Report

Milne, R.; Mobbs, D. C.; Thomson, A. M.; Matthews, R. W.; Broadmeadow, M. S. J.; Mackie, E.; Wilkinson, M.; Benham, S.; Harris, K.; Grace, J.; Quegan, S.; Coleman, K.; Powlson, D. S.; Whitmore, A. P.; Sozanska-Stanton, M.; Smith, P.; Levy, P. E.; Ostle, N.; Murray, T. D.; Van Oijen, M.; Brown, T.. 2006 *UK emissions by sources and removals by sinks due to land use, land use change and forestry activities. Report, April 2006.* Centre for Ecology and Hydrology, 278pp. (CEH: Project Report Number C02275)

UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry Activities

Report, April 2006

DEFRA Contract EPG 1/1/160
CEH No. C02275

editors: R. Milne, D.C. Mobbs

Centre for Ecology & Hydrology, Edinburgh
Centre for Ecology & Hydrology, Lancaster
Aberdeen University
Rothamsted Research
Forest Research, Alice Holt
Centre for Terrestrial Carbon Dynamics
(*Universities of Sheffield, Edinburgh, York, University College London)*

April 2006
Department for the Environment, Food and Rural Affairs
Global Atmosphere Division

Contents

Section 1

Key Activities and Results for 2005 – 2006

1. Key activities and results for 2005 – 2006

Land Use Change and Forestry: The 2004 UK Greenhouse Gas Inventory and projections to 2020

- The Categories of the IPCC Good Practice Guidance for LULUCF will from now be the basis for all reporting in the UK Greenhouse Gas Inventory. Net fluxes within Categories are used without identification of the constituent emissions and removals.
- The flux of GHGs in the UK from the Land Use Change and Forestry Sector for 1990 is shown to have been a net emission of 2,915 Gg CO_2. The level of emission fell to zero in 1998 and has become a removal more recently, equal to -1,942 Gg CO_2 in 2004.
- Within the Forest Land Category revisions to the methodology for estimating changes in stock of carbon have been implemented. The major change was to take account for some locations of conifer planting of shorter rotation periods from the 1920s to the 1950s compared to the standard.
- The methodology for assessing changes in stocks of non-forest biomass has been replaced with an approach similar to that used for changes in stocks of carbon in non-forest soils.
- Emissions of CO_2 due to the use of peat as a fuel have been removed from the Land Use Change and Forestry Sector and are now reported in the Energy Sector.
- In the Forest Land Category there was a net removal of -12,203 GgCO_2 in 1990. This increased to -16,302 Gg CO_2 in 2004. Removals to forest products are reported separately to other changes in stocks of carbon in forest carbon and fell from -1456 Gg CO_2 in 1990 to -633 Gg CO_2 in 1994. Net fluxes due to changes in stocks of wood products varied around -1100 Gg CO_2 from 1996 to 2000 before a change to a source of 619 Gg CO_2 in 2004..
- Scotland is shown to have been a net remover of -2,535 GgCO_2 in 1990 changing to -4,617 Gg CO_2 by 2004.
- Wales was a net remover of -241 Gg CO_2 in 1990 changing to -69 Gg CO_2 in 1994 returning to -249 Gg CO_2 in 2004.
- England is shown to have been a net emitter of 5,736 Gg CO_2 in 1990, falling steadily to 3,231 Gg CO_2 in 2004.
- N. Ireland was a net remover in 1990 at -45 Gg CO_2 steadily changing to -307 Gg CO_2 in 2004.
- Projections of net fluxes for the Land Use Change and Forestry Sector up to the year 2020 are presented for England, Scotland, Wales and Northern Ireland.
- The projections for the Land Use Change and Forestry Sector indicate that a peak for removals has now been reached in the UK and the net flux will be of increasing emissions over the next 15 years.
- Estimates of removals and emissions of CO_2 by post-1990 afforestation and deforestation in the UK relevant to Article 3.3 of the Kyoto Protocol are presented.
- Estimates of the trend in emissions of CO_2 by Forest Management relevant to Article 3.4 of the Kyoto Protocol are presented.

Variations in Forest Management

- Information from the National Inventory of Woodlands and Trees (NIWT) and historical woodland censuses was compared with the national planting series (afforestation since 1921) used in the C-Flow forest carbon accumulation model at the national level (England, Scotland and Wales).
- Normal harvesting practices and management of woodland established before 1921 accounted for most of the difference between the national planting series and the rate of woodland establishment inferred from the NIWT for conifer forest in Great Britain.
- Processes of change affecting forest established before 1921 (normal management, conversion of coppice, mixed and scrub woodland, natural regeneration) accounted for the differences between the national planting series and the NIWT establishment rate for broadleaf woodland in Great Britain.
- The standard management scenario in C-Flow was adjusted to take account of shorter rotations (inferred from the analysis) in conifer woodland in England and Wales (1921-1950). This adjustment did not have a large impact on the estimated carbon flux from forests (0.05 Mt C in 2004) but represents a first step in the better representation of variability in forest characteristics in C-Flow.

Survey Methods for Kyoto Protocol Monitoring and Verification of UK Forest Carbon Stocks

- The report provides an overview of the position reached in development of a methodology for a national forest carbon inventory for monitoring, validating and reporting of forestry based LULUCF activities.
- The assessment protocol has evolved from that initially proposed in 2003. The revised system has seven modules: mapping of forest areas, stand-level sample assessments, statistical relationships and models, field verification of models, model-based upscaling of carbon stock estimates, statistically based verification of upscaled carbon stock estimates and reporting.
- The system aims to use the GIS-based National Inventory of Woodlands and Trees (NIWT), the specification of which is currently being updated. NIWT data will be used as the basis for selection of forest carbon field assessment sites, and as the basis for deriving upscaled district/national/regional estimates of forest carbon stocks.
- Field assessments will consist of measurements of standing trees and soil carbon, for which draft protocols have been developed.
- The BSORT model will be applied, in conjunction with the recently developed M1 algorithmic yield model, to estimate and forecast standing carbon stocks in a diversity of forest stand types.
- A protocol for the verification of the model-based results has been developed.

Estimating Biogenic Carbon Fluxes over the UK

- Three models are available in the Centre for the estimation of carbon fluxes to terrestrial ecosystems from knowledge of land cover.
- Past management and age-of-forests strongly influences carbon flux. Age-of-forest may be estimated using radar remote sensing.

- Eddy covariance flux data are becoming available for a representative set of land cover in Eurioe, and in the UK there are examples from coniferous and broadleaved forests, grassland, moorland and agriculture.
- There is one operational tall tower in the UK, in Fife, Scotland. Tall towers are designed to measure trace gas fluxes from all sources (anthropogenic and biogenic). This is operated by Edinburgh University with European funding. Another tower, situated in mid-England, would be needed for total coverage of the UK.
- From the Sheffield Dynamic Vegetation Model (DGVM) we estimate that the land cover of England and Wales is a biotic carbon sink of strength 7.61 ± 0.61 Mt C/year.

The potential use of the Rothamsted Carbon model, RothC, in GHG inventories

- Methods to incorporate RothC into the UK soils carbon inventory were compared: (1) meta-models (extensions of the current coefficient method) and (2) call RothC directly from the spreadsheet
- Surprisingly, parameters for the meta–models derived from RothC were very variable making this route a poor prospect for the inventory
- RothC has been modified to run from a call within Microsoft® Excel©. If adopted, this route would future-proof the inventory since upgrades to RothC and add-ins such as vegetation modelling would be quickly and simply available. It also presents the smoothest and most straightforward means to move the inventory gradually towards RothCUK, the GIS version
- Some data both for RothC and RothCUK are commercially sensitive. Means to access this data without breaking confidentiality are suggested

RothC-BIOTA v05 plant-soil C turnover model – parameterization and evaluation

- RothC-BIOTA model has been developed as a coupled link between GIS-RothCv03, a model of soil C dynamics, and BIOTA, a process-based model of plant C dynamics.
- Recent model developments include the incorporation of crop rotation (with an extended range of arable crop plant functional types for the UK), the impact of nitrogen fertilization (from mineral and organic fertilizer and atmospheric N deposition) on yields, and alternative methods of estimating SOC equilibrium (using model fitting or dynamic modelling).
- Parameterization of crop yields has been undertaken: there is good simulation of cereal and oilseed rape yields but under-estimation of root crop yields
- RothC-BIOTA was evaluated at two sites, one at Rothamsted, and one in Germany. There was over-prediction of SOC at equilibrium, which is thought to be related to the N limitation effect on yields. This is an issue when previous land-use history at a site is unknown.
- Overall, RothC-BIOTA is able to accurately simulate SOC dynamics, but some adjustments in the modelling methods are required.

A plot-scale experiment to detect the effect of cultivation on soil organic carbon

- A plot-scale experiment to detect the effect of cultivation on soil organic carbon content was established on House O' Muir Farm near CEH Edinburgh.
- A Latin Square design of 81 experimental plots was laid out, with three treatments: an uncultivated control, a single cultivation, and bi-annual cultivation. The first cultivation treatment was applied in November 2005.
- Measurements of soil carbon content and soil respiration were made prior to the treatment being applied. The results show that there are no clear differences between the treatment and control plots at the start of the experiment.
- Measurements of nitrous oxide (N_2O) and methane (CH_4) flux are in progress at the time of writing (April 2006). These will allow us to calculate the effect of cultivation on the total greenhouse warming potential (GWP).

Incorporating effects of changes in climate, nitrogen deposition and CO_2 in projections of forest carbon budgets

- A process based model of forest growth (BASFOR) using an intermediate number of parameters has been developed
- Forest growth data from 2 locations in the UK has been obtained from Forest Research for calibration purposes.
- Sequential data assimilation & uncertainty quantification by Bayesian calibration of BASFOR has been shown to work well.
- BASFOR used to attribute changes in growth over 1920 to 2000 to different environmental drivers , with quantified uncertainty
- Tree data for calibration and environmental data of model drivers still limited. Key issue: soil nitrogen
- Environmental factor analysis for Dodd Wood showed importance of elevated CO_2, but may be artefact of soil data used.
- Planned use of calibrated BASFOR to calculate yield table modifiers for use by C-FLOW (effects of CO2, climate change and N-deposition), with measures of uncertainty

Section 2

Land Use Change and Forestry: The 2004 UK Greenhouse Gas Inventory and Projections to 2020

Table of Contents

2. Land Use Change and Forestry: The 2004 UK Greenhouse Gas Inventory and projections to 2020

R. Milne, A. Thomson & D. C. Mobbs
Centre for Ecology & Hydrology, Bush Estate, Penicuik.

2.1. Introduction

This sector differs from others in the Greenhouse Gas Inventory in that it contains both sources and sinks of carbon dioxide. The sinks, or *removals,* are presented as negative quantities. Emissions from land use change and forestry were approximately 2.2% of the UK total in 2004 and are declining gradually.

The estimates for Land Use Change and Forestry are from work carried out by the Centre for Ecology & Hydrology. The structure of this Section and of the main submission for the national Inventory Report and CRF Tables is based on the Categories of the Common Reporting Format tables agreed at the 9th Conference of Parties to the UNFCCC and contained in FCCC/SBSTA/2004/8 (see also IPCC 2003). The Sector 5 Report Tables in the CRF format for each year from 1990 to 2004 have been submitted using the CRF Reporter software. The relationship of this reporting format to that used in previous submissions from the UK is discussed in Section 2.3.7.

Some revision of the data and methods used for this Sector has been made for the 2004 Inventory, starting from the approaches described by Cannell *et al.* (1999) and Milne & Brown (1999). Net emissions in 1990 are estimated here to be 2915 Gg CO_2 compared to 2645 Gg CO_2 in the 2003 National Inventory Report. For 2003 a net removal of -1180 Gg CO_2 is estimated here compared to a net removal of -1489 Gg CO_2 in the 2003 Inventory.

2.2. LULUCF GHG Data on the basis of IPCC 2003 Good Practice Guidance

2.2.1. Introduction

In the IPCC Good Practice Guidance (GPG) for Land Use, Land Use Change and Forestry (IPCC 2003), a uniform structure for reporting emissions and removals of greenhouse gases was described. This format for reporting can be seen as "land based": all land in the country is identified as having remained in one of 6 classes (Forest Land, Cropland, Grassland, Wetlands, Settlements, Other Land) since a previous survey, or as having changed to a different (identified) class in the period since the last survey. A land use change matrix can be used to capture all these transitions in a compact manner. At its most basic this would be a 6x6 matrix with the diagonal being the areas that remained unchanged and the off-diagonal entries being the areas that had changed. The reporting structure simplifies this 6x6 structure to a 6x2 structure where the 2 columns describe greenhouse gas fluxes associated with i) land that remained in a specific class or ii) land converted into that class. For each of these 6x2 reporting groups, changes in stocks of carbon for above-ground biomass, below-ground biomass, dead biomass and soil organic matter should be reported, where possible. Specific activities that do not directly cause stock changes of carbon are reported in separate tables, *e.g*. greenhouse gases other than CO_2, but are combined into the totals in a summary table for the Sector.

The LULUCF GPG allows modification of the basic set of six land classes to match national databases. Further subdivision of the classes by ecosystem, administrative region or the time when the change occurred is also encouraged.

2.2.2. Forest Land (5A)

In the UK all forests can be classified as temperate and about 65% of these have been planted since 1920 on land that had not been forested for many decades. The Forest Land category is divided into *Category 5.A.1 Forest remaining Forest Land* and *Category 5.A.2 Land converted to Forest Land*. Category 5.A.1 is disaggregated into the four geographical areas of England, Scotland, Wales and Northern Ireland. Category 5.A.2 is disaggregated into afforestation of Cropland, Grassland and Settlements and further by a) the four geographical areas of England, Scotland, Wales and Northern Ireland and b) two time periods, 1920 – 1990 and 1991 onwards.

Direct N_2O emissions from N fertilization from land use, land use change and forestry changes in Category 5A are not estimated as they have been assessed as insignificant in the UK (Skiba *et al.* 2005). N_2O emissions from drainage of soils for land in Category 5A are not reported for the same reason (Skiba *et al.* 2005)

2.2.2.1 Forest Land remaining Forest Land

There are about 822,000 ha of woodland in the UK that were planted prior to 1922 or are not considered of commercial importance. These forests are assumed to fall in *Category 5.A.1 Forest Land remaining Forest Land*. It is evident from the comparison of historical forest censuses that some of this forest area is still actively managed (see Thomson, this volume), but overall this category is assumed to be carbon-neutral.

2.2.2.1.(a) Methodology

Changes in stocks of carbon in Forest Land in the UK that remains Forest Land are assumed to be zero. This category of forest across the UK has existed since before 1920 and is assumed to be in carbon balance because of its age, and hence has zero carbon stock change.

2.2.2.1.(b) Data Reporting

- *Common Reporting Format under IPCC LULUCF Good Practice Guidance*

In Table 5.A. Forest Land (see Part II) the carbon stock changes (in living biomass, dead organic matter and soils) are entered as ‘Not Occurring’ (NO). The area of forest land in this category is entered separately for England, Scotland, Wales and Northern Ireland.

2.2.2.1.(c) Planned Improvements

The possible contribution of this category to carbon emissions and removals will be considered in more detail in future reporting.

2.2.2.2 Land converted to Forest Land

The estimates of changes in carbon stock in the biomass and soils of the forests established since 1920 are based on activity data in the form of annual planting areas of forest published by the UK Forestry Commission and the Northern Ireland Department of Agriculture. Activity data are obtained consistently from the same national forestry sources, which helps ensure time series consistency of estimated removals.

The estimates of emissions and removals due to afforestation were updated with planting statistics for 2004. The main revision was an adjustment in the forest planting calculations to take account of the impact of non-standard management practices in conifer forests, which were due to either deliberately shortened harvesting rotations or a response to forest disturbance. The conifer afforestation series in England and Wales were sub-divided into the standard Sitka spruce 59 year rotation (1921-2004), a 49 year rotation (1921-1950) and a 39 year rotation (1931-1940, England only). The areas of forest planting with non-standard management were small (8.8 kha in England, 20.0 kha in Wales), so the impact on forest removals reported here is less than ±0.1Mt C a^{-1} compared to removals reported previously.

2.2.2.2.(a) Methodology

The carbon uptake by the forests planted since 1920 is calculated by a carbon accounting model, C-Flow, (Dewar & Cannell , Cannell & Dewar 1995, Milne *et al.* 1998) as the net change in pools of carbon in standing trees, litter, soil in conifer and broadleaf forests and in products. Restocking is assumed in all forests. The method can be described as Tier 3, as defined in the GPG LULUCF (IPCC 2003). Two types of input data and two parameter sets were required for the model (Cannell & Dewar 1995). The input data are: a) areas of new forest planted in each year in the past, and b) the stemwood growth rate and harvesting pattern. Parameter values are required to estimate i) stemwood, foliage, branch and root masses from the stemwood volume, and ii) the decomposition rates of litter, soil carbon and wood products.

For the estimates described here we used the combined area of new private and state planting from 1920 to 2004 for England, Scotland, Wales and Northern Ireland sub-divided into conifers and broadleaves. Restocking was dealt with in the model through the second and subsequent rotations, which occur after clearfelling at the time of Maximum Area Increment (MAI). Therefore areas restocked in each year did not need to be considered separately. The key assumption is that the forests are harvested according to standard management tables. However, a comparison of forest census data over time has indicated that there are variations in the felling/replanting date during the 20th century, i.e. non-standard management. These variations in management have been incorporated into the forest model, and the methodology will be kept under review in future reporting.

The C-Flow model uses Forestry Commission Yield Tables (Edwards & Christie 1981) to describe forest growth after thinning and an expo-linear curve for growth before thinning. It was assumed that all new conifer plantations have the same growth characteristics as Sitka spruce (*Picea sitchensis* (Bong.) Carr.) under an intermediate thinning management regime. Sitka spruce is the commonest species in UK forests being about 50% by area of conifer forests. Milne *et al.* (1998) have shown that mean Yield Class for Sitka spruce varies across Great Britain from 10-16 m^3 ha^{-1} a^{-1}, but with no obvious geographical pattern, and that this variation has an effect of less than 10% on estimated carbon uptake for the country as a whole. The Inventory data has therefore been estimated by assuming all conifers in Great Britain followed the growth pattern of Yield Class 12 m^3 ha^{-1} a^{-1}, but in Northern Ireland Yield Class 14 m^3 ha^{-1} a^{-1} was used. Milne *et al.* (1998) also showed that different assumptions for broadleaf species had little effect on carbon uptake. It is assumed that broadleaf forests have the characteristics of beech (*Fagus sylvatica* L.) of Yield Class 6 m^3 ha^{-1} a^{-1}. The most recent inventory of British woodlands (Forestry Commission 2002) shows that beech occupies about 8% of broadleaf forest area (all ages) and no single species occupies greater than 25%. Beech was selected to represent all broadleaves as it has characteristics intermediate between fast growing species e.g. birch, and very slow growing species e.g. oak. However, using oak or birch Yield Class data instead of beech data has been shown to have an effect of less than 10% on the overall removal of carbon to UK forests (Milne *et al.* 1998). The use of beech as the representative species will be kept under review.

Irrespective of species assumptions, the variation in removals from 1990 to the present is determined by the afforestation rate in earlier decades and the effect this has on the age structure in the present forest estate, and hence the average growth rate. It can be shown that if forest expansion continues at the present rate, removals of atmospheric carbon will continue to increase until about 2005 and then will begin to decrease, reflecting the reduction in afforestation rate after the 1970s. This afforestation is all on ground that has not been wooded for many decades. Table 2-1 shows the afforestation rate since 1922 and the present age structure of these forests.

A comparison of historical forest census data and the historical annual planting rates has been undertaken. Forest censuses were taken in 1924, 1947, 1965, 1980 and the late 1990s. The comparison of data sources showed that discrepancies in annual planting rates and inferred planting/establishment date (from woodland age in the forest census) are due to restocking of older (pre-1920) woodland areas and variations in the harvesting rotations. However, there is also evidence of shortened conifer rotations in some decades and transfer of woodland between broadleaved categories (e.g. between coppice and high forest). As a result, the afforestation series for conifers in England and Wales were sub-divided into the standard 59 year rotation (1921-2004), a 49 year rotation (1921-1950) and a 39 year rotation (1931-1940, England only). It is difficult to incorporate non-standard management in older conifer forests and broadleaved forests into the Inventory because it is not known whether these forests are on their first rotation or subsequent rotations (which would affect carbon stock changes, particularly in soils). Further work is planned for this area.

Table 2-1 Afforestation rate and age distribution of conifers and broadleaves in the United Kingdom since 1922

Period	Planting rate (000 ha a^{-1})		Age distribution	
	Conifers	**Broadleaves**	**Conifers**	**Broadleaves**
1922-1929	4.9	2.4	2.9%	6.7%
1930-1939	7.2	2.2	5.3%	7.8%
1940-1949	6.3	1.9	4.6%	6.7%
1950-1959	20.0	3.0	14.8%	10.7%
1960-1969	28.4	2.9	21.0%	10.4%
1970-1979	33.2	1.5	24.6%	5.3%
1980-1989	22.5	1.4	16.7%	4.9%
1990	26.8	3.1	2.0%	1.1%
1991	15.4	5.8	1.1%	2.0%
1992	13.4	6.8	1.0%	2.4%
1993	11.6	6.5	0.9%	2.3%
1994	10.1	8.9	0.7%	3.1%
1995	7.4	11.2	0.5%	4.0%
1996	9.5	10.5	0.7%	3.7%
1997	7.4	8.9	0.5%	3.2%
1998	7.0	9.7	0.5%	3.4%
1999	6.6	10.1	0.5%	3.6%
2000	6.5	10.9	0.5%	3.9%
2001	4.9	13.4	0.4%	4.8%
2002	3.9	10.0	0.3%	3.5%
2003	3.7	9.3	0.3%	3.3%
2004	2.9	8.9	0.2%	3.1%

Increases in stemwood volume were based on standard Yield Tables, as in Dewar & Cannell (1992) and Cannell & Dewar (1995). These Tables do not provide information for years prior to first thinning so a curve was developed to bridge the gap (Hargreaves *et al.* 2003). The pattern fitted to the stemwood volume between planting and first thinning from the Yield Tables follows a smooth curve from planting to first thinning. The formulation begins with an exponential pattern but progresses to a linear trend that merges with the pattern in forest management tables after first thinning.

The mass of carbon in a forest was calculated from volume by multiplying by species-specific wood density, stem: branch and stem: root mass ratios and the fraction of carbon in wood (0.5 assumed). The values used for these parameters for conifers and broadleaves are given in Table 2-2.

Table 2-2 Main parameters for forest carbon flow model for species used to estimates carbon uptake by planting of forests of Sitka spruce (*P. sitchensis)* and beech (*F. sylvatica*) in the United Kingdom (Dewar & Cannell 1992)

	P. sitchensis	***P. sitchensis***	***F. sylvatica***
	YC12	**YC14**	**YC6**
Rotation (years)	59	57	92
Initial spacing (m)	2	2	1.2
Year of first thinning	25	23	30
Stemwood density (t m^{-3})	0.36	0.35	0.55
Maximum carbon in foliage (t ha^{-1})	5.4	6.3	1.8
Maximum carbon in fine roots (t ha^{-1})	2.7	2.7	2.7
Fraction of wood in branches	0.09	0.09	0.18
Fraction of wood in woody roots	0.19	0.19	0.16
Maximum foliage litterfall (t ha^{-1} a^{-1})	1.1	1.3	2
Maximum fine root litter loss (t ha^{-1} a^{-1})	2.7	2.7	2.7
Dead foliage decay rate (a^{-1})	1	1	3
Dead wood decay rate (a^{-1})	0.06	0.06	0.04
Dead fine root decay rate (a^{-1})	1.5	1.5	1.5
Soil organic carbon decay rate (a^{-1})	0.03	0.03	0.03
Fraction of litter lost to soil organic matter	0.5	0.5	0.5
Lifetime of wood products	57	59	92

The parameters controlling the transfer of carbon into the litter pools and its subsequent decay are also given in Table 2-2. Litter transfer rate from foliage and fine roots increased to a maximum at canopy closure. A fraction of the litter was assumed to decay each year, half of which added to the soil organic matter pool, which then decayed at a slower rate. Tree species and Yield Class were assumed to control the decay of litter and soil matter. Additional litter was generated at times of thinning and felling.

Estimates of carbon losses from the afforested soils are based on measurements taken at deep peat moorland locations, covering afforestation of peat from 1 to 9 years previously, and at a 26 year old conifer forest (Hargreaves *et al.* 2003). These measurements suggest that long term losses from afforested peatlands are not as great as had been previously thought, settling to about 0.3 tC ha^{-1} a^{-1} thirty years after afforestation. In addition, a short burst of regrowth of moorland vegetation occurs before forest canopy closure.

Carbon incorporated into the soil under all new forests is included, and losses from pre-existing soil layers are described by the general pattern measured for afforestation of deep peat with conifers. The relative amounts of afforestation on deep peat and other soils in the decades since 1920 are considered. For planting on organo-mineral and mineral soils, it is assumed that the pattern of emissions after planting will follow that measured for peat, but the emissions from the pre-existing soil layers will broadly be in proportion to the soil carbon density of the top 30 cm relative to that same depth of deep peat. A simplified approach was used to decide on the proportionality factors, and it is assumed that emissions from pre-existing soil layers will be equal to those from the field measurements for all planting in Scotland and Northern Ireland and for conifer planting on peat in England and Wales. Losses from broadleaf planting in England and Wales are assumed to proceed at half the rate of those from the field measurements. These assumptions are based on consideration of mean soil carbon densities for non-forest in the fully revised UK soil carbon database. The temporary re-growth of ground vegetation before forest canopy closure is, however, assumed to occur for all planting at the same rate as for afforested peat moorland. This assumption agrees with qualitative field observations of planting on agricultural land in England.

For the 2004 inventory, there was a minor revision of the modelling of the emissions due to soil disturbance. This is now estimated within C-Flow using a time-step of 0.1 years, rather than as a separate calculation with an annual time-step as used in the 2003 Inventory.

It is assumed in the C-Flow model that harvested material from thinning and felling is made into wood products. The net change in the carbon in this pool of wood products is reported in Category 5G.

2.2.2.2.(b) Data Reporting

- *Common Reporting Format under IPCC LULUCF Good Practice Guidance*

The data for carbon stock changes in living biomass, dead organic matter and soils from afforestation are entered in Sectoral Background Table 5.A.2 Land converted to Forest Land. The data are disaggregated into afforestation of Cropland, Grassland and Settlements and further by (a) the four geographical areas of England, Scotland, Wales and Northern Ireland, and (b) two time periods, up to 1990 and 1991 onwards. The area associated with each set of disaggregated data is included in Sectoral Background Table 5.A.2.

The removals due to carbon stock changes in harvested wood products calculated here are entered into Sectoral Report Table 5, as “G Other, Harvested Wood Products”.

- *Common Reporting Format under IPCC 1996 Guidelines (no longer used)*

Removals due to changes in forest biomass stocks were previously included in the Category 5A2 (Changes in Temperate Woody Biomass) but removals to litter and soil for the afforested areas were reported under Category 5D4 (Forest Soils). Changes in stocks of harvested wood products were reported separately under Category 5A5.

2.2.2.2.(c) Planned Improvements

The method for estimating removals and emissions due to afforestation is being developed to provide data for grid cells of 20 x 20 km. Periodically updated forest inventory or grant application data will be used rather than annual planting data to drive the new version. This approach is being developed to meet the requirements of the Kyoto Protocol for more geographically explicit data than the national area for reporting removals due to afforestation and deforestation under Article 3.3. In addition, there will be further investigation into the effects of non-standard management, externally imposed disturbances on both conifer and broadleaved forests and the effect of alternative assumptions on species distribution.

2.2.3. Cropland (5B)

The category is disaggregated into *5.B.1 Cropland remaining Cropland* and *5.B.2 Land converted to Cropland*. Category 5.B.1 is further disaggregated into the four geographical areas of England, Scotland, Wales and Northern Ireland. Three activities are considered for 5.B.1: Changes in non-forest biomass (resulting from yield improvements or land use change), carbon dioxide emissions from soils due to agricultural lime application to Cropland (which is further disaggregated into application of Limestone ($CaCO_3$) and Dolomite ($CaMg(CO_3)_2$)) and the effect of fenland drainage on soil carbon stocks (which occurs only in England). Category 5.B.2 is disaggregated into conversions from Forest Land, Grassland and Settlements. These conversions are further disaggregated by a) the four geographical areas of England, Scotland, Wales and Northern Ireland, and b) two time periods, 1950 – 1990 and 1991 onwards

N_2O emissions from disturbance associated with land use conversion to Cropland are not reported as a study has shown these to be small (Skiba *et al.* 2005)

2.2.3.1 Cropland remaining Cropland

2.2.3.1.(a) Methodology - Changes in non-forest biomass resulting from yield improvements

New approaches to estimating changes in the stock of carbon in biomass other than in forests have been introduced this year.

There is an annual increase in the biomass of cropland vegetation in the UK that is due to yield improvements (from improved species strains or management, rather than fertilization or nitrogen deposition). There has been a complete revision of the activity data and methodology in this category. The increases in crop yield are now calculated separately from those resulting from land use change. Under category 5.B.1 an annual value is reported for changes in carbon stock, on the assumption that the annual average standing biomass of cereals has increased linearly with increase in yield between 1980 and 2000 (Sylvester-Bradley *et al.* 2002).

2.2.3.1.(b) Methodology – Application of Lime

Emissions of carbon dioxide from the application of limestone, chalk and dolomite to cropland were estimated using the method described in the IPCC 1996 Guidelines (IPCC, 1997a, b, c). Data on the use of limestone, chalk and dolomite for agricultural purposes is reported in BGS (2005). They also include ‘material for calcination’. In agriculture all three minerals are applied to the soil; CO_2 emissions, weight for weight, from limestone and chalk are assumed to be identical since they have the same chemical formula. Dolomite, however, will have a slightly higher emission due to the presence of magnesium. The amount of each material (applied to cropland) is estimated each year as only the total amount is published, due to commercial confidentiality rules for reporting of small quantities. It is assumed that all the carbon within the applied material is released in the year of use. These application data were combined with fluxes from agricultural grassland and reported in Category 5D of previous inventory formats.

The method for estimating CO_2 emissions due to the application of lime and related compounds is that described in the IPCC 1996 Guidelines. For limestone and chalk, an emission factor of 120 tC/kt applied is used, and for dolomite application, 130 tC/kt. These factors are based on the stoichiometry of the reaction and assume pure limestone/chalk and dolomite.

Only dolomite is subjected to calcination. However, some of this calcinated dolomite is not suitable for steel making and is returned for addition to agricultural dolomite – this fraction is reported in BGS (2005) as 'material for calcination' under agricultural end use. Calcinated dolomite, having already had its CO_2 removed, will therefore not cause the emissions of CO_2 and hence is not included here. Lime (calcinated limestone) is also used for carbonation in the refining of sugar but this is not specifically dealt with in the UK LUCF GHG Inventory.

Lime is applied to both grassland and cropland. The annual percentages of arable and grassland areas receiving lime in Great Britain for 1994-2004 were obtained from the Fertiliser Statistics Report 2005 (Agricultural Industries Confederation 2005). Percentages for 1990-1993 were assumed to be equal to those for 1994.

Uncertainty in both the activity data and emission factor used for this source are judged to be low. The main source of uncertainty in the estimates is caused by non-publication of some data due to commercial restrictions, although these are not judged to be very significant. Time-series consistency is underpinned by continuity in data source.

2.2.3.1.(c) Methodology – Lowland drainage

Fenland areas of England were drained many decades ago for agriculture. The soils in these areas are still emitting CO_2, i.e. there is an ongoing change in soil carbon stock. These data were reported in Category 5D or 5E in previous inventory formats. No recalculations were undertaken for this category.

Lowland wetlands in England were drained many years ago for agricultural purposes and continue to emit carbon from the soil. Bradley (1997) described the methods used to estimate these emissions. The baseline (1990) for the area of drained lowland wetland for the UK was taken as 150,000 ha. This represents all of the East Anglian Fen and Skirtland and limited areas in the rest of England. This total consists of 24,000 ha of land with thick peat (more than 1 m deep) and the rest with thinner peat. Different loss rates were assumed for these two thicknesses as shown in Table 2-3. The large difference between the implied emission factors is due to the observation that those peats described as 'thick' lose volume (thickness) more rapidly that those peats described as 'thin'. The 'thick' peats are deeper than 1m, have 21% carbon by mass and in general have different texture and less humose topsoil than the 'thin' peats, which have depths up to 1m (many areas ~0.45 m deep) and carbon content of 12% by mass.

Table 2-3 Area and carbon loss rates of UK fen wetland in 1990

	Area	**Organic carbon content**	**Bulk density** kg m^{-3}	**Volume loss rate** m^3 m^{-2} a^{-1}	**Carbon mass loss** GgC a^{-1}	**Implied emission factor** gC m^{-2} a^{-1}
'Thick' peat	24×10^7 m^2 (24,000 ha)	21%	480	0.0127	307	1280
'Thin' peat	126×10^7 m^2 (126,000 ha)	12%	480	0.0019	138	109
Total	**150×10^7 m^2 (150 kha)**				**445**	**297**

The emissions trend since 1990 was estimated assuming that no more fenland has been drained since then but that existing drained areas have continued to lose carbon. The annual loss for a specific location decreases in proportion to the amount of carbon remaining. Furthermore, as the peat loses carbon it becomes more mineral in structure. The Century model of plant and soil carbon was used to average the carbon losses from these fenland soils over time (Bradley 1997): further data on how these soil structure changes proceed with time is provided in Burton (1995).

The emissions due to lowland drainage are obtained from a model driven by activity data from a single source, which provides good time series consistency.

2.2.3.1.(d) Data Reporting

- *Common Reporting Format under IPCC LULUCF Good Practice Guidance*

The net emissions due to increases in non-forest biomass are disaggregated into the four geographical areas of England, Scotland, Wales and Northern Ireland and entered into Sectoral Background Table 5.B.1 (Cropland remaining Cropland) under carbon stock change in living biomass. The area of land associated with each set of data is also included in Sectoral Background Table 5.B.1.

The emissions in this Category from agricultural lime application are entered into Sectoral Background Table 5 (IV) (Carbon emissions from agricultural lime application). The data are disaggregated by application of limestone and dolomite separately on Cropland (and Grassland).

The emissions in this Category due to lowland drainage are entered into Sectoral Background Table 5.B.1 (Cropland remaining Cropland) under net carbon stock change in soils. This applies only to England so there is no further disaggregation. The area of land associated with lowland drainage is also included in Sectoral Background Table 5.B.1.

- *Common Reporting Format under IPCC 1996 Guidelines (no longer used)*

Removals of CO_2 due to changes in stocks of non-forest biomass carbon were reported in Category 5E (Other) in submissions to the UNFCCC under the IPCC 1996 Guidelines.

Emissions from liming were identified separately under Category 5D3 (CO_2 Emissions and Removals from Soils: Liming of Agricultural Soils).

Emission of CO_2 from drained lowland fens were reported in Category 5D5 (CO_2 Emissions and Removals - Other).

2.2.3.1.(e) Planned Improvements

A review of the approaches will be undertaken for this activity, with reference to input data and appropriateness of reporting category.

2.2.3.2 Land Converted to Cropland

2.2.3.2.(a) Methodology - Changes in non-forest biomass stocks resulting from land use change to Cropland

This is the annual change in the carbon stock in vegetation biomass due to all land use change to Cropland, excluding forests and woodland. Estimates of emissions and removals for this category are made using the Countryside Survey Land Use Change matrix approach, with biomass densities weighted by expert judgment.

Changes in carbon stocks in biomass due to land use change are now based on the same area matrices used for estimating changes in carbon stocks in soils (Section 2.2.3.2.(b)). The biomass carbon density for each land type is assigned by expert judgement based on the work of Milne & Brown (1997) and these are shown in Table 2-4. Five basic land uses were assigned initial biomass carbon densities, then the relative occurrence of these land uses in the four countries of the UK were used to calculate mean biomass carbon densities for each of the IPCC types, Cropland, Grassland and Settlements. Biomass carbon stock changes due to conversions to and from Forest Land are dealt with elsewhere. The mean biomass carbon densities for each land type were then weighted by the relative proportions of change occurring between land types (Table 2-5 to Table 2-8), in the same way as the calculations for changes in soil carbon densities. Changes between these equilibrium biomass carbon densities were assumed to happen in a single year.

Table 2-4 Equilibrium biomass carbon density (kg m^{-2}) for different land types

Density (kg m^{-2})	**Scotland**	**England**	**Wales**	**N. Ireland**
Arable	0.15	0.15	0.15	0.15
Gardens	0.35	0.35	0.35	0.35
Natural	0.20	0.20	0.20	0.20
Pasture	0.10	0.10	0.10	0.10
Urban	0	0	0	0
IPPC types weighted by occurrence				
Cropland	0.15	0.15	0.15	0.15
Grassland	0.18	0.12	0.13	0.12
Settlements	0.29	0.28	0.28	0.26

Table 2-5 Weighted average change in equilibrium biomass carbon density (kg m^{-2}) for changes between different land types in England (Transitions to and from Forestland are considered elsewhere)

From / To	**Forestland**	**Grassland**	**Cropland**	**Settlements**
Forestland				
Grassland		0	-0.08	-0.13
Cropland		0.08	0	-0.08
Settlements		0.13	0.08	0

Table 2-6 Weighted average change in equilibrium biomass carbon density (kg m^{-2}) for changes between different land types in Scotland. (Transitions to and from Forestland are considered elsewhere)

From / To	**Forestland**	**Grassland**	**Cropland**	**Settlements**
Forestland				
Grassland		0	-0.02	-0.14
Cropland		0.02	0	-0.09
Settlements		0.14	0.09	0

Table 2-7 Weighted average change in equilibrium biomass carbon density (kg m^{-2}) for changes between different land types in Wales. (Transitions to and from Forestland are considered elsewhere)

From / To	Forestland	Grassland	Cropland	Settlements
Forestland				
Grassland		0	-0.07	-0.13
Cropland		0.07	0	-0.08
Settlements		0.13	0.08	0

Table 2-8 Weighted average change in equilibrium biomass carbon density (kg m^{-2}) for changes between different land types in Northern Ireland. (Transitions to and from Forestland are considered elsewhere)

From / To	Forestland	Grassland	Cropland	Settlements
Forestland				
Grassland		0	-0.08	-0.11
Cropland		0.08	0	-0.06
Settlements		0.11	0.06	0

2.2.3.2.(b) Methodology – Changes in soil carbon stocks due to land use change to Cropland

Changes in soil stocks due to land use change to Cropland are estimated. All forms of land use change, including deforestation, are considered together and both mineral and organic soils are included. The Scottish soil carbon bulk densities have been updated, giving improved information on carbon content and the bulk density of organic rich soils. Estimates of emissions and removals have been updated to reflect these improvements.

The method for assessing changes in soil carbon stock due to land use change links a matrix of change from land surveys to a dynamic model of carbon stock change. For Great Britain (England, Scotland and Wales), matrices from the Monitoring Landscape Change (MLC) data from 1947 & 1980 (MLC 1986) and the Countryside Surveys (CS) of 1984, 1990 and 1998 (Haines-Young *et al.* 2000) are used. In Northern Ireland, less data are available to build matrices of land use change, but for 1990 to 1998 a matrix for the whole of Northern Ireland was available from the Northern Ireland Countryside Survey (Cooper & McCann 2002). The only data available pre-1990 for Northern Ireland are land use areas from the Agricultural Census and the Forest Service (Cruickshank & Tomlinson 2000). Matrices of land use change were then estimated for 1970-80 and 1980-90 using area data. The basis of the method devised assumed that the relationship between the matrix of land use transitions for 1990-1998 and the area data for 1990 is the same as the relationship between the matrix and area data for each of two earlier periods – 1970-79 and 1980-89. The matrices developed by this approach were used to extrapolate areas of land use transition back to 1950 to match the start year in the rest of the UK.

The Good Practice Guidance for Land Use, Land Use Change and Forestry (IPCC 2003) recommends use of six classes of land for descriptive purposes: Forest, Grassland, Cropland, Settlements, Wetlands and Other Land. The data currently available for the UK does not distinguish wetlands from other types, so land in the UK has been placed into the five other types. The more detailed categories for the two surveys in Great Britain were combined as shown in Table 2-9 for MLC and Table 2-10 for CS.

The area data used between 1947 and 1998 are shown in Table 2-11 and Table 2-12**.** The land use change data over the different periods were used to estimate annual changes by assuming that these were uniform across the measurement period. Examples of these annual changes (for the period 1990 to 1999) are given in Table 2-13 to Table 2-16. The data for afforestation and deforestation shown in the Tables are adjusted before use for estimating carbon changes to harmonise the values with those used in the calculations described in Sections 2.2.2.2.(a), 2.2.8 and 2.2.4.2.(a).

Table 2-9 Grouping of MLC land cover types for soil carbon change modelling

CROPLAND	**GRASSLAND**	**FORESTLAND**	**SETTLEMENTS (URBAN)**	**OTHER**
Crops	Upland heath	Broadleaved wood	Built up	Bare rock
Market garden	Upland smooth grass	Conifer wood	Urban open	Sand/shingle
	Upland coarse grass	Mixed wood	Transport	Inland water
	Blanket bog	Orchards	Mineral workings	Coastal water
	Bracken		Derelict	
	Lowland rough grass			
	Lowland heather			
	Gorse			
	Neglected grassland			
	Marsh			
	Improved grassland			
	Rough pasture			
	Peat bog			
	Fresh Marsh			
	Salt Marsh			

Table 2-10 Grouping of Countryside Survey Broad Habitat types for soil carbon change modelling.

CROPLAND	**GRASSLAND**	**FORESTLAND**	**SETTLEMENTS (URBAN)**	**OTHER**
Arable	Improved grassland	Broadleaved/mixed	Built up areas	Inland rock
Horticulture	Neutral grassland	Coniferous	Gardens	Supra littoral rock
	Calcareous grassland			Littoral rock
	Acid grassland			Standing waters
	Bracken			Rivers
	Dwarf shrub heath			Sea
	Fen, marsh, swamp			
	Bogs			
	Montane			
	Supra littoral sediment			
	Littoral sediment			

Table 2-11 Sources of land use change data in Great Britain for different periods in estimation of changes in soil carbon

Year or Period	**Method**	**Change matrix data**
1950 - 1979	Measured LUC matrix	MLC 1947->MLC1980
1980 - 1984	Interpolated	CS1984->CS1990
1984 - 1989	Measured LUC matrix	CS1984->CS1990
1990 - 1998	Measured LUC matrix	CS1990->CS1998
1999 - 2004	*Extrapolated*	CS1990->CS1998

Table 2-12 Sources of land use change data in Northern Ireland for different periods in estimation of changes in soil carbon. NICS = Northern Ireland Countryside Survey

Year or Period	Method	Change matrix data
1950 - 1969	Extrapolation and ratio method	NICS1990->NICS1998
1970 - 1989	Land use areas and ratio method	NICS1990->NICS1998
1990 - 1998	Measured LUC matrix	NICS1990->NICS1998
1999-2003	*Extrapolated*	NICS1990->NICS1998

Table 2-13 Annual changes (000 ha) in land use in England in matrix form for 1990 to 1999. Based on land use change between 1990 and 1998 from Countryside Surveys (Haines-Young *et al.* 2000). Data have been rounded to 100 ha.

From / To	Forestland	Grassland	Cropland	Settlements
Forestland		8.9	3.4	2.1
Grassland	8.7		55.3	3.4
Cropland	0.5	62.9		0.6
Settlements	1.2	8.5	2.1	

Table 2-14 Annual changes (000 ha) in land use in Scotland in matrix form for 1990 to 1999. Based on land use change between 1990 and 1998 from Countryside Surveys (Haines-Young *et al.* 2000). Data have been rounded to 100 ha.

From / To	Forestland	Grassland	Cropland	Settlements
Forestland		11.1	0.6	0.2
Grassland	5.0		16.8	0.7
Cropland	0.1	21.4		0.3
Settlements	0.3	2.2	0.1	

Table 2-15 Annual changes (000 ha) in land use in Wales in matrix form for 1990 to 1999. Based on land use change between 1990 and 1998 from Countryside Surveys (Haines-Young *et al.* 2000). Data have been rounded to 100 ha.

From / To	Forestland	Grassland	Cropland	Settlements
Forestland		2.4	0.2	0.2
Grassland	1.5		5.5	0.6
Cropland	0.0	8.0		0.0
Settlements	0.1	1.8	0.2	

Table 2-16 Annual changes (000 ha) in land use in Northern Ireland in matrix form for 1990 to 1999. Based on land use change between 1990 and 1998 from Northern Ireland Countryside Surveys (Cooper & McCann 2002). Data have been rounded to 100 ha.

From / To	Forestland	Grassland	Cropland	Settlements
Forestland		1.6	0.0	0.0
Grassland	0.3		5.9	0.0
Cropland	0.0	3.7		0.0
Settlements	0.1	1.0	0.0	

The database of soil carbon density for the UK (Milne & Brown 1997, Cruickshank *et al.* 1998) used prior to the 2003 GHG Inventory was extensively revised (Bradley *et al.* 2005) and incorporated into the 2003 Inventory. There are three soil survey groups covering the UK and the field data, soil classifications and laboratory methods of each group were harmonized to reduce uncertainty in the final database. The depth of soil considered was also restricted to 1 m at maximum as part of this process. Values of carbon content and bulk densities for organic soils in Scotland have been more recently revised and incorporated into the 2004 Inventory. Table 2-17 shows total stock of soil carbon (1990) for different land types in the four devolved areas of the UK.

Table 2-17 Soil carbon stock (TgC = MtC) for depths to 1m in different land types in the UK

Region / **Type**	England	Scotland	Wales	N. Ireland	**UK**
Forestland	108	295	45	20	467
Grassland	995	2,349	283	242	3,870
Cropland	583	114	8	33	738
Settlements	54	10	3	1	69
Other	0	0	0	0	-
TOTAL	**1,740**	**2,768**	**340**	**296**	**5,144**

The dynamic model of carbon stock change requires the change in equilibrium carbon density from the initial to the final land use. The core equation describing changes in soil carbon with time for any land use transition is:

$$C_t = C_f - (C_f - C_0)e^{-kt}$$

where

C_t is carbon density at time t
C_0 is carbon density of initial land use
C_f is carbon density after change to new land use
k is time constant of change

By differentiating we obtain the equation for flux f_t (emission or removal) per unit area:

$$f_t = k(C_f - C_o)e^{-kt}$$

From this equation we obtain, for any inventory year, the land use change effects from any specific year in the past. If A_T is area in a particular land use transition in year T considered from 1950 onwards then total carbon lost or gained in an inventory year, e.g. 1990, is given by:

$$F_{1990} = \sum_{T=1950}^{t=1990} kA_T(C_f - C_o)(e^{-k(1990-T)})$$

This equation is used with k, A_T and (C_f-C_0) chosen by Monte Carlo methods within ranges set by prior knowledge e.g. literature, soil carbon database, agricultural census, LUC matrices.

In the model, the change is required in equilibrium carbon density from the initial to the final land use during a transition. Here, these are calculated for each land use category as averages for Scotland, England, Wales and Northern Ireland. These averages are weighted by the area of Land Use Change occurring in four broad soil groups (organic, organo-mineral, mineral, unclassified) in order to account for the actual carbon density where change has occurred.

Hence mean soil carbon density change is calculated as:

$$\overline{C}_{ijc} = \frac{\sum_{s=1}^{6}(C_{sijc}L_{sijc})}{\sum_{s=1}^{6}L_{sijc}}$$

This is the weighted mean, for each country, of change in equilibrium soil carbon when land use changes, where:

i = initial land use (Forestland, Grassland, Cropland, Settlements)
j = new land use (Forestland, Grassland, Cropland, Settlements)
c = country (Scotland, England, N. Ireland & Wales)
s = soil group (organic, organo-mineral, mineral, unclassified)
C_{sijc} is change in equilibrium soil carbon for a specific land use transition

The most recent land use data (1990 to 1998) is used in the weighting. The averages calculated are presented in Table 2-18 to Table 2-21**.**

Table 2-18 Weighted average change in equilibrium soil carbon density (kg m^{-2}) to 1 m deep for changes between different land types in England

From / To	Forestland	Grassland	Cropland	Settlements
Forestland	0	25	32	83
Grassland	-21	0	23	79
Cropland	-31	-23	0	52
Settlements	-87	-76	-54	0

Table 2-19 Weighted average change in equilibrium soil carbon density (kg m^{-2}) to 1 m deep for changes between different land types in Scotland

From / To	Forestland	Grassland	Cropland	Settlements
Forestland	0	47	158	246
Grassland	-52	0	88	189
Cropland	-165	-90	0	96
Settlements	-253	-187	-67	0

Table 2-20 Weighted average change in equilibrium soil carbon density (kg m^{-2}) to 1 m deep for changes between different land types in Wales

From / To	Forestland	Grassland	Cropland	Settlements
Forestland	0	23	57	114
Grassland	-18	0	36	101
Cropland	-53	-38	0	48
Settlements	-110	-95	-73	0

Table 2-21 Weighted average change in equilibrium soil carbon density (kg m^{-2}) to 1 m deep for changes between different land types in Northern Ireland

To \ From	Forestland	Grassland	Cropland	Settlements
Forestland	0	94	168	244
Grassland	-94	0	74	150
Cropland	-168	-74	0	76
Settlements	-244	-150	-76	0

The rate of loss or gain of carbon is dependent on the type of land use transition (Table 2-22). For transitions where carbon is lost e.g. transition from Grassland to Cropland, a 'fast' rate is applied whilst a transition that gains carbon occurs much more slowly. A literature search for information on measured rates of changes of soil carbon due to land use was carried out and ranges of possible times for completion of different transitions were selected, in combination with expert judgement. These are shown in Table 2-23.

Table 2-22 Rates of change of soil carbon for land use change transitions. ("Fast" & "Slow" refer to 99% of change occurring in times shown in Table 2-23)

		Initial			
		Cropland	**Grassland**	**Settlement**	**Forestland**
Final	**Cropland**		*slow*	*slow*	*slow*
	Grassland	*fast*		*slow*	*slow*
	Settlement	*fast*	*fast*		*slow*
	Forestland	*fast*	*fast*	*fast*	

Table 2-23 Range of times for soil carbon to reach 99% of a new value after a change in land use in England (E), Scotland (S) and Wales (W)

	Low (years)	High (years)
Carbon loss ("fast") E, S, W	50	150
Carbon gain ("slow") E, W	100	300
Carbon gain ("slow") S	300	750

Changes in soil carbon from equilibrium to equilibrium (C_f-C_o) were assumed to fall within ranges based on 2004 database values for each transition and the uncertainty indicated by this source (up to ± 11% of mean). The areas of land use change for each transition were assumed to fall a range of uncertainty of ± 30% of mean.

A Monte Carlo approach is used to vary the rate of change, the area activity data and the values for soil carbon equilibrium (under initial and final land use) for all countries in the UK. The model of change was run 1000 times using parameters selected from within the ranges described above. The mean carbon flux for each region resulting from this imposed random variation is reported as the estimate for the Inventory. An adjustment was made to these calculations for each country to remove increases in soil carbon due to afforestation, as the C-Flow model provides a better estimate of these fluxes in the Land Converted to Forestry category (see Section 2.2.2.2). Variations from year to year in the reported net emissions reflect the trend in land use change as described by the matrices of change.

As regards data quality, land use change activity data are obtained from several sources. The sources for Great Britain have separate good internal consistency, but there is poorer consistency between sources and with the data for Northern Ireland. There may be carry-over effects on emission/removal estimates for the reported years due to the long time response of soil systems.

2.2.3.2.(c) Data Reporting

- *Common Reporting Format under IPCC LULUCF Good Practice Guidance*

The carbon stock change in living biomass due to the increase in non-forest biomass in this category is disaggregated into the four geographical areas of England, Scotland, Wales and Northern Ireland and entered into Sectoral Background Table 5.B.2 Land Converted to Cropland. The area of land associated with each set of data is also included in Sectoral Background Table 5.B.

Net carbon stock change in soils resulting from land use change is included in Sectoral Background Table 5.B.2 Land converted to Cropland. The data for deforestation is included at the UK level while conversion of Grassland and Settlements to Cropland is disaggregated into the four geographical areas of England, Scotland, Wales and Northern Ireland plus two time periods (pre and post 1990). The areas of land associated with each set of data are also included in this Table.

- *Common Reporting Format under IPCC 1996 Guidelines (no longer used)*

Removals of CO_2 due to changes in stocks of non-forest biomass carbon were reported in Category 5E (Other) in submissions to the UNFCCC under the IPCC 1996 Guidelines.

Emissions or removals in soils resulting from land use change were reported in Category 5D (Cultivation of Soils).

2.2.3.2.(d) Planned Improvements

In the long term, the UK is planning to implement the use of a process-based model for estimating emissions and removals from soils. This method is unlikely to be available for a few years, hence the enhancement of the existing approach over this and the previous inventory. A new version of the Countryside Survey is planned for 2007/2008, which will allow the extension of the land use change matrices.

2.2.4. Grassland (5C)

The Category is disaggregated into *5.C.1 Grassland remaining Grassland* and *5.C.2 Land converted to Grassland*. Category 5.C.1 is disaggregated into the four geographical areas of England, Scotland, Wales and Northern Ireland. Category 5.C.2 is disaggregated into conversions from Forest Land, Cropland and Settlements. Conversions from Cropland and Settlements to Grassland are further disaggregated by a) the four geographical areas of England, Scotland, Wales and Northern Ireland and b) two time periods, 1950 – 1990 and 1991 onwards. Biomass burning emissions due to conversion of Forest Land to Grassland is reported at the 5C level for all of the UK in two time periods, 1950-1990 and 1990 onwards.

Carbon dioxide emissions from agricultural lime application to Grassland is disaggregated into application of Limestone ($CaCO_3$) and Dolomite ($CaMg(CO_3)_2$).

2.2.4.1 Grassland remaining Grassland

2.2.4.1.(a) Methodology – Application of Lime

See 2.2.3.1.(b) for details on Agricultural liming on Cropland and Grassland. This data was combined with fluxes from Cropland and reported in Category 5D of previous formats.

2.2.4.1.(b) Methodology – Peat Extraction

Peat is extracted in the UK for use as either a fuel or in horticulture. Only peat used in horticulture is now reported in this category. Peat used as a fuel is reported in the Energy Sector of the UK Inventory. This change results in reporting of 390 Gg CO_2 for 1990, compared to 792 Gg CO_2 in the previous NIR, and 355 Gg CO_2 in 2004, compared to 894 reported for 2003 in the previous NIR. Activity data for peat extraction come from a number of sources, only some of which are reliable, which will have some effect on time series consistency.

Cruickshank & Tomlinson (1997) provide initial estimates of Emissions due to peat extraction. Since their work, trends in peat extraction in Scotland and England over the period 1990 to 2004 have been estimated from activity data taken from the UK Minerals Handbook (BGS 2005). In Northern Ireland, no new data on use of peat for horticultural use has been available but a recent survey of extraction for fuel use suggested that there is no significant trend for this purpose. The contribution of emissions due to peat extraction in Northern Ireland is therefore incorporated as constant from 1990 to 2004. Peat extraction is negligible in Wales. For 2004, emissions due to peat used as a fuel are reported in the Energy Sector while peat for horticulture use remains in Sector 5; the Sector 5 figures are therefore lower than in previous inventory reports. Emissions factors are from Cruickshank & Tomlinson (1997) and are shown in Table 2-24**.**

Table 2-24 Emission Factors for Peat Extraction

	Emission Factor kg C m^{-3}
Great Britain Horticultural Peat	55.7
Northern Ireland Horticultural Peat	44.1

2.2.4.1.(c) Data Reporting

- *Common Reporting Format under IPCC LULUCF Good Practice Guidance*

The emissions in this Category from agricultural lime application are entered into Sectoral Background Table 5 (IV) Carbon emissions from agricultural lime application. The data are disaggregated by application of limestone and dolomite separately on Grassland (and Cropland).

The emissions in this Category due to peat extraction are entered into Sectoral Background Table 5.C.1 Grassland remaining Grassland, disaggregated into the four geographical areas of England, Scotland, Wales and Northern Ireland.

- *Common Reporting Format under IPCC 1996 Guidelines (no longer used)*

For reporting to the UNFCCC under the IPCC 1996 Guidelines the emissions were identified under Category 5D3 (CO_2 Emissions and Removals from Soils: Liming of Agricultural Soils).

Removals of CO_2 due to peat extraction were reported in Category 5E (Other).

2.2.4.1.(d) Planned Improvements

There are no planned improvements for this category. The availability of data on peat extraction for horticultural use will be kept under review.

2.2.4.2 Land converted to Grassland

2.2.4.2.(a) Methodology - Emissions from biomass burning after conversion of Forest Land to Grassland

These are emissions of CO_2, CH_4 and N_2O resulting from the burning of forest biomass when Forest Land is converted to Grassland. In the 2003 Inventory deforestation was assumed only to be a conversion to Settlements. A revised interpretation of the available data allows the emissions to be disaggregated into deforestation to Grassland and Settlements. Deforestation to Cropland in the UK is negligible.

Levy & Milne (2004) discuss methods for estimating deforestation using a number of data sources. Here we use their approach of combining Forestry Commission felling licence data for rural areas with Ordnance Survey data for non-rural areas.

In Great Britain, some activities that involve tree felling require permission from the Forestry Commission, in the form of a felling licence, or a felling application within the Woodland Grant Scheme. Under the Forestry Act 1967, there is a presumption that the felled areas will be restocked, usually by replanting. Thus, in the 1990s, around 14,000 ha a^{-1} was felled and restocked. However, some licences are granted without the requirement to restock, where there is good reason – so-called unconditional felling licences. Most of these areas are small (1-20 ha), but their summation gives some indication of areas deforested. These areas are not published, but recent figures from the Forestry Commission have been collated. These provide estimates of rural deforestation rates in England for 1990 to 2002 and for GB in 1999 to 2001. The most recent deforestation rate available for rural areas is for 2002 so rates for 2003 and 2004 were estimated by extrapolating forwards from the rates for 1999 to 2002

Only local planning authorities hold documentation for allowed felling for urban development, and the need for collation makes estimating the national total difficult. However, in England, the Ordnance Survey (national mapping agency) makes an annual assessment of land use change (Office of The Deputy Prime Minister 2004) from the data it collects for map updating. Eleven broad land-use categories are defined, with a number of sub-categories. The data for England (1990 to 2004) were available to produce a land-use change matrix, quantifying the transitions between land-use classes. Deforestation rate was calculated as the sum of transitions from all forest classes to all non-forest classes providing estimates on non-rural deforestation.

The rural and non-rural values for England were each scaled up to GB scale, assuming that England accounted for 72 per cent of deforestation, based on the distribution of licensed felling between England and the rest of GB in 1999 to 2001. However, the Ordnance Survey data come from a continuous rolling survey programme, both on the ground and from aerial photography. The changes reported each year may have actually occurred in any of the preceding 1-5 years (the survey frequency varies among areas, and can be up to 10 years for moorland/mountain areas). Consequently, a three-year moving average was applied to the data to smooth out the between-year variation appropriately, to give a suitable estimate with annual resolution. Deforestation is not currently estimated for Northern Ireland. Rural deforestation is assumed to convert the land to Grassland use (reported in Category 5C2) and non-rural deforestation causes conversion to the Settlement land type (reported in 5E2). Information from land use change matrices shows that conversion of Forest to Cropland is negligible.

On deforestation it is assumed that 60% of the standing biomass is removed as timber products and the remainder is burnt. The annual area loss rates were used in the method described in the IPCC 1996 guidelines (IPCC 1997c, 1997a, 1997b) to estimate immediate emissions of CO_2, CH_4 and N_2O from this biomass burning. Only immediate losses are considered because sites are normally completely cleared for development, leaving no debris to decay. Changes in stocks of soil carbon after deforestation are included with those due to other land use transitions as described in Section 2.2.3.2.(b).

The time series consistency of emissions from this activity is medium given that the two constituent data series are not both available for each year and the values for several years are partially derived from data in one region. Areas deforested in non-rural areas have been revised for each year from 1990 and updated to 2004. Data on rural deforestation is only available up to 2002; therefore areas for 2003 and 2004 were estimated by extrapolation from earlier years.

2.2.4.2.(b) Methodology – Changes in Non forest biomass due to land use change to Grassland

This is the annual change in the carbon stock in biomass of vegetation due to all land use change, excluding forests and woodland, to Grassland. See 2.2.3.2.(a) for details on non-forest biomass calculations.

2.2.4.2.(c) Methodology – Changes in soil carbon stocks due to land use change to Grassland

Changes in soil stocks due to land use change to Grassland are estimated. All forms of land use change, including deforestation, are considered together and both mineral and organic soils are included. Land use change activity data are obtained from several sources. The sources for Great Britain have separate good internal consistency, but there is poorer consistency between these sources and with the data for Northern Ireland. There may be carry-over effects on emission/removal estimates for the reported years due to the long time response of soil systems. The Scottish soil carbon bulk densities have been updated, giving improved information on carbon content and the bulk density of organic rich soils. Estimates of emissions and removals have been updated to reflect these improvements in the data. Details of the Methodology are given in Section 2.2.3.2.(b).

2.2.4.2.(d) Data Reporting

- *Common Reporting Format under IPCC LULUCF Good Practice Guidance*

Emissions of CO_2, CH_4 and N_2O from biomass burning after conversion of land to Grassland are included in Sectoral Background Table 5 (V) Biomass Burning.

The carbon stock change in living biomass due to the increase in non-forest biomass in this category is disaggregated into the four geographical areas of England, Scotland, Wales and Northern Ireland and entered into Sectoral Background Table 5.C.2 Land Converted to Grassland. The area of land associated with each set of data is also included in Sectoral Background Table 5.C.

Net carbon stock change in soils resulting from land use change is included in Sectoral Background Table 5.C.2 Land converted to Grassland. The data for deforestation is included at the UK level while conversion of grassland and settlements to Grassland is disaggregated into the four geographical areas of England, Scotland, Wales and Northern Ireland plus two time periods (pre- and post-1990).

- *Common Reporting Format under IPCC 1996 Guidelines (no longer used)*

The net emissions associated with this activity were reported under Source Category 5B2, 5D and 5E.

2.2.4.2.(e) Planned Improvements

Future improvements of the method for biomass burning emissions will include collating Forestry Commission unconditional felling licence data for Scotland and Wales. Similar information for Northern Ireland has also become available recently and will be incorporated in next year's Inventory. All emission factors and activity data will be kept under review.

2.2.5. Wetlands (5D)

In the UK, Wetlands will either be saturated land (e.g. bogs, marshes) falling within the Grassland category (due to the classifications used in the Countryside Survey) or open water (e.g. lakes, rivers, reservoirs), which is included in the Other Land category. Sectoral Background Table 5.D. Wetlands is therefore completed with 'IE' (Included Elsewhere).

2.2.6. Settlements (5E)

Category 5.E (Settlements) is disaggregated into *5.E.1 Settlements remaining Settlements* and *5.E.2 Land converted to Settlements*. The area of Settlements in Category 5.E.1 is considered not to have long term changes in carbon stock. Category 5.E.2 is disaggregated into conversions from Forest Land, Cropland and Grassland and these conversions are further disaggregated by a) the four geographical areas of England, Scotland, Wales and Northern Ireland and b) two time periods, 1950 – 1990 and 1991 onwards. Biomass burning emissions due to conversion of Forest Land to Settlements are reported at the 5E level for all of the UK in two time periods, 1950-1990 and 1990 onwards.

2.2.6.1 Settlements remaining Settlements

No changes in carbon stocks are reported for land remaining under Settlements. A possible cause of carbon stock change with time would be increasing or decreasing stock of biomass in parks or gardens. This conceptually dealt with under the "changes in stock of non-forest biomass" but further work is required

2.2.6.1.(a) Data Reporting

- *Common Reporting Format under IPCC LULUCF Good Practice Guidance*

Sectoral Background Table 5.E.1 Settlements remaining Settlements is completed with 'NO' (Not Occurring).

2.2.6.1.(b) Planned Improvements

None are planned at the present time.

2.2.6.2 Land converted to Settlements

2.2.6.2.(a) Methodology – Emissions from biomass burning after conversion of Forest Land to Settlements

These are emissions of CO_2, CH_4 and N_2O resulting from the burning of forest biomass when Forest Land is converted to Settlements. In the 2003 Inventory deforestation was assumed only to be a conversion to Settlements. A revised interpretation of the available data allows the emissions to be disaggregated into deforestation to Grassland and Settlements. Deforestation to Cropland is negligible. The methodology is described in Section 2.2.4.1.(a).

2.2.6.2.(b) Methodology - Changes in non-forest biomass due to land use change to Settlements

This includes annual changes in the biomass of vegetation in the UK due to all land use change, excluding forests and woodland. Estimates of emissions and removals for this category are now made using the Countryside Survey Land Use Change matrix approach, with biomass densities weighted by expert judgment. See Section 2.2.3.2.(a) for details.

2.2.6.2.(c) Methodology – Changes in soil carbon stocks due to land use change to Settlements

Changes in soil stocks due to land use change to Settlements are estimated (see Section 2.2.3.2.(b) for details). All forms of land use change, including deforestation, are considered together and both mineral and organic soils are included. Land use change activity data are obtained from several sources. The sources for Great Britain have separate good internal consistency, but there is poorer consistency between these sources and with the data for Northern Ireland. There may be carry-over effects on emission/removal estimates for the reported years due to the long time response of soil systems. The Scottish soil carbon bulk densities have been updated, giving improved information on carbon content and the bulk density of organic rich soils. Estimates of emissions and removals have been updated to reflect these improvements in the data.

2.2.6.2.(d) Data Reporting

- *Common Reporting Format under IPCC LULUCF Good Practice Guidance*

Emissions of CO_2, CH_4 and N_2O from biomass burning after conversion of land to Settlements are included in Sectoral Background Table 5 (V) Biomass Burning.

The carbon stock change in living biomass due to the increase in non-forest biomass in this category is disaggregated into the four geographical areas of England, Scotland, Wales and Northern Ireland and entered into Sectoral Background Table 5.E.2 Land Converted to Settlements. The area of land associated with each set of data is also included in Sectoral Background Table 5.E.

Net carbon stock change in soils resulting from land use change is included in Sectoral Background Table 5.E.2 Land converted to Settlements. The data for deforestation is included at the UK level while conversion of Grassland and Cropland to Settlements is disaggregated into the four geographical areas of England, Scotland, Wales and Northern Ireland plus two time periods (pre- and post-1990).

- *Common Reporting Format under IPCC 1996 Guidelines (no longer used)*

The net emissions associated with this activity were reported under Category 5B2, 5D and 5E.

2.2.6.2.(e) Planned Improvements

Future improvements of the method for biomass burning emissions will include collating Forestry Commission unconditional felling licence data for Scotland and Wales. Similar information for Northern Ireland has also become available recently and will be incorporated in next year's Inventory. All emission factors and activity data will be kept under review.

2.2.7. Other Land (5F)

No emissions or removals are reported in this category. It is assumed that there are very few areas of land of other types that become bare rock or water bodies, which make up the majority of this type. Therefore Sectoral Background Table 5.F Other Land is completed with 'NO' (Not Occurring).

2.2.8. Other Activities (5G)

Changes in stocks of carbon in harvested wood products (HWP) are reported here.

2.2.8.1.(a) Methodology

The net change in the pool of products from harvested material from conifer and broadleaf forests is calculated by the carbon accounting model, C-Flow (see Section 2.2.2.2.(a) for further details). Dewar & Cannell (1992) and Cannell & Dewar (1995) provided a detailed description of all the assumptions in the model. Only products from UK forests planted since 1920 (i.e. those for which biomass and soil carbon stock changes are reported) are considered at present. It is not considered to be of high priority to consider the decay of imported products etc. as there is no international agreement on a single methodology to be used for reporting.

The C-Flow model adopts a simple approach to the decay of HWP. A carbon stock loss of 5% is assumed to occur immediately at harvest. Subsequently, the decay time (time to 95% loss of carbon stock) of products is set equal to the rotation time for that species. This approach captures differences in wood product use: fast growing softwoods tend to be used for shorter lived products than slower growing hardwoods. Exponential single decay constants are used for HWP from conifers and broadleaves. Products from thinnings are assumed to have a lifetime (time to 95% loss) of 5 years (half life~0.9 years). The main harvest products have a lifetime equal to rotation length. For conifers this equates to a half life of 14 years and for broadleaves a half life of 21 years. These values fall mid range between those tabled in the LULUCF GPG (IPCC 2003) for paper and sawn products. Limited data were available for the decay of products in the UK when the model was originally developed. The mix of products may be changing in the UK and this could affect the 'true' mean value of product lifetime but there is very limited accurate data on either decay rates or volume statistics for different products. The method used in the UK takes a top-down approach by assuming that the decay of all conifer products and all broadleaf products can be approximated by separate single decay constants. Given the uncertainty on decay of products it is difficult to decide if this is worse than a bottom-up approach where each product is given an (uncertain) decay and combined with (uncertain) decay of other products using harvest statistics which are in themselves uncertain.

Calculated in this way, the total wood products pool from UK forests is presently increasing due to continuing expansion in forest area. The time pattern of HWP stock changes is due to the historical pattern of new planting and by the resulting history of production harvesting (and thinning). The stock of carbon in HWP (from UK forests planted since 1920) has been increasing since 1990 but this rate of rise has recently reversed, reflecting a dip in new planting during the 1940s. The stock of carbon in HWP will fall for a few more years but will then begin to rise steeply due to harvesting of the extensive conifer forests planted between 1950 and the late 1980s.

2.2.8.1.(b) Data Reporting

- *Common Reporting Format under IPCC LULUCF Good Practice Guidance*

Removals of CO_2 associated with harvested wood products are included in Sectoral Report Table 5, as “G Other, Harvested Wood Products”.

- *Common Reporting Format under IPCC 1996 Guidelines (no longer used)*

Changes in stocks of harvested wood products were reported under Category 5A5.

2.2.8.1.(c) Planned Improvements

The emission factors and activity data for harvested wood products will be kept under review. It is likely that the current calculation method for HWP in the UK will be replaced in the next few years by one which uses information on the volume and decay characteristics of different products.

2.3. Results

Data for the 1990 to 2004 GHG Inventory are presented in Appendices 1 to 4 of this volume. The data for this period (2006 Inventory submission date) are summarised in Table 2-28

The Appendices contain data in the following formats:

A.1. Summary Tables for 1990 to 2020 in LULUCF GPG Format and 1996 Guidelines Format (with High and Low future scenarios)

A.2. Sectoral Tables for Land Use Change and Forestry Sector submitted as UK 2004 Greenhouse Gas Inventory in format defined by IPCC LULUCF Good Practice Guidance

A.3. Sectoral Tables for Land Use Change and Forestry Sector for the Devolved Administration Regions

A.4. Removals and Emissions by post-1990 afforestation and deforestation in the UK

In addition the Sectoral and Background Tables (5, 5A, 5B, 5C, 5D, 5E, 5F, 5(I), 5(II), 5(III), 5(IV) and 5(V)) in the Common Reporting Format of the LULUCF GPG are presented in a companion Data Table volume for each year 1990 to 2004. Summary data is also provided in the Data Table volume for the Devolved Administration areas of England, Scotland, Wales and Northern Ireland.

2.3.1. Forest Land

2.3.1.1 Forest Land Remaining Forest Land

Changes in stocks of carbon in Forest Land in the UK that remains Forest Land are assumed to be zero. This category is identified with 820,000 ha of forest that has existed since before

1920 and is also assumed to be in carbon balance because of its age and therefore has zero stock change.

2.3.1.2 Land converted to Forest Land

All afforestation occurring since 1920 is reported in this category. Stock changes in above and below ground biomass, dead material and soil carbon are estimated by the C-Flow model as described in Section 2.2.2.2.(a). Carbon stock changes resulting in atmospheric removals increased from 12,203 Gg in 1990 to 14,193 Gg in 1994, then fell to 13,406 in 1998 but now appear to be on an upward trend, reaching 16,302 Gg in 2004. These changes reflect variation in planting rates in past decades which feed through growth and harvesting to the carbon uptake trends reported here.

2.3.2. Cropland

2.3.2.1 Cropland Remaining Cropland

Changes in carbon stocks resulting from changes in non-forest biomass resulting from yield improvements, application of lime and lowland drainage are reported in this category. Overall, the carbon stock changes in this category result in net emissions, which appear to be on a downward trend, from a peak of 1951 Gg in 1991 to 1050 Gg in 2004. This trend is mainly driven by the declining emissions from lowland drainage which have fallen steadily from 1650 Gg in 1990 to 1195 Gg in 2004. Removals from non-forest biomass yield improvements are constant, and emissions due to liming, although varying during the 1990s, appear to have stabilized around 480 Gg since 1998.

2.3.2.2 Land Converted to Cropland

Carbon stock changes resulting from changes in non-forest biomass and soil carbon stocks due to land use change to Cropland are reported in this category. Emissions from land converted to Cropland show a small but steady rate of increase, from 14,037 Gg in 1990 to 14,279 Gg in 2004. This trend is due to changes in soil carbon stocks as changes in non-forest biomass stocks occur at a fixed rate.

2.3.3. Grassland

2.3.3.1 Grassland Remaining Grassland

Changes in carbon stocks due to application of lime to Grassland and peat extraction are reported in this category. Emissions from this category are variable over the time period, starting at 1,025 Gg in 1990, with a peak of 1,255 Gg in 1995, and then falling away to 563 Gg in 2002, with an emission of 674 Gg in 2004. Both of the carbon stock changes which contribute to this category are variable over time, but the downward trend between 1995 and 2002 seems to be mainly due to a reduction in emissions from liming of Grassland.

2.3.3.2 Land Converted to Grassland

Changes in carbon stocks due to emissions from biomass burning after conversion of Forest Land to Grassland and changes in non-forest biomass and soil carbon stocks due to land use change to Grassland are reported in this category. Overall, this category results in a net removal from the atmosphere, which has increased over time, from 7,218 Gg in 1990 to 8,510 Gg in 2004. This trend is entirely due to changes in soil carbon stocks from land converted to Grassland, as changes in non-forest biomass stocks are a small and constant removal (198

Gg a^{-1}), and changes due to biomass burning after deforestation are an equally small although variable emission (30-178 Gg a^{-1}).

2.3.4. Settlements

2.3.4.1 Settlements Remaining Settlements

No changes in carbon stocks are reported in this category.

2.3.4.2 Land Converted to Settlements

Changes in carbon stocks due to emissions from biomass burning after conversion of Forest Land to Settlements and changes in non-forest biomass and soil carbon stocks due to land use change to Settlements are reported in this category. Overall, this category results in a net emission to the atmosphere, although this is slowly decreasing over time, from 6,858 Gg in 1990 to 6,245 Gg in 2004. This trend is due to changes in soil carbon stocks from land converted to Settlements, as removals due to biomass changes and emissions due to biomass burning after deforestation are both small (50 and 53-122 Gg a^{-1} respectively).

2.3.5. Other Activities

Changes in carbon stocks in this category result from changes in harvested wood products. This category results in a net removal from the atmosphere in 1990 of 1,456 Gg, decreasing to 633 Gg in 1994, then rising to 1,306 Gg in 1998, before rapidly decreasing (and becoming a net emission in 2002) to a net emission of 619 Gg in 2004. This variability is driven by forest planting and harvesting patterns in previous decades (see Section 2.2.8.1.(a)). The current net emission from HWP results from the reduced levels of new planting during the 1940s, and we would expect this trend to reverse from 2006 onwards.

2.3.6. Net UK Emissions/Removals

The picture of net emissions/removals from the Land Use Change and Forestry Sector in the UK has not changed significantly from the previous Inventory, as the data revisions that have been made are relatively minor. The net emission in 1990 is calculated to be slightly larger than that calculated in the 2003 inventory (2,915 Gg rather than 2,645 Gg). England is a net emitter between 1990 and 2004 (although on a downwards trend), while Scotland and Northern Ireland are net removers (with removals increasing over time). Wales has a small net removal but does not have the strong trend shown in the other countries. The net emissions for the UK follow a downward trend, reaching zero in 1998 and continuing to a net removal of 1,942 Gg in 2004.

2.3.7. LUCF GHG Data on basis of IPCC 1996 Guidelines

The structures of this report and the 2006 submissions of the National Inventory Report and the main submission of CRF Tables, are based on the Categories of the Common Reporting Format tables agreed at the 9th Conference of Parties to the UNFCCC and contained in FCCC/SBSTA/2004/8, also referred to as the IPCC 2003 Good Practice Guidelines CRF categories. Table 2-25 outlines the relationship between this current reporting format and the older IPCC 1996 Guidelines CRF categories used as the basis of reports prior to the 2003 Inventory. A summary of the emissions and removals according to the IPCC 1996 Guidelines categories is given in Table 2-29. The reported totals for emissions and removals for the LULUCF Sector are the same in either format.

Table 2-25 This table shows how the older IPCC 1996 Guidelines categories map onto the current IPCC 2003 Good Practice Guidance categories for reporting.

IPCC 1996 Guidelines CRF Categories	IPCC 2003 GPG CRF Categories
5A2 Temperate Forests	5A2 Land converted to Forest Land (Living biomass)
5A5 Other (Harvested Wood)	5G Harvested Wood Products
5B2 Temperate Forests	5C2 Land converted to Grassland (Deforestation)
5B2 Temperate Forests	5E2 Land converted to Settlements (Deforestation)
5D Cultivation of Mineral Soils (includes 5D organic soils)	5B2 Land converted to Cropland (Change in soils due to LUC)
5D Cultivation of Mineral Soils (includes 5D organic soils)	5C2 Land converted to Grassland (Change in soils due to LUC)
5D Cultivation of Mineral Soils (includes 5D organic soils)	5E2 Land converted to Settlements (Change in soils due to LUC)
5D Forest Soils	5A2 Land converted to Forest Land (Soils)
5D Liming of Agricultural Soils	5B1 Cropland remaining Cropland (Liming)
5D Liming of Agricultural Soils	5C1 Grassland remaining Grassland (Liming)
5D Lowland Drainage	5B1 Cropland remaining Cropland (Lowland drainage)
5E Other (Changes in Non-forest Biomass)	5B1 Cropland remaining Cropland (Yield improvements)
5E Other (Changes in Non-forest Biomass)	5B2 Land converted to Cropland
5E Other (Changes in Non-forest Biomass)	5C2 Land converted to Grassland
5E Other (Changes in Non-forest Biomass)	5E2 Land converted to Settlements
5E Other (Peat Extraction)	5C1 Grassland remaining Grassland (Peat extraction)

2.3.8. Uncertainties

Approximate uncertainties for different activities used in the IPCC 1996 Guidelines reporting structure are shown in Table 2-26. These were reassigned and rounded to the nearest 5% for the LULUCF GPG reporting structure (Table 2-27). An uncertainty of 20% was estimated for CH_4 and N_2O emissions from biomass burning after deforestation (categories 5C2 and 5E2). A full analysis of uncertainties is planned for future versions of the Inventory.

Table 2-26 Approximate uncertainty of estimates of emissions or removals in each of the Categories reported.

Category	5A Changes in Forest Biomass	5B Forest Conversion	5D Soils	5E Other
Uncertainty in Emission/Removal, %	30	20	60	50

Table 2-27: Approximate uncertainties of estimates of emissions/removals for categories in LULUCF GPG reporting structure

IPCC Source Category	Uncertainty in 1990 CO_2 emissions/removals, %	Uncertainty in 2004 CO_2 emissions/removals, %
5A Forest Land	25	25
5B Cropland	45	50
5C Grassland	70	55
5D Wetland	-	-
5E Settlements	35	50
5F Other Land	-	-
5G Other Activities	30	30

Table 2-28: Emissions and removals in categories within the Land Use Change and Forestry Sector as reported in the format used for the UNFCCC Common Reporting Format defined by the IPCC LULUCF Good Practice Guidance.

Gg CO_2/year		1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
5	**NET**	**2915**	**2782**	**2290**	**1082**	**889**	**1034**	**902**	**552**	**0**	**-234**	**-440**	**-596**	**-1120**	**-1180**	**-1942**
5A	**Forest-Land**	**-12203**	**-12715**	**-13340**	**-13714**	**-14193**	**-13948**	**-13720**	**-13512**	**-13406**	**-13504**	**-13805**	**-14348**	**-15045**	**-15646**	**-16302**
5A1	*Forest-Land remaining Forest-Land*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
5A2	*Land converted to Forest-Land*	*-12203*	*-12715*	*-13340*	*-13714*	*-14193*	*-13948*	*-13720*	*-13512*	*-13406*	*-13504*	*-13805*	*-14348*	*-15045*	*-15646*	*-16302*
5B	**Cropland**	**15842**	**16001**	**16004**	**15579**	**15632**	**15771**	**15802**	**15542**	**15427**	**15328**	**15339**	**15287**	**15314**	**15380**	**15329**
5B1	*Cropland remaining Cropland*	*1805*	*1951*	*1940*	*1499*	*1536*	*1659*	*1673*	*1395*	*1262*	*1145*	*1136*	*1065*	*1073*	*1120*	*1050*
5B2	*Land converted to Cropland*	*14037*	*14050*	*14064*	*14080*	*14096*	*14112*	*14130*	*14147*	*14165*	*14183*	*14202*	*14222*	*14241*	*14260*	*14279*
5B (liming)	*Liming of Cropland*	*795*	*978*	*1003*	*599*	*673*	*832*	*883*	*642*	*546*	*465*	*493*	*445*	*474*	*543*	*496*
5C	**Grassland**	**-6193**	**-6146**	**-6254**	**-6660**	**-6605**	**-6536**	**-6786**	**-6889**	**-7288**	**-7275**	**-7427**	**-7449**	**-7742**	**-7526**	**-7836**
5C1	*Grassland remaining Grassland*	*1025*	*1190*	*1196*	*914*	*1081*	*1255*	*1107*	*1124*	*827*	*853*	*728*	*746*	*563*	*878*	*674*
5C2	*Land converted to Grassland*	*-7218*	*-7336*	*-7450*	*-7573*	*-7686*	*-7791*	*-7894*	*-8013*	*-8115*	*-8128*	*-8154*	*-8195*	*-8305*	*-8403*	*-8510*
5C (liming)	*Liming of Grassland*	*635*	*794*	*806*	*531*	*597*	*697*	*632*	*704*	*512*	*421*	*301*	*280*	*265*	*374*	*319*
5D	**Wetland**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
5D1	*Wetland remaining Wetland*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*
5D2	*Land converted to Wetland*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*	*IE*
5E	**Settlements**	**6925**	**6851**	**6799**	**6719**	**6688**	**6647**	**6627**	**6607**	**6573**	**6485**	**6402**	**6358**	**6306**	**6274**	**6248**
5E1	*Settlements remaining Settlements*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
5E2	*Land converted to Settlements*	*6925*	*6851*	*6799*	*6719*	*6688*	*6647*	*6627*	*6607*	*6573*	*6485*	*6402*	*6358*	*6306*	*6274*	*6248*
5F	**Other-Land**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
5F1	*Other-Land remaining Other-land*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
5F2	*Land converted to Other-Land*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*	*0*
5G	**Other activities**	**-1456**	**-1210**	**-920**	**-842**	**-633**	**-900**	**-1021**	**-1197**	**-1306**	**-1268**	**-950**	**-445**	**47**	**337**	**619**
5G1	*Harvested Wood Products*	*-1456*	*-1210*	*-920*	*-842*	*-633*	*-900*	*-1021*	*-1197*	*-1306*	*-1268*	*-950*	*-445*	*47*	*337*	*619*
5B2, 5C2, 5E2	**Biomass burning Gg CH_4/year**	*0.659*	*0.598*	*0.619*	*0.453*	*0.519*	*0.549*	*0.664*	*0.681*	*0.691*	*0.834*	*0.925*	*1.106*	*0.928*	*0.876*	*0.798*
5B2, 5C2, 5E2	**Biomass burning Gg N_2O/year**	*0.0045*	*0.0041*	*0.0043*	*0.0031*	*0.0036*	*0.0038*	*0.0046*	*0.0047*	*0.0048*	*0.0057*	*0.0064*	*0.0076*	*0.0064*	*0.0060*	*0.0055*

Table 2-29 Emissions and removals in categories with the Land Use Change and Forestry Sector as reported in the format used for the UNFCCC Common Reporting Format based on the IPCC 1996 Guidelines.

CRF	**Gg CO_2**	**1990**	**1991**	**1992**	**1993**	**1994**	**1995**	**1996**	**1997**	**1998**	**1999**	**2000**	**2001**	**2002**	**2003**	**2004**	***Category***	
Temperate forest	Removal	-9112	-9597	-10212	-10487	-10972	-10470	-10038	-9612	-9397	-9500	-9934	-10693	-11599	-12297	-13073	*5A2*	Removals due to Changes in forest biomass.
Harvested wood	Removal	-1456	-1210	-920	-842	-633	-900	-1021	-1197	-1306	-1268	-950	-445	47	337	619	*5A5*	Removals to Harvested wood
Deforestation	Emission	151	137	142	104	119	126	152	156	158	191	212	253	213	201	183	*5B*	Emissions (CO_2) due to Deforestation
Soils	Emission	16679	16819	16663	15798	15757	15843	15661	15330	14885	14561	14321	14123	14013	14070	13850	*5D*	Sum of Emissions from soils due to Land use change on agricultural soils (net emissions), Lowland drainage and liming of agricultural land
Soils	Removal	-3091	-3118	-3128	-3227	-3220	-3479	-3682	-3900	-4010	-4005	-3871	-3655	-3446	-3349	-3229	*5D*	Removals to Forest litter & soils.
Other	Emission	390	396	390	383	484	558	475	420	315	432	427	466	298	503	355	*5E*	Emissions from soils due to Peat extraction
Other	Removal	-646	-646	-646	-646	-646	-646	-646	-646	-646	-646	-646	-646	-646	-646	-646	*5E*	Removals due to changes in non-forest biomass
Total	Emission	17220	17353	17195	16284	16360	16527	16289	15906	15358	15184	14960	14842	14524	14775	14387	*5*	Gross LUCF Emissions
Total	Removal	-14304	-14571	-14905	-15202	-15471	-15494	-15387	-15354	-15358	-15418	-15401	-15439	-15643	-15954	-16329	*5*	Gross LUCF Removals
Total	Net	2915	2782	2290	1082	889	1034	902	552	0	-234	-440	-596	-1120	-1180	-1942	*5*	Net LUCF Emissions

2.4. Projections of Emissions and Removals to 2020

2.4.1. Introduction

Projections of emissions for years from 2005 to 2020 have been made for each activity for each of the Devolved Administration areas of England, Scotland, Wales and Northern Ireland. A “central” (Mid), high emission (High) and low emission scenario (Low) was developed for each activity and the basis of these is described in Section 2.4.2. The UK emissions, removals and net flux for each scenario are presented in Tables of Appendix A.1 Summary Tables. For simplicity detailed information on the emissions and removals is only supplied on the basis of the reporting format defined by the IPCC LULUCF Good Practice Guidance.

Table 2-30 Inventory (1990 to 2000) and projected (2005 to 2020) Emissions and Removals data ($GgCO_2$/year). (-ve sign indicates Removal)

Year	Net (LOW)	Net (MID)	Net (HIGH)
1990	2915	**2915**	2915
1995	1034	**1034**	1034
2000	-440	**-440**	-440
2005	-9411	**-2067**	6161
2010	-9564	**-1797**	6923
2015	-8788	**243**	9831
2020	-8417	**2115**	12654

2.4.2. Basis for projections

The basis for projection of each activity varied between Scotland, England, Wales and N. Ireland as appropriate. These assumptions are described in Table 2-31, Table 2-32, Table 2-33 and

Table 2-34 respectively.

2.4.3. Results for projections of LUCF Categories

The projections for Mid, Low and High emissions scenarios for the UK, England, Scotland, Wales and N. Ireland are presented in the Tables of Appendix A.1 Summary Tables. The UK emissions, removals and net flux for each scenario are presented in Table A1.1 and plotted in

Figure 2-1. The reporting format of the GPG on LULUCF is used for these data. Projections to 2020 of Forest Land, Cropland, Grassland and Settlements (Urban) Emissions and Removals of carbon from atmosphere in United Kingdom are plotted in Figure 2-2. Projections to 2020 of Net Emissions and Removals of carbon from atmosphere in England, Scotland, Wales and N. Ireland are plotted in Figure 2-3. Projections of net fluxes for Forest Land, Cropland, Grassland and Settlements for each scenario for England, Scotland, Wales and N. Ireland are plotted in Figure 2-4, Figure 2-5, Figure 2-6 and Figure 2-7.

Table 2-31 Scenario assumptions for projection of LUCF net Emissions (Scotland)

Scenario assumption: Scotland			
Category	**LOW Emission**	**MID Emission**	**HIGH Emission**
Afforestation	UK Total of 30 kha/yr from 2005 in proportion to 2004 planting	Conifer planting from 2005 assumed to be as in 2004. Broadleaf planting from 2005 assumed to be as in 2004.	Conifer planting from 2005 assumed to be 0 ha/yr. Broadleaf planting from 2005 assumed to be 0 ha/yr.
Deforestation	As MID but trend adjusted to lower value (95% C.L) of 1990 to 2004 trend	Autoregressive model (10 terms) fitted to 1990 to 2004 UK data	As MID but trend adjusted to upper value (95% C.L) of 1990 to 2004 trend
Land Use Change (Soils)	Annual area land use change for 2005 to 2020 based on annual rate of change for 1990 to 2004. but minimum values from Monte Carlo simulation with range of areas	Annual area land use change for 2005 to 2020 assumed to be same as annual rate of change for 1990 to 2004. – mean values from Monte Carlo simulation starting from 2004	Annual area land use change for 2005 to 2020 based on annual rate of change for 1990 to 2004. but maximum values from Monte Carlo simulation with range of areas
Peat extraction	As MID but trend adjusted to lower value (95% C.L) of 1990 to 2004 trend	Autoregressive model (10 terms) fitted to 1990 to 2004 Scottish data	As MID but trend adjusted to upper value (95% C.L) of 1990 to 2004 trend
Liming	As MID but trend adjusted to lower value (95% C.L) of 1990 to 2004 trend	Autoregressive model (10 terms) fitted to 1990 to 2004 UK data	As MID but trend adjusted to upper value (95% C.L) of 1990 to 2004 trend
Lowland drainage	NA	NA	NA
Non-forest biomass	Flux remains at 2004 value	Flux remains at 2004 value	Flux remains at 2004 value

Table 2-32 Scenario assumptions for projection of LUCF net Emissions (England)

Scenario assumption: England			
Category	**LOW Emission**	**MID Emission**	**HIGH Emission**
Forestry	UK Total of 30 kha/yr from 2005 in proportion to 2004 planting	Conifer planting from 2005 assumed to be as in 2004. Broadleaf planting from 2005 assumed to be as in 2004.	Conifer planting from 2005 assumed to be 0 ha/yr. Broadleaf planting from 2005 assumed to be 0 ha/yr.
Deforestation	As MID but trend adjusted to lower value (95% C.L) of 1990 to 2004 trend	Autoregressive model (10 terms) fitted to 1990 to 2004 UK data	As MID but trend adjusted to upper value (95% C.L) of 1990 to 2004 trend
Land Use Change (Soils)	Annual area land use change for 2005 to 2020 based on annual rate of change for 1990 to 2004. but minimum values from Monte Carlo simulation with range of areas	Annual area land use change for 2005 to 2020 assumed to be same as annual rate of change for 1990 to 2004. – mean values from Monte Carlo simulation starting from 2004	Annual area land use change for 2005 to 2020 based on annual rate of change for 1990 to 2004. but maximum values from Monte Carlo simulation with range of areas
Peat extraction	As MID but trend adjusted to lower value (95% C.L) of 1990 to 2004 trend	Autoregressive model (10 terms) fitted to 1990 to 2004 UK data	As MID but trend adjusted to upper value (95% C.L) of 1990 to 2004 trend
Liming	As MID but trend adjusted to lower value (95% C.L) of 1990 to 2004 trend	Autoregressive model (10 terms) fitted to 1990 to 2004 UK data	As MID but trend adjusted to upper value (95% C.L) of 1990 to 2004 trend
Lowland drainage	Flux changes from 2004 at modelled rate of change for 1990 to 2000	Flux changes from 2004 at modelled rate of change	Flux changes from 2004 value at modelled rate of change for 2010 to 2020
Non-forest biomass	Flux remains at 2004 value	Flux remains at 2004 value	Flux remains at 2004 value

Table 2-33 Scenario assumptions for projection of LUCF net Emissions (Wales)

Scenario assumption: Wales			
Category	**LOW Emission**	**MID Emission**	**HIGH Emission**
Forestry	UK Total of 30 kha/yr from 2005 in proportion to 2004 planting	Conifer planting from 2005 assumed to be as in 2004. Broadleaf planting from 2005 assumed to be as in 2004.	Conifer planting from 2005 assumed to be 0 ha/yr. Broadleaf planting from 2005 assumed to be 0 ha/yr.
Deforestation	As MID but trend adjusted to lower value (95% C.L) of 1990 to 2004 trend	Autoregressive model (10 terms) fitted to 1990 to 2004 UK data	As MID but trend adjusted to upper value (95% C.L) of 1990 to 2004 trend
Land Use Change (Soils)	Annual area land use change for 2005 to 2020 based on annual rate of change for 1990 to 2004. but minimum values from Monte Carlo simulation with range of areas	Annual area land use change for 2005 to 2020 assumed to be same as annual rate of change for 1990 to 2004. – mean values from Monte Carlo simulation starting from 2004	Annual area land use change for 2005 to 2020 based on annual rate of change for 1990 to 2004. but maximum values from Monte Carlo simulation with range of areas
Peat extraction	Flux zero	Flux zero	Flux zero
Liming	As MID but trend adjusted to lower value (95% C.L) of 1990 to 2004 trend	Autoregressive model (10 terms) fitted to 1990 to 2004 UK data	As MID but trend adjusted to upper value (95% C.L) of 1990 to 2004 trend
Lowland drainage	NA	NA	NA
Non-forest biomass	Flux remains at 2004 value	Flux remains at 2004 value	Flux remains at 2004 value

Table 2-34 Scenario assumptions for projection of LUCF net Emissions (Northern Ireland)

Scenario assumption: Northern Ireland			
Category	**LOW Emission**	**MID Emission**	**HIGH Emission**
Forestry	UK Total of 30 kha/yr from 2005 in proportion to 2004 planting	Conifer planting from 2005 assumed to be as in 2004. Broadleaf planting from 2005 assumed to be as in 2004.	Conifer planting from 2005 assumed to be 0 ha/yr. Broadleaf planting from 2005 assumed to be 0 ha/yr.
Deforestation	NA	NA	NA
Land Use Change (Soils)	Annual area land use change for 2005 to 2020 based on annual rate of change for 1990 to 2004. but minimum values from Monte Carlo simulation with range of areas	Annual area land use change for 2005 to 2020 assumed to be same as annual rate of change for 1990 to 2004. – mean values from Monte Carlo simulation starting from 2004	Annual area land use change for 2005 to 2020 based on annual rate of change for 1990 to 2004. but maximum values from Monte Carlo simulation with range of areas
Peat extraction	Flux remains at 2004 value	Flux remains at 2004 value	Flux remains at 2004 value
Liming	As MID but trend adjusted to lower value (95% C.L) of 1990 to 2004 trend	Autoregressive model (10 terms) fitted to 1990 to 2004 UK data	As MID but trend adjusted to upper value (95% C.L) of 1990 to 2004 trend
Lowland drainage	NA	NA	NA
Non-forest biomass	Flux remains at 2004 value	Flux remains at 2004 value	Flux remains at 2004 value

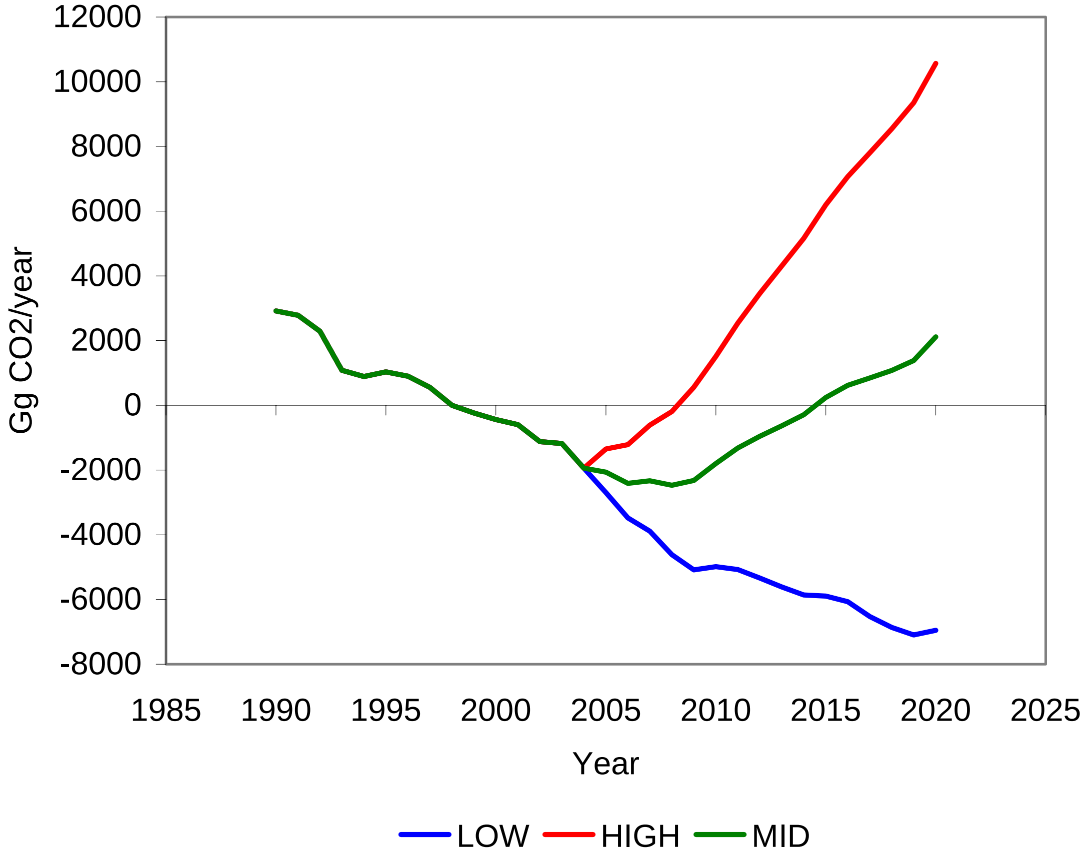


Figure 2-1 Projections to 2020 of Net Emissions and Removals of carbon from atmosphere in United Kingdom by land use, land use change and forestry for 3 future emissions scenarios

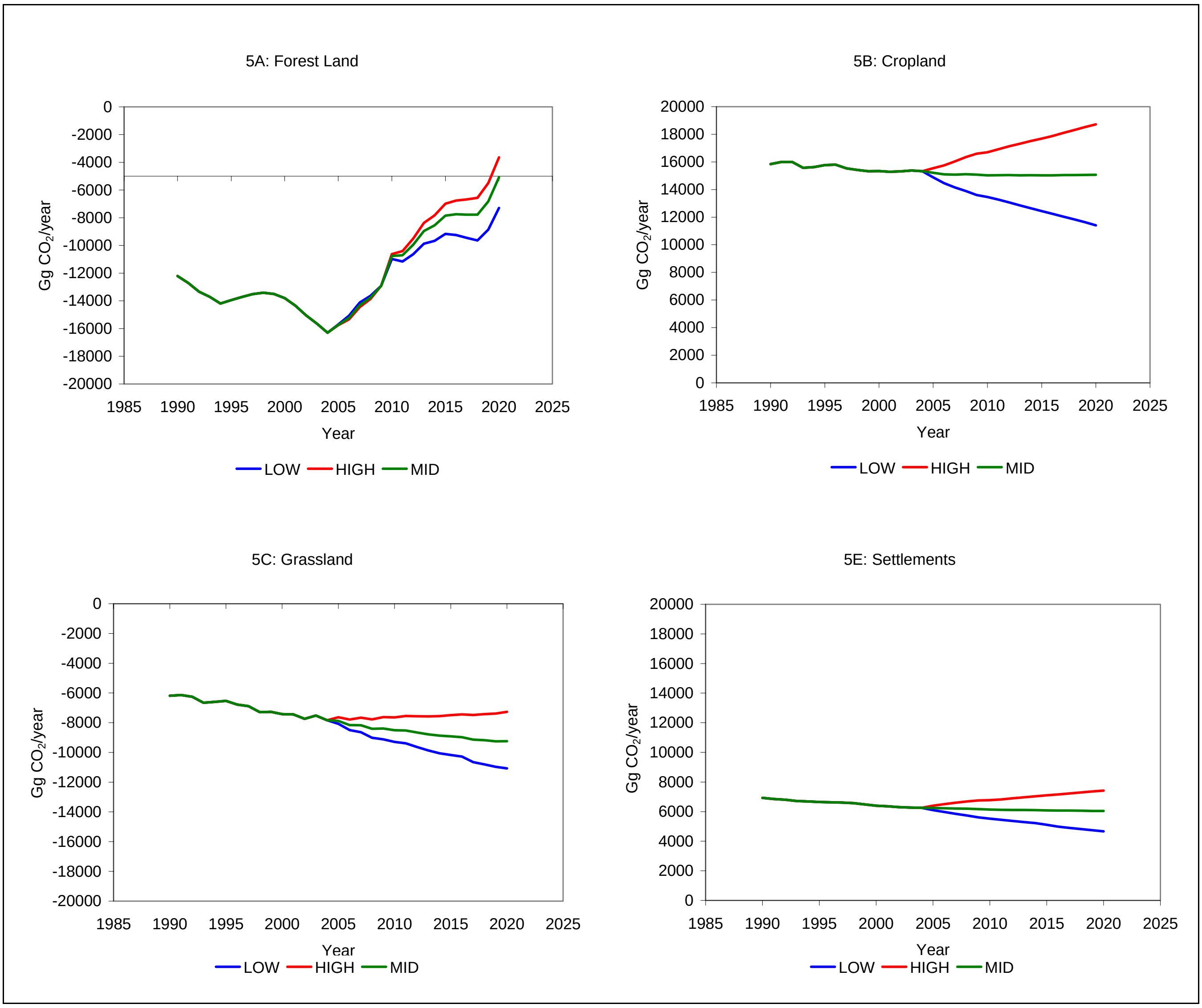


Figure 2-2 Projections to 2020 of Forest Land, Cropland, Grassland and Settlements (Urban) Net Emissions of carbon from atmosphere in United Kingdom by land use, land use change and forestry for 3 future emissions scenarios.

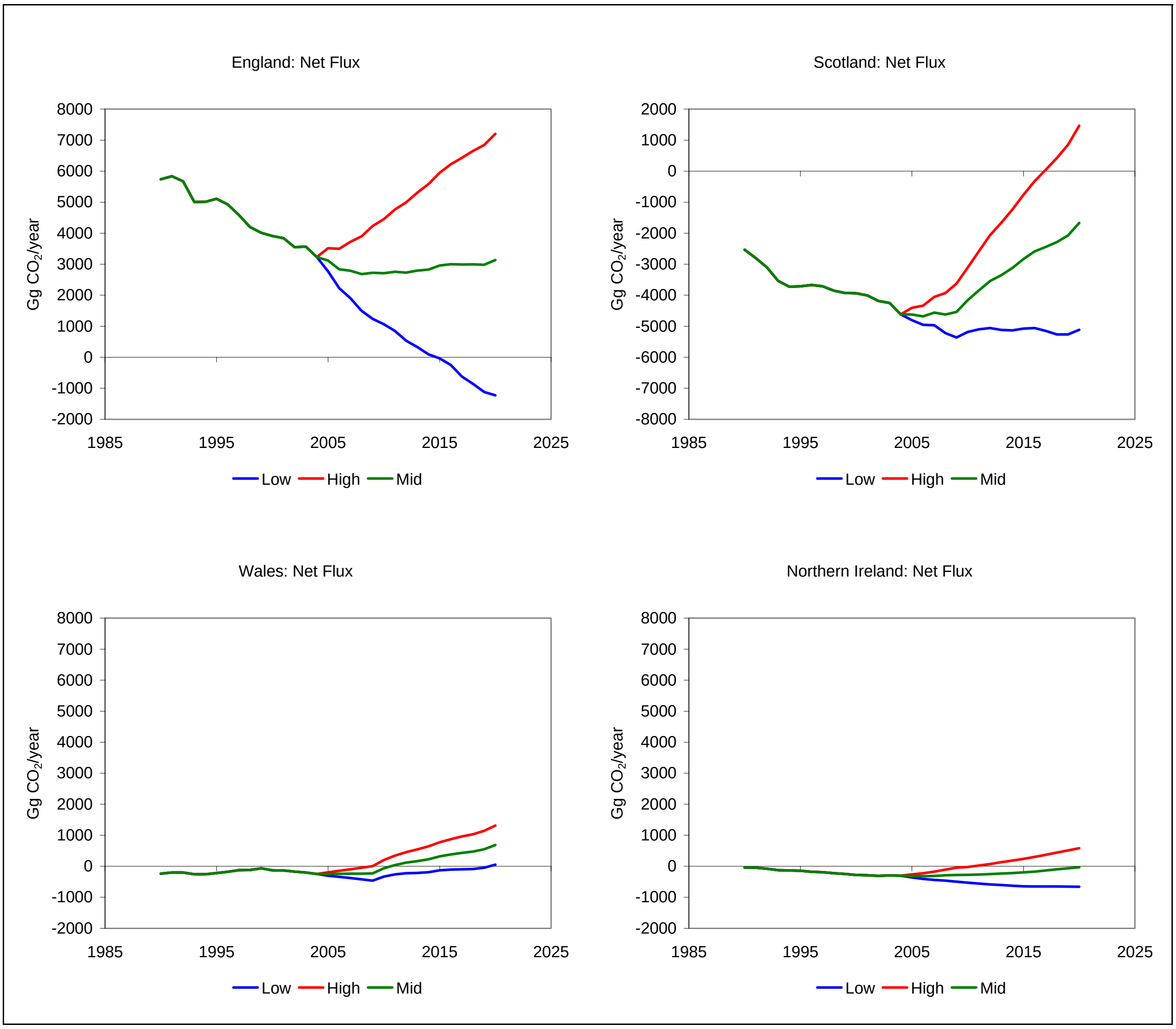


Figure 2-3 Projections to 2020 of Net Emissions of carbon from atmosphere in England, Scotland, Wales and N. Ireland by land use, land use change and forestry for 3 future emissions scenarios.

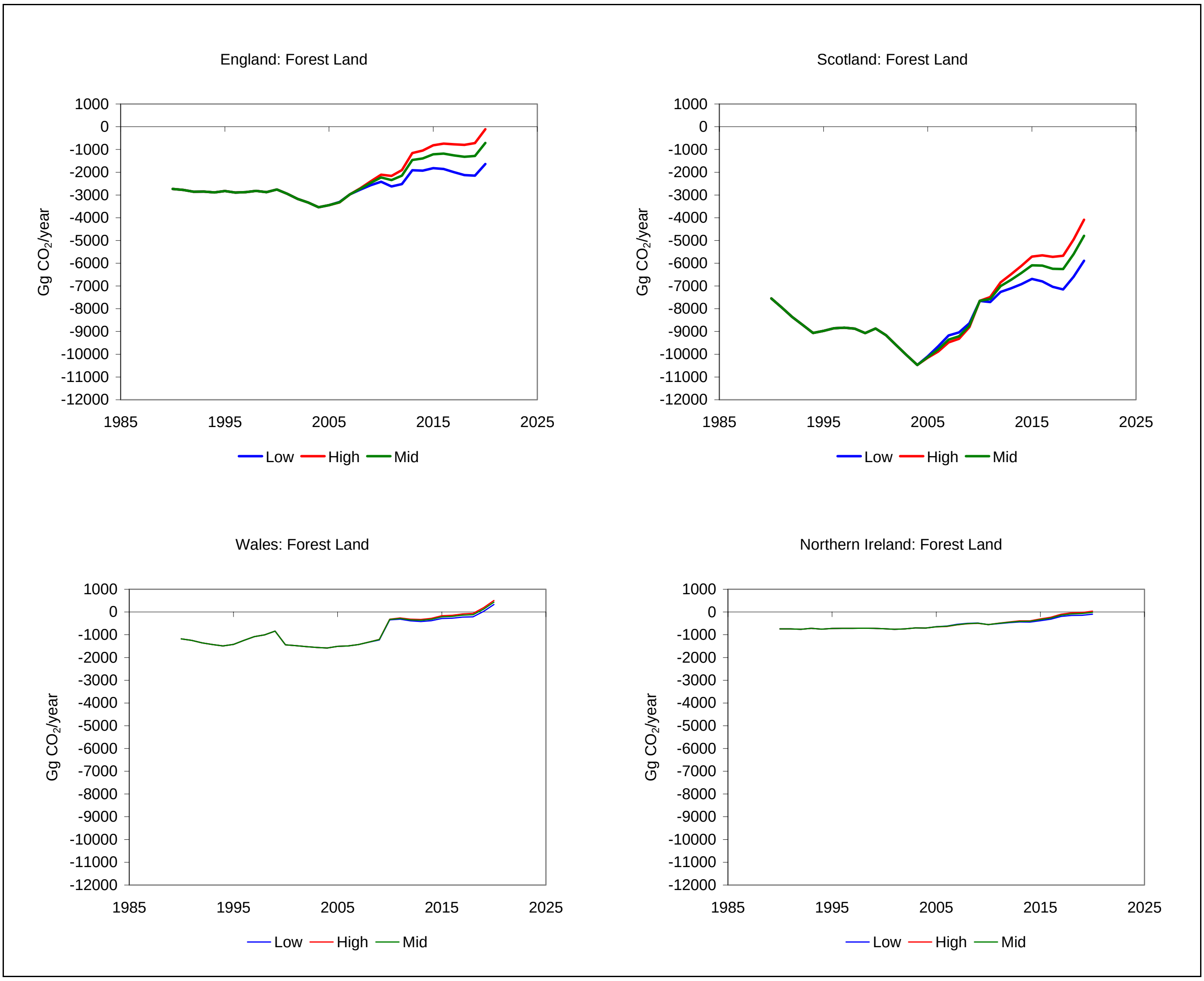


Figure 2-4 Projections to 2020 of Net Emissions of carbon from atmosphere in England, Scotland, Wales and N. Ireland by Forest Land Category of land use, land use change and forestry sector for 3 future emissions scenarios.

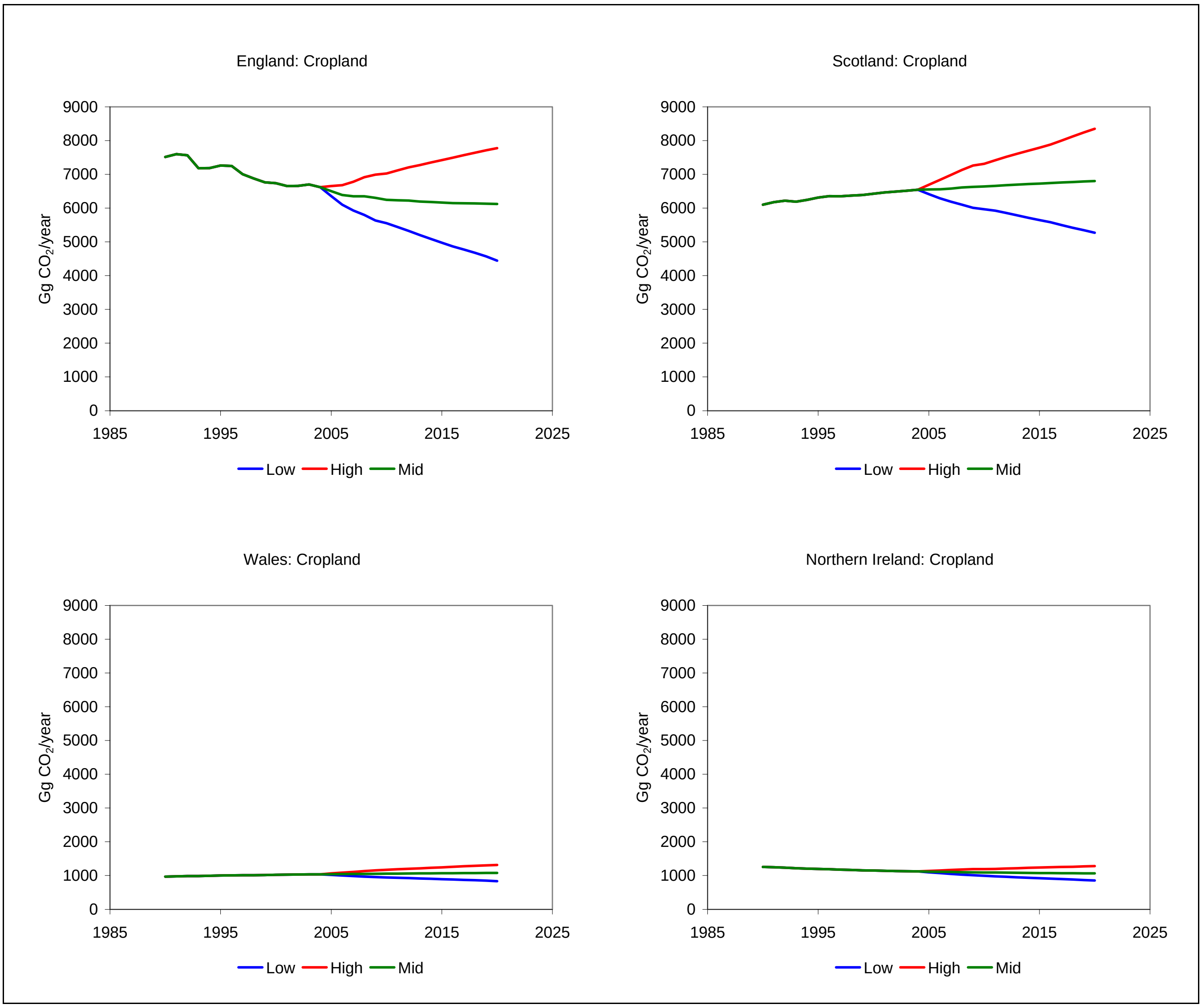


Figure 2-5 Projections to 2020 of Net Emissions of carbon from atmosphere in England, Scotland, Wales and N. Ireland by Cropland Category of land use, land use change and forestry sector for 3 future emissions scenarios

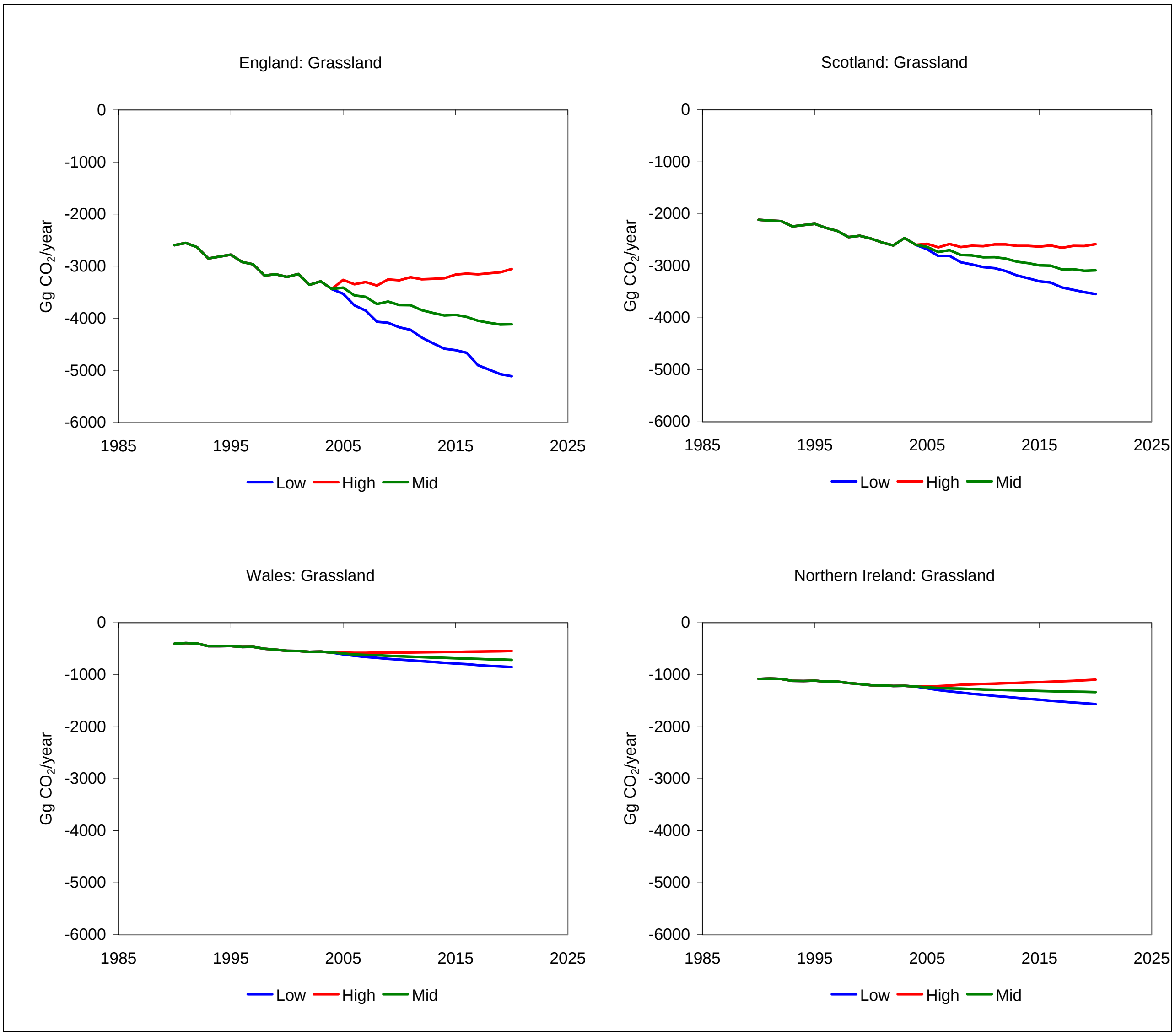


Figure 2-6 Projections to 2020 of Net Emissions of carbon from atmosphere in England, Scotland, Wales and N. Ireland by Grassland Category of land use, land use change and forestry sector for 3 future emissions scenarios

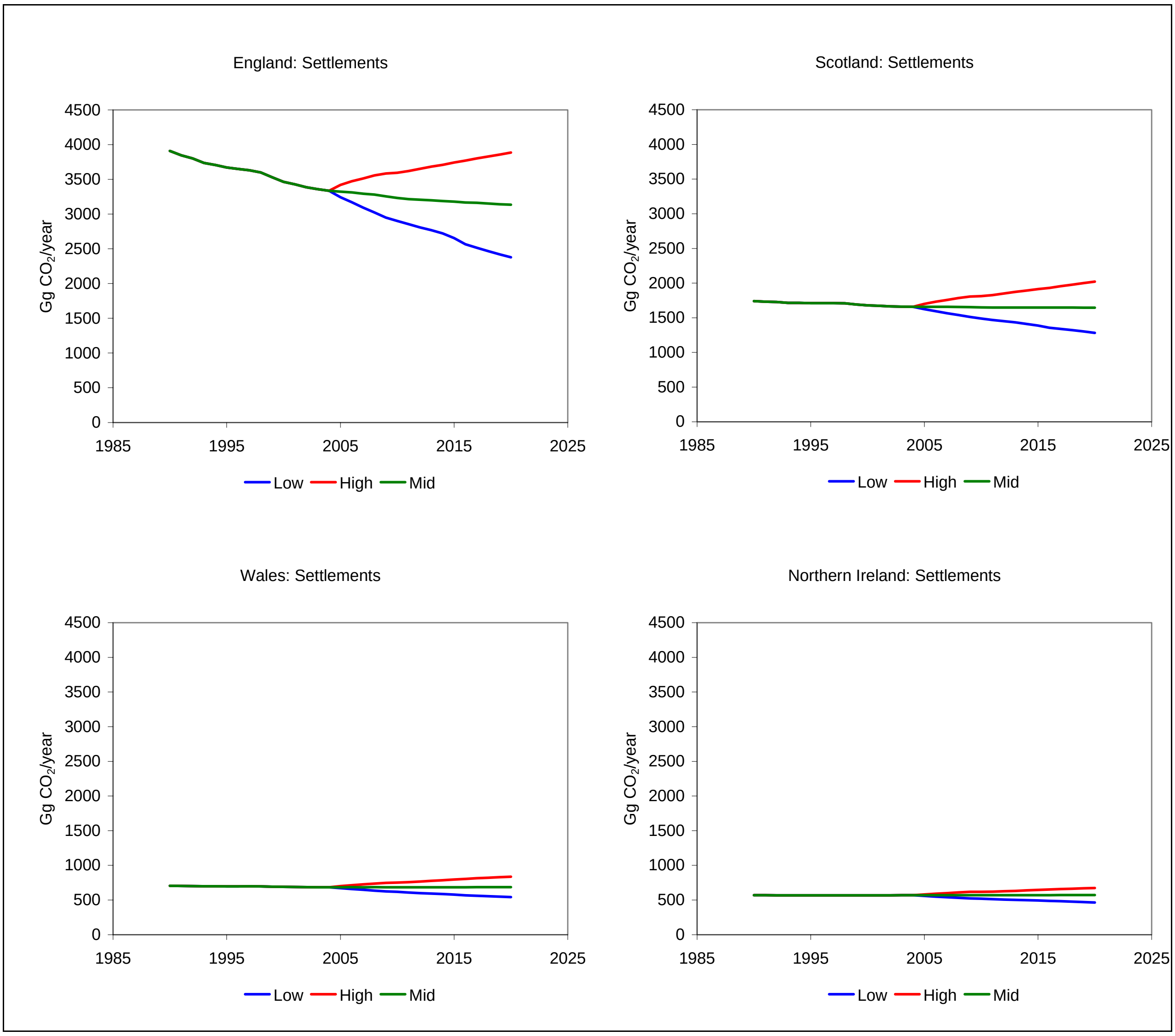


Figure 2-7 Projections to 2020 of Net Emissions of carbon from atmosphere in England, Scotland, Wales and N. Ireland by Settlements (Urban) Category of land use, land use change and forestry sector for 3 future emissions scenarios

2.4.4. Kyoto Protocol Article 3.3: Removals and emissions associated with post-1990 afforestation and deforestation

Projections of emissions associated with afforestation and deforestation since 1990 as required by the Kyoto Protocol Article 3.3 have been made. The scenarios used for the projections described above formed the basis for these post 1990 calculations. For changes in biomass and soil carbon stocks due to afforestation the C-Flow model was used but with planting data restricted to the post-1990 period. Biomass carbon stock changes and non-CO_2 emissions from burning occur immediately in the year of forest clearance therefore this contribution is equal to that reported for the annual UNFCCC Inventory. However a separate calculation of the changes in soil carbon stock due to post-1990 deforestation specifically was made.

These projections are presented for Mid, Low and High emissions scenarios for the UK, England, Scotland, Wales and N. Ireland in Appendix A.4 Removals and Emissions by post-1990 afforestation and deforestation in the UK and in Figure 2-8.

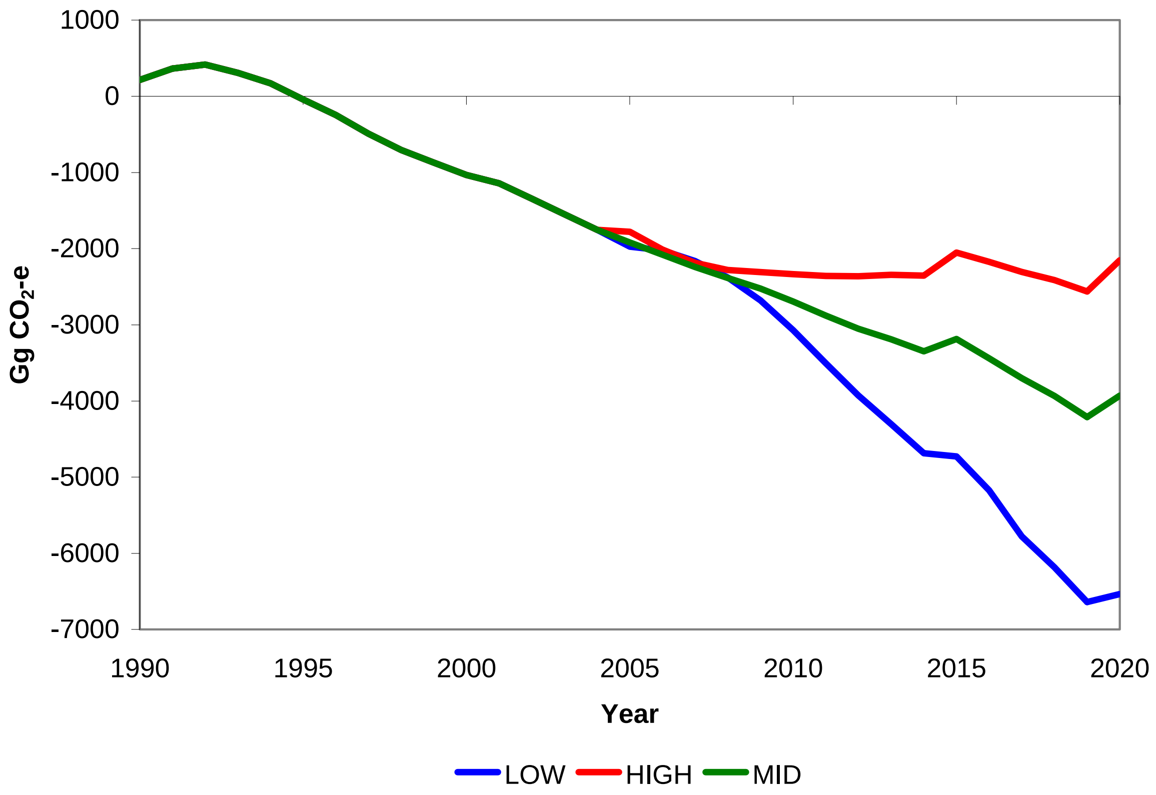


Figure 2-8 Kyoto Protocol Article 3.3: Net flux associated with post 1990 afforestation and deforestation for the Mid, High and Low emissions scenarios.

2.4.5. Kyoto Protocol Article 3.4: Removals and emissions associated with Forest Management, Cropland Management and Grassland Management

Under Article 3.4 of the Kyoto Protocol countries may elect to use net sinks within Forest Management, Cropland Management (CM) and Grassland Management (GM) to offset emissions in the commitment period. In January 2006 the UK elected to use only Forest Management. The uncertainties associated with estimating emissions and removals due to

Cropland and Grassland Management were considered to be too large for the purposes of achieving acceptable emission reductions under the Protocol.

Fluxes associated with Forest Management were estimated to be those due to changes in carbon stocks in forests planted prior to 1990. The primary driver for these fluxes, as estimated by the C-Flow model, is the pattern of afforestation in that period and hence the age structure of the forest. This established age structure and the resulting patterns of stock change through rotation cycles are considered to be the standard “Forest Management” in the UK. Under the Kyoto Protocol it is agreed that such effects and any changes in carbon stock due to climate or environmental change should not be included under Article 3.4 emission offsets. Detailed methods to identify the contribution of these drivers to overall changes in forest carbon stock have not been internationally agreed. In order to provide an ad-hoc method to remove these effects a cap was negotiated for each KP signatory for Forest Management sinks. For the UK this sink is capped at 0.37 MtC/year in the 1st Commitment period.

Removals of carbon to pre-1990 forests after 2004 for the Mid scenario (i.e. business as Usual) were found to be (Figure 2-9) greater than the cap for all years except 2020.

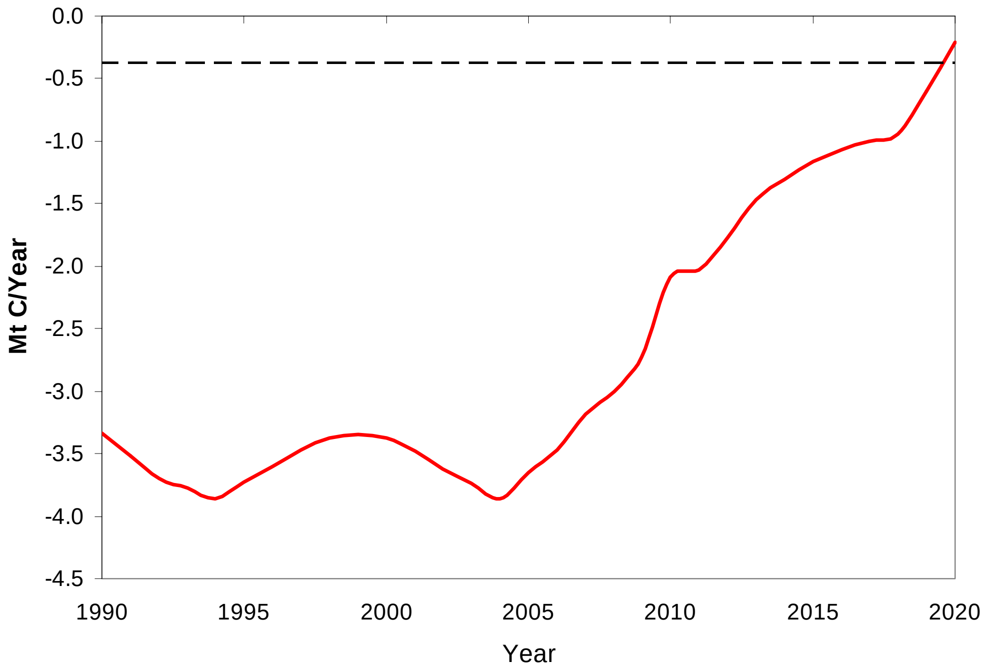


Figure 2-9 Kyoto Protocol Article 3.4: Removals and emissions associated with Forest Management for the MID scenario. The cap of -0.37 MtC/year is shown by the broken line.

2.4.6. Kyoto Protocol Article 3.7: Deforestation emissions in Base Year

Under Kyoto protocol Article 3.7 countries with a net emission in 1990 from the LULUCF Sector must count that part of the emission due to deforestation for estimating “Base Year Emission”. These “Base Year Emissions” then become the basis for the emissions allowance for that country during the First Commitment Period. In 1990 the UK LULUCF Sector is estimated to have been a net emitter of 2915 Gg CO_2, therefore Article 3.7 applies. The deforestation emission in 1990 for the purposes of this Article has been taken to be that associated with all deforestation prior to and including 1990. For 1990 the immediate emissions due to biomass removal and burning are relevant but there will also be delayed soil carbon stock change resulting from deforestation in earlier years. The emissions to be used for

Article 3.7 are therefore the full deforestation component for 1990 from the 2004 GHG Inventory, which equals 366 Gg CO_2 - equivalent (including CH_4 and N_2O emissions). This is smaller than the value estimated from the 2003 GHG Inventory due to a revised treatment of soil carbon stock changes

2.5. References

Agricultural Industries Confederation (2005). Fertiliser Statistics 2005 Report www.agindustries.org.uk

BGS (2005). United Kingdom Minerals Yearbook, (ed Survey, B.G.). Natural Environment Research Council.

Bradley, R. I. (1997). Carbon loss from drained lowland fens. In: *Carbon Sequestration in Vegetation and Soils* (ed Cannell, M.G.R.). Department of Environment, London.

Bradley, R. I., Milne, R., Bell, J., *et al.* (2005). A soil carbon and land use database for the United Kingdom. *Soil Use and Management,* **21,** 363-369.

Burton, R. (1995). Evaluating organic matter dynamics in cultivated organic topsoils – use of historical analytical data. MAFF Contract to SSLRC No. LE0203 –81/3830.

Cannell, M. G. R. and Dewar, R. C. (1995). The Carbon Sink Provided by Plantation Forests and Their Products in Britain. *Forestry,* **68,** 35-48.

Cannell, M. G. R., Milne, R., Hargreaves, K. J., *et al.* (1999). National inventories of terrestrial carbon sources and sinks: The UK experience. *Climatic Change,* **42,** 505-530.

Cooper, A. and McCann, T. (2002). Technical Report of the Northern Ireland Countryside Survey. University of Ulster.

Cruickshank, M. and Tomlinson, R. (1997). Carbon loss from UK peatlands for fuel and horticulture. In: *Carbon Sequestration in Vegetation and Soils* (ed Cannell, M.G.R.). Department of Environment, London.

Cruickshank, M. and Tomlinson, R. (2000). Changes in soil carbon storage in Northern Ireland: estimated by the IPCC default and matrix methods. *Carbon Sequestration in Vegetation and Soils*. DETR Contract EPG 1/1/39, (ed Milne, R.). Department of Environment, London.

Cruickshank, M. M., Tomlinson, R. W., Devine, P. M. and Milne, R. (1998). Carbon in the vegetation and soils of Northern Ireland. *Biology and Environment-Proceedings of the Royal Irish Academy*, **98B,** 9-21.

Dewar, R. C. and Cannell, M. G. R. (1992). Carbon Sequestration in the Trees, Products and Soils of Forest Plantations - an Analysis Using UK Examples. *Tree Physiology,* **11,** 49-71.

Edwards, P. N. and Christie, J. M. (1981). Yield models for forest management. *Forestry Commission Booklet*. 48. Forestry Commission, Edinburgh.

Forestry Commission (2002). National Inventory of Woodland and Trees Forestry Commission http://www.forestry.gov.uk/forestry/hcou-54pg4d

Haines-Young, R. H., Barr, C. J., Black, H. I. J., *et al.* (2000). *Accounting for nature: assessing habitats in the UK countryside.* DETR Countryside Survey 2000, London.

Hargreaves, K. J., Milne, R. and Cannell, M. G. R. (2003). Carbon balance of afforested peatland in Scotland. *Forestry*, **76,** 299-317.

IPCC (1997a). *Greenhouse Gas Inventory Reference Manual.* IPCC WGI Technical Support Unit, Hadley Centre, Meteorological Office, Bracknell, UK.

IPCC (1997b). *Greenhouse Gas Inventory Reporting Instructions.* IPCC WGI Technical Support Unit, Hadley Centre, Meteorological Office, Bracknell, UK.

IPCC (1997c). *Greenhouse Gas Inventory Workbook.* IPCC WGI Technical Support Unit, Hadley Centre, Meteorological Office, Bracknell, UK.

IPCC (2003). *Good Practice Guidance for Land Use, Land-Use Change and Forestry.* Institute for Global Environmental strategies (IGES) for the Intergovernmental Panel on Climate Change, Kanagawa, Japan.

Levy, P. E. and Milne, R. (2004). Estimation of deforestation rates in Great Britain. *Forestry*, **77,** 9-16.

Milne, R. and Brown, T. A. (1997). Carbon in the vegetation and soils of Great Britain. *Journal of Environmental Management*, **49,** 413-433.

Milne, R. and Brown, T. A. W. (1999). Methods and data for Land Use Change and Forestry Sector in the 1997 IPCC Greenhouse Gas Inventory. In: *Carbon Sequestration in Vegetation and Soils* (ed Milne, R.).

Milne, R., Brown, T. A. W. and Murray, T. D. (1998). The effect of geographical variation in planting rate on the uptake of carbon by new forests of Great Britain. *Forestry*, **71,** 298-309.

MLC (1986). *Monitoring Landscape Change.* Report prepared by Hunting Surveys & Consultants Ltd for Department of the Environment and the Countryside Commission.

Office of The Deputy Prime Minister (2004). Land Use Change Statistics Index http://www.planning.odpm.gov.uk/luc/lucindex.htm

Skiba, U., Di Marco, C., Dragositz, U., *et al.* (2005). Quantification and validation of the total annual UK nitrous oxide budget. *Final report to NERC - GANE*. Centre for Ecology and Hydrology.

Sylvester-Bradley, R., Lunn, G., Foulkes, J., *et al.* (2002). Management strategies for high yields of cereals and oilseed rape. In *HGCA R&D Conference - Agronomic Intelligence: The basis for profitable production*, pp. 8.1-8.17. Home-Grown Cereals Authority.

APPENDIX 1

A.1. Summary Tables for 1990 to 2020
in
LULUCF GPG Format
and
1996 Guidelines Format
(with High and Low future scenarios)

Table A1. 1: United Kingdom data for 2004 UK GHG Inventory: A: LULUCF GPG Format – with MID projection, B: LULUCF GPG Format – with LO projection, C: LULUCF GPG Format – with HI projection, D: "1996 GUIDELINES" summary of Inventory period (Italics are projections) (HWP = Harvested Wood Products)

A (Mid) UK Gg CO2/year	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	**2915**	**-12203**	**15842**	**-6193**	**6925**	**-1456**
1991	2782	-12715	16001	-6146	6851	-1210
1992	2290	-13340	16004	-6254	6799	-920
1993	1082	-13714	15579	-6660	6719	-842
1994	889	-14193	15632	-6605	6688	-633
1995	**1034**	**-13948**	**15771**	**-6536**	**6647**	**-900**
1996	902	-13720	15802	-6786	6627	-1021
1997	552	-13512	15542	-6889	6607	-1197
1998	0	-13406	15427	-7288	6573	-1306
1999	-234	-13504	15328	-7275	6485	-1268
2000	**-440**	**-13805**	**15339**	**-7427**	**6402**	**-950**
2001	-596	-14348	15287	-7449	6358	-445
2002	-1120	-15045	15314	-7742	6306	47
2003	-1180	-15646	15380	-7526	6274	337
2004	-1942	-16302	15329	-7836	6248	619
2005	***-2067***	***-15735***	***15215***	***-7880***	***6237***	***96***
2006	*-2412*	*-15227*	*15103*	*-8162*	*6227*	*-354*
2007	*-2329*	*-14315*	*15086*	*-8173*	*6205*	*-1133*
2008	*-2469*	*-13770*	*15114*	*-8411*	*6193*	*-1595*
2009	*-2321*	*-12917*	*15080*	*-8389*	*6165*	*-2259*
2010	***-1797***	***-10760***	***15037***	***-8513***	***6137***	***-3698***
2011	*-1320*	*-10701*	*15042*	*-8522*	*6117*	*-3256*
2012	*-956*	*-9952*	*15052*	*-8662*	*6110*	*-3503*
2013	*-631*	*-8962*	*15038*	*-8787*	*6104*	*-4025*
2014	*-293*	*-8553*	*15040*	*-8877*	*6093*	*-3995*
2015	***243***	***-7847***	***15035***	***-8921***	***6084***	***-4108***
2016	*621*	*-7742*	*15037*	*-8979*	*6072*	*-3766*
2017	*847*	*-7771*	*15048*	*-9137*	*6068*	*-3362*
2018	*1078*	*-7778*	*15055*	*-9178*	*6056*	*-3076*
2019	*1386*	*-6822*	*15065*	*-9254*	*6045*	*-3647*
2020	***2115***	***-5084***	***15070***	***-9251***	***6038***	***-4658***

B (Low) UK Gg CO2/year	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	**2915**	**-12203**	**15842**	**-6193**	**6925**	**-1456**
1991	2782	-12715	16001	-6146	6851	-1210
1992	2290	-13340	16004	-6254	6799	-920
1993	1082	-13714	15579	-6660	6719	-842
1994	889	-14193	15632	-6605	6688	-633
1995	**1034**	**-13948**	**15771**	**-6536**	**6647**	**-900**
1996	902	-13720	15802	-6786	6627	-1021
1997	552	-13512	15542	-6889	6607	-1197
1998	0	-13406	15427	-7288	6573	-1306
1999	-234	-13504	15328	-7275	6485	-1268
2000	**-440**	**-13805**	**15339**	**-7427**	**6402**	**-950**
2001	-596	-14348	15287	-7449	6358	-445
2002	-1120	-15045	15314	-7742	6306	47
2003	-1180	-15646	15380	-7526	6274	337
2004	-1942	-16302	15329	-7836	6248	619
2005	***-9411***	***-15699***	***11333***	***-9875***	***4733***	***96***
2006	*-9741*	*-15065*	*11169*	*-10208*	*4718*	*-354*
2007	*-9732*	*-14117*	*11102*	*-10273*	*4689*	*-1133*
2008	*-10058*	*-13629*	*11073*	*-10575*	*4668*	*-1595*
2009	*-10162*	*-12923*	*10999*	*-10613*	*4634*	*-2259*
2010	***-9564***	***-10976***	***11136***	***-10712***	***4685***	***-3698***
2011	*-9272*	*-11152*	*11159*	*-10737*	*4714*	*-3256*
2012	*-9157*	*-10639*	*11155*	*-10904*	*4735*	*-3503*
2013	*-9101*	*-9872*	*11115*	*-11061*	*4741*	*-4025*
2014	*-9051*	*-9672*	*11082*	*-11188*	*4722*	*-3995*
2015	***-8788***	***-9163***	***11039***	***-11240***	***4684***	***-4108***
2016	*-8678*	*-9245*	*11001*	*-11282*	*4614*	*-3766*
2017	*-8842*	*-9454*	*10970*	*-11594*	*4598*	*-3362*
2018	*-8902*	*-9637*	*10933*	*-11700*	*4578*	*-3076*
2019	*-8854*	*-8856*	*10900*	*-11809*	*4557*	*-3647*
2020	***-8417***	***-7294***	***10862***	***-11863***	***4536***	***-4658***

C (High) UK Gg CO2/year	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	**2915**	**-12203**	**15842**	**-6193**	**6925**	**-1456**
1991	2782	-12715	16001	-6146	6851	-1210
1992	2290	-13340	16004	-6254	6799	-920
1993	1082	-13714	15579	-6660	6719	-842
1994	889	-14193	15632	-6605	6688	-633
1995	**1034**	**-13948**	**15771**	**-6536**	**6647**	**-900**
1996	902	-13720	15802	-6786	6627	-1021
1997	552	-13512	15542	-6889	6607	-1197
1998	0	-13406	15427	-7288	6573	-1306
1999	-234	-13504	15328	-7275	6485	-1268
2000	**-440**	**-13805**	**15339**	**-7427**	**6402**	**-950**
2001	-596	-14348	15287	-7449	6358	-445
2002	-1120	-15045	15314	-7742	6306	47
2003	-1180	-15646	15380	-7526	6274	337
2004	-1942	-16302	15329	-7836	6248	619
2005	***6161***	***-15758***	***19264***	***-5341***	***7900***	***96***
2006	*5850*	*-15332*	*19212*	*-5578*	*7902*	*-354*
2007	*6029*	*-14444*	*19252*	*-5537*	*7890*	*-1133*
2008	*6051*	*-13862*	*19338*	*-5718*	*7888*	*-1595*
2009	*6417*	*-12914*	*19360*	*-5634*	*7864*	*-2259*
2010	***6923***	***-10620***	***19258***	***-5758***	***7741***	***-3698***
2011	*7532*	*-10407*	*19268*	*-5738*	*7666*	*-3256*
2012	*8070*	*-9505*	*19293*	*-5843*	*7629*	*-3503*
2013	*8584*	*-8369*	*19295*	*-5925*	*7608*	*-4025*
2014	*9108*	*-7824*	*19313*	*-5972*	*7586*	*-3995*
2015	***9831***	***-6990***	***19332***	***-5972***	***7568***	***-4108***
2016	*10395*	*-6764*	*19360*	*-5984*	*7549*	*-3766*
2017	*10803*	*-6676*	*19396*	*-6094*	*7537*	*-3362*
2018	*11222*	*-6568*	*19429*	*-6089*	*7526*	*-3076*
2019	*11728*	*-5498*	*19464*	*-6120*	*7528*	*-3647*
2020	***12654***	***-3646***	***19495***	***-6070***	***7533***	***-4658***

D UK Gg CO2	**Changes in woody biomass**	**HWP**	**Forest Conversion**	**Soils**	**Other**	**Other**	**NET Emission (+) Removal (-)**
1990	**-12203**	**-1456**	**151**	**15029**	**2040**	**-646**	**2915**
1991	-12715	-1210	137	15206	2010	-646	2782
1992	-13340	-920	142	15087	1966	-646	2290
1993	-13714	-842	104	14258	1923	-646	1082
1994	-14193	-633	119	14254	1987	-646	889
1995	**-13948**	**-900**	**126**	**14377**	**2025**	**-646**	**1034**
1996	-13720	-1021	152	14231	1905	-646	902
1997	-13512	-1197	156	13937	1813	-646	552
1998	-13406	-1306	158	13528	1671	-646	0
1999	-13504	-1268	191	13241	1752	-646	-234
2000	**-13805**	**-950**	**212**	**13038**	**1710**	**-646**	**-440**
2001	-14348	-445	253	12862	1727	-646	-596
2002	-15045	47	213	12773	1538	-646	-1120
2003	-15646	337	201	12853	1721	-646	-1180
2004	-16302	619	183	12654	1550	-646	-1942
1996 GUIDELINES Format	5A (Removals)	5A (Removals)	5B (Emissions)	5D (Emissions)	5E (Emissions)	5E (Removals)	
	Forest biomass, soils, litter.	Forest products	Deforestation (Biomass burning)	Effect of LUC (Net), liming of soils	Drainage of lowland soils, peat extraction	Non-forest biomass	

Table A1. 2: England data for 2004 UK GHG Inventory: A: LULUCF GPG Format – with MID projection, B: LULUCF GPG Format – with LO projection, C: LULUCF GPG Format – with HI projection, D: "1996 GUIDELINES" summary (Italics are projections) (HWP = Harvested Wood Products)

A (Mid) England Gg CO2/year	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	**5736**	**-2733**	**7515**	**-2594**	**3909**	**-361**
1991	5835	-2775	7600	-2552	3848	-285
1992	5672	-2856	7565	-2633	3802	-206
1993	5007	-2851	7182	-2851	3738	-211
1994	5013	-2889	7187	-2816	3708	-177
1995	**5111**	**-2825**	**7261**	**-2778**	**3672**	**-219**
1996	4928	-2894	7250	-2918	3651	-162
1997	4587	-2872	7005	-2965	3630	-212
1998	4200	-2818	6879	-3177	3600	-284
1999	4013	-2874	6765	-3156	3531	-252
2000	**3911**	**-2760**	**6741**	**-3207**	**3466**	**-330**
2001	3842	-2946	6657	-3149	3429	-149
2002	3550	-3169	6661	-3357	3387	29
2003	3569	-3333	6701	-3291	3360	133
2004	3231	-3540	6622	-3439	3336	253
2005	***3119***	***-3448***	***6504***	***-3411***	***3324***	***150***
2006	*2838*	*-3317*	*6390*	*-3561*	*3313*	*13*
2007	*2786*	*-2969*	*6352*	*-3588*	*3293*	*-302*
2008	*2683*	*-2729*	*6353*	*-3727*	*3281*	*-495*
2009	*2723*	*-2466*	*6303*	*-3678*	*3257*	*-693*
2010	***2708***	***-2230***	***6247***	***-3745***	***3233***	***-796***
2011	*2754*	*-2346*	*6234*	*-3747*	*3216*	*-602*
2012	*2729*	*-2149*	*6224*	*-3844*	*3207*	*-709*
2013	*2793*	*-1457*	*6197*	*-3896*	*3200*	*-1252*
2014	*2827*	*-1394*	*6183*	*-3945*	*3189*	*-1206*
2015	***2960***	***-1209***	***6164***	***-3934***	***3180***	***-1241***
2016	*3000*	*-1182*	*6151*	*-3973*	*3168*	*-1165*
2017	*2992*	*-1257*	*6146*	*-4046*	*3163*	*-1013*
2018	*2996*	*-1320*	*6138*	*-4084*	*3152*	*-891*
2019	*2980*	*-1284*	*6133*	*-4120*	*3142*	*-890*
2020	***3135***	***-710***	***6125***	***-4115***	***3135***	***-1299***

B (Low) England Gg CO2/year	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	**5736**	**-2733**	**7515**	**-2594**	**3909**	**-361**
1991	5835	-2775	7600	-2552	3848	-285
1992	5672	-2856	7565	-2633	3802	-206
1993	5007	-2851	7182	-2851	3738	-211
1994	5013	-2889	7187	-2816	3708	-177
1995	**5111**	**-2825**	**7261**	**-2778**	**3672**	**-219**
1996	4928	-2894	7250	-2918	3651	-162
1997	4587	-2872	7005	-2965	3630	-212
1998	4200	-2818	6879	-3177	3600	-284
1999	4013	-2874	6765	-3156	3531	-252
2000	**3911**	**-2760**	**6741**	**-3207**	**3466**	**-330**
2001	3842	-2946	6657	-3149	3429	-149
2002	3550	-3169	6661	-3357	3387	29
2003	3569	-3333	6701	-3291	3360	133
2004	3231	-3540	6622	-3439	3336	253
2005	***-191***	***-3449***	***4943***	***-4335***	***2501***	***150***
2006	*-519*	*-3305*	*4794*	*-4510*	*2489*	*13*
2007	*-642*	*-2968*	*4725*	*-4564*	*2468*	*-302*
2008	*-860*	*-2767*	*4686*	*-4737*	*2453*	*-495*
2009	*-945*	*-2570*	*4612*	*-4722*	*2428*	*-693*
2010	***-926***	***-2420***	***4630***	***-4781***	***2441***	***-796***
2011	*-967*	*-2627*	*4602*	*-4789*	*2451*	*-602*
2012	*-1095*	*-2521*	*4567*	*-4899*	*2468*	*-709*
2013	*-1138*	*-1913*	*4521*	*-4964*	*2470*	*-1252*
2014	*-1229*	*-1929*	*4482*	*-5029*	*2454*	*-1206*
2015	***-1215***	***-1817***	***4435***	***-5018***	***2425***	***-1241***
2016	*-1287*	*-1858*	*4394*	*-5032*	*2373*	*-1165*
2017	*-1528*	*-1999*	*4360*	*-5235*	*2360*	*-1013*
2018	*-1642*	*-2124*	*4321*	*-5291*	*2343*	*-891*
2019	*-1779*	*-2150*	*4286*	*-5352*	*2327*	*-890*
2020	***-1743***	***-1638***	***4247***	***-5365***	***2312***	***-1299***

C (High) England **Gg CO2/year**	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	**5736**	**-2733**	**7515**	**-2594**	**3909**	**-361**
1991	5835	-2775	7600	-2552	3848	-285
1992	5672	-2856	7565	-2633	3802	-206
1993	5007	-2851	7182	-2851	3738	-211
1994	5013	-2889	7187	-2816	3708	-177
1995	**5111**	**-2825**	**7261**	**-2778**	**3672**	**-219**
1996	4928	-2894	7250	-2918	3651	-162
1997	4587	-2872	7005	-2965	3630	-212
1998	4200	-2818	6879	-3177	3600	-284
1999	4013	-2874	6765	-3156	3531	-252
2000	**3911**	**-2760**	**6741**	**-3207**	**3466**	**-330**
2001	3842	-2946	6657	-3149	3429	-149
2002	3550	-3169	6661	-3357	3387	29
2003	3569	-3333	6701	-3291	3360	133
2004	3231	-3540	6622	-3439	3336	253
2005	***6834***	***-3446***	***8132***	***-2242***	***4241***	***150***
2006	*6607*	*-3325*	*8055*	*-2372*	*4237*	*13*
2007	*6630*	*-2970*	*8054*	*-2375*	*4223*	*-302*
2008	*6624*	*-2705*	*8091*	*-2484*	*4216*	*-495*
2009	*6779*	*-2398*	*8078*	*-2402*	*4194*	*-693*
2010	***6714***	***-2107***	***7980***	***-2471***	***4109***	***-796***
2011	*6821*	*-2162*	*7982*	*-2453*	*4058*	*-602*
2012	*6890*	*-1907*	*7997*	*-2528*	*4038*	*-709*
2013	*7044*	*-1159*	*7994*	*-2558*	*4019*	*-1252*
2014	*7165*	*-1046*	*8006*	*-2585*	*3997*	*-1206*
2015	***7383***	***-814***	***8012***	***-2552***	***3977***	***-1241***
2016	*7506*	*-742*	*8024*	*-2569*	*3957*	*-1165*
2017	*7580*	*-775*	*8043*	*-2618*	*3943*	*-1013*
2018	*7669*	*-796*	*8060*	*-2633*	*3929*	*-891*
2019	*7750*	*-720*	*8079*	*-2647*	*3929*	*-890*
2020	***8001***	***-106***	***8095***	***-2619***	***3930***	***-1299***

D England Gg CO2	**Changes in woody biomass**	**HWP**	**Forest Conversion**	**Soils**	**Other**	**Other**	**NET Emission (+) Removal (-)**
1990	-2733	-361	108	7367	1878	-524	5736
1991	-2775	-285	98	7462	1859	-524	5835
1992	-2856	-206	102	7359	1797	-524	5672
1993	-2851	-211	75	6760	1758	-524	5007
1994	-2889	-177	85	6733	1784	-524	5013
1995	-2825	-219	90	6799	1789	-524	5111
1996	-2894	-162	109	6699	1698	-524	4928
1997	-2872	-212	112	6439	1644	-524	4587
1998	-2818	-284	114	6164	1548	-524	4200
1999	-2874	-252	137	5956	1570	-524	4013
2000	-2760	-330	152	5832	1540	-524	3911
2001	-2946	-149	182	5719	1559	-524	3842
2002	-3169	29	153	5647	1414	-524	3550
2003	-3333	133	144	5681	1468	-524	3569
2004	-3540	253	131	5532	1380	-524	3231
1996 GUIDELINES Format	5A (Removals)	5A (Removals)	5B (Emissions)	5D (Emissions)	5E (Emissions)	5E (Removals)	
	Forest biomass, soils, litter.	Forest products	Deforestation (Biomass burning)	Effect of LUC (Net), liming of soils	Drainage of lowland soils, peat extraction	Non-forest biomass	

Table A1. 3: Scotland data for 2004 UK GHG Inventory: A: LULUCF GPG Format – with MID projection, B: LULUCF GPG Format – with LO projection, C: LULUCF GPG Format – with HI projection, D: “1996 GUIDELINES” summary (Italics are projections) (HWP = Harvested Wood Products)

A (Mid) Scotland Gg CO2/year	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	-2535	-7547	6102	-2116	1741	-714
1991	-2805	-7951	6178	-2128	1732	-635
1992	-3102	-8365	6222	-2139	1727	-546
1993	-3541	-8714	6194	-2241	1715	-495
1994	-3726	-9062	6246	-2218	1714	-406
1995	-3712	-8973	6313	-2195	1710	-567
1996	-3669	-8860	6359	-2272	1711	-607
1997	-3715	-8837	6353	-2329	1712	-615
1998	-3855	-8878	6371	-2449	1708	-607
1999	-3929	-9075	6391	-2422	1693	-516
2000	-3940	-8869	6427	-2477	1679	-699
2001	-4011	-9164	6464	-2552	1672	-431
2002	-4188	-9611	6489	-2609	1664	-122
2003	-4250	-10054	6514	-2465	1661	93
2004	-4617	-10473	6546	-2596	1658	247
2005	*-4622*	*-10130*	*6553*	*-2635*	*1659*	*-69*
2006	*-4683*	*-9790*	*6560*	*-2734*	*1659*	*-379*
2007	*-4561*	*-9358*	*6582*	*-2700*	*1657*	*-742*
2008	*-4622*	*-9212*	*6611*	*-2791*	*1657*	*-887*
2009	*-4535*	*-8746*	*6628*	*-2800*	*1653*	*-1269*
2010	*-4159*	*-7653*	*6642*	*-2838*	*1649*	*-1959*
2011	*-3848*	*-7575*	*6662*	*-2833*	*1647*	*-1750*
2012	*-3545*	*-7008*	*6682*	*-2863*	*1648*	*-2004*
2013	*-3357*	*-6731*	*6696*	*-2920*	*1649*	*-2050*
2014	*-3123*	*-6430*	*6713*	*-2949*	*1648*	*-2105*
2015	*-2835*	*-6094*	*6728*	*-2991*	*1648*	*-2126*
2016	*-2586*	*-6104*	*6744*	*-2998*	*1647*	*-1875*
2017	*-2441*	*-6241*	*6760*	*-3071*	*1648*	*-1536*
2018	*-2290*	*-6255*	*6775*	*-3065*	*1647*	*-1391*
2019	*-2073*	*-5596*	*6790*	*-3096*	*1646*	*-1817*
2020	*-1670*	*-4795*	*6804*	*-3088*	*1646*	*-2237*

B (Low) Scotland **Gg CO2/year**	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	**-2535**	**-7547**	**6102**	**-2116**	**1741**	**-714**
1991	-2805	-7951	6178	-2128	1732	-635
1992	-3102	-8365	6222	-2139	1727	-546
1993	-3541	-8714	6194	-2241	1715	-495
1994	-3726	-9062	6246	-2218	1714	-406
1995	**-3712**	**-8973**	**6313**	**-2195**	**1710**	**-567**
1996	-3669	-8860	6359	-2272	1711	-607
1997	-3715	-8837	6353	-2329	1712	-615
1998	-3855	-8878	6371	-2449	1708	-607
1999	-3929	-9075	6391	-2422	1693	-516
2000	**-3940**	**-8869**	**6427**	**-2477**	**1679**	**-699**
2001	-4011	-9164	6464	-2552	1672	-431
2002	-4188	-9611	6489	-2609	1664	-122
2003	-4250	-10054	6514	-2465	1661	93
2004	-4617	-10473	6546	-2596	1658	247
2005	***-7373***	***-10094***	***4783***	***-3258***	***1265***	***-69***
2006	*-7370*	*-9653*	*4772*	*-3374*	*1263*	*-379*
2007	*-7239*	*-9175*	*4778*	*-3358*	*1257*	*-742*
2008	*-7351*	*-9042*	*4791*	*-3467*	*1253*	*-887*
2009	*-7365*	*-8644*	*4794*	*-3493*	*1247*	*-1269*
2010	***-6998***	***-7657***	***4881***	***-3530***	***1268***	***-1959***
2011	*-6789*	*-7703*	*4920*	*-3535*	*1278*	*-1750*
2012	*-6622*	*-7261*	*4943*	*-3578*	*1277*	*-2004*
2013	*-6577*	*-7104*	*4947*	*-3648*	*1278*	*-2050*
2014	*-6484*	*-6917*	*4952*	*-3690*	*1276*	*-2105*
2015	***-6324***	***-6688***	***4955***	***-3735***	***1271***	***-2126***
2016	*-6207*	*-6800*	*4959*	*-3747*	*1258*	*-1875*
2017	*-6184*	*-7038*	*4964*	*-3830*	*1257*	*-1536*
2018	*-6182*	*-7150*	*4968*	*-3864*	*1256*	*-1391*
2019	*-6079*	*-6589*	*4972*	*-3896*	*1252*	*-1817*
2020	***-5823***	***-5888***	***4975***	***-3921***	***1248***	***-2237***

C (High) Scotland **Gg CO2/year**	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	**-2535**	**-7547**	**6102**	**-2116**	**1741**	**-714**
1991	-2805	-7951	6178	-2128	1732	-635
1992	-3102	-8365	6222	-2139	1727	-546
1993	-3541	-8714	6194	-2241	1715	-495
1994	-3726	-9062	6246	-2218	1714	-406
1995	**-3712**	**-8973**	**6313**	**-2195**	**1710**	**-567**
1996	-3669	-8860	6359	-2272	1711	-607
1997	-3715	-8837	6353	-2329	1712	-615
1998	-3855	-8878	6371	-2449	1708	-607
1999	-3929	-9075	6391	-2422	1693	-516
2000	**-3940**	**-8869**	**6427**	**-2477**	**1679**	**-699**
2001	-4011	-9164	6464	-2552	1672	-431
2002	-4188	-9611	6489	-2609	1664	-122
2003	-4250	-10054	6514	-2465	1661	93
2004	-4617	-10473	6546	-2596	1658	247
2005	***-1546***	***-10153***	***8388***	***-1796***	***2084***	***-69***
2006	*-1631*	*-9879*	*8414*	*-1877*	*2089*	*-379*
2007	*-1497*	*-9477*	*8454*	*-1824*	*2091*	*-742*
2008	*-1509*	*-9323*	*8501*	*-1895*	*2095*	*-887*
2009	*-1338*	*-8813*	*8536*	*-1884*	*2093*	*-1269*
2010	***-912***	***-7651***	***8550***	***-1913***	***2062***	***-1959***
2011	*-529*	*-7492*	*8570*	*-1900*	*2042*	*-1750*
2012	*-149*	*-6843*	*8589*	*-1921*	*2030*	*-2004*
2013	*134*	*-6488*	*8604*	*-1962*	*2030*	*-2050*
2014	*461*	*-6113*	*8621*	*-1975*	*2033*	*-2105*
2015	***839***	***-5707***	***8637***	***-2001***	***2037***	***-2126***
2016	*1175*	*-5650*	*8652*	*-1991*	*2039*	*-1875*
2017	*1406*	*-5723*	*8669*	*-2047*	*2043*	*-1536*
2018	*1642*	*-5673*	*8685*	*-2024*	*2045*	*-1391*
2019	*1943*	*-4950*	*8701*	*-2038*	*2047*	*-1817*
2020	***2432***	***-4083***	***8716***	***-2013***	***2049***	***-2237***

D Scotland Gg CO2	**Changes in woody biomass**	**HWP**	**Forest Conversion**	**Soils**	**Other**	**Other**	**NET Emission (+) Removal (-)**
1990	-7547	-714	34	8128	-2416	60	-79
1991	-7951	-635	31	8232	-2451	49	-79
1992	-8365	-546	32	8275	-2486	68	-79
1993	-8714	-495	23	8182	-2521	63	-79
1994	-9062	-406	27	8248	-2555	102	-79
1995	-8973	-567	28	8334	-2589	134	-79
1996	-8860	-607	34	8360	-2623	106	-79
1997	-8837	-615	35	8368	-2656	68	-79
1998	-8878	-607	36	8341	-2689	22	-79
1999	-9075	-516	43	8339	-2721	80	-79
2000	-8869	-699	48	8345	-2754	69	-79
2001	-9164	-431	57	8325	-2786	66	-79
2002	-9611	-122	48	8371	-2817	22	-79
2003	-10054	93	45	8442	-2849	151	-79
2004	-10473	247	41	8457	-2880	69	-79
1996 GUIDELINES Format	5A (Removals)	5A (Removals)	5B (Emissions)	5D (Emissions)	5E (Emissions)	5E (Removals)	
	Forest biomass, soils, litter.	Forest products	Deforestation (Biomass burning)	Effect of LUC (Net), liming of soils	Drainage of lowland soils, peat extraction	Non-forest biomass	

Table A1. 4: Wales data for 2004 UK GHG Inventory: A: LULUCF GPG Format – with MID projection, B: LULUCF GPG Format – with LO projection, C: LULUCF GPG Format – with HI projection, D: "1996 GUIDELINES" summary (Italics are projections) (HWP = Harvested Wood Products)

A (Mid) Wales Gg CO2/year	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	-241	-1178	969	-402	705	-336
1991	-201	-1246	978	-392	703	-244
1992	-203	-1358	985	-400	701	-130
1993	-258	-1432	986	-449	698	-62
1994	-258	-1491	993	-451	698	-7
1995	-219	-1427	1001	-448	697	-42
1996	-179	-1247	1007	-465	697	-170
1997	-127	-1083	1009	-465	697	-286
1998	-120	-1001	1012	-501	696	-326
1999	-69	-837	1016	-518	693	-423
2000	-133	-1441	1021	-542	689	139
2001	-136	-1477	1025	-543	688	171
2002	-173	-1522	1030	-560	686	193
2003	-202	-1559	1035	-556	685	192
2004	-249	-1584	1038	-572	685	185
2005	*-251*	*-1510*	*1041*	*-591*	*685*	*124*
2006	*-246*	*-1491*	*1043*	*-610*	*686*	*127*
2007	*-242*	*-1430*	*1046*	*-620*	*685*	*77*
2008	*-238*	*-1321*	*1050*	*-626*	*685*	*-27*
2009	*-231*	*-1213*	*1053*	*-635*	*685*	*-121*
2010	*-69*	*-325*	*1055*	*-645*	*684*	*-838*
2011	*40*	*-281*	*1058*	*-653*	*684*	*-768*
2012	*114*	*-345*	*1061*	*-660*	*684*	*-626*
2013	*165*	*-365*	*1063*	*-669*	*685*	*-549*
2014	*223*	*-319*	*1066*	*-676*	*685*	*-532*
2015	*318*	*-210*	*1068*	*-684*	*685*	*-542*
2016	*379*	*-192*	*1070*	*-691*	*685*	*-494*
2017	*432*	*-139*	*1073*	*-697*	*686*	*-490*
2018	*471*	*-121*	*1075*	*-703*	*686*	*-465*
2019	*547*	*126*	*1077*	*-708*	*686*	*-633*
2020	*685*	*437*	*1079*	*-714*	*686*	*-804*

B (Low) Wales Gg CO2/year	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	**-241**	**-1178**	**969**	**-402**	**705**	**-336**
1991	-201	-1246	978	-392	703	-244
1992	-203	-1358	985	-400	701	-130
1993	-258	-1432	986	-449	698	-62
1994	-258	-1491	993	-451	698	-7
1995	**-219**	**-1427**	**1001**	**-448**	**697**	**-42**
1996	-179	-1247	1007	-465	697	-170
1997	-127	-1083	1009	-465	697	-286
1998	-120	-1001	1012	-501	696	-326
1999	-69	-837	1016	-518	693	-423
2000	**-133**	**-1441**	**1021**	**-542**	**689**	**139**
2001	-136	-1477	1025	-543	688	171
2002	-173	-1522	1030	-560	686	193
2003	-202	-1559	1035	-556	685	192
2004	-249	-1584	1038	-572	685	185
2005	***-839***	***-1510***	***767***	***-740***	***520***	***124***
2006	*-839*	*-1490*	*767*	*-764*	*521*	*127*
2007	*-844*	*-1430*	*768*	*-778*	*519*	*77*
2008	*-855*	*-1325*	*770*	*-789*	*517*	*-27*
2009	*-863*	*-1225*	*771*	*-803*	*515*	*-121*
2010	***-669***	***-347***	***794***	***-805***	***527***	***-838***
2011	*-565*	*-314*	*800*	*-814*	*531*	*-768*
2012	*-505*	*-388*	*802*	*-825*	*531*	*-626*
2013	*-468*	*-417*	*804*	*-837*	*532*	*-549*
2014	*-423*	*-381*	*805*	*-847*	*532*	*-532*
2015	***-341***	***-280***	***807***	***-857***	***531***	***-542***
2016	*-292*	*-270*	*808*	*-863*	*528*	*-494*
2017	*-259*	*-225*	*809*	*-882*	*528*	*-490*
2018	*-231*	*-214*	*811*	*-890*	*528*	*-465*
2019	*-167*	*26*	*812*	*-899*	*528*	*-633*
2020	***-40***	***330***	***813***	***-907***	***528***	***-804***

C (High) Wales Gg CO2/year	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	**-241**	**-1178**	**969**	**-402**	**705**	**-336**
1991	-201	-1246	978	-392	703	-244
1992	-203	-1358	985	-400	701	-130
1993	-258	-1432	986	-449	698	-62
1994	-258	-1491	993	-451	698	-7
1995	**-219**	**-1427**	**1001**	**-448**	**697**	**-42**
1996	-179	-1247	1007	-465	697	-170
1997	-127	-1083	1009	-465	697	-286
1998	-120	-1001	1012	-501	696	-326
1999	-69	-837	1016	-518	693	-423
2000	**-133**	**-1441**	**1021**	**-542**	**689**	**139**
2001	-136	-1477	1025	-543	688	171
2002	-173	-1522	1030	-560	686	193
2003	-202	-1559	1035	-556	685	192
2004	-249	-1584	1038	-572	685	185
2005	***398***	***-1509***	***1323***	***-403***	***863***	***124***
2006	*410*	*-1492*	*1329*	*-418*	*864*	*127*
2007	*422*	*-1430*	*1335*	*-423*	*864*	*77*
2008	*437*	*-1318*	*1342*	*-424*	*865*	*-27*
2009	*457*	*-1205*	*1347*	*-429*	*864*	*-121*
2010	***614***	***-311***	***1344***	***-441***	***860***	***-838***
2011	*727*	*-260*	*1347*	*-449*	*857*	*-768*
2012	*808*	*-317*	*1349*	*-454*	*855*	*-626*
2013	*866*	*-330*	*1352*	*-460*	*854*	*-549*
2014	*932*	*-279*	*1354*	*-464*	*853*	*-532*
2015	***1034***	***-164***	***1356***	***-468***	***852***	***-542***
2016	*1103*	*-141*	*1358*	*-470*	*850*	*-494*
2017	*1164*	*-83*	*1360*	*-472*	*850*	*-490*
2018	*1213*	*-61*	*1362*	*-474*	*850*	*-465*
2019	*1298*	*191*	*1364*	*-475*	*851*	*-633*
2020	***1445***	***507***	***1366***	***-476***	***852***	***-804***

D **Wales** **Gg CO2**	**Changes in woody biomass**	**HWP**	**Forest Conversion**	**Soils**	**Other**	**Other**	**NET Emission (+) Removal (-)**
1990	-1178	-336	9	1760	-487	0	-9
1991	-1246	-244	8	1789	-499	0	-9
1992	-1358	-130	8	1798	-511	0	-9
1993	-1432	-62	6	1760	-522	0	-9
1994	-1491	-7	7	1775	-533	0	-9
1995	-1427	-42	7	1796	-544	0	-9
1996	-1247	-170	9	1793	-554	0	-9
1997	-1083	-286	9	1806	-564	0	-9
1998	-1001	-326	9	1782	-574	0	-9
1999	-837	-423	11	1773	-584	0	-9
2000	-1441	139	12	1759	-593	0	-9
2001	-1477	171	14	1767	-603	0	-9
2002	-1522	193	12	1764	-611	0	-9
2003	-1559	192	11	1783	-620	0	-9
2004	-1584	185	10	1778	-629	0	-9
1996 GUIDELINES Format	5A (Removals)	5A (Removals)	5B (Emissions)	5D (Emissions)	5E (Emissions)	5E (Removals)	
	Forest biomass, soils, litter.	Forest products	Deforestation (Biomass burning)	Effect of LUC (Net), liming of soils	Drainage of lowland soils, peat extraction	Non-forest biomass	

Table A1. 5: Northern Ireland data for 2004 UK GHG Inventory: A: LULUCF GPG Format – with MID projection, B: LULUCF GPG Format – with LO projection, C: LULUCF GPG Format – with HI projection, D: "1996 GUIDELINES" summary (Italics are projections) (HWP = Harvested Wood Products)

A (Mid) N. Ireland Gg CO2/year	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	**-45**	**-744**	**1256**	**-1081**	**569**	**-45**
1991	-47	-742	1245	-1073	569	-46
1992	-78	-761	1232	-1081	569	-37
1993	-126	-718	1216	-1119	569	-74
1994	-139	-750	1205	-1120	568	-43
1995	**-146**	**-723**	**1196**	**-1116**	**568**	**-72**
1996	-177	-719	1187	-1131	568	-82
1997	-192	-721	1175	-1131	568	-84
1998	-226	-709	1165	-1161	568	-89
1999	-249	-718	1156	-1179	568	-77
2000	**-279**	**-736**	**1149**	**-1201**	**568**	**-60**
2001	-291	-762	1141	-1204	569	-35
2002	-309	-744	1135	-1216	569	-53
2003	-296	-700	1130	-1215	569	-80
2004	-307	-705	1123	-1228	569	-66
2005	***-313***	***-648***	***1117***	***-1243***	***569***	***-108***
2006	*-321*	*-628*	*1110*	*-1257*	*569*	*-115*
2007	*-313*	*-558*	*1105*	*-1264*	*570*	*-166*
2008	*-291*	*-508*	*1101*	*-1268*	*570*	*-187*
2009	*-279*	*-492*	*1097*	*-1276*	*570*	*-177*
2010	***-277***	***-551***	***1092***	***-1284***	***570***	***-104***
2011	*-266*	*-499*	*1088*	*-1290*	*570*	*-135*
2012	*-254*	*-451*	*1085*	*-1295*	*570*	*-164*
2013	*-232*	*-410*	*1081*	*-1302*	*571*	*-173*
2014	*-219*	*-409*	*1078*	*-1307*	*571*	*-153*
2015	***-200***	***-334***	***1075***	***-1313***	***571***	***-199***
2016	*-171*	*-264*	*1072*	*-1318*	*571*	*-233*
2017	*-137*	*-134*	*1070*	*-1322*	*571*	*-322*
2018	*-99*	*-81*	*1067*	*-1326*	*571*	*-329*
2019	*-68*	*-68*	*1065*	*-1330*	*572*	*-306*
2020	***-34***	***-17***	***1063***	***-1335***	***572***	***-318***

B (Low) **N. Ireland** **Gg CO2/year**	**5** **NET**	**5A** **Forestland**	**5B** **Cropland**	**5C** **Grassland**	**5E** **Settlements**	**5G** **HWP**
1990	**-45**	**-744**	**1256**	**-1081**	**569**	**-45**
1991	-47	-742	1245	-1073	569	-46
1992	-78	-761	1232	-1081	569	-37
1993	-126	-718	1216	-1119	569	-74
1994	-139	-750	1205	-1120	568	-43
1995	**-146**	**-723**	**1196**	**-1116**	**568**	**-72**
1996	-177	-719	1187	-1131	568	-82
1997	-192	-721	1175	-1131	568	-84
1998	-226	-709	1165	-1161	568	-89
1999	-249	-718	1156	-1179	568	-77
2000	**-279**	**-736**	**1149**	**-1201**	**568**	**-60**
2001	-291	-762	1141	-1204	569	-35
2002	-309	-744	1135	-1216	569	-53
2003	-296	-700	1130	-1215	569	-80
2004	-307	-705	1123	-1228	569	-66
2005	***-1008***	***-645***	***841***	***-1542***	***447***	***-108***
2006	*-1014*	*-618*	*835*	*-1561*	*446*	*-115*
2007	*-1007*	*-544*	*830*	*-1573*	*446*	*-166*
2008	*-992*	*-495*	*827*	*-1582*	*445*	*-187*
2009	*-990*	*-484*	*822*	*-1595*	*445*	*-177*
2010	***-972***	***-551***	***830***	***-1597***	***450***	***-104***
2011	*-951*	*-509*	*838*	*-1599*	*455*	*-135*
2012	*-934*	*-469*	*843*	*-1603*	*459*	*-164*
2013	*-918*	*-437*	*843*	*-1612*	*461*	*-173*
2014	*-916*	*-445*	*844*	*-1621*	*459*	*-153*
2015	***-908***	***-378***	***843***	***-1631***	***457***	***-199***
2016	*-892*	*-316*	*840*	*-1639*	*455*	*-233*
2017	*-871*	*-193*	*837*	*-1647*	*453*	*-322*
2018	*-847*	*-148*	*833*	*-1655*	*452*	*-329*
2019	*-830*	*-142*	*830*	*-1662*	*450*	*-306*
2020	***-811***	***-99***	***827***	***-1670***	***448***	***-318***

C (High) N. Ireland Gg CO2/year	**5 NET**	**5A Forestland**	**5B Cropland**	**5C Grassland**	**5E Settlements**	**5G HWP**
1990	**-45**	**-744**	**1256**	**-1081**	**569**	**-45**
1991	-47	-742	1245	-1073	569	-46
1992	-78	-761	1232	-1081	569	-37
1993	-126	-718	1216	-1119	569	-74
1994	-139	-750	1205	-1120	568	-43
1995	**-146**	**-723**	**1196**	**-1116**	**568**	**-72**
1996	-177	-719	1187	-1131	568	-82
1997	-192	-721	1175	-1131	568	-84
1998	-226	-709	1165	-1161	568	-89
1999	-249	-718	1156	-1179	568	-77
2000	**-279**	**-736**	**1149**	**-1201**	**568**	**-60**
2001	-291	-762	1141	-1204	569	-35
2002	-309	-744	1135	-1216	569	-53
2003	-296	-700	1130	-1215	569	-80
2004	-307	-705	1123	-1228	569	-66
2005	***475***	***-650***	***1422***	***-901***	***712***	***-108***
2006	*465*	*-635*	*1415*	*-911*	*712*	*-115*
2007	*474*	*-567*	*1409*	*-915*	*712*	*-166*
2008	*499*	*-516*	*1404*	*-914*	*712*	*-187*
2009	*519*	*-497*	*1399*	*-919*	*712*	*-177*
2010	***506***	***-551***	***1384***	***-933***	***710***	***-104***
2011	*513*	*-493*	*1370*	*-937*	*708*	*-135*
2012	*521*	*-439*	*1357*	*-940*	*706*	*-164*
2013	*541*	*-392*	*1345*	*-944*	*705*	*-173*
2014	*550*	*-385*	*1333*	*-948*	*703*	*-153*
2015	***575***	***-305***	***1328***	***-951***	***702***	***-199***
2016	*611*	*-231*	*1326*	*-954*	*702*	*-233*
2017	*653*	*-95*	*1324*	*-956*	*702*	*-322*
2018	*698*	*-38*	*1322*	*-958*	*702*	*-329*
2019	*736*	*-19*	*1320*	*-960*	*701*	*-306*
2020	***777***	***37***	***1319***	***-962***	***701***	***-318***

D N. Ireland Gg CO2	**Changes in woody biomass**	**HWP**	**Forest Conversion**	**Soils**	**Other**	**Other**	**NET Emission (+) Removal (-)**
1990	-744	-45	0	1948	-1272	102	-34
1991	-742	-46	0	1953	-1280	102	-34
1992	-761	-37	0	1940	-1287	102	-34
1993	-718	-74	0	1893	-1295	102	-34
1994	-750	-43	0	1888	-1302	102	-34
1995	-723	-72	0	1890	-1309	102	-34
1996	-719	-82	0	1872	-1316	102	-34
1997	-721	-84	0	1867	-1322	102	-34
1998	-709	-89	0	1833	-1329	102	-34
1999	-718	-77	0	1813	-1335	102	-34
2000	-736	-60	0	1790	-1342	102	-34
2001	-762	-35	0	1786	-1348	102	-34
2002	-744	-53	0	1773	-1354	102	-34
2003	-700	-80	0	1776	-1360	102	-34
2004	-705	-66	0	1762	-1366	102	-34
1996 GUIDELINES Format	5A (Removals)	5A (Removals)	5B (Emissions)	5D (Emissions)	5E (Emissions)	5E (Removals)	
	Forest biomass, soils, litter.	Forest products	Deforestation (Biomass burning)	Effect of LUC (Net), liming of soils	Drainage of lowland soils, peat extraction	Non-forest biomass	

APPENDIX 2

A.2. Sectoral Tables for Land Use Change and Forestry Sector submitted as UK 2004 Greenhouse Gas Inventory in format defined by IPCC LULUCF Good Practice Guidance

Table A2. 1. Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 1990 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**2,915.429**	**0.659**	**0.005**	**0.164**	**5.767**
A. Forest Land	**-12,202.570**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-12,202.570	NE,NO	NE,NO	NO	NO
B. Cropland	**15,841.672**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	1,009.609			NO	NO
2. Land converted to Cropland	14,036.826	NE,NO	NE,NO	NO	NO
C. Grassland	**-6,192.802**	**0.147**	**0.001**	**0.036**	**1.282**
1. Grassland remaining Grassland	389.539	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-7,217.550	0.147	0.001	0.036	1.282
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,925.013**	**0.513**	**0.004**	**0.127**	**4.485**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,807.558	IE	IE	0.127	4.485
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**-1,455.883**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	-1,455.883	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	350.349	0.659	0.005	0.164	5.767
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 2 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 1991 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**2,782.027**	**0.598**	**0.004**	**0.149**	**5.234**
A. Forest Land	**-12,714.630**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-12,714.630	NE,NO	NE,NO	NO	NO
B. Cropland	**16,001.318**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	972.942			NO	NO
2. Land converted to Cropland	14,050.098	NE,NO	NE,NO	NO	NO
C. Grassland	**-6,145.606**	**0.156**	**0.001**	**0.039**	**1.369**
1. Grassland remaining Grassland	396.256	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-7,335.535	0.156	0.001	0.039	1.369
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,851.140**	**0.442**	**0.003**	**0.110**	**3.865**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,749.910	IE	IE	0.110	3.865
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**-1,210.195**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	-1,210.195	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	344.088	0.598	0.004	0.149	5.234
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 3 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 1992 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**2,289.511**	**0.619**	**0.004**	**0.154**	**5.419**
A. Forest Land	**-13,340.088**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-13,340.088	NE,NO	NE,NO	NO	NO
B. Cropland	**16,004.231**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	936.275			NO	NO
2. Land converted to Cropland	14,064.471	NE,NO	NE,NO	NO	NO
C. Grassland	**-6,253.834**	**0.171**	**0.001**	**0.043**	**1.498**
1. Grassland remaining Grassland	389.721	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-7,449.654	0.171	0.001	0.043	1.498
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,798.804**	**0.448**	**0.003**	**0.111**	**3.921**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,696.109	IE	IE	0.111	3.921
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**-919.602**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	-919.602	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	356.195	0.619	0.004	0.154	5.419
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 4 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 1993 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**1,082.190**	**0.453**	**0.003**	**0.112**	**3.961**
A. Forest Land	**-13,714.070**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-13,714.070	NE,NO	NE,NO	NO	NO
B. Cropland	**15,578.642**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	899.609			NO	NO
2. Land converted to Cropland	14,079.764	NE,NO	NE,NO	NO	NO
C. Grassland	**-6,659.693**	**0.131**	**0.001**	**0.033**	**1.146**
1. Grassland remaining Grassland	382.640	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-7,573.387	0.131	0.001	0.033	1.146
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,719.306**	**0.322**	**0.002**	**0.080**	**2.815**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,645.590	IE	IE	0.080	2.815
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**-841.994**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	-841.994	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	324.876	0.453	0.003	0.112	3.961
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 5 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 1994 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**889.216**	**0.519**	**0.004**	**0.129**	**4.541**
A. Forest Land	**-14,192.631**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-14,192.631	NE,NO	NE,NO	NO	NO
B. Cropland	**15,631.569**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	862.942			NO	NO
2. Land converted to Cropland	14,095.816	NE,NO	NE,NO	NO	NO
C. Grassland	**-6,604.748**	**0.140**	**0.001**	**0.035**	**1.221**
1. Grassland remaining Grassland	484.077	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-7,685.832	0.140	0.001	0.035	1.221
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,687.802**	**0.379**	**0.003**	**0.094**	**3.320**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,600.855	IE	IE	0.094	3.320
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**-632.776**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	-632.776	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	346.545	0.519	0.004	0.129	4.541
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 6 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 1995 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**1,033.528**	**0.549**	**0.004**	**0.137**	**4.807**
A. Forest Land	**-13,948.207**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-13,948.207	NE,NO	NE,NO	NO	NO
B. Cropland	**15,771.111**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	826.275			NO	NO
2. Land converted to Cropland	14,112.482	NE,NO	NE,NO	NO	NO
C. Grassland	**-6,536.314**	**0.155**	**0.001**	**0.039**	**1.359**
1. Grassland remaining Grassland	558.009	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-7,791.407	0.155	0.001	0.039	1.359
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,646.812**	**0.394**	**0.003**	**0.098**	**3.448**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,556.505	IE	IE	0.098	3.448
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**-899.875**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	-899.875	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	359.636	0.549	0.004	0.137	4.807
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 7 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 1996 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**901.905**	**0.664**	**0.005**	**0.165**	**5.806**
A. Forest Land	**-13,720.064**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-13,720.064	NE,NO	NE,NO	NO	NO
B. Cropland	**15,802.361**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	789.609			NO	NO
2. Land converted to Cropland	14,129.632	NE,NO	NE,NO	NO	NO
C. Grassland	**-6,786.447**	**0.183**	**0.001**	**0.045**	**1.600**
1. Grassland remaining Grassland	475.295	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-7,893.784	0.183	0.001	0.045	1.600
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,627.146**	**0.481**	**0.003**	**0.119**	**4.206**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,516.992	IE	IE	0.119	4.206
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**-1,021.090**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	-1,021.090	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	391.598	0.664	0.005	0.165	5.806
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 8 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 1997 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals(1), (2)	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**552.151**	**0.681**	**0.005**	**0.169**	**5.961**
A. Forest Land	**-13,511.595**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-13,511.595	NE,NO	NE,NO	NO	NO
B. Cropland	**15,542.396**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	752.942			NO	NO
2. Land converted to Cropland	14,147.153	NE,NO	NE,NO	NO	NO
C. Grassland	**-6,889.040**	**0.152**	**0.001**	**0.038**	**1.328**
1. Grassland remaining Grassland	419.947	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-8,013.064	0.152	0.001	0.038	1.328
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands (3)	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,607.311**	**0.529**	**0.004**	**0.132**	**4.633**
1. Settlements remaining Settlements (3)	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,485.972	IE	IE	0.132	4.633
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land (4)		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* (5)	**-1,196.922**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products (6)	-1,196.922	NE	NE	NE	NE
Information items(7)					
Forest Land converted to other Land-Use Categories	401.132	0.681	0.005	0.169	5.961
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 9 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 1998 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**-0.063**	**0.691**	**0.005**	**0.172**	**6.050**
A. Forest Land	**-13,406.214**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-13,406.214	NE,NO	NE,NO	NO	NO
B. Cropland	**15,427.296**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	716.275			NO	NO
2. Land converted to Cropland	14,164.941	NE,NO	NE,NO	NO	NO
C. Grassland	**-7,288.132**	**0.158**	**0.001**	**0.039**	**1.387**
1. Grassland remaining Grassland	314.563	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-8,114.661	0.158	0.001	0.039	1.387
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,572.856**	**0.533**	**0.004**	**0.132**	**4.663**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,450.734	IE	IE	0.132	4.663
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**-1,305.869**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	-1,305.869	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	408.642	0.691	0.005	0.172	6.050
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 10 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 1999 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**-234.349**	**0.834**	**0.006**	**0.207**	**7.294**
A. Forest Land	**-13,504.349**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-13,504.349	NE,NO	NE,NO	NO	NO
B. Cropland	**15,327.949**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	679.609			NO	NO
2. Land converted to Cropland	14,182.907	NE,NO	NE,NO	NO	NO
C. Grassland	**-7,274.654**	**0.392**	**0.003**	**0.097**	**3.432**
1. Grassland remaining Grassland	431.589	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-8,127.739	0.392	0.003	0.097	3.432
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,484.711**	**0.441**	**0.003**	**0.110**	**3.862**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,383.552	IE	IE	0.110	3.862
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**-1,268.007**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	-1,268.007	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	446.153	0.834	0.006	0.207	7.294
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 11 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 2000 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**-440.306**	**0.925**	**0.006**	**0.230**	**8.096**
A. Forest Land	**-13,804.831**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-13,804.831	NE,NO	NE,NO	NO	NO
B. Cropland	**15,338.879**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	642.942			NO	NO
2. Land converted to Cropland	14,202.456	NE,NO	NE,NO	NO	NO
C. Grassland	**-7,426.563**	**0.589**	**0.004**	**0.146**	**5.150**
1. Grassland remaining Grassland	427.096	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-8,154.356	0.589	0.004	0.146	5.150
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,402.293**	**0.337**	**0.002**	**0.084**	**2.946**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,325.130	IE	IE	0.084	2.946
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**-950.083**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	-950.083	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	471.834	0.925	0.006	0.230	8.096
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 12 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 2001 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**-596.489**	**1.106**	**0.008**	**0.275**	**9.678**
A. Forest Land	**-14,347.953**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-14,347.953	NE,NO	NE,NO	NO	NO
B. Cropland	**15,287.306**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	620.942			NO	NO
2. Land converted to Cropland	14,221.843	NE,NO	NE,NO	NO	NO
C. Grassland	**-7,448.854**	**0.775**	**0.005**	**0.193**	**6.780**
1. Grassland remaining Grassland	465.900	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-8,194.736	0.775	0.005	0.193	6.780
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,358.242**	**0.331**	**0.002**	**0.082**	**2.898**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,282.339	IE	IE	0.082	2.898
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**-445.230**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	-445.230	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	517.703	1.106	0.008	0.275	9.678
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 13 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 2002 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**-1,119.831**	**0.928**	**0.006**	**0.231**	**8.122**
A. Forest Land	**-15,045.120**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-15,045.120	NE,NO	NE,NO	NO	NO
B. Cropland	**15,314.062**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	598.942			NO	NO
2. Land converted to Cropland	14,241.023	NE,NO	NE,NO	NO	NO
C. Grassland	**-7,741.998**	**0.673**	**0.005**	**0.167**	**5.891**
1. Grassland remaining Grassland	298.224	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-8,304.951	0.673	0.005	0.167	5.891
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,305.806**	**0.255**	**0.002**	**0.063**	**2.231**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,247.377	IE	IE	0.063	2.231
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**47.418**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	47.418	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	481.150	0.928	0.006	0.231	8.122
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 14 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 2003 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**-1,179.628**	**0.876**	**0.006**	**0.218**	**7.666**
A. Forest Land	**-15,645.775**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-15,645.775	NE,NO	NE,NO	NO	NO
B. Cropland	**15,380.229**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	576.942			NO	NO
2. Land converted to Cropland	14,259.961	NE,NO	NE,NO	NO	NO
C. Grassland	**-7,525.585**	**0.634**	**0.004**	**0.158**	**5.549**
1. Grassland remaining Grassland	503.479	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-8,403.423	0.634	0.004	0.158	5.549
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,274.226**	**0.242**	**0.002**	**0.060**	**2.117**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,218.780	IE	IE	0.060	2.117
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**337.277**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	337.277	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	473.198	0.876	0.006	0.218	7.666
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

Table A2. 15 Emissions and Removals by Land Use, Land Use Change and Forestry (Sector 5) in 2004 for United Kingdom in Sectoral Report Table Format recommended by IPCC Good Practice Guidance for LULUCF.

GREENHOUSE GAS SOURCE AND SINK CATEGORIES	Net CO_2 emissions/ removals[(1), (2)]	CH_4	N_2O	NO_x	CO
	(Gg)				
Total Land-Use Categories	**-1,941.558**	**0.798**	**0.005**	**0.198**	**6.983**
A. Forest Land	**-16,302.000**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Forest Land remaining Forest Land	NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Forest Land	-16,302.000	NE,NO	NE,NO	NO	NO
B. Cropland	**15,329.120**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Cropland remaining Cropland	554.942			NO	NO
2. Land converted to Cropland	14,278.623	NE,NO	NE,NO	NO	NO
C. Grassland	**-7,835.517**	**0.565**	**0.004**	**0.141**	**4.948**
1. Grassland remaining Grassland	354.797	NE,NO	NE,NO	NO	NO
2. Land converted to Grassland	-8,509.639	0.565	0.004	0.141	4.948
D. Wetlands	**IE,NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Wetlands remaining Wetlands [(3)]	IE,NE,NO	NE,NO	NE,NO	NO	NO
2. Land converted to Wetlands	IE,NE,NO	NE,NO	NE,NO	NO	NO
E. Settlements	**6,248.017**	**0.233**	**0.002**	**0.058**	**2.035**
1. Settlements remaining Settlements [(3)]	IE,NO	NO	NO	NO	NO
2. Land converted to Settlements	6,194.718	IE	IE	0.058	2.035
F. Other Land	**NE,NO**	**NE,NO**	**NE,NO**	**NO**	**NO**
1. Other Land remaining Other Land [(4)]		NO	NO	NO	NO
2. Land converted to Other Land	NO	NO	NO	NO	NO
G. Other *(please specify)* [(5)]	**618.822**	**NE**	**NE**	**NE**	**NE**
Harvested Wood Products [(6)]	618.822	NE	NE	NE	NE
Information items[(7)]					
Forest Land converted to other Land-Use Categories	459.062	0.798	0.005	0.198	6.983
Grassland converted to other Land-Use Categories	NO	NO	NO	NO	NO

APPENDIX 3

A.3. Sectoral Tables for Land Use Change and Forestry Sector for the Devolved Administration Regions

Table A3. 1: United Kingdom

UK			1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
5	**Total Land-Use Categories**	**Gg CO2**	**2,915.4**	**2,782.0**	**2,289.5**	**1,082.2**	**889.2**	**1,033.5**	**901.9**	**552.2**	**-0.1**	**-234.3**	**-440.3**	**-596.5**	**-1,119.8**	**-1,179.6**	**-1,941.6**
5A	Forest Land	Gg CO2	-12,202.6	-12,714.6	-13,340.1	-13,714.1	-14,192.6	-13,948.2	-13,720.1	-13,511.6	-13,406.2	-13,504.3	-13,804.8	-14,348.0	-15,045.1	-15,645.8	-16,302.0
5A1	Forest-Land remaining Forest-Land	Gg CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5A2	Land converted to Forest-Land	Gg CO2	-12,202.6	-12,714.6	-13,340.1	-13,714.1	-14,192.6	-13,948.2	-13,720.1	-13,511.6	-13,406.2	-13,504.3	-13,804.8	-14,348.0	-15,045.1	-15,645.8	-16,302.0
5B	**Cropland**	**Gg CO2**	**15,841.7**	**16,001.3**	**16,004.2**	**15,578.6**	**15,631.6**	**15,771.1**	**15,802.4**	**15,542.4**	**15,427.3**	**15,327.9**	**15,338.9**	**15,287.3**	**15,314.1**	**15,380.2**	**15,329.1**
5B1	Cropland remaining Cropland	Gg CO2	1,009.6	972.9	936.3	899.6	862.9	826.3	789.6	752.9	716.3	679.6	642.9	620.9	598.9	576.9	554.9
5B2	Land converted to Cropland	Gg CO2	14,036.8	14,050.1	14,064.5	14,079.8	14,095.8	14,112.5	14,129.6	14,147.2	14,164.9	14,182.9	14,202.5	14,221.8	14,241.0	14,260.0	14,278.6
5B (liming)	*Liming of Cropland*	*Gg CO2*	*795.2*	*978.3*	*1,003.5*	*599.3*	*672.8*	*832.4*	*883.1*	*642.3*	*546.1*	*465.4*	*493.5*	*444.5*	*474.1*	*543.3*	*495.6*
5C	**Grassland**	**Gg CO2**	**-6,192.8**	**-6,145.6**	**-6,253.8**	**-6,659.7**	**-6,604.7**	**-6,536.3**	**-6,786.4**	**-6,889.0**	**-7,288.1**	**-7,274.7**	**-7,426.6**	**-7,448.9**	**-7,742.0**	**-7,525.6**	**-7,835.5**
5C1	Grassland remaining Grassland	Gg CO2	389.5	396.3	389.7	382.6	484.1	558.0	475.3	419.9	314.6	431.6	427.1	465.9	298.2	503.5	354.8
5C2	Land converted to Grassland	Gg CO2	-7,217.5	-7,335.5	-7,449.7	-7,573.4	-7,685.8	-7,791.4	-7,893.8	-8,013.1	-8,114.7	-8,127.7	-8,154.4	-8,194.7	-8,305.0	-8,403.4	-8,509.6
5C (liming)	*Liming of Grassland*	*Gg CO2*	*635.2*	*793.7*	*806.1*	*531.1*	*597.0*	*697.1*	*632.0*	*704.1*	*512.0*	*421.5*	*300.7*	*280.0*	*264.7*	*374.4*	*319.3*
5D	**Wetland**	**Gg CO2**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
5D1	Wetland remaining Wetland	Gg CO2	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
5D2	Land converted to Wetland	Gg CO2	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
5E	**Settlements**	**Gg CO2**	**6,925.0**	**6,851.1**	**6,798.8**	**6,719.3**	**6,687.8**	**6,646.8**	**6,627.1**	**6,607.3**	**6,572.9**	**6,484.7**	**6,402.3**	**6,358.2**	**6,305.8**	**6,274.2**	**6,248.0**
5E1	Settlements remaining Settlements	Gg CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5E2	Land converted to Settlements	Gg CO2	6,807.6	6,749.9	6,696.1	6,645.6	6,600.9	6,556.5	6,517.0	6,486.0	6,450.7	6,383.6	6,325.1	6,282.3	6,247.4	6,218.8	6,194.7
5E (Biomass burning)	*Forest Land converted to Settlement*	*Gg CO2*	*117.5*	*101.2*	*102.7*	*73.7*	*86.9*	*90.3*	*110.2*	*121.3*	*122.1*	*101.2*	*77.2*	*75.9*	*58.4*	*55.4*	*53.3*
5F	**Other-Land**	**Gg CO2**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
5F1	Other-Land remaining Other-land	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5F2	Land converted to Other-Land	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5G	**Other activities**	**Gg CO2**	**-1,455.9**	**-1,210.2**	**-919.6**	**-842.0**	**-632.8**	**-899.9**	**-1,021.1**	**-1,196.9**	**-1,305.9**	**-1,268.0**	**-950.1**	**-445.2**	**47.4**	**337.3**	**618.8**
5G1	Harvested Wood Products	Gg CO2	-1,455.9	-1,210.2	-919.6	-842.0	-632.8	-899.9	-1,021.1	-1,196.9	-1,305.9	-1,268.0	-950.1	-445.2	47.4	337.3	618.8
Information Item	Forest Land converted to other Land-Use Categories	Gg CO2	350.3	344.1	356.2	324.9	346.5	359.6	391.6	401.1	408.6	446.2	471.8	517.7	481.2	473.2	459.1
Information Item	Grassland converted to other Land-Use Categories	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg CH4**	**0.659**	**0.598**	**0.619**	**0.453**	**0.519**	**0.549**	**0.664**	**0.681**	**0.691**	**0.834**	**0.925**	**1.106**	**0.928**	**0.876**	**0.798**
5C2	Land converted to Grassland	Gg CH4	0.147	0.156	0.171	0.131	0.140	0.155	0.183	0.152	0.158	0.392	0.589	0.775	0.673	0.634	0.565
5E	Settlements	Gg CH4	0.513	0.442	0.448	0.322	0.379	0.394	0.481	0.529	0.533	0.441	0.337	0.331	0.255	0.242	0.233
Information Item	Forest Land converted to other Land-Use Categories	Gg CH4	0.659	0.598	0.619	0.453	0.519	0.549	0.664	0.681	0.691	0.834	0.925	1.106	0.928	0.876	0.798
Information Item	Grassland converted to other Land-Use Categories	Gg CH4	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg N2O**	**0.005**	**0.004**	**0.004**	**0.003**	**0.004**	**0.004**	**0.005**	**0.005**	**0.005**	**0.006**	**0.006**	**0.008**	**0.006**	**0.006**	**0.005**
5C2	Land converted to Grassland	Gg N2O	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.003	0.004	0.005	0.005	0.004	0.004
5E	Settlements	Gg N2O	0.004	0.003	0.003	0.002	0.003	0.003	0.003	0.004	0.004	0.003	0.002	0.002	0.002	0.002	0.002
Information Item	Forest Land converted to other Land-Use Categories	Gg N2O	0.005	0.004	0.004	0.003	0.004	0.004	0.005	0.005	0.005	0.006	0.006	0.008	0.006	0.006	0.005
Information Item	Grassland converted to other Land-Use Categories	Gg N2O	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg NOx**	**0.164**	**0.149**	**0.154**	**0.112**	**0.129**	**0.137**	**0.165**	**0.169**	**0.172**	**0.207**	**0.230**	**0.275**	**0.231**	**0.218**	**0.198**
5C2	Land converted to Grassland	Gg NOx	0.036	0.039	0.043	0.033	0.035	0.039	0.045	0.038	0.039	0.097	0.146	0.193	0.167	0.158	0.141
5E	Settlements	Gg NOx	0.127	0.110	0.111	0.080	0.094	0.098	0.119	0.132	0.132	0.110	0.084	0.082	0.063	0.060	0.058
Information Item	Forest Land converted to other Land-Use Categories	Gg NOx	0.164	0.149	0.154	0.112	0.129	0.137	0.165	0.169	0.172	0.207	0.230	0.275	0.231	0.218	0.198
Information Item	Grassland converted to other Land-Use Categories	Gg NOx	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg CO**	**5.767**	**5.234**	**5.419**	**3.961**	**4.541**	**4.807**	**5.806**	**5.961**	**6.050**	**7.294**	**8.096**	**9.678**	**8.122**	**7.666**	**6.983**
5C2	Land converted to Grassland	Gg CO	1.282	1.369	1.498	1.146	1.221	1.359	1.600	1.328	1.387	3.432	5.150	6.780	5.891	5.549	4.948
5E	Settlements	Gg CO	4.485	3.865	3.921	2.815	3.320	3.448	4.206	4.633	4.663	3.862	2.946	2.898	2.231	2.117	2.035
Information Item	Forest Land converted to other Land-Use Categories	Gg CO	5.767	5.234	5.419	3.961	4.541	4.807	5.806	5.961	6.050	7.294	8.096	9.678	8.122	7.666	6.983
Information Item	Grassland converted to other Land-Use Categories	Gg CO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

Table A3. 2 : England

England			1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
5	**Total Land-Use Categories**	**Gg CO2**	**5,735.6**	**5,835.1**	**5,671.9**	**5,006.9**	**5,012.7**	**5,110.5**	**4,927.5**	**4,587.2**	**4,199.6**	**4,012.9**	**3,911.0**	**3,841.6**	**3,550.5**	**3,569.0**	**3,231.3**
5A	**Forest Land**	**Gg CO2**	**-2,733.0**	**-2,775.4**	**-2,855.7**	**-2,850.9**	**-2,889.0**	**-2,825.1**	**-2,893.9**	**-2,871.5**	**-2,817.9**	**-2,874.0**	**-2,759.6**	**-2,945.8**	**-3,169.1**	**-3,333.1**	**-3,540.4**
5A1	Forest-Land remaining Forest-Land	Gg CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5A2	Land converted to Forest-Land	Gg CO2	-2,733.0	-2,775.4	-2,855.7	-2,850.9	-2,889.0	-2,825.1	-2,893.9	-2,871.5	-2,817.9	-2,874.0	-2,759.6	-2,945.8	-3,169.1	-3,333.1	-3,540.4
5B	**Cropland**	**Gg CO2**	**7,515.1**	**7,600.4**	**7,565.0**	**7,182.4**	**7,187.2**	**7,261.1**	**7,249.8**	**7,005.2**	**6,878.7**	**6,764.7**	**6,741.5**	**6,657.0**	**6,660.7**	**6,700.5**	**6,621.6**
5B1	Cropland remaining Cropland	Gg CO2	1,124.7	1,088.0	1,051.3	1,014.7	978.0	941.3	904.7	868.0	831.3	794.7	758.0	736.0	714.0	692.0	670.0
5B2	Land converted to Cropland	Gg CO2	5,755.7	5,730.8	5,708.1	5,687.4	5,668.6	5,651.4	5,635.8	5,621.5	5,608.6	5,596.9	5,586.4	5,576.9	5,568.3	5,560.5	5,553.5
5B (liming)	*Liming of Cropland*	*Gg CO2*	*634.8*	*781.6*	*805.6*	*480.3*	*540.7*	*668.3*	*709.4*	*515.7*	*438.7*	*373.2*	*397.1*	*344.1*	*378.4*	*448.0*	*398.2*
5C	**Grassland**	**Gg CO2**	**-2,594.1**	**-2,552.1**	**-2,633.4**	**-2,850.7**	**-2,816.1**	**-2,777.9**	**-2,917.8**	**-2,964.5**	**-3,176.9**	**-3,156.3**	**-3,206.6**	**-3,149.5**	**-3,356.9**	**-3,290.7**	**-3,438.9**
5C1	Grassland remaining Grassland	Gg CO2	228.1	245.5	220.4	218.5	280.8	322.3	268.2	250.6	191.2	250.0	256.9	298.0	174.8	250.6	184.2
5C2	Land converted to Grassland	Gg CO2	-3,166.0	-3,226.9	-3,285.4	-3,351.0	-3,408.9	-3,462.0	-3,513.2	-3,576.7	-3,627.8	-3,615.6	-3,613.0	-3,620.6	-3,678.5	-3,728.3	-3,783.9
5C (liming)	*Liming of Grassland*	*Gg CO2*	*343.8*	*429.3*	*431.6*	*281.9*	*311.9*	*361.8*	*327.2*	*361.6*	*259.7*	*209.3*	*149.4*	*173.1*	*146.8*	*187.1*	*160.8*
5D	**Wetland**	**Gg CO2**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
5D1	Wetland remaining Wetland	Gg CO2	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
5D2	Land converted to Wetland	Gg CO2	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
5E	**Settlements**	**Gg CO2**	**3,908.9**	**3,847.6**	**3,802.2**	**3,737.6**	**3,707.8**	**3,671.5**	**3,650.9**	**3,630.4**	**3,599.7**	**3,530.8**	**3,466.2**	**3,429.5**	**3,386.9**	**3,359.5**	**3,336.3**
5E1	Settlements remaining Settlements	Gg CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5E2	Land converted to Settlements	Gg CO2	3,824.6	3,774.9	3,728.4	3,684.6	3,645.3	3,606.6	3,571.8	3,543.3	3,512.0	3,458.1	3,410.8	3,374.9	3,344.9	3,319.7	3,298.0
5E (Biomass burning)	*Forest Land converted to Settlement*	*Gg CO2*	*84.4*	*72.7*	*73.8*	*52.9*	*62.4*	*64.9*	*79.1*	*87.1*	*87.7*	*72.7*	*55.4*	*54.5*	*42.0*	*39.8*	*38.3*
5F	**Other-Land**	**Gg CO2**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
5F1	Other-Land remaining Other-land	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5F2	Land converted to Other-Land	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5G	**Other activities**	**Gg CO2**	**-361.3**	**-285.3**	**-206.2**	**-211.4**	**-177.2**	**-219.1**	**-161.5**	**-212.4**	**-284.0**	**-252.3**	**-330.5**	**-149.5**	**28.9**	**132.7**	**252.6**
5G1	Harvested Wood Products	Gg CO2	-361.3	-285.3	-206.2	-211.4	-177.2	-219.1	-161.5	-212.4	-284.0	-252.3	-330.5	-149.5	28.9	132.7	252.6
Information Item	Forest Land converted to other Land-Use Categories	Gg CO2	167.8	167.9	180.9	162.5	181.9	194.9	221.2	231.3	239.7	269.4	290.6	326.0	302.1	298.7	290.6
Information Item	Grassland converted to other Land-Use Categories	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg CH4**	**0.473**	**0.430**	**0.445**	**0.325**	**0.373**	**0.395**	**0.477**	**0.489**	**0.497**	**0.599**	**0.665**	**0.794**	**0.667**	**0.629**	**0.573**
5C2	Land converted to Grassland	Gg CH4	0.105	0.112	0.123	0.094	0.100	0.112	0.131	0.109	0.114	0.282	0.423	0.556	0.484	0.455	0.406
5E	Settlements	Gg CH4	0.368	0.317	0.322	0.231	0.272	0.283	0.345	0.380	0.383	0.317	0.242	0.238	0.183	0.174	0.167
Information Item	Forest Land converted to other Land-Use Categories	Gg CH4	0.473	0.430	0.445	0.325	0.373	0.395	0.477	0.489	0.497	0.599	0.665	0.794	0.667	0.629	0.573
Information Item	Grassland converted to other Land-Use Categories	Gg CH4	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg N2O**	**0.003**	**0.003**	**0.003**	**0.002**	**0.003**	**0.003**	**0.003**	**0.003**	**0.003**	**0.004**	**0.005**	**0.005**	**0.005**	**0.004**	**0.004**
5C2	Land converted to Grassland	Gg N2O	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.003	0.004	0.003	0.003	0.003
5E	Settlements	Gg N2O	0.003	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.003	0.002	0.002	0.002	0.001	0.001	0.001
Information Item	Forest Land converted to other Land-Use Categories	Gg N2O	0.003	0.003	0.003	0.002	0.003	0.003	0.003	0.003	0.003	0.004	0.005	0.005	0.005	0.004	0.004
Information Item	Grassland converted to other Land-Use Categories	Gg N2O	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg NOx**	**0.118**	**0.107**	**0.111**	**0.081**	**0.093**	**0.098**	**0.118**	**0.122**	**0.123**	**0.149**	**0.165**	**0.197**	**0.166**	**0.156**	**0.142**
5C2	Land converted to Grassland	Gg NOx	0.026	0.028	0.031	0.023	0.025	0.028	0.033	0.027	0.028	0.070	0.105	0.138	0.120	0.113	0.101
5E	Settlements	Gg NOx	0.091	0.079	0.080	0.057	0.068	0.070	0.086	0.094	0.095	0.079	0.060	0.059	0.045	0.043	0.042
Information Item	Forest Land converted to other Land-Use Categories	Gg NOx	0.118	0.107	0.111	0.081	0.093	0.098	0.118	0.122	0.123	0.149	0.165	0.197	0.166	0.156	0.142
Information Item	Grassland converted to other Land-Use Categories	Gg NOx	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg CO**	**4.142**	**3.759**	**3.892**	**2.845**	**3.261**	**3.452**	**4.170**	**4.281**	**4.345**	**5.239**	**5.814**	**6.951**	**5.833**	**5.506**	**5.015**
5C2	Land converted to Grassland	Gg CO	0.921	0.983	1.076	0.823	0.877	0.976	1.149	0.954	0.996	2.465	3.698	4.869	4.231	3.986	3.553
5E	Settlements	Gg CO	3.221	2.776	2.816	2.021	2.384	2.476	3.021	3.327	3.349	2.774	2.116	2.081	1.602	1.520	1.462
Information Item	Forest Land converted to other Land-Use Categories	Gg CO	4.142	3.759	3.892	2.845	3.261	3.452	4.170	4.281	4.345	5.239	5.814	6.951	5.833	5.506	5.015
Information Item	Grassland converted to other Land-Use Categories	Gg CO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

Table A3. 3 : Scotland

Scotland			1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
5	**Total Land-Use Categories**	**Gg CO2**	**-2,534.6**	**-2,805.1**	**-3,102.0**	**-3,540.6**	**-3,726.1**	**-3,711.8**	**-3,669.5**	**-3,715.5**	**-3,854.5**	**-3,929.2**	**-3,939.8**	**-4,011.0**	**-4,188.2**	**-4,250.1**	**-4,617.2**
5A	**Forest Land**	**Gg CO2**	**-7,547.4**	**-7,951.4**	**-8,364.7**	**-8,714.0**	**-9,062.0**	**-8,973.0**	**-8,860.1**	**-8,837.0**	**-8,878.0**	**-9,075.3**	**-8,869.0**	**-9,163.7**	**-9,610.8**	**-10,053.5**	**-10,472.5**
5A1	Forest-Land remaining Forest-Land	Gg CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5A2	Land converted to Forest-Land	Gg CO2	-7,547.4	-7,951.4	-8,364.7	-8,714.0	-9,062.0	-8,973.0	-8,860.1	-8,837.0	-8,878.0	-9,075.3	-8,869.0	-9,163.7	-9,610.8	-10,053.5	-10,472.5
5B	**Cropland**	**Gg CO2**	**6,101.5**	**6,178.1**	**6,221.7**	**6,193.9**	**6,245.8**	**6,312.7**	**6,358.7**	**6,353.5**	**6,371.0**	**6,390.5**	**6,427.3**	**6,464.0**	**6,488.6**	**6,514.5**	**6,545.9**
5B1	Cropland remaining Cropland	Gg CO2	-78.9	-78.9	-78.9	-78.9	-78.9	-78.9	-78.9	-78.9	-78.9	-78.9	-78.9	-78.9	-78.9	-78.9	-78.9
5B2	Land converted to Cropland	Gg CO2	6,040.3	6,085.4	6,128.8	6,170.6	6,210.7	6,249.2	6,286.3	6,321.9	6,356.1	6,389.0	6,421.8	6,453.2	6,483.3	6,512.0	6,539.6
5B (liming)	*Liming of Cropland*	*Gg CO2*	*140.1*	*171.6*	*171.8*	*102.2*	*114.0*	*142.4*	*151.3*	*110.5*	*93.8*	*80.5*	*84.4*	*89.7*	*84.3*	*81.4*	*85.2*
5C	**Grassland**	**Gg CO2**	**-2,115.9**	**-2,128.5**	**-2,139.4**	**-2,240.9**	**-2,218.1**	**-2,195.2**	**-2,271.9**	**-2,329.0**	**-2,448.8**	**-2,421.6**	**-2,477.3**	**-2,552.5**	**-2,608.7**	**-2,464.5**	**-2,595.8**
5C1	Grassland remaining Grassland	Gg CO2	59.9	49.2	67.8	62.6	101.7	134.2	105.6	67.8	21.9	80.1	68.6	66.4	21.9	151.3	69.0
5C2	Land converted to Grassland	Gg CO2	-2,309.0	-2,344.7	-2,379.7	-2,417.0	-2,452.0	-2,485.5	-2,518.5	-2,555.3	-2,588.4	-2,601.6	-2,618.0	-2,637.7	-2,673.1	-2,706.0	-2,740.7
5C (liming)	*Liming of Grassland*	*Gg CO2*	*133.2*	*167.0*	*172.5*	*113.6*	*132.2*	*156.1*	*141.0*	*158.5*	*117.7*	*99.9*	*72.1*	*18.8*	*42.6*	*90.1*	*75.9*
5D	**Wetland**	**Gg CO2**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
5D1	Wetland remaining Wetland	Gg CO2	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
5D2	Land converted to Wetland	Gg CO2	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
5E	**Settlements**	**Gg CO2**	**1,741.4**	**1,731.8**	**1,726.7**	**1,715.1**	**1,713.9**	**1,710.3**	**1,711.1**	**1,711.6**	**1,708.5**	**1,693.0**	**1,678.5**	**1,672.5**	**1,664.3**	**1,660.6**	**1,658.0**
5E1	Settlements remaining Settlements	Gg CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5E2	Land converted to Settlements	Gg CO2	1,714.9	1,709.1	1,703.6	1,698.5	1,694.4	1,689.9	1,686.3	1,684.3	1,681.0	1,670.3	1,661.2	1,655.4	1,651.1	1,648.1	1,646.0
5E (Biomass burning)	*Forest Land converted to Settlement*	*Gg CO2*	*26.4*	*22.8*	*23.1*	*16.6*	*19.6*	*20.3*	*24.8*	*27.3*	*27.5*	*22.8*	*17.4*	*17.1*	*13.1*	*12.5*	*12.0*
5F	**Other-Land**	**Gg CO2**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
5F1	Other-Land remaining Other-land	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5F2	Land converted to Other-Land	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5G	**Other activities**	**Gg CO2**	**-714.2**	**-635.1**	**-546.4**	**-494.7**	**-405.6**	**-566.5**	**-607.3**	**-614.5**	**-607.1**	**-515.8**	**-699.4**	**-431.3**	**-121.6**	**92.8**	**247.3**
5G1	Harvested Wood Products	Gg CO2	-714.2	-635.1	-546.4	-494.7	-405.6	-566.5	-607.3	-614.5	-607.1	-515.8	-699.4	-431.3	-121.6	92.8	247.3
Information Item	Forest Land converted to other Land-Use Categories	Gg CO2	99.3	96.8	98.5	90.5	94.5	96.6	102.9	104.3	105.3	113.1	118.2	127.9	119.1	116.8	113.1
Information Item	Grassland converted to other Land-Use Categories	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg CH4**	**0.148**	**0.135**	**0.139**	**0.102**	**0.117**	**0.124**	**0.149**	**0.153**	**0.156**	**0.188**	**0.208**	**0.249**	**0.209**	**0.197**	**0.180**
5C2	Land converted to Grassland	Gg CH4	0.033	0.035	0.039	0.029	0.031	0.035	0.041	0.034	0.036	0.088	0.132	0.174	0.151	0.143	0.127
5E	Settlements	Gg CH4	0.115	0.099	0.101	0.072	0.085	0.089	0.108	0.119	0.120	0.099	0.076	0.075	0.057	0.054	0.052
Information Item	Forest Land converted to other Land-Use Categories	Gg CH4	0.148	0.135	0.139	0.102	0.117	0.124	0.149	0.153	0.156	0.188	0.208	0.249	0.209	0.197	0.180
Information Item	Grassland converted to other Land-Use Categories	Gg CH4	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg N2O**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.001**	**0.002**	**0.001**	**0.001**	**0.001**
5C2	Land converted to Grassland	Gg N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001	0.001
5E	Settlements	Gg N2O	0.001	0.001	0.001	0.000	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.000	0.000	0.000
Information Item	Forest Land converted to other Land-Use Categories	Gg N2O	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.001	0.002	0.001	0.001	0.001
Information Item	Grassland converted to other Land-Use Categories	Gg N2O	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg NOx**	**0.037**	**0.033**	**0.035**	**0.025**	**0.029**	**0.031**	**0.037**	**0.038**	**0.039**	**0.047**	**0.052**	**0.062**	**0.052**	**0.049**	**0.045**
5C2	Land converted to Grassland	Gg NOx	0.008	0.009	0.010	0.007	0.008	0.009	0.010	0.008	0.009	0.022	0.033	0.043	0.038	0.035	0.032
5E	Settlements	Gg NOx	0.029	0.025	0.025	0.018	0.021	0.022	0.027	0.030	0.030	0.025	0.019	0.019	0.014	0.014	0.013
Information Item	Forest Land converted to other Land-Use Categories	Gg NOx	0.037	0.033	0.035	0.025	0.029	0.031	0.037	0.038	0.039	0.047	0.052	0.062	0.052	0.049	0.045
Information Item	Grassland converted to other Land-Use Categories	Gg NOx	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg CO**	**1.298**	**1.178**	**1.219**	**0.891**	**1.022**	**1.082**	**1.306**	**1.341**	**1.361**	**1.641**	**1.822**	**2.178**	**1.827**	**1.725**	**1.571**
5C2	Land converted to Grassland	Gg CO	0.288	0.308	0.337	0.258	0.275	0.306	0.360	0.299	0.312	0.772	1.159	1.525	1.326	1.249	1.113
5E	Settlements	Gg CO	1.009	0.870	0.882	0.633	0.747	0.776	0.946	1.042	1.049	0.869	0.663	0.652	0.502	0.476	0.458
Information Item	Forest Land converted to other Land-Use Categories	Gg CO	1.298	1.178	1.219	0.891	1.022	1.082	1.306	1.341	1.361	1.641	1.822	2.178	1.827	1.725	1.571
Information Item	Grassland converted to other Land-Use Categories	Gg CO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

Table A3. 4 : Wales

Wales			1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
5	**Total Land-Use Categories**	**Gg CO2**	**-241.1**	**-201.4**	**-202.5**	**-258.1**	**-258.4**	**-219.4**	**-179.0**	**-127.2**	**-119.5**	**-69.2**	**-132.6**	**-136.4**	**-173.1**	**-202.0**	**-248.6**
5A	**Forest Land**	**Gg CO2**	**-1,178.2**	**-1,245.9**	**-1,358.4**	**-1,431.5**	**-1,491.4**	**-1,427.4**	**-1,247.3**	**-1,082.5**	**-1,001.2**	**-837.5**	**-1,440.7**	**-1,476.8**	**-1,521.6**	**-1,558.8**	**-1,583.9**
5A1	Forest-Land remaining Forest-Land	Gg CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5A2	Land converted to Forest-Land	Gg CO2	-1,178.2	-1,245.9	-1,358.4	-1,431.5	-1,491.4	-1,427.4	-1,247.3	-1,082.5	-1,001.2	-837.5	-1,440.7	-1,476.8	-1,521.6	-1,558.8	-1,583.9
5B	**Cropland**	**Gg CO2**	**969.3**	**978.2**	**985.1**	**986.3**	**993.3**	**1,000.9**	**1,006.9**	**1,008.9**	**1,012.5**	**1,016.3**	**1,021.2**	**1,024.9**	**1,029.9**	**1,035.4**	**1,038.4**
5B1	Cropland remaining Cropland	Gg CO2	-11.1	-11.1	-11.1	-11.1	-11.1	-11.1	-11.1	-11.1	-11.1	-11.1	-11.1	-11.1	-11.1	-11.1	-11.1
5B2	Land converted to Cropland	Gg CO2	969.4	976.0	982.5	988.6	994.5	1,000.2	1,005.7	1,011.0	1,016.0	1,020.9	1,025.6	1,030.2	1,034.5	1,038.7	1,042.7
5B (liming)	*Liming of Cropland*	*Gg CO2*	*11.0*	*13.2*	*13.7*	*8.7*	*9.8*	*11.7*	*12.2*	*9.0*	*7.5*	*6.5*	*6.6*	*5.8*	*6.4*	*7.7*	*6.7*
5C	**Grassland**	**Gg CO2**	**-402.0**	**-392.4**	**-400.3**	**-449.4**	**-450.9**	**-447.6**	**-465.4**	**-464.9**	**-501.4**	**-517.8**	**-541.5**	**-542.9**	**-560.0**	**-555.6**	**-572.5**
5C1	Grassland remaining Grassland	Gg CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5C2	Land converted to Grassland	Gg CO2	-489.3	-501.0	-512.3	-524.0	-534.9	-545.2	-555.2	-566.0	-575.7	-580.2	-585.4	-591.2	-600.9	-609.8	-618.9
5C (liming)	*Liming of Grassland*	*Gg CO2*	*87.3*	*108.6*	*112.0*	*74.6*	*84.0*	*97.6*	*89.8*	*101.1*	*74.3*	*62.5*	*43.9*	*48.3*	*40.9*	*54.1*	*46.5*
5D	**Wetland**	**Gg CO2**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
5D1	Wetland remaining Wetland	Gg CO2	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
5D2	Land converted to Wetland	Gg CO2	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
5E	**Settlements**	**Gg CO2**	**705.4**	**702.7**	**701.2**	**698.1**	**697.7**	**696.8**	**697.0**	**697.2**	**696.5**	**692.7**	**689.2**	**687.8**	**685.9**	**685.2**	**684.8**
5E1	Settlements remaining Settlements	Gg CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5E2	Land converted to Settlements	Gg CO2	698.7	696.9	695.4	693.9	692.8	691.6	690.7	690.3	689.5	686.9	684.8	683.5	682.6	682.1	681.7
5E (Biomass burning)	*Forest Land converted to Settlement*	*Gg CO2*	*6.7*	*5.8*	*5.8*	*4.2*	*4.9*	*5.1*	*6.3*	*6.9*	*6.9*	*5.7*	*4.4*	*4.3*	*3.3*	*3.1*	*3.0*
5F	**Other-Land**	**Gg CO2**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
5F1	Other-Land remaining Other-land	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5F2	Land converted to Other-Land	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5G	**Other activities**	**Gg CO2**	**-335.5**	**-243.9**	**-130.2**	**-61.6**	**-7.1**	**-42.0**	**-170.2**	**-285.8**	**-325.8**	**-423.0**	**139.3**	**170.6**	**192.6**	**191.8**	**184.6**
5G1	Harvested Wood Products	Gg CO2	-335.5	-243.9	-130.2	-61.6	-7.1	-42.0	-170.2	-285.8	-325.8	-423.0	139.3	170.6	192.6	191.8	184.6
Information Item	Forest Land converted to other Land-Use Categories	Gg CO2	20.3	19.9	20.5	18.7	19.9	20.7	22.5	23.0	23.4	25.5	27.0	29.6	27.5	27.0	26.2
Information Item	Grassland converted to other Land-Use Categories	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg CH4**	**0.037**	**0.034**	**0.035**	**0.026**	**0.029**	**0.031**	**0.038**	**0.039**	**0.039**	**0.047**	**0.053**	**0.063**	**0.053**	**0.050**	**0.045**
5C2	Land converted to Grassland	Gg CH4	0.008	0.009	0.010	0.007	0.008	0.009	0.010	0.009	0.009	0.022	0.033	0.044	0.038	0.036	0.032
5E	Settlements	Gg CH4	0.029	0.025	0.025	0.018	0.022	0.022	0.027	0.030	0.030	0.025	0.019	0.019	0.014	0.014	0.013
Information Item	Forest Land converted to other Land-Use Categories	Gg CH4	0.037	0.034	0.035	0.026	0.029	0.031	0.038	0.039	0.039	0.047	0.053	0.063	0.053	0.050	0.045
Information Item	Grassland converted to other Land-Use Categories	Gg CH4	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg N2O**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
5C2	Land converted to Grassland	Gg N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5E	Settlements	Gg N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Information Item	Forest Land converted to other Land-Use Categories	Gg N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Information Item	Grassland converted to other Land-Use Categories	Gg N2O	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg NOx**	**0.009**	**0.008**	**0.009**	**0.006**	**0.007**	**0.008**	**0.009**	**0.010**	**0.010**	**0.012**	**0.013**	**0.016**	**0.013**	**0.012**	**0.011**
5C2	Land converted to Grassland	Gg NOx	0.002	0.002	0.002	0.002	0.002	0.002	0.003	0.002	0.002	0.006	0.008	0.011	0.010	0.009	0.008
5E	Settlements	Gg NOx	0.007	0.006	0.006	0.005	0.005	0.006	0.007	0.007	0.008	0.006	0.005	0.005	0.004	0.003	0.003
Information Item	Forest Land converted to other Land-Use Categories	Gg NOx	0.009	0.008	0.009	0.006	0.007	0.008	0.009	0.010	0.010	0.012	0.013	0.016	0.013	0.012	0.011
Information Item	Grassland converted to other Land-Use Categories	Gg NOx	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg CO**	**0.328**	**0.297**	**0.308**	**0.225**	**0.258**	**0.273**	**0.330**	**0.339**	**0.344**	**0.414**	**0.460**	**0.550**	**0.461**	**0.436**	**0.397**
5C2	Land converted to Grassland	Gg CO	0.073	0.078	0.085	0.065	0.069	0.077	0.091	0.075	0.079	0.195	0.293	0.385	0.335	0.315	0.281
5E	Settlements	Gg CO	0.255	0.220	0.223	0.160	0.189	0.196	0.239	0.263	0.265	0.219	0.167	0.165	0.127	0.120	0.116
Information Item	Forest Land converted to other Land-Use Categories	Gg CO	0.328	0.297	0.308	0.225	0.258	0.273	0.330	0.339	0.344	0.414	0.460	0.550	0.461	0.436	0.397
Information Item	Grassland converted to other Land-Use Categories	Gg CO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

Table A3. 5 : N. Ireland

Northern Ireland			1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004
5	**Total Land-Use Categories**	**Gg CO2**	**-44.5**	**-46.7**	**-77.9**	**-126.1**	**-139.0**	**-145.8**	**-177.1**	**-192.3**	**-225.6**	**-248.9**	**-279.0**	**-290.7**	**-308.9**	**-296.5**	**-307.0**
5A	**Forest Land**	**Gg CO2**	**-743.9**	**-741.8**	**-761.4**	**-717.6**	**-750.1**	**-722.7**	**-718.8**	**-720.6**	**-709.1**	**-717.6**	**-735.6**	**-761.6**	**-743.6**	**-700.3**	**-705.2**
5A1	Forest-Land remaining Forest-Land	Gg CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5A2	Land converted to Forest-Land	Gg CO2	-743.9	-741.8	-761.4	-717.6	-750.1	-722.7	-718.8	-720.6	-709.1	-717.6	-735.6	-761.6	-743.6	-700.3	-705.2
5B	**Cropland**	**Gg CO2**	**1,255.7**	**1,244.6**	**1,232.4**	**1,216.1**	**1,205.3**	**1,196.5**	**1,187.0**	**1,174.9**	**1,165.2**	**1,156.4**	**1,148.9**	**1,141.4**	**1,134.9**	**1,129.8**	**1,123.2**
5B1	Cropland remaining Cropland	Gg CO2	-25.1	-25.1	-25.1	-25.1	-25.1	-25.1	-25.1	-25.1	-25.1	-25.1	-25.1	-25.1	-25.1	-25.1	-25.1
5B2	Land converted to Cropland	Gg CO2	1,271.5	1,257.8	1,245.1	1,233.2	1,222.0	1,211.6	1,201.9	1,192.7	1,184.2	1,176.2	1,168.6	1,161.5	1,154.9	1,148.7	1,142.9
5B (liming)	*Liming of Cropland*	*Gg CO2*	*9.4*	*11.9*	*12.4*	*8.0*	*8.4*	*10.0*	*10.2*	*7.2*	*6.1*	*5.3*	*5.4*	*4.9*	*5.1*	*6.2*	*5.5*
5C	**Grassland**	**Gg CO2**	**-1,080.8**	**-1,072.6**	**-1,080.8**	**-1,118.8**	**-1,119.6**	**-1,115.6**	**-1,131.3**	**-1,130.6**	**-1,161.0**	**-1,179.0**	**-1,201.1**	**-1,204.0**	**-1,216.4**	**-1,214.8**	**-1,228.3**
5C1	Grassland remaining Grassland	Gg CO2	101.5	101.5	101.5	101.5	101.5	101.5	101.5	101.5	101.5	101.5	101.5	101.5	101.5	101.5	101.5
5C2	Land converted to Grassland	Gg CO2	-1,253.3	-1,262.9	-1,272.3	-1,281.3	-1,290.1	-1,298.7	-1,306.9	-1,315.0	-1,322.8	-1,330.3	-1,337.9	-1,345.3	-1,352.4	-1,359.3	-1,366.1
5C (liming)	*Liming of Grassland*	*Gg CO2*	*70.9*	*88.7*	*89.9*	*61.0*	*69.0*	*81.5*	*74.0*	*82.8*	*60.2*	*49.8*	*35.3*	*39.8*	*34.4*	*43.0*	*36.2*
5D	**Wetland**	**Gg CO2**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**	**IE**
5D1	Wetland remaining Wetland	Gg CO2	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
5D2	Land converted to Wetland	Gg CO2	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE	IE
5E	**Settlements**	**Gg CO2**	**569.3**	**569.0**	**568.7**	**568.5**	**568.4**	**568.3**	**568.2**	**568.2**	**568.2**	**568.2**	**568.4**	**568.5**	**568.7**	**568.8**	**569.0**
5E1	Settlements remaining Settlements	Gg CO2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
5E2	Land converted to Settlements	Gg CO2	569.3	569.0	568.7	568.5	568.4	568.3	568.2	568.2	568.2	568.2	568.4	568.5	568.7	568.8	569.0
5E (Biomass burning)	*Forest Land converted to Settlement*	*Gg CO2*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*
5F	**Other-Land**	**Gg CO2**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**	**NO**
5F1	Other-Land remaining Other-land	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5F2	Land converted to Other-Land	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5G	**Other activities**	**Gg CO2**	**-44.9**	**-45.8**	**-36.8**	**-74.3**	**-42.9**	**-72.2**	**-82.1**	**-84.2**	**-88.9**	**-76.9**	**-59.6**	**-35.0**	**-52.5**	**-80.1**	**-65.8**
5G1	Harvested Wood Products	Gg CO2	-44.9	-45.8	-36.8	-74.3	-42.9	-72.2	-82.1	-84.2	-88.9	-76.9	-59.6	-35.0	-52.5	-80.1	-65.8
Information Item	Forest Land converted to other Land-Use Categories	Gg CO2	63.0	59.5	56.2	53.2	50.3	47.5	45.0	42.5	40.3	38.1	36.1	34.2	32.4	30.7	29.2
Information Item	Grassland converted to other Land-Use Categories	Gg CO2	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg CH4**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
5C2	Land converted to Grassland	Gg CH4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5E	Settlements	Gg CH4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Information Item	Forest Land converted to other Land-Use Categories	Gg CH4	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Information Item	Grassland converted to other Land-Use Categories	Gg CH4	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg N2O**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
5C2	Land converted to Grassland	Gg N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5E	Settlements	Gg N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Information Item	Forest Land converted to other Land-Use Categories	Gg N2O	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Information Item	Grassland converted to other Land-Use Categories	Gg N2O	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg NOx**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
5C2	Land converted to Grassland	Gg NOx	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5E	Settlements	Gg NOx	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Information Item	Forest Land converted to other Land-Use Categories	Gg NOx	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Information Item	Grassland converted to other Land-Use Categories	Gg NOx	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO
5	**Total Land-Use Categories**	**Gg CO**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**	**0.000**
5C2	Land converted to Grassland	Gg CO	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
5E	Settlements	Gg CO	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Information Item	Forest Land converted to other Land-Use Categories	Gg CO	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Information Item	Grassland converted to other Land-Use Categories	Gg CO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO	NO

APPENDIX 4

A.4. Removals and Emissions by post-1990 afforestation and deforestation in the UK

- The following notes apply to all Tables

Low, Mid, High refer to **Emissions** Scenarios;

Low means more forestry - proportion of UK planting of 30,000 ha/year distributed by conifer & broadleaf to the four individual countries by proportions in 2002.

Mid means policy based or business as usual forestry proportion of UK planting of that occurred in 2004 distributed across England, Scotland, Wales and N. Ireland

High means less forestry - 0 kha/year conifer, 0 kha/year broadleaf

These data include, biomass, litter, soils and products.

Products are small in the time period covered

Units are Gg CO_2 per year

Projected deforestation follows 10 term autoregressive model fitted to 1990 - 2003 for short term variation: unadjusted for Mid scenario but with upward long term trend for High scenario and downward long term trend for Low scenario.

Table A4. 1: Removal of atmospheric carbon by post-1990 afforestation – United Kingdom A: Mid emissions scenario, B: Low emission scenario, C: High emission scenario

A (Mid) UK	**Afforestation**		**Deforestation**				**Art 3.3 (excludes HWP)**
Gg CO_2 /year or GWP equiv Gg CO_2/year	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Immediate loss (Biomass) CH_4**	**Immediate loss (Biomass) N_2O**	**Delayed loss (Soil) CO_2**	**Afforestation + Deforestation**
1990	28	0	151	14	1.4	19	213
1991	177	0	137	13	1.3	36	364
1992	208	0	142	13	1.3	53	417
1993	125	0	104	10	1.0	69	308
1994	-44	0	119	11	1.1	83	170
1995	**-278**	**0**	**126**	**12**	**1.2**	**97**	**-42**
1996	-522	0	152	14	1.4	110	-245
1997	-784	0	156	14	1.5	123	-490
1998	-1014	0	158	15	1.5	134	-705
1999	-1227	0	191	18	1.8	145	-872
2000	**-1422**	**0**	**212**	**19**	**2.0**	**156**	**-1033**
2001	-1586	0	253	23	2.4	166	-1142
2002	-1751	0	213	19	2.0	175	-1342
2003	-1954	0	201	18	1.9	184	-1549
2004	-2148	0	183	17	1.7	192	-1755
2005	***-2329***	***0***	***192***	***18***	***1.8***	***200***	***-1918***
2006	*-2489*	*0*	*184*	*17*	*1.7*	*207*	*-2079*
2007	*-2632*	*0*	*161*	*15*	*1.5*	*214*	*-2240*
2008	***-2773***	***0***	***150***	***14***	***1.4***	***221***	***-2386***
2009	***-2910***	***0***	***144***	***13***	***1.3***	***227***	***-2525***
2010	***-3092***	***0***	***149***	***14***	***1.4***	***233***	***-2695***
2011	***-3270***	***0***	***138***	***13***	***1.3***	***239***	***-2879***
2012	***-3445***	***0***	***136***	***12***	***1.3***	***244***	***-3051***
2013	*-3580*	*-21*	*128*	*12*	*1.2*	*249*	*-3190*
2014	*-3746*	*-6*	*130*	*12*	*1.2*	*254*	*-3349*
2015	***-3587***	***-210***	***130***	***12***	***1.2***	***259***	***-3186***
2016	*-3840*	*-94*	*123*	*11*	*1.1*	*263*	*-3441*
2017	*-4095*	*-25*	*115*	*11*	*1.1*	*267*	*-3702*
2018	*-4325*	*-1*	*108*	*10*	*1.0*	*271*	*-3935*
2019	*-4606*	*40*	*108*	*10*	*1.0*	*275*	*-4213*
2020	***-4324***	***-255***	***105***	***10***	***1.0***	***278***	***-3930***

B (Low) UK	Afforestation		Deforestation				Art 3.3 (excludes HWP)
Gg CO_2 /year or GWP equiv Gg CO_2/year	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Immediate loss (Biomass) CH_4**	**Immediate loss (Biomass) N_2O**	**Delayed loss (Soil) CO_2**	**Afforestation + Deforestation**
1990	**28**	**0**	**151**	**14**	**1.4**	**19**	**213**
1991	177	0	137	13	1.3	36	364
1992	208	0	142	13	1.3	53	417
1993	125	0	104	10	1.0	69	308
1994	-44	0	119	11	1.1	83	170
1995	**-278**	**0**	**126**	**12**	**1.2**	**97**	**-42**
1996	-522	0	152	14	1.4	110	-245
1997	-784	0	156	14	1.5	123	-490
1998	-1014	0	158	15	1.5	134	-705
1999	-1227	0	191	18	1.8	145	-872
2000	**-1422**	**0**	**212**	**19**	**2.0**	**156**	**-1033**
2001	-1586	0	253	23	2.4	166	-1142
2002	-1751	0	213	19	2.0	175	-1342
2003	-1954	0	201	18	1.9	184	-1549
2004	-2148	0	183	17	1.7	192	-1755
2005	***-2293***	***0***	***188***	***17***	***1.8***	***110***	***-1976***
2006	*-2327*	*0*	*172*	*16*	*1.6*	*115*	*-2022*
2007	*-2433*	*0*	*137*	*13*	*1.3*	*120*	*-2162*
2008	***-2632***	***0***	***115***	***11***	***1.1***	***125***	***-2380***
2009	***-2916***	***0***	***96***	***9***	***0.9***	***130***	***-2680***
2010	***-3308***	***0***	***90***	***8***	***0.8***	***137***	***-3072***
2011	***-3721***	***0***	***66***	***6***	***0.6***	***143***	***-3506***
2012	***-4132***	***0***	***51***	***5***	***0.5***	***149***	***-3927***
2013	*-4490*	*-21*	*31*	*3*	*0.3*	*153*	*-4303*
2014	*-4866*	*-6*	*20*	*2*	*0.2*	*158*	*-4686*
2015	***-4903***	***-210***	***13***	***1***	***0.1***	***161***	***-4728***
2016	*-5343*	*-94*	*6*	*1*	*0.1*	*163*	*-5172*
2017	*-5778*	*-25*	*0*	*0*	*0.0*	*0*	*-5778*
2018	*-6184*	*-1*	*0*	*0*	*0.0*	*0*	*-6184*
2019	*-6640*	*40*	*0*	*0*	*0.0*	*0*	*-6640*
2020	***-6533***	***-255***	***0***	***0***	***0.0***	***0***	***-6533***

C (High) UK	**Afforestation**		**Deforestation**				**Art 3.3 (excludes HWP)**
Gg CO_2 /year or GWP equiv Gg CO_2/year	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Immediate loss (Biomass) CH_4**	**Immediate loss (Biomass) N_2O**	**Delayed loss (Soil) CO_2**	**Afforestation + Deforestation**
1990	**28**	**0**	**151**	**14**	**1.4**	**19**	**213**
1991	177	0	137	13	1.3	36	364
1992	208	0	142	13	1.3	53	417
1993	125	0	104	10	1.0	69	308
1994	-44	0	119	11	1.1	83	170
1995	**-278**	**0**	**126**	**12**	**1.2**	**97**	**-42**
1996	-522	0	152	14	1.4	110	-245
1997	-784	0	156	14	1.5	123	-490
1998	-1014	0	158	15	1.5	134	-705
1999	-1227	0	191	18	1.8	145	-872
2000	**-1422**	**0**	**212**	**19**	**2.0**	**156**	**-1033**
2001	-1586	0	253	23	2.4	166	-1142
2002	-1751	0	213	19	2.0	175	-1342
2003	-1954	0	201	18	1.9	184	-1549
2004	-2148	0	183	17	1.7	192	-1755
2005	***-2353***	***0***	***196***	***18***	***1.8***	***358***	***-1779***
2006	*-2594*	*0*	*195*	*18*	*1.8*	*366*	*-2013*
2007	*-2761*	*0*	*184*	*17*	*1.7*	*373*	*-2185*
2008	***-2864***	***0***	***185***	***17***	***1.7***	***380***	***-2280***
2009	***-2907***	***0***	***191***	***18***	***1.8***	***387***	***-2310***
2010	***-2952***	***0***	***209***	***19***	***1.9***	***386***	***-2336***
2011	***-2976***	***0***	***210***	***19***	***2.0***	***386***	***-2359***
2012	***-2998***	***0***	***220***	***20***	***2.0***	***391***	***-2364***
2013	*-2987*	*-21*	*226*	*21*	*2.1*	*394*	*-2345*
2014	*-3017*	*-6*	*240*	*22*	*2.2*	*398*	*-2355*
2015	***-2730***	***-210***	***253***	***23***	***2.3***	***400***	***-2053***
2016	*-2862*	*-94*	*259*	*24*	*2.4*	*402*	*-2175*
2017	*-3000*	*-25*	*263*	*24*	*2.4*	*404*	*-2306*
2018	*-3115*	*-1*	*269*	*25*	*2.5*	*406*	*-2413*
2019	*-3282*	*40*	*282*	*26*	*2.6*	*408*	*-2564*
2020	***-2885***	***-255***	***292***	***27***	***2.7***	***410***	***-2154***

Table A4. 2: Removal of atmospheric carbon by post-1990 afforestation – England A: Mid emissions scenario, B: Low emission scenario, C: High emission scenario

A (Mid) England	**Afforestation**		**Deforestation**				**Art 3.3 (excludes HWP)**
Gg CO_2 /year or GWP equiv Gg CO_2/year	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Immediate loss (Biomass) CH_4**	**Immediate loss (Biomass) N_2O**	**Delayed loss (Soil) CO_2**	**Afforestation + Deforestation**
1990	**-3.3**	**0.0**	**108.5**	**9.9**	**1.0**	**13.4**	**129.6**
1991	2.9	0.0	98.4	9.0	0.9	26.1	137.4
1992	-2.4	0.0	101.9	9.3	0.9	38.0	147.8
1993	-28.6	0.0	74.5	6.8	0.7	49.2	102.7
1994	-69.2	0.0	85.4	7.8	0.8	59.8	84.7
1995	**-123.7**	**0.0**	**90.4**	**8.3**	**0.8**	**69.8**	**45.7**
1996	-194.6	0.0	109.2	10.0	1.0	79.2	4.8
1997	-271.1	0.0	112.1	10.3	1.0	88.0	-59.6
1998	-344.2	0.0	113.8	10.4	1.1	96.4	-122.6
1999	-410.8	0.0	137.2	12.6	1.3	104.3	-155.4
2000	**-465.3**	**0.0**	**152.3**	**14.0**	**1.4**	**111.8**	**-185.9**
2001	-512.7	0.0	182.0	16.7	1.7	118.9	-193.4
2002	-560.3	0.0	152.8	14.0	1.4	125.6	-266.5
2003	-612.4	0.0	144.2	13.2	1.3	131.9	-321.7
2004	-664.2	0.0	131.3	12.0	1.2	137.9	-381.8
2005	***-721.5***	***0.0***	***137.9***	***12.6***	***1.3***	***143.5***	***-426.1***
2006	*-774.4*	*0.0*	*132.1*	*12.1*	*1.2*	*148.8*	*-480.2*
2007	*-822.3*	*0.0*	*115.4*	*10.6*	*1.1*	*153.9*	*-541.4*
2008	***-865.9***	***0.0***	***107.8***	***9.9***	***1.0***	***158.7***	***-588.5***
2009	***-906.7***	***0.0***	***103.1***	***9.4***	***1.0***	***163.2***	***-630.0***
2010	***-950.0***	***0.0***	***107.3***	***9.8***	***1.0***	***167.5***	***-664.4***
2011	***-994.6***	***0.0***	***99.1***	***9.1***	***0.9***	***171.6***	***-713.9***
2012	***-1040.8***	***0.0***	***97.4***	***8.9***	***0.9***	***175.4***	***-758.2***
2013	*-1090.1*	*0.0*	*92.1*	*8.4*	*0.9*	*179.0*	*-809.6*
2014	*-1134.5*	*0.0*	*93.6*	*8.6*	*0.9*	*182.5*	*-849.0*
2015	***-1167.6***	***-13.8***	***93.2***	***8.5***	***0.9***	***185.8***	***-879.3***
2016	*-1230.8*	*-7.6*	*88.4*	*8.1*	*0.8*	*188.9*	*-944.5*
2017	*-1296.5*	*-1.2*	*82.4*	*7.5*	*0.8*	*191.8*	*-1014.0*
2018	*-1353.7*	*-3.2*	*77.5*	*7.1*	*0.7*	*194.6*	*-1073.7*
2019	*-1431.9*	*2.7*	*77.4*	*7.1*	*0.7*	*197.3*	*-1149.5*
2020	***-1444.3***	***-28.6***	***75.2***	***6.9***	***0.7***	***199.8***	***-1161.7***

B (Low) England	**Afforestation**		**Deforestation**				**Art 3.3 (excludes HWP)**
Gg CO_2 /year or GWP equiv Gg CO_2/year	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Biomass stocks**
1990	**-3.3**	**0.0**	**108.5**	**9.9**	**1.0**	**13.4**	**129.6**
1991	2.9	0.0	98.4	9.0	0.9	26.1	137.4
1992	-2.4	0.0	101.9	9.3	0.9	38.0	147.8
1993	-28.6	0.0	74.5	6.8	0.7	49.2	102.7
1994	-69.2	0.0	85.4	7.8	0.8	59.8	84.7
1995	**-123.7**	**0.0**	**90.4**	**8.3**	**0.8**	**69.8**	**45.7**
1996	-194.6	0.0	109.2	10.0	1.0	79.2	4.8
1997	-271.1	0.0	112.1	10.3	1.0	88.0	-59.6
1998	-344.2	0.0	113.8	10.4	1.1	96.4	-122.6
1999	-410.8	0.0	137.2	12.6	1.3	104.3	-155.4
2000	**-465.3**	**0.0**	**152.3**	**14.0**	**1.4**	**111.8**	**-185.9**
2001	-512.7	0.0	182.0	16.7	1.7	118.9	-193.4
2002	-560.3	0.0	152.8	14.0	1.4	125.6	-266.5
2003	-612.4	0.0	144.2	13.2	1.3	131.9	-321.7
2004	-664.2	0.0	131.3	12.0	1.2	137.9	-381.8
2005	***-723.4***	***0.0***	***135.2***	***12.4***	***1.3***	***78.9***	***-495.7***
2006	*-762.1*	*0.0*	*123.8*	*11.3*	*1.2*	*82.8*	*-543.0*
2007	*-821.0*	*0.0*	*98.7*	*9.0*	*0.9*	*86.5*	*-625.9*
2008	***-903.5***	***0.0***	***82.5***	***7.6***	***0.8***	***90.1***	***-722.7***
2009	***-1010.8***	***0.0***	***69.0***	***6.3***	***0.6***	***93.6***	***-841.2***
2010	***-1139.5***	***0.0***	***64.4***	***5.9***	***0.6***	***98.6***	***-970.1***
2011	***-1276.3***	***0.0***	***47.3***	***4.3***	***0.4***	***102.9***	***-1121.4***
2012	***-1412.7***	***0.0***	***36.5***	***3.3***	***0.3***	***106.7***	***-1265.8***
2013	*-1546.5*	*0.0*	*22.1*	*2.0*	*0.2*	*110.1*	*-1412.0*
2014	*-1669.3*	*0.0*	*14.6*	*1.3*	*0.1*	*113.2*	*-1540.0*
2015	***-1775.2***	***-13.8***	***9.2***	***0.8***	***0.1***	***115.3***	***-1649.8***
2016	*-1906.8*	*-7.6*	*4.6*	*0.4*	*0.0*	*117.2*	*-1784.5*
2017	*-2037.9*	*-1.2*	*0.0*	*0.0*	*0.0*	*0.0*	*-2037.9*
2018	*-2158.2*	*-3.2*	*0.0*	*0.0*	*0.0*	*0.0*	*-2158.2*
2019	*-2298.3*	*2.7*	*0.0*	*0.0*	*0.0*	*0.0*	*-2298.3*
2020	***-2372.1***	***-28.6***	***0.0***	***0.0***	***0.0***	***0.0***	***-2372.1***

C (High) England	Afforestation		Deforestation				Art 3.3 (excludes HWP)
Gg CO_2 /year or GWP equiv Gg CO_2/year	Biomass stocks	Harvested Wood Products	Immediate loss (Biomass) CO_2	Biomass stocks	Harvested Wood Products	Immediate loss (Biomass) CO_2	Biomass stocks
1990	**-3.3**	**0.0**	**108.5**	**9.9**	**1.0**	**13.4**	**129.6**
1991	2.9	0.0	98.4	9.0	0.9	26.1	137.4
1992	-2.4	0.0	101.9	9.3	0.9	38.0	147.8
1993	-28.6	0.0	74.5	6.8	0.7	49.2	102.7
1994	-69.2	0.0	85.4	7.8	0.8	59.8	84.7
1995	**-123.7**	**0.0**	**90.4**	**8.3**	**0.8**	**69.8**	**45.7**
1996	-194.6	0.0	109.2	10.0	1.0	79.2	4.8
1997	-271.1	0.0	112.1	10.3	1.0	88.0	-59.6
1998	-344.2	0.0	113.8	10.4	1.1	96.4	-122.6
1999	-410.8	0.0	137.2	12.6	1.3	104.3	-155.4
2000	**-465.3**	**0.0**	**152.3**	**14.0**	**1.4**	**111.8**	**-185.9**
2001	-512.7	0.0	182.0	16.7	1.7	118.9	-193.4
2002	-560.3	0.0	152.8	14.0	1.4	125.6	-266.5
2003	-612.4	0.0	144.2	13.2	1.3	131.9	-321.7
2004	-664.2	0.0	131.3	12.0	1.2	137.9	-381.8
2005	***-720.2***	***0.0***	***140.6***	***12.9***	***1.3***	***257.3***	***-308.1***
2006	*-782.4*	*0.0*	*140.3*	*12.9*	*1.3*	*262.7*	*-365.2*
2007	*-823.2*	*0.0*	*132.1*	*12.1*	*1.2*	*268.2*	*-409.6*
2008	***-841.3***	***0.0***	***133.1***	***12.2***	***1.2***	***273.2***	***-421.6***
2009	***-838.9***	***0.0***	***137.2***	***12.6***	***1.3***	***277.8***	***-410.0***
2010	***-826.6***	***0.0***	***150.2***	***13.8***	***1.4***	***277.1***	***-384.2***
2011	***-811.2***	***0.0***	***151.0***	***13.8***	***1.4***	***277.4***	***-367.5***
2012	***-798.6***	***0.0***	***158.3***	***14.5***	***1.5***	***280.9***	***-343.5***
2013	*-792.9*	*0.0*	*162.1*	*14.9*	*1.5*	*283.0*	*-331.5*
2014	*-786.4*	*0.0*	*172.7*	*15.8*	*1.6*	*285.7*	*-310.6*
2015	***-772.1***	***-13.8***	***181.4***	***16.6***	***1.7***	***287.0***	***-285.3***
2016	*-790.6*	*-7.6*	*185.9*	*17.0*	*1.7*	*288.5*	*-297.5*
2017	*-813.9*	*-1.2*	*189.0*	*17.3*	*1.8*	*289.9*	*-315.8*
2018	*-830.0*	*-3.2*	*193.4*	*17.7*	*1.8*	*291.5*	*-325.5*
2019	*-867.9*	*2.7*	*202.5*	*18.6*	*1.9*	*293.0*	*-352.0*
2020	***-840.3***	***-28.6***	***209.7***	***19.2***	***2.0***	***294.5***	***-315.0***

Table A4. 3: Removal of atmospheric carbon by post-1990 afforestation – Scotland A: Mid emissions scenario, B: Low emission scenario, C: High emission scenario

A (Mid) Scotland	**Afforestation**		**Deforestation**				**Art 3.3 (excludes HWP)**
Gg CO_2 /year or GWP equiv Gg CO_2/year	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Immediate loss (Biomass) CH_4**	**Immediate loss (Biomass) N_2O**	**Delayed loss (Soil) CO_2**	**Afforestation + Deforestation**
1990	**30.8**	**0.0**	**34.0**	**3.1**	**0.3**	**4.2**	**72.4**
1991	159.1	0.0	30.8	2.8	0.3	8.2	201.2
1992	196.9	0.0	31.9	2.9	0.3	11.9	244.0
1993	152.4	0.0	23.3	2.1	0.2	15.4	193.5
1994	38.3	0.0	26.8	2.5	0.2	18.7	86.5
1995	**-120.4**	**0.0**	**28.3**	**2.6**	**0.3**	**21.9**	**-67.4**
1996	-268.5	0.0	34.2	3.1	0.3	24.8	-206.0
1997	-429.9	0.0	35.1	3.2	0.3	27.6	-363.6
1998	-563.4	0.0	35.6	3.3	0.3	30.2	-493.9
1999	-690.4	0.0	43.0	3.9	0.4	32.7	-610.4
2000	**-814.8**	**0.0**	**47.7**	**4.4**	**0.4**	**35.0**	**-727.3**
2001	-919.5	0.0	57.0	5.2	0.5	37.2	-819.4
2002	-1022.7	0.0	47.9	4.4	0.4	39.3	-930.6
2003	-1158.1	0.0	45.2	4.1	0.4	41.3	-1067.0
2004	-1286.4	0.0	41.1	3.8	0.4	43.2	-1197.9
2005	***-1396.5***	***0.0***	***43.2***	***4.0***	***0.4***	***45.0***	***-1303.9***
2006	*-1490.9*	*0.0*	*41.4*	*3.8*	*0.4*	*46.6*	*-1398.7*
2007	*-1574.6*	*0.0*	*36.1*	*3.3*	*0.3*	*48.2*	*-1486.6*
2008	***-1656.0***	***0.0***	***33.8***	***3.1***	***0.3***	***49.7***	***-1569.1***
2009	***-1738.1***	***0.0***	***32.3***	***3.0***	***0.3***	***51.1***	***-1651.4***
2010	***-1861.8***	***0.0***	***33.6***	***3.1***	***0.3***	***52.5***	***-1772.3***
2011	***-1979.0***	***0.0***	***31.1***	***2.8***	***0.3***	***53.7***	***-1891.1***
2012	***-2092.5***	***0.0***	***30.5***	***2.8***	***0.3***	***55.0***	***-2003.9***
2013	*-2201.2*	*0.0*	*28.9*	*2.6*	*0.3*	*56.1*	*-2113.3*
2014	*-2297.8*	*0.0*	*29.3*	*2.7*	*0.3*	*57.2*	*-2208.4*
2015	***-2090.7***	***-190.6***	***29.2***	***2.7***	***0.3***	***58.2***	***-2000.3***
2016	*-2271.1*	*-79.2*	*27.7*	*2.5*	*0.3*	*59.2*	*-2181.4*
2017	*-2436.7*	*-23.8*	*25.8*	*2.4*	*0.2*	*60.1*	*-2348.2*
2018	*-2616.9*	*16.1*	*24.3*	*2.2*	*0.2*	*61.0*	*-2529.2*
2019	*-2798.3*	*42.3*	*24.2*	*2.2*	*0.2*	*61.8*	*-2709.8*
2020	***-2488.4***	***-222.1***	***23.6***	***2.2***	***0.2***	***62.6***	***-2399.8***

B (Low) Scotland	Afforestation		Deforestation				Art 3.3 (excludes HWP)
Gg CO_2 /year or GWP equiv Gg CO_2/year	Biomass stocks	Harvested Wood Products	Immediate loss (Biomass) CO_2	Biomass stocks	Harvested Wood Products	Immediate loss (Biomass) CO_2	Biomass stocks
1990	**30.8**	**0.0**	**34.0**	**3.1**	**0.3**	**4.2**	**72.4**
1991	159.1	0.0	30.8	2.8	0.3	8.2	201.2
1992	196.9	0.0	31.9	2.9	0.3	11.9	244.0
1993	152.4	0.0	23.3	2.1	0.2	15.4	193.5
1994	38.3	0.0	26.8	2.5	0.2	18.7	86.5
1995	**-120.4**	**0.0**	**28.3**	**2.6**	**0.3**	**21.9**	**-67.4**
1996	-268.5	0.0	34.2	3.1	0.3	24.8	-206.0
1997	-429.9	0.0	35.1	3.2	0.3	27.6	-363.6
1998	-563.4	0.0	35.6	3.3	0.3	30.2	-493.9
1999	-690.4	0.0	43.0	3.9	0.4	32.7	-610.4
2000	**-814.8**	**0.0**	**47.7**	**4.4**	**0.4**	**35.0**	**-727.3**
2001	-919.5	0.0	57.0	5.2	0.5	37.2	-819.4
2002	-1022.7	0.0	47.9	4.4	0.4	39.3	-930.6
2003	-1158.1	0.0	45.2	4.1	0.4	41.3	-1067.0
2004	-1286.4	0.0	41.1	3.8	0.4	43.2	-1197.9
2005	***-1360.8***	***0.0***	***42.3***	***3.9***	***0.4***	***24.7***	***-1289.4***
2006	*-1353.6*	*0.0*	*38.8*	*3.6*	*0.4*	*25.9*	*-1284.9*
2007	*-1391.7*	*0.0*	*30.9*	*2.8*	*0.3*	*27.1*	*-1330.6*
2008	***-1485.8***	***0.0***	***25.8***	***2.4***	***0.2***	***28.2***	***-1429.1***
2009	***-1635.4***	***0.0***	***21.6***	***2.0***	***0.2***	***29.3***	***-1582.2***
2010	***-1865.6***	***0.0***	***20.2***	***1.8***	***0.2***	***30.9***	***-1812.5***
2011	***-2106.9***	***0.0***	***14.8***	***1.4***	***0.1***	***32.2***	***-2058.3***
2012	***-2345.8***	***0.0***	***11.4***	***1.0***	***0.1***	***33.4***	***-2299.8***
2013	*-2574.7*	*0.0*	*6.9*	*0.6*	*0.1*	*34.5*	*-2532.6*
2014	*-2784.6*	*0.0*	*4.6*	*0.4*	*0.0*	*35.5*	*-2744.1*
2015	***-2684.7***	***-190.6***	***2.9***	***0.3***	***0.0***	***36.1***	***-2645.4***
2016	*-2967.6*	*-79.2*	*1.5*	*0.1*	*0.0*	*36.7*	*-2929.3*
2017	*-3232.9*	*-23.8*	*0.0*	*0.0*	*0.0*	*0.0*	*-3232.9*
2018	*-3511.4*	*16.1*	*0.0*	*0.0*	*0.0*	*0.0*	*-3511.4*
2019	*-3791.1*	*42.3*	*0.0*	*0.0*	*0.0*	*0.0*	*-3791.1*
2020	***-3581.1***	***-222.1***	***0.0***	***0.0***	***0.0***	***0.0***	***-3581.1***

C (High) Scotland	**Afforestation**		**Deforestation**				**Art 3.3 (excludes HWP)**
Gg CO_2 /year or GWP equiv Gg CO_2/year	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Biomass stocks**
1990	**30.8**	**0.0**	**34.0**	**3.1**	**0.3**	**4.2**	**72.4**
1991	159.1	0.0	30.8	2.8	0.3	8.2	201.2
1992	196.9	0.0	31.9	2.9	0.3	11.9	244.0
1993	152.4	0.0	23.3	2.1	0.2	15.4	193.5
1994	38.3	0.0	26.8	2.5	0.2	18.7	86.5
1995	**-120.4**	**0.0**	**28.3**	**2.6**	**0.3**	**21.9**	**-67.4**
1996	-268.5	0.0	34.2	3.1	0.3	24.8	-206.0
1997	-429.9	0.0	35.1	3.2	0.3	27.6	-363.6
1998	-563.4	0.0	35.6	3.3	0.3	30.2	-493.9
1999	-690.4	0.0	43.0	3.9	0.4	32.7	-610.4
2000	**-814.8**	**0.0**	**47.7**	**4.4**	**0.4**	**35.0**	**-727.3**
2001	-919.5	0.0	57.0	5.2	0.5	37.2	-819.4
2002	-1022.7	0.0	47.9	4.4	0.4	39.3	-930.6
2003	-1158.1	0.0	45.2	4.1	0.4	41.3	-1067.0
2004	-1286.4	0.0	41.1	3.8	0.4	43.2	-1197.9
2005	***-1419.7***	***0.0***	***44.1***	***4.0***	***0.4***	***80.6***	***-1290.6***
2006	*-1580.3*	*0.0*	*44.0*	*4.0*	*0.4*	*82.3*	*-1449.6*
2007	*-1693.8*	*0.0*	*41.4*	*3.8*	*0.4*	*84.0*	*-1564.2*
2008	***-1766.9***	***0.0***	***41.7***	***3.8***	***0.4***	***85.6***	***-1635.4***
2009	***-1805.0***	***0.0***	***43.0***	***3.9***	***0.4***	***87.0***	***-1670.6***
2010	***-1859.2***	***0.0***	***47.1***	***4.3***	***0.4***	***86.8***	***-1720.6***
2011	***-1895.8***	***0.0***	***47.3***	***4.3***	***0.4***	***86.9***	***-1756.8***
2012	***-1927.5***	***0.0***	***49.6***	***4.5***	***0.5***	***88.0***	***-1784.9***
2013	*-1957.9*	*0.0*	*50.8*	*4.7*	*0.5*	*88.7*	*-1813.4*
2014	*-1980.8*	*0.0*	*54.1*	*5.0*	*0.5*	*89.5*	*-1831.8*
2015	***-1703.9***	***-190.6***	***56.8***	***5.2***	***0.5***	***89.9***	***-1551.4***
2016	*-1817.6*	*-79.2*	*58.2*	*5.3*	*0.5*	*90.4*	*-1663.1*
2017	*-1918.4*	*-23.8*	*59.2*	*5.4*	*0.6*	*90.8*	*-1762.3*
2018	*-2034.6*	*16.1*	*60.6*	*5.6*	*0.6*	*91.3*	*-1876.6*
2019	*-2151.9*	*42.3*	*63.5*	*5.8*	*0.6*	*91.8*	*-1990.2*
2020	***-1776.9***	***-222.1***	***65.7***	***6.0***	***0.6***	***92.3***	***-1612.3***

Table A4. 4: Removal of atmospheric carbon by post-1990 afforestation – Wales A: Mid emissions scenario, B: Low emission scenario, C: High emission scenario

A (Mid) Wales	**Afforestation**		**Deforestation**				**Art 3.3 (excludes HWP)**
Gg CO_2 /year or GWP equiv Gg CO_2/year	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Immediate loss (Biomass) CH_4**	**Immediate loss (Biomass) N_2O**	**Delayed loss (Soil) CO_2**	**Afforestation + Deforestation**
1990	**-1.3**	**0.0**	**8.6**	**0.8**	**0.1**	**1.1**	**9.3**
1991	-0.3	0.0	7.8	0.7	0.1	2.1	10.3
1992	-2.0	0.0	8.1	0.7	0.1	3.0	9.9
1993	-6.0	0.0	5.9	0.5	0.1	3.9	4.3
1994	-12.0	0.0	6.8	0.6	0.1	4.7	0.2
1995	**-18.3**	**0.0**	**7.2**	**0.7**	**0.1**	**5.5**	**-4.9**
1996	-25.4	0.0	8.6	0.8	0.1	6.3	-9.7
1997	-32.9	0.0	8.9	0.8	0.1	7.0	-16.2
1998	-40.2	0.0	9.0	0.8	0.1	7.6	-22.6
1999	-46.5	0.0	10.9	1.0	0.1	8.3	-26.3
2000	**-52.0**	**0.0**	**12.0**	**1.1**	**0.1**	**8.8**	**-29.9**
2001	-57.0	0.0	14.4	1.3	0.1	9.4	-31.7
2002	-63.5	0.0	12.1	1.1	0.1	9.9	-40.3
2003	-70.5	0.0	11.4	1.0	0.1	10.4	-47.5
2004	-76.3	0.0	10.4	1.0	0.1	10.9	-53.9
2005	***-80.4***	***0.0***	***10.9***	***1.0***	***0.1***	***11.4***	***-57.0***
2006	*-83.9*	*0.0*	*10.4*	*1.0*	*0.1*	*11.8*	*-60.6*
2007	*-87.4*	*0.0*	*9.1*	*0.8*	*0.1*	*12.2*	*-65.2*
2008	***-91.5***	***0.0***	***8.5***	***0.8***	***0.1***	***12.6***	***-69.6***
2009	***-96.3***	***0.0***	***8.2***	***0.7***	***0.1***	***12.9***	***-74.4***
2010	***-102.7***	***0.0***	***8.5***	***0.8***	***0.1***	***13.2***	***-80.1***
2011	***-108.9***	***0.0***	***7.8***	***0.7***	***0.1***	***13.6***	***-86.7***
2012	***-114.9***	***0.0***	***7.7***	***0.7***	***0.1***	***13.9***	***-92.6***
2013	*-120.7*	*0.0*	*7.3*	*0.7*	*0.1*	*14.2*	*-98.6*
2014	*-126.2*	*0.0*	*7.4*	*0.7*	*0.1*	*14.4*	*-103.6*
2015	***-122.6***	***-6.0***	***7.4***	***0.7***	***0.1***	***14.7***	***-99.7***
2016	*-132.9*	*-1.6*	*7.0*	*0.6*	*0.1*	*14.9*	*-110.3*
2017	*-142.7*	*0.7*	*6.5*	*0.6*	*0.1*	*15.2*	*-120.3*
2018	*-152.3*	*1.9*	*6.1*	*0.6*	*0.1*	*15.4*	*-130.1*
2019	*-159.5*	*0.8*	*6.1*	*0.6*	*0.1*	*15.6*	*-137.1*
2020	***-154.9***	***-6.6***	***6.0***	***0.5***	***0.1***	***15.8***	***-132.6***

B (Low) Wales	Afforestation		Deforestation				Art 3.3 (excludes HWP)
Gg CO_2 /year or GWP equiv Gg CO_2/year	Biomass stocks	Harvested Wood Products	Immediate loss (Biomass) CO_2	Biomass stocks	Harvested Wood Products	Immediate loss (Biomass) CO_2	Biomass stocks
1990	**-1.3**	**0.0**	**8.6**	**0.8**	**0.1**	**1.1**	**9.3**
1991	-0.3	0.0	7.8	0.7	0.1	2.1	10.3
1992	-2.0	0.0	8.1	0.7	0.1	3.0	9.9
1993	-6.0	0.0	5.9	0.5	0.1	3.9	4.3
1994	-12.0	0.0	6.8	0.6	0.1	4.7	0.2
1995	**-18.3**	**0.0**	**7.2**	**0.7**	**0.1**	**5.5**	**-4.9**
1996	-25.4	0.0	8.6	0.8	0.1	6.3	-9.7
1997	-32.9	0.0	8.9	0.8	0.1	7.0	-16.2
1998	-40.2	0.0	9.0	0.8	0.1	7.6	-22.6
1999	-46.5	0.0	10.9	1.0	0.1	8.3	-26.3
2000	**-52.0**	**0.0**	**12.0**	**1.1**	**0.1**	**8.8**	**-29.9**
2001	-57.0	0.0	14.4	1.3	0.1	9.4	-31.7
2002	-63.5	0.0	12.1	1.1	0.1	9.9	-40.3
2003	-70.5	0.0	11.4	1.0	0.1	10.4	-47.5
2004	-76.3	0.0	10.4	1.0	0.1	10.9	-53.9
2005	***-80.7***	***0.0***	***10.7***	***1.0***	***0.1***	***6.2***	***-62.6***
2006	*-82.5*	*0.0*	*9.8*	*0.9*	*0.1*	*6.6*	*-65.2*
2007	*-87.3*	*0.0*	*7.8*	*0.7*	*0.1*	*6.8*	*-71.8*
2008	***-95.9***	***0.0***	***6.5***	***0.6***	***0.1***	***7.1***	***-81.6***
2009	***-108.4***	***0.0***	***5.5***	***0.5***	***0.1***	***7.4***	***-94.9***
2010	***-124.7***	***0.0***	***5.1***	***0.5***	***0.0***	***7.8***	***-111.3***
2011	***-141.5***	***0.0***	***3.7***	***0.3***	***0.0***	***8.1***	***-129.3***
2012	***-157.9***	***0.0***	***2.9***	***0.3***	***0.0***	***8.4***	***-146.3***
2013	*-173.5*	*0.0*	*1.8*	*0.2*	*0.0*	*8.7*	*-162.9*
2014	*-188.0*	*0.0*	*1.2*	*0.1*	*0.0*	*9.0*	*-177.8*
2015	***-192.8***	***-6.0***	***0.7***	***0.1***	***0.0***	***9.1***	***-182.9***
2016	*-211.1*	*-1.6*	*0.4*	*0.0*	*0.0*	*9.3*	*-201.4*
2017	*-228.3*	*0.7*	*0.0*	*0.0*	*0.0*	*0.0*	*-228.3*
2018	*-245.2*	*1.9*	*0.0*	*0.0*	*0.0*	*0.0*	*-245.2*
2019	*-259.6*	*0.8*	*0.0*	*0.0*	*0.0*	*0.0*	*-259.6*
2020	***-262.1***	***-6.6***	***0.0***	***0.0***	***0.0***	***0.0***	***-262.1***

C (High) Wales	**Afforestation**		**Deforestation**				**Art 3.3 (excludes HWP)**
Gg CO_2 /year or GWP equiv Gg CO_2/year	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Biomass stocks**
1990	**-1.3**	**0.0**	**8.6**	**0.8**	**0.1**	**1.1**	**9.3**
1991	-0.3	0.0	7.8	0.7	0.1	2.1	10.3
1992	-2.0	0.0	8.1	0.7	0.1	3.0	9.9
1993	-6.0	0.0	5.9	0.5	0.1	3.9	4.3
1994	-12.0	0.0	6.8	0.6	0.1	4.7	0.2
1995	**-18.3**	**0.0**	**7.2**	**0.7**	**0.1**	**5.5**	**-4.9**
1996	-25.4	0.0	8.6	0.8	0.1	6.3	-9.7
1997	-32.9	0.0	8.9	0.8	0.1	7.0	-16.2
1998	-40.2	0.0	9.0	0.8	0.1	7.6	-22.6
1999	-46.5	0.0	10.9	1.0	0.1	8.3	-26.3
2000	**-52.0**	**0.0**	**12.0**	**1.1**	**0.1**	**8.8**	**-29.9**
2001	-57.0	0.0	14.4	1.3	0.1	9.4	-31.7
2002	-63.5	0.0	12.1	1.1	0.1	9.9	-40.3
2003	-70.5	0.0	11.4	1.0	0.1	10.4	-47.5
2004	-76.3	0.0	10.4	1.0	0.1	10.9	-53.9
2005	***-80.2***	***0.0***	***11.1***	***1.0***	***0.1***	***20.4***	***-47.7***
2006	*-84.8*	*0.0*	*11.1*	*1.0*	*0.1*	*20.8*	*-51.8*
2007	*-87.4*	*0.0*	*10.4*	*1.0*	*0.1*	*21.2*	*-54.7*
2008	***-88.6***	***0.0***	***10.5***	***1.0***	***0.1***	***21.6***	***-55.4***
2009	***-88.4***	***0.0***	***10.9***	***1.0***	***0.1***	***22.0***	***-54.5***
2010	***-88.4***	***0.0***	***11.9***	***1.1***	***0.1***	***21.9***	***-53.4***
2011	***-87.7***	***0.0***	***11.9***	***1.1***	***0.1***	***21.9***	***-52.6***
2012	***-86.9***	***0.0***	***12.5***	***1.1***	***0.1***	***22.2***	***-50.9***
2013	*-86.4*	*0.0*	*12.8*	*1.2*	*0.1*	*22.4*	*-49.9*
2014	*-86.0*	*0.0*	*13.7*	*1.3*	*0.1*	*22.6*	*-48.3*
2015	***-76.8***	***-6.0***	***14.3***	***1.3***	***0.1***	***22.7***	***-38.3***
2016	*-82.1*	*-1.6*	*14.7*	*1.3*	*0.1*	*22.8*	*-43.1*
2017	*-86.9*	*0.7*	*15.0*	*1.4*	*0.1*	*22.9*	*-47.5*
2018	*-91.8*	*1.9*	*15.3*	*1.4*	*0.1*	*23.1*	*-51.9*
2019	*-94.3*	*0.8*	*16.0*	*1.5*	*0.1*	*23.2*	*-53.5*
2020	***-85.1***	***-6.6***	***16.6***	***1.5***	***0.2***	***23.3***	***-43.6***

Table A4. 5: Removal of atmospheric carbon by post-1990 afforestation – N. Ireland A: Mid emissions scenario, B: Low emission scenario, C: High emission scenario

A (Mid) N. Ireland	**Afforestation**		**Deforestation**				**Art 3.3 (excludes HWP)**
Gg CO_2 /year or GWP equiv Gg CO_2/year	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Immediate loss (Biomass) CH_4**	**Immediate loss (Biomass) N_2O**	**Delayed loss (Soil) CO_2**	**Afforestation + Deforestation**
1990	**2.2**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**2.2**
1991	14.9	0.0	0.0	0.0	0.0	0.0	14.9
1992	15.7	0.0	0.0	0.0	0.0	0.0	15.7
1993	7.6	0.0	0.0	0.0	0.0	0.0	7.6
1994	-1.5	0.0	0.0	0.0	0.0	0.0	-1.5
1995	**-15.5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**-15.5**
1996	-34.0	0.0	0.0	0.0	0.0	0.0	-34.0
1997	-50.2	0.0	0.0	0.0	0.0	0.0	-50.2
1998	-66.0	0.0	0.0	0.0	0.0	0.0	-66.0
1999	-79.6	0.0	0.0	0.0	0.0	0.0	-79.6
2000	**-89.6**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**-89.6**
2001	-97.1	0.0	0.0	0.0	0.0	0.0	-97.1
2002	-105.0	0.0	0.0	0.0	0.0	0.0	-105.0
2003	-112.7	0.0	0.0	0.0	0.0	0.0	-112.7
2004	-121.4	0.0	0.0	0.0	0.0	0.0	-121.4
2005	***-130.7***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-130.7***
2006	*-139.4*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*-139.4*
2007	*-147.2*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*-147.2*
2008	***-159.2***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-159.2***
2009	***-169.2***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-169.2***
2010	***-177.8***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-177.8***
2011	***-187.6***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-187.6***
2012	***-196.6***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-196.6***
2013	*-168.1*	*-21.4*	*0.0*	*0.0*	*0.0*	*0.0*	*-168.1*
2014	*-187.6*	*-6.5*	*0.0*	*0.0*	*0.0*	*0.0*	*-187.6*
2015	***-206.3***	***0.9***	***0.0***	***0.0***	***0.0***	***0.0***	***-206.3***
2016	*-205.1*	*-5.9*	*0.0*	*0.0*	*0.0*	*0.0*	*-205.1*
2017	*-219.5*	*-0.6*	*0.0*	*0.0*	*0.0*	*0.0*	*-219.5*
2018	*-202.2*	*-15.3*	*0.0*	*0.0*	*0.0*	*0.0*	*-202.2*
2019	*-216.5*	*-6.2*	*0.0*	*0.0*	*0.0*	*0.0*	*-216.5*
2020	***-236.0***	***1.9***	***0.0***	***0.0***	***0.0***	***0.0***	***-236.0***

B (Low) N. Ireland	**Afforestation**		**Deforestation**				**Art 3.3 (excludes HWP)**
Gg CO_2 /year or GWP equiv Gg CO_2/year	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Biomass stocks**
1990	**2.2**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**2.2**
1991	14.9	0.0	0.0	0.0	0.0	0.0	14.9
1992	15.7	0.0	0.0	0.0	0.0	0.0	15.7
1993	7.6	0.0	0.0	0.0	0.0	0.0	7.6
1994	-1.5	0.0	0.0	0.0	0.0	0.0	-1.5
1995	**-15.5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**-15.5**
1996	-34.0	0.0	0.0	0.0	0.0	0.0	-34.0
1997	-50.2	0.0	0.0	0.0	0.0	0.0	-50.2
1998	-66.0	0.0	0.0	0.0	0.0	0.0	-66.0
1999	-79.6	0.0	0.0	0.0	0.0	0.0	-79.6
2000	**-89.6**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**-89.6**
2001	-97.1	0.0	0.0	0.0	0.0	0.0	-97.1
2002	-105.0	0.0	0.0	0.0	0.0	0.0	-105.0
2003	-112.7	0.0	0.0	0.0	0.0	0.0	-112.7
2004	-121.4	0.0	0.0	0.0	0.0	0.0	-121.4
2005	***-128.0***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-128.0***
2006	*-129.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*-129.1*
2007	*-133.5*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*-133.5*
2008	***-146.3***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-146.3***
2009	***-161.3***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-161.3***
2010	***-177.8***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-177.8***
2011	***-196.8***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-196.8***
2012	***-215.2***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-215.2***
2013	*-195.7*	*-21.4*	*0.0*	*0.0*	*0.0*	*0.0*	*-195.7*
2014	*-223.6*	*-6.5*	*0.0*	*0.0*	*0.0*	*0.0*	*-223.6*
2015	***-250.4***	***0.9***	***0.0***	***0.0***	***0.0***	***0.0***	***-250.4***
2016	*-257.0*	*-5.9*	*0.0*	*0.0*	*0.0*	*0.0*	*-257.0*
2017	*-278.9*	*-0.6*	*0.0*	*0.0*	*0.0*	*0.0*	*-278.9*
2018	*-269.1*	*-15.3*	*0.0*	*0.0*	*0.0*	*0.0*	*-269.1*
2019	*-290.9*	*-6.2*	*0.0*	*0.0*	*0.0*	*0.0*	*-290.9*
2020	***-318.0***	***1.9***	***0.0***	***0.0***	***0.0***	***0.0***	***-318.0***

C (High) N. Ireland	Afforestation		Deforestation				Art 3.3 (excludes HWP)
Gg CO_2 /year or GWP equiv Gg CO_2/year	**Biomass stocks**	**Harvested Wood Products**	**Immediate loss (Biomass) CO_2**	**Immediate loss (Biomass) CH_4**	**Immediate loss (Biomass) N_2O**	**Delayed loss (Soil) CO_2**	**Afforestation + Deforestation**
1990	**2.2**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**2.2**
1991	14.9	0.0	0.0	0.0	0.0	0.0	14.9
1992	15.7	0.0	0.0	0.0	0.0	0.0	15.7
1993	7.6	0.0	0.0	0.0	0.0	0.0	7.6
1994	-1.5	0.0	0.0	0.0	0.0	0.0	-1.5
1995	**-15.5**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**-15.5**
1996	-34.0	0.0	0.0	0.0	0.0	0.0	-34.0
1997	-50.2	0.0	0.0	0.0	0.0	0.0	-50.2
1998	-66.0	0.0	0.0	0.0	0.0	0.0	-66.0
1999	-79.6	0.0	0.0	0.0	0.0	0.0	-79.6
2000	**-89.6**	**0.0**	**0.0**	**0.0**	**0.0**	**0.0**	**-89.6**
2001	-97.1	0.0	0.0	0.0	0.0	0.0	-97.1
2002	-105.0	0.0	0.0	0.0	0.0	0.0	-105.0
2003	-112.7	0.0	0.0	0.0	0.0	0.0	-112.7
2004	-121.4	0.0	0.0	0.0	0.0	0.0	-121.4
2005	***-132.4***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-132.4***
2006	*-146.1*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*-146.1*
2007	*-156.2*	*0.0*	*0.0*	*0.0*	*0.0*	*0.0*	*-156.2*
2008	***-167.5***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-167.5***
2009	***-174.3***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-174.3***
2010	***-177.8***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-177.8***
2011	***-181.5***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-181.5***
2012	***-184.5***	***0.0***	***0.0***	***0.0***	***0.0***	***0.0***	***-184.5***
2013	*-150.2*	*-21.4*	*0.0*	*0.0*	*0.0*	*0.0*	*-150.2*
2014	*-164.1*	*-6.5*	*0.0*	*0.0*	*0.0*	*0.0*	*-164.1*
2015	***-177.5***	***0.9***	***0.0***	***0.0***	***0.0***	***0.0***	***-177.5***
2016	*-171.3*	*-5.9*	*0.0*	*0.0*	*0.0*	*0.0*	*-171.3*
2017	*-180.8*	*-0.6*	*0.0*	*0.0*	*0.0*	*0.0*	*-180.8*
2018	*-158.6*	*-15.3*	*0.0*	*0.0*	*0.0*	*0.0*	*-158.6*
2019	*-168.1*	*-6.2*	*0.0*	*0.0*	*0.0*	*0.0*	*-168.1*
2020	***-182.6***	***1.9***	***0.0***	***0.0***	***0.0***	***0.0***	***-182.6***

Section 3

Variations in Forest Management in Great Britain

Table of Contents

3. Variations in Forest Management in Great Britain

A.M. Thomson
Centre for Ecology and Hydrology, Edinburgh

3.1. Introduction

The C-Flow model developed by CEH (Cannell and Dewar, 1995; Dewar and Cannell, 1992; Milne et al., 1998) models the carbon accumulation over time in forest biomass, dead material, soil and forest products, as reported under category 5A2 (Land converted to Forest Land) in the GHG inventory. The input data for C-Flow are (a) areas of new forest planted in each year in the past and (b) the stemwood growth rate and harvesting pattern. The areas of annual new planting come from time series of broadleaf and conifer planting in each country of the UK, obtained from national statistics compiled by the Forestry Commission (Great Britain) and Forest Service (Northern Ireland). Stemwood growth rates and harvesting patterns are based on tree species and yield classes, with standard management scenarios for thinning and felling ages.

Up to the present inventory, C-Flow has not made use of the more detailed data available from the National Inventory of Woodland and Trees (NIWT) for Great Britain (Forestry Commission, 2003). Potentially this would provide more detailed information on forest species and age structure, at a larger spatial scale than the national level. Previous work (Milne and Brown, 2003) has shown that there are large discrepancies between the national planting time series and forest establishment rates inferred from the NIWT (Figure 3-1) and the causes of these merit further investigation. Additional data and management information on GB forests can be found in the historical woodland censuses. These censuses can be used with the NIWT to provide a more detailed picture of forest management in GB and to investigate the validity of C-Flow's standard management assumption.

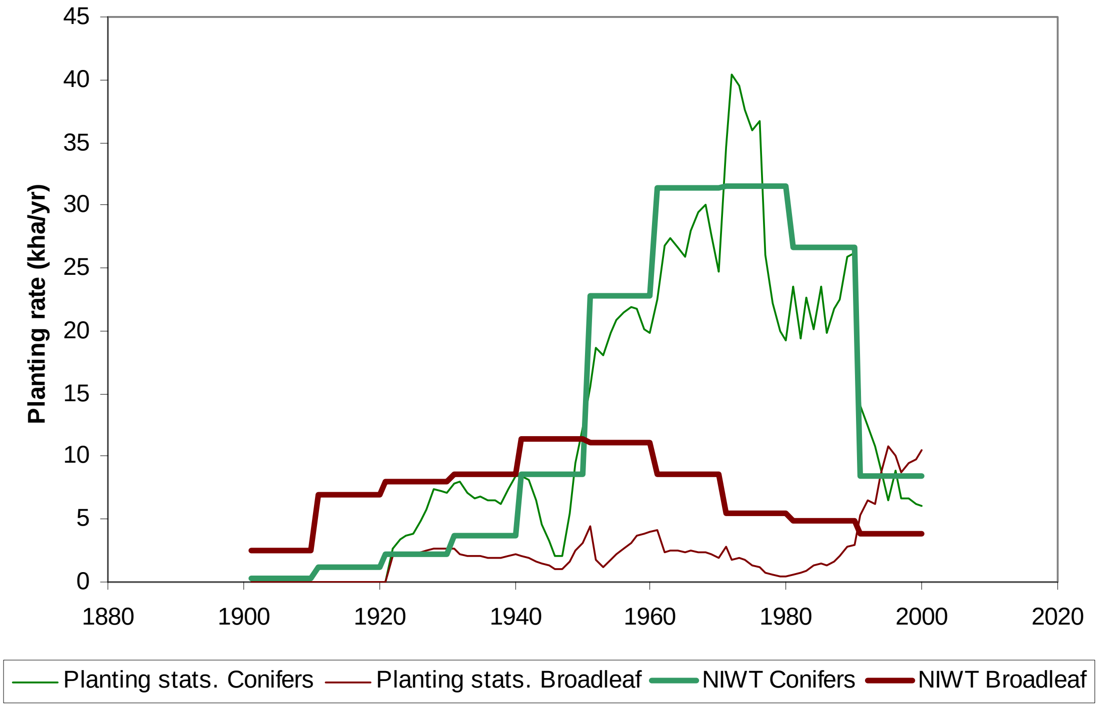


Figure 3-1 National planting rates vs. forest establishment rates inferred from the NIWT

By using these additional sources of information to explore variations in forest planting and management over time, the work in this chapter aims to fulfil three main objectives:

1. to explain the difference between the national planting time series and the NIWT;
2. to assess the validity of the assumption of standard management in C-Flow using information from the historical woodland censuses; and,
3. if applicable, to derive and apply new planting series for C-Flow.

3.2. Materials and methods

3.2.1. Data sources

3.2.1.1 National planting statistics

These statistics record the area of conifer and broadleaf woodland planted annually on previously unforested land. The statistics have been recorded since 1921 for England, Scotland and Wales by the Forestry Commission, and since 1900 for Northern Ireland by the Forest Service.

3.2.1.2 The National Inventory of Woodland and Trees (NIWT)

The NIWT consists of two surveys: the Main Woodland Survey (MWS) of woods ≥2 hectares, and the Survey of Small Woodland and Trees. The MWS is composed of a digital woodland map (derived from 1:25 000 aerial photographs) and a ground sample survey to evaluate woodland information, such as species, age and stocking (Forestry Commission, 2003). Survey fieldwork was undertaken between 1994 and 2000. Planning is underway to undertake a second inventory of GB woodlands (NIWT2) from 2007 onwards. There is no equivalent woodland inventory for Northern Ireland.

The establishment 'date' (within a decade) for a woodland stand is inferred from the average age of its trees recorded by the NIWT sample survey. For newly planted woodland the establishment dates and the planting date should be equivalent. However, because the NIWT functions as a 'snapshot' of woodland in the late 1990s, the following points should be noted. (1) Not all woodland established within a certain decade will appear in the equivalent age class in the NIWT, due to deforestation or disturbance. (2) The NIWT does not distinguish whether a woodland stand was afforested (i.e. established on previously unforested land) or replanted (established on land that had previously been forested but whose tree cover had been felled or disturbed in some way).

3.2.1.3 Historical woodland censuses

Censuses of woodland in Great Britain were carried out in 1924, 1947, 1965 and 1980 (Forestry Commission, 1928; Forestry Commission, 1952; Locke, 1970; Locke, 1987). The censuses are reported at the GB, national (England, Scotland, Wales) and county scale, but are not linked to woodland maps at the larger scales.

There are differences in sampling methodologies and minimum mapping units (from 1 to 5 acres, or 0.4 to 2 hectares) between censuses. However, very small woodlands are a small proportion of the total woodland area and sampling is sufficiently dense that the censuses are broadly comparable at the national level. Woodland area, type, species composition and age classes (from <10 years to pre-1860) are reported in all censuses. After a quality assessment, the 1965 census was omitted from analyses, as it was not a complete survey of all woodlands (both state and private) and was not comparable with the other censuses. The quality issues associated with the different censuses were kept in mind during the analysis and interpretation. Commentaries in the census reports also give useful information on the processes affecting woodland areas in different parts of Great Britain.

3.2.2. Methods

The national planting series and the NIWT inferred establishment dates were compared for conifer and broadleaf woodlands, and for England, Scotland and Wales (NIWT is not available for Northern Ireland). The annual figures in the national planting series were aggregated into decadal figures to match the NIWT.

Changes in woodland categories and age classes were compared between censuses, to investigate changes over time. The 1924 and 1947 censuses report woodlands in 10 to 20 year age classes, while the 1980 and NIWT census link the age classes more closely with specific decades. The different classes were combined for analysis as shown in Table 3-1. Care was taken when interpreting changes in very young woodland (under 20 years old) as it is difficult to correctly identify the age of such woodlands during fieldwork. The 1947 census also lists an uneven aged class, which contained around half of the broadleaved woodland in England and Wales and 17% in Scotland.

Table 3-1 Combination of census age classes for analysis

Analysis age class	**Census age class, age in years**			
	1924 census	**1947 census**	**1980 census**	**NIWT (1999)**
1991-99				(1-9)
1981-90				(10-19)
1971-80			(1-10)	(20-29)
1961-70			(11-20)	(30-39)
1951-60			(21-30)	(40-49)
1941-50		(1-10)	(31-40)	(50-59)
1931-40		(11-20)	(41-50)	(60-69)
1921-30		(21-30)	(51-60)	(70-79)
1911-20	(1-10)	(31-40)	(61-70)	(80-89)
1901-10	(11-20)	*0.5**(41-60)	(71-80)	(90-99)
1861-1900	(21-40) + *0.5**(41-80)	*0.5**(41-60) + (61-80) + *0.25**(81-120)	(81-120)	(100-139)
pre-1861	*0.5**(41-80) + (over 80)	*0.75**(81-120) + (over 120)	(over 121)	(over 140)

The 1924 and 1947 censuses split forests between conifer, hardwood and mixed categories, but the 1947 census also reports forest as mainly coniferous and mainly broadleaved. This two-way split is used by subsequent censuses. The 1924 mixed woodland category is of varying significance between countries (30% of English woodlands, 20% of Welsh woodlands and 11% of Scottish woodlands) and falls predominantly into the pre-1900 age classes. In 1947 mixed woodland accounted for 11% of English woodland, 6% of Welsh woodland and 6% of Scottish woodland. The mixed woodland is split between the mainly conifer and mainly broadleaf categories in 1924 in the same proportion for pre- and post-1900 woodland as in 1947.

- Pre-1900 broadleaf:conifer split: 60:40 (England), 69:31 (Wales), 58:42 (Scotland)
- Post-1900 broadleaf:conifer split: 40:60 (England), 33:66 (Wales and Scotland).

3.3. Results

3.3.1. Differences in the national planting time series and the NIWT

Conifer planting in Scotland since the 1950s dominates the UK total, as shown in Figure 3-2 While both national planting series and NIWT inferred establishment rates of conifer woodland are broadly similar for individual countries over time, there are greater differences between the two data sources during certain periods. In the 1920s-1940s national planting rates ("afforestation") exceeds NIWT establishment rates in all countries. Afforestation rates dip in the 1940s in England and Scotland, but both afforestation and NIWT establishment rates increase in all countries between 1950 and 1970. Afforestation rates decline in England and Wales after 1970, but in Scotland rates do not fall until after 1990. The difference between afforestation rates and NIWT-inferred establishment rates increases in England and Wales from the 1970s, but this is not evident in Scotland.

In contrast, Figure 3-3 clearly shows that NIWT-inferred establishment rates of broadleaf woodland exceed afforestation rates in all countries from the 1920s to the 1990s. England and Scotland have increased rates of inferred woodland establishment between 1940 and 1960, which then gradually decline to 1990. In Wales, inferred establishment rates are higher in the 1930s and then decline to 1970, remaining steady after that. Afforestation exceeds NIWT-inferred establishment rates from 1990 onwards in England and Scotland. This is thought to be an artefact of the NIWT sampling method, as different regions within each country were sampled at different times (England was completed in 1998, Scotland in 1995 and Wales in 1997).

3.3.2. Evidence from the historical woodland censuses

The majority of conifer woodland in the UK is plantation forest established during the 20th century (Figure 3-4), which can be assumed to have a harvesting rotation of 50-70 years. Felling of woodland (or loss of area due to other disturbances) can be inferred from loss of area in age classes between successive censuses. Normal harvesting practice would explain some of the differences in planting/establishment rates at either end of the time period (shown in Figure 3-2), as in normal circumstances woodland planted in 1921-1940 would be felled and replanted in the 1980s and 1990s. This can be seen in the reduction in area between the 1980 and NIWT census in the 1921-30 and 1931-40 age classes. Other sources of difference may arise from normal management of conifer woodland planted before 1920 and the perturbation caused by the extensive felling during and after the 1939-1945 war. (This is particularly evident in the difference between the 1924 and 1947 censuses in the pre-1900 age class). There was also a reduction in rates of new planting at this time (presumably due to a lack of materials and labour).

Harvesting of pre-existing conifer woodland, if replanting is assumed, is sufficient to account for most of the difference between the afforestation rate and the NIWT-inferred rate during the 20th century. The uneven age class in the 1947 census only contains a small amount of conifer woodland, so does not affect the shape of the graphs. Loss of area in the 1950-1980 age classes between the 1980 and NIWT censuses is apparent in Figure 3-4. These changes in age structure between censuses suggest that some conifer forest may be managed on shorter rotations than that assumed by the standard management scenario. Conversely, some forests planted in the early decades of the 20th century may be managed on longer rotations. This may be due to the use of different conifer species: the standard scenario in C-Flow assumes that all conifer planting is of Sitka spruce with a 59 year rotation, but Scots pine (rotation of 71-75 years) and larch (rotation of 40-45 years) have also been widely planted. A shorter rotation might also be a response to losses from natural disturbance, particularly wind throw (Grayson, 1989; Quine et al., 1995). The census reports also mention that replanting was not immediate after the extensive felling during the 1939-1945 war, and the age structure suggest that this replanting continued into the 1960s.

Analysis of the changing age class structure between censuses for broadleaf woodland (Figure 3-5) indicates different processes of woodland change, operating over longer timescales. In the UK the broadleaf woodland area has an older age structure than the conifer woodland area, and woodland that was established before 1920 is a larger component of the total. The uneven age class in the 1947 census is a very significant component in England (Figure 3-5(b)), complicating interpretation. Broadleaved woodland in Scotland was poorly reported in the 1924 census so the interpretation of change using these figures should be treated with caution.

Commentary in the census reports suggest that the difference between the broadleaf afforestation rate and the NIWT-inferred establishment rate has arisen from a combination of sources. These are: normal management (i.e. harvesting and replanting) of broadleaf woodland planted before 1920, conversion of coppice woodland to broadleaved 'high forest', the reclassification of mixed or scrub woodland to broadleaved woodland, and natural regeneration on forested areas that were cleared but not replanted between 1914 and 1945.

1. Normal management of pre-1920 broadleaf woodland. Given that harvest rotations for broadleaved woodlands under normal conditions are in the region of 90-120 years, some of the difference between the afforestation rate and the NIWT-inferred rate is a result of normal harvesting and replanting, although active management of broadleaf woodland also declined during the 20^{th} century.

2. Conversion of coppice to broadleaved 'high forest'. The total area of broadleaf-based woodland categories (broadleaf high forest, coppice and mixed woodland) changed relatively little between 1924 and 1947 (Figure 3-6). In all countries the area of broadleaf high forest increased at the expense of coppice and mixed woodland categories. Commentary in the 1947 woodland census suggests that the expansion in the area of broadleaved forest, given the relatively small scale of active replanting, has been obtained partly by the reclassification of coppice (after abandonment of coppice management systems) and mixed forest as broadleaved forest (Forestry Commission, 1952). This process of coppice conversion seems to have continued between 1947 and 1980 in England and Wales (coppice in Scotland had almost entirely disappeared during the previous period). Coppice may also have been over-exploited and degraded to scrub woodland.

3. Mixed woodland and scrub conversion. The definition of mixed and scrub woodland changes between the historical censuses, and mixed woodland is not described separately after 1947, but is divided between the "mainly broadleaved" and "mainly coniferous" categories. Woodland that was not classified as broadleaved woodland at the time of one census, but as scrub or mixed woodland, may have developed into broadleaved woodland with age, and therefore will appear in the NIWT age classes as having been established further back in time. This process is reflected by comments in the census reports, for example:

> 'Most of the younger crops classified as mixed have been established with the object of raising crops of broadleaved trees with the aid of conifer nurses, and will, in due course, become classifiable as broadleaved when the conifers have served their purpose.' (Forestry Commission, 1952):50.

And:

> '…owing to less intensive agricultural land use and better control of fires, many commons and open spaces which fifty years ago were quite bare, today carry Stands of timber. In nearly all such cases an initial stage in this process is the establishment of Scrub.'(Forestry Commission, 1952):105.

4. Natural regeneration on cleared areas. Extensive felling of mature broadleaf woodland took place during and after the 1939-1945 war. Large areas were also cleared and abandoned during and after the 1914-1918 war. Such areas were classified as "felled" or "devastated" in the 1924 and 1947 census, and commentary in the reports suggests that only a percentage of these areas were replanted in the short term. The remaining unplanted areas, particularly in England, tended to revert to some form of broadleaved scrub or forest. This process may explain the peak in broadleaved woodland establishment between 1941 and 1960:

> 'Many of these crops are ones which arose from fellings during the Second World War, either from broadleaved crops cleared during the period or as a result of broadleaved species naturally regenerating sites which had previously carried coniferous or broadleaved crops…It is likely that many of the crops on sites felled during the First World War and in the twenties and thirties also arose in this fashion.' (Locke, 1987): 48

Both conversion of coppice to forest and natural regeneration of felled woodland will produce relatively young broadleaved woodlands on woodland sites that pre-date the 1920s. These woodlands do not contribute to the broadleaf planting statistics as they have not arisen from deliberate new planting, but should be visible in the NIWT age classes as woodlands between 30 and 80 years old. Coppice conversion (particularly of coppice-with-standards) and natural regeneration of devastated woodland would produce a bi-model age distribution, and would therefore account for the large area in the uneven age class in 1947. The proportionately large increase in the 1941-50 age classes between the 1947 and 1980 census in all countries is interpreted as being largely due to natural regeneration. Losses of mature timber (some due to normal harvesting, and some probably due to extensive felling during the 1939-45 war) are particularly evident in the change in the pre-1861 class after the 1924 census. In Scotland and Wales, the age classes in the 1980 and NIWT censuses seem to be stable after 1950.

In summary, different processes affecting broadleaf woodland age structure were more active in some countries than others: coppice conversion and active management (felling and replanting) is more prevalent in England, while scrub reclassification and natural regeneration are thought to play a greater role in Scotland and Wales. After 1990 the broadleaved planting rate exceeds that derived from the NIWT. This is thought to be due to the fact that the age classes recorded in the NIWT are based on samples collected in the early 1990s, and therefore do not capture later planting.

3.3.3. Standard and non-standard management in C-Flow

Changes in the standard management assumptions in C-Flow will affect the modelled carbon flux because the timing of forest growth and harvesting is altered. There is not necessarily a direct relationship between increased forest area and increased carbon fluxes. This variable impact is illustrated in Figure 3-7, which shows the estimated carbon flux (conifer and broadleaf woodland) by country. The greatest differences are apparent for England, where the inclusion of coppice/scrub conversion and natural regeneration of existing woodland increases the carbon flux by approximately 0.4 MtC a^{-1} between 1990 and 2004.

It was decided to include only adjustments to post-1921 woodland in this inventory, as with forest planted before 1921 and processes of woodland conversion and regeneration it is impossible to estimate the original establishment date of the woodland area. Evidence from a comparison of the various data sources suggests that the standard conifer management scenario of post-1921 forest in C-Flow could be adjusted. At present all conifer planting is assumed to be Sitka spruce, with a harvesting rotation of 59 years, and a yield class of 12 m^3 $ha^{-1}a^{-1}$. The C-Flow management scenario could be adjusted by using the current species class and afforestation series, but split between different rotation lengths.

Standard planting scenarios

- Planting 1921-1989– Sitka, 59 year rotation – England, Wales, Scotland, Northern Ireland
- Planting 1990-2004 – England, Wales, Scotland, Northern Ireland

Additional non-standard planting scenarios

- Planting 1921-1950, Sitka, 50 year rotation – England and Wales
- Planting 1931-1940, Sitka, 40 year rotation – England

The impact of these adjustments is relatively minor, producing an estimated carbon flux of 4.45 Mt C in 2004 compare to a flux of 4.40 Mt C without the adjustments (Figure 3-8), but represents a first attempt at improving the modelling of actual forest management in C-Flow.

With respect to broadleaf woodland, at present all broadleaf planting in C-Flow is assumed to be beech, with a harvesting rotation of 92 years and a yield class of 6 m^3 ha^{-1} a^{-1}. The management adaptation used for conifer cannot be used for broadleaved woodland as it is difficult to tell whether the length of the harvesting rotation has changed as the assumed standard rotation is so long. There is also the issue of whether conversion/regeneration is unintentional or deliberate forest management: sometimes it may begin as a natural process and then be brought under management at a later stage. The issue of how to modify base carbon emission/removal factors when woodland change does not result in soil disturbance also needs to be resolved. Therefore, at the present time, the standard management assumption for broadleaf woodland in C-Flow is left unaltered.

3.4. Conclusions

The additional information in the NIWT and the historical woodland censuses is useful for unpicking changes in woodland structure in Great Britain during the 20th century at the national scale, producing a more detailed picture than was previously available. The discrepancies between the national planting series and the NIWT can be explained in terms of normal harvesting practice and management and regeneration of woodland that existed before 1921. Broad-scale variation in harvesting rotations and unintentional processes of woodland change (coppice conversion and natural regeneration) can be inferred by examining the changes in forest age structure over time and using the commentaries in the censuses.

These historical data sources open the possibility of including woodland that was first established before 1920 (i.e. visible in the NIWT but not in the afforestation rates) in C-Flow. This would make it possible to include all British woodland in the C-Flow model, and therefore in the greenhouse gas inventory, but key issues remain. At present, forest carbon fluxes are reported under category 5A2 (Land converted to Forest Land) and zero flux is assumed for category 5A1 (Forest land remaining Forest land). The inclusion of older forest would invalidate this assumption, and the assignment of forest fluxes between the two sub-categories (5A1 and 5A2) needs to be considered. Secondly, carbon fluxes in soil, as a result of forest planting on previously unforested land, are an important component of the overall forest flux. However, because the planting series only date from 1921 it is not possible to say whether forest dating from before this time was newly planted or of considerable age. Thirdly, the variability in methodologies and data quality between historical woodland censuses would make it unwise to extend the analysis below the national/regional level, making it difficult to model spatially disaggregated forest carbon fluxes (a long term aim in the greenhouse gas inventory). Finally, issues remain with the mismatch between the national planting series and the NIWT in the 1990s, but it is hoped that this can be resolved by using data from the Woodland Grant Scheme to produce a more spatially detailed picture of recent forest planting.

3.5. References

Cannell, M.G.R. and Dewar, R.C., 1995. The Carbon Sink Provided by Plantation Forests and Their Products in Britain. Forestry, 68(1): 35-48.

Dewar, R.C. and Cannell, M.G.R., 1992. Carbon Sequestration in the Trees, Products and Soils of Forest Plantations - an Analysis Using Uk Examples. Tree Physiology, 11(1): 49-71.

Forestry Commission, 1928. Report on census of woodlands and census of production of home-grown timber, 1924, HMSO, London.

Forestry Commission, 1952. Census of woodlands 1947-1949. Woodlands of 5 acres and over. (Forestry Commission Census Report 1). HMSO, London, 264 pp.

Forestry Commission, 2003. National Inventory of Woodland and Trees. Great Britain., Forestry Commission, Edinburgh.

Grayson, A.J. (Editor), 1989. The 1987 storm: impacts and responses. Forestry Commission Bulletin, 87. HMSO, London, 56 pp.

Locke, G.M.L., 1970. Census of woodlands 1965-67. A report on Britain's forest resources., Forestry Commission, London.

Locke, G.M.L., 1987. Census of woodlands and trees 1979-82. Forestry Commission Bulletin 63., Forestry Commission, London.

Milne, R. and Brown, T.A.W., 2003. Mapping of carbon uptake in British afforestation and land use change, Annual report (2003) for DEFRA Contract EPG1/1/160.

Milne, R., Brown, T.A.W. and Murray, T.D., 1998. The effect of geographical variation in planting rate on the uptake of carbon by new forests in Great Britain. Forestry, 71: 298-309.

Quine, C.P., Coutts, M., Gardiner, B.A. and Pyatt, G., 1995. Forests and wind: management to minimise damage. Forestry Commission Bulletin, 114. HMSO, London, 35 pp.

A)
B)
C)

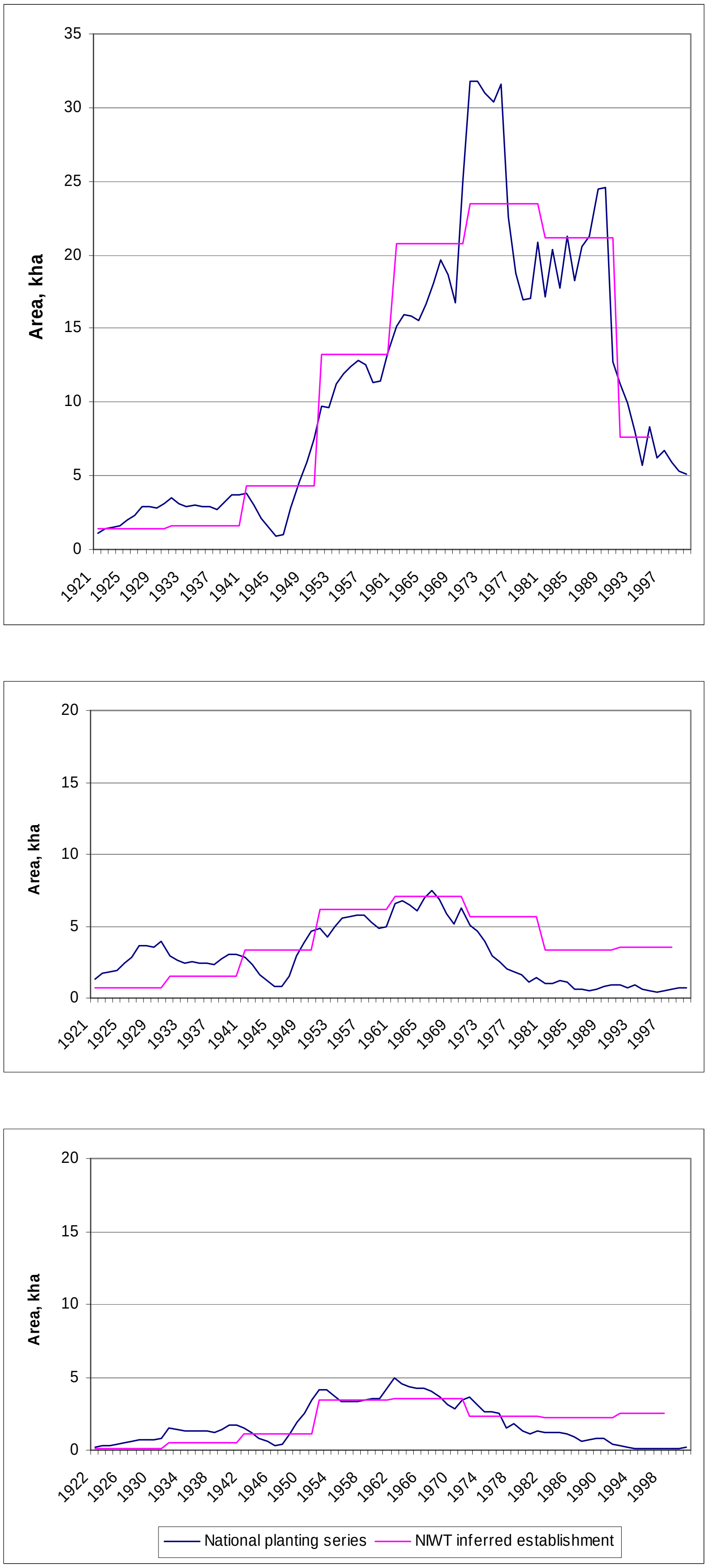


Figure 3-2 Differences in conifer planting rates in A) Scotland, B) England and C) Wales.

A)

B)

C)

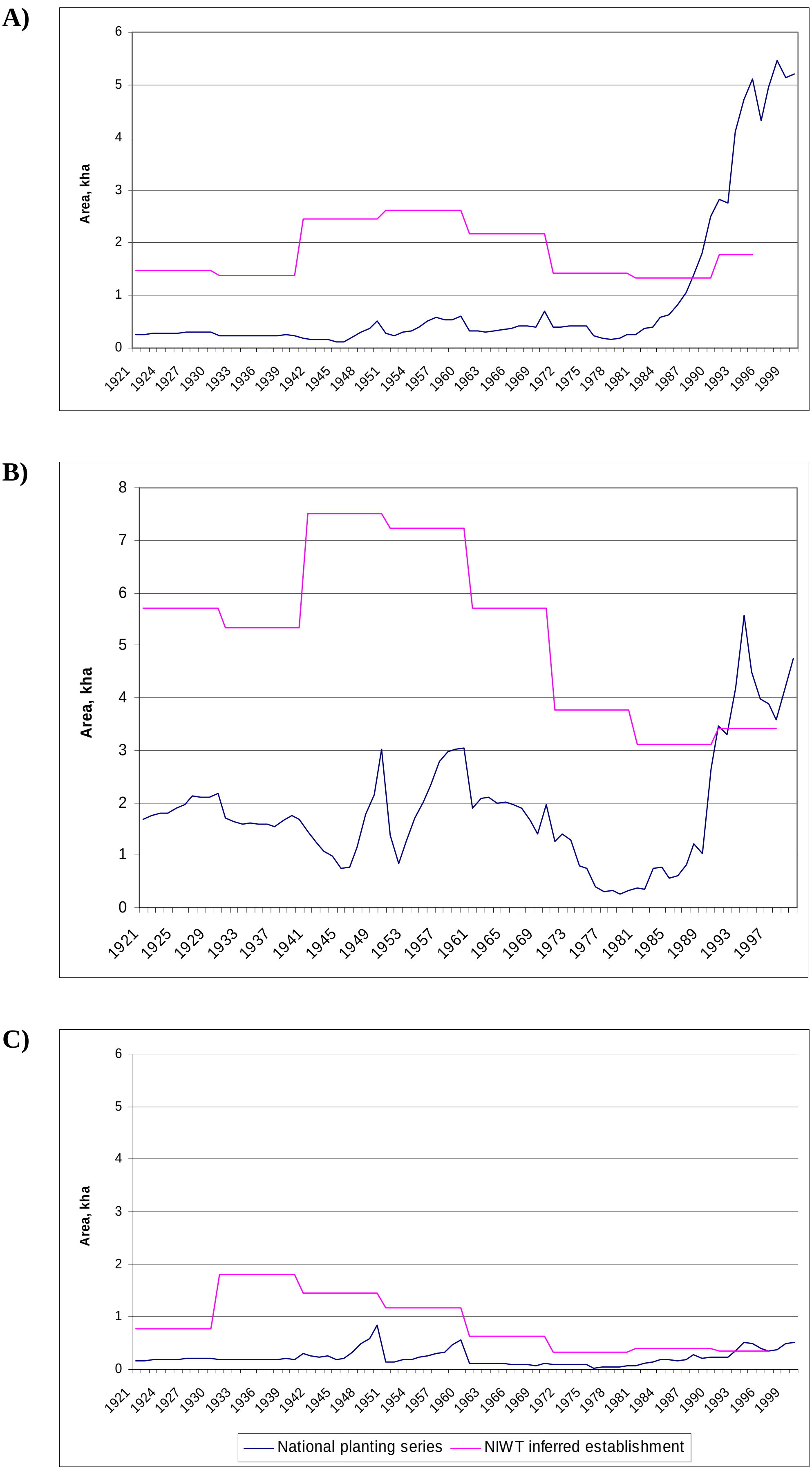


Figure 3-3 Differences in broadleaf planting rates in A) Scotland, B) England and C) Wales.

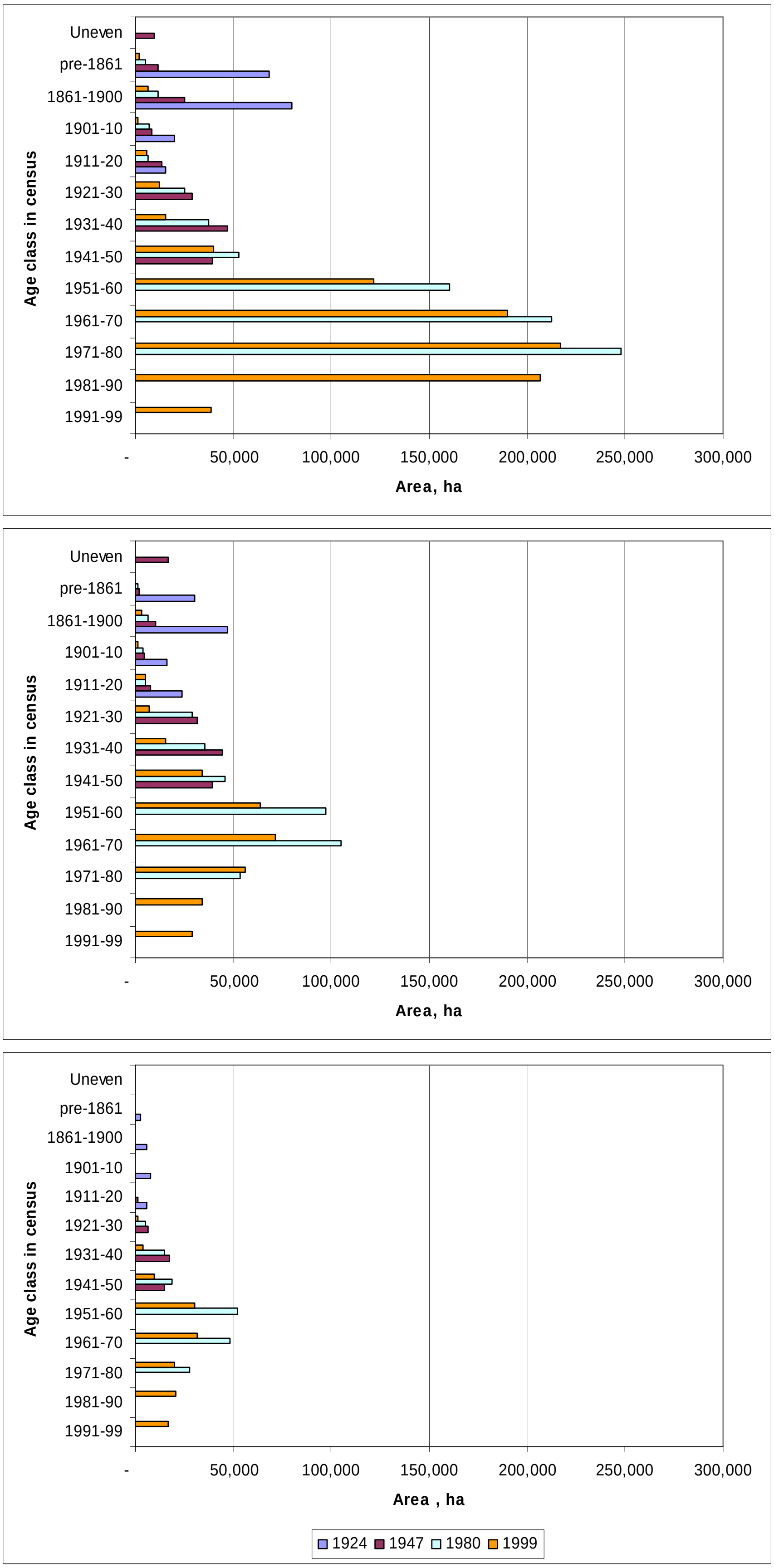


Figure 3-4 Conifer woodland age classes from the historical woodland censuses in A) Scotland, B) England and C) Wales. (1924 values include some mixed woodland).

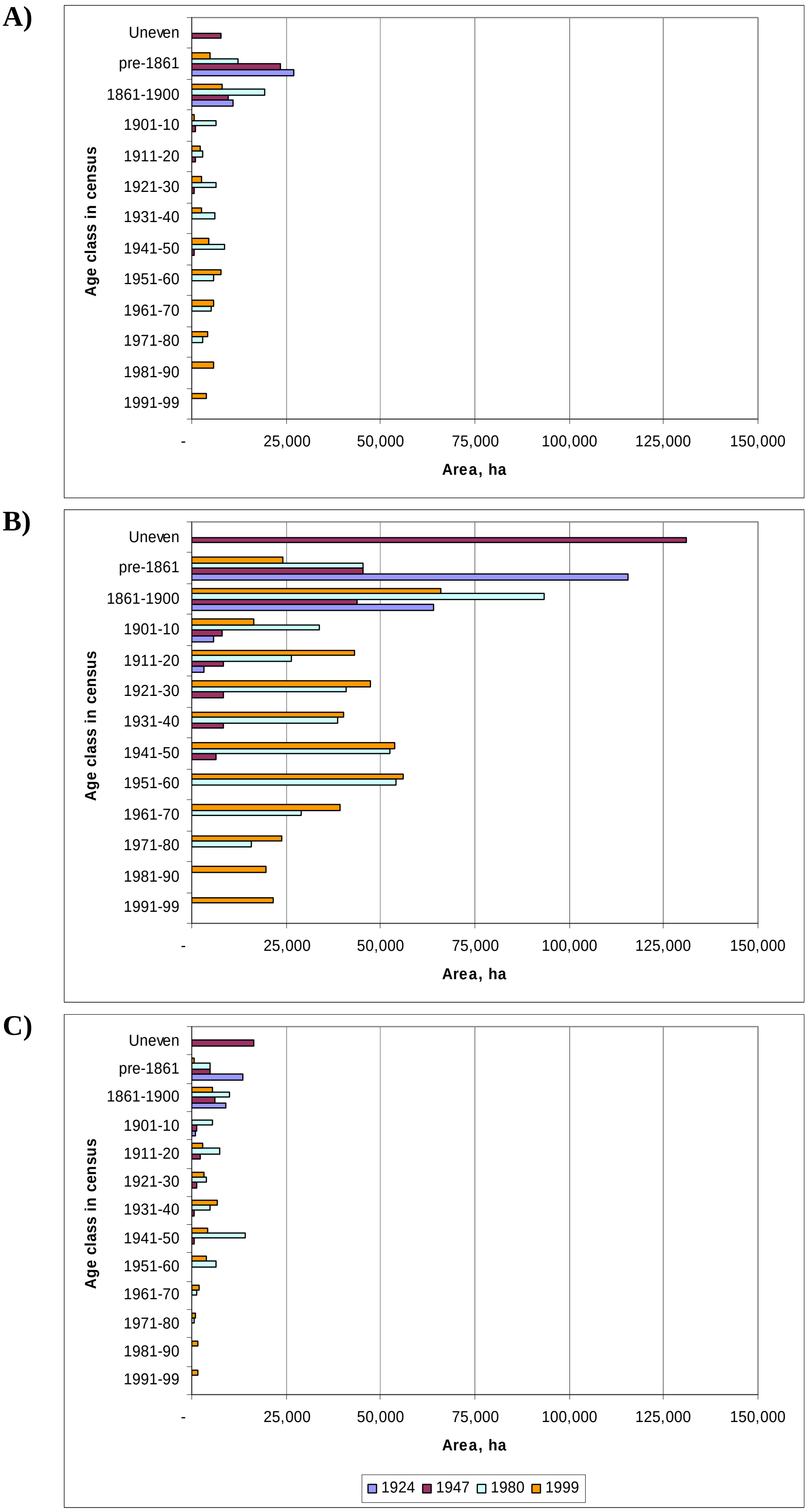


Figure 3-5 Broadleaved woodland age classes from the historical woodland censuses in A) Scotland, B) England and C) Wales. (1924 values include some mixed woodland).

A)

B)

C)

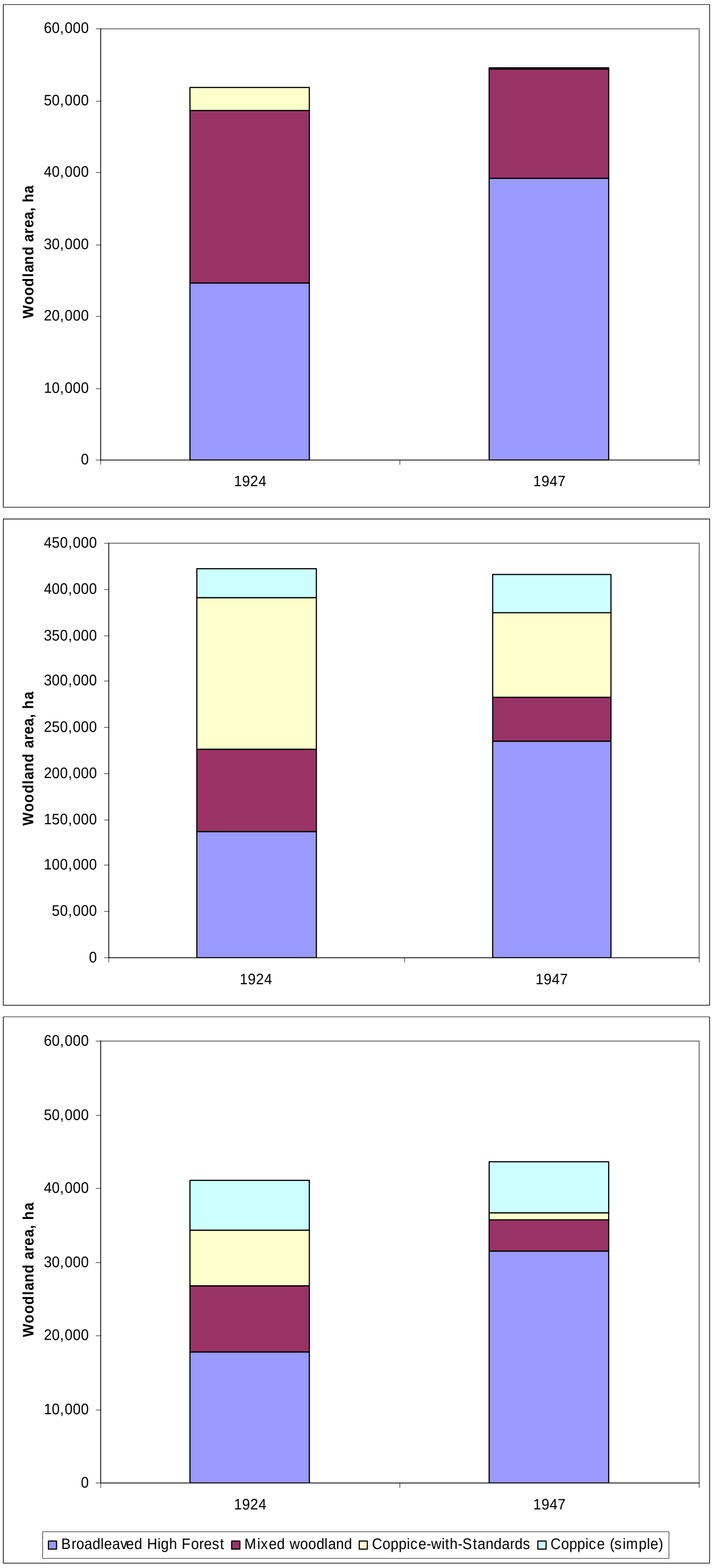


Figure 3-6 Areas of broadleaf-based woodland categories in the 1924 and 1947 censuses, in A) Scotland, B) England and C) Wales.

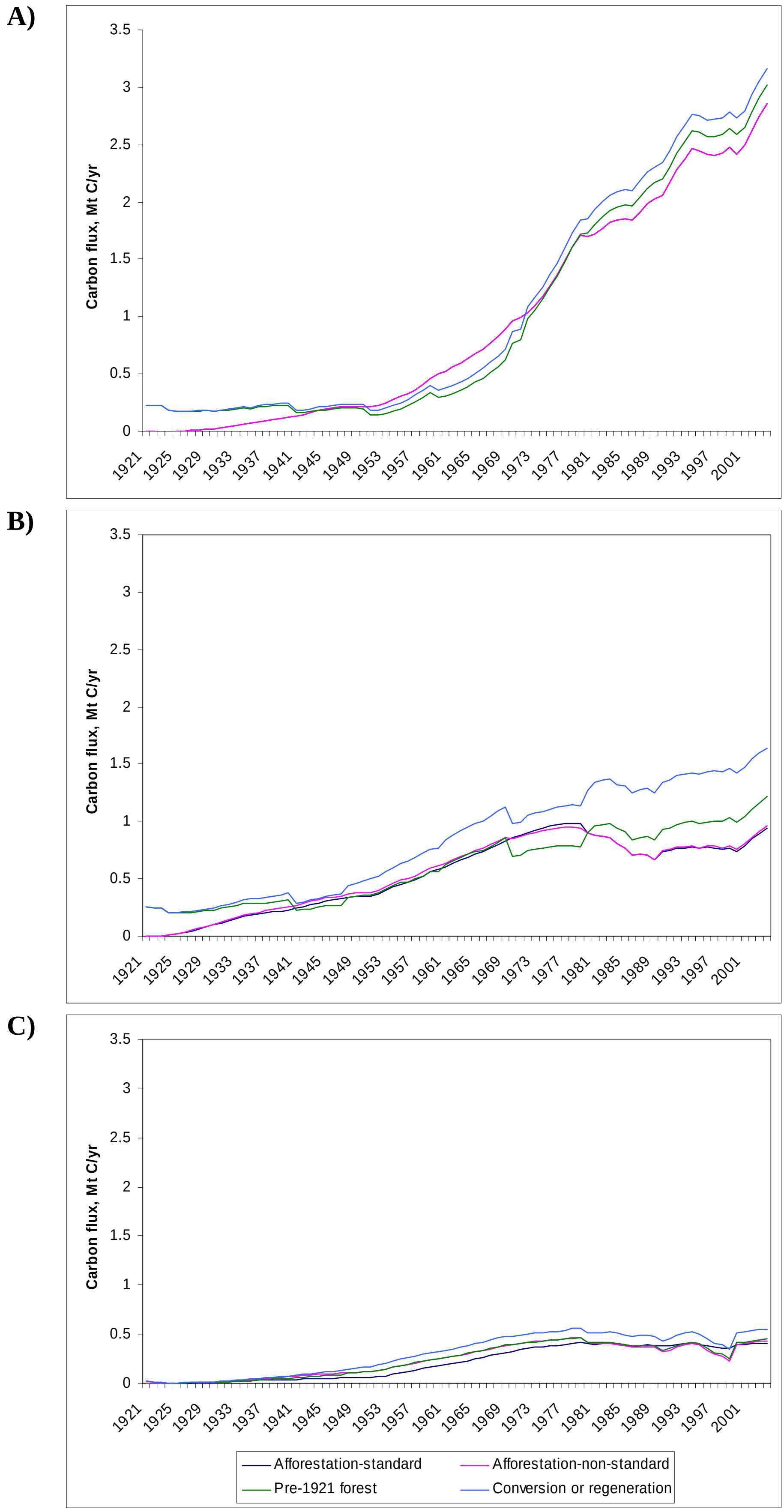


Figure 3-7 Additional impact on forest carbon fluxes through changes in management and inclusion of pre-1921 forest, in A) Scotland, B) England, and C) Wales.

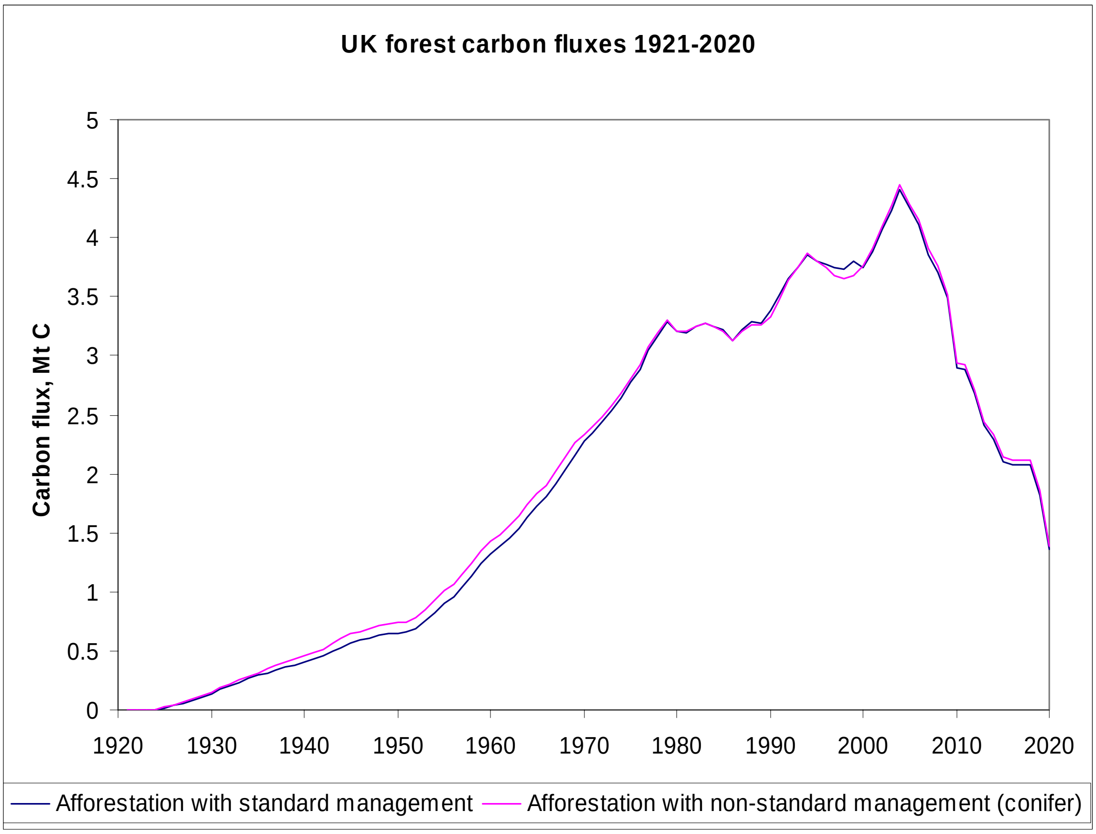


Figure 3-8 Impact on forest carbon fluxes in the UK modelled by C-Flow with standard and non-standard management.

Section 4

Survey Methods for Kyoto Protocol Monitoring and Verification of UK Forest Carbon Stocks

Table of Contents

4. Survey Methods for Kyoto Protocol Monitoring and Verification of UK Forest Carbon Stocks

R.W. Matthews, M.S.J. Broadmeadow, E. Mackie, M. Wilkinson S. Benham and K. Harris
Forest Research, Alice Holt Research Station, Farnham, Surrey, GU10 4LH, UK

4.1. Summary

This report provides an overview of the position reached in developing a methodology for monitoring and reporting a national forest carbon inventory. A description is provided of the state of development of the principal building blocks comprising the methodology, including assessment protocols and supporting models. The methodology under development has evolved from the system proposed originally in Matthews and Broadmeadow (2003). Significant progress has been made leading to a revised methodology which clarifies the key functions needed for the main system components. Seven system modules are identified dealing with mapping of forest areas, stand-level sample assessments, statistical relationships and models, field verification of models, model-based upscaling of carbon stock estimates, statistically based verification of upscaled carbon stock estimates and reporting. Progress in development of these modules has been considerable but a fully articulated system has not yet been constructed. Future work will concentrate on linking modules to form a comprehensive, integrated and robust carbon monitoring methodology.

4.2. Introduction

The Kyoto Protocol (UNFCCC, 1998) contains a number of stipulations concerning the reporting by participating countries of net changes in greenhouse gas emissions by sources and removals by sinks resulting from direct human-induced land-use change and forestry activities. The Protocol places restrictions on precisely what sources and sinks should be counted as part of a national greenhouse gas balance (notably in terms of any forestry activities initiated before 1990). However there is an implicit requirement for participating countries to develop the capability to periodically monitor and report carbon stocks and stock changes associated with national forests. In particular, countries are required to provide data to establish the level of national forest carbon stocks in 1990 and to enable an estimate to be made of changes in carbon stocks in subsequent years. The Protocol further stipulates that all such monitoring must be undertaken in a transparent and verifiable manner.

The purpose of this report is to provide an overview of the position reached in developing a methodology for monitoring and reporting a national forest carbon inventory. A description is provided of the state of development of the principal building blocks comprising the methodology, including assessment protocols and supporting models. The potential for integrating carbon monitoring into existing forest monitoring and research networks is explored. In particular, the current status of the National Inventory of Woodland and Trees (NIWT), a key component of the proposed methodology, is discussed. Progress towards field testing of the methodology is also reported.

4.3. Development of methodology

The methodology under development has been evolved from the system proposed originally in Matthews and Broadmeadow (2003). From the earliest stages of development, emphasis was placed on maximising the use/re-use of existing monitoring networks and available models. This is reflected in the modular design proposed by Matthews and Broadmeadow (Table 4-1 and Figure 4-1) which made explicit reference to the incorporation and application of existing research outputs. The system as specified in 2003 was composed of four main 'Modules' (A-D):

- Module A consisted of a forest inventory-based approach supported by forest carbon accounting models, used to generate district-level and national-level estimates of carbon stocks in forest biomass, litter and soil.
- Modules B, C and D were intended to supply data and assessments for the verification of estimates generated by Module A, or to support development, calibration and validation of underlying models.

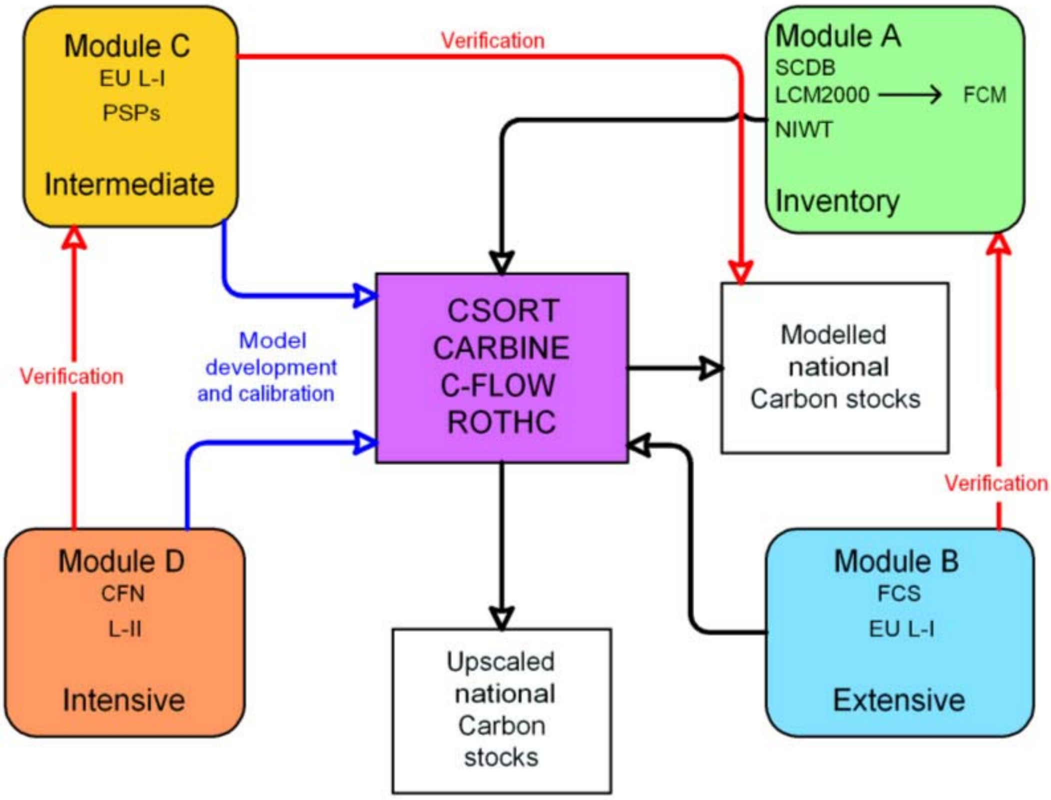


Figure 4-1 System diagram for carbon monitoring network as proposed by Matthews and Broadmeadow (2003)

This represented a critical first step in thinking, particularly in terms of how existing systems might be integrated to address the carbon-monitoring problem. However, the details of data flows, precise linkages between systems and a distinction between calculations involved in verifying as opposed to deriving carbon stock estimates were not explicitly defined. Significant progress has since been made in these areas of detailed system specification, leading to the revised system diagram shown in Figure 4-2.

Table 4-1 Description of 4 'Modules' comprising carbon monitoring system proposed by Matthews and Broadmeadow (2003)

Module	Sampling design and intensity	Siting within stand	Plot/assessment layout	Assessment protocols	Application	Cost and accuracy/precision	Comments
A	Complete representation of forest stands down to a threshold minimum area.	Sampling at random locations through stand, but with stratification according to CS2000, NIWT and FE SCDB methodologies.	Point sampling based on nominal 0.01 ha plots?	According to updated CS2000/NIWT methodology, harmonised with existing FE SCDB strategic and tactical survey procedures (also subject to revision).	Input data to GIS and database, coupled to unified CFLOW/CARBINE/ROTHC model for estimation of carbon stocks. Possible re-survey of a sample of plots.	Cost not yet quantified but high. Marginal costs for partial re-survey might be ~£400k. Accuracy and precision unknown but could be quantified. Scope exists to adapt inventories and models to improve precision.	Potential applications for remote sensing to provide estimates of area, top height and stocking.
B	Stratified sample of forest stands by site, climate, species, age class and management including 16 km x 16 km grid. Around 500 sites.	Centre of stand.	Based on EU Level I N, S, E, W plots within 25 m radius of centre sited within nominal 0.25 ha plot. Individual plots take area 0.01 ha – collapses to full 0.25 ha plot when stocking is below specified threshold.	Forest condition (EU Level I), soil type, species, planting year top height, stocking, tree dbh, nominal or actual management history and future management.	Input data to FRED*, coupled to allometric equations and ROTHC model for estimation of carbon stocks. Also link to CFLOW/CARBINE for short-term projection of stocks. Validation and error estimation for Module A.	Establishment cost £180k which could be spread over several years. Cost of periodic surveys £90k. Marginal cost depends on future priority given to existing Forest Condition Survey. Worst case scenario is £150k (establishment) and £75k (periodic survey).	Potential to succeed Forest Condition Survey. Potential to evolve into integrated EU Level I, Forest Condition Survey and mensuration permanent sample plot network.
C	Based on forest stands including a proportion at 16 km x 16 km locations. Around 100 sites.	Within uniform area, accessible but avoiding forest edges.	Based on mensuration permanent sample plot design with area 0.1 to 0.15 ha with marked boundaries and tree numbers.	Full permanent mensuration sample plot procedure, forest condition (Level I). Including: • Biomass – sample plot procedure + allometric bolt-ons (BSORT) • Understorey – methodology based on literature review • Coarse woody debris – Level II methodology, under development • Ground vegetation – could be done as part of litter but questionable value • Litter – rough and ready assessment carried out as part of Level II soil survey. – needs to be evolved • Soil – Level II methodology down to 1 m.	Input data to FRED*, coupled to allometric equations and ROTHC model for estimation of carbon stocks. Also link to CFLOW/CARBINE for short-term projection of stocks. Validation and error estimation in Modules A and B.	Establishment cost £400k which could be spread over several years. Cost of periodic surveys £220k. Marginal cost depends on scope for integration with mensuration permanent sample plot network and is estimated at £200k (establishment) and £100k (periodic surveys).	
D	Based on forest stands in principal tree species. Around 20 sites. CFN sites also included to provide additional level of data capture for model development.	Within uniform area, accessible but avoiding forest edges.	Based on EU Level II plot design (0.3 ha) containing mensuration permanent sample plot (0.1 to 0.15 ha) with marked boundaries and tree numbers.	As Module C plus assessments of climate, litter dynamics and DOC. To include sites containing flux towers.	Input data to FRED*, coupled to allometric equations and ROTHC model for estimation of carbon stocks. Also link to CFLOW/CARBINE for short-term projection of stocks. Validation and error estimation in Levels A and B. Also support to development, calibration and validation of process-based models of carbon dynamics.	Total cost £510k per year. Marginal cost depends on level of commitment to EU Level II network and is estimated at £110k per year.	Equivalent to EU Level II and CFN.

This new diagram clarifies the key functions needed for the main system components as:

1. Mapping of forest areas and stand composition.
2. Stand-level sample assessment of forest carbon stocks.
3. Development of statistical relationships and models to support stand-level assessments (2).
4. Field measurement and experimentation to verify statistical relationships and models (3).
5. Model-based upscaling of carbon stocks, including forecasting based on scenarios.
6. Statistically-based upscaling of directly-assessed stand-level carbon stocks for verification of model-based estimates (5).
7. Reporting of estimates.

Relationships between the original Modules A-D and the new 'functional' Modules 1-7 in the evolved system design are also shown in Figure 4-2. Research and development work has concentrated on the development of Modules 1-5. Progress in development of these five Modules is described below.

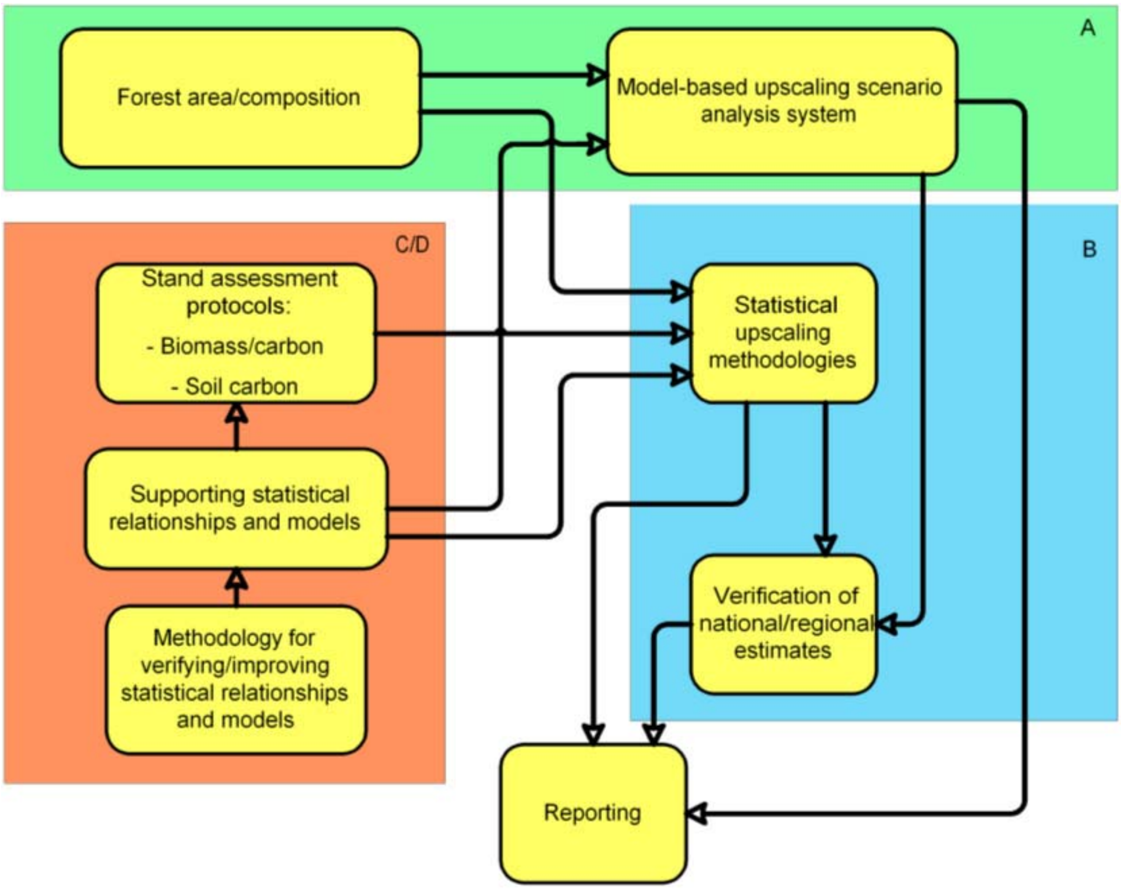


Figure 4-2**.** Revised system diagram for carbon monitoring network emphasising functions of individual modules

4.4. Module 1: mapping of forest areas and stand composition

A fundamental requirement for the carbon monitoring methodology is a database of forest areas and stand composition in the UK, preferably in spatially explicit form. The proposed methodology will refer to the forest cover map being developed as part of the National

Inventory of Woodlands and Trees (NIWT). Surveying and data analysis required for preparation of the map has already commenced in Scotland and will extend in time to cover Britain.

The NIWT forest cover map will be GIS-based (ArcGIS 9) and will in turn refer to existing geographical data available from the Ordnance Survey. All forest areas will be classified in terms of broad stand composition, i.e. conifer, broadleaf or mixed.

It is probable that the carbon monitoring methodology will also need to make use of a forest inventory being carried out in Northern Ireland, which is being organised by DARDNI. This may raise issues related to requirements for consistency of methodology and data collection across the two inventories.

4.5. Module 2: stand-level assessments

Stand-level assessments are required across a series of forest sample sites, in order to attribute to the woodland map meaningful estimates of the distributions of particular tree species, stand productivity classes and local silvicultural practice. These data are the minimum required for deriving model-based upscaled estimates of carbon in forest biomass. Related assessments of soil carbon are also required. In addition to the assessments needed to run models, for the purposes of statistical validation of model-based estimates, direct assessments of carbon in standing biomass and soils are required.

In the last year, a great deal of development work has been carried out on the detailed specification of the various stand-level assessment protocols. In the case of assessments on standing trees, this has involved a number of pilot field trials.

4.5.1. Forest sampling scheme

The statistical basis for identifying sample stands for assessment is being carried out within the framework of the NIWT project. Significant progress has been made and, at present, the proposal is to carry out assessments in 1 hectare squares (where these contain woodland) located in the southwest corners of each of a set of 1 km grid-squares covering Britain. It has been estimated that this will involve assessments in 45,000 locations constituting a sample of approximately 1% of the GB forest area. It must be emphasised that this scheme is still at proposal stage and may be subject to further development or revision by the NIWT management committee.

4.5.2. Assessments on standing trees

Considerable efforts have been made to establish a reliable protocol for the measurement of standing trees in sample areas. The primary objectives of this assessment protocol are to provide data for deriving:

- Model-based upscaled estimates of standing forest carbon
- Direct assessments of standing forest carbon for use in verification.

A draft protocol has been developed (Annex 1) and this been used in pilot trials across a range of uniform and diverse woodland types in Scotland and England. The methodology involves a point-based sampling scheme based on kNN statistical techniques (e.g. Kendall and Moran, 1963). Investigations into the feasibility of this protocol are continuing, including development of methods for calculation of standing carbon estimates.

A number of fundamental issues are still the subject of debate between various experts and stakeholders involved in the development of NIWT methodologies. In particular, there are a number of different ways in which measures such as the area occupied by a species in a mixed woodland, and/or the 'stocking' of that species within an area, can be defined. It is essential that these measures are specified carefully and rigorously, and in a manner that can be used meaningfully by the models and statistical techniques intended for use in upscaling of carbon estimates. While good progress has been achieved, reaching agreement on definitions for these quantities remains an important challenge.

4.5.3. Assessment of soil carbon

The primary objectives of this assessment protocol are to provide data for deriving:

- Model-based upscaled estimates of forest soil carbon
- Direct assessments of forest soil carbon for use in verification.

A draft protocol has been developed (Annex 2) and this is being considered by the NIWT management committee.

4.6. Module 3: statistical relationships and models in support of stand assessments

Two major initiatives in this area have involved the development of the BSORT model for estimating standing biomass and the M1 growth model for use in forest estate-level forecasting.

4.6.1. BSORT biomass model

The BSORT model (Matthews and Duckworth, 2005) was developed by integrating a number of existing and newly developed sub-models:

- Published models of stand growth and yield in Britain.
- Improved models for estimating tree size class distributions from stand level data.
- An improved version of ASORT, an existing computer based model for estimating volumes of stem wood potentially available for different product specifications.
- A new suite of functions for estimating the biomass of non-stem components of trees.

A critical innovation involved adopting a flexible, modular structure that could work with diverse combinations of inputs and outputs (Figure 4-3). Users of the model might provide input from other sources and with varying levels of detail, for example:

- Field measurements collected for commercial stand inventory, in national woodland inventory plots or research monitoring plots.
- Measurements taken on specific trees of special interest.
- Model 'tree lists' or size class frequency distributions generated as outputs by individual tree based growth simulation models.
- Stand summary data variables (e.g. top height, basal area per hectare) from stand-level growth models or yield tables.

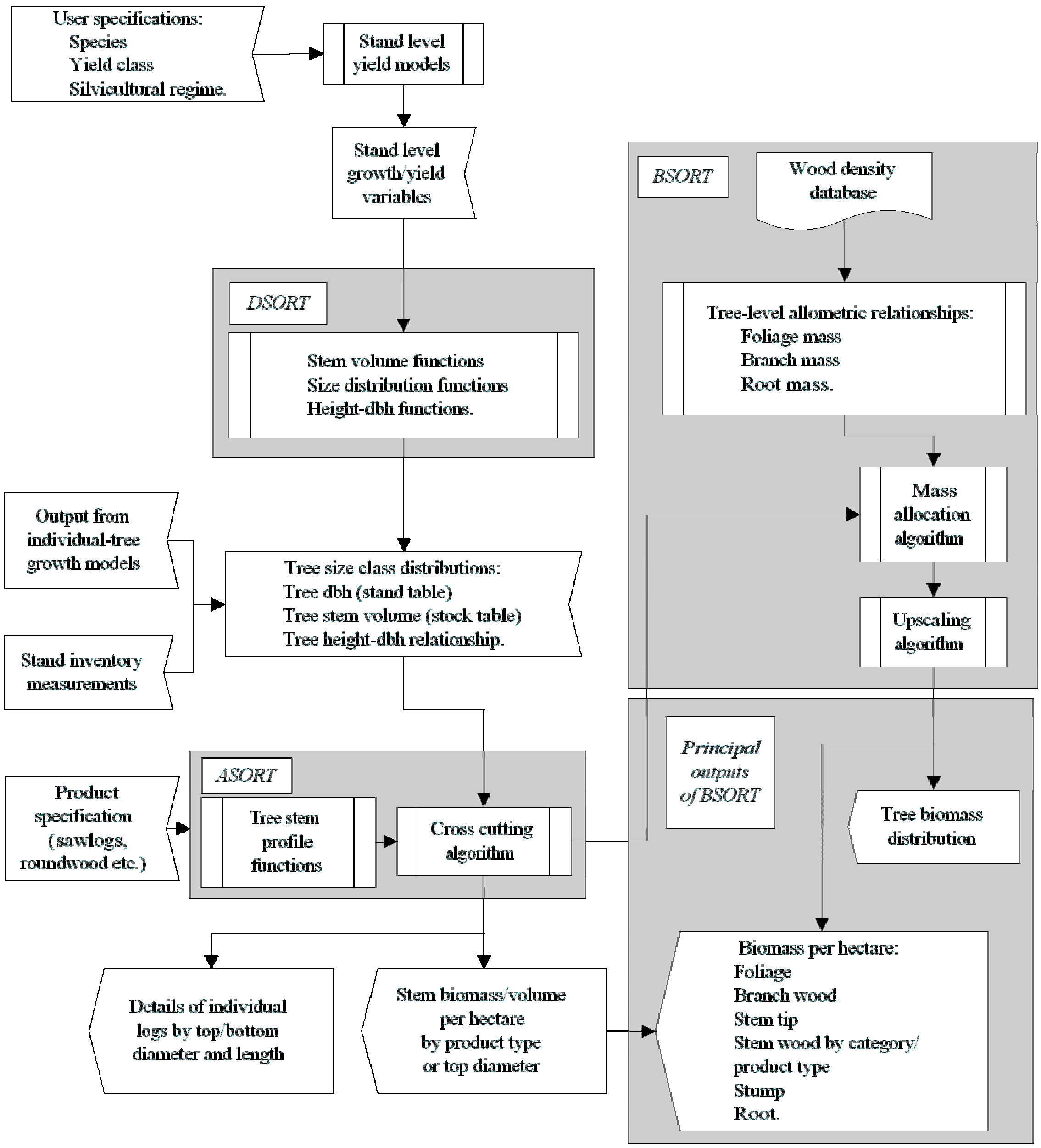


Figure 4-3 Structure of BSORT model.

The computer implementation of BSORT uses COM technology, enabling the easy use, re-use and sharing of the model. BSORT has already been linked to the Forestry Commission's national production forecasting programs to estimate the potential extent of the wood fuel resource in Britain (www.woodfuelresource.org).

The BSORT model can generate a large body of biomass estimates for a range of tree species growing under a diversity of conditions. Figure 4-4 shows an example of results for an even aged stand of Sitka spruce calculated by BSORT using the following input data:

- Annual estimates of stand yield (top height, number of trees and volume per hectare, mean dbh) were obtained from Edwards and Christie (1981). The specific results considered here were based on the yield table for Sitka spruce, yield class 12, planted at 2 m spacing and subjected to silvicultural thinnings on a 5 year cycle.

- Two broad product types derived from stem wood were defined, specifically 'sawlogs' having a minimum top diameter of 16 cm over bark and 'roundwood' constituting the remaining, smaller diameter stem material.

Figure 4-4 shows the estimated timecourse of biomass accumulation in the model Sitka stand over the period from 20 to 75 years. The general pattern of biomass accumulation is consistent with that described by the earlier models developed by Forest research, and implied by UK forest carbon accounting models. The overall amount of biomass in the stand predicted by BSORT also appears to be reasonably consistent with previous estimates over typical rotations (up to 50 years). However, it is known that predictions made by BSORT for some species show marked differences to estimates implied by carbon accounting models. It is evident from Figure 4-4 that stem wood makes the most significant contribution to total stand biomass but the contribution due to below ground biomass is also noteworthy.

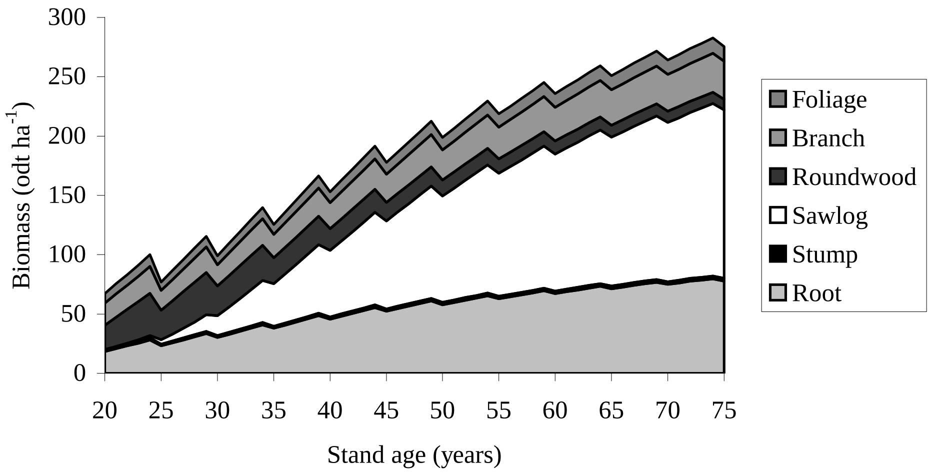


Figure 4-4 Biomass accumulation by tree component in a representative even-aged stand of Sitka spruce growing in Britain, as estimated by BSORT.

The BSORT model and its underlying methodology have proved effective in enabling the synthesis of disparate sources of information to produce transparent and defendable estimates of tree and stand biomass. In particular, the model represents a significant improvement on calculations of forest biomass and carbon that rely on notional expansion factors or other simplifying assumptions. Some of the data sets used in the calibration of BSORT were very limited and there is a case for improving these elements of the model by carrying out new field assessments. Nevertheless there is a case for applying the model in its current form very widely, for example through integration with national forest inventories, estate forecasting systems, stand management appraisal packages and forest carbon accounting models.

4.6.1.1 M1 algorithmic yield model

The yield models currently available in Britain (Edwards and Christie, 1981) provide a static description of forest growth and yield under a set of prescribed management regimes. The increasing diversity of forest management requires a more flexible approach to growth and yield modelling and forecasting. The aim of this project is to construct a new computer-based model able to reflect specific local conditions and represent different silvicultural treatments and management regimes. The new model, M1, is being developed by integrating the growth patterns already represented in Forestry Commission yield models with improved descriptions of key processes, notably tree mortality and thinning. Both old and new growth and management process descriptions are being expressed as a unified set of algorithms capable of producing consistent growth and yield predictions over a very wide range of stand productivity classes and silvicultural systems. Key aspects of the 'M1 approach' included:

- A simplified but robust approach to representing stand composition, growth and yield, based on stand-level variables.
- Minimizing of development time by relying as far as possible on existing scientific understanding and descriptions or mathematical functions of growth processes.
- A flexible structure that allows easy incorporation of new information, such as revised or improved mathematical functions.
- Ability of the model to work with field data and management prescriptions typically available to model users, with the minimum of preparation, processing or interpretation.

Work on model development is quite advanced and consists of four main phases:

1. Comprehensive model specification. Before starting model development, a careful model scoping exercise was carried out, leading to a full technical specification of the M1 model algorithms. This included details of how input data define stand conditions at a point in time, the range of outputs to be produced by the model, how inputs and outputs are controlled by the user, and how various estimates, mathematical relationships and projection (increment) equations work together to produce the required outputs from the model inputs. The specification was translated into a work plan, permitting incremental development of successive model versions with increasing flexibility and functionality.

2. Development of new analytical submodels. The model design aimed to maximise the use of existing estimates and mathematical relationships. However, work on the specification identified several requirements for revised or reformulated submodels, notably for describing tree survival in the presence of inter-tree competition and the impacts of different types and intensities of thinning. Estimation of tree survival in presence of competition has been based on Reineke's law. From analysis of sample plot data from unthinned stands it has been possible to classify different species into three categories, 'light demanding', 'shade tolerant' and 'very shade tolerant', each of which is associated with a characteristic survival curve. Despite the limits imposed by lack of reliable data, especially for broadleaves, the curves represent an improvement on the approach adopted in the construction of Forestry Commission yield tables. A requirement to represent a wide range of silvicultural regimes led to the construction of purpose-designed submodels able to predict volume, basal area, and number of trees harvested and remaining in a stand in response to different thinning treatments.

3. Software development. The algorithms comprising the M1 model have been implemented in C++ using an object-oriented approach, which allows easy update and reuse of the different program components. The development is already completed and the various components have been combined in a DLL that can be accessed through a simple graphical interface primarily for research use and testing.

4. Software and algorithm testing. The computer implementation has been thoroughly tested through a series of trial runs in which input variables have been given extreme values to verify robustness. Tests of the validity of the predictions by comparison of new projections against Forestry Commission yield tables are still in progress. Figure 4-5 shows examples of predictions of cumulative volume production and mean dbh development made by the M1 model for a stand of yield class 12 Scots pine planted at 2 metre spacing, subjected to three contrasting management regimes. These can be compared to the estimates given in an equivalent FC yield table, based on the standard 'Management Table' (MT) thinning regime. Note that predictions of dbh development for the standard management regime are different to those in FC yield tables due to application of the new thinning submodels.

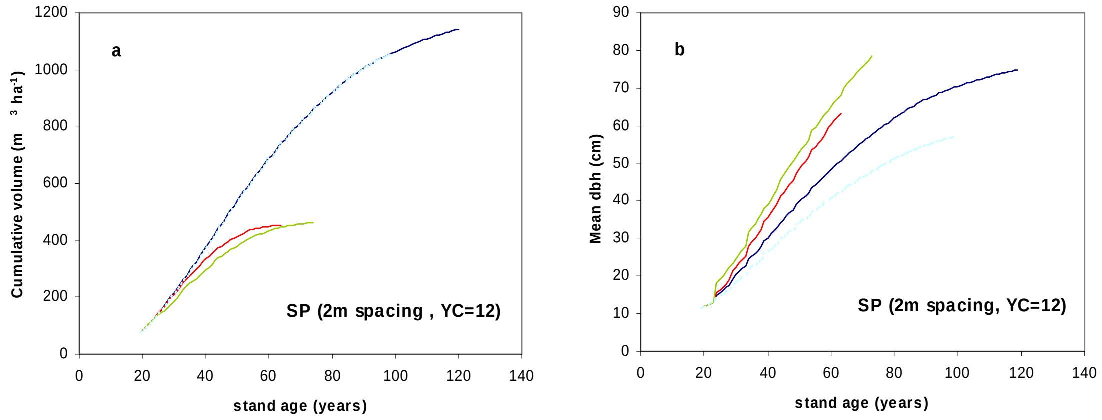


Figure 4-5 Examples of predictions made by the M1 model for a stand of yield class 12 Scots pine (2 m planting spacing). a: cumulative volume production; b mean dbh. Dark blue line: standard (1.0 MT) thinning regime; light blue line: predictions made by equivalent Booklet 48 model for comparison; red line: M1 prediction, as standard management regime but with standard thinning intensity increased to 1.3 MT; green line: M1 prediction, as standard management regime but with thinning cycle (and cut) set at 10 years. The M1 simulation for the standard management regime is projected up to an arbitrary stand age of 120 years. The M1 simulations for 1.3 MT intensity and 10 year thinning cycle terminate early because the prescribed management regimes are predicted to result in complete removal of all trees before age 120.

The M1 model is generating considerable interest among potential users and other researchers. Plans are already being made to incorporate the model into FC production forecasting systems. (A crude realisation is already in use as part of the Forest Enterprise Production Forecast system.) Discussions are taking place with silvicultural researchers on the possible extension of M1 algorithms to explicitly represent continuous cover forestry systems. Critically, for the purposes of this project, the opportunity exists to use M1 as the link between forecasting systems and the BSORT biomass estimation model. Initially, future work will concentrate on:

- Validation of the new models against data from sample plots.
- Preparation of program and algorithm documentation.
- Development of complete software package for external distribution.

4.7. Module 4: verification of statistical relationships and models

Research has concentrated on developing a methodology for validating allometric relationships and biomass expansion factors used in forest biomass estimation and carbon accounting models, including BSORT and C-FLOW (Broadmeadow *et al*., 2005). This has involved significant fieldwork.

Eleven of the twenty sites comprising the UK Intensive Forest Monitoring (Level II) network were thinned for silvicultural reasons in 2005. At each of these sites, ten sample trees were selected from across the full diameter range and subjected to detailed mensurational analysis (Figure 4-6). Results are presented for the six plots planted with beech (*Fagus sylvatica*).

4.7.1. Methodology

The ten sample trees were felled, and conventional mensuration measurements taken: total height; timber height; timber volume to 7 cm diameter. In addition, sawlog volume (>16 cm diameter) was measured. Trees were then separated into five components: stemwood; branchwood (>7 cm diameter); brash; saddle, stump and non-merchantable stemwood; standing deadwood. Each component was weighed separately, using a 50 kg balance (Salter) suspended from a tripod. For each component, three separate samples were taken (where sufficient material was available) and comminuted using an arboricultural chipper. Sub-samples (>1 kg) were taken off-site in polythene bags for moisture content determination, with additional sub-samples retained for subsequent chemical analysis. Moisture content was determined gravimetrically after drying at 105^{o}C for 48 hours.

4.7.2. Results

Above-ground stemwood biomass was calculated as the product of measured timber volume and specific density (0.55 for beech: Lavers, 1983). Corrections were not applied for the difference in density between bark (~0.40) and stemwood, to maintain consistency with the approach adopted in the current LULUCF methodology using C-FLOW (R. Milne, per, comm.). Total biomass was calculated as the sum of the five components with component specific moisture contents applied to measured fresh weight. Tree level biomass expansion factors were then calculated as the ratio of total measured biomass to estimated stemwood biomass. Figure 4-7 presents the results as a function of measured stem volume, with individual trees across the six sites plotted as individual data points.

The data presented in Figure 4-7 clearly demonstrate that the use of a single biomass expansion factor is inappropriate where it is applied to young trees. However, this analysis does indicate that for individual beech trees of measurable volume greater than 0.1 m^3 (of the order of 15 cm dbh, total height 15 m), the application of a single BEF may be appropriate. A value of 1.35 is calculated as the average BEF for all trees of measurable volume greater than 0.1 m^3. However, it should be noted that the data-set is restricted (16 points), but does include trees from five of the six sites sampled. The value differs markedly from the value of 1.18 that is assumed for broadleaf species in C-FLOW.

Figure 4-6 Mensurational assessment of sample trees in progress. Top left: measurement of stem volume of felled tree; Top right: measurement of fresh weight of tree sections; Bottom: comminution of tree section samples for subsequent moisture content measurement.

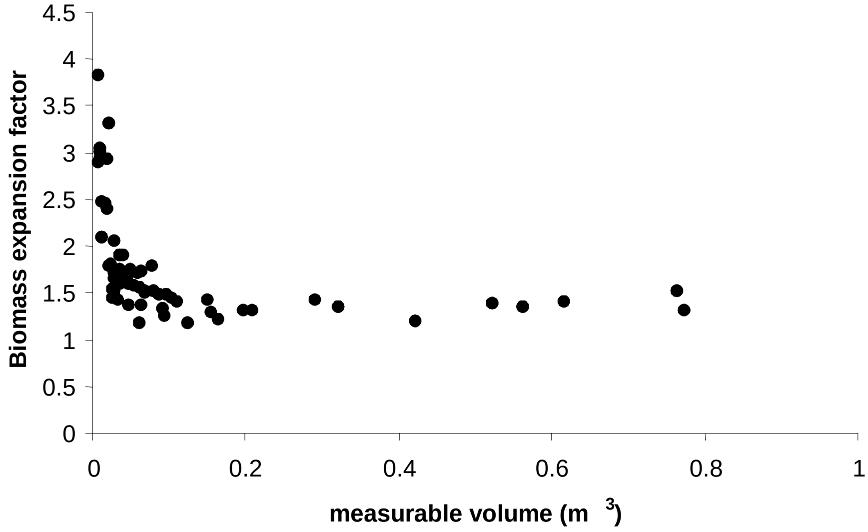


Figure 4-7 Biomass expansion factor plotted as a function of measured stem volume for beech (*Fagus sylvatica*) in six plots of the UK Level II network.

4.7.3. Derivation of plot level biomass expansion function

For each of the six plots, the data described above were used to derive a plot specific relationship between above-ground biomass and basal area. This relationship was then applied to the full diameter distribution reported for the ~0.1 ha mensuration permanent sample plot. A single biomass expansion factor was then calculated for each plot based on all trees present within the sample plot. This value is thus representative of the entire plot and not restricted to the ten sample trees which may not be fully representative of the plot. If plot 1827 is excluded from the analysis on account of the small volume of the individual trees and thus the inappropriateness of the single biomass expansion factor (see above), a mean plot level biomass expansion factor of 1.20 is calculated. It should be noted that the BEFs given in Table 4-2 are based on measured specific density (mean value of 0.59), which is higher than most published values (typically 0.55: Lavers, 1983). Alternatively, if stemwood biomass is calculated as a product of measured volume and the default specific gravity for beech (0.55), the BEF for the five plots (excluding 1827) rises to 1.31. This is more in line with the value derived from the individual tree analysis described above. This latter value is appropriate if estimates of stemwood biomass are based on measurements of stemwood volume; the lower value of 1.2 is appropriate if measurements of stemwood biomass are available.

Table 4-2 Plot level estimates of stemwood biomass, above-ground biomass and biomass expansion factors for the six beech plots in the UK Level II network. Values of dbh and volume are means of all trees in the sample plot, while estimates of biomass are totals for the sample plot (~0.1 ha).

Plot No.	dbh	Volume	Stemwood biomass	Above-ground biomass	Biomass expansion factor
	cm	m^3	Tonnes	tonnes	
1827: Cannonteign	14.2	15.7	8.7	13.6	(1.53)
1829: Covet Wood	32.5	27.5	15.1	21.4	1.25
1831: Wangford	20.4	34.7	19.1	23.0	1.12
1833: Wykeham	20.5	33.8	18.6	25.3	1.29
2316: Brechfa	21.5	29.3	16.1	21.6	1.24
3766: Kelty	26.0	33.5	18.4	22.3	1.13
Mean					1.20

4.7.4. Comparison of plot level estimates of above ground biomass

A number of different options are available for calculating above-ground biomass. These options broadly mirror the range of options that will be applied in a nested scheme to carbon stock and stock change assessment, verification and model parameterisation. At the most basic level, summary patch-level data (age of crop, species and yield class) will be input to inventory or carbon accounting models (BSORT or C-FLOW, respectively). This approach will be used to derive carbon stock and stock change assessments from the forest cover map together with associated data from the SCDB or assigned data from the private sector production forecast. The next level of detail involves the input of stand level data in the form of diameter distribution and stocking density. These data will be derived from mensuration data collected as part of NIWT. Upscaled plot-level data using this approach will form the basis of the verification process for national carbon stocks and stock changes. The most detailed level of data input involves the approach described in the preceding section, in which measured biomass in branchwood and other non-merchantable fractions are available. Data input of this intensity is only required to parameterise and/or validate the models that are used for either stock (or stock change) assessment or its verification.

Estimates of carbon stocks in standing biomass are given for the six Level II plots analysed in the preceding section in Table 4-3. It is clear that these estimates encompass a large range of values with, for example, C-FLOW predicting only 46% of measured standing biomass, on average. This result is not unexpected, since it is widely acknowledged that yield models generally underestimate standing stocks. A brief description of the approach used to derive each of the estimates of standing biomass is given below:

- <u>C-FLOW model:</u> Standing volume predicted on the basis of conventional yield models (Edwards and Christie, 1981), with ‘default’ values for specific density (0.55) and BEF (1.18) assumed to derive standing biomass.
- <u>BSORT model:</u> Standing volume predicted on the basis of integral yield models. ‘Default’ value for specific density (0.55) applied together with detailed,species group biomass functions to derive standing biomass.
- <u>C-FLOW plot:</u> Sample plot measurements of standing volume converted to estimates of standing biomass using ‘default’ values for specific density (0.55) and BEF (1.18).
- BSORT plot: Standing volume predicted from plot-level diameter distribution, and height-diameter relationship. ‘Default’ value for specific density (0.55) applied together with detailed,species group biomass functions to derive standing biomass.
- <u>SPLOT:</u> Plot level standing biomass calculated as described in the preceding section.

Table 4-3 Comparison of estimates of standing biomass (t ha^{-1}) on the the six Level II plots planted with beech.

Plot no.	LYC	P-year	Plot measurements			Model estimates	
			SPLOT	BSORT	CFLOW	BSORT	CFLOW
1827: Cannonteign	10	1972	113	133	85	118	47
1829: Covet Wood	8	1950	201	172	168	168	140
1831: Wangford	7	1955	230	237	225	153	104
1833: Wykeham	8	1957	203	169	176	138	112
2316: Brechfa	6	1952	205	236	180	118	95
3766: Kelty	4	1958	222	215	216	78	47
mean			196	194	175	129	91
% of SPLOT			100	99	89	66	46

4.7.5. Verification procedures for above ground carbon stock assessments

Estimates of forest carbon stocks will be derived from the forest cover map using the stand inventory model BSORT. Data held within the sub-compartment database and currently used to generate the production forecast will be used as input for Forestry Commission woodland. Private sector woodland will be assigned attributes on a region by region basis, as is current practice for generating the private sector production forecast.

National carbon stock and stock changes will be verified using data collected within the mensuration sub-plots of the NIWT sample square. Data input to BSORT will include the diameter distribution recorded within the plot, and a derived, plot specific height-diameter function.

4.8. Module 5: model-based upscaling of carbon stocks

Initiatives have been made aimed at integrating the M1 growth and yield model, BSORT biomass model and FC estate and national forecasting systems. Work is at an early stage but, as already reported, results of early versions of the integrated system have already been used in the estimation of the extent of the wood fuel resource in Britain. The existing forecasting systems, which are focussed on timber production, have the potential to provide a wider range of outputs including predictions of the dynamics of the growing stock in districts and countries caused by management interventions in response to market or policy drivers. Such results could be particularly relevant if expressed in terms of carbon stock changes.

4.9. Future work

The essential structure of a forest carbon monitoring methodology is now fully articulated. However, it is evident that significant further development of assessment protocols and model systems is still required before a fully integrated and robust operational system can be put in place. This will require careful review and consultation with key stakeholders to ensure that the system is delivering relevant outputs. A methodical approach to construction of the key component systems will be essential to ensure their suitability for integration.. A pilot field trial of the survey methodology and supporting analysis is still in progress and will be completed in summer 2006. A full description of the results and lessons learnt will be presented in a supplementary report to this contract when the pilot study is completed.

4.10. Acknowledgements

The hard work of John Proudfoot, Ian Craig, Rory Cobb and, particularly, Steve Coventry, James Duff and Harry Watson in assessing stand level biomass is greatly appreciated. The Forestry Commission (Corporate and Forestry Support) is acknowledged for part-funding the work.

4.11. References

Broadmeadow, M.S.J., Matthews, R.W., Mackie, E.D., Wilkinson, M., Benham, S., and Harris, K. (2005) Survey methods for Kyoto Protocol monitoring and verification of UK forest carbon stocks. In: UK Emissions by Sources and Removals by Sinks due to

Land Use, Land Use Change and Forestry Activities. Report, June 2005. DEFRA: London.

Edwards, P.N. and Christie, J.M. (1981) Yield Models for Forest Management. Forestry Commission Booklet 48. Forestry Commission: Edinburgh.

Kendall, M.G. and Moran, P.A.P. (1963) Geometrical Probability. Griffin: London.

Lavers, G.M. (1983) Strength properties of timber. Building Research Establishment Report Cl/SfB 1976. HMSO: London.

Matthews, R.W. and Broadmeadow, M.S.J. (2003) Survey methods for Kyoto Protocol monitoring and verification of UK forest carbon stocks. In: UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry Activities. Report, April 2003. DEFRA: London.

Matthews, R. W. and Duckworth, R. R. (2005) BSORT: a Model of Tree and Stand Biomass Development and Production in Great Britain. In: Imbabi, M.S. and Mitchell, C.P. (eds.) Proceedings of World Renewable Energy Congress (WREC 2005), 22-27 May 2005, Aberdeen, UK. Elsevier: Oxford, 404-409.

UNFCCC (1998) Kyoto Protocol to the United Nations Framework Convention of Climate Change (with addendum). Document FCCC/CP/1997/7/Add.1. http://www.unfccc.de/resource/docs/convkp/kpeng.pdf.

A.1. Annex 1: NIWT mensuration assessment protocol (DRAFT)

Selection of section to be assessed

This assessment is carried out in one (and one only) of the sections identified in each 1 hectare sample square.

The section to be assessed is selected at random from those comprising the 1 hectare square, excluding those enclosing no trees or trees that are not measurable. If there are no suitable sections then no assessment is made.

A measurable tree is defined as having a dbh of 7 cm or greater.

Selection of sampling scheme

If the selected section is judged to contain no more than 30 *measurable* trees then sampling scheme A is adopted, otherwise sampling scheme B is adopted.

If the stand contains a multi-stemmed trees (i.e. stems originating from the same stump or stool below 1.3 m height), then the section needs to be judged to contain no more than 30 measurable *stems* for sampling scheme A to be adopted.

Sampling scheme A

Once sampling scheme A has been adopted, this scheme is used even if it transpires that there in fact are more than 30 measurable stems in the section.

Assessment of species

The species of each measurable stem is recorded. A code should be used to indicated where individual stems belong to the same tree.

Assessment of dbh

All measurable stems are assessed for dbh. Conventions for assessment of dbh are given in Appendix (in preparation).

Assessment of height

Every third measurable stem is assessed for total height. Conventions for the assessment of total height are given in Appendix (in preparation).

Sampling scheme B

Identification of sample points

A series of sample points is located at random within the section. The required number of sample points is based on an initial estimate of the number of *measurable stems* in the section. In practice this will not be known and will need to be judged by the surveyor, possibly from a consideration of the 'typical' distance between measurable stems. Appendix (in preparation) gives guidance on the numbers of stems per section indicated by the spacing between stems for different section areas, accounting for the presence of multi-stemmed trees as necessary.

If there are at least 150 measurable stems in the section, the selection of the number of sample points and also depends on whether the trees forming the section are uniform or variable (Table A1. 1):

- A uniform section consists of trees (elements) of a single species, *and* similar in age (falling within a 5 year range) *and* forming a single storey.
- A variable section consists of trees (elements) of more than one species, *and/or* dissimilar in age (falling within an age range exceeding 5 years) *and/or* forming more than one storey.

In some situations it may be acceptable to regard several distinct elements as forming a uniform section. Guidance on this approach is given in Appendix (in preparation).

Table A1. 1 number of sample points required

Measurable stems in section		**Uniform**	**Variable**
At least	**Less than**		
	31	Sampling scheme A	
31	75	5	5
75	100	8	8
100	150	12	12
150		12	16

Identification of sample and distance trees

The nearest measurable stem to each sample point is identified as a 'sample tree'. If two sample points are associated with the same sample stem then, at the second sample point, the second-nearest measurable stem should be identified as the 'sample tree'.

If the nearest tree to the sample point is multi-stemmed, the measurable stem that is judged to be nearest to the average dbh of all the measurable stems arising from the root or stool should be taken as the sample tree. If there are only two measurable stems arising from the root or stool then, on the first such occasion, the measurable stem with largest dbh should be selected; on the second occasion the measurable stem with smallest dbh should be selected and so on.

Each sample tree has an associated 'distance tree'. The measurable stem which is third-nearest to each sample tree is identified as a 'distance tree'.

Note that in some cases involving multi-stemmed trees this may mean that the sample tree and the distance tree are in fact stems arising from the same tree root or stool. A code should be associated with the two stems to indicate when this occurs.

Assessment of species

The species of each sample tree and each distance tree is recorded.

Assessment of dbh

Each sample tree and each distance tree is assessed for dbh. Conventions for assessment of dbh are given in Appendix (in preparation). Where the sample tree and/or distance tree is one of several stems arising from the same root or stool, all measurable stems arising from the same root or stool should be assessed and recorded. A code should be associated with the two stems to indicate when this occurs, also distinguishing the sample tree and/or distance tree.

Assessment of height

Each sample tree is assessed for total height. Conventions for the assessment of total height are given in Appendix (in preparation).

A.2. Annex 2: NIWT soil assessment (DRAFT)

Objectives

The principal objective of the NIWT soil assessment is to identify broad (FC) soil type and not to provide an identification of soil series, soil chemistry or soil profile description. Additional variables recorded will provide indicators or input to the following analyses:

- Input to empirical models of soil carbon, based on the attributes held in the NSRI soils database for England and Wales and a similar data-set held by MLURI for Scotland; the assessment will contribute to verification of carbon stocks and stock changes reporting of the LULUCF sector under the Kyoto Protocol and UNFCCC.
- An assessment of carbon stocks in litter.
- Input to the derivation of NVC woodland type from records of tree and shrub species present.
- The ability to interpret changing woodland condition and tree mortality in terms of available water capacity, if and when climate change-induced drought effects begin to take effect.

Procedure

1. Locate soil pit at centre of section that mensuration plot is located in. Ideally, the pit should be further than 2 m from nearest tree. If this is not possible, locate mid-way between rows and between trees. The location of the pit should be representative of the section and avoid ditches, cultural features, windblow etc. If ground preparation for establishment is evident, the pit should be located where ploughing (or other practices) has not disturbed the soil profile.
2. Within a 2 m radius of the soil pit, assess and record modal litter depth, including an assessment of how representative it is of the remainder of the section. Litter is defined as whole leaf or needles discernible.
3. Using graduated trowel and serrated breadknife, excavate 15 cm square pit to 20 cm depth.
4. Record depth of organic fermentation and/or humous layer(s).
5. Fermentation layer is defined as material still containing discernible plant material; humous layer is defined as organic material, with no mineral soil present, containing no discernible plant parts.
6. Record basic humus classification mull, moder and mor according to definitions given below:

    Mull - is characterised by an organic layer without any humification. Organic material breakdown is mainly by soil macrofauna. The humus form is characterised by a crumb of fine blocky structure intimately mixed with an Ah horizon of more than 2 cm thickness. The granular structure can be tested by hand.

Moder – is an organic layer with visible accumulation of decomposed organic matter. Decomposition is mainly accomplished by soil fauna. Humus forms are with three distinct layers, L, F and H. The H layer is the diagnostic layer, which is at least as thick as the combined L+F layers. The transition between the F and H and between H and A are gradual.

Mor – is an organic layer with visible humification, but soil fauna activity is absent and humus decay is more important. There are discernible L, F and H horizons with a total thickness usually greater than 5 cm. The H horizon is usually less than half the thickness of the L+H horizon combined. There is a sharp transition to the A horizon. When tested by hand, it is 'greasy'.

7. Record thickness and texture of Ah horizon. The Ah horizon is defined as mineral soil containing organic material and is generally darker in colour than deeper horizons.
8. Continue sampling with auger to 80 cm, recording depth to unweathered parent material or rock. Major boundaries in colour, texture or stoniness should be recorded. An estimate of stoniness should be made.
9. For each horizon, test for calcareous soils using acid bottle. A single drop of 0.1 molar hydrochloric acid should be added to a sample of soil; effervescence indicates a calcareous soils (or secondary deposits) and should be recorded.
10. Key out to major soil type using Forestry Commission field soil key.
11. Measure pH of Ah horizon: take 4 cm^3 sample of the full depth of Ah horizon. Add to 25 ml plastic vial containing 10 ml 0.01 molar calcium chloride. Shake for 10 seconds, allow to settle for 30 seconds, measure pH of solution above soil using appropriate pH papers. Compare colour of paper with chart and record to nearest pH unit.
12. Backfill soil pit minimising signs of disturbance.

Analysis

Carbon stocks in organic horizons

Carbon stock in the litter layer is calculated from the modal depth, assuming a bulk density (dry weight basis) of 100 kg m^{-3} and a carbon content of 0.5 kgC kg^{-1}. Carbon stock of the fermentation layer is calculated on the same basis as the litter layer. Different values are used for the calculation of the carbon stock of the humous layer, if present (bulk density 300 kg m^{-3}; carbon content 0.4 kgC kg^{-1}). If L, F and H layers cannot be distinguished, the parameter values for the L/F horizon should be assumed for the combined organic (O) horizon. Parameters are summarised in Table A2.1.

Table A2.1 Parameters for soil organic horizons.

Horizon/layer	Bulk density (kg m^{-3})	Carbon content (kgC kg^{-1})
Litter (L)	100	0.5
Fermentation (F)	100	0.5
Humous (H)	300	0.4
Organic (O)	100	0.5

Soil carbon stocks to 80 cm

Total carbon stock of the soil profile to 80 cm is calculated on the same basis as for the organic horizons. Modal values of bulk density and carbon content for each major soil type in each region of the Soil Survey of England and Wales will be derived from the representative soil profiles held on the NSRI database. All horizons below the Ah horizon are combined, after correction for stoniness, according to equation 1,

$$SOC = BD_{\mathrm{Ah}}\, d_{\mathrm{Ah}}\, C_{\mathrm{Ah}}\, S_{\mathrm{Ah}} + \Sigma_{\mathrm{B..80cm}}\, (BD_{\mathrm{B+}}\, d_{\mathrm{B+}}\, C_{\mathrm{B+}}\, S_{\mathrm{B+}}) \qquad \text{eqn. 1}$$

where *SOC* is soil organic carbon stock to 80 cm, *BD* is bulk density, *d* is horizon thickness, *C* is organic carbon content and *S* is estimate of stone content on a proportional basis. Parameter values are given in Table A2. 2.

Table A2. 2 Mineral soil parameters broken down by Soil Survey of England and Wales region.

SSEW region	Ah horizon		B+ mineral horizons	
	BD	C	*BD*	*C*
Brown earth				
Podzol				
Calcareous				
Ground-water gley				
Peaty surface water gley				
Surface water				
Gley				
Deep peat				

Soil doughtiness

The data collected in the soil assessment will enable future analysis of climate change driven drought impacts on woodland condition and tree mortality. Two options are available, (1) using the data to confirm mapped soil type in NRSI NATMAP, and calculating available water capacity (AWC) on basis of NATMAP attributes; (2) calculating AWC on similar basis to carbon content of soil profile to 80 cm, using SSEW regional values for AWC of the Ah and combined other mineral horizons, correcting for stoniness.

Potential for additional measurements

If funding was made available for laboratory analysis, soil samples could be collected at no additional cost for subsequent analysis of carbon content, bulk density or soil chemistry.

A sub-set of 160 plots will have detailed soil description and chemical analysis conducted as part of the pan-European ‘Biosoil’ project. Data will be available by December 2008. The more detailed protocol employed in the Biosoil project will be fully compatible with that outlined here.

Section 5

Estimating Biogenic Carbon Fluxes over the UK

Table of Contents

5. Estimating Biogenic Carbon Fluxes over the UK

Prepared by John Grace and Shaun Quegan on behalf of The Centre for Terrestrial Carbon Dynamics (Universities of Sheffield, Edinburgh, York, University College London, and Forest Research at Alice Holt)

5.1. Rationale

The research effort within CTCD has three main objectives, all of which relate to Defra's interest:

1. Provision of 'best possible' process-based biospheric carbon flux estimates at local, catchment, UK, European and continental/global scale, together with well-founded estimates of uncertainty, partitioned into uncertainty arising from internal parameters, input data, initial conditions and model deficiencies.
2. Development of methods to reduce the uncertainty in carbon flux predictions by combining data with models, with special emphasis on the use of EO data.
3. Investigation of new sensors, theory and information recovery methods that have the potential to improve our estimates of carbon fluxes.

A key feature of the CTCD is its highly integrated approach, shown schematically in Figure 5-1, involving dynamic models that are based on the latest process understanding, strongly linked to EO data and ground measurements, and coupled with state of the art treatment of uncertainty. This comprehensive structure allows us to make particular contributions to terrestrial carbon cycle science by characterising uncertainty in model calculations and using EO data to reduce this uncertainty.

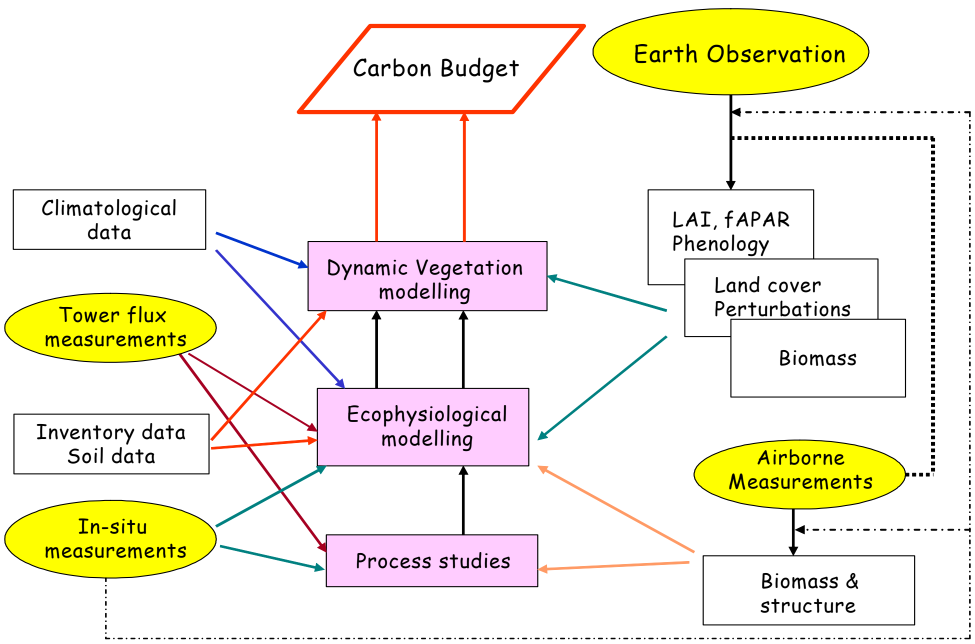


Figure 5-1 The inter-linking of models and measurements within the CTCD. Threaded through the whole structure is characterisation of uncertainty and its consequences.

To understand how this works, it is worthwhile to consider the simple conceptual diagram in Figure 5-2, which illustrates the process of making C flux and stock calculations within a Dynamic Vegetation Model. A state vector describes the condition of the plant-soil system at time t_n. The processes represented in the model, which typically involve internal parameters and depend on current atmospheric conditions, then predict the state vector at the next timestep, t_{n+1}. Soil texture is an input, but soil carbon evolves as part of the state space. An initial state vector is needed to start the calculation.

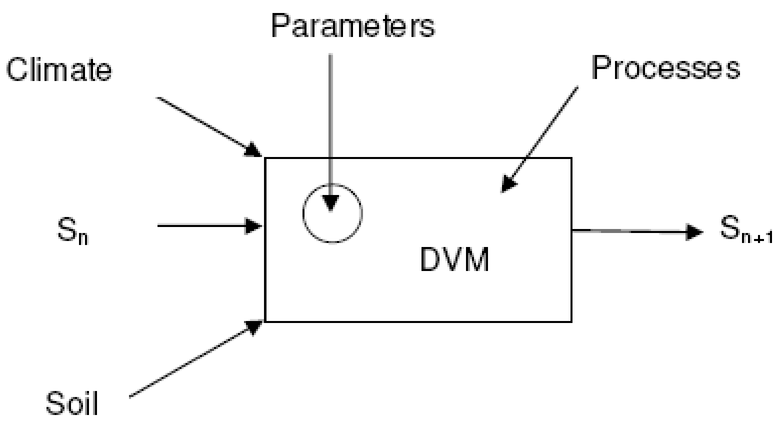


Figure 5-2 Essential structure of how the state space evolves in the Dynamic Vegetation Model.

The structure shown in Figure 5-2 readily lends itself to analysis of uncertainty and partitioning uncertainty between its components. A major drive of the Centre is to quantify and reduce this uncertainty by full use of the range of data (especially EO data) that can interact with this structure. Relevant data are climate and soil texture, but also multiple data sources that can provide information on the state space, the internal parameters or processes, and that can be used to test model predictions. Here, we report especially on the aspects of the research that relate to the UK biospheric carbon fluxes, and we give preliminary estimates of the UK carbon fluxes.

5.2. Models and model testing

Three models to calculate carbon and water vapour fluxes are in use within the Centre: SDGVM (Sheffield), SPA/DALEC (Edinburgh) and ForestETP (Forest Research). More can be found about these models at http://www.ctcd.group.shef.ac.uk/science/vegmodels/part2.html. Here we outline their distinctive features.

5.2.1. SDGVM

Dynamic Vegetation Models (DVMs) were originally designed to model the response of terrestrial ecosystems to long-term atmospheric changes in temperature, precipitation and gas concentrations. Such models represent many of the processes that occur in natural ecosystems, although species are characterised by broad categories based on life-history of the species, known as *plant functional types* (PFTs). DVMs aim to simulate the dynamic changes in ecosystems in relation to environmental change and time-from-disturbance. A core set of coupled modules represents the interactions of ecosystem carbon and water exchanges with vegetation dynamics, under given soil and atmospheric conditions. The biochemical processes of photosynthesis and the dependence of gas exchange on stomatal conductance are explicitly modelled; these depend on temperature and soil moisture. Canopy conductance controls soil water loss by transpiration, and thus the model can be constrained by readily available river-flow data (Picard *et al.* 2005). In SDGVM the assignment of nitrogen uptake to leaf layers is proportional to irradiance and respiration, and maximum assimilation rates depend on nitrogen uptake and temperature. Total nitrogen uptake is derived from soil carbon and nitrogen and depends on temperature. The SDGVM has been developed in Sheffield for global modelling, but may also be used to model changes in stocks and fluxes for regional scale land cover with a highly managed landscape, such as the UK, as in this project.

5.2.2. SPA-DALEC

This is an ecosystem carbon model specifically designed for calibration and testing against eddy flux data. We have undertaken experiments with the model to test and extend its capabilities.

1. We have performed detailed calibration against flux data from 10 forest sites across Europe, including the Griffin, Perthshire site in the UK. This calibration and testing has revealed how critical parameters vary across Europe, and the uncertainty associated with model calibration. With this information we are now better able to extrapolate predictions across Europe.
2. We have coupled SPA-DALEC to a model of the planetary boundary layer (PBL). This coupling means that the interaction of the land surface with the lower atmosphere is explicitly modelled. We have calibrated the model against surface flux data and shown for the first time that a coupled model is capable of predicting the dynamics of atmospheric CO_2 in the PBL over the day. By linking atmospheric CO_2 with surface processes, we are now better able to use atmospheric data from aircraft, satellites and tall towers to infer processes occurring at the land surface, such as source and sink dynamics.

5.2.3. ForestETP

This is an ecological model designed to predict water movement through the soil-plant-atmosphere continuum and carbon exchanges in UK forests. It incorporates additional ‘realism’ because it is conceived as a model to aid forest management, and so its outputs include production of wood, and reflectance properties of leaf canopies such as those which can be viewed from satellite. Three versions are under development. The ForestETP-1D model is a point scale, daily timestep soil-vegetation-atmosphere transfer (SVAT) model. It simulates relevant terrestrial hydrological processes; soil water movement, runoff, soil and canopy evaporation, and N-sensitive photosynthesis-coupled transpiration) for a known tree species growing in a locally-defined soil and climate. ForestETP is coupled with a weather generator that allows the downscaling of summary meteorological data and the generation of climate change time series. The ForestETP-3D model runs at the catchment scale and includes lateral hydrological fluxes induced by topography, soil and vegetation heterogeneities and climate variability. ForestGrowth is a further extension of ForestETP-1D in which assimilated carbon is allocated to foliage, stem and roots to dynamically simulate tree growth over periods of years and decades, enabling it to be used as a tool in forest management. Questions like: ‘If we were to extend the period of the forest rotation, how much more carbon would be sequestered?’ may be addressed with this model.

Although conceived as a model for use in the UK, ForestETP is quite general and can be applied to any forest; for example, it has been validated against pan-European eddy covariance C-flux data.

5.3. Data assimilation

Data assimilation, or model-data fusion, is a process that blends information from models (*i.e.* our best understanding of how a system functions) with observations (our best quantification of system states and activity). Some examples were given in our last report. Since then, developments we have made in the application of Bayesian statistics have provided a structured and optimal means to link *a priori* knowledge (the model) with observations, to produce an analysis that is better than either model or observations alone. We have already demonstrated how the Ensemble Kalman filter, a Bayesian tool, can provide improved analyses of ecosystem carbon budgets (Williams *et al.* 2005). Since then, we have developed a technique for assimilating reflectance data from satellites directly into the DALEC model. This is vital because it means that large datasets from earth observation can be effectively integrated with a model to produce regional estimates of C exchange *with quantifiable error*. We are currently working on generating such products.

5.4. Incorporating new data

5.4.1. Fluxes and Stocks

Carbon fluxes can be measured or inferred at several scales using flux towers, aircraft flights and tall towers), and these methods should eventually deliver continuous monitoring of CO_2 fluxes. Any flux changes that are sustained should be evident over several years as changes in carbon stocks. For forest stands, biomass C is quantifiable using conventional methods developed in forestry, as there are well-developed ground-based observations that show the empirical relationships between stem diameter, age and biomass of trees from measurement of girth. One complication is that all European forests are highly managed and subject to felling and storm damage, and so attempts have been made in the CTCD to devise remote sensing approaches to the measurement of tree height and tree biomass, using either lidar or the ESA ERS Tandem missions (http://www.esa.int/esaCP/SEMDKSLVGJE_index_0.html). Both have proved promising. Airborne sensors have demonstrated that lidar can be very valuable in providing detailed information on stand structure, but suitable spaceborne lidars are still in the proposal phase. The Tandem missions, which allowed images from the two ERS synthetic aperture radar sensors to be combined into a quantity called interferometric coherence, produced unexpectedly useful results. The two plots in Figure 5-3 indicate that information on the age of young forests can be derived from coherence. This can be combined with relations between carbon flux and age to estimate Net Ecosystem exchange in UK forests (Drezet and Quegan, submitted). Also, the changes in the coherence-age relation clear from Figure 5-3 can be explained in terms of weather conditions and corrected using SVAT models combined with radar scattering models (Drezet and Quegan, in press).

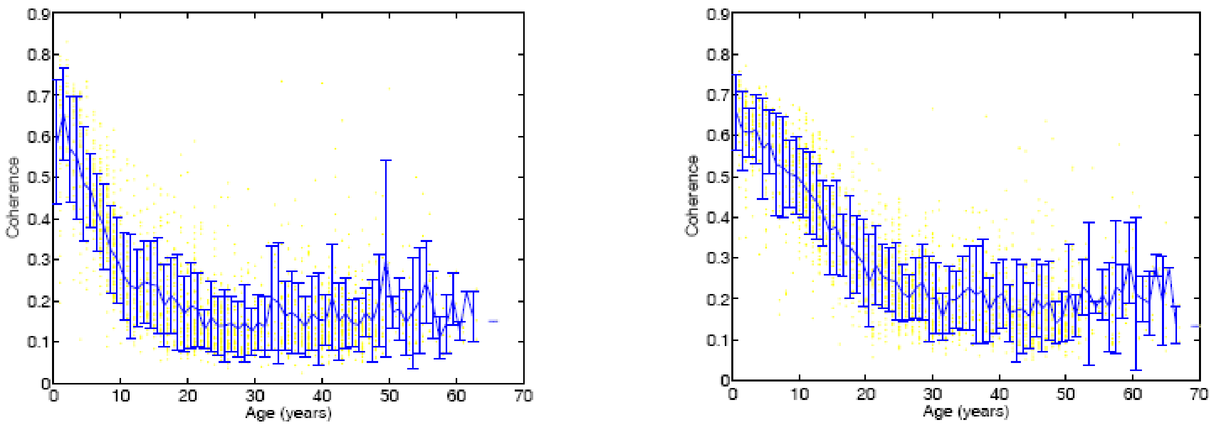


Figure 5-3 Radar remote sensing may be used to detect the age of a forest up to a saturation level. Plot of age versus 'Tandem Coherence' obtained by Synthetic Aperture Radar for Sitka spruce in Kielder forest in July 1995 (left) and August 1999 (right). From Drezet & Quegan, IEEE Trans Geosci. Remote Sensing, in press.

However, whilst it is possible to use inventory methods and possibly remote sensing methods to measure the stock changes in biomass carbon of forests, it is much more difficult to measure the changes in the carbon stocks of soils; of all European countries it is only the UK which has spatially explicit reference data (Bellamy *et al.*. 2005, *Nature* 437, 245-248). Even in that case, the adequacy is questionable because soil carbon has only been measured to a reference depth of 15 cm and the changes in bulk density over the measurement period 1978-2003 were not recorded. Moreover, soil carbon is inherently extremely variable, especially for forest soils (Conen *et al.*. 2005). Thus, inventory-based estimates of carbon stocks have severe limitations, as has been recognised by the IPCC. In the long run, therefore, flux data are likely to be a more sensitive indication of carbon sinks than stock-taking. A primary aim in the CTCD is to promote and develop the use of flux measurements and remote sensing to complement stock measurements (as implied by Figure 5-1).

5.4.1.(a) Eddy covariance data- ecosystem CO_2 and H_2O fluxes

Flux data from various land use types are available through the CarboeuropeIP data base, which can be accessed at http://gaia.agraria.unitus.it/cpz/index3.asp, whilst older data are available from the Euroflux web site, http://132.180.60.7/WRZLPRMPFT/welco.htm. The sites are well-distributed in Europe (Figure 5-9), although the varied nature of the land surface cover, and the diversity of crops, semi-natural shrubland/grassland and forests places a heavy dependency on modelling if we are to upscale from a basic knowledge and understanding of fluxes to behaviour at the landscape and regional levels. Use of the Euroflux data is unrestricted, but availability of the newer CarboeuropeIP data is controlled by the respective PIs for the first 12 months. CTCD has used both sources in parameterising and validating models. In the UK, data are becoming available for coniferous and deciduous forests, for moorlands, grasslands and agricultural systems. Many of these new data sets have only gone on-line in the last few months.

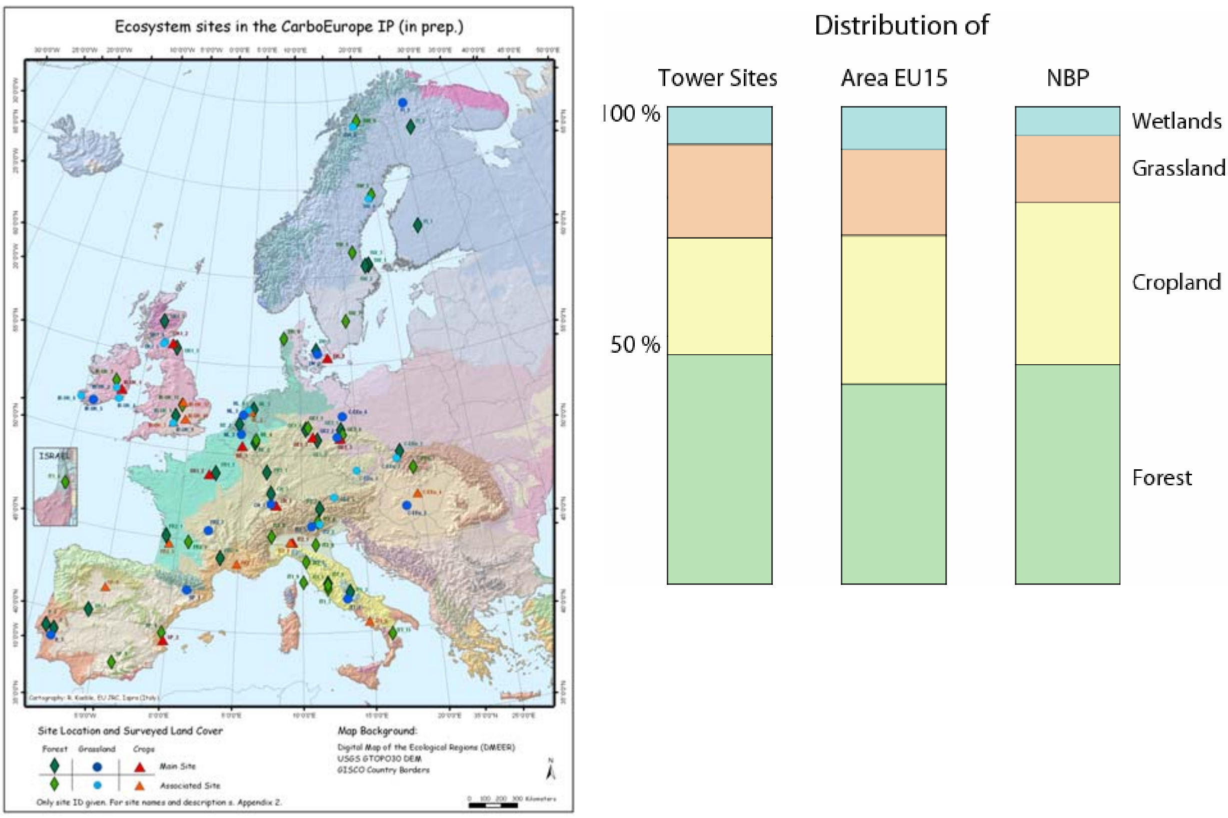


Figure 5-4 Distribution of Carboeurope-IP flux stations (forests, green diamonds; grasslands, blue circles; crops, red triangles). The histogram bars show the fractional distribution of stations numerically (left bar) and the distribution of European land area and biological production between wetlands, grasslands, croplands and forest.

5.4.1.(b) Atmospheric data

The approach to a greenhouse gas observing system as measured using atmospheric observations is currently developing in Europe (as part of CarboEurope-IP) and in North America (as part of the North American Carbon program, see Gloor *et al.* 2001). Progress has been delayed in Europe as a result of negotiations about rental charges of space on towers in some parts of Europe, but the system is finally operational.

The approach is to make use of atmospheric concentration measurements of greenhouse gases at three distinctly different spatial scales and to link them via inverse modelling activities. Such an integrated approach in the UK is available as part of the University of Edinburgh's role within CTCD. In brief, there are tower measurements of greenhouse gas concentration in the atmospheric surface layer *i.e.* within 30 m of the land surface; tower measurements in the well-mixed planetary boundary layer at heights of 200 m and above; and aircraft profile measurements made at levels in and above the planetary boundary layer (typically to 3000 m asl). Measurements of trace gas concentration made from the small towers will be representative of the local sources and sinks on a scale of several km from the observing site; measurements on tall towers are representative of regional scale sources and sinks (typically 70% of the gas concentration measured on these tall towers comes from within 300 km of the tower). Aircraft can essentially be used as 'roving towers' and can sample at a range of heights from within a few tens of metres of the ground surface to heights up to 3000 m; they can also be used in 'box-budget' studies to obtain greenhouse gas balance on a country-wide scale by measuring the air flowing into the borders of a country and then measuring that same air as it leaves several hundred km downwind from its entry point.

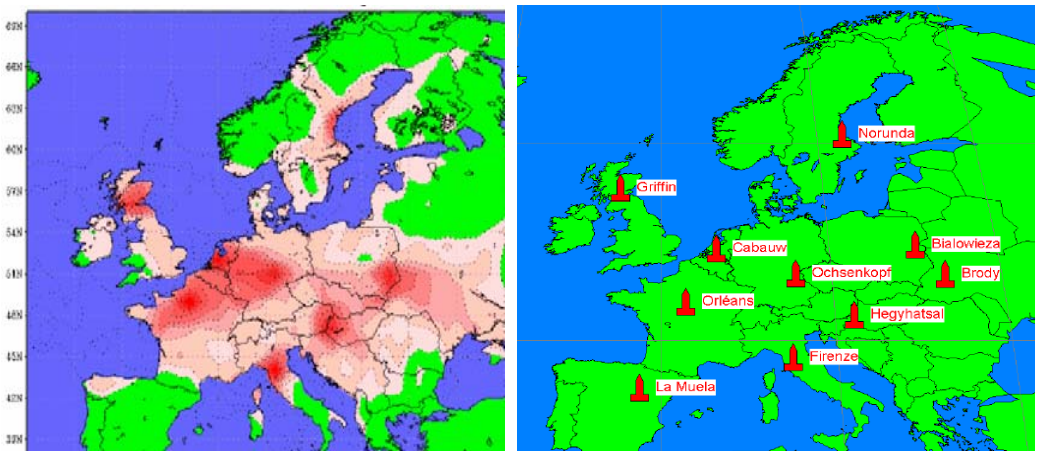


Figure 5-5 Coverage of Europe by the Carboeurope system of tall towers. Tall towers 'see' the signal from about 100 km around them as an increase or decrease in concentration. Note the coverage of the northern part of GB by the tower in Fife Scotland and the weaker coverage of the southern part of UK, partly covered by towers in France. A further tower in England would enable strong coverage of the UK. Data analysis has been delayed by the completion of the network: methodology has been developed (e.g. Peylin *et al.* 2005) and first results were shown in the Carboeurope meeting in December 2005.

In the UK, the UoE operates nearly co-located surface layer and tall tower systems near Dundee and they also operate a small research aircraft that has greenhouse gas sampling equipment on board. The aircraft can be set up to provide continuous profiles of the main greenhouse gases or can be used with an automatic flask sampling system to grab samples of air at different locations over and above different landscapes. The UoE will have a PDRA and a PhD student working on the inverse modelling aspects of the data obtained from both surface layer and tall towers in collaboration with the Met. Office. The measurement system is in place and calibration standards traceable to WMO protocols have been tested and met. The atmospheric observing system operated by the UoE is in place and working; extending the system to the rest of the UK would require one additional Tall Tower and regular aircraft profiling somewhere in England.

Coverage of *all greenhouse gases* is available using this approach and attempts to use tracers (carbon monoxide and isotopes of C) for quantifying the fossil fuel vs biogenic component of the CO_2 signal are underway in Carboeurope using carbon monoxide and isotopes as tracers.

5.4.2. Reducing uncertainty in the behaviour of carbon stocks in the soil

We located a new data-base for soil organic matter carbon (ISLSCP II) and examined relationships between carbon stocks and mean temperature. Latest updates of the UK soils data have recently been supplied to us from NSRI and MLURI (including Scottish texture data) but the delay in their provision has prevented us from preparing final conclusions on the link between all-UK soils data and climate. From what we have already, there is undoubtedly a signal, suggesting that warming of UK soils will reduce the C-stocks in much the same way as reported by Bellamy *et al.* (2005). The slope of the relationship for the UK (Figure 5-6) suggests that a 1^{o}C warming in the cold wet parts of the UK might lead to a loss of soil carbon of as much as 15 kg m^{-2} or 25% whereas, for the same regions of the UK, Bellamy *et al.* (2005) found 2% per year over 25 years.

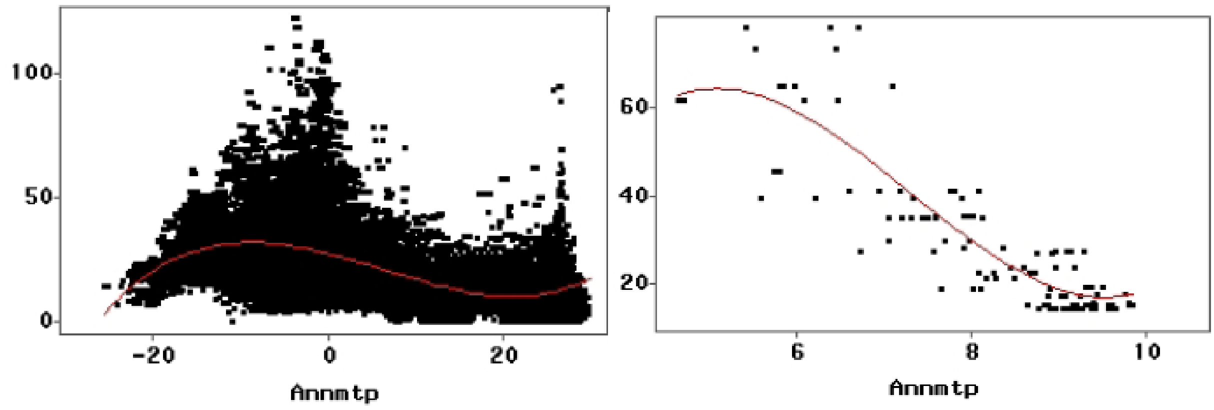


Figure 5-6 Relationship between soil carbon (kg m^{-2}) and annual mean temperature (Celsius). Soil is to 150 cm in depth and data are ISLSCP II. The graphs show global relationships (left) and UK relationships (right).

Work is underway at York and Edinburgh to characterise the vulnerability of the carbon sink to temperature and soil moisture, and to partition the observed 'soil respiration' between autotrophic and heterotrophic components.

5.5. Overall biogenic carbon fluxes and uncertainty calculations

Using SDGVM we attempted to calculate the biogenic carbon fluxes for the year 2000, with associated uncertainties (Figure 5-9). The model was run with interpolated monthly climatic data, distributing the land between four Plant Functional Types (PFTs): deciduous broadleaved trees, evergreen needle trees, crops and C3 grasses, based on a high resolution land cover map for the UK (LCM2000). The uncertainty in the PFT parameter inputs was estimated by the process of 'elicitation', whereby the statistical modeller seeks expert opinion from the ecologists on such parameters as 'leaf longevity'. Uncertainty in the soil properties at the sixth of a degree spacing of the model grid-cells was derived from the latest soil texture maps for England and Wales. The overall biogenic carbon budget for England and Wales was a 'sink' of 7.61 MtC with an uncertainty of 0.61 MtC. The greatest biospheric uptake and the greatest uncertainty both arise from grassland. The estimated carbon uptake is not directly comparable with calculations made for the National Inventory Report (Milne & Cannell 2005) as the geographical basis is different and the SDGVM covers all vegetation types. However, the 'changes in forest biomass' from the National Inventory of 2002 was 2.58 MtC, and the figure derived from rather limited eddy covariance data over European forests suggests 2 tC ha^{-1} yr^{-1} which translates to 2.5 MtC when multiplied by the area of forests in the UK.

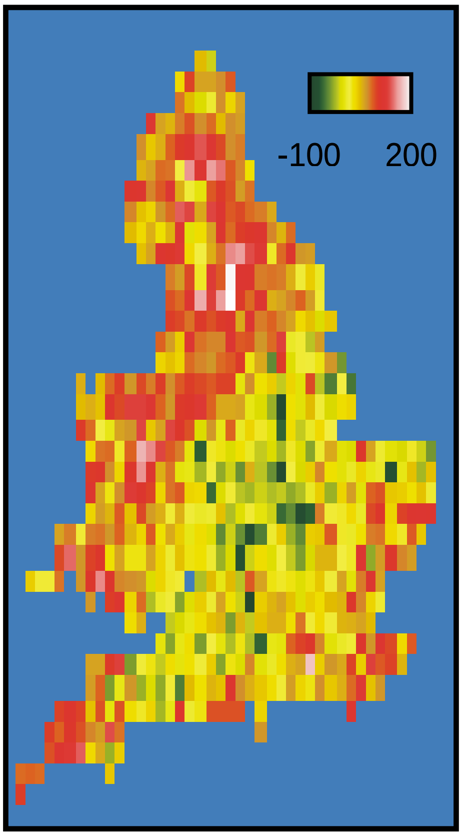


Figure 5-7 Maps of (left) best estimates of the biogenic uptake of CO_2 for England and Wales for 2000 (C-sinks are shown as positive and sources are negative) and (right) the standard deviation of the estimates, arising from uncertainty in the Plant Functional Types and soil parameters. The units are gC m^{-2}. Uncertainties due to errors in the underlying land cover map have also been assessed, but not yet combined consistently with the results shown here.

PFT	Mean (Mt C)	SD (Mt C)
Grassland	4.65	0.57
Crop	0.50	0.19
DcBl	1.69	0.09
EvNl	0.78	0.03
Covariances		0.03
Total	7.61	0.61

Table 5-1 Contribution to the mean and standard deviation of total Net Biome Production by different plant functional types and covariances between these types.

Uncertainty analysis (Figure 5-9) shows that lack of knowledge of soil parameters is especially important in the case of forests, but less so for grasslands and croplands.

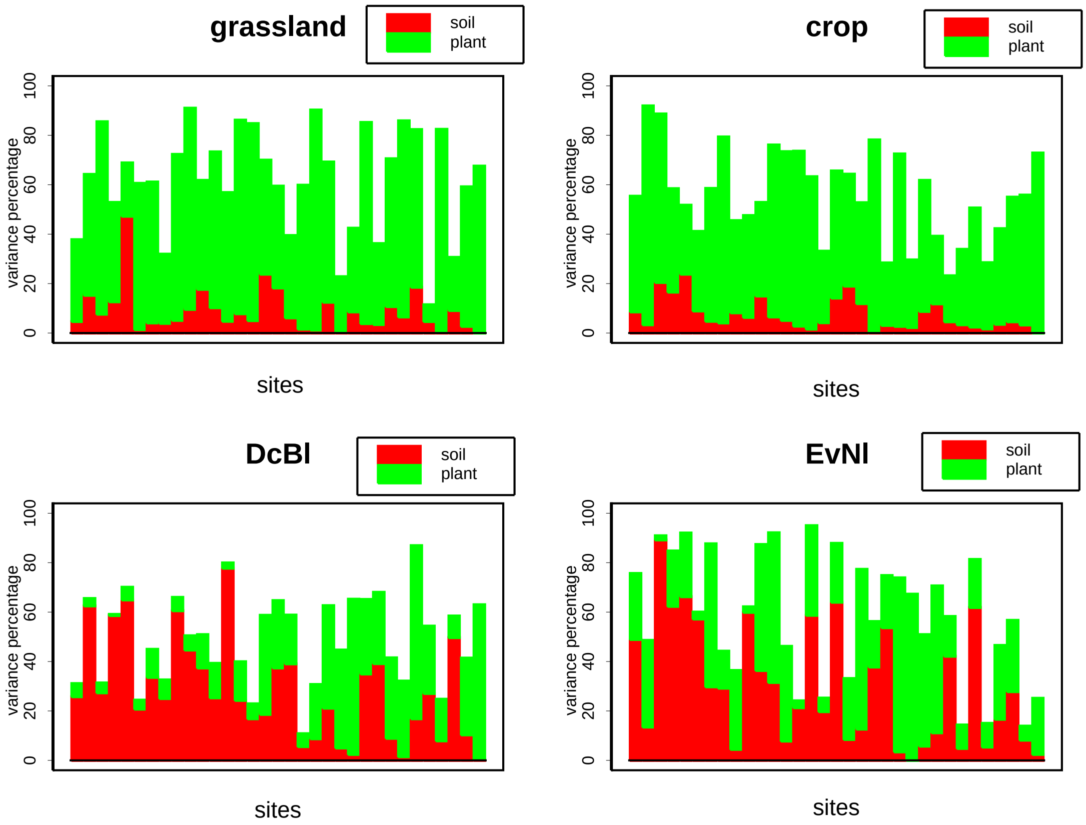


Figure 5-8 Percentages of uncertainty in NBP output from SDGVMd (for grasslands, croplands, Broadleaved Trees and Evergreen Trees) at 33 test sites due to PFT parameter uncertainty (green) and soil parameter uncertainty (red). Note that these do not sum to 100% because of interaction effects.

5.6. Conclusions and Forward Look

Progress has been made towards the development of a carbon-observing system to cover UK and Europe, and it is now possible to envisage an automatic and continuous surveillance system based upon a combination of the approaches which have been explored in this project (Figure 5-9). Achieving this goal will require good co-operation between research agencies, and adequate funding for specific research themes to be taken forward. We have identified several critical areas for discussion:

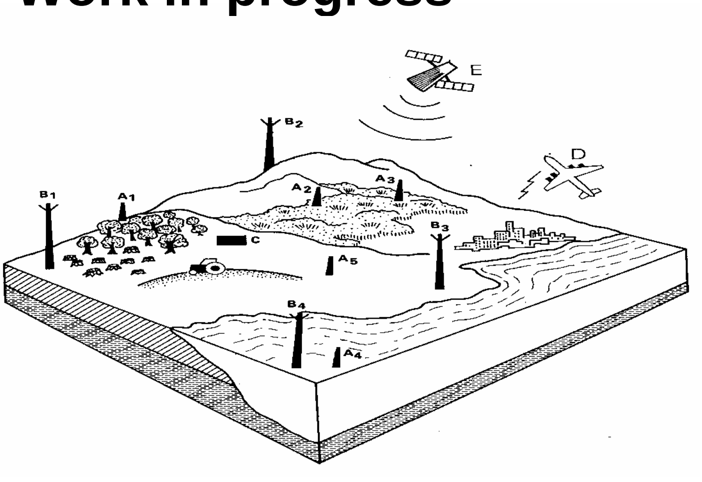
1. In the UK we are fortunate to have an excellent map of land cover (through the CEH Countryside Survey and Land Cover Map 2000) which is due for an update soon. We have shown that using moderate resolution satellite-based land cover products leads to biases in estimates of the UK net carbon uptake, although the SPOT-VEGETATION GLC2000 yields significantly better estimates than any of the available MODIS land cover products. Collaboration between the CTCD and CEH during the next phase of CTCD's programme is likely to be beneficial to see how far year-to-year changes in land use may be detectable from satellite data, using some of the techniques for change-detection which have been developed in this project. For this purpose, we should also exploit the data from the recently launched Japanese ALOS L-band radar satellite.

2. Exploitation of tall-tower measurements has featured less in this project than was hoped for at the outset, due to delays in establishing towers. It is clear that one more

tower would be especially useful to achieve coverage of the southern part of the UK. The towers offer the prospect of estimating the total greenhouse gas fluxes and apportioning the CO_2 fluxes between anthropogenic and biogenic.

3. Since the project started, it has become technically possible to measure methane and nitrous oxide fluxes by eddy covariance, as a result of the development of fast response analysers (based on tunable diode lasers). These sensors can now be installed at CO_2 flux sites and in 'roving towers' and mobile laboratories for examination of particular sites and management practices. Consideration should be given to establishing a network of them.
4. The Orbiting Carbon Observatory (OCO) will be launched in 2008 and will provide global column-averaged coverage of CO_2 concentrations (http://oco.jpl.nasa.gov). The precision of the single measurement will not be as great as that from an infra red gas analyser mounted on a tower, but because there will be so many measurements the data will be important in constraining the global, regional and national carbon inventories.
5. Relationships between the 'whole-carbon accounting' and inventory-based reporting need further discussion. With some modification, models could produce outputs of both the total biogenic carbon fluxes and the carbon fluxes that are to be 'counted' by the inventory approach.
6. Co-ordination of the UK's research effort to understand the future of the carbon sink is now a priority, as part of the global concern that sinks will turn into sources as a result of warming and drying (Grace 2004). Experimental studies using field manipulations should now be pursued in different climatic regions of the UK.
7.

Work in progress



Observations + Models

+ Data Assimilation

= high-resolution C fluxes

Figure 5-9 Surveillance of greenhouse gas emissions using eddy covariance towers to define the fluxes over specific land-use types (A), tall towers to investigate the fluxes over regions of 100-200 km (B), ground-based data acquisition systems to characterise the soil fluxes and their sensitivity to climate change (C), aircraft to carry out independent 'snapshot' mass-balance calculations of fluxes (D), satellite data for detecting land use change and photosynthetic activity, and (from 2008) measuring column-average CO_2 concentrations (D).

5.7. References

Bellamy PH, Loveland PJ, Bradley RI *et al.* (2005) Carbon losses from all soils across England and Wales 1978-2003. *Nature* 437, 245-248.

Conen F, Zerva A, Arrouays CJ *et al.* (2005) The carbon balance of forest soils: detectability of changes in soil carbon stocks in Temperate and Boreal forests. Pp 235-249 In Carbon Balance of Forest Biomes, eds H Griffiths and PG Jarvis, Taylor and Francis, Oxford.

Drezet PML and Quegan S, Environmental effects on the interferometric repeat-pass coherence of forests, *IEEE Trans. Geosci. Remote Sensing* (in press)

Drezet PML and Quegan S, Satellite-based radar mapping of British forest age and net ecosystem exchange using ERS tandem coherence, *Forest Ecology* (submitted).

Gloor, M., Bakwin, P., Hurst, D., Lock, L., Draxler, R and Tans, P. (2001) What is the concentration footprint of a tall tower? *Journal of Geophysical Research* 106, 17831-17840.

Grace J (2004) Understanding and managing the carbon cycle. *Journal of Ecology* 92, 189-202.

P. Peylin, P.J. Rayner, P. Bosquet, C. Carouge, F. Hourdin, P. Heinrich, P Ciais and EROCARB contributors (2005). Daily CO_2 flux estimates over Europe from continuous atmospheric measurements: 1, inverse methodology. *Atmospheric Chemistry and Physics Discussions.* 5, 1647-78.

Picard G, Quegan S, Delbart N, *et al.* (2005). Budburst modelling in Siberia and its impact on quantifying the carbon budget. *Global Change Biology* 11, 2164-2176.

Picard G, Woodward FI, Lomas MR, *et al.*.(2005) Constraining the Sheffield dynamic global vegetation model using stream-flow measurements in the United Kingdom. *Global Change Biology* 11, 2196-2210.

Section 6

The potential use of the Rothamsted Carbon model, RothC, in GHG inventories

Table of Contents

6. The potential use of the Rothamsted Carbon model, RothC, in GHG inventories

K.Coleman[*]*, D.S. Powlson*[*]*, R. Milne and A.P. Whitmore*[*]
[*]*Rothamsted Research, Harpenden, Hertfordshire. AL5 2JQ. UK*

6.1. Abstract

Currently there is a great need to document the world's carbon stocks in soils and changes in those stocks with time. Signatories to the UNFCC are obliged to make annual returns. Most make use of IPCC methodology but this is crude and there have been several attempts at improvement. Inevitably, however, improvements are costly in computer time and even with advances in processor speed, this cost can be prohibitive in detailed analyses. The Rothamsted Carbon model, RothC-26.3 (referred to hereafter as RothC), is a mechanistic model of the processes affecting the dynamics of carbon in soil that works at a time-scale appropriate to inventories. It has been embedded into an Excel spreadsheet for the Australian inventory (Richards, 2001) and has been used as an aid to validating the General Linear Model used in the New Zealand inventory (Tate *et al*., 2005). It forms the basis of RothCUK a spatially distributed version of RothC for the UK at a 1 km spatial resolution (Falloon *et al*., 2006). In practice, however, current inventories worldwide lag behind the detailed data collection needed to run RothCUK. Given this gap but given too the need to improve on IPCC methodology, the task we set ourselves to investigate is this: How might the mechanistic capability of RothC best be introduced into the UK carbon reporting process simply but with the capability for gradual improvement as data collection and reporting improve with time? We compare two likely options: (1) simple systems of equations; what we lose in mechanism we hope to gain in simplicity by this approach. (2) call the RothC model directly from within the inventory spreadsheet.

Although the meta-model system performed well in the sense that it could emulate RothC, it presents poor prospects in practice since the parameters required were rather variable. This is surprising because a simple meta-model is at the heart of the current UK inventory. An analytical solution to the differential equations underlying RothC appears attractive for some purposes such as assessing variability and uncertainty, but is likely to still require too many different parameter sets for deployment within the inventory. We conclude that the most effective means to improve the UK inventory is to call RothC directly from the inventory spreadsheet. Although this is a costly option in computer time, it future-proofs the system, since upgrades to RothC will always be easily available. This option supports the gradual adaptation of the inventory not only to improvements in databases as and when such information becomes available but also the incorporation new modules such as the introduction of vegetation modelling (BIOTA elsewhere in this report). Because we see evolution of the inventory as vital, we discount embedding RothC directly in the inventory.

6.2. Introduction

There is currently a great need to estimate the effect of changes in land use and climate on the global environment. RothC-26.3 (RothC) is a model of the turnover of carbon in soils and is one of a very few models currently used world-wide to study global carbon dynamics and to report in national inventories of carbon stocks for the United Nations Framework Convention on Climate Change (e.g. Richards 2001). Although current computing power is large and although RothC is a relatively simple model, computer-intensive applications such as estimating changes in carbon stocks world-wide may still require programme components to be simplified as far as is possible in order to run in realistic times. This is especially important where estimates of uncertainty are required and obtained by running the models many time with different inputs to reflect all possible outcomes (Monte-Carlo methods). For these reasons and for uniformity or reporting, current national inventories have tended to make use of the IPCC methodology for specifying the changes that happen to soil carbon following land-use change (LUC). Although a little crude, IPCC (1996 and 2000) methodology is reviewed and updated periodically (e.g. Paustian *et al.*, 1997). In the UK our current inventory makes use of knowledge derived from an analogue of the IPCC methodology that has become known as the coefficient method (Cannell, *et al.*, 1999). Essentially the turnover processes of organic carbon dynamics in soil are expressed by means of a simple equation. There is, however, a half-way house between the simplicity of say a single equation and a fully mechanistic model known as a meta-model. A great advantage of meta-models is that they can be used easily in order to study its sensitivity to particular changes in a computer-intensive Monte-Carlo fashion. Furthermore it can be helpful to have a simplified version of a more complex model in other mathematical expressions of parameter optimisation routines such as the Levenberg-Marquadt algorithm.

6.3. The Rothamsted carbon model (RothC)

The Rothamsted carbon model (RothC) is a model for the turnover of organic carbon in non-waterlogged topsoils that allows for the effects of soil type, temperature, moisture content and plant cover on the turnover process. It uses a monthly time step to calculate total soil organic carbon, microbial biomass carbon and delta^{14}C (from which the equivalent radiocarbon age of the soil can be calculated) on a years to centuries timescale. (Jenkinson *et al.* 1987; Jenkinson, 1990; Jenkinson *et al.* 1991; Jenkinson *et al.* 1992; Jenkinson and Coleman, 1994).

Soil organic carbon is split into four active fractions and one small inert organic matter (IOM) fraction (Figure 6-1). The active fractions are: decomposable plant material (DPM), resistant plant material (RPM), microbial biomass (BIO), and humified organic matter (HUM). Each fraction decomposes by a first-order process with its own characteristic rate. The IOM fraction is considered to be resistant to decomposition.

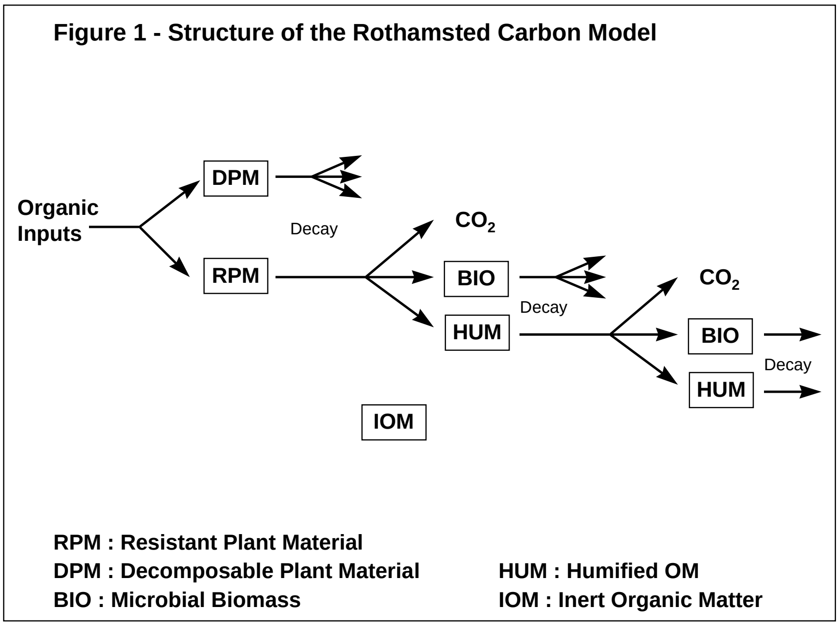


Figure 6-1 Structure of the Rothamsted Carbon model RothC, showing the compartments and flows of carbon between compartments.

RothC was originally developed and parameterized to model the turnover of organic C in arable topsoils from the Rothamsted Long Term Field Experiments - hence the name. Later, it was extended to model turnover in grassland and in woodland and to operate in different soils and under different climates. It should be used cautiously on subsoils, soils developed on recent volcanic ash, soils from the tundra and taiga and not at all on soils that are permanently waterlogged.

RothCUK is itself an interface to the code for the RothC model. RothCUK utilises 1km scale soils, land use and land use change data developed under the parallel DEFRA projects, along with relevant current and future climatic datasets, and has been used to investigate the effects of changes in land use, land management and climate change on national C stocks. The model may be run for Great Britain or Northern Ireland, and runs separately for different land uses (arable, grass, semi-natural and forest) and two soil depths (0-30cm and 30-100cm). These choices were based on the available datasets, as well as for land use change matrix data for Great Britain. Output data include total soil C and CO_2 emissions in formats suitable for import into GIS packages.

Whatever the basis of the underlying description of organic matter processes in soil, current inventories tend to be written for widely used and accessible frameworks such as the spreadsheet package Excel©. We investigate here the best means by which RothC might be incorporated into a carbon inventory with particular reference to the UK reporting requirements. We consider and evaluate the performance of four options:

1. Meta-models equivalent to RothC.

2. Using a version of RothC encoded directly within a spreadsheet (Richards, 2001; Janik *et al*. 2002).

3. Obtaining an analytical solution for the equations underlying RothC (Parshotam 1996)

4. Using a version of RothC linked through an interface.

Option (2) has been attempted before (Richards, 2001) and so will be given less space here. Options (1) and (4) are novel and will form the majority of this report.

6.4. Materials and Methods

6.4.1. RothC as a meta-model

RothC supposes soil organic carbon to consist of five compartments in soil each with a characteristic decay rate (Figure 6-1). Expected inputs of carbon from plant cover are supplied to the model.

Since RothC is itself a combination of exponential decays of carbon in soil, it seems logical to see if the changes in soil organic carbon might be simulated with a simpler system of fewer equations. What we lose by no longer being able to ascribe mathematical meaning to the exponentials we hope to gain in simplicity. We test here three simplifications of the RothC system against the output from RothC itself. In particular Eqs [3] were chosen to be multi-exponential improvements of the forms of the equations currently used in the inventory (Baggott *et al*., 2004; Cannell *et al*., 1999, who used Eq [3a]). The systems are:

(1) Simple (parallel) exponentials

$$C = A_1(1-\exp(-k_1 t)) \quad [1a]$$
$$C = A_1(1-\exp(-k_1 t)) + A_2(1-\exp(-k_2 t)) \quad [1b]$$
$$C = A_1(1-\exp(-k_1 t)) + A_2(1-\exp(-k_2 t)) + A_3(1-\exp(-k_3 t)) \quad [1c]$$
$$C = A_1(1-\exp(-k_1 t)) + A_2(1-\exp(-k_2 t)) + A_3(1-\exp(-k_3 t)) + A_4(1-\exp(-k_4 t)) \quad [1d]$$

(2) Sequential single exponentials (terms are added to A_0 if LUC leads to an increase in soil C, otherwise subtracted).

Two:

$$\begin{aligned} C &= A_0 \pm A_1(1-\exp(-k_1 t)); t < t_1 \\ &= A_0 \pm (A_1(1-\exp(-k_1 t_1)) + A_2(1-\exp(-k_2(t-t_1)))); t \ge t_1 \quad [2a] \end{aligned}$$

Three:

$$\begin{aligned} C &= A_0 \pm A_1(1-\exp(-k_1 t)); t < t_1 \\ &= A_0 \pm (A_1(1-\exp(-k_1 t_1)) + A_2(1-\exp(-k_2(t-t_1)))); t \ge t_1; t < t_2 \\ &= A_0 \pm (A_1(1-\exp(-k_1 t_1)) + A_2(1-\exp(-k_2(t_2-t_1)) + A_3(1-\exp(-k_3(t-t_2)))) \quad [2b] \end{aligned}$$

Four:

$$\begin{aligned} C &= A_0 \pm A_1(1-\exp(-k_1 t)); t < t_1 \\ &= A_0 \pm (A_1(1-\exp(-k_1 t_1)) + A_2(1-\exp(-k_2(t-t_1)))); t \ge t_1; t < t_2 \\ &= A_0 \pm (A_1(1-\exp(-k_1 t_1)) + A_2(1-\exp(-k_2(t_2-t_1)) + A_3(1-\exp(-k_3(t-t_2)))); t \ge t_2; t < t_3 \\ &= A_0 \pm (A_1(1-\exp(-k_1 t_1)) + A_2(1-\exp(-k_2(t_2-t_1)) + A_3(1-\exp(-k_3(t_3-t_2))) + A_4(1-\exp(-k_4(t-t_3)))) \quad [2c] \end{aligned}$$

(3) Differential forms (against transformed data) analogous to the coefficient method

$$C = C_f - (C_f - C_0)\exp(-k_1 t) \quad [3a]$$
$$C = C_f - (C_f - C_0) * (M_1 \exp(-k_1 t) + M_2 \exp(-k_2 t)) \quad [3b]$$
$$C = C_f - (C_f - C_0) * (M_1 \exp(-k_1 t) + M_2 \exp(-k_2 t) + M_3 \exp(-k_3 t)) \quad [3c]$$

where C is the change in soil carbon, A_1, A_2, A_3 and A_4 are coefficients representing the change in carbon stock, M_1, M_2 and M_3 fractional changes of carbon stocks, k_1, k_2, k_3 and k_4 are coefficients representing the rate of that change and t_1, t_2 and t_3 are the times at which a transition from one set of coefficients to another takes place.

Models can be compared statistically two at a time, one with another using a variance ratio (F) test as follows,

F = (ΔRSS / ΔDF) / (RMS more complex model)

where ΔRSS is the change in the residual sum of squares in moving from one model to the next, ΔDF is the change in the number of degrees of freedom and RMS is the residual mean square. This $F_{(\Delta DF,\ DF\ \text{more complex model})}$ was tested against standard values at known probabilities (Table 6-1 and Table 6-2).

Table 6-1 (a) Values of parameters and variability found during fitting Arable-2-Forest 100 year data, (b) Values of parameters and variability found during fitting Pasture-2-arable 100 year data, (c) Values of parameters and variability found during fitting Pasture-2-seminatural 100 year data, (d) Values of parameters and variability found during fitting Pasture-2-Forest 100 year data

(a)

Equation	RSS	Df	RMS	Comparison	Delta df	F
1a	256.9	98	2.622	1c with 1a	4	230091.2
1b	0.1083	96	1.128e-3	1c with 1b	2	147.0
1c	0.02624	94	2.791e-4			
1d				Not converged		
2a	1.333	94	1.418e-2			
2b	0.09029	91	9.922e-4	2c with 2b	3	153.3
2c	0.0145	88	1.648e-4	2c with 1c	6	11.9
3a	2148	99	21.7			
3b	0.03516	96	3.662e-4	3c with 3b	2	8.5
3c	0.02979	94	3.169e-4	2c with 3c	6	15.46

(b)

Equation	RSS	Df	RMS	Comparison	Delta df	F
1a	42.64	98	0.4351	1c with 1a	4	139.7
1b	0.1739	96	0.001811	1c with 1b	2	45.7
1c	6.140	94	0.06532			
1d				Not converged		
2a	0.2904	94	3.03e-3			
2b	0.05761	91	5.761e-2	2c with 2b	3	225.02
2c	6.644e-3	88	7.55e-5	2c with 1c	6	13539.42
3a	132.8	99	1.342			
3b	0.06019	96	6.27e-4	3c with 3b	2	113007
3c	2.502e-5	94	2.662e-7	2c with 3c	6	14.61

(c)

Equation	RSS	Df	RMS	Comparison	Delta df	F
1a	280.3	98	2.860204	1a 1c	4	7078259.3
1b	0.1951	96	0.002032			
1c				Not converged		
1d				Not converged		
2a	1.441	94	0.01533			
2b	1.15E-01	91	0.001259	2c 2b	3	126.4
2c	2.17E-02	88	0.000246	2c 1c	6	14.1
3a	1807	99	18.25253			
3b	6.41E-03	96	6.68E-05	3c 3b	2	23.24
3c	1.27E-02	94	0.000135	2c 3c	6	6.08

(d)

Equation	RSS	Df	RMS	Comparison	Delta df	F
1a	59.85	98	0.610714286	1a 1c	4	8293.9
1b	0.7124	96	0.007420833			
1c				Not converged		
1d				Not converged		
2a	6.02E-01	94	0.006406383			
2b	7.03E-02	91	0.000772418	2c 2b	3	5.24
2c	5.96E-02	88	0.000677614	2c 1c	6	26.9
3a	968.3	99	9.780808081			
3b	1.65E-01	96	0.001714583	3c 3b	2	0.3
3c	1.64E-01	94	0.001748936	2c 3c	6	25.77

Table 6-2 (a) Values of parameters and variability found during fitting Arable-2-Forest 300 year data, (b) Values of parameters and variability found during fitting Pasture-2-arable 300 year data, (c) Values of parameters and variability found during fitting Pasture-2-seminatural 300 year data, (d) Values of parameters and variability found during fitting Pasture-2-Forest 300 year data

(a)

Equation	**RSS**	**Df**	**RMS**	**Comparison**	**Delta df**	**F**
1a	2428	299	8.121	1a 1c	4	14347.7
1b	13.53	297	4.554e-2			
1c				Not converged		
1d				Not converged		
2a	4.147	295	1.406e-2			
2b	1.90E-01	292	6.489e-4	2c 2b	3	568.4
2c	2.75E-02	289	9.53e-5	2c 1c	6	21672.8
3a	5580	300	18.60			
3b	4.92E-02	297	1.656e-4	3c 3b	2	62.2
3c	3.46E-02	295	1.174e-4	2c 3c	6	12.4

(b)

Equation	**RSS**	**Df**	**RMS**	**Comparison**	**Delta df**	**F**
1a	162.3	299	0.5427	1a 1c	4	10300.8
1b	0.8201	297	2.761e-3			
1c				Not converged		
1d				Not converged		
2a	4.51E-01	295	1.527e-3			
2b	7.65E-02	292	2.62e-4	2c 2b	3	604.2
2c	1.05E-02	289	3.641e-5	2c 1c	6	5234.4
3a	272.5	300	9.084e-1			
3b	6.20E-02	297	2.086e-4	3c 3b	2	283995.4
3c	3.22E-05	295	1.091e-7	2c 3c	6	47.9

(c)

Equation	**RSS**	**Df**	**RMS**	**Comparison**	**Delta df**	**F**
1a	2181	299	7.293	1a 1c	4	15212.2
1b	11.72	297	3.945e-2	1c 1b	2	16.8
1c	10.52	295	3.567e-2			
1d				Not converged		
2a	9.331	295	3.163e-2			
2b	2.25E-01	292	7.692e-4	2c 2b	3	481.5
2c	3.75E-02	289	1.298e-4	2c 1c	6	13459.8
3a	4681	300	15.6			
3b	1.14E-02	297	3.828e-5	3c 3b	2	30.6
3c	9.44E-03	295	3.199e-5	2c 3c	6	36.0

(d)

Equation	**RSS**	**Df**	**RMS**	**Comparison**	**Delta df**	**F**
1a	861.7	299	2.8832	1a 1c	4	6815.4
1b	9.246	297	0.03113	1c 1b	2	0.4
1c	9.224	295	0.03127			
1d	2.65E-03	295	9.052e-6			
2a	1.55	295	5.247e-3			
2b	9.08E-02	292	3.11e-4	2c 2b	3	46.1
2c	6.14E-02	289	2.126e-4	2c 1c	6	7183.0
3a	2473	300	8.244			
3b	1.934e-1	297	6.513e-4	3c 3b	2	0.0
3c	1.934e-1	295	6.557e-4	2c 3c	6	103.5

RothC was run with four land-use changes: arable to pasture, pasture to semi-natural, arable to forest and pasture to forest. Baseline data of the change in soil carbon stocks using RothC was generated for 300 years. The functions above were evaluated for their ability to reproduce the full 300 years of data and separately for their ability to reproduce the first 100 years only. Climate will also affect the results and so a meta-model system will either need to incorporate the affects of climate directly within the calculations as in RothC or different parameters, particularly the rates of decomposition, will be required in a model. Accordingly we assess the effects of a range of climate zones in the UK and North West Europe (Table 6-3), in order to mimic potential climate change) on the stability of the parameters sets in our meta-model systems. We focus on a single LUC as an example: pasture to forest.

Table 6-3 Meteorological data used to asses the variability of parameters within the meta-model systems.

Met station	Average Temp	Total Rainfall	Total Evaporation
Rothamsted	9.3	704	597
Newport_Salop	9.0	657	963
Morley_St_Botolph	8.9	640	606
Warsop	9.0	627	559
Terrington_St_Clement	9.6	592	607
Martyr_worthy	9.5	774	595
Cranwell & Kirton	9.1	588	603
Bad Lauchstadt, Germany	9.0	474	644
Ruzyne, Czech Rep.	7.9	526	852
Calhoun, USA	15.5	1263	1344

6.4.2. RothC into an Excel spreadsheet

The model was re-written, changing the top part of the program so that the compiler would make a .DLL and not an .EXE file (orthodox compiled application to run directly under an operating system). Code was added to pass the arguments to and from the .DLL. The STOP statement was replaced with a RETURN statement and input-output operations were directed to files on disks rather than to and from the screen. In this way the model could be compiled as a .DLL and declared separately in Excel visual basic code. After creating a macro to call the .DLL a new toolbar is needed with a button to the toolbar and the macro is assigned to the button. If preferred, instead of creating a toolbar and button, a new menu could be created with a sub-menu and the macro would then be assigned to the sub-menu.

6.5. Results and Discussion

6.5.1. RothC as a meta-model

Generally the agreement between each of the models [1-3] and RothC is very good indeed in the statistical sense (residual mean square values, RMS, in Table 6-1 & Table 6-2). Taking account of the loss of degrees of freedom that occurs with increasing complexity, it appears that model [2c] is the best overall, although for one land-use change (pasture to arable), model [3c] was better. Model [2c] is best in the sense that it can be fitted to curves of output from RothC better than the other models (least RMS). Two important reservations must be expressed in relation to this conclusion, however, both of which have to do with the values of the estimated parameters. First the parameter set differs depending upon whether the land-use change studied increases the amount of carbon in soil or decreases it. The break points t_i and amounts of carbon active during each time period A_i or M_i differ significantly with LUC (Figure 6-2 to Figure 6-5, Table 6-4 & Table 6-5). The rates of change also differ with weather. These differences between land-use changes make it necessary to use a different set of parameters for the separate LUC. Because of the large number of parameters that would be needed to calculate changes in carbon stocks at many different locations, it seems that RothC is simpler in this sense than any of the meta-models derived from it. This result is not immediately intuitive but the essence is that RothC is *robust* in its parameters. The RothC model has been widely tested and found to work well in a range of environments and LUC without the need to alter internal parameters. The meta-models need many more sets of parameters in order to describe different LUC whereas RothC which uses just one set for all LUC. The differences between parameters lie mainly in the break point times (t_i) and values for the storage of carbon (A_i, M_i) at these times (Figure 6-2 to Figure 6-5, Table 6-4 & Table 6-5). Generally the agreement between rate constants (k_i) is much closer, apart from the value of k_1 under pasture-to-arable (Figure 6-2 & Figure 6-3). No explanation can be offered for this oddity but it may well explain the preference for model [3c] with this land-use change (Table 6-1b & Table 6-2b). As well as the other parameters, rate constants vary with climate data. This is not unexpected, however, since RothC itself varies the rate of decomposition with climate. This component of the meta-model system could probably adjusted for climate in the same way as is done for RothC, but the variability in the other parameters does not make it worthwhile to attempt. Similarly clay content modifies the way in which carbon is retained in soil within RothC and the ways in which carbon decomposes depends on the different moisture relations found in different soils. Given the variability found above not attempt has been made to take account of the effect of different soil types within the meta-model system. It seems likely that it would add to the complexity still further.

The sheer number of parameters (Table 6-4) needed to make the meta-model system work begins to tell against its use. In principle a database might be constructed to hold the values and an inventory could access these numbers as well as any others. But the system is clumsy compared with the elegance of RothC. Some models fail to converge during fitting (Table 6-1 &Table 6-2), which in this instance is a sure sign that the model is over parameterised with respect to the data and that a simpler model is better. Even more telling, however, is the empirical nature of these numbers as opposed to the universal values in RothC that describe decomposition under a wide range of soils and climates for most LUC. Their empirical nature means that a separate set must be obtained for each new LUC transition brought into the inventory. Equally the anticipated change in climate will mean that new parameter values must be obtained periodically. RothC, on the other hand, has been widely tested, validated and used in current climates world-wide and on this basis will not tread outside its tested range of climate within the UK during the foreseeable future. Other further advantages derive from accepting that somehow RothC should be used within an inventory as opposed to translating it into meta-models. Firstly updates, improvements and extensions (e.g. BIOTA see elsewhere in this report) to RothC can be easily and automatically incorporated by this means, secondly the system is future-proofed against climate or other major environmental change and thirdly the system as a whole can move gradually towards implementation of the spatial version of RothC, RothCUK, the current input demands of which exceed the information currently available with reliability at the spatial resolution required in the inventory.

The standard errors (SE) of parameter values derived in fitting the meta-models to RothC output are also reported in Table 6-4 (100 year data). It can be seen that these SEs also vary with LUC. This is a potentially serious issue since it means that the model variance is not stable. Note that the variance of models fitted to *real* data, as with the current inventory (Eq. [3a]), is not tested by this analysis. It raises another question mark, however, against the use of a meta-model whose parameters are derived from comparison with the parent model, RothC. An estimate of uncertainty derived using such a meta-model within an inventory would be suspect.

Table 6-4 a Arable-2-Forest parameters derived from 100 year runs

Equation	K1	SE	K2	se	K3	Se	K4	se
1a	0.04541	.00156						
1b	0.119234	0.000447	0.007626	0.000128				
1c	0.114798	0.000752	0.0065295	0.0000546	0.12144	0.00448		
1d								* not converged
2a	0.08148	.00085	.01124	.000348				
2b	.090754	.000553	.04246	.0016	.00861	.000167		
2c	.093586	.00036	.06375	.0016	.024403	.000657	0.007910	08.45e-7
3a	0.01458	0.000393						
3b	0.1187	0.000187	0.007114	5.05e-6				
3c	0.1181	0.000216	0.007192	0.000261	0.007039	0.000165		

Equation	A0	SE	A1/M1	se	A2/M2	Se	A3/M3	se	A4	SE
1a			36.64	0.348						
1b			19.3911	0.0609	37.043	0.323				
1c			16.982	0.305	40.272	0.197	2.929	0.306		
1d										* not converged
2a	62.16	.0915	30.78	.0905						
2b	61.74	.0325	29.70	.0638	11.712	.277	26.17	.000553		
2c	61.66	.0151	29.30	0.0482	10.94	0.320	13.01	0.272	26.26	0.0156
3a										
3b			0.3820	0.000281	0.6675	0.00022				
3c			0.3820	0.000336	0.2627	0.00873	0.4041	0.00864		

Equation	T1	SE	T2	SE	T3	SE
1a						
1b						
1c						
1d						
2a	28.40	0.79				
2b	18.62	.581	37.27	1.06		
2c	14.626	0.542	26.98	*	44.36	*
3a						
3b						
3c						

Table 6-4b Pasture-2-Arable parameters derived from 100 year runs

Equation	K1	SE	K2	se	K3	Se	K4	se
1a	0.02521	0.00089						
1b	0.2094	0.00457	0.010452	0.000161				
1c								* not converged
1d								* not converged
2a	0.07999	0.00326	0.01033	0.000246				
2b	0.14584	0.00698	0.046665	0.0000439	0.009636	0.000000249		
2c	0.436	0.0209	8.20E-02	5.45E-08	2.79E-02	4.23E-08	9.33E-03	3.28E-10
3a	0.011934	0.000167						
3b	0.16902	0.00169	0.009041	0.0000097				
3c	0.156553	0.0000329	3.6811	0.0832	0.009009	0.000000174		

Equation	A0	SE	A1/M1	se	A2/M2	Se	A3/M3	se	A4	SE
1a			-18.98	0.289						
1b			-3.8878	0.0452	-22.404	0.151				
1c										* not converged
1d										* not converged
2a	92.9006	0.0708	10.52	0.142	18.903	0.284				
2b	93.3843	0.0473	7.941	0.162	8.243	0.202				
2c	94.1525	0.0582	4.989	0.0497	7.7242	0.0224	9.2525	0.0114	18.03854	0.00663
3a										
3b			0.174949	0.000893	0.854486	0.000482				
3c			0.166591	0.0000296	0.5006	0.0411	0.852584	0.00000846		

Equation	T1	SE	T2	SE	T3	SE
1a						
1b						
1c						
1d						
2a	18.263	0.898				
2b	7.557	0.505	23.92	*		
2c	2.9989	0.0309	13.956	0.00114	29.28	*
3a						
3b						
3c						

Table 6-4c Pasture-2-semi natural parameters derived from 100 year runs

Equation	K1	SE	K2	se	K3	Se	K4	se
1a	0.03638	0.00128						
1b	0.12543	0.000731	0.008201	0.000131				
1c								* not converged
1d								* not converged
2a	0.075012	0.000939	0.010347	0.000257				
2b	0.08637	0.000726	0.03774	0.00117	0.008295	0.000121		
2c	0.091024	0.000616	0.05937	0.0012	0.022252	0.000686	0.007758	0.0000715
3a	0.012418	0.000274						
3b	0.119899	0.0000921	0.00712	0.00000169				
3c	0.120705	0.000224	0.008269	0.000166	0.006343	0.0000956		

Equation	A0	SE	A1/M1	se	A2/M2	Se	A3/M3	se	A4	SE
1a			40.104	0.462						
1b			16.5778	0.0786	45.327	0.358				
1c										* not converged
1d										* not converged
2a	90.554	0.0929	30.529	0.54						
2b	90.1032	0.0373	28.8814	0.0952	15.215	0.328	34.33	0.000726		
2c	89.9878	0.02	28.1346	0.0931	13.618	0.337	17.561	0.435	34.128	0.251
3a										
3b			0.29517	0.000106	0.743781	8.18E-05				
3c			0.29403	0.000333	0.32431	0.00811	0.42091	0.00815		

Equation	T1	SE	T2	SE	T3	SE
1a						
1b						
1c						
1d						
2a	25.854	0.743				
2b	17.008	0.575	35.59	*		
2c	12.666	0.493	24.91	*	42.4	*
3a						
3b						
3c						

Table 6-4d Pasture-2-Forest parameters derived from 100 year runs

Equation	K1	SE	K2	se	K3	Se	K4	se
1a	0.06562	0.00181						
1b	0.010665	0.000567	0.11723	0.00119				
1c								* not converged
1d								* not converged
2a	0.093205	0.000747	0.015933	0.000808				
2b	0.096499	0.000445	0.04721	0.00368	0.009177	0.000548		
2c	0.096999	0.000546	0.06236	0.00471	0.02447	0.00395	0.008102	*
3a	0.021431	0.000799						
3b	0.115035	0.000494	0.007009	0.0000291				
3c	0.114843	0.000326	0.006996	*	0.007008	*		

Equation	A0	SE	A1/M1	se	A2/M2	Se	A3/M3	se	A4	SE
1a			21.229	0.124						
1b			12.031	0.231	14.7	0.122				
1c										* not converged
1d										* not converged
2a	90.3552	0.0637	20.8066	0.0547	7.046	0.246				
2b	90.3465	0.0256	20.4672	0.0274	4.321	0.311	9.259	0.315		
2c	90.3324	0.0244	20.4334	0.0288	3.988	0.206	4.714	0.601	9.449	0.036
3a										
3b			0.58447	0.00117	0.492364	0.000943				
3c			0.5845	0.0016	0.361	0.468	0.131	0.468		

Equation	T1	SE	T2	SE	T3	SE
1a						
1b						
1c						
1d						
2a	35.369	0.794				
2b	23.53	1.15	42.08	3.73		
2c	21.4	*	33.72	*	50.47	*
3a						
3b						
3c						

Table 6-5 Time taken to run RothC from within Excel, ms

	Intel 2.4 GHz 512MB Ram	**Athlon 2.4GHz 1024 RAM**	
	DOS-RothC	**DOS-RothC**	**EXCEL-ROTHC**
Equilibrium	46	16	15
Equilibrium +10 years yearly output	54	15	16
Equilibrium +10 years monthly output	114	31	25
Equilibrium+10 years different inputs yearly output	761	122	53
Equilibrium+10 years different inputs monthly output	743	119	66
Broadbalk No inputs	1,336	231	109
Broadbalk mineral N	1,406	240	122
Broadbalk FYM	1,386	253	116
Broadbalk FYM+mineral N	1,426	238	135

As well as the methodology evaluated here, Parshotam (1996) has described how RothC might be expressed in continuous form, as a system of equations. This idea has merit: it has the advantage of preserving the error structure inherent in the mechanisms described in RothC and so avoids the problems with model variance described in the previous paragraph, but it is limited to a single set of unmodifiable rate constants. Because environmental conditions modify the rate constants in RothC, different versions of Parshotam's derivation would be needed for each cell in the inventory. In addition, RothC makes a distinction in decomposition between cropped and uncropped land. In this way different versions of Parshotham's model would be needed for each land-use change. Although not impossible to arrange, Parshotam's equations suffer from the majority of the disadvantages of the meta-model and would make it difficult to incorporate developments to RothC such as a vegetation model. Because Parshotam's derivation preserves the error structure of RothC, however, it might be very useful for studying sensitivity of particular conditions to change.

The Australian national GHG reporting system makes use of a version of RothC embedded directly into the spreadsheet model (FullCaM, Richards, 2001). Clearly this will work as well as any other method using RothC, but will not easily allow upgrades or add-ins if the inventory or the need for the inventory evolves with time.

6.5.2. Running RothC from within a spreadsheet

RothC has been prepared to accept inputs and instructions from cells within an Excel spreadsheet. In general the compiled Fortran programme that does this (.DLL file) is rather different from the standalone executable image (.EXE file). However, the differences are largely concerned with how the programme starts and where it gets its information from. The time from calling RothC .DLL within the spreadsheet to receiving the requested numbers back into the spreadsheet was less than running RothC directly under the DOS system (Table 6-5). This statistic is misleading, however, since the DOS version of RothC accepts much input interactively. Processor time can only be calculated after all input has been made. Other versions include access time for reading input data. A typical requirement for which an inventory might interrogate RothC would be 10 years under LUC. If no starting conditions are available, RothC will need to derive these by running to equilibrium (typically 10,000 years) and simulating on for 10 years with the new land-use. Typically this will require 53 ms with output in the final year only and a change to carbon inputs if not to weather (Table 6-5). Although the extra time required for a further 10 years of calculation with the same inputs (i.e. no LUC) is small (~1ms), in practice input and output to files on the hard disk or within Excel costs time. These issues could be addressed reasonably easily in a .DLL file issued for use within the inventory. At these rates and assuming minimal further input-output, simulations for the whole of the UK (244,810 km^2) will take 3.6 hours if one simulation is need per km^2 with an averaged LUC Simulations at lower resolutions will take proportionally less time. If starting conditions are defined within the spreadsheet, as is likely, the determination of equilibrium conditions could be dispensed with and the inputs and environmental conditions would not need to be read in again. Under these conditions our results suggest that the model would run in about 1ms. This is 50 times faster than the calculations suggest above and would bring the computer time used by RothC in calculation for each km^2 down to about 4 minutes.

Furthermore, RothC carries out calculations that are unlikely to be of use to the inventory such as the tracing of radioactive ^{14}C in soil. These calculations could be taken out, or more attractively, made optional in the definitive version of RothC, so that more computer time could be saved.

6.5.3. Data resolution and availability

Two critical issues for the use of RothC are to know *when* and *where* a particular LUC takes place. The issue of where is also important because the soil on which the change takes place will also influence any eventual change in carbon. Much information is available in confidential databases. The UK has relatively good soils information systems available (usually for a fee) from NSRI, MLURI and DARD. General statistics on agricultural land-use are available from Defra, DARD and SEERAD but location-specific information is confidential because it is commercially sensitive. In principle, confidentiality is not an issue since the end-user of the information derived with the inventory does not need access to the confidential information. The *inventory* (including e.g. RothC) requires the access and it should be possible for an inventory to interrogate databases over a computer network without being allowed to report unprocessed data back to an end-user. A fee might be paid if required. Extensive negotiation with data-holders and land-owners is likely to be necessary before this can happen, however.

6.6. Conclusions

We conclude that the most sensible course of action if RothC is required within the current UK soils carbon inventory, is to call RothC directly from the inventory spreadsheet. However, since input-output operations are costly in computer terms, it seems wise to allow RothC to access the information it requires directly from disk rather than to pass data between spreadsheet and model many times. The current inventory makes use of Monte-Carlo methods in order to estimate uncertainty; this multiplies the number of simulations many-fold. If computer time to use RothC with orthodox Monte-Carlo methods is prohibitive, clever sampling design may help reduce the number of simulations greatly (e.g. Jansen, 1999). If the eventual aim is to amalgamate the inventory with RothCUK for LUC, soil and climate, calling RothC from within a spreadsheet has the advantage both that the code is ready now and that the inventory interface can be adapted progressively as reliable estimates of LUC and other data at finer and finer scales become available until the system converges with RothCUK. Other modules such as one for plant growth might be incorporated into this development in a straightforward fashion. A .DLL version of the RothC model is available for use and the following steps will allow its incorporation

1. Define computer locations of all ancillary information: weather, soils, LUC

2. Adapt RothC-Excel to obtain required information from a disk store defined by the inventory with a single (or few) read operation(s). Store information in memory.

3. Adapt the inventory to write the information required by RothC to the disk store

4. Adapt RothC-Excel to return the information required by the inventory in a single (or few) write operation(s).

5. Test run the combined system against a standalone RothC

If computer times for the Monte-Carlo runs appear prohibitive and design cannot help, the computer time needed to run RothC within the inventory could potentially be reduced by distributing the tasks in a parallel computing scheme.

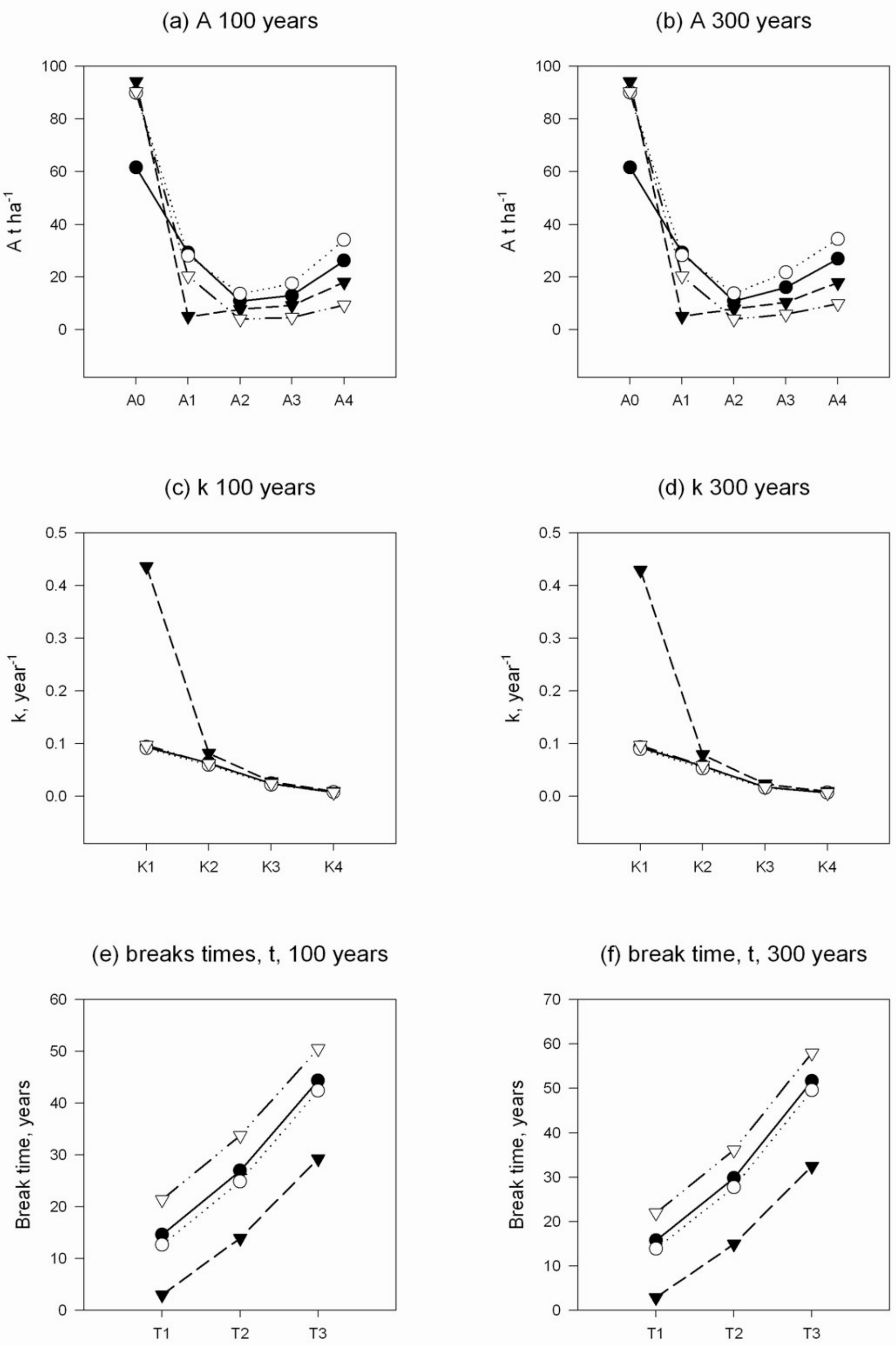


Figure 6-2 Sensitivity of the values of parameters of model [2c] to different land-use changes: (a, b) the A_i describing changes in carbon stocks, (c, d) the k_i describing the rate of turnover of carbon stocks, (e, f) the t_i describing the times over which the k_i are effective; for 100 years of comparisons between parameters (a, c, e) and 300 years of comparisons, (b, d, f), under land-use changes: —●—, arable to forest; · · ○ · ·, pasture to semi-natural; --▼--, pasture to arable; —— · ·▽· · ——, pasture to forest. For SEs see Table 6-1 and Table 6-2

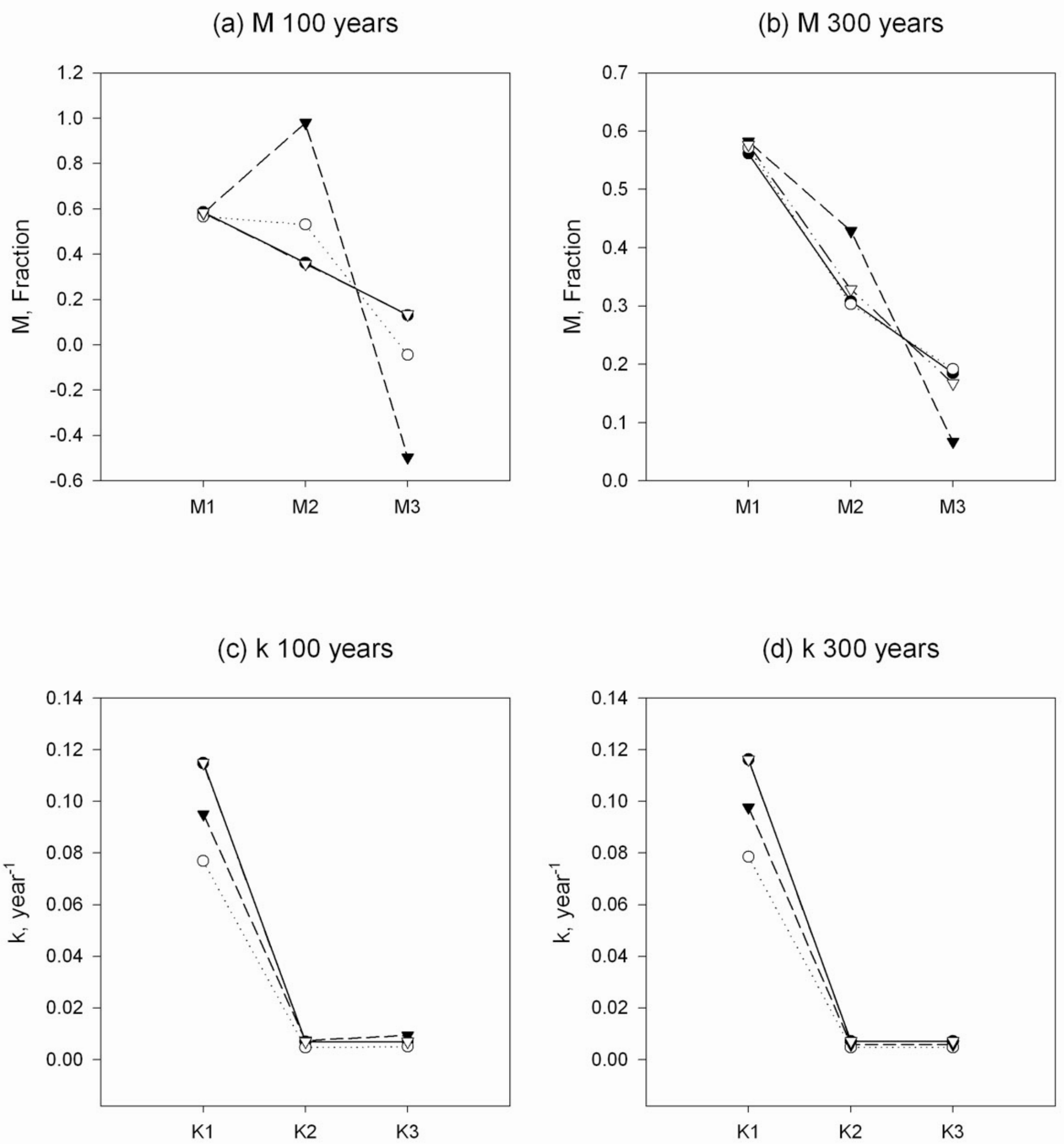


Figure 6-3 Sensitivity of the values of parameters of model [3c] to different land-use changes: (a, b) the Mi describing fractional extent of change of the carbon stocks under LUC, (c, d) the ki describing the rate of turnover of carbon stocks; for 100 years of comparisons between parameters (a, c) and 300 years of comparisons, (b, d), under land-use changes: ─●─, arable to forest; · · ○ · ·, pasture to semi-natural; --▼--, pasture to arable; ── · ·▽· · ──, pasture to forest. For SEs see Table 6-1 and Table 6-2.

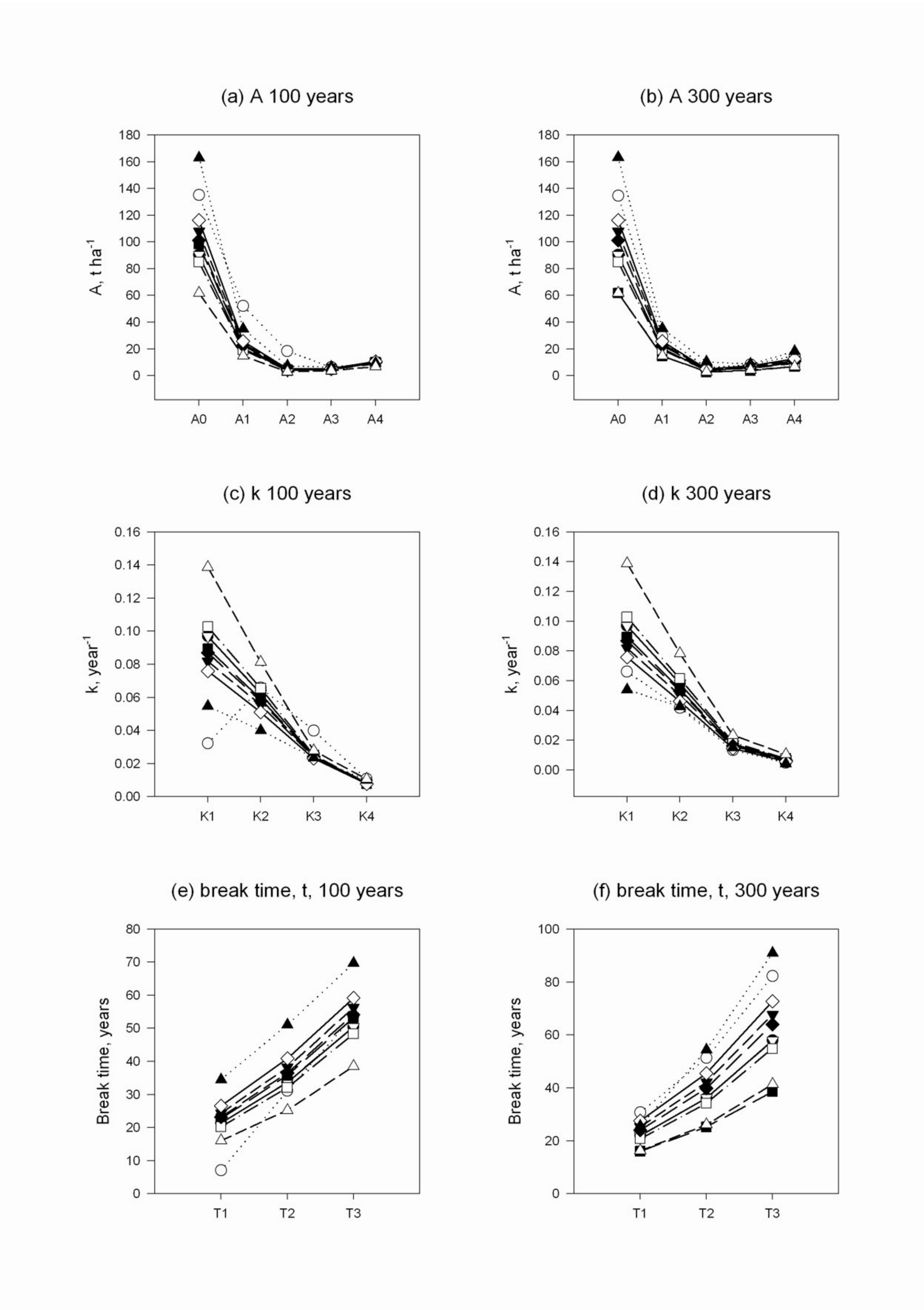


Figure 6-4 Sensitivity of the values of parameters of model [2c] to changes in weather data: (a,b) the Ai describing changes in carbon stocks, (c, d) the ki describing the rate of turnover of carbon stocks, (e, f) the ti describing the times over which the ki are effective; for 100 years of comparisons between parameters (a, c, e) and 300 years of comparisons, (b, d, f). For details of the conditions see text and Table 6-3.

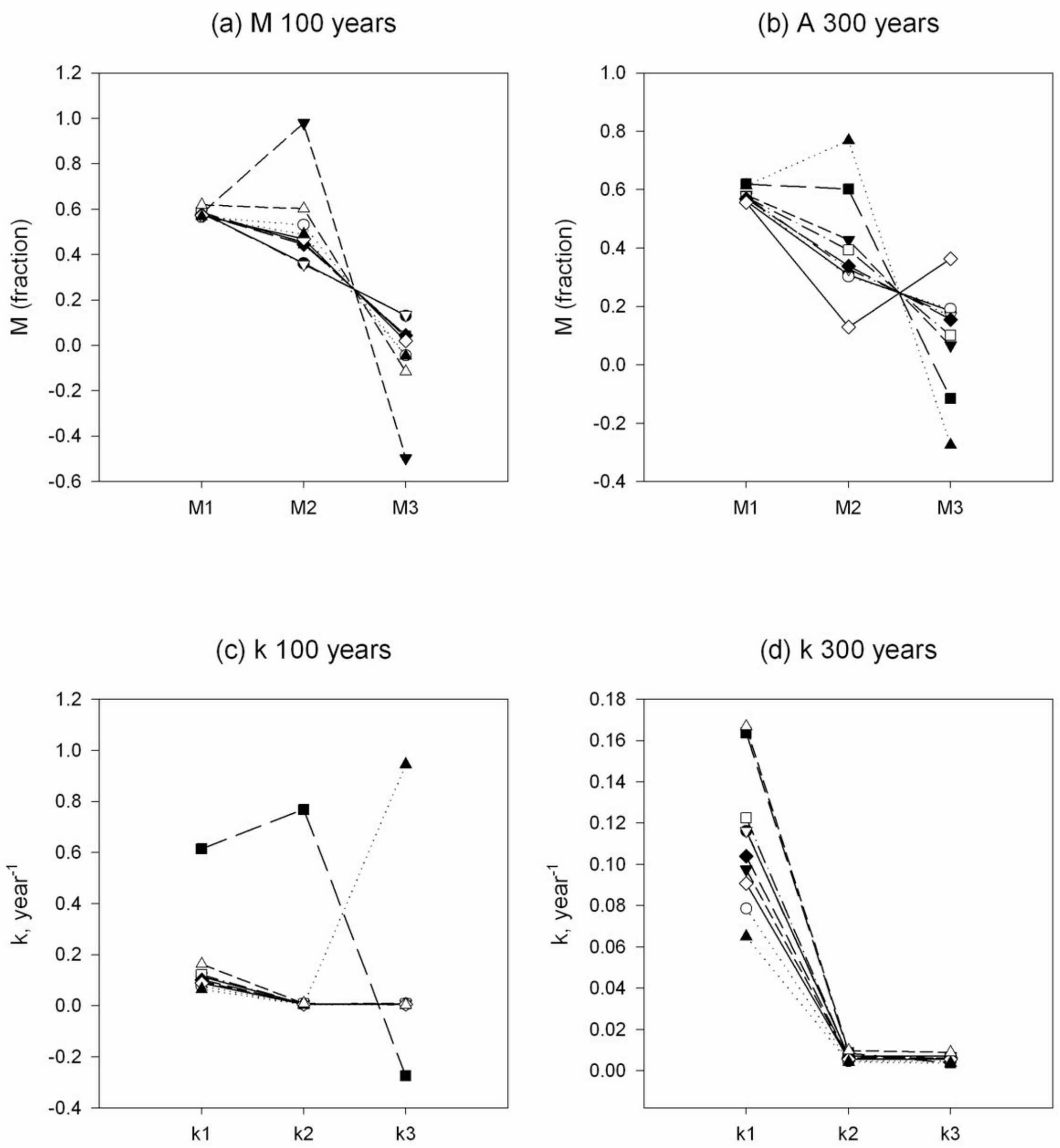


Figure 6-5 Sensitivity of the values of parameters of model [3c] to changes in weather data: (a,b) the M_i describing changes in carbon stocks, (c, d) the k_i describing the rate of turnover of carbon stocks; for 100 years of comparisons between parameters (a, c) and 300 years of comparisons, (b, d). For details of the conditions see text and Table 6-3.

6.7. Acknowledgements

This work was supported by a subcontract from CEH underpinned by a Defra contract. Rothamsted Research is grant-aided by the UK Biotechnology and Biological Sciences Research Council. APW gratefully acknowledges the provision of facilities by Landcare Research New Zealand, during a period of study leave in 2005 and 2006.

6.8. References

Baggott SL, Brown L, Milne R, Murrells TP, Passant N, Thistlethwaite JD (2004) Greenhouse Gas Inventories for England, Scotland, Wales and Northern Ireland: 1990 – 2002. AEAT/ENV/R/176101/10/2004 National Environmental Technology Centre, AEA Technology Centre.

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

Falloon P, Smith P, Bradley RI, Milne R, Tomlinson R, Viner D, Livermore M and Brown T (2006) RothCUK – a dynamic modeling system for estimating changes in soil C from mineral soils at 1-km resolution in the UK. *Soil use and management*, in press

Janik L, Spouncer L, Correll R and Skjemstad J (2002) Sensitivity analysis of the Roth-C soil carbon model (Ver. 26.3 Excel©). Technical report 30 of the Australian Greenouse Office, pp61

Jansen MJW (1999) Analysis of variance designs for model output. *Computer Physics Communications* **117**, 35-43.

Jenkinson DS (1990) The turnover of organic carbon and nitrogen in soil. *Philosophical transactions of the Royal Society, B.* **329**, 361-368

Jenkinson DS, Adams DE and Wild A (1991) Model estimates of CO2 emissions from soil in response to global warming. *Nature*, **351**(6322), 304-306

Jenkinson DS and Coleman K (1994) Calculating the annual input of organic matter to soil from measurements of total organic carbon and radiocarbon. *European Journal of Soil Science*, **45**, 167-174

Jenkinson DS, Harkness DD, Vance ED, Adams DE and Harrison AF (1992) Calculating net primary production and annual input of organic matter to soil from the amount and radiocarbon content of soil organic matter. *Soil Biology & Biochem*istry **24**(4), 295-308

Jenkinson DS, Hart PBS, Rayner JH and Parry LC (1987) Modelling the turnover of organic matter in long-term experiments at Rothamsted. INTECOL Bulletin **15**, 1-8

IPCC (Intergovernmental Panel on Climate Change) (2000) Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

IPCC (Intergovernmental Panel on Climate Change) (1996) The revised 1996 guidelines for national greenhouse gas inventories. Volumes 1, 2 and 3. IPCC, Geneva, Switzerland.

Paustian K, Mosier A, Janzen H, Tiessen H, van Noordwijk M, Andren O, Davidson E, Eswaran H, Fernandes E, Grace P, Houghton R, Kimble J, Kolchingna T, Lal R, Scholes M, Smith P, Tian G, Woomer P and Zhong L (1997) Chapter 5. Land Use Change and Forestry: Emissions and Uptake of CO2 from Soils. In: Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories, WMO, Bracknell, Berks, UK: 5.23-5.38

Parshotam A (1996) The Rothamsted soil-carbon turnover model – discrete to continuous form. *Ecol mod*, **86**:283-289

Richards GP (2001) The FullCam carbon accounting model: Development calibration and implementation for the national carbon accounting system. Technical report 28 of the Australian Greenouse Office, pp60

Tate KR, Wilde RH, Giltrap DJ, Baisden WT, Saggar S, Trustrum NA, Scott NA and Barton JP (2005). Soil organic carbon stocks and flows in New Zealand: System development, measurement and modelling. *Can. J. Soil Sci*. **85**: 481–489.

Section 7

RothC-BIOTA v05 plant-soil C turnover model

Table of Contents

7. RothC-BIOTA v05 plant-soil C turnover model

M. Sozanska-Stanton, P. Smith
Aberdeen University

7.1. Model description

RothC-BIOTA model was developed as a coupled link between GIS-RothCv03, the model of soil C dynamics (Coleman and Jenkinson, 1996; Falloon, 2004; Smith *et al*., 2005; 2006) and a process-based C model in semi-natural plant systems (Wang and Polglase, 1995). RothC-BIOTA v05 was fully utilised for site applications, but it retained the spatial framework of GIS-RothCv03 so to enable future applications of RothC-BIOTA for regional and national inventories. The model input requirements are relatively simple i.e. seven monthly climate variables and some principal information on land management and soil type (Figure 7-1). Climate variables needed for RothC-BIOTA were described by Sozanska-Stanton *et al*. (2005). *Landuse.ini* input file controls climate data input (weather files are named: <sitename><simulationyear>.mon) and information on crop types and fertiliser input (Appendix A.1). Crop parameters and monthly carbon input (debris) proportions are defined for each of nine major crop types, fallow land and two grass types referred to in the model as 'INDEXes' (Appendix A.2). In the most recent version of RothC-BIOTAv05, draft inputs were defined for forests. Plant parameters for grasslands and forests need more refinement and testing.

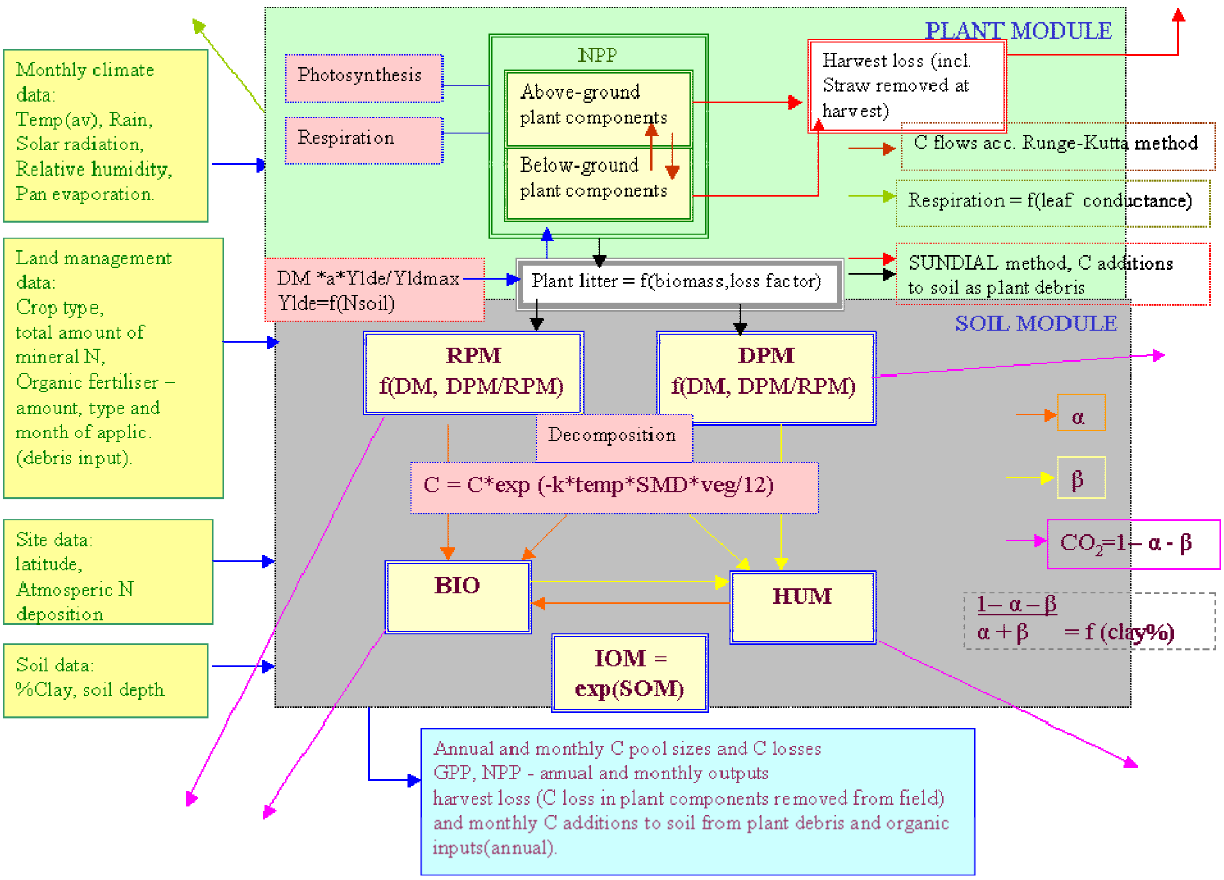


Figure 7-1 RothC-BIOTA

As BIOTA was originally developed and parameterised for natural forests and semi-natural grasslands (Wang and Polglase, 1995), it was necessary to extend the range of plant functional types to major arable crops in the UK to enable its application for agricultural soils (Table A5. 1, Sozanska-Stanton *et al*., 2005). A method of crop rotations was then developed to allow for different types of crop management in UK agriculture ($ 7.2.1). Further changes to the model design involved introduction of a fertiliser effect on crop growth (Figure 7-1, $7.2.2). The model can be applied either using the pre-determined plant carbon additions to soils (RothC stand-alone) or with the application of dynamic plant component (when BIOTA is activated, Figure 7-1; Sozanska-Stanton *et al*., 2005). In the former case, monthly debris inputs are set as default inputs in the model for major crop types and management levels. Their values have been determined by fitting RothC to measurements of C inputs into soils (Jenkinson and Coleman, 1994). When the BIOTA plant component is activated, monthly plant C inputs into soils are estimated as a function of simulated standing plant biomass at the end of each month and monthly proportions of plant debris determined with the DEBRIS calculator (Figure 7-1, Sozanska-Stanton *et al*., 2005). BIOTA simulates the physical processes of photosynthesis and C transfer between plant components at a canopy level at daily time-steps (Figure 7-1). Method of estimating SOC equilibrium was adjusted in RothC to make it compatible with the C transfer processes described by the plant module (Sozanska-Stanton *et al*., 2005). The new RothC equilibrium method describes C decomposition and C transfers between the soil pools as a function of time on an arithmetic scale. The equilibrium is reached when the total SOC changes by less than 1 kg C ha^{-1} over the period of 20 years (in the previous version of RothC, SOC equilibrium was assumed at 10000 years). Additionally, the original RothC method ‘fitting to equilibrium’ was retained in RothC-BIOTA to extend application of the model to conditions with limited knowledge of land use history. Under these conditions, the model can be fixed to run to a ‘fitted’ equilibrium, the dynamic plant module (BIOTA) can then be activated for ‘short-term’ runs. This method was used in some simulations described further in the text ($7.4.2).

Apart for the summary outputs of annual soil and plant C, RothC-BIOTAv05 calculates monthly values of NPP, C content of plant and litter pools and CO_2 emissions from soils (Figure 7-2). Figure 7-2a and Figure 7-2b present C dynamics in soil/plant systems for (a) winter wheat with optimum nutrient supply to crop growth, and (b) oilseed rape on soil with nutrient stress. Subsequently those data can be then used to calculate monthly NEP.

7.2. Recent changes in model design

7.2.1. Crop rotations

RothCBIOTAv05 initiates simulation with the equilibrium model, which models C dynamics for a selected equilibrium land use type (input from *landuse.ini*) until an equilibrium in soil is reached. After the equilibrium is reached, each annual model cycle is controlled by landuse.ini file (Appendix A.1), which informs the model on the change of crop types between simulation years. The *Landuse.ini* file is read with the subroutine ReadRotationsFile. The code controlling rotations is defined in the subroutine SetNextRotation (Appendix A.3-1) and loading crop parameters in the subroutine SelectCrop (Appendix A.3-2).

7.2.2. N fertiliser method

The coupled model could only be applied to agricultural systems, when effects of different management levels were accounted for in the biomass production. The original BIOTA had already taken into account the limiting effect of climate on the plant growth in non-optimal conditions. Consequently, the effect of nutrient availability was to be introduced using the same approach, in which the biomass growth would be reduced on soils with nutrient (N[1]) stress. This methodology was developed as follows. The model contains a reference table of the optimum yields for all major UK crops (Table A5. 2) based on published research (http://www.hri.ac.uk/envveg/paper/pap-eng.htm; http://www.agr.gov.sk.ca/DOCS/crops/). Total soil N available to crops (soil N) is estimated in the model as a simple summary of mineral N and organic fertiliser inputs and the level of atmospheric N deposition. The expected crop yield is calculated as a function of plant N uptake (equation 2, Figure 7-1) which was adopted from SUNDIAL model (Smith and Leech, 1995; equation 1).

$$Ut = k1(e^{k2*G} - 1) \tag{1}$$

$$G = \ln((Ut + k1)/k1)/k2 \tag{2}$$

where: Ut- crop N uptake at harvest, k1 and k2 are crop parameters defined by SUNDIAL, G- crop yield

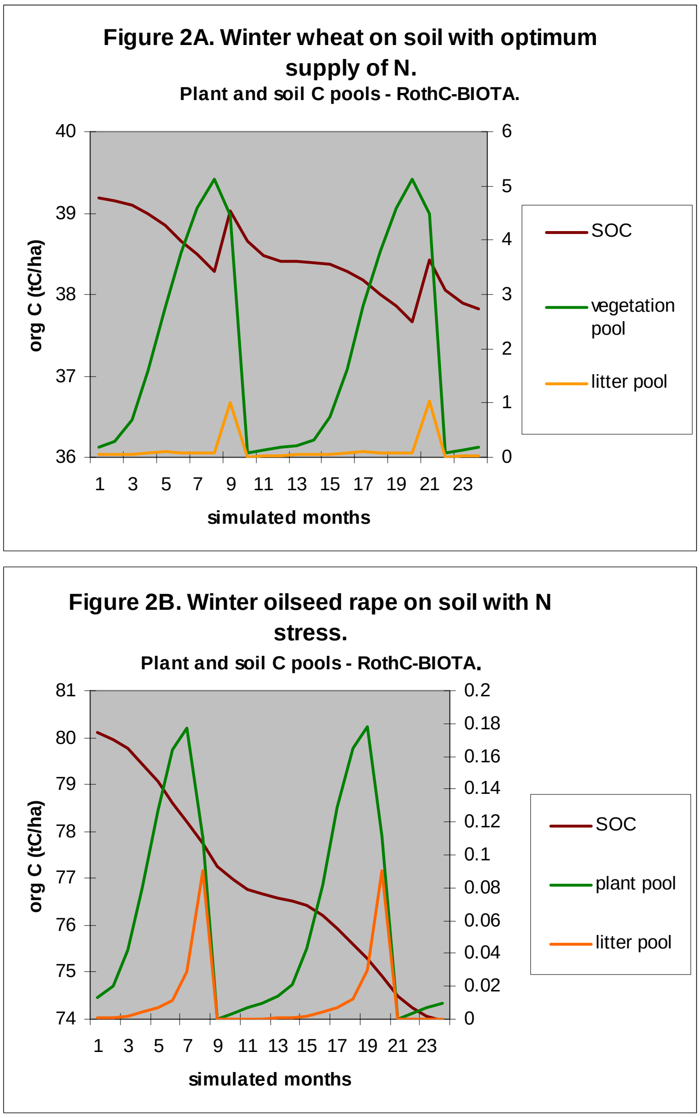


Figure 7-2 Monthly C dynamics in plant pools and soil for two crop types.

[1] *Note that we excluded P and K effect in the current version of the model.*

The RothC-BIOTAv05 model does not simulate N losses from soils, which will introduce some uncertainty[2] to the estimated yield. The ratio of the yield in simulated conditions and the maximum yield in optimum conditions (Table A5. 2) is then applied to reduce the monthly plant biomass (equation 2). This approach assumes that the entire plant biomass will be reduced proportionately to the grain.

The methods to calculate N additions and their effect on plant biomass are included in module Nfertiliser_cap. The following routines were designed to calculate the stages of N fertiliser method:

1. Yield is calculated by function ExpectedYield (Appendix A.3-1)
2. Yield ratio is estimated by function Ratio (Appendix A.3-2)
3. Biomass is adjusted with function AdjustBiomassWithRatio (Appendix A.3-2).

7.3. Parameterization of RothC-BIOTA

Initial crop parameters were defined on the basis of literature (Table A5. 1). The coupled model with plant parameters from literature was then applied to estimate average yields for different UK crops. The yields were calculated for three different levels of crop management defined in plant parameter files by FertLow and FertMed. The ranges of yields simulated by RothCBIOTA were compared with the average yields published in literature (Figure 7-3; MAFF, 1998). The average yields were simulated for cereals and oilseed rape with standard error of 0.649 and a maximum residual error of 15% (for winter oats). Model considerably under-predicted yields for root crops, particularly potatoes, sugar beet and carrots (Figure 7-3). Standard error for root crops was 8.137, with the maximum residual difference of 70% for potatoes. The crop parameters were satisfactory for cereals and oilseed rape, as the average yields were well within the ranges simulated by the model for different management levels (Figure 7-3). As there was a considerable difference between simulated and measured yields for root crops, the crop parameters for those PFTs had to be adjusted. We subsequently carried out sensitivity analysis for selected plant parameters important for DM production in BIOTA module. Their values were varied within the ranges reported in literature (Table A5. 2, based on Table A5. 1). Model was most sensitive for the changes to partitioning of C between above-ground plant components and roots. The highest yields were simulated for potatoes when C split between above and below ground plant was 20:80, for sugar beet 40:60 and carrots and turnips 50:50. Those values were applied together with the highest values for the other tested parameters to obtain the best fit. There was a considerable improvement in the simulated average fresh yields with the observed average yields for potatoes and turnips falling now within the range of yields simulated for low and high fertiliser inputs (Figure 7-3). Standard error for the selected crops was reduced from 8.137 to 5.154 and the residual difference for potatoes decreased to 41%.

[2] *This limitation ought to be addressed in the future by means of linking the model to another N-cycle model that dynamically simulates N losses (SUNDIAL, NCYCLE).*

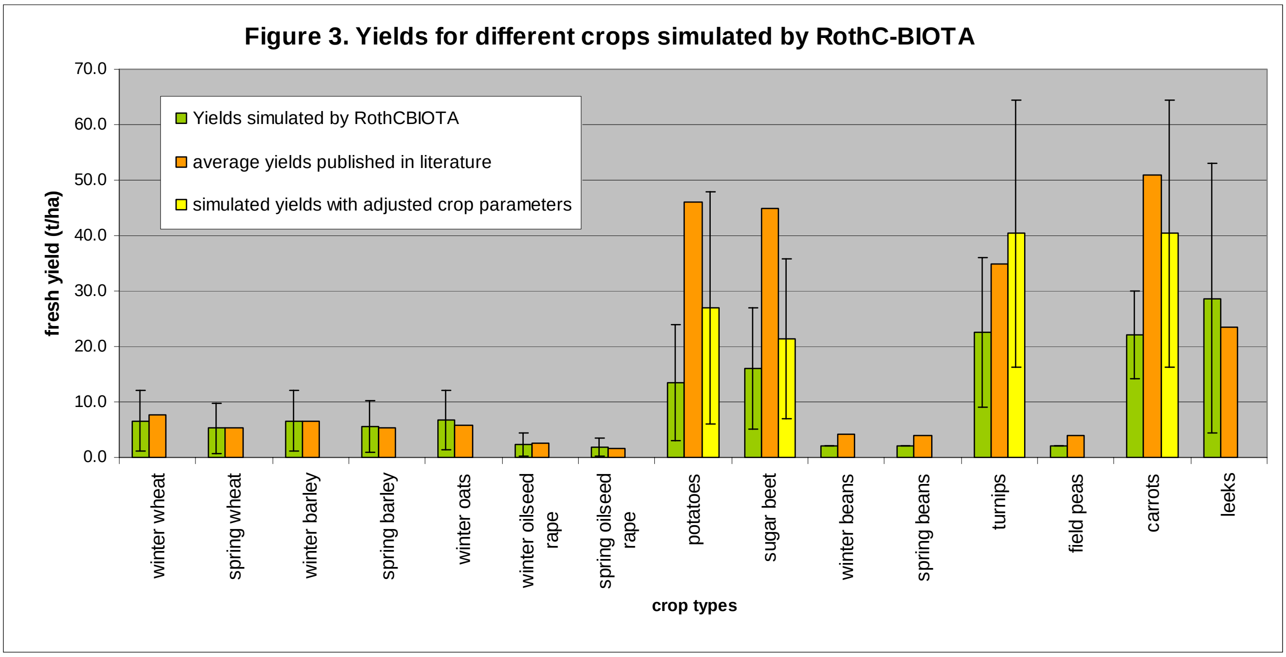


Figure 7-3 Yields for different crops simulated by RothC-BIOTA

7.4. Evaluation of RothC-BIOTA

7.4.1. Broadbalk site

The site is located 40 km north of London at IACR-Rothamsted (latitude=51ºN49', longitude=0ºW21'), it has cool temperate climate with mean annual temperature of 9.1 ºC and rainfall 693 mm. Soil is classified as flinty-silty clay loam over clay-with-flints (25 % clay, 57 % silt and 15 % sand) also known as stagnogleyic brown earth. The field experiment started in 1844, there are several sections with continuous wheat and four other rotation sites (involving also potatoes, forage maize, winter oats and legumes). There are several replicated plots with mineral and organic fertiliser treatments including no additions since 1852, plots N1,N2,N3,N4,N5,N6 with mineral N input as ammonium nitrate of 48, 96, 144, 192, 240 & 288 kg N/ha/y, respectively, FYM plot with 35t/ha added and a plot with a combination of FYM+N2. More details can be obtained on SOMNET Web site.

7.4.2. Simulation of soil C

The coupled model was evaluated for Broadbalk site, section 8, on the following plots:

Plot 3 - no fertiliser amendments

Plot 8 - mineral N input of 144 kg N /ha

Plot 21 – FYM input of 35t/ha and mineral N of 96 kg N/ha.

The old version of RothC showed a good fit to measurements with fixed equilibrium SOC of 30 t C ha^{-1} and pre-determined debris inputs to soil (based on measurements) (Figure 7-4a, Figure 7-4b, Figure 7-4c). When RothC-BIOTA was first used to simulate the C dynamics on that site, the results were worse than the fitted RothC, as we observed a higher SOC at equilibrium (>40 t C ha^{-1}) and steady decline of SOC for plots 3 and 8. SOC increased on plot 21, but not sufficiently for the model to accurately simulate the observed C levels in soil. As the equilibrium level simulated with RothC-BIOTA was too high for plot 3, we fitted the equilibrium level to 32 t C ha^{-1}, which was higher than when RothC was fitted. The new simulated trend corresponded better with the measurements on plot 3 and suggests that there is a steady decline in SOC (Figure 7-4a), which confirms previously published work (Glendining *et al.*, 1996). The best fit of RothC-BIOTA was obtained when we reduced the limiting N effect on the yield ratio by 100% (Figure 7-4a).

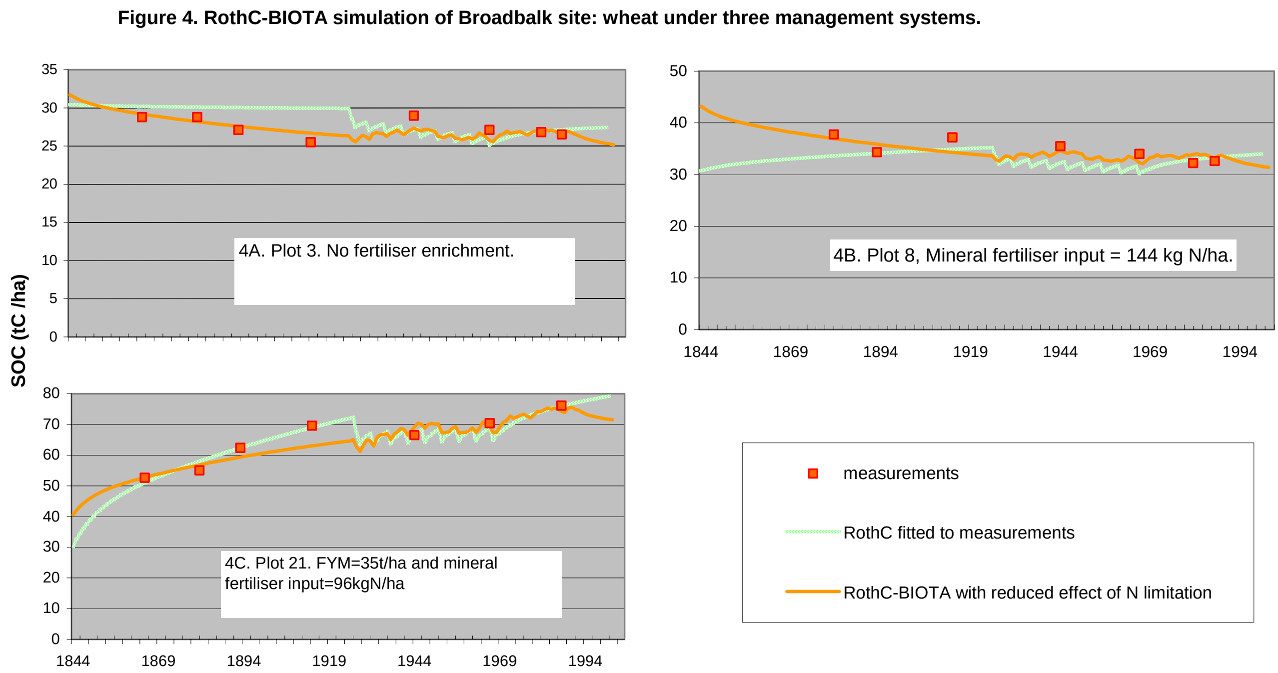


Figure 7-4 RothC-BIOTA simulation of Broadbalk site: wheat under three management systems

In order to improve the model results, the N limitation effect on yield ratio was reduced by 75% and 50% for plots 8 and 21, respectively. There was a decreasing trend in SOC simulated for plot 8 (with N mineral input), which might be explained by the equilibrium SOC simulated too high on that plot (Figure 7-4b). SOC simulated by RothC-BIOTA at equilibrium on plot 21 better corresponded with SOC dynamics in succeeding measurements than the previously used 30 t C ha^{-1} (Figure 7-4c). Although the fitted RothC results suggest a higher rate of increase in SOC, there is a large unexplained decline in soil C in 1926-1929 (Figure 7-4c). The lower rate of SOC increase estimated by RothC-BIOTA does not explain a very high measurement of 70 t C ha^{-1} in 1914. It is very possible, however, that there were some unusual conditions that caused apparent high C sequestration, e.g. larger plant addition to soil due to climatic conditions.

Broadbalk results suggested that the current N-cap method introduces too high a limitation to the plant development simulated by BIOTA. The SOC level at equilibrium can benefit from fitting to measurements in some conditions. This was particularly confirmed by further evaluation of the model on BadLauchstaedt site, where soil receives organic fertiliser inputs every other year. RothC-BIOTA calculated SOC of 18.7 t C ha^{-1}, much lower than measured 88.2 t C ha^{-1}. The reason for poor reflection of initial soil C level is a very limited knowledge of land use management prior to equilibrium. The model can only simulate single crop type without fertilisation (in this case, spring barley), which might be different from the actual crop and management. It is known that the site was originally under grass, but there is no information on the timing of land use change – this may have greatly influenced the initial level of SOC. Under these conditions RothC-BIOTA benefits from fitting the equilibrium SOC to the measurement.

7.4.3. Modelled DM and debris inputs to soils

The accurate simulation of SOC with the dynamic plant component of RothC-BIOTA depends on (1) simulated plant biomass and (2) proportion of DM input to soil. Evaluation of the simulated plant biomass was carried out using yield data from the Electronic Rothamsted Archive Broadbalk (ERA). RothC-BIOTA estimates yield for each crop type as a proportion of above ground biomass (unit: t C ha^{-1}) removed from the field at harvest. The proportions are fixed values for each major crop type and they include harvested part e.g. grain for cereals, and part of cartable plant e.g. straw. Cartable plant components can contribute to harvested plant from 0% e.g. cereal straw incorporation to 100% e.g. all above-ground components of the potato plants. The knowledge of crop management is often very limited, particularly for long-term experiments. Previous evaluation of the coupled model for the Hoosfield site (Sozanska-Stanton *et al.*, 2005) suggested that when all straw was assumed to be removed from the field (i.e. 100% contribution to harvested DM), the simulation was most accurate. The same scenario was assumed for Broadbalk.

The results for optimal nutrient conditions showed that the average C content in winter wheat on section 9 (continuous crop) was accurately simulated for the study period (1968-2001) at 3.77 t C ha^{-1} (measured average = 3.8 t C ha^{-1}), and on section 1 it was within one standard variation from the measured mean (4.5 t C ha^{-1}). On plots with no fertiliser input, C content in DM was underestimated by the model, but still within one standard deviation from the measured mean. The climatic effect on DM variability between different years was not well represented by the model (Figure 7-5). The model underestimated DM on more than 20 occasions, with better estimates on the fertilised plot.

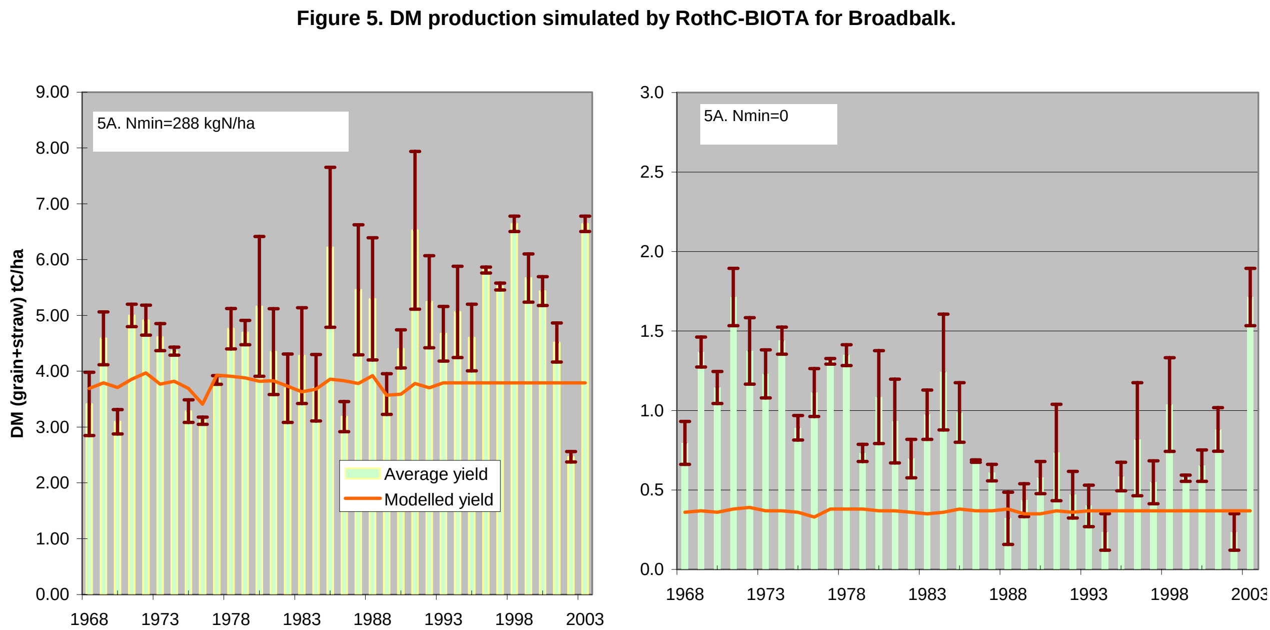


Figure 7-5 DM production simulated by RothC-BIOTA for Broadbalk

Evaluation of the % DM input to soil was estimated for plot 3 (N fertilizer inputs=0 kg N ha^{-1}) and plot 8 (N = 144 kg N ha^{-1}). The ratio of plant debris input to total DM was calculated at 0.2 for plot 8, and 0.6 for plot 3. RothC-BIOTA estimated the ratio at 0.2 for both plots. The modelled debris input is too low on unfertilised plots, which is caused by a strong limitation of N-cap method.

7.5. Conclusions

RothC-BIOTA was developed as a coupled link between RothC, the model of soil C dynamics, and BIOTA, a process-based C model extended in this project to agricultural systems. The model was parameterised for 30 different crop types and evaluated with average yield data published in literature for major 15 crop types. Detailed evaluation of SOC dynamics under three management regimes was carried out for one UK site (continuous wheat and arable crops rotations) and a German site (arable crops rotation, results not presented in detail). We have also presented model results of DM production on two contrasting replicated plots at the same UK site. The evaluation showed that the model was able to simulate accurately SOC dynamics, but some adjustments to the modelling methods were required. RothC-BIOTA was also recently developed to simulate C dynamics in ley-arable systems and forests. Further evaluation of RothC-BIOTA in other systems, particularly in ley-arable rotations, will be necessary, and an alternative approach to representing N limitation may be necessary.

7.6. References

Coleman K. and D. S. Jenkinson (1996) RothC-26.3- A model for turnover of carbon in soil. In: *Evaluation of Soil Organic Matter Models Using Existing, Long-Term datasets*, eds. D.S. Powlson, P. Smith and J.U. Smith, NATO ASI Series I, Vol. 38, Springer-Verlad, Heidelberg pp. 237-246.

ERA, http://www.era.iacr.ac.uk/

Falloon, P. (2004) Using RothC with climate and land use change at 1 km scale. In: *UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry Activities.* (ed. Milne, R.), DEFRA, Global Atmosphere Division.

Glendining, M.J., Powlson, D.S., Poulton, P.R., Bradbury, N.J., Palazzo, D. and Li, X. (1996) The effects of long-term applications of inorganic nitrogen fertilizer on soil nitrogen in the Broadbalk wheat experiment. *Journal of Agricultural Science* 127, 347-363.

Jenkinson, D.S. and Coleman, K. 1994. Calculating the annual input of organic matter to soil from measurements of total organic carbon and radiocarbon. *European Journal of Soil Science*, 45, pp.167-174.

MAFF (1998) SUNDIAL-FRS Version 1.0. User Guide. IACR-Rothamsted, Harpenden. 60pp.

Smith J.U. and Leech, P. (1995) Computer simulation of soil nitrogen turnover in Nitrate Sensitive Areas. Annual Report. MAFF Grant CSA1962.

Smith, J.U., Smith, P., Wattenbach, M., Zaehle, S., Hiederer, R., Jones, R.J.A., Montanarella, L., Rounsevell, M.D.A., Reginster, I., Ewert, F., 2005. Projected changes in mineral soil carbon of European croplands and grasslands, 1990-2080. *Global Change Biology* 11, 2141–2152.

Smith, P., Smith, J.U., Wattenbach, M., Meyer, J., Lindner, M., Zaehle, S., Hiederer, R., Jones, R., Montanarella, L., Rounsevell, M., Reginster, I., Kankaanpää, S. 2006. Projected changes in mineral soil carbon of European forests, 1990-2100. *Canadian Journal of Soil Science* 86, 159-169.

SOMNET, http://www.rothamsted.bbsrc.ac.uk/aen/somnet/

Sozanska-Stanton, M., Zhang, C., Brown, T.A.W., Milne, R. & Smith, P. (2005) RothC-BIOTA v05 plant-soil C turnover model – parameterization and evaluation. In: *UK Emissions by Sources and Removals by Sinks due to Land Use, Land-Use Change and Forestry Activities*, (ed: Milne, R & Mobbs, D.C.), Defra, Global Atmosphere Division, pp. 9.1-9.14.

Wang, Y.P. and Polglase, P.J. (1995) Carbon balance in the tundra, boreal forest and humid tropical forest during climate-change - scaling-up from leaf physiology and soil carbon dynamics. *Plant Cell And Environment* 18, 1226-1244.

7.7. Appendices

A.1. An example of landuse.ini

An example of landuse.ini defined for Wind Farm site with ley-arable rotation for years 1973 – 2004. Mineral N fertiliser varied between 150 – 220 kg N/ha, except for years with grass cover (null input). There was no organic N input (normally specified in each line after mineral fertiliser).

```
[SiteName]
site=WindFarm
latitude=51.78
Natmodepo=-9999 ; use -9999 for NODATA

[SoilData]
Clay=25.0
SoilDepth=23.0
Ceq=35.0 ;arbitrary from Rothamsted
BaseYear=1972

[Equilibrium]
Weather=equi
landUse=PermGrass

[Rotations]
lines=32
; Columns below represent: Crop type, climate year,year counter, minN input, orgN input<optional>, orgfert type<optional>, month of org input<optional>
; NOTE: real climate file will be called <site>yy.mon
1=WinOilRape 1973 1 150.0
2=WinWheat 1974 1 185.0
3=WinWheat 1975 1 185.0
4=WinWheat 1976 1 185.0
5=WinWheat 1977 1 185.0
6=AnnGrass 1978 1 0.0
7=WinOilRape 1979 1 185.0
8=WinWheat 1980 1 185.0
9=WinWheat 1981 1 185.0
10=WinWheat 1982 1 185.0
11=WinOilRape 1983 1 150.0
(…)
32=WinWheat 2004 1 220.0
```

A.2. Crop classification in RothC-BIOTA model.

Table A2. 1: Crop types and other vegetation classes in RothC-BIOTA

Crop / plant types	Reference name in RothC-BIOTA	RothC-BIOTA INDEXes
Winter wheat	WinWheat	WinCer
Winter barley	Win Barley	
Winter oats	Win Oats	
Winter rye	Win Rye	
Linseed	Linseed	
Spring wheat	SprWheat	SprCer
Spring barley	SprBarley	
Spring oats	SprOats	
Triticale	Triticale	
Winter oilseed rape	WinOilRape	WinOtCrop
Setaside	Setaside	
Spring oilseed rape	SprOilRape	SprOtCrop
Forage maize	ForMaize	
Forage rape	ForRape	
Forage rye	ForRye	
Winter beans	WinBeans	Legume
Spring beans	SprBeans	
Field peas	FieldPeas	
Vining peas	ViningPeas	
Potatoes	Potatoes	Potat
Sugar beet	SugarBeet	SugBeet
Heart cabbage	HeartCabbage	NRootVeg
Spring cabbage	SprCabbage	
Leeks	Leeks	
Cauliflowers	Cauliflowers	
Lettuce	Lettuce	
Brussels sprouts	BrusselsSprout	
Onions	Onions	RootVeg
Carrots	Carrots	
Turnips	Turnips	
Fallow land	Fallow	Fall
Annual grass	AnnGrass	AnnGrass
Permanent grass	PermGrass	PermGrass
Forest	Forest	For

A.3. RothCBIOTAv05.

A3-1. Method controlling land use change in RothCBIOTAv05.

```
!       ============================
        subroutine SetNextRotation()
!       ============================
        use RothCBiota
        use management
        use vegparams
        use yield
        implicit none

        character(len=255) vegName
        character(len=255) vegClass
        integer(kind=4) cropIndex

        if(Get_RunningEquilibrium()) return

        if(currentRotation .eq. privNumRotations) then
              if(privRotations(privNumRotations)%years .eq. 0) return
        end if

if((currentRotation  .eq.  0)  .or.  (privRotations(currentRotation)%years  .eq.  0))
then
              currentRotation=currentRotation+1
              vegName = trim( privRotations( currentRotation )%crop)
vegClass    =    CropIndexToName(SubCropToCrop(SubCropNameToIndex(    privRotations(
currentRotation )%crop ) ) )

              if(oldVegName .ne. vegName) then
                    call LoadVegParams( trim(vegClass)//'.ini' )
                    oldVegName=vegName
                    cropIndex=CropNameToIndex(trim(vegClass))
                    call SelectCrop(cropIndex)
              end if
          end if
privRotations(currentRotation)%years=privRotations(currentRotation)%years-1
end subroutine SetNextRotation
```

A3-2. Fragment of subroutine SelectCrop that control input of crop parameters according to current crop (selected by the code above).

```
!         Copy the correct crop data to the "global" array

          if(FIT .eq. .false.) PLADD(:,1) = privPLADD(:,1,CropType)
          ICROP(:,1) = privICROP(:,1,CropType)
          if (IFYMOT .eq. 0) FYMADD(:,1) = privFYMADD(:,1,CropType)
```

A.4. Method of biomass adjustment by fertiliser.

A4-1.

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      real*8 function ExpectedYield(vegIndex, soilNmin)
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      integer(kind=4), intent(in) :: vegIndex
      real(kind=8) :: soilNmin
real(kind=8) a,b
! Initialise
      a=kpar1(vegIndex)
      b=kpar2(vegIndex)
if (soilNmin .lt. 20) soilNmin = 20.0
! Estimate current yield using Smith, Leech (1995) function
      ExpectedYield=(LOG((soilNmin + a)/ a))/ b                   !called also 'y2'
end function ExpectedYield
```

A4-2.

```
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      real(kind=8) function Ratio(y1,y2)
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      real(kind=8), intent(in) :: y1,y2
      Ratio = y2/y1
      end function Ratio

The above function is used in Biotamodel as follows:
if ((SubCropIndex .ne. 32) .or. (SubCropIndex .ne. 33)) then
yieldRatio = Ratio( MaxYield(subCropIndex), ExpectedYield( subCropIndex, soilN ) )
end if ; this excludes grasslands

!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      real(kind=8) function AdjustBiomasswithRatio(biomass,ratio)
!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!!
      real(kind=8), intent(in) :: biomass
      real(kind=8), intent(in) :: ratio
      real(kind=8)  adjustedbiomass, factor
      factor=1.0! introduced to test sensitivity of the model
      adjustedbiomass=biomass*ratio*factor
      AdjustBiomasswithRatio=adjustedbiomass
      end function AdjustBiomasswithRatio

The above function is applied in Biotamodel to adjust plant pools:

do p=1,4
      if ((currentRotation .ne. 0) .and. (yieldRatio .lt. 1.0d0)) then
         Vegetation(p)= AdjustBiomasswithRatio(RunningPools(p), yieldRatio )
      else
         Vegetation(p)=RunningPools(p)
      end if
enddo
```

A.5. Crop parameters.

Table A5. 1: List of vegetation parameters used by RothC-BIOTA.

Parameter	Name (BIOTA model)	Value for						Units
		grass	w/ spr wheat	w/spr barley	sugar-beet	oil-seed rape	potato	
Biomass respiration at 0°C	Rmo	0.003	0.003	0.003	0.003	0.003	0.003	gC/day/gC
Specific Leaf Area index	SLA	0.02	0.02* 0.08*1 (0.05-0.13)	0.02* 0.08*1 (0.05-0.13)	0.02* 0.08*1 (0.05-0.13)	0.02* 0.08*1 (0.05-0.13)	0.02* 0.08*1 (0.05-0.13)	m^2/gC
Max potential electron transport rate	ejmax	85	160	169	226	187	140	μmol/m^2/gC
partitioning of C in veg pools	falp(1)	0.6	0.81**	0.81**	0.40**	0.74**	0.95**	fraction
partitioning of C in veg pools	falp(4)	0.4	0.19**	0.19**	0.60**	0.26**	0.05**	fraction
fraction of litter entering DPM pool	fbet(1)	0.6	0.6	0.6	0.6	0.6	0.6	fraction
fraction of litter entering DPM pool	fbet(4)	0.6	0.6	0.6	0.6	0.6	0.6	fraction
vegetation residence time of leaves (years)	resdL	1.2	1.0	1.0	1.0	1.0	1.0	years
vegetation residence time of roots (years)	resdR	1.2	1.0	1.0	1.0	1.0	1.0	years
fraction of roots in soil layer 1	FracRootLayer1	1.0	0.43[2]	0.43	0.59[3]	0.72[4]	0.5-0.6[5]	fraction
fraction of roots in soil layer 2	FracRootLayer1	0.0	0.57[2]	0.57	0.41[3]	0.28[4]	0.4-0.5[5]	fraction
aerodynamic conductance	g_s	0.03	0.03 (0.02-0.05)	0.03 (0.02-0.05)	0.03 (0.02-0.05)	0.03 (0.02-0.05)	0.03 (0.02-0.05)	m/s
Luening/Lohamer model for stomatal cond vs. Humidity	a_1	6.6	6.6	6.6	6.6	6.6	6.6	kPa
Luening/Lohamer model for stomatal cond vs. humidity	d_0	1.0	1.0	1.0	1.0	1.0	1.0	
Thickness of soil payer 1		230	200″	200″	200″	200″	200″	mm
Thickness of soil layer 2		770	1200″″	1200″″	1000″″	1600″″	800″″	mm

* parameters obtained from WOFOST model (Boons-Prins *et al*., 1993); in brackets measurements by Filler and Hay (2002).
*1 average from the range suggested by Fitter and Hay (2002) in 'Environmental physiology of plants', p.47.
** proportions were estimated on the basis of measured dry weight of above and below ground components obtained from literature (all references used).
[2] proportion of roots was estimated from measurements of root length at different depths on 5 August (Gregory *et al*., 1978). Top layer (0-20cm) had ~9 cm/cm3 of roots, and the rest of soil (20 – 140 cm) had ~11.7 cm/cm3 roots. This suggested that with similar root diameter for entire root system, there were 43.5% and 56.5% roots in the top layer and in the subsoil.
[3] proportion of sugar beet roots in the soil layers was estimated on the basis of root density in top 50 cm measured by Brown and Biscoe (1985) for 8 soil samples (Figure 7-4, attached). Top soil layer (0-20 cm) had total root length of 3.8 cm/cm3, the remainder of the soil (20-50cm) had 2.6 cm/cm3. This represented proportions of 59.4% and 40.6% respectively.

[4]proportion of oilseed rape roots in the two soil layers (0-20 and 20 – 100cm) was estimated from the root length measured on 23 July by Barraclough (1989), table 1, attached. The roots' lengths in top and lower soil layers were: 7.46 and 2.91 km/m2, which represented 72% and 28%, respectively.
[5]proportion of potato roots in two soil layers was estimated on the basis of mean root lenghts of the third sample presented by Vos and Groenwold (1986) on Figure 7-5, attached. The range of roots depths for top (0-20 cm and subsoil (20-80 cm) layers in 1982 and 1983 were 2.3 – 3.6 cm/cm3 and 1.6 – 3.4 cm/cm3, respectively. This represented proportions of 60-50% and 40-50%, respectively. The top measurement for the hill location (-20cm) was excluded, so the estimated proportions represent plant for below hill location.

Table A5. 2: Simulated fresh yields for four selected arable crops and different values of selected crop parameters.

Crop parameter	Parameter ranges	Average simulated fresh yields* [t/ha]			
Selected root crops		Potatoes (46 t/ha)**	sugar beet (44.8 t/ha)**	Turnips (35 t/ha)**	Carrots (51 t/ha)**
Specific Leaf Area Index (SLA) [m^2/gC]	0.04	13.4 (3-23.8)	16.1 (5.1-27.1)	22.5 (9-36)	22.1 (14.1-30)
	0.05	17.1 (3.8-30.3)	18.4 (6.1-30.7)	30 (12-48)	29.5 (19-40)
	0.06	19.3 (4.3-34.2)	19.6 (6.5-32.7)	34.7 (14-55.5)	34.2 (22.1-46.3)
	0.07	20.7 (4.7-36.8)	20.3 (6.7-33.8)	37.6 (15-60.3)	37.1 (24-50.2)
	0.08	21.7 (4.9-38.5)	20.7 (6.8-34.6)	39.5 (15.8-63.3)	38.9 (25.2-52.7)
	0.09	22.3 (5-39.7)	20.9 (6.9-35)	41 (16.5-65.5)	40.3 (26-54.6)
	0.1	22.9 (5.1-40.6)	21.1 (6.9-35.3)	41.8 (16.8-67)	41.2 (26.7-55.8)
	0.11	23.2 (5.2-41.2)	21.3 (7.1-35.5)	42.6 (17-68.3	41.9 (27.1-56.9)
	0.12	23.5 (5.3-41.7)	21.4 (7.1-35.7)	43.2 (17.3-68.3)	42.6 (27.5-57.7)
	0.13	23.7 (42.1)	21.5 (7.1-35.9)	43.8 (17.5-70)	43 (27.7-58.3)
Maximum potential electron transport rate (Ejmax) [$\mu mol/m^2/gC$]	85	8.4 (1.8-15)	9.1 (3-15.2)	13.6 (5.5-21.7)	13.3 (8.5-18.1)
	90	8.9 (1.9-15.9)	9.6 (3.1-15.9)	14.5 (5.8-23.2)	14.2 (9.2-19.3)
	95	9.5 (2.1-16.8)	10 (3.4-16.8)	15.5 (6.3-24.7)	15.2 (9.8-20.6)
	100	10 (2.3-17.8)	10.5 (3.5-17.5)	16.3 (6.5-26.2)	16.1 (10.4-21.8)
	105	10.5 (2.4-18.6)	10.9 (3.6-18.1)	17.3 (7-27.7)	17.1 (11-23.1)
	110	11 (2.5-19.5)	11.2 (3.7-18.8)	18.1 (7.3-29)	17.8 (11.5-24.2)
	115	11.4 (2.6-20.3)	11.6 (3.8-19.4)	18.8 (7.530.2)	18.6 (12.1-25.2)
	120	11.8 (2.6-20.9)	11.9 (3.9-20)	19.8 (8-31.5)	19.3 (12.5-26.2)
	125	12.2 (2.7-21.7)	12.3 (4-20.5)	20.5 (8.3-32.7)	20.1 (12.9-27.3)
	130	12.5 (2.8-22.3)	12.5 (4.1-20.9)	21.1 (8.5-33.7)	20.7 (13.3-28.1)
	135	12.9 (2.9-22.9)	12.9 (4.2-21.5)	21.8 (8.8-34.7)	21.3 (13.8-28.9)

	140	13.4 (3-23.8)	13.1 (4.3-21.9)	22.5 (9-36)	22.1 (14.2-30)
	145	13.5 (3-24.1)	13.4 (4.4-22.4)	23 (9.3-36.7)	22.6 (14.6-30.6)
	150	13.8 (3.1-24.6)	13.6 (4.4-22.7)	23.6 (9.5-37.7)	23.2 (15-31.4)
	155	14.2 (3.2-25.1)	13.8 (4.4-23.1)	24.2 (9.8-38.7)	23.8 (15.4-32.3)
	160	14.4 (3.2-25.6)	14.1 (4.7-23.5)	24.7 (10-39.5)	24.3 (15.6-32.9)
	165	14.7 (3.3-26.1)	14.3 (4.7-23.9)	25.1 (10-40.2)	24.8 (16-33.5)
	170	14.9 (3.3-26.6)	14.5 (4.8-24.2)	25.6 (10.3-41)	25.2 (16.3-34.1)
	175	15.2 (3.4-27.4)	14.7 (4.9-24.4)	26.1 (10.5-41.7)	25.7 (16.7-34.7)
	180	15.4 (3.4-27.4)	14.8 (4.9-24.8)	26.6 (10.8-42.5)	26.1 (16.9-35.4)
	185	15.6 (3.5-27.8)	15 (5-25.1)	27 (10.8-43.2)	26.5 (17.1-36)
	190	15.9 (3.5-28.2)	15.1 (5-25.3)	27.5 (11-44)	27.1 (17.9-37.7)
	195	16.1 (3.6-28.6)	15.3 (5-25.6)	27.8 (11.3-44.5)	27.4 (17.7-37)
	200	16.3 (3.6-28.9)	15.4 (5.1-25.8)	28.2 (11.3-45.2)	27.8 (17.9-37.7)
	205	16.5 (3.75-29.3)	15.7 (5.2-26.1)	28.6 (11.5-45.7)	28.1 (18.1-38.1)
	210	16.7 (3.75-29.7)	15.8 (5.2-26.4)	29 (11.5-46.5)	28.5 (18.3-38.7)
	215	16.9 (3.8-30)	15.9 (5.2-26.6)	29.3 (11.8-47)	28.8 (18.5-39.1)
	220	17.1 (3.8-30.3)	15.9 (5.2-26.6)	29.7 (12-47.5)	29.1 (18.8-39.6)
	225	16.1 (3.9-30.5)	16 (5.3-26.8)	30 (12-48)	29.5 (19-40)
Partitioning of C in vegetation pools (a	20/80	18.9 (1.4-36.4)	14.7 (3.9-25.5)	9.5 (3.8-15.2)	9.4 (6-12.7)
	30/70	18.7 (2.9-34.4)	13.7 (3.1-24.2)	17 (6.8-27.2)	16.8 (10.8-22.7)
	40/60	16.1 (3-23.8)	16.1 (5.1-27.1)	22.5 (9-36)	22.1 (14.2-30)
	50/50	13.6 (4.3-22.8)	12.3 (4.7-19.8)	23.1 (9.3-37)	22.7 (14.6-30.8)
	60/40	8.2 (4.6-11.8)	10.5 (5.1-15.9)	20.6 (8.3-33)	20.3(13.1-27.5)

* Values represent average simulated fresh yields, in brackets: fresh yields with low and high level of fertilising; ** In brackets there are average published fresh yields for the crop types.

Section 8

A plot-scale experiment to detect the effect of cultivation on soil organic carbon

Table of Contents

8. A plot-scale experiment to detect the effect of cultivation on soil organic carbon

P.E. Levy, N. Ostle, R. Milne and T.D. Murray.
CEH Edinburgh, Bush Estate, Penicuik, Midlothian, EH26 0QB

8.1. Introduction

The UK LUCF Carbon Emission Inventory requires information on the fluxes arising in the transition between different land uses (Milne 2003). Grassland soils represent a substantial part of the terrestrial carbon stocks in the UK, and there are potentially large losses when these are cultivated, either for conversion to arable land or for improvement of pasture. Globally, it is estimated that around 50 Pg C have been emitted to the atmosphere from soils, following conversion of natural land to cultivated, agricultural land (Paustian *et al.*, 2000). The physical basis for this is that disturbance associated with soil tillage increases the turnover of soil aggregates and accelerates the decomposition of aggregate-associated soil organic matter (SOM). However, the number of experimental data quantifying this effect are rather small, and there are very few experimental data from the UK. Here, we describe a plot-scale experiment to detect the effect of cultivation on soil organic carbon content. Recent work (Smith et al. 2004) suggests that the increase in N_2O emissions in “no-till” agriculture outweighs the effect of carbon sequestration, in terms of Global Warming Potential (GWP). As a secondary aim, we include measurements of N_2O emission in this study, to obtain a more complete picture of the effect of cultivation on the greenhouse gas balance.

8.2. Methods

8.2.1. Field site and treatment

The experimental site chosen was on House O’ Muir Farm near CEH Edinburgh (Figure 8-1), which is managed by the Scottish Agricultural College. The site is at an altitude of 290 m in an area which is used for rough grazing at a very low stocking density, but has received no improvement or cultivation. Nearby fields have been improved, and though the experimental site is similar, it is surrounded by steep slopes where improvement or cultivation using farm machinery would be impractical. The soil is relatively shallow (10-15 cm), but relatively high in organic matter (10 % carbon content).

In June 2005, an 11 x 11 m area was fenced to exclude sheep. The vegetation within was cut to a height of 10 cm using a strimmer and the litter removed from the experimental area. Glyphosate herbicide (‘Roundup’) was applied on 8 July, with a further treatment on 14 July. This killed the remaining vegetation over a number of weeks, and the litter was removed by strimming and raking in August.

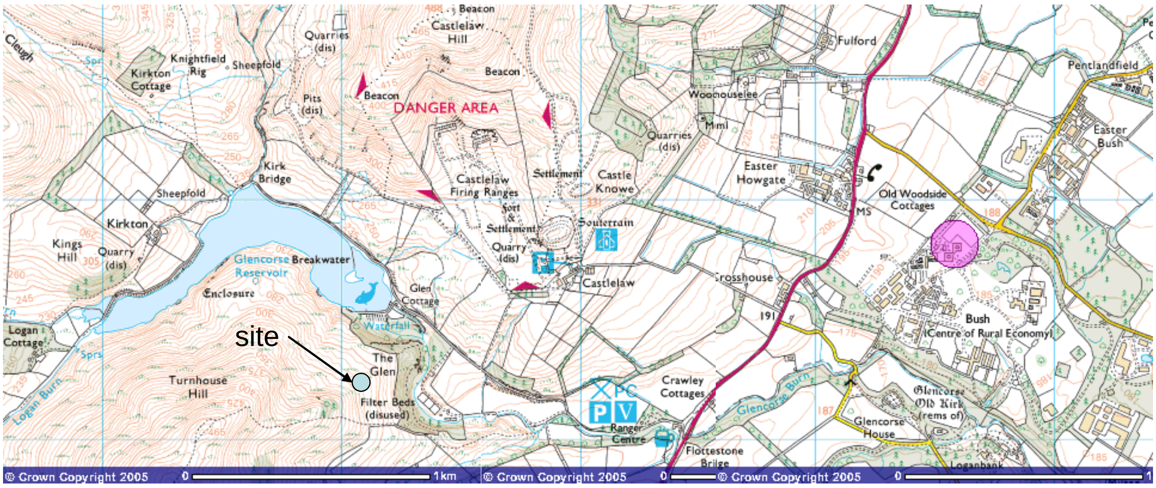


Figure 8-1 Location map of experimental site at House O' Muir Farm.

Within the fenced area, the outermost 1 m was reserved as a buffer zone to reduce edge effects from surrounding vegetation. The inner 9 x 9 m was divided into 1 x 1 m plots. A Latin Square design of 81 experimental plots was laid out, with three treatments: an uncultivated control, a single cultivation, and bi-annual cultivation (Figure 8-2). The first cultivation treatment was applied in November 2005. Treatments 1 & 2 were cultivated to a depth of 10 cm using an edging tool and digging fork to cut out, turn over, and break up turves.

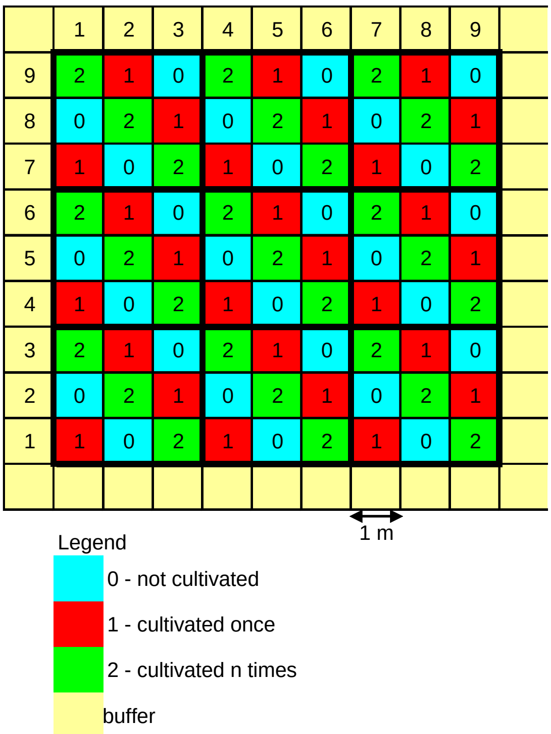


Figure 8-2   Replicated Latin Square experimental design, showing 11 x 11 m area with three treatments applied to 1 x 1 m plots in a 3 x 3 Latin Square, repeated 3 x 3 times.

8.2.2. Soil carbon measurements

Immediately following cultivation in November 2005, soil samples were taken from all plots for analysis of carbon content. Cores were removed by inserting sections of plastic tubing into the soil, and then cutting these out with a knife. Cores were 8 cm deep x 3.8 cm diameter. Taking deeper cores proved impractical because of the limited soil depth. Samples were analysed at CEH Lancaster for total carbon by loss on ignition (LOI) and bulk density. A sub-sample of 18 cores were analysed using an Elemental Analyser for carbon and nitrogen content. These data were used to establish the following relationship between LOI and carbon content (C):

$$C\ (\%) = 0.497 \cdot \mathrm{LOI}\ (\%)$$

which was applied to the other samples to calculate carbon content.

8.2.3. Soil respiration measurements

A dynamic closed-chamber system (EGM-4, PP Systems, Hitchin, UK) was used to measure soil respiration on each of the 81 plots in October 2005, prior to the treatment being applied. An opaque chamber 10 cm in diameter and 15 cm in height was pressed into the soil. An internal fan provided mixing whilst air was pumped through the chamber and an infra-red gas analyser in a closed circuit. The chamber was left in position until a rise of 50 ppm CO_2 was measured, usually ~70 s. The soil respiration rate, R, from the soil was calculated as

$$R = \mathrm{d}CO_2/\mathrm{d}t \cdot w$$

where $\mathrm{d}CO_2/\mathrm{d}t$ is the rate of increase in CO_2 with time (μmol mol^{-1} s^{-1}), and w is the system volume: area ratio in units of mol air m^{-2}. Corrections to this equation, using polynomial functions of time to correct for effects of leaks were investigated but made little difference.

8.3. Results and Discussion

Figure 8-3 shows the spatial pattern in soil respiration and soil carbon before cultivation. Some pattern may be discernible in the soil respiration data, increasing from left to right, but this is not very clear. Although there is variability in the soil carbon data, no spatial pattern is present. Figure 8-4 and Table 8-1 show the results of a one-way analysis of variance. There are no significant differences in the means for the plots allocated to the different treatments, prior to cultivation.

Table 8-1 Analysis of Variance table for pre-treatment differences between plots allocated to the three treatments. There are no significant differences prior to treatments.

Source	**DF**	**SS**	**MS**	**F**	**P**
Treatment	2	10945	5472	0.77	0.469
Error	78	557707	7150		
Total	80	568651			

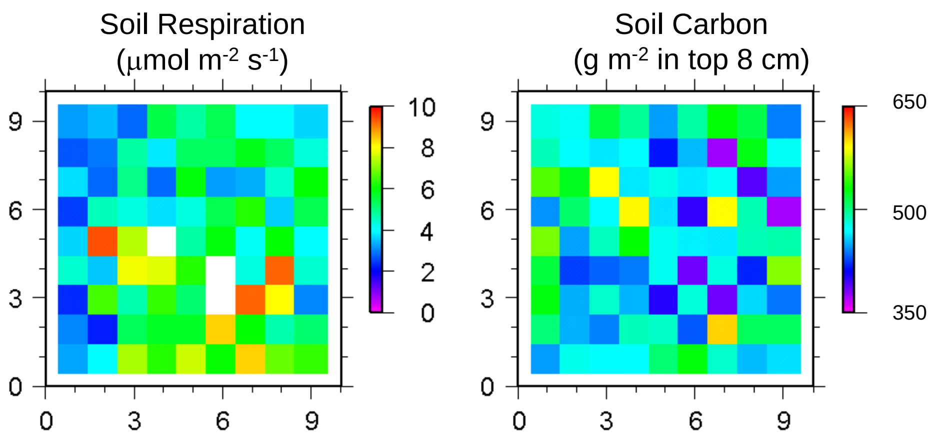


Figure 8-3 Plots of soil respiration and soil carbon measured before cultivation in October/ November 2005. X- and y- axes give the spatial position within the experimental area, in metres. The origin is the NE corner of the area.

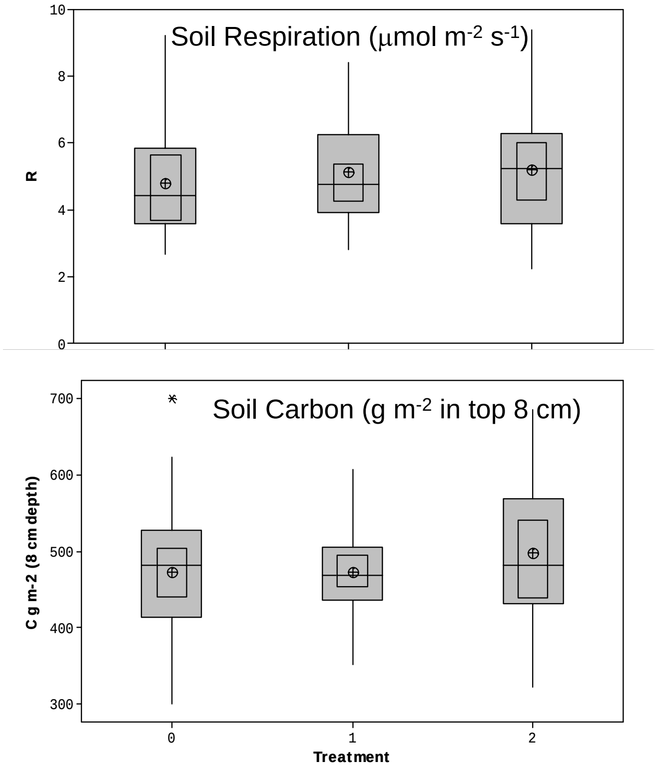


Figure 8-4 Box-plots for pre-treatment soil respiration and soil carbon measurements shown in Fig 8.3. Treatments are: 0 – uncultivated control; 1 – cultivated once; 2- cultivated bi-annually. Statistics shown are: means (circle), median (horizontal line), 95 % confidence interval (inner box), inter-quartile range (outer box), and range (vertical line) excluding outliers (asterisk). There are no significant differences prior to treatments.

The results show that there are no clear differences between the treatments at the start of the experiment. The advantages of this experimental design are that the major source of variation, the initial soil carbon content, can be accounted for as a co-variate when analysing future samples, and any remaining spatial variation can be largely removed due to the blocking of the plots. Because the Latin Square design ensures that all treatments are distributed across the experimental area in a balanced way, this can be analysed as a simple ANOVA with no block effect, as a full Latin Square, or with intermediate degrees of blocking, depending on the spatial variation observed in the data. If the variation between blocks is negligible, the number of degrees of freedom (and the statistical power of the experiment) is maximised by analysing as a completely randomised design with no block effect.

Measurements of nitrous oxide (N_2O) and methane (CH_4) flux are in progress at the time of writing (April 2006) and will be reported on if the experiment is continued under a future contract. These will allow us to calculate the effect of cultivation on the total greenhouse warming potential (GWP). GWP is calculated by adding changes to the N_2O and CH_4 fluxes to the change in soil carbon stock, weighted by their relative effects on radiative forcing (297 and 23, respectively). CO_2 and N_2O fluxes will be analysed in the same way as for stocks, with the exception that a time series of data should be available at ~bi-monthly intervals. A repeated measures technique may be applied to account for changes with time.

8.4. References

Milne, R., (2003). UK Emissions by Sources and Removals by Sinks due to Land Use, Land Use Change and Forestry Activities. Annual report for Defra Contract EPG1/1/160. CEH, Edinburgh.

Paustian, K., Six, J., Elliott, E. T., Hunt, H. W. (2000). Management options for reducing CO2 emissions from agricultural soils. *Biogeochemistry*, **48,** 147-163.

Smith, K. A., Conen, F. (2004). Impacts of land management on fluxes of trace greenhouse gases. *Soil Use and Management*, **20,** 255-263.

8.5. Acknowledgements

We acknowledge the co-operation and assistance provided by Alex Moir of the Scottish Agricultural College, Bush Estate.

Section 9

Incorporating effects of changes in climate, nitrogen deposition and CO_2 in projections of forest carbon budgets

Table of Contents

9. Incorporating effects of changes in climate, nitrogen deposition and CO_2 in projections of forest carbon budgets

M. van Oijen & T.Brown
Centre for Ecology & Hydrology, Edinburgh

9.1. Summary

Methodology used in previous UK greenhouse gas inventories and projections for forestry-related C-sequestration did not consider the effects of environmental change. C-input into the forests was represented by constant site-specific values (yield classes). However, recent studies found significant effects of environmental change on C-dynamics in European forests. This showed the need to make inventory methodology environmentally responsive. To achieve this, we here employed the process-based forest model BASFOR. The model was parameterized by means of Bayesian calibration, which allowed quantifying the uncertainty in parameter values and the propagation of the uncertainty to model outputs. Application of the model to the UK showed large spatial variation in sequestration rates and in the effect of environmental change. Factor analysis for one forest site identified a key role for increasing atmospheric CO_2 and, to lesser extent, warming, but sensitivity to changes in N-deposition may have been underestimated by the use of a global soils database according to which UK soils have very high N-contents. We conclude that the methodology of using process-based models in combination with Bayesian calibration and uncertainty quantification works well and can be used to make inventory methodology environmentally responsive provided the quality of input data is increased.

9.2. Introduction

Methodology employed in previous UK greenhouse gas inventories and projections did not account for changes in forest carbon use caused by changes in the environmental drivers climate, nitrogen deposition and CO_2 (Milne *et al*. 2003). Projections were made for forest carbon use until the year 2020, using simple models like CFLOW that are based on yield tables derived from trees grown before 1990. However, European forests have been affected by changing growing conditions during the 20th century, invalidating the use of static yield tables (Spiecker *et al.* 1996). Studies using process-based modelling have estimated the effects of the changing environmental drivers on forest growth in Europe (project RECOGNITION: Milne & Van Oijen 2005) and the UK (Murray & Thornley, in Milne *et al*., 2003). The process-based models as such are too complex to be applied directly to mapping carbon budgets at high spatial resolution, but their output can be analysed to derive simplified relationships - linking environmental drivers and site conditions to forest carbon use - that can be incorporated in the simple models.

Although complex process-based models are attractive because of their capability to calculate the consequences of changes in various environmental factors, both soil-related and atmospheric, their use has been hampered by two practical problems. First, they require a large body of data both for driving the model and for quantifying their many parameters. Secondly, the data invariably are incomplete or imprecisely measured, which leads to an accumulation of uncertainty in model outputs (Levy *et al*., 2004). These two problems are significantly smaller when inventories are made using simpler and more robust models like CFLOW, which lump the effects of the growing environment together in the widely available measurement of yield class (*i.e.* average annual wood volume production). The data problem can not be overcome at short notice, but the present study does show how the inevitable uncertainty can be rigorously quantified and systematically reduced.

Here, we shall present results for UK-wide carbon sequestration in conifer plantation forests, derived using the relatively complex process-based forest model BASFOR. The method of quantifying and analysing uncertainties, involving Bayesian statistics, will be explained and areas of major uncertainty identified. Finally, we show an analysis of past and future forest growth at one particular Sitka spruce site, Dodd Wood, in which the contributions of changes in climate, CO_2 and N-deposition to changes in yield class and C-sequestration were quantified. This example shows how the input to CFLOW, *i.e.* yield class, could be made sensitive to actual and envisaged environmental change, thus making the inventory construction environmentally responsive.

9.3. Methods

9.3.1. Model

The BASic FORest simulator, BASFOR, is a process-based forest model that simulates carbon and nitrogen cycling in trees, soil organic matter and litter (Van Oijen *et al*., 2005). It simulates the response of trees and soil to radiation, temperature, precipitation, humidity, wind speed, atmospheric CO_2 and N-deposition, as well as tree thinning regime. The model has 11 state variables, representing carbon and nitrogen pools in trees and soil, and 32 parameters controlling the rate of physiological processes and morphological characteristics. Besides time series for the state variables, output may be produced of net primary productivity (NPP), tree height, ground cover, LAI, N-mineralisation and other tree and soil variables. BASFOR is built from well known process-representations. Light absorption is calculated by Beer's law. Gross primary productivity (GPP) is calculated as light absorption times a light-use efficiency (LUE). NPP is calculated as a fixed ratio of GPP. LUE is temperature- and CO_2-dependent and may be reduced if insufficient nitrogen is taken up by the plants. Potential nitrogen uptake scales with root system area. Actual nitrogen uptake is the minimum of demand, determined by tissue N-concentration, and potential uptake. Allocation of assimilates follows allometric rules, but water stress may limit leaf area index (LAI). Turnover of tree and soil components proceeds at constant relative rates.

The model is deterministic and is solved by Euler integration with a time step of one day.

9.3.2. Data

This modelling study required the use of a considerable amount of data. The data were used for two different purposes. First, environmental data were used as drivers for the forest model simulations, as described in section 9.3.1. Secondly, literature data and data from UK forests were used to provide estimates of the model parameters. Both types of data are described in this section.

9.3.2.1 Weather

All weather data used in the study were taken from the climate scenarios provided by UKCIP (Hulme & Jenkins, 1998). For future weather, only the values in the "Medium-high" scenario were used. Figure 9-1 and Figure 9-2 show average temperature and rate of precipitation across the UK for the period 1920-2000. The data are given for a regular spatial grid of 655 cells of 20 by 20 km each. Spatial gradients for temperature and precipitation are dominated by latitudinal and longitudinal effects, respectively. Figure 9-3 shows the degree of warming predicted by the selected climate change scenario, expressed as the difference in temperature between the periods 2000-2080 and 1920-2000. Warming is expected to show a decreasing pattern from the South-East to the North-West.

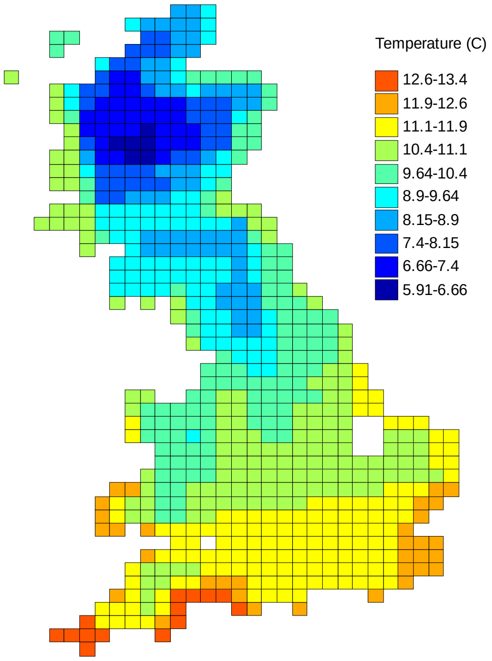


Figure 9-1 Mean temperature for 1920-2000. Data source: UKCIP

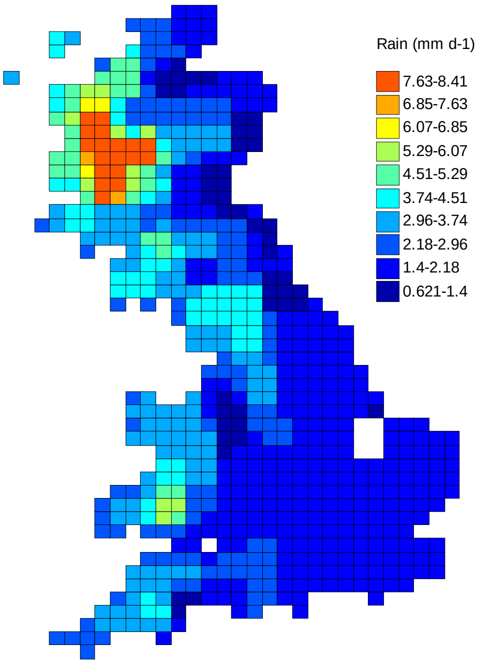


Figure 9-2 Mean precipitation for 1920-2000. Data source: UKCIP

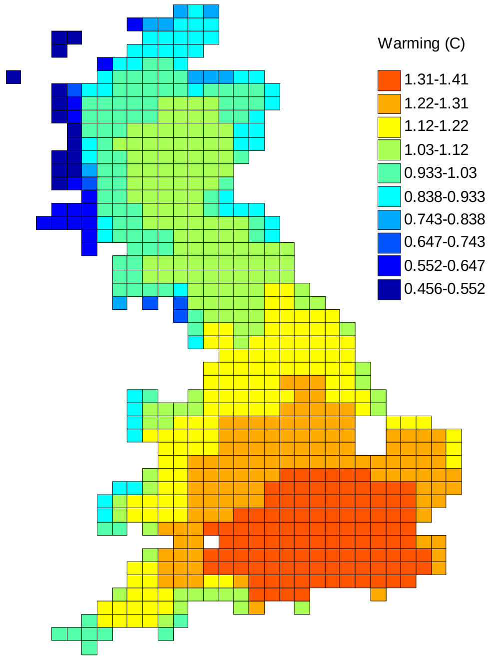


Figure 9-3 Change in mean temperature from 1920-2000 to 2000-2080. Data source: UKCIP

A summary of UK-average weather for the same two time periods but for all five variables used in the model (radiation, temperature, precipitation, vapour pressure and wind speed) is given in Table 9-1. According to the chosen UKCIP scenario, only temperature is expected to change significantly.

Table 9-1 Mean weather conditions for 1920-2000 and 2000-2080. Averages, standard deviations and extremes of global radiation (GR), temperature (T), precipitation (RAIN), vapour pressure (VP) and wind speed (WN), for 655 grid cells of 20 x 20 km (see Figure 9-1 to Figure 9-3) covering Great Britain. Data source: UKCIP.

		GR	T	RAIN	VP	WN
		$MJ\ m^{-2}\ d^{-1}$	°C	$mm\ d^{-1}$	kPa	$m\ s^{-1}$
1920-2000	Mean	9.54	9.46	2.80	1.00	7.01
	Standard deviation	1.17	1.04	0.80	0.07	1.31
	Minimum	6.58	5.71	0.61	0.79	4.27
	Maximum	12.79	12.30	5.41	1.20	8.73
2000-2080	Mean	9.58	10.30	2.83	1.06	6.97
	Standard deviation	1.27	0.98	0.81	0.07	1.29
	Minimum	6.53	6.74	0.62	0.84	4.28
	Maximum	13.00	13.06	5.42	1.26	8.63

9.3.2.2 Atmospheric CO_2 concentration.

Measurements of [CO_2] are more precise than those of most other environmental variables, and spatial variation is limited. Hence the literature is quite unanimous in its estimates of past CO_2 levels, with values of about 300 ppm in 1920 increasing to current levels of around 380 ppm. The average CO_2 level for the whole period 1920-2000 has been about 325 ppm. There is less unanimity regarding future CO_2 levels. We employed the predictions of the Bern model (Joos *et al*., 1996) for the mid-range IPCC emission scenario IS92a. This predicts an average CO_2 concentration for the period 2000-2080 of 480 ppm.

9.3.2.3 N-deposition

The time course of yearly total atmospheric N-deposition for the years 1920–2080 was estimated using three sources of information (Van Oijen *et al*. 2006). First, literature information suggested very low levels of N-deposition (< 3 kg N ha^{-1} yr^{-1}) across Europe in the year 1900 (Galloway, 1985). Second, data and calculations by the Co-operative Programme for Monitoring and Evaluation of the Long-Range Transmission of Air Pollutants in Europe (EMEP) show increasing N-deposition values during most of the 20th century with maxima reached around 1990. Third, the 1999 Gothenburg Protocol to Abate Acidification, Eutrophication and Ground-level Ozone sets emission ceilings for 2010 for NO_x, ammonia and other pollutants. Hence further reductions of N-deposition until the year 2010 were assumed and deposition was assumed to remain constant thereafter. These temporal patterns with overlaid with the spatial distribution determined for deposition on 2004 across the UK (R.I. Smith, pers. comm., Figure 9-4).

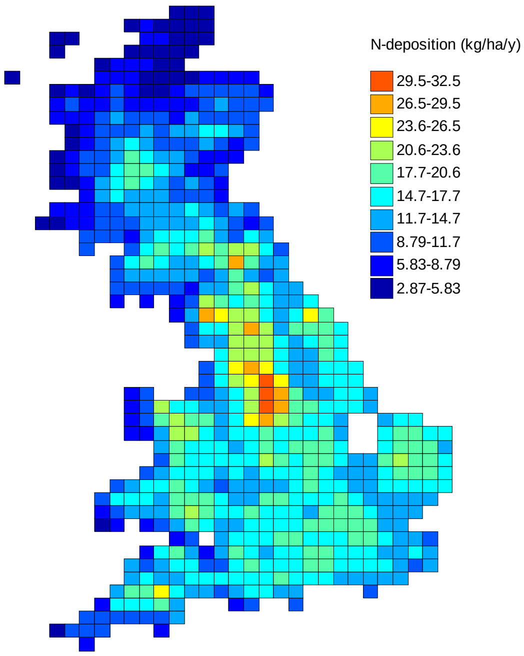


Figure 9-4 Atmospheric N-deposition in 2004. Data provided by R. Smith, CEH-Edinburgh

9.3.2.4 Soils

All soil information used in this study was taken from the global soils database produced by the Data and Information Services of the International Geosphere-Biosphere Programme (IGBP-DIS, Global Soil Data Task 2000). The IGBP-DIS database was used primarily because of its data on soil nitrogen content (Figure 9-5), but for consistency its data on soil carbon (Figure 9-6) and on plant available soil water content (PAWC, Figure 9-7) were used as well.

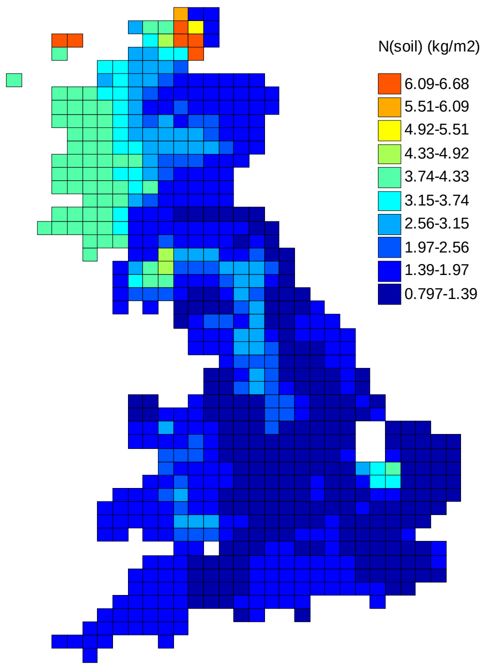


Figure 9-5 Total nitrogen in top 100 cm soil. Data source: IGBP-DIS

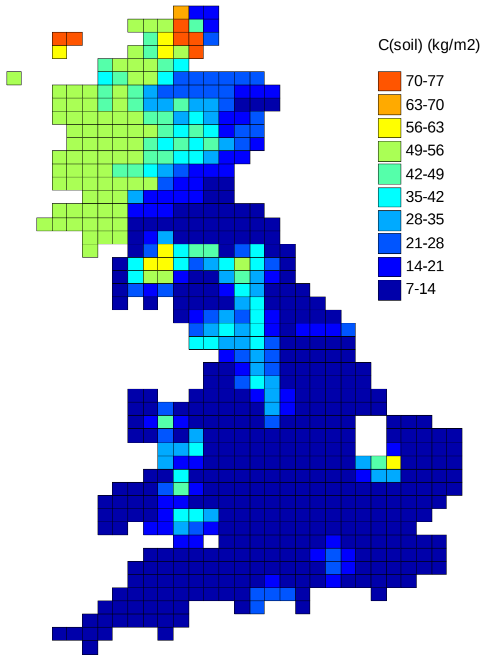


Figure 9-6 Total carbon in top 100 cm soil. Data source: IGBP-DIS

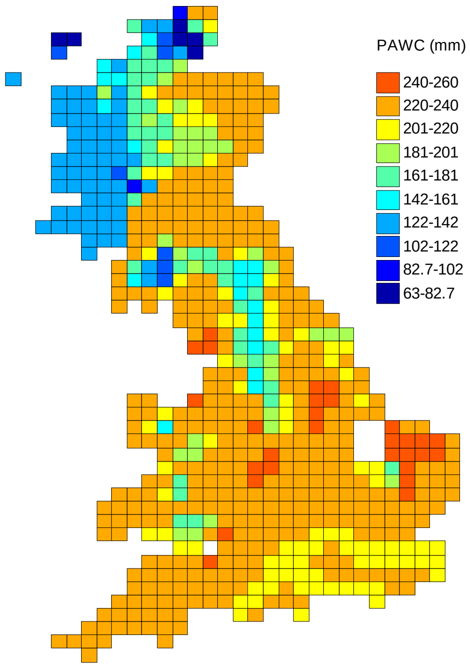


Figure 9-7 Maximum plant available water in top 100 cm soil. Data source: IGBP-DIS

9.3.2.5 Trees

Forest Research provided data on tree growth and soil characteristics from two Sitka spruce stands, for use in model calibration (R. Matthews & P. Taylor, pers. comm.). The sites were Dodd Wood (54.64 °N, 3.17 °W, alt. 381 m., indurated brown earth sandy soil) and Rheola (51.74 °N, 3.68 °W, alt. 220 m., brown earth soil) (Figure 9-8). Trees were planted in 1927 and 1935, respectively, and management followed a 5-year thinning cycle on both sites.

Figure 9-8 Model calibration data sites (Forest Research, UK)

9.3.2.6 Bayesian calibration and uncertainty quantification

The parameters of the BASFOR model were quantified by means of Bayesian calibration, using the Forest Research data for Dodd Wood and Rheola (see 9.3.2.5). Bayesian calibration provided estimates of the parameters of BASFOR, with measures of their uncertainty and correlations. The procedure began with quantifying the uncertainty about the parameter values in the form of a prior probability distribution. The prior information was taken from the literature on conifer growth. The Forest Research data on model output variables were used to update the parameter distribution by application of Bayes' Theorem. This yielded a posterior, calibrated probability distribution for the parameters. The predictive uncertainty of the model was then quantified by running the model with different parameter settings, sampled from the posterior distribution (n=5). Because Bayesian calibration of process-based models like BASFOR cannot be performed analytically, the posterior parameter distribution was approximated in the form of a representative sample of parameter values. This was achieved by means of Markov Chain Monte Carlo simulation. For further details of the Bayesian calibration procedure, see Van Oijen *et al*. (2005).

One limitation of the present study was that only the uncertainty in model parameters was quantified. Uncertainty in model drivers (climate, soils) was not quantified, nor was the uncertainty relating to the structure of the BASFOR model itself assessed.

9.4. Results

9.4.1. Bayesian calibration and uncertainty quantification

The results of model parameterisation using the method of Bayesian calibration are summarized in Table 9-2. The table lists the major parameters of BASFOR, with their prior uncertainty before application of data from UK forests. For most parameters, prior uncertainty was quite large, as is evident from wide ranges of possible values, *i.e.* lower and upper limits being far apart. The high level of prior uncertainty is typical whenever forest parameter values need to be quantified from the literature (Levy *et al.*). Figure 9-9 (black dotted lines) shows for four model output variables (tree and soil carbon, height and total produced wood volume) how the prior parameter uncertainty effected uncertainty in model outputs at the Dodd Wood site. For example, the uncertainty interval (2 standard deviations wide) for tree carbon at the end of the eighty-year rotation ranged from below 40 to above 80 ton carbon ha^{-1}. Table 9-2 and Figure 9-9 also show to what extent uncertainties were reduced by the Bayesian calibration using the data from the Dodd Wood and Rheola sites, described in section 9.3.2.5. The marginal posterior probability distributions were much narrower than the prior distributions, as can be seen from the small coefficients of variation. The data from Dodd Wood were not equally informative for all parameters, with CVs for three parameters – initial leaf and stem carbon content and N/C ratio of wood – exceeding 20%. However, Figure 9-9, red unbroken lines, show that overall parameter uncertainty had been reduced enough to significantly reduce output uncertainty for the four selected variables.

Table 9-2 Prior and posterior probability distributions for parameters of BASFOR. The prior is beta-distributed between specified lower and upper limits. The posterior, derived using data from Dodd Wood and Rheola, is not analytical and is characterized here by the mean values of the marginal parameter probability distribution and the coefficients of variation (CV = standard deviation / mean) (correlation matrix not shown).

Parameter vector			Prior probability distribution		Posterior probability distribution	
Symbol	Unit	Meaning	Lower limit	Upper limit	Mean	CV
$C_{B,0}$	(kg m^{-2})	Initial value branch C	0.00005	0.005	0.0010	0.18
$C_{L,0}$	(kg m^{-2})	Initial value leaf C	0.0001	0.01	0.0015	0.38
$C_{R,0}$	(kg m^{-2})	Initial value root C	0.0001	0.01	0.0017	0.16
$C_{S,0}$	(kg m^{-2})	Initial value stem C	0.00005	0.005	0.00090	0.34
B	(-)	CO_2-response factor	0.4	0.6	0.52	0.06
$CO_{2,0}$	(ppm)	CO_2-response base level	320	380	362	0.02
f_B	(-)	Allocation to branches	0.25	0.30	0.29	0.02
$f_{L,max}$	(-)	Maximum allocation to leaves	0.27	0.37	0.29	0.03
f_S	(-)	Allocation to stem	0.25	0.3	0.28	0.01
Γ	(-)	Respiration fraction	0.4	0.6	0.48	0.06
k_{CA}	(m^2)	Crown area allometric normalisation constant	5	15	11	0.12
$k_{CA,exp}$	(-)	Crown area allometric exponent	0.3	0.45	0.36	0.07
k_h	(m)	Tree height allometric normalisation constant	4	12	7.5	0.07
$k_{h,exp}$	(-)	Tree height allometric exponent	0.2	0.3	0.26	0.04
LAI_{max}	(m^2 m^{-2} mm^{-1})	Maximum LAI	4	10	6.3	0.06
LUE_0	(kg MJ^{-1})	Light-Use Efficiency	0.001	0.003	0.0014	0.10
$NC_{L, max}$	(kg kg^{-1})	Maximum C/N ratio leaves	0.02	0.05	0.028	0.12
$NC_{R,con}$	(kg kg^{-1})	C/N ratio roots	0.02	0.04	0.023	0.06
$NC_{W,con}$	(kg kg^{-1})	C/N ratio woody parts	0.0005	0.002	0.00080	0.23
SLA	(m^2 kg^{-1})	Specific Leaf Area	5	40	6.0	0.05
T_{opt}	(°C)	Temperature optimum	12	28	19	0.12
$TC_{L,max}$	(d)	Maximum survival time coefficient leaves	365	1460	1048	0.09
δ	(kg C m^{-3})	Wood density	150	250	182	0.04

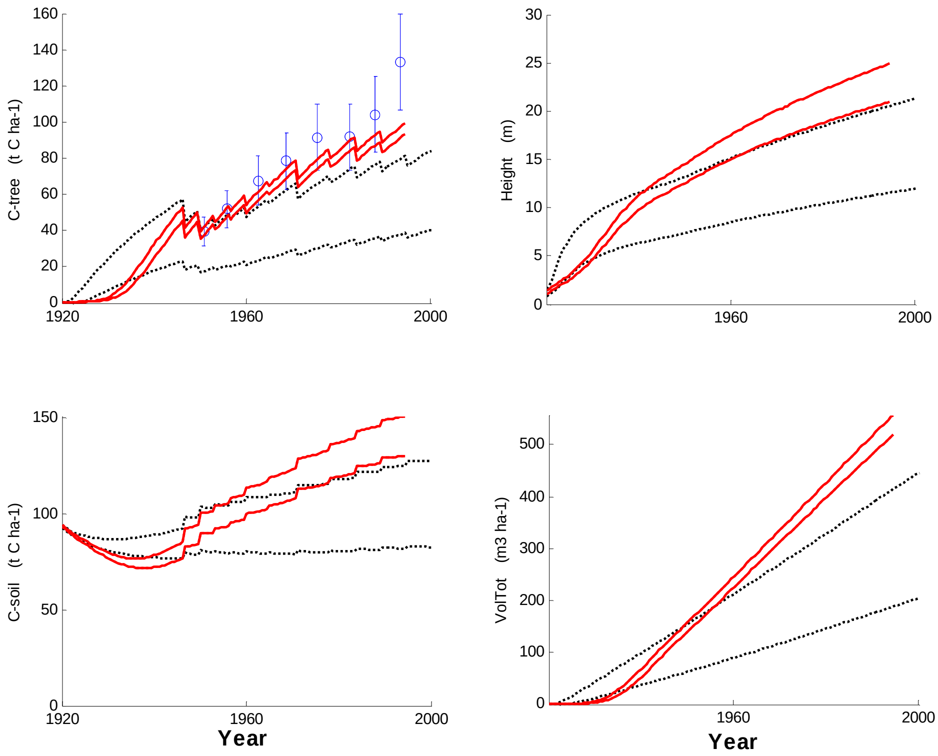


Figure 9-9 Prior (black,dotted lines) and posterior (red, unbroken lines) model output uncertainty for Dodd Wood. Output variables are tree and soil carbon content, tree height and cumulative wood volume production. Blue circles and vertical lines: data with estimated measurement error

9.4.2. Past and future UK-wide C-sequestration

9.4.2.1 C-sequestration 1920-2000

The calibrated model was applied to calculate UK-wide C-sequestration between 1920 and 2000 for a standardized conifer rotation with a 5-yearly thinning interval (Figure 9-10). C-sequestration was defined as the average annual total accumulation of carbon in soil, standing biomass and wood removed at thinnings. Calculated sequestration rates were highest in the South-West of the country, which is the area which combines moderately high temperature and precipitation (Figure 9-1, Figure 9-2). In the far North, possibilities for forestry-related C-sequestration may even be non-existent, as the model identifies these areas as being a net C-source rather than a sink (Figure 9-10). The spatial pattern of C-sequestration was not closely related to the spatial distribution of atmospheric N-deposition and soil nitrogen (Figure 9-4, Figure 9-5).

The propagation of parameter uncertainty to uncertainty about C-sequestration rates was calculated by taking five samples from the posterior parameter probability distribution (Table 9-2) and calculating the standard deviation for the five different results. Figure 9-11 shows the resulting map of sequestration uncertainty. The spatial pattern of sequestration uncertainty differs strongly from that of sequestration itself (Figure 9-10), indicating that the coefficient of variation varies between different growing conditions.

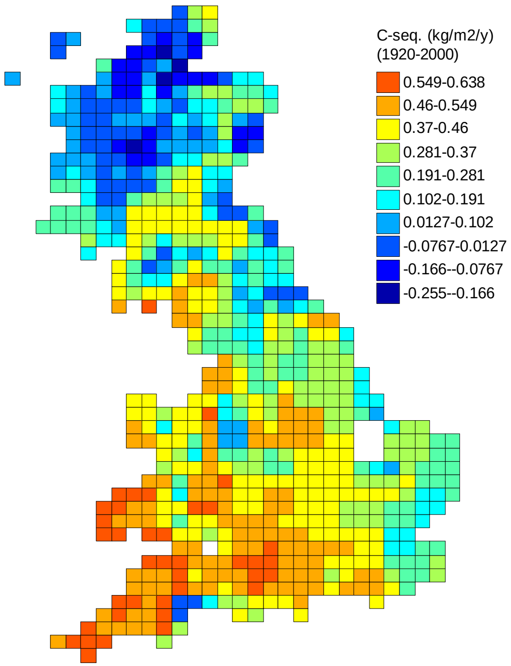


Figure 9-10 Simulated average annual C-sequestration (in soil, living trees and wood products) for 1920-2000. Results from model BASFOR

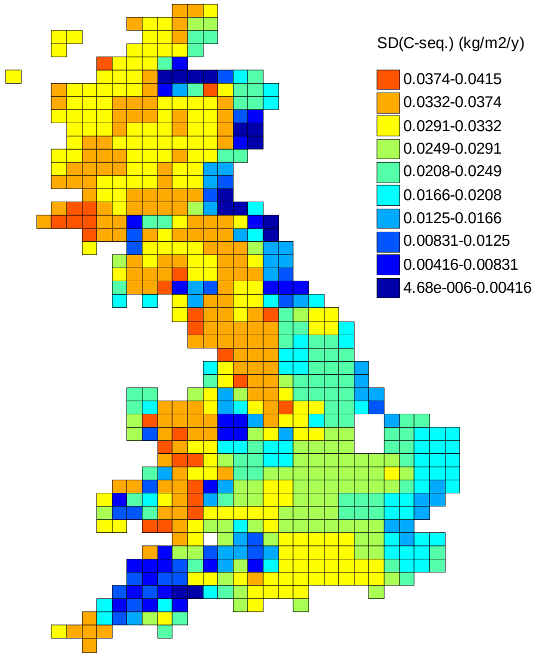


Figure 9-11 Uncertainty in simulated average annual C-sequestration (in soil, living trees and wood products) for 1920-2000. Results from model BASFOR

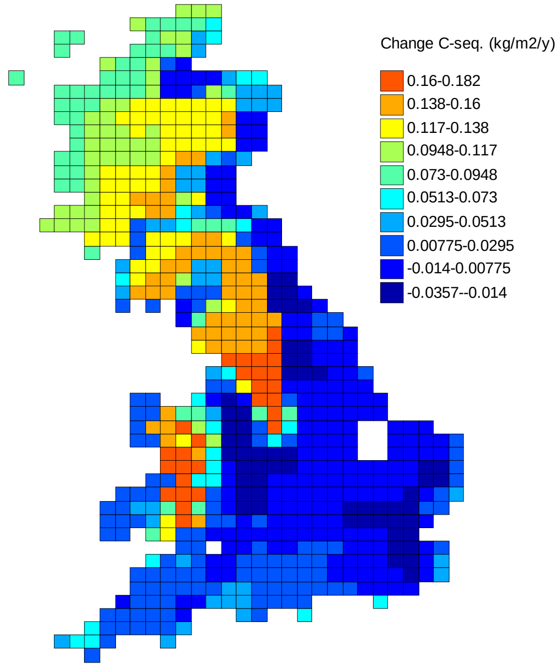


Figure 9-12 Simulated change in average annual C-sequestration (in soil, living trees and wood products) from 1920-2000 to 2000-2080. Results from model BASFOR

9.4.2.2 C-sequestration 2000-2080

The same calculations of C-sequestration were repeated for the environmental conditions expected for the period 2000-2080 (see section 9.3). Figure 9-12 shows the spatial distribution of expected changes in sequestration, relative to 1920-2000. The changes are not closely related to the magnitude of expected changes in temperature, as the spatial patterns differ (compare Figure 9-3 and Figure 9-12). However, some degree of warming is expected across the whole country, causing C-sequestration to change mainly in the higher, colder regions of Wales, North-England and Scotland.

9.4.3. Analysis in terms of environmental change factors: climate, CO_2, N-deposition

The preceding UK-wide assessments of the effects of environmental change on expected C-sequestration rates in conifer forests did not separate out the effects of the different environmental factors subject to change. For the purpose of such analysis, we ran simulations for the Dodd Wood site with a range of temperatures, atmospheric CO_2 concentrations and N-deposition rates, in a full-factorial set-up. Average temperature was varied from 6.8 to 9.9 °C (which amounts to expanding the UKCIP-estimates for the site for 1920-2000 and 2000-2080 with one degree on either side of the range), atmospheric CO_2 was varied from 320 to 480 ppm (corresponding to changes estimated by the Bern model using the IS92a emissions scenario for 1920-2000 and 2000-2080), and N-deposition was varied from 0 to double the 1920-2000 average value of 8.0 kg N ha^{-1} y^{-1}.

Table 9-3 summarizes the results of application of the model for these environmental conditions. The first data column of the table lists the average values of yield class and annual C-sequestration rate across the considered set of environmental conditions, with standard deviations indicating the uncertainty arising from both the variation in environmental conditions as well as the parametric uncertainty determined before (section 9.4.1). The final thee data columns of Table 9-3 give the average effect on yield class and sequestration of changes in temperature, CO_2 and N-deposition, with uncertainties. On the examined site, Dodd Wood, changes in each of the three environmental factors has an effect on the output variables, but with the strongest effect (relative to its expected degree of change) for CO_2. The analysis further suggests that C-sequestration rates are likely to increase to similar extent in soils and in tree biomass.

Table 9-3 Simulated change in average yield class and annual C-sequestration at the Dodd Wood site due to changes in temperature, CO_2 and N-deposition. The standard deviations are due to uncertainty in parameterisation and to variation in interacting environmental factors, but not including soil characteristics.

		Impact of environmental change		
Ecosystem variable	Dodd Wood value	Effect of temperature (per °C)	Effect of [CO_2] (per 100 ppm)	Effect of N-deposition (per 10 kg N ha^{-1} y^{-1})
Yield class (m^3 ha^{-1} y^{-1})	7.91 ± 1.11	0.18 ± 0.05	1.32 ± 0.38	0.74 ± 0.26
C-sequestration (t C ha^{-1} y^{-1})	3.99 ± 0.64	0.10 ± 0.03	0.76 ± 0.21	0.41 ± 0.14
C-sequestration, soil (t C ha^{-1} y^{-1})	1.58 ± 0.31	0.05 ± 0.01	0.36 ± 0.10	0.18 ± 0.07
C-sequestration, trees and products (t C ha^{-1} y^{-1})	2.41 ± 0.34	0.05 ± 0.02	0.40 ± 0.12	0.23 ± 0.07

9.5. Discussion and Conclusions

9.5.1. Methodology

This study has tried out a range of methods that may be used to improve the construction of the UK carbon inventory. The process-based forest model BASFOR was parameterised efficiently using Bayesian calibration, allowing for uncertainty quantification when using the model to calculate UK-wide conifer forest C-sequestration and yield class. However, the procedure likely suffered from low quality of some data, in particular those on soils. We used the IGBP-DIS global soils database to quantify soil nitrogen content, but the values seemed high in comparison to values reported commonly for North-West European soils (Van Oijen *et al*., 2006). Weather data seemed sufficient, but more data on tree growth need to be incorporated and the study needs to be expanded to different evergreen and deciduous tree species.

9.5.2. Uncertainties

Throughout our study we found relatively little sensitivity of UK forest C-sequestration rates and yield class to soil nitrogen content and atmospheric N-deposition, as opposed to the calculated sensitivities to changes in temperature and atmospheric CO_2 concentration. This finding may be an artefact from the use of the IGBP-DIS dataset with its possibly overestimated values of nitrogen contents of UK soils, leading to apparent nitrogen saturation (Van Oijen & Jandl, 2004). In follow-up research there is an urgent need to identify better soil data sources and to quantify the uncertainty associated with the soils data. In fact, uncertainties in all environmental factors, soil-related and atmospheric, need to be included in the Bayesian procedure, in order to give a realistic estimate of current uncertainties regarding C-sequestration.

9.5.3. The impacts of changes in environmental factors

The use of a process-based model for calculating C-sequestration, rather than a semi-empirical model like CFLOW, allowed us to analyse the contributions of changes in temperature, CO_2 and N-deposition to changes in sequestration. The analysis for the Dodd Wood site identified changing CO_2 as the major factor expected to affect sequestration. However, this finding should be seen as a proof of concept for the methodology rather than as a high-probability identification of a key environmental variable. This caution is needed because of the likely poor quality of the soils data, as mentioned above, but also because the factor analysis needs to be repeated for the whole of the UK first. Our analysis showed that the impact of environmental change varies across the country depending on the starting condition upon which the change was superimposed. For example, temperature increase only had a significant effect in the colder areas. Besides such nonlinear effects of individual factors like temperature, this study also suggests that important interactive effects, e.g. CO_2 x N-deposition, need to be taken into account. Even the spatial pattern of uncertainties, both expressed in absolute terms and as coefficients of variation showed distinct spatial trends across the country, so not only the calculation of main effects, but also uncertainty quantification needs to be calculated country-wide.

The presence of nonlinear individual and interactive effects limits the usefulness of response factors as calculated in Table 9-3. For example, the yield class temperature response factor of 0.18 ± 0.05 (m^3 ha^{-1} y^{-1}) (°C)$^{-1}$ does not necessarily apply outside the Dodd Wood area. This has implications for the way in which we can use results from the process-based modelling to derive modifiers for the yield class values that are used as input for the carbon inventory calculations using CFLOW. In short, the yield class modifiers should be complex multivariate functions of the set of different environmental factors. However, we can calculate such functions if we redo the current factor analysis at a UK-wide scale and with improved input information. This needs to be accompanied by quantification of the uncertainties from incomplete knowledge of parameters, environmental drivers and model structure.

9.6. Acknowledgments

We thank Robert Matthews and Paul Taylor (Forest Research, Alice Holt) for providing information about the Sitka spruce stands at Dodd Wood and Rheola, and Ron Smith (CEH-Edinburgh) for the data on UK-wide atmospheric N-deposition.

9.7. References

Galloway, J.N. (1985). The deposition of sulphur and nitrogen from the remote atmosphere. In: Biogeochemical Cycling of Sulphur and Nitrogen in the Remote Atmosphere (edited by J.N. Galloway, R.J. Charlson, M.O. Andrew and H. Rodhe). NATO ASI Series D. Reidel, Dordrecht. Pp. 143-175.

Global Soil Data Task (2000). Global Gridded Surfaces of Selected Soil Characteristics (IGBP-DIS). International Geosphere-Biosphere Programme – Data and Information Services. [http://www.daac.ornl.gov]

Hulme, M. & Jenkins, G.J. (1998). Climate Change Scenarios for the United Kingdom: Scientific Report. UKCIP Technical report Report No. 1. Climatic Research Unit, Norwich, 80 pp. [http://www.cru.uea.ac.uk/link/ukcip/ukcip_report.html].

Joos, F., Bruno, M., Fink, R., Siegenthaler, U., Stocker, T.F., Le Quere, C. and Sarmiento, J.L. 1996. An efficient and accurate representation of complex oceanic and biospheric models of anthropogenic carbon uptake. Tellus 48B: 397–416.

Levy, P.E., Wendler, R., Van Oijen, M., Cannell, M.G.R. & Millard, P. (2004). The effects of nitrogen enrichment on the carbon sink in coniferous forests: uncertainty and sensitivity analyses of three ecosystem models. Water, Air and Soil Pollution: Focus, 4, 67-74.

Milne RM *et al*. (2003). UK Emissions by Sources and Removals by Sinks due to land Use, Land Use Change and Forestry Activities. Report, April 2003, DEFRA Contract EPG1/1/160.

Milne, R. & Van Oijen, M. (2005). A comparison of two modelling studies of environmental effects on carbon stocks across Europe. Annals of Forest Science 62: 1-13.

Spiecker H *et al*. (Eds) (1996). Growth Trends in European Forests. EFI Research Report 5. Springer.

Van Oijen, M., Ågren, G.I., Chertov, O.G., Kellomäki, S., Komarov, A., Mobbs, D.C. & Murray, M.B. (2006). Application of process-based models to explain and predict changes in European forest growth. In press for: Causes and Consequences of Forest Growth Trends in Europe - Results of the RECOGNITION Project. Eds. T. Karjalainen *et al*. Brill, Chapter 3.2.

Van Oijen, M., Rougier, J. & Smith, R. (2005). On Bayesian calibration and evaluation of process-based forest models: bridging the gap between models and data. Tree Physiology 25: 915-927.

Van Oijen, M. & Jandl, R. (2004). Nitrogen fluxes in two Norway spruce stands in Austria: An analysis by means of process-based modelling. Austrian Journal of Forest Science 121: 167-172.