

Section 9

Estimating Land Cover Specific Carbon Fluxes From Flux Tower Measurements and Earth Observation Data

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9. Estimating land cover specific Carbon fluxes from Flux Tower measurements and Earth Observation data

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9.1. Underlying rationale

In this project we hope to establish a method of measuring the exchanges of greenhouse gases (GHGs) between the UK land surface and the atmosphere which integrates the available technologies. The technologies are:

- (i) Remote sensing, to describe the distribution, physical/radiometric properties and phenology of the main land covers;
- (ii) Models, calibrated using eddy covariance flux data, which enable gas exchange activity to be associated with particular land surface covers;
- (iii) Atmospheric data on concentrations of gases measured on strategically located European tall towers; these data are to be used to infer the land surface fluxes;
- (iv) Inventory data, of the kind that have been in use by CEH since 1990 and are covered by IPCC guidelines.

Of these, (i) and (ii) are combined to form a spatially integrated estimate of GHG fluxes; (iii) is capable of yielding distributions of fluxes over the European landscape including the UK, with very high (daily) temporal resolution; and (iv) provides a historical baseline. Key to the integration of these data sources will be to develop an understanding of the uncertainties associated with the approaches, models and data sources. All these technologies have strengths and weaknesses, and it is only by comparison and combination that we are likely to arrive at an operational system which will be useful in the Second Commitment Period of the Kyoto Protocol.

The UK is characterised by a high spatial diversity in land use, which challenges the first approach based on remote sensing and flux models. The second, the tall tower approach, provides spatial integration and so overcomes this difficulty.

In this First Report we outline sources of data and models, and show some preliminary results.

9.2. Sources and availability of data/models

9.2.1. Remote sensing

A wide range of remote sensing (RS) data sources are available to and pertinent to this work. Initially the data derived from RS will concentrate on land cover classification, although we will show how phenological and other RS measurements can potentially reduce uncertainties in an integrated approach.

9.2.1.(a) Land Cover

In this study we will concentrate on four main land cover datasets.

(1) LCM2000

We are fortunate in the UK that we have a high quality, high spatial resolution UK-wide land cover map (LCM2000¹) based on a classification of (mainly Landsat Thematic Mapper) summer and winter remote sensing images. The data are UK-wide, at a nominal spatial resolution of 25m, Level 2 product data comprise 26 land cover classes², which have been grouped into 8 plant functional types for the purpose of this study (Figure 9-1)

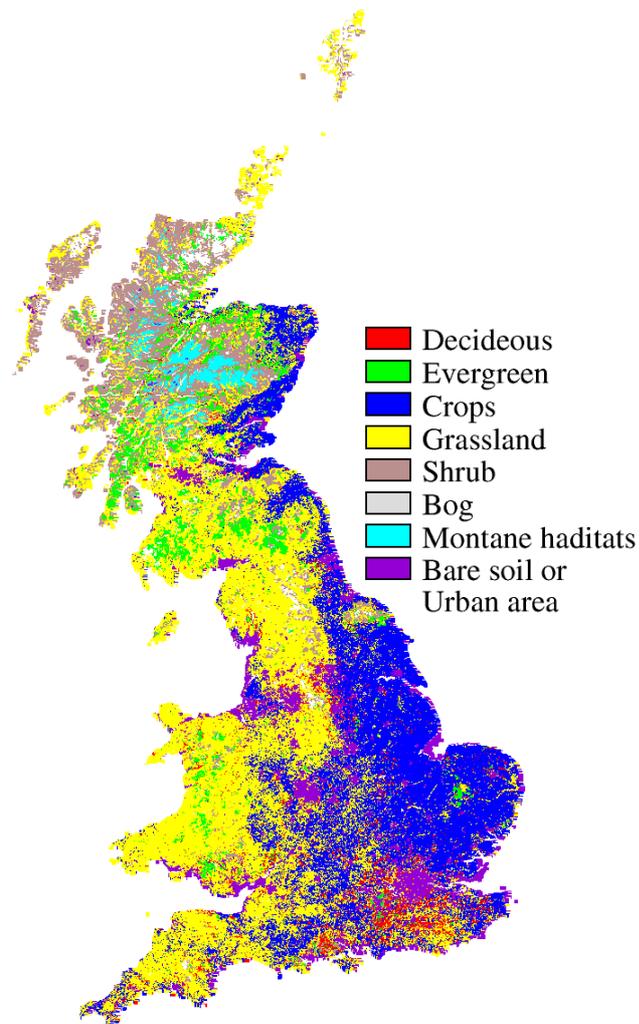


Figure 9-1_LCM2000 re-grouped classification (GB only shown here)

¹ <http://www.ceh.ac.uk/data/lcm/LCM2000.shtm>

² http://www.ceh.ac.uk/data/lcm/lcm2000_fulldatasetdescription.pdf

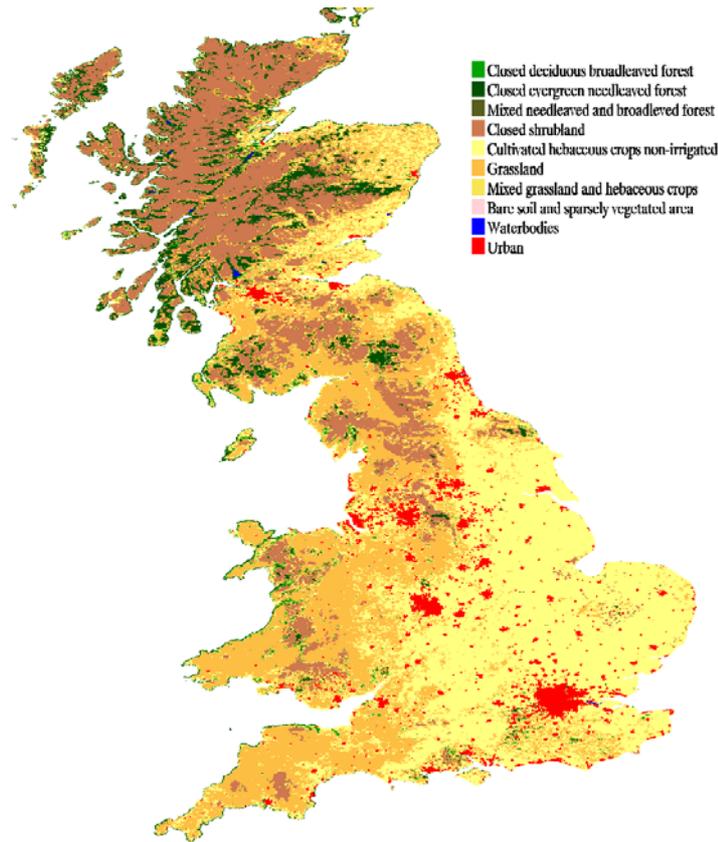


Figure 9-2 *GLC2000 land cover classification (UK only)*

(2) GLC2000³.

A world-wide land cover classification at 1 km spatial resolution. The data were derived from global 1 km observations from the SPOT VEGETATION sensor for the year 2000. The classification scheme comprises 22 cover types⁴, which have been regrouped into 8 plant functional types for this study. The GLC2000 product represents an improvement over global classification schemes available from sensors such as MODIS as it is calibrated on a regional basis.

(3) Forest Research/Woodland Survey UK Forest map

This vector dataset is derived from ground surveys and provides parcel-based information on UK forested areas (both Forestry Commission land and private areas). It is considered as a high quality dataset with which we can assess the quality of RS-derived datasets over the UK.

(4) MODIS Vegetation Cover Fraction (VCF) product

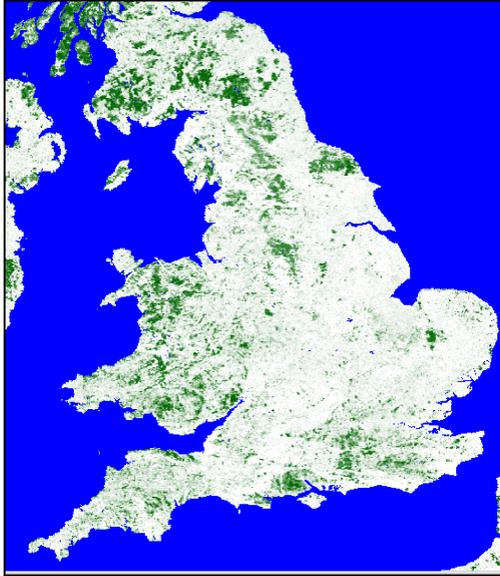
The MODIS VCF product⁵ is a global raster dataset of the proportion of forest cover within 500m grid cells. It is derived from an analysis of 250m/500m observations from the MODIS sensor onboard the NASA Terra and Aqua satellites.

³ <http://www.gvm.sai.jrc.it/glc2000/defaultGLC2000.htm>

⁴ http://www.lantmateriet.se/cms/files/pdf/pdf/geografisk_information/MMA_article_glc2000.pdf

⁵ <http://glcf.umiacs.umd.edu/data/modis/vcf/>

(a) MODIS VCF (Satellite)



(b) FR Woodland Survey (Ground monitoring)

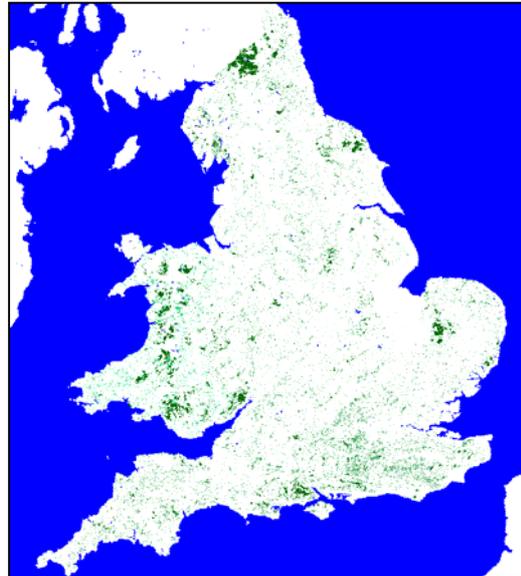


Figure 9-3 Forest Cover datasets

Comments on the datasets:

When grouped into plant functional types, the agreement between the two classification datasets (GLC2000 and LCM2000) is good, with maximum discrepancies around 5% (bare soil). What is more important for a study of this sort, however, is the impact of such discrepancies on the calculation of carbon fluxes. An initial examination of this is presented in Figure 9-4, showing the impact of the classification product used to be relatively small. This finding suggests that the GLC2000 product (or similar products) available should provide a suitable land cover classification scheme and accuracy to apply the methods developed here to areas outside of the UK (at least those of similar land cover types to the UK, e.g. Northern Europe).

Figure 9-3 shows a comparison of the Forest Cover datasets (MODIS VCF and Forest Research-Woodland Survey (FR)) over England and Wales. The correspondence between the two datasets is mixed – where the FR dataset shows forest, this is generally reflected in the VCF data product. The VCF product also shows significant areas of England and Wales classified as having a high proportion of forest cover where this is not the case (errors of commission). The total (England and Wales) forested area is calculated as 16.96 % of the land surface from VCF, but only 8.84 % from the FR data. A comparison with the other land cover datasets available suggests that the main misclassification comes from the VCF product giving areas of moorland as forest, an error likely to have a large impact on Carbon budget calculations. This suggests that the VCF product is not currently highly appropriate for the UK (or UK-like) land cover, although the findings here are being fed back to the product scientists with the aim of improving VCF in later versions. Attractive features of the VCF product (should it be reliable enough over areas of interest) are: (i) it is global; (ii) it can be updated year-on-year; (iii) it provides estimates of the proportion of forest cover within a pixel (rather than simply classifying a pixel as forest/non-forest).

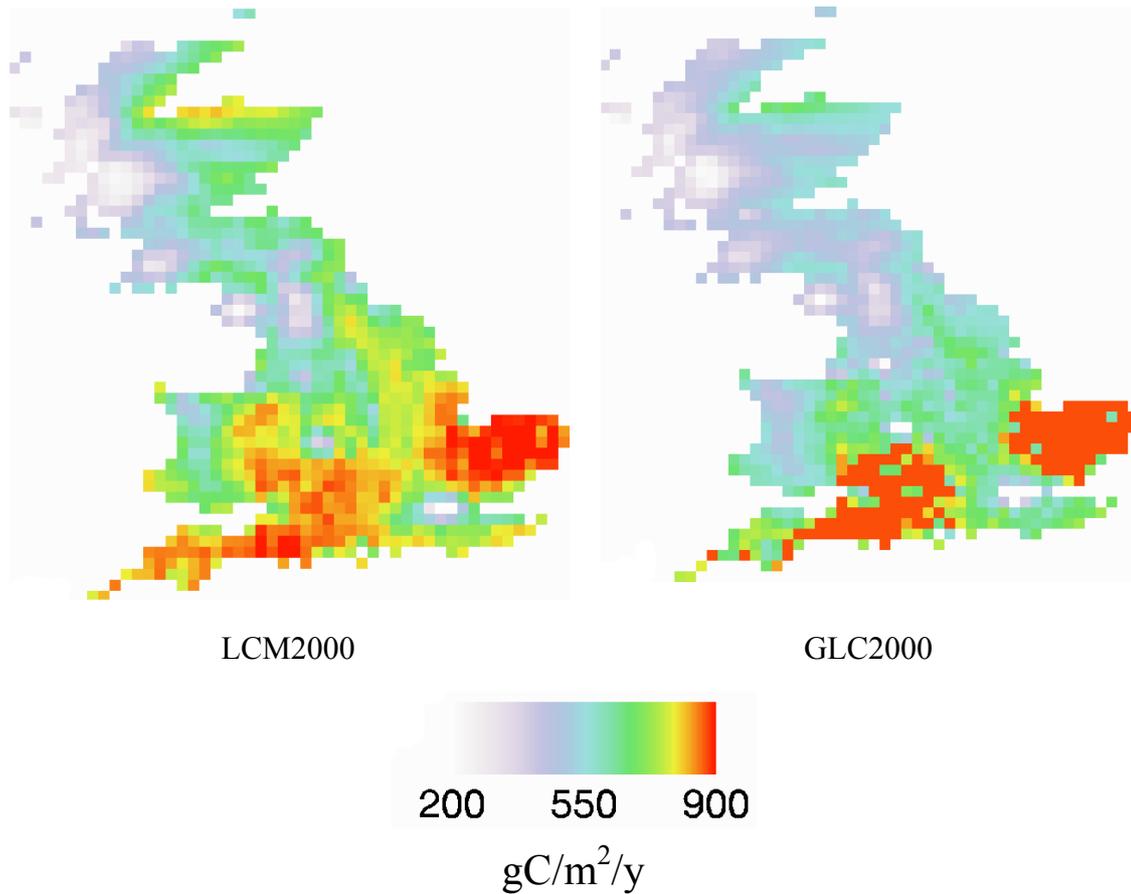


Figure 9-4 NPP predicted from SDGVM for the year 2000 using the LCM2000 and the GLC2000 land cover products. The results are in close agreement ($RMSE = 51 \text{ gC/m}^2/\text{y}$) suggesting that EO classifications are appropriate sources of land cover.

9.2.1.(b) Phenology

CTCD activities are providing phenology datasets based on RS observations. The method involves tracking a remote sensing measurement related to ‘greenness’ (the Normalised Difference Vegetation Index – NDVI, or similar) and detecting turning points in time series of data to relate to phenological events (budburst etc.). Figure 9-5 shows an example product over Great Britain for the year 2000, providing a spatial map of the timing (day of year) of ‘green-up’. Vegetation phenology is known to be an important factor in the error budget of vegetation model calculations, with phenology parameters used by SDGVM (see below) typically contributing at least 10 to 20% of the uncertainty in NEP calculations under UK conditions (CTCD uncertainty report⁶). Calibration of SDGVM phenology using RS observations should therefore reduce the uncertainty in SDGVM calculations by at least this amount.

Phenology datasets therefore form part of the core RS datasets to this project, although results using these data have not yet been factored into CTCD Carbon budget calculations. This is because several issues have arisen in trying to calibrate SDGVM with RS phenology over the UK, namely: (i) complications arising from the heterogeneity of the landscape (mixed cover types within a given pixel – see Figure 9-6); (ii) the large number of missed observations due to cloud cover over the UK, further compounding the mixed pixel issue; (iii) SDGVM does not currently have an adequate representation of crop phenology (anthropogenic factors such as planting date).

⁶ currently unpublished: examples presented in <http://www.shef.ac.uk/ctcd/science/uncertainty/emulators.html>

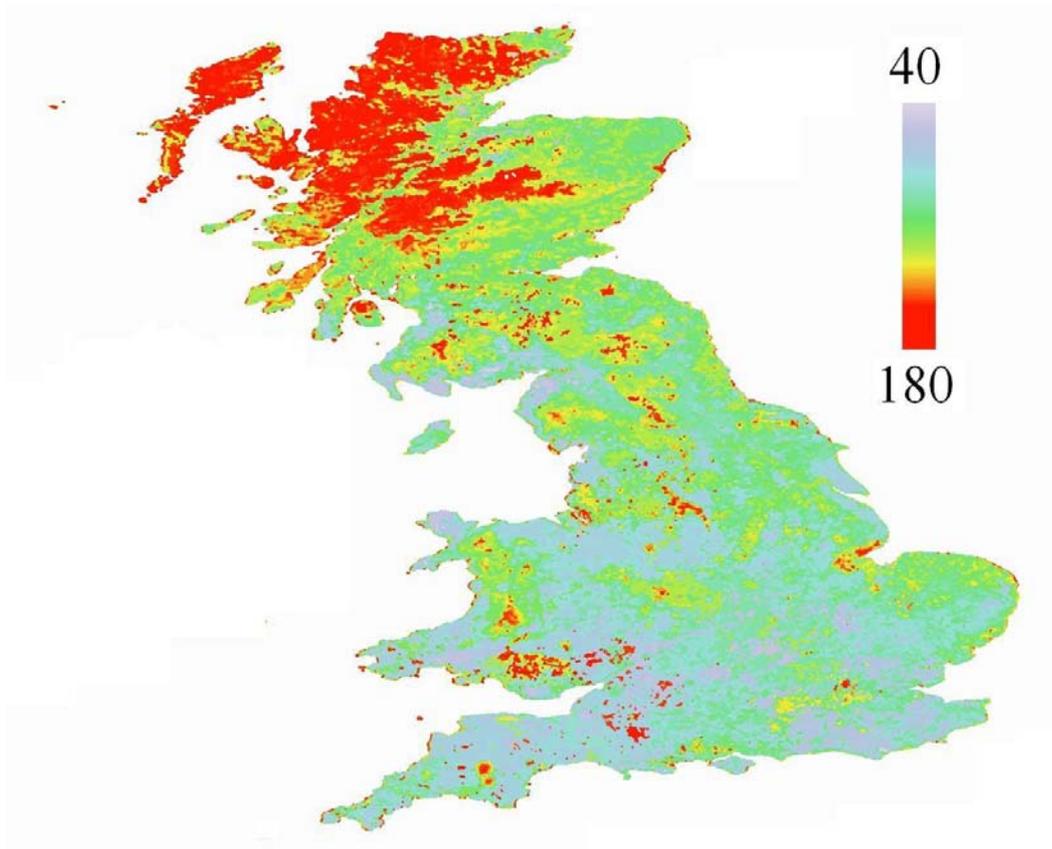


Figure 9-5 SPOT-VGT derived day of 'green-up'

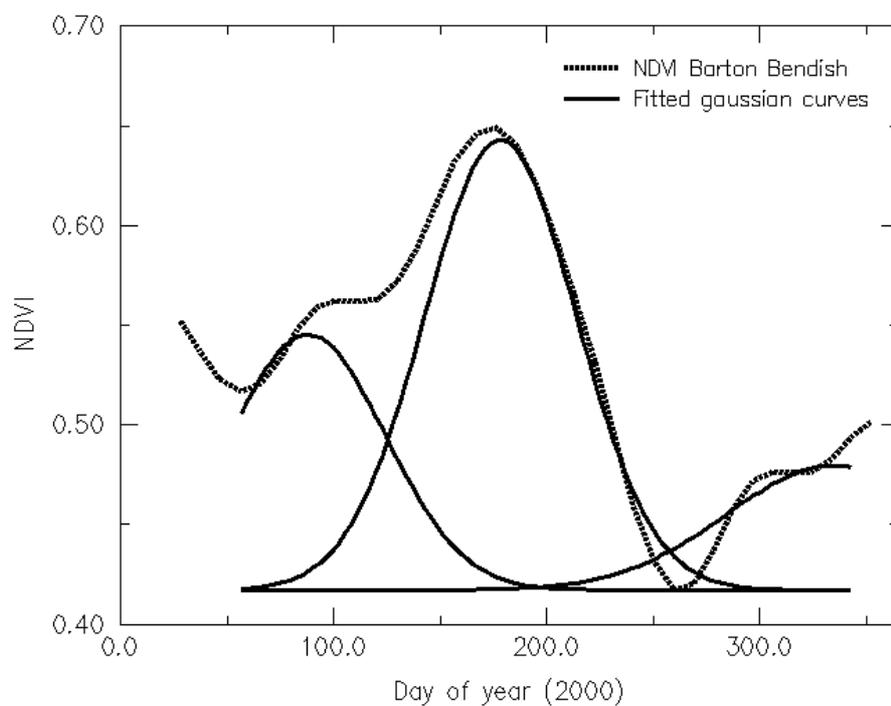


Figure 9-6 NDVI 1 km resolution signal over an agricultural site in East Anglia (Barton Bendish): The greenness signal (NDVI) shows clear evidence of contributions from different crop phenologies, complicating the extraction of individual phenological signals. We have been exploring ways of unmixing this signal (e.g. assuming a mixture of Gaussian curves), but this research has yet to yield robust measures.

9.2.1.(c) fAPAR

There is a strong relationship between RS measurements of vegetation indices (such as NDVI) and the fraction of absorbed photosynthetically active radiation (fAPAR). Many attempts at integration RS measurements with vegetation models have therefore used RS NDVI products to estimate fAPAR and drive production-efficiency-type vegetation models (PEMs) to provide estimates of biomass production. Note that the approach used in a PEM is rather different to that used in the models discussed below, which attempt to model physiological processes. However, fAPAR/PEM methods provide one more method for calculating carbon fluxes which should be considered for this interactive approach. As an example, Figure 9-7 shows annual NPP calculations (1/6th degree resolution) over the UK calculated by SDGVM (a process-based model described below) and the PEM approach driven by RS estimates of fAPAR ($r^2 = 0.44$, $\text{SDGVM} = 0.72 \text{ VGT} + 251.08 \text{ gC/m}^2/\text{y}$). Whilst there is broad agreement in some areas, there is a significant bias between these two estimates. Right now, we are unable to say which of these estimates is the more reliable, however, an integration of the various approaches, constrained by atmospheric measurements, should provide much better estimates of UK Carbon budgets, with known uncertainties.

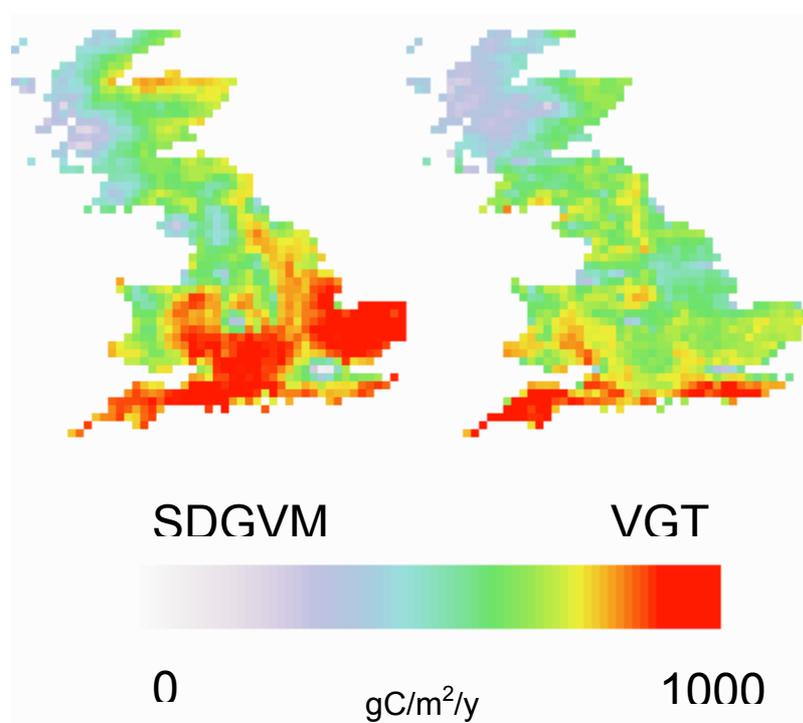


Figure 9-7 Annual NPP calculated from SDGVM (see below) and using a PEM driven by fAPAR data from the SPOT VGT sensor

9.2.2. Models and Flux data

There are three models in use in the CTCD.

(i) ForestETp developed by Sam Evans and colleagues at Forest Research is a forest stand model which models photosynthesis, respiration and translocation of carbon in the plant, and also decomposition of the soil organic matter produced, to yield the overall carbon balance (Net Ecosystem Production, NEP). The model has been completed in the last year and tested against various eddy covariance data sets. One of the longest data sets readily available is from southern

Finland (Figure 9-8) where the model is seen to fit the data very well. Moreover, water usage by real forests is also well matched by the model.

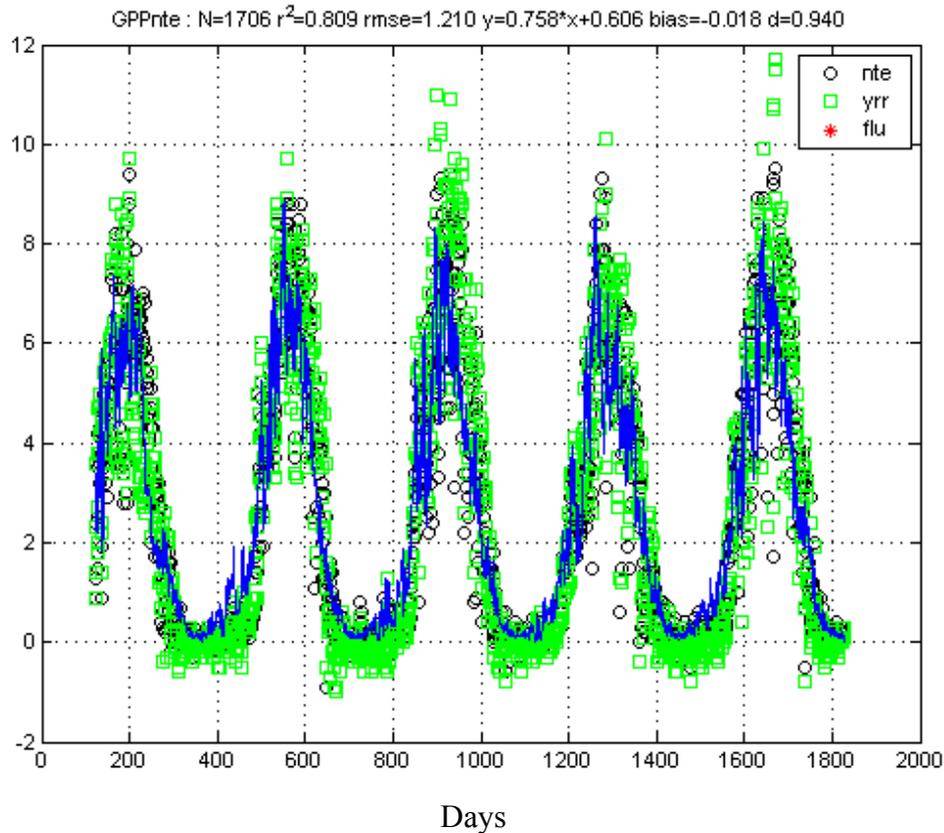


Figure 9-8 Comparison of the Gross Primary Productivity as calculated by ForestETp and as measured by an eddy covariance system at a forest in Hyytaila, Finland. Units are $\text{gC m}^{-2} \text{day}^{-1}$

(ii) **SDGVM** (Sheffield Dynamic Global Vegetation Model) developed by Ian Woodward, Mark Lomas and others at Sheffield, simulates vertical carbon and water fluxes for vegetation and is an example of a class of models which was developed to investigate longer term (years, decades, centuries) changes in the composition and biomass of vegetation which are associated with climate change (Cramer et al. 2001 *Global Change Biology* 7, 357-372). Equally well, the model may be 'spun up' and then used to estimate carbon and water fluxes over shorter periods (a year); and recent modifications in Sheffield have demonstrated that the model may be validated by referring to the water yields of a catchment. It provides a way to estimate carbon fluxes on a UK scale (Figure 9-9).

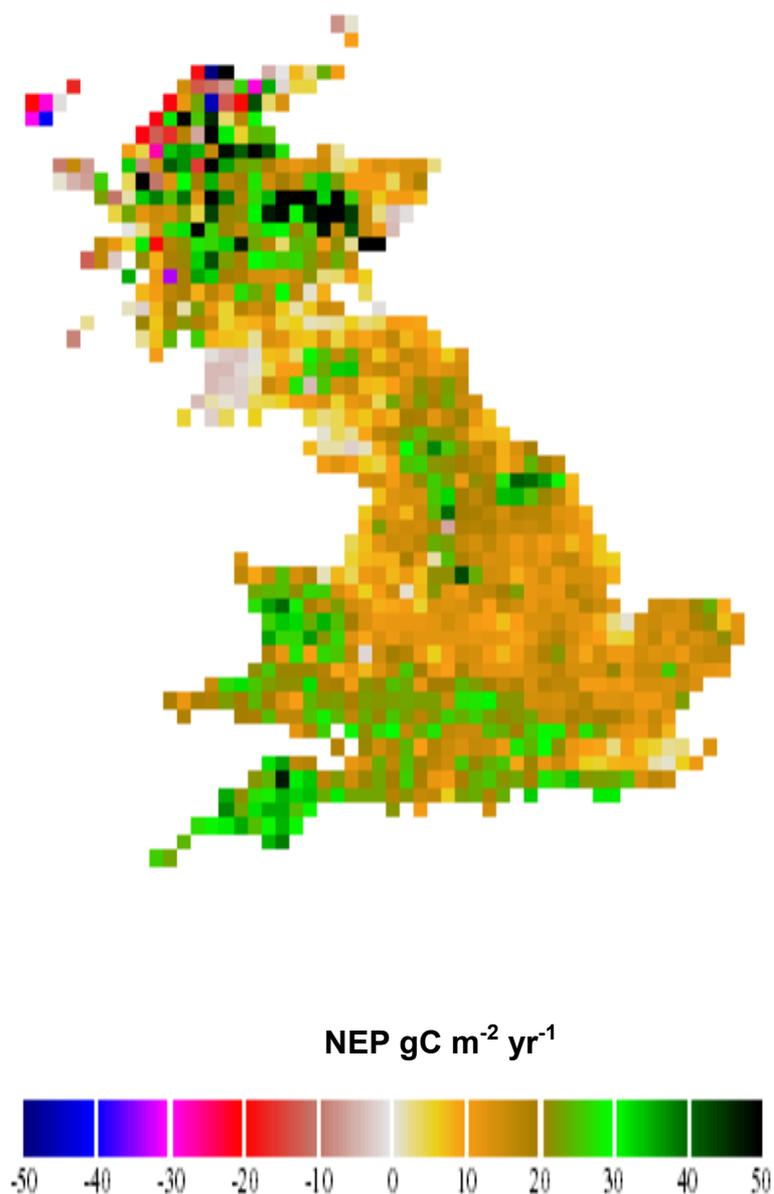


Figure 9-9 Net ecosystem production (NEP) as predicted by SDGVM where both the vegetation and the soil C model are run interactively; the model is initialised using the current land cover map and 1900-1920 climate in random order. The model is then run for the 20th Century initial results indicate the areas with greatest sequestration are the wetter zones of the country, characterised by more natural vegetation.

(iii) SPA (Soil Plant Atmosphere Model), developed by Mat Williams of the University of Edinburgh to link flows of water and carbon between the soil and the atmosphere at high temporal resolution. It is being calibrated in versions that correspond to different land covers: forest, agriculture, grassland, moorland. Already, SPA has been parameterised and tested for temperate deciduous and coniferous forest, tundra and rain forest making it one of the most comprehensively tested land surface simulators (e.g. Williams M et al. 2000 *Plant, Cell & Environment* 21, 953-968).

Flux data are used to validate these models. So far, models have been calibrated or verified against flux data from 15 Europe-wide forests in EUROFLUX, which are freely available at the CARBODATA web site⁷.

In CarboEurope-IP (started January 2004) there are far more flux towers: 16 flux towers within the UK/Ireland 'cluster', all measuring CO₂ fluxes more or less continuously. They cover representative land uses (Table 9-1), and will enable the models to be calibrated for land uses other than forests. Use of the data will require permission from the scientists involved, operating within the data policy agreement of their EU contracts. The models can be run without the validation steps but the results are more uncertain.

Table 9-1 Flux towers in CARBOEUROPE-IP which lie within the UK/Ireland cluster, and which will provide data for parameterisation of models

Name	Land use	Land cover	Lat (N) (degrees, min)	Long (W) (degrees, min)	Mean Temperature °C	Precip. mm	LAI
Griffin	Spruce	forest	56,36	3,47	8.2	1200	8
East Saltoun	Barley/grass	crop	55,54	2,51	8.5		
Harwood	Spruce	forest	55,14	2,06	9	950	12
Easter Bush	Grassland	grassland	55,52	3,10	8.0	890	
Auchencorth Moss	Blanket peat	grassland	55,46	3,16	7.4	900	
Carlow	arable	crop	52,51	6,54	5.5-13	804	0.6
Carlow	grassland	grassland	52,51	6,54	5.5-13	804	
Co. Laois	spruce	forest	52,57	7,15	5.5-13	804	
Wexford	grassland	grassland	52,17	6,30	7.2-13.8	1049	
Dripsey	grassland	grassland	51,55	8,45	5.3-13	1450	
Killorglin	bog	grassland	51,58	9,55	4.5-12.5	1450	
Pang/Lambourne	Arable	crop	51,32	1,29	9.2	800	0-5
Pang/Lambourne	grassland	grassland	51,32	1,29	9.2	800	
Pang/Lambourne	Broadleaved forest	forest	51,32	1,29	9.2	800	0-5
Hertfordshire	arable	crop	51,46	0,28	5.6-13.3	695	0-5
Hampshire	Broadleaved forest	forest	52,11	0,51	5.5-13	790	
Cirencester	arable	crop	52,42	1,59	5.6-13.8	786	0.5

9.2.3. Atmospheric data from tall towers

The European atmospheric data set comes from a network of 23 ground and tall towers, and consists of high resolution concentration measurements of GHGs and ²²²Rn (Table 9-2). There are two ways such data can be used. In the first method, one or two towers may be used in association with knowledge of the trajectory of air masses (Biraud S, Ciais P *et al.* 2002 *Tellus* 54b, 41-60). If the flux of ²²²Rn is constant over the land surface, and known, then it is possible to estimate the flux of any GHG from the concentration of that gas and the concentration of the tracer ²²²Rn, as Biraud *et al.* did. However, this method requires further development, as the emanation of ²²²Rn from the ground turns out not to be constant, but varies naturally with soil wetness and geological substrate. This variation is so great, that the method as it stands may not be reliable. The alternative method, as adopted by CARBOEUROPE-IP, is to utilise *all the available stations*, and using an atmospheric transport model, to infer the spatial pattern of sources and sinks of GHGs. This approach has been pioneered by Phillippe Ciais (Le Laboratoire des Sciences du Climat et l'Environnement, Paris).

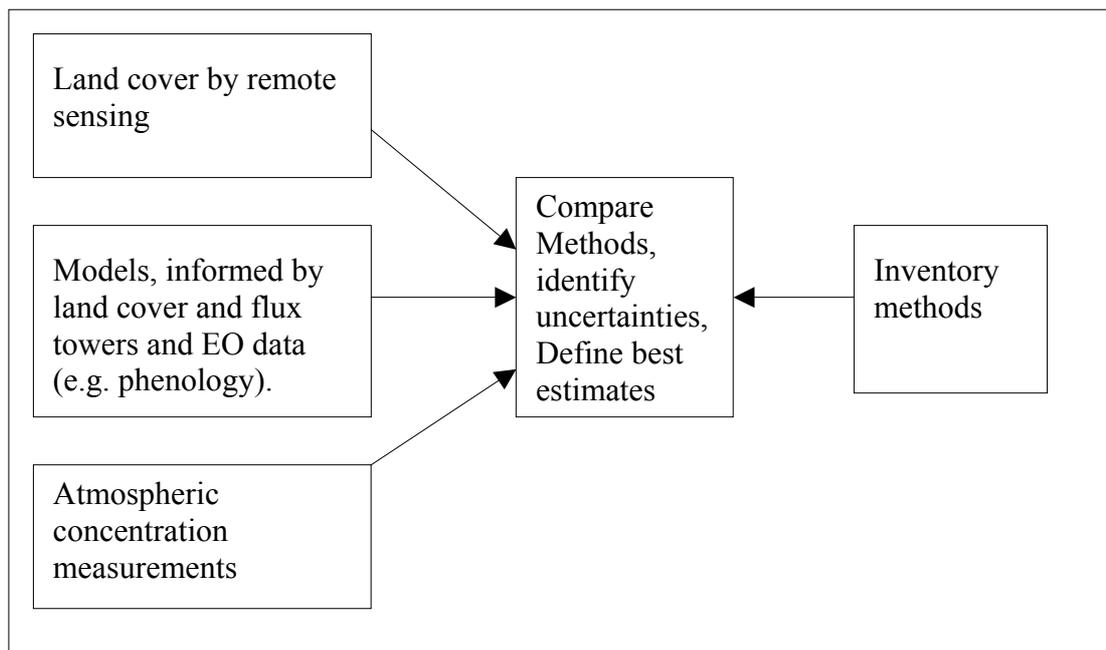
⁷ <http://www.bgc-jena.mpg.de/public/carboeur/projects/cda.html>

Table 9-2 European sites from which we expect concentration measurements to be available (from CARBOEUROPE-IP), for CO₂, N₂O and CH₄, and sometimes ²²²Rn. These are tall towers of samples on the coast or highlands, remote from pollution sources.

Site name	Lat (N) (degrees, min)	Long (degrees, min)	country	notes
Mace Head	53,19	9,53W	IRL	Includes ²²² Rn
Zeppelin	78,54	11,53E	NW	Includes ²²² Rn
Lampedusa	35,31	12,38E	I	CO ₂ only
Puv de Dome	45,45	3,00E	FR	Includes ²²² Rn
Schauinsland	47,55	7,55E	D	Includes ²²² Rn
Monte Cimone	44,11	10,42E	I	Includes ²²² Rn
Plateua Rosa	45,56	7,42E	I	CO ₂ only
Jungfraujoch	46,33	7,59E	CH	Includes ²²² Rn
Lutiewad	53,23	6,22E	N	Includes ²²² Rn
Westerland	54,56	8,19E	D	Includes ²²² Rn
Kasprowy Weirch	49,14	19,56E	PL	
Palas	67,58	24,07	FIN	Includes ²²² Rn
Cabauw	51,58	4,55E	NL	
Orleans	47,58	2,06E	FR	Includes ²²² Rn
Ochsenkopf	50,09	4,52E	D	
Bialystok	53,20	22,75E	PL	
Angus	55,57	3,13E	UK	Includes ²²² Rn
Hegyhatsal	46,57	16,39E	HUN	
Firenze	43,48	11,12	I	
Norunda	60,05	17,28	S	
La Muela	41,35	1,50	ES	CO ₂ only
Labouhevre	44,12	0.54	FR	CO ₂ only

9.3. Strategy to obtain best estimates of the C-budget of UK

We have outlined several approaches towards obtaining the C-budget of the UK. These approaches are all actively being developed and can be combined to provide a best-possible estimate. Over time, as the uncertainties will be reduced by refinements in models and observation, we would expect convergence of the separate estimates:



To achieve this scheme, there are a few institutional barriers to be overcome, relating to data availability from the numerous institutes and research consortia wherein they reside. In the Centre, progress made in modelling has been strong, but to properly implement C-flux calculations we do need to link with soil models being developed elsewhere. Priorities for the next period are therefore:

- (i) discussions with research colleagues regarding availability of results from atmospheric models which infer sinks from concentrations (this work is being done at the Laboratory of Climate and Environmental Sciences, Paris and the Max Planck Institute in Jena)
- (ii) further development of models, especially in relation to ecosystem respiration.

The optimal method of combining the separate measurements (i.e. the tower and EO estimates of Carbon fluxes from PEMs) is to assimilate them into models. This, however, relies on good knowledge of the errors present in both the data and requires additional model development to be undertaken. To assimilate the tall tower measurements it may also be necessary to work at the European level to ensure sufficient data.

9.4. Acknowledgements

The authors wish to acknowledge the input of the members of the CTCD, in particular Shaun Quegan, Mark Lomas, Ian Woodward, Ghislain Picard, Sam Evans, Sebastien Lafont, Mat Williams, Jennifer Pellenq and Caroline Nichols.

A: Appendix 1: Expected precision of measurements from tall towers

Expected precision of the analytical methods in relation to the resolution of the available instruments is given in the table below. We calculate the change in concentration ΔC likely to occur when the air flows across 500 km of landscape at a speed of 5 m s^{-1} with a planetary boundary layer of depth 1 km.

Gas	Typical flux	Reference	Expected ΔC (units)	Instrument Resolution
CO ₂ ^A	$1.8 \mu\text{mol m}^{-2} \text{ s}^{-1}$	Salway et al. (2002)	3.6 ppm	0.15 ppm
CO ₂ ^B	$3 \mu\text{mol m}^{-2} \text{ s}^{-1}$	Valentini et al. (2000)	6.0 ppm	0.15 ppm
CO ₂ ^C	$8 \mu\text{mol m}^{-2} \text{ s}^{-1}$	Valentini <i>et al.</i> (2000)	16 ppm	0.15 ppm
CH ₄	$29 \text{ nmol m}^{-2} \text{ s}^{-1}$	Salway <i>et al.</i> (2002)	58 ppb	3 ppb
N ₂ O	$0.6 \text{ nmol m}^{-2} \text{ s}^{-1}$	Salway <i>et al.</i> (2002)	1.2 ppb	0.1 ppb
²²² Rn	$4.7 \text{ mBq m}^{-2} \text{ s}^{-1}$	Robertson <i>et al.</i> (2002)	470 mBq m^{-3}	20 mBq m^{-3}

A, anthropogenic flux; **B**, biogenic (net ecosystem exchange) flux at night in summer; **C**, biogenic flux at noon on a sunny day in summer.