) are within the range of 3.5-11 t ha^{-1}, as estimated by Fogel (1985) for coniferous forests. The estimation of fine root biomass with equation (4) gives results in agreement with Deans (1981), who estimated fine root biomass (<2 mm) of 5.2 t C

ha^{-1} for a 16-years-old Sitka spruce plantation. If this age is used in the above equation we obtain 5.3 t C ha^{-1}. Fine root biomass was estimated to decrease with stand age, based on modelling of gross primary productivity and a carbon balance approach. The same trend was observed in *Pinus kesiya* stands in North East India (John *et al*., 2001). Vanninen and Makela (1999) studied fine root biomass in Scots pine (*Pinus sylvestris*) stands of different ages in poor and fertile stands in Finland. They found that fine root biomass increased with age at the poor site, while root biomass decreased with stand age at the fertile sites. Vogt *et al*. (1983) found that fine root biomass decreased after canopy closure in a Douglas fir (*Pseudotsuga menziesii*, (Mirb) Franco) chronosequence in Washington.

Coarse root mass was estimated to increase with stand age, as expected, since coarse roots primarily serve a support function and need to increase with stand size and age (Giardina *et al*., 2003). The increase of coarse root biomass with age is confirmed by results by John *et al*. (2001). They measured an increase in coarse root biomass from 1.69 t ha^{-1} in a 6-years-old *Pinus kesiya* stand to 4.66 t ha^{-1} in a 23-year-old stand.

5.4.2 Total belowground carbon allocation

The *TBCA* in this study for the stands growing in second rotation is within the range of 2.33-10.13 t C ha^{-1} y^{-1} for temperate forests referred to by Gower *et al*. (1996), and the global range of 2.6-11 t C ha^{-1} y^{-1} by Raich and Nadelhoffer (1989). However, Raich and Nadelhoffer (1989) only estimated *TBCA* in near-steady-state forests; the chronosequence in this study cannot considered to be steady-state, since it is probably still affected by the land use change which took place between 40 and 70 years ago.

TBCA increased with stand age in 12 to 20 years old growing in second rotation, but it decreased at the age of 30 years. Giardina and Ryan (2002) found a linear decline with age in *TBCA* in a *Eucalyptus saligna* stand over a period of 4 years, from 0.224

t C ha^{-1} y^{-1} in year 1 to 0.161 t C ha^{-1} y^{-1} in year 4. Similarly Smith and Resh (1999) found a decline of *TBCA* with age in lodgepole pine (*Pinus contorta*) stands in Wyoming.

Law *et al.* (1999) found that about 61% of GPP was allocated belowground, in a ponderosa pine (*Pinus ponderosa*) forest in Oregon, which consisted of old (250 years), young (45 years) and mixed-aged stands. A comparison of the estimates for *TBCA* with values of GPP measured with eddy covariance suggests that between 36% and 46% of GPP was allocated below ground in the 20-yr and 30-yr stands at British Sitka spruce sites (Clement *et al.*, 2003 (for Griffin, Scotland); Kowalski *et al.*, 2004 (for Harwood)). Giardina *et al.* (2003) estimated that *TBCA* was about 50% of GPP in a *Eucalyptus salinga* plantation during four years of measurements.

Accurate estimations of *TBCA* depend on measuring the annual fluxes of inputs, outputs and changes in soil C stock and root mass with a reasonable precision. Since F_S and ΔC_S are the major fluxes controlling *TBCA* they have the greatest potential contribution to the error in the estimation of *TBCA*. Different methods for measuring F_S can give different values and a correction factor may be needed (Norman *et al.*, 1997). In this study, F_S was measured with static closed chambers for most of the sites, and a correction factor using the dynamic closed chamber method was required. Also the F_S in the 12-yr and the 40-yr (second rotation) stands had to be estimated, as no soil respiration measurements were available at these sites.

ΔC_S can be negative during the first rotation, due to decomposition of the drying peat, and positive during second rotation when C starts accumulating again as the trees produce more and more litter. Measurements at smaller time intervals would be required in order to determine changes in the storage of soil C more accurately.

The variance in *TBCA* was estimated as the sum of variances of each component plus the sum of any covariance between each pair of variables (Moore and McCabe,

1993). Since ΔC_R was estimated using allometric equations, its variance was not estimated. However, since ΔC_R is a small component in *TBCA* (compared with F_S and ΔC_S), even a 100% error in its estimation would result in an overestimation or underestimation of *TBCA* of between 9 and 15 % for the second rotation stands and 56% for the 40-yr stand at first rotation.

Finally, although F_A was measured with reasonable accuracy, because litterfall is dependent on climatic conditions (i.e. precipitation, temperature) (Pedersen and Bille-Hansen, 1999; Berg and Meentemeyer, 2001) and year-to-year variations can be large, more measurements during a longer period are required. Klopatek (2002) suggests that *TBCA* should be estimated from long term averages of litterfall and soil respiration and changes in soil C storage.

In summary, average estimates of *TBCA* suggest fairly high rates of C transfer below ground as a result of the high productivity of plantations of Sitka spruce in the British Isles. However, our estimates of soil respiration appear lower than equivalent estimates for temperate coniferous forests. The rates of C accumulation in the soil of second rotation forests found in this study are substantial, but similar to values found for Sitka spruce stands in Ireland (K. Byrne, personal communication).

5.5 Conclusions

The establishment of Sitka spruce forests on previous grassland on peaty gley soils may lead to a decrease in soil C during the first rotation but also to net accumulation of soil carbon during a second rotation. Soil C stocks at the age of 30 years (second rotation) although still below those of the unplanted grassland, were not significantly different from them. It is likely that the rates of accumulation will slow down during a third rotation, but additional research is required to establish this. C accumulation in the soil during the second rotation was probably caused by fairly high rates of C

transfer below ground, coupled to low rates of soil respiration. Finally, a more intensive investigation of C efflux and storage in the chronosequence over a longer period is required to better understand the soil C balance of these forests.