

**SECTION 4**  
Carbon balance of afforested peatland in Scotland



# Carbon balance of afforested peatland in Scotland

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## Summary

The annual net CO<sub>2</sub> exchange over undisturbed deep peatland in Scotland was measured continuously for 22 months using eddy covariance. Annual CO<sub>2</sub> exchanges over peatlands that had been drained, ploughed and afforested with conifers 1, 2, 3, 4, 8, 9 and 26 years previously were estimated by extrapolating 2-4 weekly measurements, using relationships between daytime fluxes and solar radiation and night-time fluxes and air temperature. The contribution of the trees to the overall net CO<sub>2</sub> flux was estimated using a carbon accounting model, calibrated to fit conifer volume yield data. The carbon exchange of the peat and ground vegetation was then the difference between the overall carbon flux and the amount accumulated in trees and tree litter.

The undisturbed peat accumulated about 0.25 tC ha<sup>-1</sup> y<sup>-1</sup>. Newly drained peatland (2-4 years after ploughing) emitted between 2 and 4 tC ha<sup>-1</sup> y<sup>-1</sup>, but when ground vegetation recolonized, the peatland became a sink again, absorbing about 3 tC ha<sup>-1</sup> y<sup>-1</sup> 4-8 years after tree planting. Thereafter, the trees dominated the budget and afforested peatlands absorbed up to 5 tC ha<sup>-1</sup> y<sup>-1</sup>. Assuming that the trees accumulated carbon at rates commensurate with Yield Class 10 m<sup>3</sup> ha<sup>-1</sup> y<sup>-1</sup>, the peat beneath the trees after canopy closure was estimated to be decomposing at only about 1 tC ha<sup>-1</sup> y<sup>-1</sup> or less. This is slower than previously thought and suggested that afforested peatlands in Scotland accumulate more carbon in trees, litter, forest soil and products than is lost from the peat for 90-190 years.

## Introduction

Peatlands (including mires, fens, bogs and other wetlands) contain huge reservoirs of carbon (C). Globally, they represent over one-third of the C in all soils, similar to the amount of C in the atmosphere. In the UK, deep peats (over 45 cm deep) contain about 5000 MtC, representing about half of the C in all soils and about 40 times the C in UK vegetation (Cannell and Milne, 1995; Milne and Brown, 1997).

During the 1950s to 1980s, about 190 thousand hectares of deep peatland in the UK (9 percent of the total area) and about 315 thousand hectares of shallow peatlands, were drained, ploughed and planted with coniferous forests. Planting on deep peats ceased in the 1980s, largely to conserve wetland habitats and species.

In their undisturbed state, peatlands emit the greenhouse gas methane, but accumulate C derived from atmospheric CO<sub>2</sub> (as they have done at a decelerating rate since the last ice age, about 10,000 years ago). Their net contribution to greenhouse warming may be slightly positive, negative or neutral, depending on the site (Crill *et al.*, 2000).

When peatlands are drained and well-aerated for forestry - to enable trees to grow rapidly and be stable in the wind - methane emission and peat C accumulation virtually cease. Two different opposing processes now occur. Peat decomposition is accelerated, releasing CO<sub>2</sub> to the atmosphere, but the rate of C fixation is increased and C accumulates in the trees, tree litter and forest soil and occurs for some time in wood products.

There is, however, a limit to the amount of C that is added to any site by growing trees. Sometime after the first rotation, the amount of C fixed by photosynthesis - averaged over a rotation - is balanced by the oxidation of dead organic matter (litter, soil organic matter and wood products). The average maximum amount of C added to a site in the UK by most conifer forests (the equilibrium carbon storage) lies in the range 150-200 MgC ha<sup>-1</sup>, depending on the Yield Class (Dewar and Cannell, 1992). Cannell *et al* (1993) showed that 150-250 MgC ha<sup>-1</sup> is contained in about 30-40 cm depth of peat. Thus, when 30-40 cm depth of peat has decomposed, afforested peatlands become in carbon deficit, with an overall emission of CO<sub>2</sub> to the atmosphere.

The critical question is: how long will it take for an afforested site to reach the point of carbon deficit? If aerated peat decomposes rapidly following afforestation, the deficit point may be reached within a few decades, in which case afforested peatlands may be regarded as a contributor to greenhouse warming within the next century - when mitigation measures are required. However, if aerated peat decomposes slowly, afforested peatlands may be regarded, like other new forests, as giving a short-term mitigation benefit.

The problem of determining the rate of decomposition of drained peat is not trivial, because of the growth of ground vegetation and trees. In Europe, most work has been done in Finland and Norway (Braekke, 1987; Korhola *et al.*, 1995; Laine *et al.*, 1992; Minkkinen and Laine, 1998; Minkkinen, 1999; Crill *et al.*, 2000). Peat loss or gain has generally been estimated by measuring the difference in amount of C at drained and undrained sites, using volumetric cores, estimates of bulk density and changes in content of minerals. These methods average peat loss or gain over decades and are subject to sampling error. An alternative method, used here, is to directly measure the net flux of CO<sub>2</sub> using eddy covariance. The overall net C loss or gain of the site can then be estimated fairly accurately. However, measurements are generally for periods of only weeks or months, requiring extrapolation in time, and the component contributions to the overall C exchange of peat C efflux and vegetation/trees C influx have to be deduced using models.

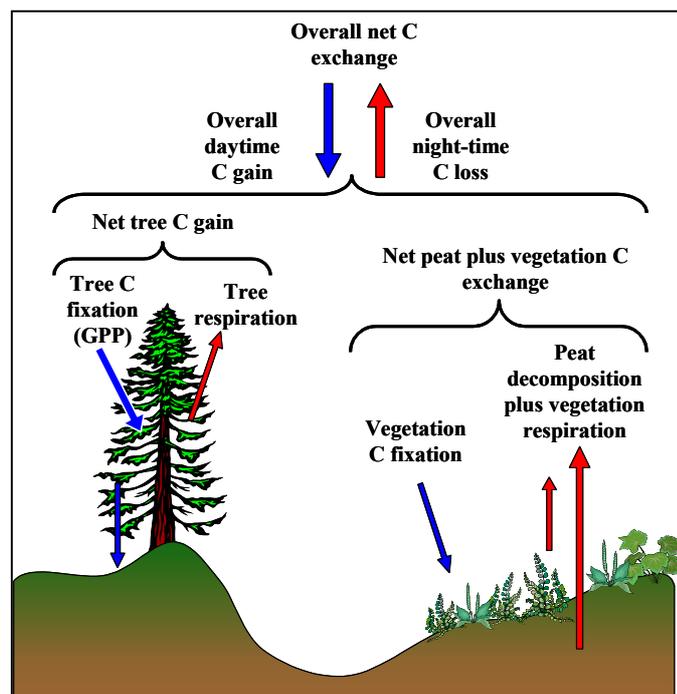


Figure 1. Diagrammatic representation of the components of carbon exchange in an afforested peatland.

## Separating the components of carbon exchange

Figure 1 illustrates the major components of carbon flux over an afforested peatland. These components were derived using a combination of CO<sub>2</sub> flux measurements and forest growth simulation. The terminology used in Figure 1 (the terms underlined below) is used throughout this paper.

### *Overall net C exchange*

The overall annual net exchange of C at peatland sites was estimated by directly measuring CO<sub>2</sub> fluxes between the land and atmosphere using micrometeorological methods. During the day, net fluxes were negative (towards the ground) indicating overall C gain due to photosynthesis. During the night, net fluxes were positive (towards the atmosphere) indicating overall C loss due to plant and soil respiration (Figure 1).

Measurements were taken continuously from March 1995 to December 1996 at a site with undisturbed peat (Auchencorth Moss), giving the annual carbon exchange at this site. These measurements were used to derive relationships between (i) daytime negative fluxes and solar radiation, and (ii) night-time positive fluxes and temperature, for each month of the year. Flux measurements were then taken for periods of 3-4 weeks, in different months during 1995-1999, at three peatland sites which had been drained and planted with conifers up to 26 years before (see below). These measurements were extrapolated to obtain annual overall net C exchanges at these sites, using the daytime and night-time relationships derived at Auchencorth Moss (see below). Clearly, the overall net C exchange could be disaggregated into the annual daytime net C gain (due to photosynthesis exceeding plant and soil respiration) and annual night-time C loss (due to plant and soil respiration) (Figure 1).

The overall net C exchange at an afforested peatland site is the net result of (i) a net gain in carbon due to tree growth, and (ii) a net exchange (loss or gain) of carbon due to the growth of vegetation other than the planted trees (grass, heather etc.) and peat decomposition (Figure 1).

### *Tree carbon gain*

Estimates of the amount of carbon added to a site as a result of tree growth were made using a simulation model called C-flow (Milne *et al.*, 1998) based on the model of Dewar (1991) and Dewar and Cannell (1992), using parameters for *Picea sitchensis* with an annual timestep.

In the model, C gain during forest growth is represented by the increase in C in woody (stems, branches and woody roots) and non-woody (foliage and fine roots) tree parts, which have different growth dynamics, rates of litterfall and decay characteristics. The growth in stem C is constrained to fit the observed increase in stem volume in yield tables. Other woody C is then estimated as fractions of stem wood. Foliage and fine root C are assumed to increase to an asymptote at the time of canopy closure, at 0.25 rotation length. The output is the annual tree C gain - comprised of C in trees, their litter and derived soil (Figure 1).

During the early years of a rotation, most of the C accumulates in the trees and so the annual net tree C gain approximates what is commonly known as net primary productivity. It is then assumed that tree respiration is a fixed fraction of carbon fixation

(about 0.5; Waring *et al.*, 1998) it is possible to estimate tree C fixation (gross primary production) and tree respiration (Figure 1).

### *Net peat plus vegetation carbon exchange*

The net exchange (loss or gain) of carbon due to vegetation growth and peat decomposition can now be found, approximately, by difference. That is:

Net peat plus vegetation C exchange = Overall net C exchange - Net tree C gain  
Vegetation C fixation . Overall daytime C gain - Tree C fixation, and  
Peat decomposition plus vegetation respiration . Overall night-time C loss - tree respiration.

## **Methods details**

### *Meteorological Measurements*

Basic meteorological measurements were made of air temperature and relative humidity (at 2 m above the ground) (Rotronic MP100 probe), solar radiation (Skye SP1000), rainfall and soil temperature at 10 cm depth. Data were logged every 10 seconds and averaged over a 30 minute period using a Campbell 21X data-logger.

### *Micrometeorological Measurements*

The eddy covariance (also known as eddy correlation) approach was used, where the net flux of CO<sub>2</sub> ( $F_c$ , mmol m<sup>-2</sup> h<sup>-1</sup>) is given by:

$$F_c = \overline{w' \chi'} \quad (1)$$

where  $w'$  is the instantaneous deviation of the vertical component of windspeed from the mean and  $\chi'$  is the instantaneous deviation of CO<sub>2</sub> concentration from the mean. The three components of windspeed were measured using a Solent ultrasonic anemometer Model 1012RA (Gill Instruments, Lymington, Hants). Air was sampled from a point approximately 5 cm downwind of the sonic sampling volume down a 1/4" outside diameter Dekabon tube (Dekoron Corp., Illinois) at a flow rate of 6.0 l min<sup>-1</sup>, maintained within 0.2% by a mass flow controller. Carbon dioxide concentrations were measured using a Licor 6262 infra-red gas analyser (Licor Inc., Lincoln, Nebraska) which had a pneumatic response time of 6.3 Hz at the chosen flow rate. The CO<sub>2</sub> concentration was output as a 0-5 volt analogue signal which was fed to the anemometer analogue inputs. These were digitised by the anemometer and logged digitally together with the three components of wind velocity and speed of sound at 20.8 Hz on a computer running "Edisol" software (Moncrieff *et al.*, 1996). Edisol performs the necessary coordinate rotations and a 200 s running mean was applied to detrend the data. Sensible and latent heat fluxes, CO<sub>2</sub> fluxes and other micrometeorological parameters were stored as 10 min averages and subsequently averaged to 30 min intervals to synchronize with the meteorological data.

The micrometeorological data were screened to remove periods when the wind was from directions with inadequate fetch, or when instrument problems were apparent. In addition, corrections were applied to fluxes measured at very low windspeeds (less than  $1 \text{ m s}^{-1}$ ) in order to avoid systematic underestimation of the fluxes. These corrections were made assuming that true fluxes remained constant when windspeeds steadily changed and on nights when the temperature and wind direction remained near-constant for several hours.

*Table 1:* Forest locations and months when measurements of CO<sub>2</sub> flux were made. All the measurement sites had peats at least 0.5 m deep and planted sites were dominated by *Picea sitchensis*.

<b>Forest age (years since planting)</b>	<b>Location and site</b>	<b>Measurement months</b>
0 (Undisturbed peat)	Auchencorth Moss, Midlothian (NT22563) 270 m. altitude. About 900 mm. rainfall. Ombrotrophic blank peat 3-5 m. depth, dominated by heather.	March 1995 to December 1996
1	Bealach Burn, Forsinard, Sutherland (NC908412) 170 m. altitude. About 900 mm. rainfall. Ombrotrophic blanket peat 3-5 m. deep. Double mould board ploughed. Sparse grass and heather cover in year 1. Trees 8-10 cm. tall at planting.	May and August
2	“	February
3	“	July and December
4	“	October
8	Channain Forest, Forsinard, Sutherland (NC926411) 240 m. altitude. About 900 mm. rainfall. Peat about 1 m. deep. Double mouldboard ploughed. Grass and heather. Trees 1-2 m. tall.	August
9		February
26	Mindork Moss, Newton Stewart (NX305565) 85 m. altitude. About 1100 mm. Rainfall. Peat over 2 m. deep. Double mouldboard ploughed. Complete tree cover with little ground vegetation. Trees at Yield Class $8 \text{ m}^3 \text{ ha}^{-1} \text{ yr}^{-1}$	February and June

### *Sites*

Table 1 gives details of the sites. All were in Scotland (Ordnance Survey reference given) and were chosen to have deep peat and uninterrupted fetch in most directions to enable accurate flux measurements to be made.

A chronosequence of afforested sites was obtained by choosing a newly planted forest and taking measurements for periods of 3-4 weeks within years 1 to 4 after

planting (Bealach Burn), a young forest measured for periods of 3-4 weeks within years 8 and 9 (Channain Forest) and a 26-year-old forest (Mindork Moss).

The sites ranged in altitude between 85 m (Mindork Moss) and 270 m (the reference site with undisturbed peat at Auchencorth Moss). Average annual precipitation varied in the range 800-1100 mm. Average January and July temperatures were in the ranges 1-3 °C and 13-16 °C, respectively.

*Relating net CO<sub>2</sub> fluxes at the undisturbed peatland (Auchencorth Moss) to solar radiation and temperature*

At Auchencorth Moss, the daytime net CO<sub>2</sub> flux,  $F_d$  (mmol m<sup>-2</sup> h<sup>-1</sup>), averaged over 30 minute periods during daylight (solar radiation exceeding 2 Wm<sup>-2</sup>), was related to 30-minute averaged incident solar (global) radiation  $S_t$  (Wm<sup>-2</sup>). The greater the solar radiation the more negative the flux, indicating net CO<sub>2</sub> uptake from the atmosphere. Daytime net CO<sub>2</sub> flux and solar radiation were plotted for each month and the relationship was fitted using a hyperbolic light response function:

$$F_d = A - \left( \frac{B \cdot S_t}{1 + C \cdot S_t} \right) \quad (2)$$

where  $A$ ,  $B$  and  $C$  were fitted parameters which differed in each month. Seasonal variation in  $A$ ,  $B$  and  $C$  reflected seasonal variation in net ecosystem uptake in response to light and temperature.

Similarly, at Auchencorth Moss, night-time 30-minute measurements of net CO<sub>2</sub> flux,  $F_n$  (mmol m<sup>-2</sup> h<sup>-1</sup>) were related to 30-minute averages of air temperature,  $T_a$  (°C, measured at 2 m height). Higher temperatures were associated with larger, positive fluxes, indicating net CO<sub>2</sub> emission to the atmosphere. Net CO<sub>2</sub> flux and air temperature were plotted, using data for the whole year, and the relationship was fitted using a simple exponential function:

$$F_n = D \cdot \exp(E \cdot T_a) \quad (3)$$

where  $D$  and  $E$  were fitted parameters. There was no evidence that  $F_n$  was more closely dependent on soil temperature than air temperature (Wofsy *et al.*, 1993). Also, there was no evidence that the relationship between night-time CO<sub>2</sub> emission and air temperature varied seasonally, so annual mean values of parameters  $D$  and  $E$  in equation (3) were calculated using data for the whole year.

*Estimating the annual net CO<sub>2</sub> fluxes at the undisturbed peatland (Auchencorth Moss)*

The annual net CO<sub>2</sub> flux at Auchencorth Moss was first calculated by summing the available 30 minute CO<sub>2</sub> flux measurements taken throughout the year (1996 was used as a reference). Periods when CO<sub>2</sub> fluxes were not measured (when wind direction was unsuitable or windspeed too low) were estimated using equations (2) and (3) together with the monthly mean values of  $A$ ,  $B$  and  $C$ .

A more refined approach to the calculation was also employed using a model written within ModelMaker 4.0 (Cherwell Scientific, Oxford, UK) on a 30 minute timestep. Values of  $A$ ,  $B$  and  $C$  were fixed for the middle of each calendar month and a 30-minute interpolated timestep of the parameters used to calculate 30 minute mean

fluxes derived entirely from solar radiation and temperature data (i.e. no directly measured flux data were included).

These two methods gave annual fluxes differing by less than 1%, and very similar monthly mean net CO<sub>2</sub> fluxes. This exercise showed that the Modelmaker program performed correctly and gave confidence in using equations (2) and (3) to calculate annual fluxes from monthly mean values of  $A$ ,  $B$  and  $C$  and annual values of  $D$  and  $E$ .

To enable valid comparisons to be made with afforested sites, annual fluxes were also estimated using Auchencorth Moss parameters but climatic data for the 26-year-old forest site at Mindork Moss (see below).

#### *Derivation of annual CO<sub>2</sub> fluxes at the afforested site (Mindork Moss)*

Measurements of net CO<sub>2</sub> fluxes at the drained and afforested sites were obtained on a 'campaign' basis, providing snapshots of the daytime-light and night-time-temperature response curves for only one or two months (see Table 1). Also, there were no continuous measurements of solar radiation and temperature at these sites.

Consequently, annual net CO<sub>2</sub> fluxes were estimated making three assumptions. First, it was assumed that the seasonal pattern of change in  $A$ ,  $B$  and  $C$  in equation (2) was the same at the afforested sites as at the undisturbed site (Auchencorth Moss), so that values in the 'missing' months could all be scaled using measured values in one or two months. For example, if measurements made at Bealach Burn in May and August at age 1 showed that parameter  $A$  was, on average,  $x\%$  greater than in May and August at Auchencorth Moss, it was assumed that parameter  $A$  at Bealach Burn was  $x\%$  greater than at Auchencorth Moss in all months. The underlying assumption was that the seasonal pattern of the relationship between daytime net CO<sub>2</sub> flux and solar radiation was the same at the afforested sites as at the undisturbed site.

Second, it was assumed that the annual mean value of parameter  $E$  in equation (3) at afforested sites had the same value as at Auchencorth Moss ( $E = 0.1379$ ), whereas annual values of parameter  $D$  were estimated for each afforested site from the short-term measurements. That is, it was assumed that the curve of the exponential relationship between night-time CO<sub>2</sub> emission and temperature was the same at all sites and that only the position of the curve differed between sites.

Third, in order to obtain a valid comparison between sites, annual net CO<sub>2</sub> fluxes were calculated using solar radiation and temperatures estimated at the 26-year-old forest site at Mindork Moss in 1996. Solar radiation data for 1996 were derived from Meteosat images and measurements of turbidity (Satel-Light, 2000). Air temperatures were obtained from the British Atmospheric Data Centre ([www.badc.rl.ac.uk](http://www.badc.rl.ac.uk)) for West Freugh airfield near Stranraer (NX 117555), 19 km west of Mindork Moss. These were corrected for altitude using the atmospheric adiabatic lapse rate. Calculations were made using the same Modelmaker program that was evaluated using Auchencorth Moss data. As before, the program used 30-minute values of solar radiation and temperature, monthly mean values of  $A$ ,  $B$  and  $C$  to interpolate 30-minute values and single values of  $D$  and  $E$  throughout the year.

In this way, estimates were made of annual net CO<sub>2</sub> fluxes at drained and afforested peatland sites in years 1, 2, 3, 4, 8, 9 and 26 (Table 1).

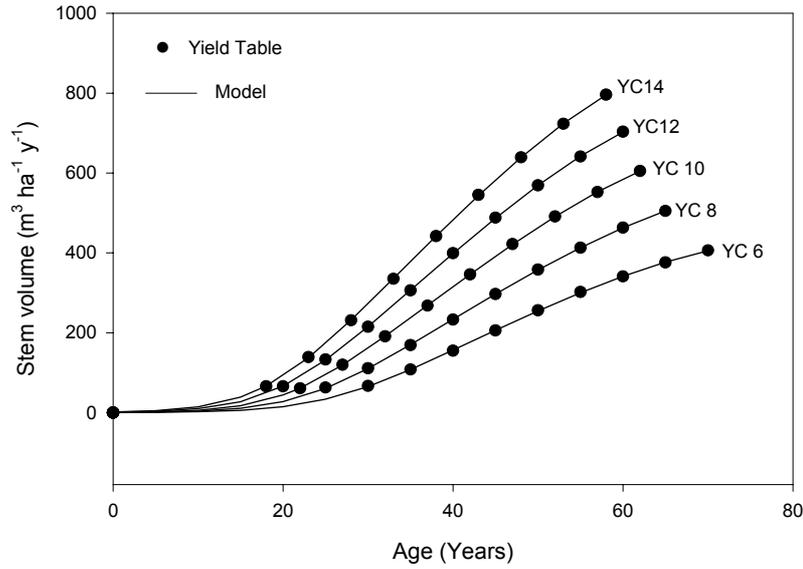


Figure 2. Increase in stem volume in *Picea sitchensis* stands to age 26, taken from yield table observations (points) and fitted using a modified expo-linear equation (equations (4) and (5) in the text).

#### *Estimating net tree C gain using the C-flow model*

The C-flow model was parameterized to simulate carbon accumulation a *Picea sitchensis* forest growing in Scotland at different yield classes ( $\text{m}^3 \text{ha}^{-1} \text{y}^{-1}$ ). The model is fully described elsewhere (Dewar, 1991; Dewar and Cannell, 1992; Milne *et al.*, 1998). For this application, the model was modified in three ways to more accurately simulate growth in the early years of rotation.

First, the increase in stem volume, and hence in all woody carbon, to age 26 was simulated using a modified expo-linear growth function (Monteith 2000). Stem volume,  $S(t)$  was given by:

$$S(t) = M(t) \frac{1 - e^{-k_s(k_t - t)}}{1 - e^{-k_s k_t t}} \quad (4)$$

where

$$M(t) = \frac{C_m}{R_m} \ln \left[ 1 + \frac{C_0}{C_m} e^{R_m t} \right] \quad (5)$$

$M(t)$  is an implementation of Monteith's (2000) function where  $C_m$  is maximum absolute growth rate,  $C_0$  is initial absolute growth rate and  $R_m$  is the initial relative growth rate. In the function for stem volume,  $S(t)$ ,  $k_s$  and  $k_t$  are parameters which progressively reduce the growth rate from time  $t$  (about mid-rotation age). The five parameters in equations (4) and (5) were fitted to stem volume observations for *P. sitchensis* at yield classes 6 to 14  $\text{m}^3 \text{ha}^{-1} \text{y}^{-1}$  (Edwards and Christie, 1981), assuming stem volume to be zero at planting. A good fit was obtained (Figure 2). The fitted

models were then used to generate input volume series for the C-Flow model from which woody C was derived (Dewar, 1991; Milne *et al.*, 1998).

Second, the increase in mass of non-woody material (foliage and fine roots) was assumed to follow a logistic rather than an exponential function, as in Dewar (1991), in order to describe a more realistic increase in mass up to an asymptote at 25% of rotation age.

Third, it was assumed that the fraction of wood in branches decreased from 0.31 at planting to 0.09 at age 15 years (approximately canopy closure, or 25% of rotation age) rather than remained constant at 0.09 as assumed by Dewar and Cannell (1992). However, this change had little effect on predicted carbon gain.

It was further assumed that net tree carbon gain (net primary productivity) was 53% of tree C fixation (gross primary productivity, GPP) - the other 47% being tree respiration. This is a realistic approximation for young trees with a high fraction of growth (as opposed to maintenance) respiration (Waring *et al.*, 1998; Thornley and Cannell, 2000).

## Results

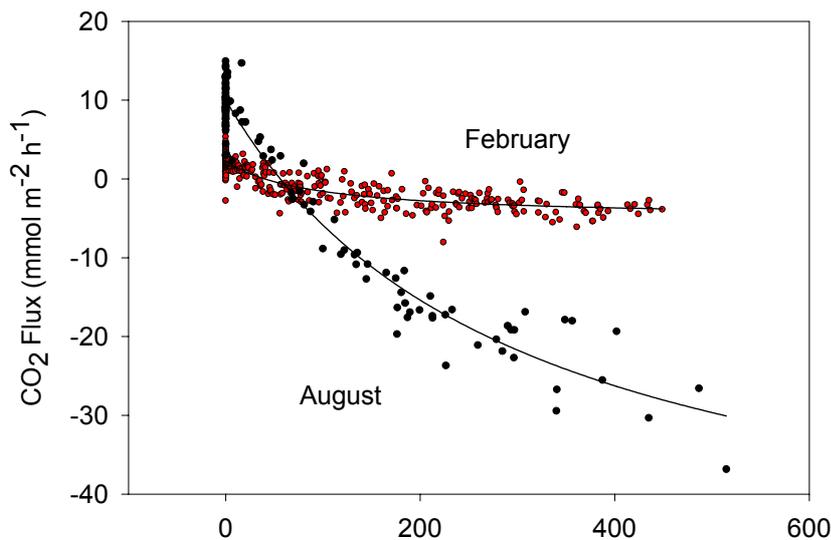
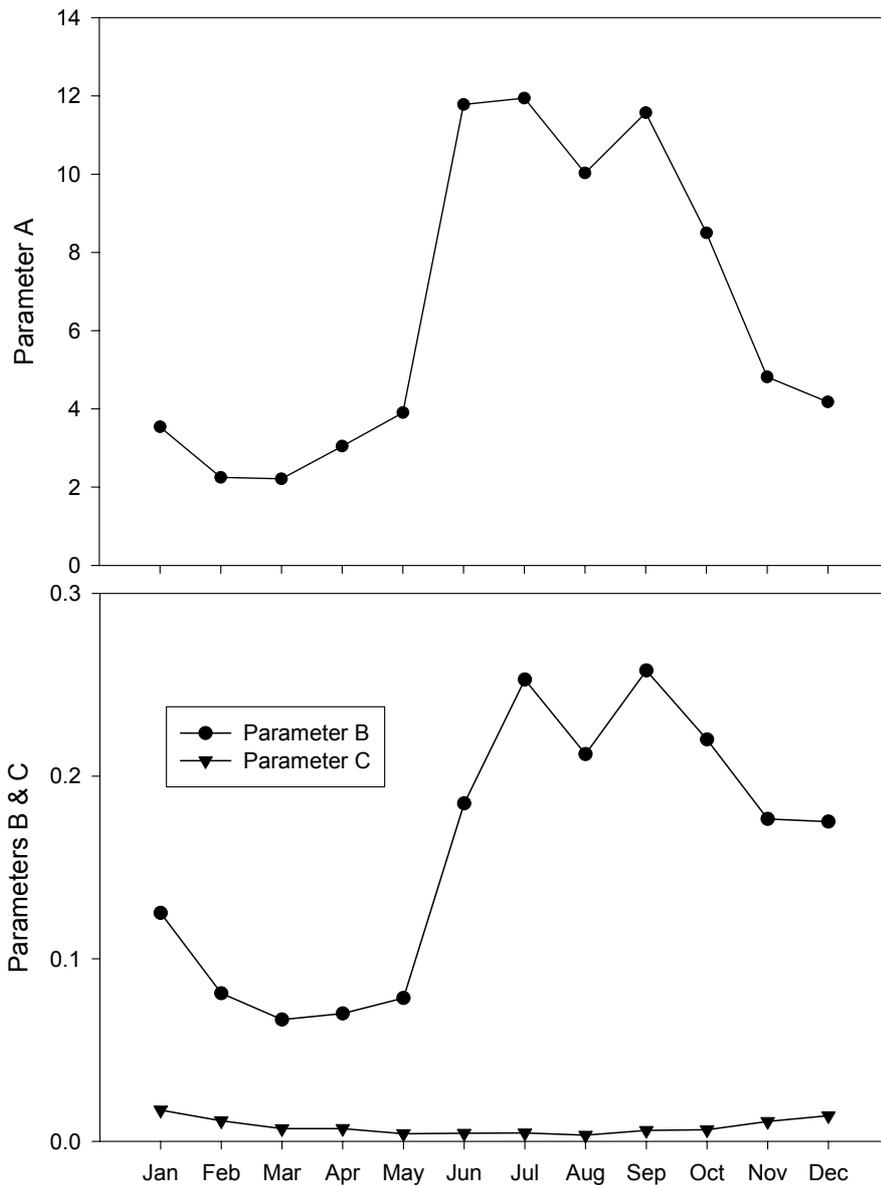


Figure 3. Above: Relationship between the net flux of CO<sub>2</sub> and solar radiation in February and August over an undisturbed peatland (Auchencorth Moss). The points are 30-minute averages. Below: Seasonal variation in parameters *A*, *B* and *C* in text equation (2), describing the relationship between the net flux of CO<sub>2</sub> and solar radiation at an undisturbed peatland (Auchencorth Moss).



*Daytime CO<sub>2</sub> flux responses to light, and night-time responses to temperature*

As expected, net CO<sub>2</sub> uptake (a negative flux) at the undisturbed peatland site (Auchencorth Moss) was greater on summer than winter days at a given level of solar radiation. The light response curves for February and August are illustrated in Figure 3 (top graph). Such different curves gave different values of the fitted parameters *A*, *B* and *C* in equation (2). Figure 3 (bottom graph) shows seasonal variation in these parameters at Auchencorth Moss, reflecting changes in leaf area, temperature and physiological state of the photosynthetic apparatus of the ground vegetation.

Figure 4 shows the exponential response of the night-time net CO<sub>2</sub> flux to temperature at Auchencorth Moss. This response showed no seasonal variation. The values of *D* and *E* in equation (3) at this site were 2.1669 and 0.1379, respectively.

Table 2 gives the percentages by which the monthly values of *A*, *B* and *C*, and the mean annual value of *D*, were altered to simulate the CO<sub>2</sub> flux responses at the

afforested sites to light and temperature. These adjustments were based on one or two measurement periods of 2-4 weeks for each forest age (see Table 1).

*Table 2:* Percentage change in the parameters in equations (2) and (3) required to fit measured net CO<sub>2</sub> fluxes to daytime solar radiation and night-time temperature. The percentage changes were based on net CO<sub>2</sub> fluxes measured over 2-3 weeks, in 1 or 2 months of the year (see Table 1) and were assumed to apply to the whole year. Thus, all monthly points on the curves for *A*, *B* and *C* in Figure 3b were adjusted by the same percentage.

Forest age (years since planting)	Site	Parameter change (%)			
		Daytime light response (Eqn. 2, Fig. 3)			Night-time temperature response (Eqn. 3, Fig. 4)
		<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>
0	Auchencorth Moss	0	0	0	0
1	Bealach Burn	45	63	100	23.5
2	“ “	16	124	567	13.1
3	“ “	-23	29	262	2.7
4	“ “	-61	-66	-43	-16.8
8	Channain Forest	53	76	33	-24.7
9	“ “	52	75	33	-23.2
26	Mindork Moss	37	40	-29	1.2

### *Seasonal changes in net CO<sub>2</sub> exchange*

The undisturbed peatland was a net carbon sink only in the months of May to early September, fixing most carbon in June and July (Figure 5). It was a net source of carbon in all other months, including mid-winter, when mean monthly temperatures in this mild maritime climate remained above zero.

In the first year following ploughing and tree planting (Bealach Burn, year 1) the peatland was barely able to produce a net negative carbon flux (i.e. there was little net carbon uptake) even in mid-summer. The reasons were twofold. First, drainage exposed previously anaerobic peat to the air, so that respiration rates increased. Nocturnal respiration rates were much larger at Bealach Burn following ploughing than at the undisturbed peatland site. Second, ploughing destroyed about 70% of the area of photosynthetically active vegetation.

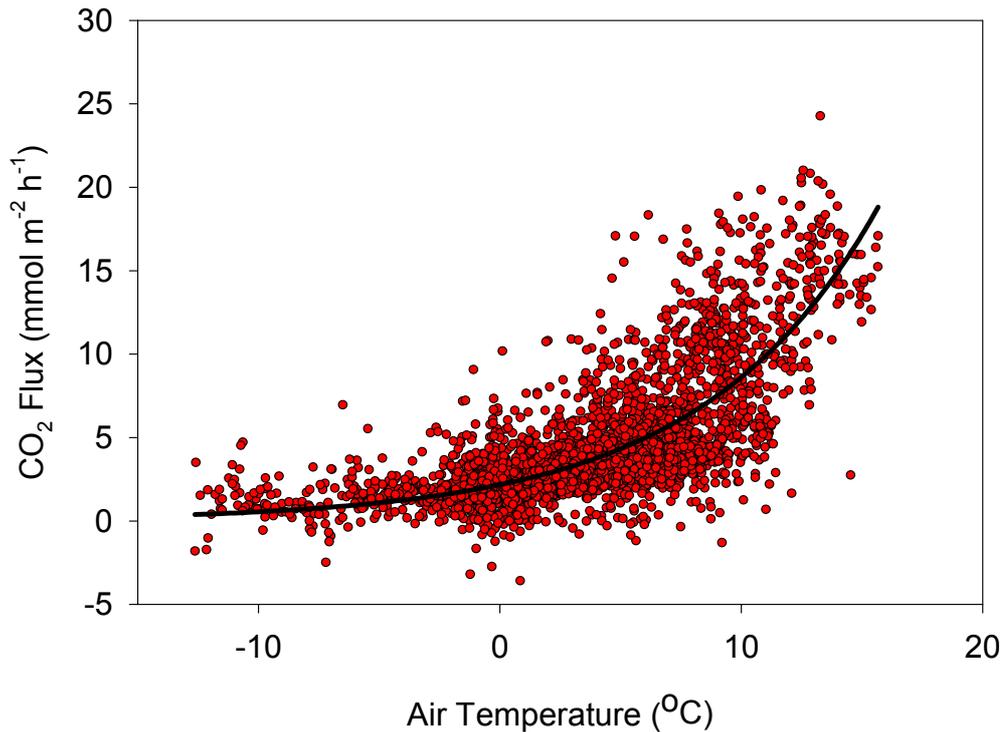


Figure 4. Relationship between air temperature at night (when solar radiation is less than  $2 \text{ Wm}^{-2}$ ) and the net flux of  $\text{CO}_2$  over an undisturbed peatland (Auchencorth Moss). The points are 30-minute averages. The data are fitted by the equation  $F_n = 2.1669 \cdot \exp(0.1379 T_a)$ , where  $F_n$  is the night-time  $\text{CO}_2$  flux ( $\text{mmol m}^{-2} \text{ h}^{-1}$ ) and  $T_a$  is air temperature ( $^{\circ}\text{C}$ ).

As the trees became established and grasses colonized the exposed peat surfaces, the summer carbon sink reappeared. By age 8, the afforested site (Channain Forest) was once again a carbon sink from May to early September (Figure 5). Although nocturnal respiration rates were slightly larger than those at age 1 (presumably because of the added tree respiration), the tree canopy was able to fix large amounts of carbon during daylight.

At age 26, the forest was an even stronger carbon sink during the summer months (Figure 5).

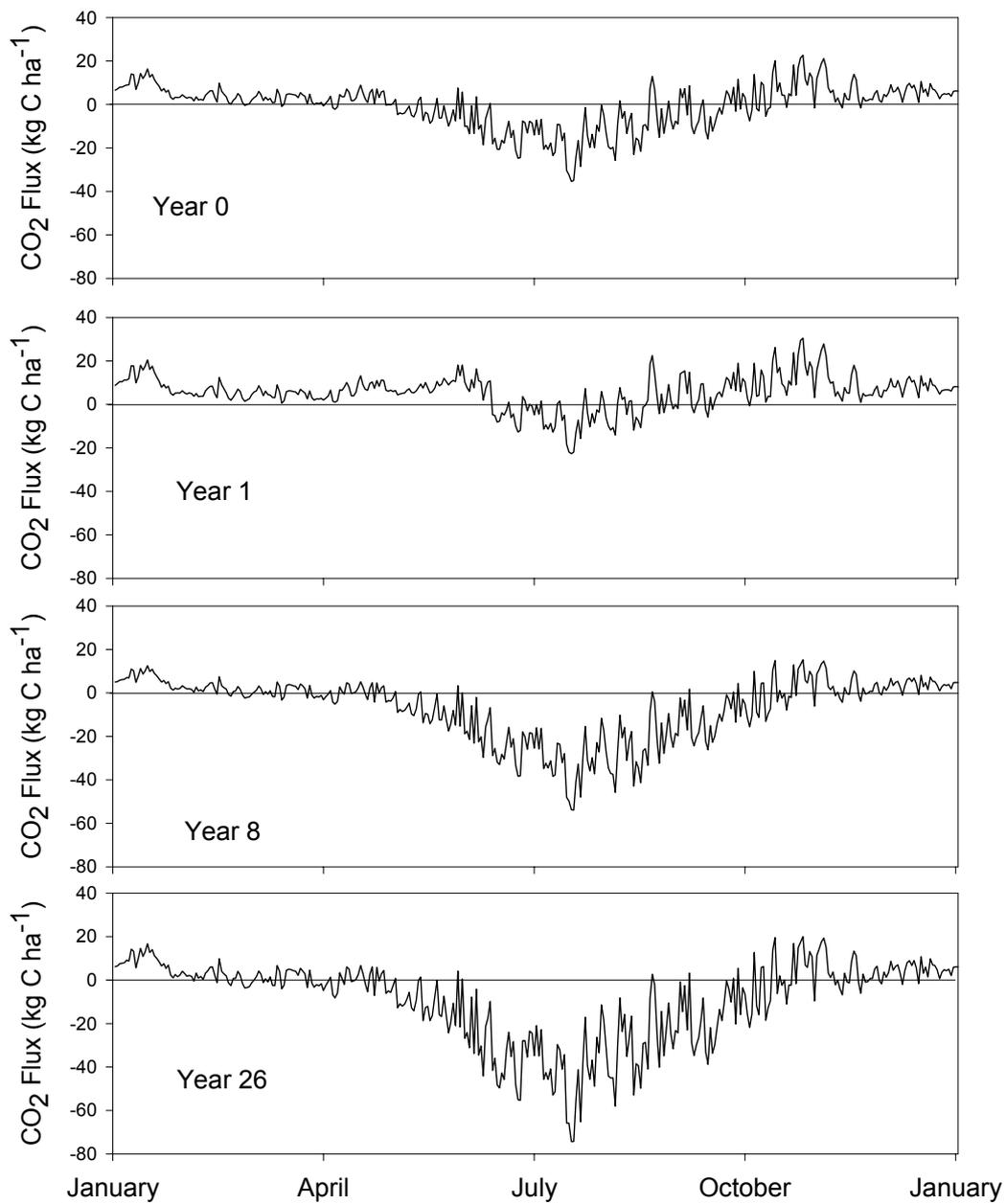


Figure 5. Seasonal variation in the net carbon flux over an undisturbed peatland before ploughing (year 0) and 1, 8 and 26 years after ploughing and planting with conifers. All graphs refer to the climate at Mindork Moss (the 26-year-old forest), but seasonal variation in parameters *A*, *B*, *C* and *D* in text equations (2) and (3) were derived from measurements at Auchencorth Moss (year 0), Bealach Burn (year 1), Channain Forest (year 8) and Mindork Moss (year 26).

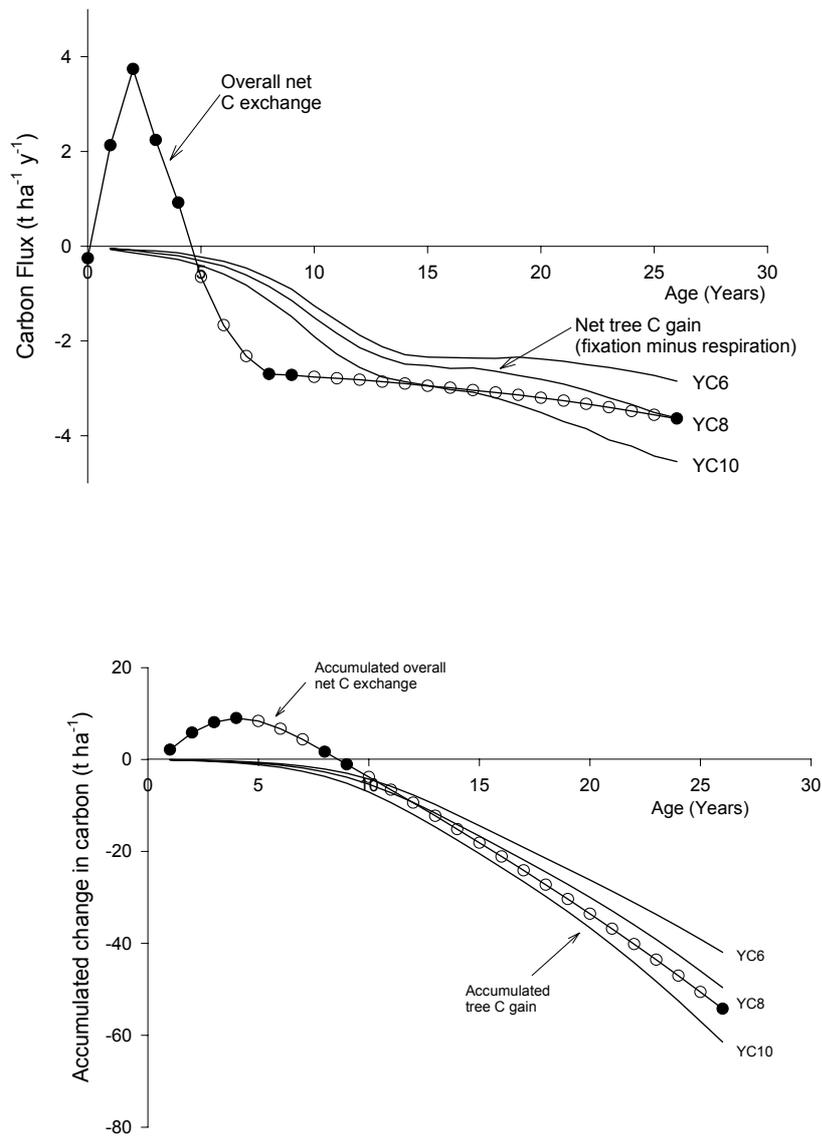


Figure 6. Above: annual overall net carbon exchange of an afforested peatland to age 26 (points) shown in relation to the net tree carbon gain estimated using the C-flow model with yield classes 6, 8 and 10 (lines). Below: the same data expressed as an accumulated total amount of carbon starting at year zero.

The measured carbon exchange values (solid points) were estimated for the climate at Mindork Moss (the 26-year-old forest), but using parameters *A*, *B*, *C* and *D* in text equations (2) and (3) derived from measurements at Auchencorth Moss (year 0), Bealach Burn (years 1-4), Channain Forest (years 8 and 9) and Mindork Moss (year 26). Values for intervening years (shown with open circles) were estimated by interpolation.

## Changes in C exchange and accumulation to age 26

Figure 6 shows the C exchange of an afforested peatland up to age 26 in the climate of Mindork Moss in 1996. The top graph shows the estimated C flux each year and the bottom graph shows the accumulated change in the total amount of C in the system. In both graphs, the time course is given of the overall net C exchange (solid points, measured using eddy covariance, open points interpolated) and the component of that flux due to net gain of carbon in the trees and associated litter and soil (lines, estimated using the C-flow model for Yield Classes 6, 8 and 10  $\text{m}^3 \text{ha}^{-1} \text{y}^{-1}$ ).

The undisturbed peatland was estimated to accumulate  $0.25 \text{ tC ha}^{-1} \text{y}^{-1}$  (i.e. be sink of  $-0.25 \text{ tC ha}^{-1} \text{y}^{-1}$ , Figure 6 top), compared with  $0.22 \text{ tC ha}^{-1} \text{y}^{-1}$  in the cooler climate at Auchencorth Moss. In the first year after ploughing, the peatland emitted about  $2.0 \text{ tC ha}^{-1} \text{y}^{-1}$  (i.e. it was source of  $2.0 \text{ tC ha}^{-1} \text{y}^{-1}$ ). In the second year this source rose to  $3.5 \text{ tC ha}^{-1} \text{y}^{-1}$  as the peat dried out. As herbaceous vegetation spread and the planted trees became established, the source decreased to about  $2.1 \text{ tC ha}^{-1} \text{y}^{-1}$  in year 3 and  $0.9 \text{ tC ha}^{-1} \text{y}^{-1}$  in year 4 (Figure 6, top). Thereafter, the forest was estimated to be a net carbon sink. By ages 8 and 9 the afforested site was a net sink of about  $-2.5 \text{ tC ha}^{-1} \text{y}^{-1}$  and by year 26 a sink of  $-3.4 \text{ tC ha}^{-1} \text{y}^{-1}$ .

The cumulative effect of this time course of C exchange was that the afforested peatland was a net source of carbon until age 9, losing about  $9.0 \text{ tC ha}^{-1}$  over this period in the climate of Mindork Moss (*cf.*  $8.5 \text{ tC ha}^{-1}$  at Auchencorth Moss). But by age 26, the afforested site had accumulated  $-54.4 \text{ tC ha}^{-1}$  (*cf.*  $-50.2 \text{ tC ha}^{-1}$  at Auchencorth Moss).

As expected, the planted trees were estimated to be an increasing C sink from the time of planting (year 1) to age 26, especially during the period before canopy closure (about age 15; Figure 6, top). However, the tree sink was could not account for the large overall net C sink of the site during years 6-10. Thus, ground vegetation must account for a considerable sink during that period.

However, by age 26, the rate of C uptake by the trees (net tree C gain) was estimated to be similar to the overall net C exchange of the site. If the Yield Class was less than  $8 \text{ m}^3 \text{ha}^{-1} \text{y}^{-1}$  (e.g. YC6) the trees were estimated to be a smaller C sink than the site as a whole (i.e. the line is above the points in Figure 6, top) meaning that the peat was absorbing C - which is unrealistic. If the Yield Class was greater the  $8 \text{ m}^3 \text{ha}^{-1} \text{y}^{-1}$  (e.g. YC10) the trees were estimated to be a greater C sink than the site as a whole, which would mean that the peat was losing C.

Figure 6 (bottom) shows that the accumulated C gain by the trees exceeded that of the site as a whole to age 26 when the Yield Class was assumed to be above about  $9 \text{ m}^3 \text{ha}^{-1} \text{y}^{-1}$ .

The difference between the overall net C exchange of the site and the net tree C gain must be due to net peat plus ground vegetation C exchange (Figure 1). Table 3 shows that, to age 26, this difference varied from a net sink of  $-12.3 \text{ tC ha}^{-1}$  if it was assumed that the trees were growing at Yield Class  $6 \text{ m}^3 \text{ha}^{-1} \text{y}^{-1}$  to a net source of  $+28.4 \text{ tC ha}^{-1}$  if the trees were growing at Yield Class  $14 \text{ m}^3 \text{ha}^{-1} \text{y}^{-1}$ .

The Yield Class of the forest at Mindork Moss was estimated by the Forestry Commission to be  $12\text{-}14 \text{ m}^3 \text{ha}^{-1} \text{y}^{-1}$  at age 14 years. However, the stand declined in growth rate thereafter and, at age 26, height estimates made by the Centre for Ecology and Hydrology showed that the Yield Class had fallen to about  $8 \text{ m}^3 \text{ha}^{-1} \text{y}^{-1}$ . The average Yield Class over the 26 year period may be expected to be in the range  $10\text{-}12 \text{ m}^3 \text{ha}^{-1} \text{y}^{-1}$ .

*Table 3:* Estimated net loss or gain of carbon by peat plus ground vegetation over 26 years following afforestation in Scotland with trees growing at different rates (Yield Classes). These estimates are obtained as the difference between (A) the measured overall net C exchange of forest sites and (B) model calculations of the amount of carbon accumulated by the trees (in biomass, litter and soil).

	A	B	A-B
Yield Class of the trees	Measured overall net C exchange over 26 years (amount of C added to the site)	Calculated net tree C gain over 26 years (amount of C added to the site by the trees)	Net peat plus vegetation C exchange over 26 years (gain [-] or loss [+] of C from peat and vegetation)
(m <sup>3</sup> ha <sup>-1</sup> y <sup>-1</sup> )	(t C ha <sup>-1</sup> )	(t C ha <sup>-1</sup> )	(t C ha <sup>-1</sup> )
6	- 54.2	- 41.9	- 12.3
8	- 54.2	- 49.6	- 4.6
10	- 54.2	- 61.6	+7.3
12	- 54.2	- 70.2	+16
14	- 54.2	- 82.6	+28.4

Thus, the net peat plus vegetation C exchange at the Mindork Moss site over 26 years was estimated to result in a loss of 7.3 to 16.0 tC ha<sup>-1</sup> (assuming tree YC10-12, Table 3). But about 9 tC ha<sup>-1</sup> of this loss occurred during the first 9 years. Thus, the loss of C during years 10-26 was estimated to be around 5 tC ha<sup>-1</sup> or less, equivalent to less than 0.5 tC ha<sup>-1</sup> y<sup>-1</sup>.

#### *Net peat plus vegetation C exchange*

Figure 7 (top graph) shows that time course of the net peat plus vegetation C exchange, derived from the difference between the overall net C exchange (measured by eddy covariance) and the net tree C gain (estimated using the C-flow model). The bottom figure shows the two components of that flux: C fixation and respiration/decomposition. Vegetation C fixation is the difference between overall daytime C gain and tree C fixation (gross primary productivity, assumed to be twice net tree C gain), while respiration/decomposition is the difference between overall night and daytime C loss (derived using the temperature function in Figure 4) and tree respiration (assumed to be half tree gross primary productivity).

During the first 5 years, the trees play little part in the overall net C exchange and so the net emission shown in Figure 6 (top) is the same as that in Figure 7 (top). Between years 5 and about 10, before canopy closure, the peat plus vegetation is a net sink, as mentioned above. That is, C fixation by ground vegetation exceeds the loss of C by peat decomposition. After year 15, when there is little ground vegetation, the peat is an increasing source of C if the trees are assumed to be growing at Yield Class 10 m<sup>3</sup> ha<sup>-1</sup> y<sup>-1</sup> or above (Figure 7, top).

The time course of respiration/decomposition and C fixation shows some interesting features, not all of which may be explained by the considerable uncertainty in such derived estimates. Notably, during the first 4 years after drainage, the

decomposition/respiration rate falls, perhaps owing to the loss of labile substrates, and also the rate of C fixation falls, perhaps owing to the death of pre-existing vegetation. After year 4, the bare peat is recolonized with ground vegetation and this results in increased C fixation and plant respiration. After about year 7, the ground vegetation becomes progressively shaded out, there is less C fixation and the respiration/decomposition rate falls to a base level due solely to peat decomposition.

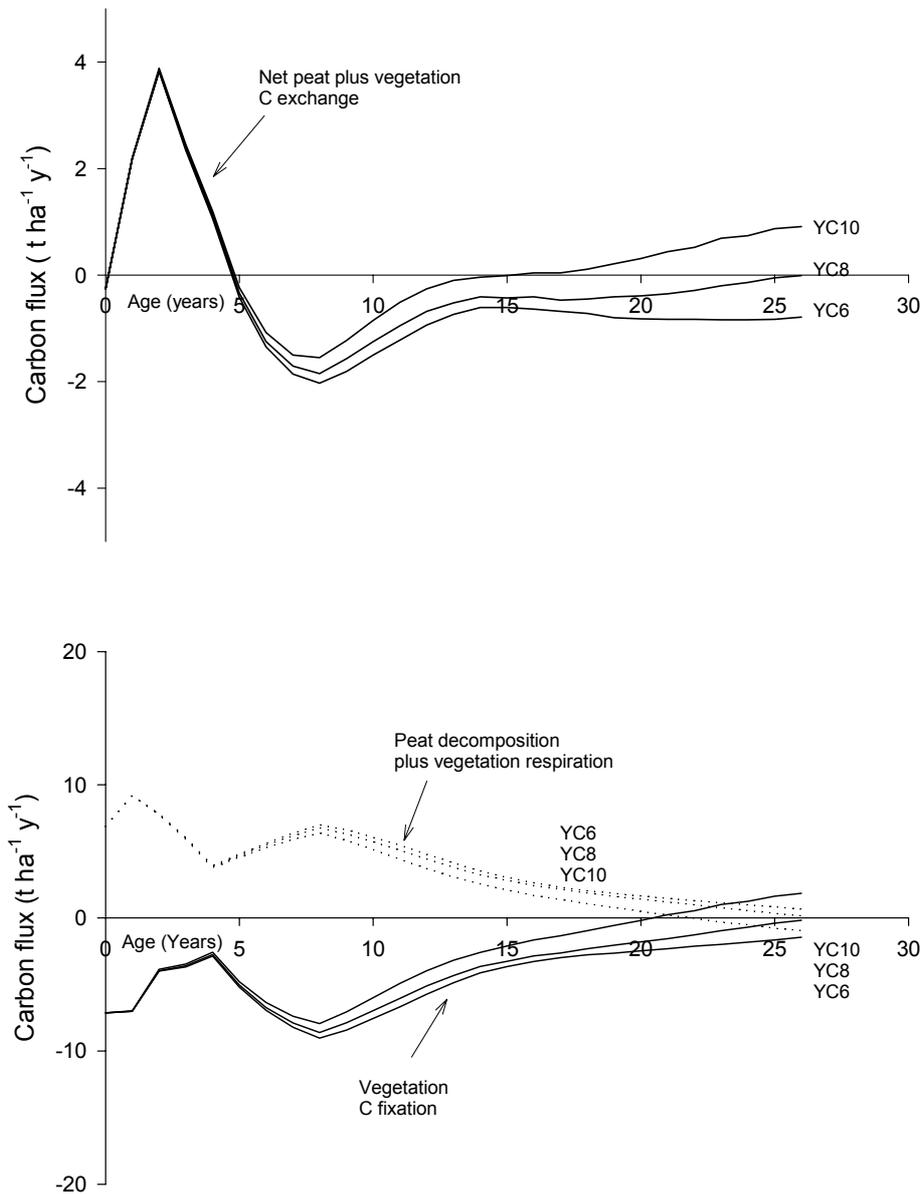


Figure 7. Estimated carbon exchanges within an afforested peatland involving just the peat and ground vegetation. That is, the net tree carbon gain has been subtracted from the overall net carbon exchange (see Figure 1).

## Discussion

The salient findings of this study are summarized in Figure 8. Four peatland states were identified. First, the undisturbed peatland is a C sink, absorbing about  $-0.25 \text{ t C ha}^{-1} \text{ y}^{-1}$ .

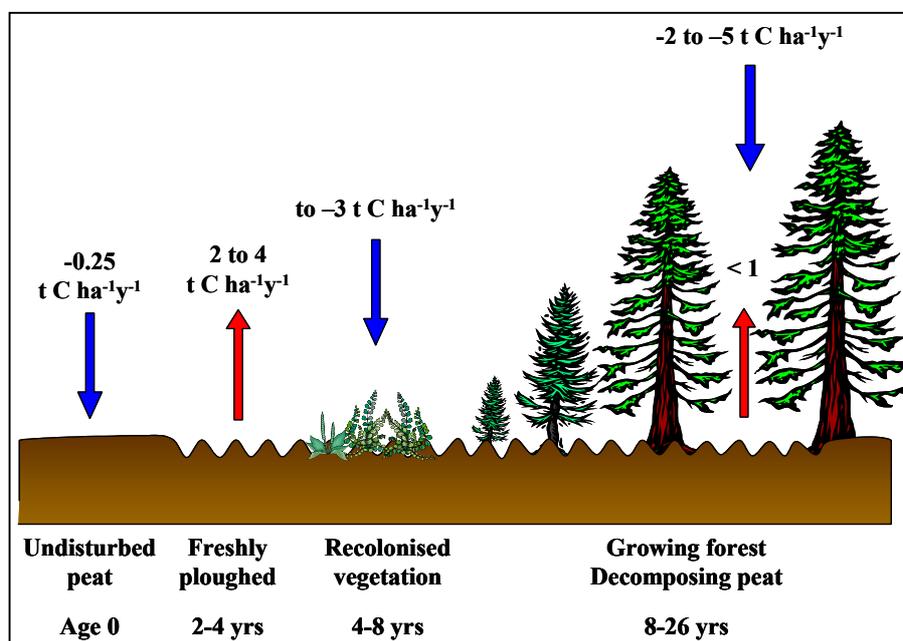


Figure 8. Diagrammatic representation of the estimated net fluxes of carbon ( $\text{t ha}^{-1} \text{ y}^{-1}$ ) at different stages of peatland afforestation in Scotland to age 26.

Table 4: Published estimates of uptake of carbon by undisturbed bogs/mires/fens

Net uptake (negative) or loss (positive) of CO <sub>2</sub> ( $\text{t C ha}^{-1} \text{ a}^{-1}$ )	Location	Reference
-0.25	Auchencorth, Scotland, peat bog	This study
-0.4–0.7	UK, mean range	Immirzi <i>et al.</i> (1992)
-0.15 to -0.30	Finland, mean range	Korhula <i>et al.</i> (1995)
-0.21	Finland, minerotrophic fen	Laine <i>et al.</i> (1997)
-0.18	Finland, oligotrophic fen	Alm <i>et al.</i> (1997)
-0.17 to -0.26	Finland, mean range	Turunen <i>et al.</i> (1999)
-0.03 to -0.64	Manitoba, fen, May-Oct.	Bubier <i>et al.</i> (1999)
-0.23	Saskatchewan, fen, May-Oct.	Suyker <i>et al.</i> (1997)
-0.26	Greenland, sedge fen	Soegaard and Nordstroem (1999)

Second, the freshly drained and ploughed peatland is a carbon source, emitting 2 - 4 tC ha<sup>-1</sup> y<sup>-1</sup>. Third, the peatland becomes a C sink of up to -3 tC ha<sup>-1</sup> y<sup>-1</sup> owing to C fixation by mainly recolonized ground vegetation, while the trees are only 4-8 years old. And fourthly, the growing forest dominates the budget, with a net uptake of up to -5 tC ha<sup>-1</sup> y<sup>-1</sup> at Yield Class 10 m<sup>3</sup> ha<sup>-1</sup> y<sup>-1</sup>, with the peat decomposing at a rate of about 1 tC ha<sup>-1</sup> y<sup>-1</sup> or less.

The rate C accumulation by undisturbed peatland measured in this study of -0.25 tC ha<sup>-1</sup> y<sup>-1</sup> is less than the mean range of UK studies reviewed by Immirzi et al (1992), but is similar to the rates observed in boreal peatlands (Table 4). However, the net annual C exchange over peatlands varies greatly, depending on the age and type of peatland (Korhola et al., 1995; Minkkinen and Laine, 1998) and on the weather. A measure of this year-to-year variation was obtained at Auchencorth Moss by accumulating net C fluxes over different 12-monthly periods over the period March 1998 to December 1991. Depending on the period used, the sink ranged from -0.12 to -0.38 tC ha<sup>-1</sup> y<sup>-1</sup>. Figure 4 shows the sensitivity of night-time C emission to temperature; if this relationship were sustained with 2 C warming, the -0.25 tC ha<sup>-1</sup> y<sup>-1</sup> sink would switch to a + 0.16 tC ha<sup>-1</sup> y<sup>-1</sup> source. There is increasing evidence that northern wetlands do switch from being a sink in cool years to a source in warm years (Bousquet et al., 2000).

A rapid loss of C from peat may be expected in the first 2-4 years after drainage, when the summer water table in drained UK peatland commonly falls over 50 cm below the ridges (Pyatt and Craven, 1979) and readily metabolizable C is exposed to microbial decomposition following the removal of phenolics by phenol oxidase (Freeman et al., 2001).

C fixation by recolonizing vegetation has been shown in other studies to offset the loss of C from decomposing peat. Thus, when averaged over several decades since drainage, the net C exchange of peatlands in Finland can be positive or negative, depending on the rate of recolonization and tree regeneration (Laine et al., 1995; Minkkinen et al., 1999).

Perhaps the most surprising and significant finding in this study was that peat beneath mature spruce stands decompose at a rate of only 1 tC ha<sup>-1</sup> y<sup>-1</sup> or less. This estimate is the difference between two large uncertain numbers (the total net C exchange and net tree C gain) and so is subject to considerable uncertainty. However, Minkkinen et al., (1999) pointed to several factors that may inhibit the decomposition of aerated peat in forests: (i) a loss of base cations and addition of organic acids may lower the pH, (ii) a reduction in temperature owing to tree shading and a decrease in thermal conductivity of the surface peat, and (iii) reduced litter quality with increased lignin content.

The important conclusion from this study is that the rate of peat loss averaged over a 60-year rotation may be no more than 1-2 tC ha<sup>-1</sup> y<sup>-1</sup>. Figure 9 reproduces calculations made by Cannell et al. (1993) of the amount of C in the total peat-forest-wood product system over five 60-year rotations, assuming different average rates of loss of peat (50-300 gC m<sup>-2</sup> y<sup>-1</sup>, 0.5-3.0 tC ha<sup>-1</sup> y<sup>-1</sup>). From these calculations, it is possible to derive the curve in Figure 10 showing the time taken before the loss of C from peat exceed the amount of C added to the system (as biomass, litter, soil and products) by growing trees. If, as this study suggests, the average peat loss rate is only 1-2 tC ha<sup>-1</sup> y<sup>-1</sup>, the system will be in C credit for 90-190 years.

The conclusion may be that, over the past 50 years and throughout most of this century, afforested peatlands in the UK will be a net C sink. Furthermore, methane emission has been virtually stopped by aeration. Thus, over the timescale of interest,

afforesting peatlands gives a greenhouse benefit. Laine et al. (1997) came to the same conclusion in Finland using estimates of warming potential. However, the carbon stock in most peatlands greatly exceeds the stock that can be added by growing trees, so, eventually it will become beneficial to return peatlands to their saturated state (Cannell et al., 1993).

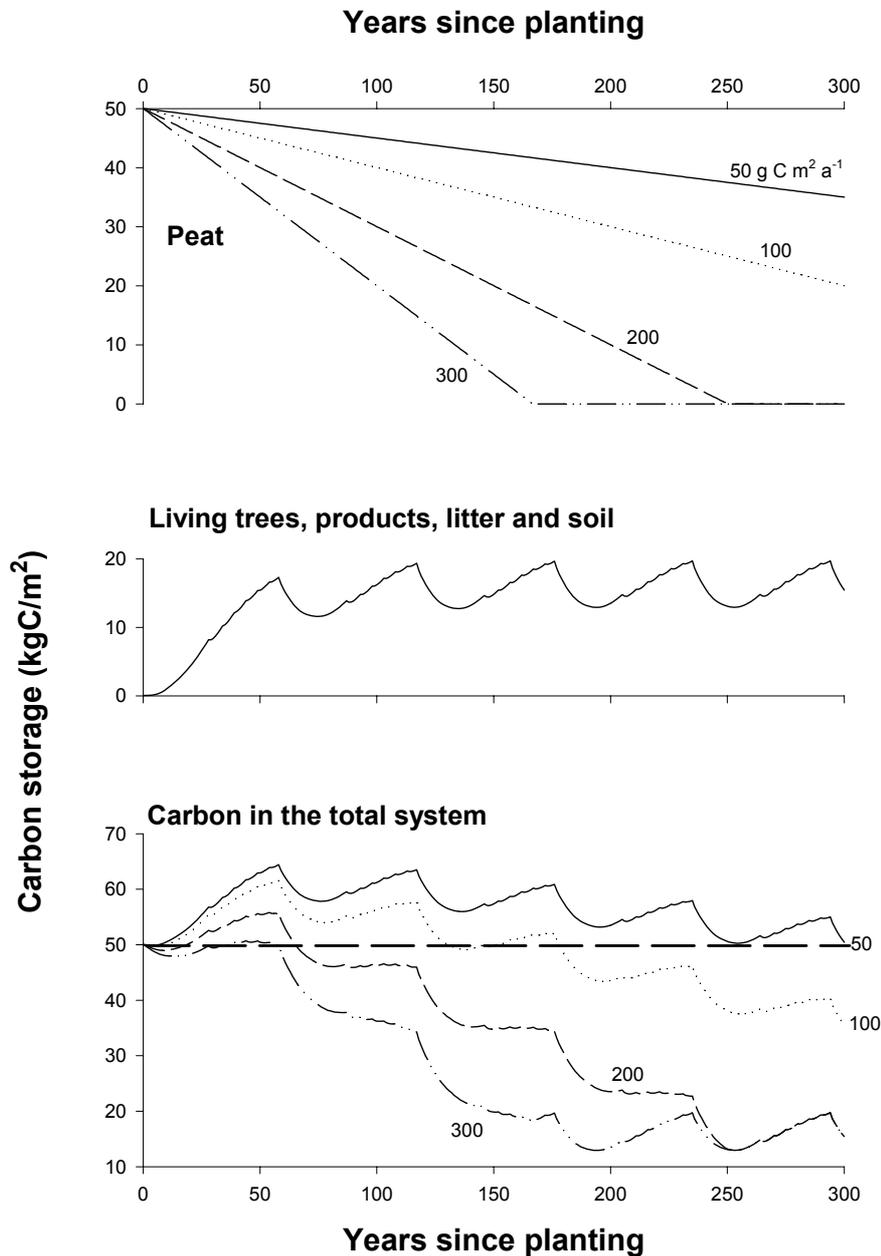
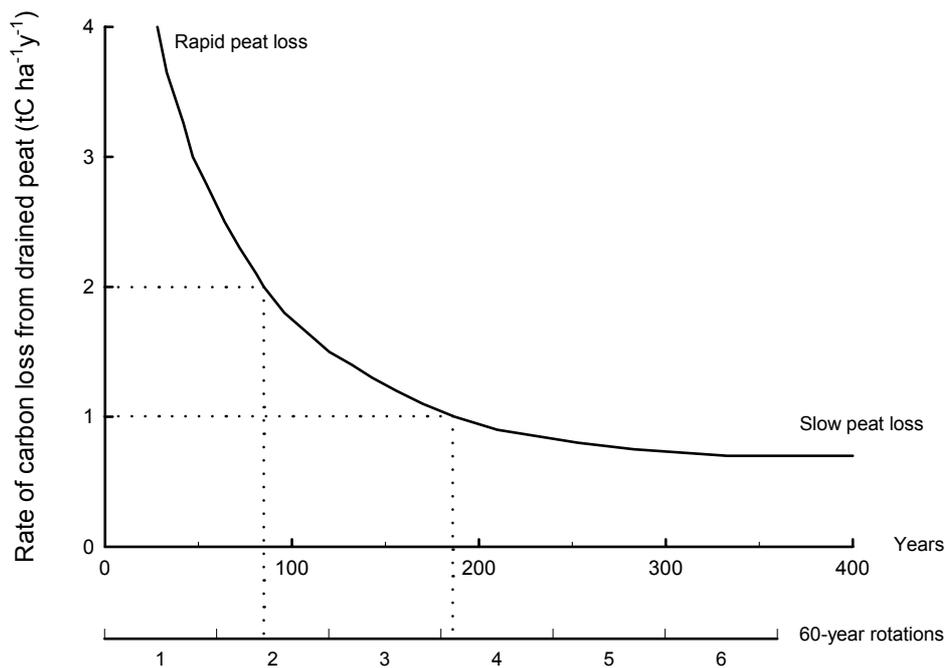


Figure 9. Possible changes in the carbon stored in peat (top graph), trees, products, litter and forest soil when growing conifers at Yield Class 12 m<sup>3</sup> ha<sup>-1</sup> y<sup>-1</sup> (middle graph) and the total system (bottom graph), assuming constant loss rates from the original peat of 50, 100, 200 and 300 g C m<sup>-2</sup> y<sup>-1</sup> (0.5, 1, 2, and 3 t C ha<sup>-1</sup> y<sup>-1</sup>) with an initial carbon content of 50 kg C m<sup>-2</sup>. (Modified from Cannell *et al.*, 1993).



Time after drainage and afforestation when the amount of carbon in the whole system (trees+products+peat) falls permanently below that in the original peatland before drainage

Figure 10. Estimates, derived from Figure 9, of the time after peat drainage and afforestation when the amount of carbon in the whole system (trees, products and peat) falls permanently below that in the original peatland before drainage, assuming different rates of peat loss. Thus, if peat were lost at  $100 \text{ gC m}^{-2} \text{ y}^{-1}$  ( $1 \text{ tC ha}^{-1} \text{ y}^{-1}$ ) it would take about 190 years, or over three tree rotations, before more carbon was lost from the peat than was accumulated in the system by growing trees.

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