B A
S E
Biotechnol. Agron. Soc. Environ. 2000 **4** (4), 290–293

Carbon stocks and sinks in forestry for the United Kingdom greenhouse gas inventory

Ronnie Milne, Ken Hargreaves, Maureen Murray

Centre for Ecology and Hydrology (Edinburgh). Bush Estate.Penicuik EH26 0QB.(United Kingdom). E-mail: rmilne@ceh.ac.uk

Afforestation in the UK has been significant and continuing since 1920 (up to 30,000 ha per year). Planting data is used to drive a dynamic process-based carbon accounting model (C-Flow) to estimate removals of atmospheric CO_2 to these forests. It is assumed that the afforestation can be represented by the characteristics of Sitka spruce for conifers and beech for broadleaves. The present area of forest considered for these estimates is 1.6 Mha. In 1990 the uptake to trees, litter, soil and products was 2.6 TgC, rising to 2.8 TgC in 1998. Deforestation is believed to be small. Supporting measurements show that the model predicts long term uptake by conifers well but that losses from planted peat shortly after establishment need further consideration. Process modelling of beech growth suggests that it is primarily dependant on atmospheric CO_2 concentration and not on stomatal control *per se*. UK research priorities relevant to preparation of GHG Inventories are presented.
Keywords. Carbon sequestration, greenhouse gas inventory, forest growth models, United Kingdom.

1. INTRODUCTION

The Department of Environment, Transport and The Regions (DETR) is the lead government agency in the UK for issues related to the United Nations Framework Convention on Climate Change (UNFCCC). Two Communications on Climate Change have been submitted to the UNFCCC (DETR, 1994, 1997). Annual Inventories of Greenhouse Gas (GHG) emissions following Intergovernmental Pannel on Climate Change (IPCC) Guidelines are published (Salway, 1999) and submitted to the EU and UNFCCC. The compilation of the GHG inventories is contracted to the National Environmental Technology Centre except for the Land-Use Change and Forestry Sector which is prepared by the Centre for Ecology & Hydrology (Edinburgh). National Forest Inventories (NFI) are conducted by the Forestry Commission. The latest NFI has been conducted in two phases; the main section quantifying woodlands of over 2 ha was completed in 1999 and a survey of smaller woodlands less than 2 ha but greater than 0.25 ha is due for completion in 2001. These inventories are not used directly in estimating the uptake of carbon (C) by the United Kingdom woodlands or forests.

GHG emissions by the UK for the "Basket-of Six" gases amounted to 773 Tg eq.–CO_2 in 1990 but this total has been reducing steadily thereafter (**Table 1**). In 1990 the emissions were distributed by sector as shown in **table 2**. Removals of atmospheric CO_2 by land use change processes and forestry were 10.6 $Tg{\cdot}y^{-1}$ in 1990 of which 9.5 $Tg{\cdot}y^{-1}$ were due to the forestry sink. This report describes work carried out by the Centre for Ecology and Hydrology (Edinburgh) for DETR to provide data on the forestry sink for the UK GHG inventory and supporting research projects.

Table 1. Global Warming Potential weighted emissions of greenhouse gases in the UK as $Tg{\cdot}y^{-1}$ equivalent-CO_2.

Tg - eq.–CO_2	1990	1991	1992	1993	1994	1995	1996	1997
Carbon dioxide	616.1	620.1	605.4	589.8	583.9	574.8	594.0	567.7
Methane	76.4	75.3	73.4	65.9	61.0	60.4	59.1	57.3
Nitrous Oxide	66.1	64.1	57.1	53.4	58.1	55.8	57.8	59.5
HFCs	11.4	11.9	12.3	12.9	13.8	15.2	16.3	18.4
PFCs	2.3	1.8	1.0	0.8	1.0	1.1	0.9	0.7
SF6	0.7	0.8	0.8	0.8	1.0	1.1	1.2	1.2
UK Total	**773.0**	**774.0**	**750.0**	**723.7**	**718.7**	**708.3**	**729.3**	**704.8**

Table 2. Emission and removal of CO_2 ($Tg\ CO_2{\cdot}y^{-1}$) in 1990 by sector in the UK GHG inventory.

$Tg\ CO_2{\cdot}y^{-1}$	Emissions	Removals
1 Energy	569.6	
2 Industrial processes	13.9	
3 Solvent and Other Product Use		
4 Agriculture		
5 Land-Use Change Forestry	32	-10.6
6 Waste	0.7	
UK Total	**616.1**	**-10.6**

2. GREENHOUSE GAS INVENTORIES

The UK's annual GHG inventory includes data for the sector covering land-use change and forestry, in accordance with the IPCC's guidelines (Salway, 1999). The methods used have been reported in peer reviewed scientific literature (Cannell, Milne, 1995; Cannell, Milne, 2000; Cannell *et al.*, 1999).

The Forestry Commission (FC) has carried out inventories of woodlands in Great Britain (UK) at 15–20 year intervals since 1924. The most recent inventory, which began in 1995, is close to completion and future woodland inventories will be carried out as part of a 10-year rolling programme that starts in 2003. However the estimates for forest C-sinks in the GHG inventory are based primarily on the annual planting and felling data which are used to update information on the size and age structure of the national forest estate between the periodic inventories. The planting information, together with data derived from the growth characteristics of UK forests is used in a dynamic C-accounting model (C-Flow) (Dewar, Cannell, 1992; Cannell, Dewar, 1995; Milne *et al.*, 1998) to estimate annual uptake and storage of atmospheric C by forests. Growth characteristics are kept under review through a national system of mensuration plots and associated yield models. This information will be used to keep the C-accounting model up to date.

The estimates are based on data for the areas of forest planting published by the UK Forestry Commission and the Northern Ireland Department of Agriculture. The C-uptake is calculated by C-Flow (Dewar, Cannell, 1992; Cannell, Dewar, 1995; Milne *et al.*, 1998) as the net change in pools of C in standing trees, litter, soil in broadleaf forests and products. Conifer forest is represented as Sitka spruce (Yield Class 12 in GB and Yield Class 14 in NI) and broadleaf forest is represented as beech (Yield Class 6). All commercial forest is assumed to be restocked. Milne *et al.* (1998) have shown that allowing for yield class to vary across the country has only a small effect (about 10%) on estimated uptake rates of C. The model tracks C in tree biomass, litter, soil and timber products separately and the sink uptake data presented here consists of the total change from year to year in these pools. Afforestation for this estimate is that since 1,920 and has a total area of 1,561 Mha. An additional 801 Mha is not included in the estimates and is assumed to be in long-term C-balance. The C-stock of these forests has also been assessed (Cruickshank *et al.*, 1998; Cruickshank *etal.*, 2000; Milne, Brown, 1997; Milne, Brown, 2000). Deforestation in the UK is relatively unimportant at around 1,000 ha·y^{-1} compared to the present afforestation rate of about 7,000 ha·y^{-1} of conifers and 10,000 ha·y^{-1} of broadleaves. The uptake of C to UK forest biomass, litter, soil and products was about 2.8 Tg in 1998 which is equivalent to 1.8 t C·ha^{-1}·y^{-1}, 67% to biomass, 22% to soil and litter and 11% to products.

Table 3 summarises the main trends in UK sinks in forestry. The 1990 and 1995 data are consistent with the UK GHG emissions inventory. Three planting scenarios have been considered:

- "High Sink" with planting increasing to 10,000 ha·y^{-1} of conifers and 20,000 ha·y^{-1} of broadleaves from 2000,
- "Mid Sink" with planting continuing at present rate of 7,000 ha·y^{-1} conifers and 10,000 ha·y^{-1} of broadleaves,
- "Low Sink" with no further afforestation after 2000. The possible range of future uptake for all of the productive forests and for those planted since 1990 (the UK Kyoto forest) is shown in **table 3** and **figure 1**.

New forests and woodlands have been planted at rates between 16,000 and 21,000 ha·y^{-1} across the UK since 1990 as a result of Government policy implemented

Table 3. Trends in removals by sinks for UK forestry activities. Includes carbon accumulated by woody biomass, soils, litter and changes in the quantity of forest products from timber grown in the UK (see text for definitions of sink scenarios).

	Tg C·y^{-1}					
	All productive forest			**Post- 1990 forest only**		
	a(1)	b(2)	c(3)	a(1)	b(2)	c(3)
1990	-2.6	-2.6	-2.6	0.0	0.0	0.0
1995	-2.8	-2.8	-2.8	-0.2	-0.2	-0.2
2000	-2.9	-2.9	-2.9	-0.3	-0.3	-0.3
2005	-3.0	-3.2	-3.3	-0.3	-0.4	-0.6
2010	-2.8	-3.1	-3.4	-0.3	-0.6	-0.8
2015	-2.2	-2.7	-3.0	-0.4	-0.9	-1.2
2020	-1.8	-2.4	-2.8	-0.6	-1.2	-1.6

(1) "Low sink"; (2) "Mid sink"; (3) "High Sink".

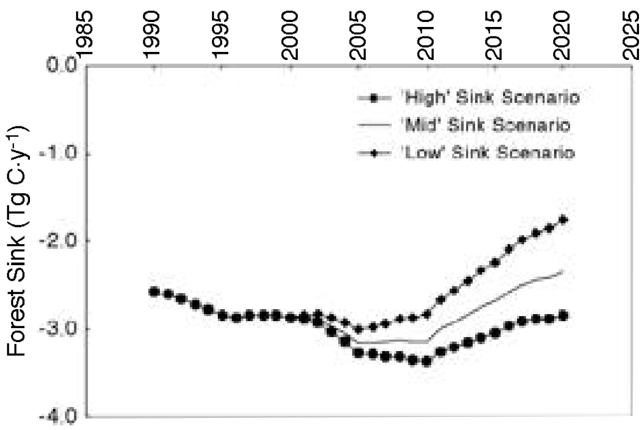

Figure 1. Trends in removals of carbon by all productive forest from the atmosphere for 3 scenarios of afforestation in the UK.

by the Forestry Commission and the Northern Ireland Forest Service. The Government and the devolved administrations are committed to expanding the UK's woodland area. The effect of afforestation since 1990 illustrates how taking account of forestry activities under Article 3.3 of the Kyoto Protocol might help the UK meet its commitment to reduce its 1990 CO_2-equivalent emissions of 616 Tg·y^{-1} by 12.5% (= 77 Tg·y^{-1}) under the European Union burden sharing arrangements for the Protocol commitments.

3. WORKING GROUP 1 RELATED ACTIVITIES (Inventory of C sinks and sources)

3.1. Measurement of uptake by forest on peatland

A field project combining soil analyses and eddy covariance measurements of CO_2 flux has been completed to investigate the net exchange of C by conifer plantations. Soil analyses showed that the total C in the peat under the trees at a low productivity conifer forest had an average gain over 26 years of +0.4 t C·ha^{-1}·y^{-1} compared with the undisturbed peatland. When tree production and litter C were included, accumulation in the plantation was +46.8 t C·ha^{-1} relative to the undisturbed peatland. A similar value to that obtained previously for a higher productivity site.

Eddy covariance measurements of CO_2 exchange in the atmosphere over drained and afforested peatland showed that the C-uptake by two undisturbed peatlands over a 27 year period were 6.0 t C·ha^{-1} for a site in SE Scotland and 6.9 t C·ha^{-1} for a site in SW Scotland. The upper limit for the change in peat C resulting from drainage and afforestation was estimated to be loss at -8.5 t C·ha^{-1} for the SE site and 9.0 t C·ha^{-1} for the SW site and confined to the first few years after drainage. The overall enhancement to the C sink by the 26th year after drainage and afforestation was calculated to be 44.2 t C·ha^{-1} for the SE site and 47.5 t C·ha^{-1} for the SW site. These findings are in broad agreement with those from the soil analyses and with the results from the C-Flow model used in estimates for the GHG inventory (**Figure 2**).

3.2. Modelling of the effect of climate change on beech growth

Beech trees have been shown to be particularly susceptible to summer droughts and could therefore, potentially suffer productivity losses as a result of changing stomatal conductance (g_s) under future elevated [CO_2] conditions. In order to predict the potential effect of changing gs on future growth rates in the UK, a series of stomatal response scenarios was investigated using the process based Edinburgh Forest Model (Thornley, 1991; also on line at: < http://www.nbu.ac.uk/efm>). The results showed that growth, and hence yield class (YC), is primarily dependant on atmospheric [CO_2] and not on stomatal control *per se*. Doubling atmospheric [CO_2] resulted in beech yield class increasing from ~6 to ~10 m^3·ha^{-1}·y^{-1} at Eskdalemuir, while reducing g_s had little effect. This result may however be site specific,as the results depend strongly on the weather (**Figure 3**).

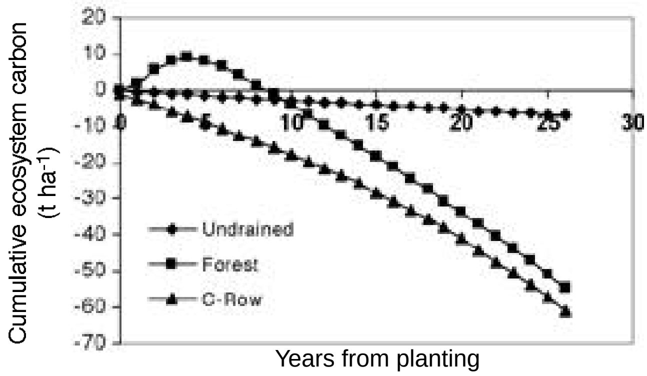

Figure 2. Cumulative C-exchange following drainage/afforestation of peatland in SW Scotland. Year 0 represents the undrained state, drainage/planting is assumed to take place on the first day of year 1. The output from the C-Flow model simulates a 90% *Picea Sitchensis* (Bong.) Carr and 10% *Pinus contorta* Douglas mixture on a mineral soil.

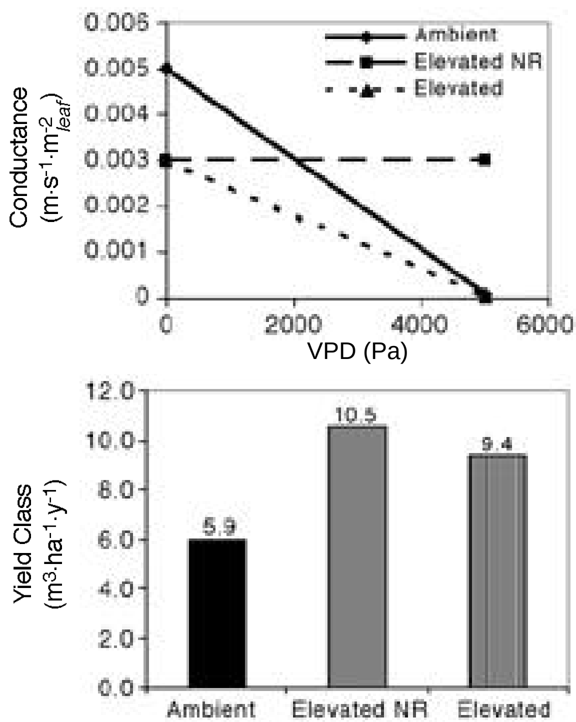

Figure 3. Effect of different assumptions of stomatal conductance response on Yield Class of Beech at Eskdalemuir, Scotland. Ambient: CO_2 350 ppm. Elevated NR: CO_2 700 ppm no stomatal response to VDP. Elevated CO_2 700 ppm closing response to VPD.

4. RESEARCH PRIORITIES

- Better understanding of C-exchange between forests and the atmosphere after establishment and throughout rotation;
- Improved methods to model C in timber products;
- Assessment of methods for geo-referencing of forest plots;
- Usefulness of forest mensuration plots for GHG inventory purposes;
- Further "validation" of C-flow models.

Bibliography

Cannell MGR., Dewar RC. (1995). The carbon sink provided by plantation forests and their products in Britain. *Forestry* **68** (1), p. 35–48.

Cannell MGR., Milne R. (1995). Carbon pools and sequestration in forest ecosystems. *Forestry* **68** (4), p. 361–378.

Cannell MGR., Milne R., Hargreaves KJ., Brown TAW., Cruickshank MM., Bradley RI., Spencer T., Hope D., Billett MF., Adger WN., Subak S. (1999). National inventories of terrestrial carbon sources and sinks. The UK experience. *Clim. Change* **42**, p. 505–530.

Cannell MGR., Milne R. (2000). Kyoto, carbon and Scottish forestry. *Scott. For.* **54**, p. 11–16.

Cruickshank MM., Tomlinson RW., Devine PM., Milne R. (1998). Carbon in the vegetation and soils of Northern Ireland. *Biol. Environ. Proc. R. Ir. Acad.* **98B**, p. 9–21.

Cruickshank MM., Tomlinson RW., Milne R. (2000). Application of CORINE land cover mapping to estimate surface carbon pools in Northern Ireland. *In* Alexander R., Millington AC. (eds.). *Veg. Mapp. Patch Planet*. London: Wiley, p. 259–272.

DETR (1994). *Climate change. United Kingdom's report under the framework convention on climate change*. London: HMSO (Cmd; 2427).

DETR (1997). *Climate Change. United Kingdom's second report under the framework convention on climate change*. London: Stationery Office (Cmd; 3558).

Dewar RC., CannellMGR. (1992). Carbon sequestration in the trees, products and soils of forest plantations. An analysis using UK examples. *Tree Physiol.* **11**, p. 49–72.

Milne R., Brown TAW., Murray TD. (1998). The effect of geographical variation in planting rate on the uptake of carbon by new forests of Great Britain. *Forestry* **71**, p. 298–309.

Milne R., Brown TA. (1997). Carbon in the vegetation and soils of Great Britain. *J. Environ. Manage.* **49**, p. 413–433.

Milne R., Brown TA. (2000). Mapping of carbon pools in the vegetation and soils of Great Britain. *In* Alexander R., Millington AC. (eds.). *Veg. Mapp. Patch Planet*. London: Wiley, p. 273–282.

Salway AG. (1999). *UK greenhouse gas inventory, 1990 to 1998. Annual report for submission under framework convention on climate change*. Abingdon, UK: National Environmental Technology Centre. (AEAT; 5689). ISBN 0-7058-1786-5.

Thornley JHM. (1991). A transport-resistance model of forest growth and partitioning. *Ann. Bot.* **68**, p. 211–226.

(14 ref.)

Manuscript received 3 October 2000