Section 5

Estimating Biogenic Carbon Fluxes over the UK

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5. Estimating Biogenic Carbon Fluxes over the UK

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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.

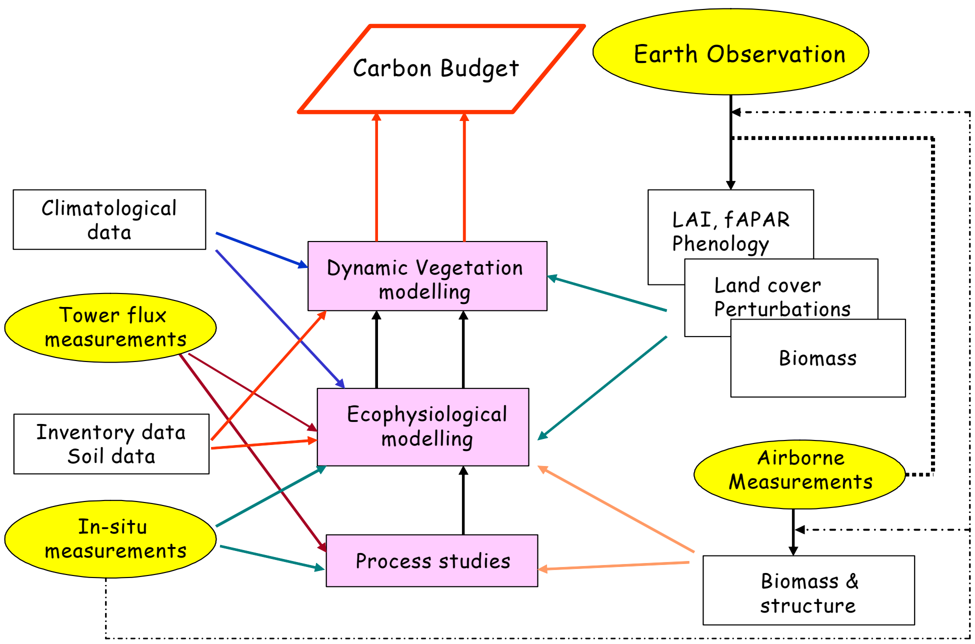


Figure 5-1 The inter-linking of models and measurements within the CTCD. Threaded through the whole structure is characterisation of uncertainty and its consequences.

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.

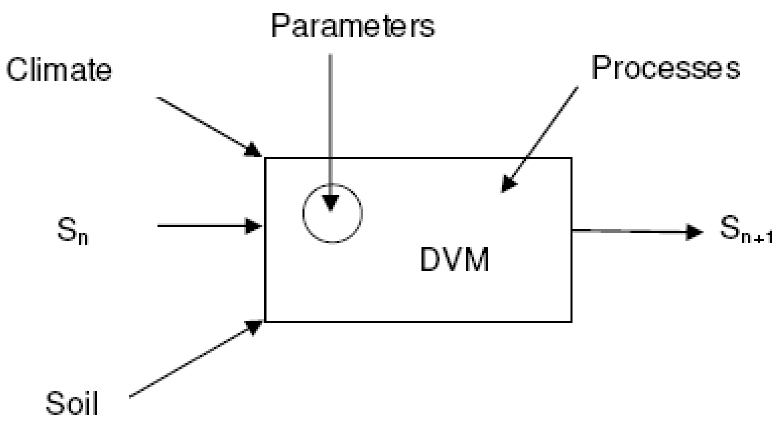


Figure 5-2 Essential structure of how the state space evolves in the Dynamic Vegetation Model.

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).

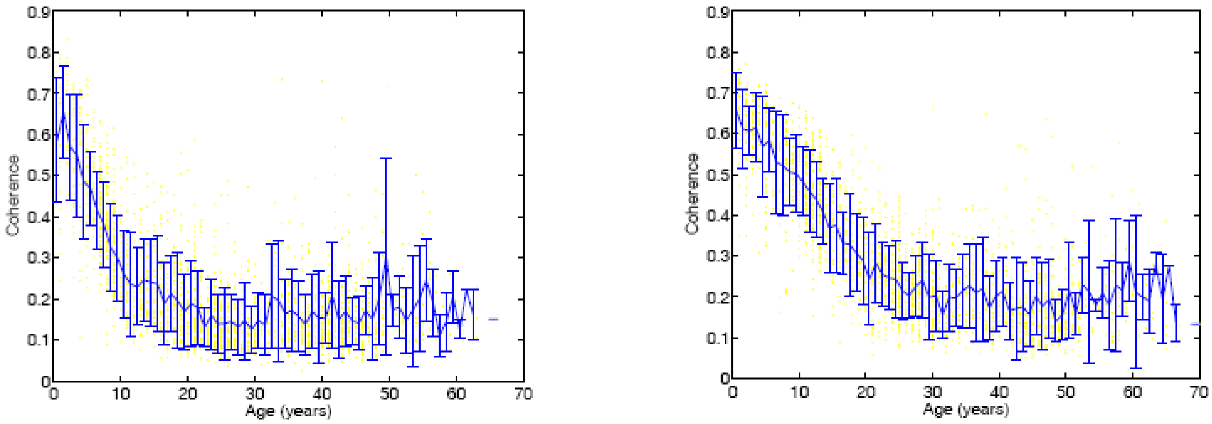


Figure 5-3 Radar remote sensing may be used to detect the age of a forest up to a saturation level. Plot of age versus 'Tandem Coherence' obtained by Synthetic Aperture Radar for Sitka spruce in Kielder forest in July 1995 (left) and August 1999 (right). From Drezet & Quegan, IEEE Trans Geosci. Remote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

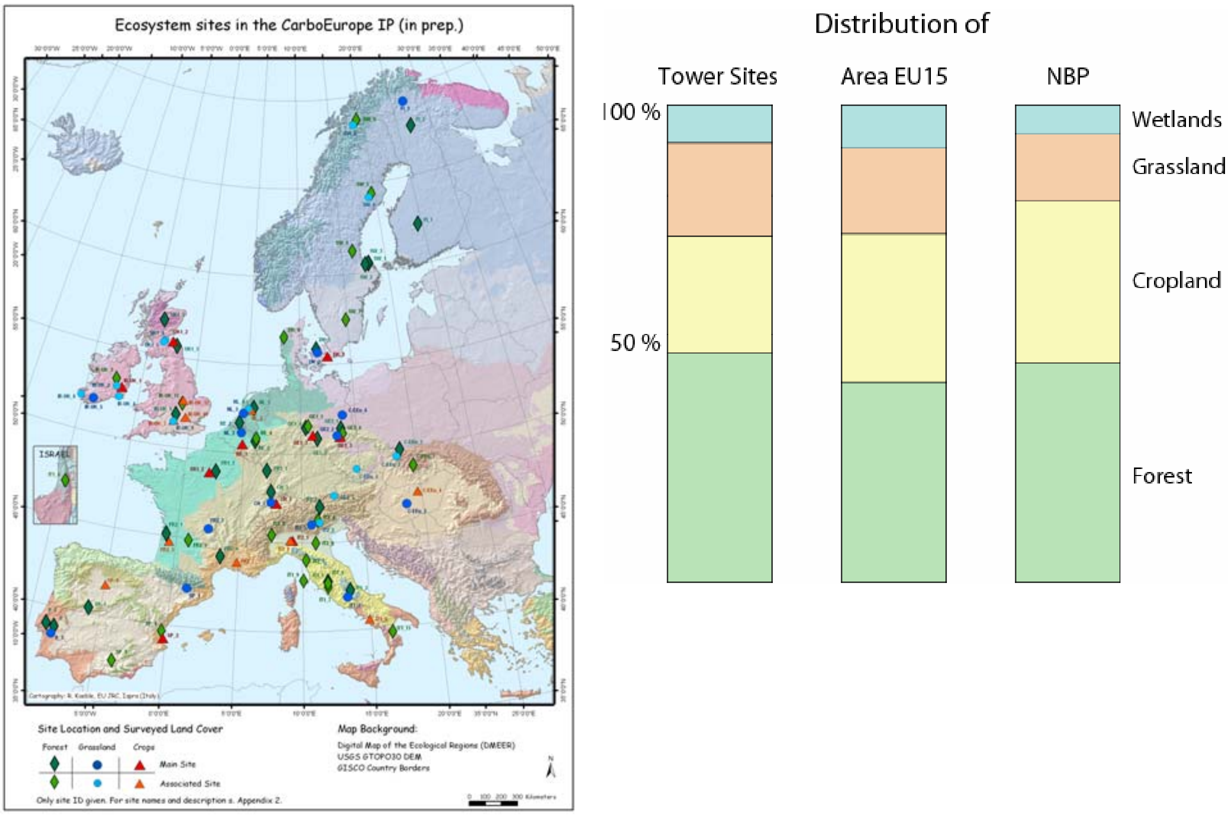


Figure 5-4 Distribution of Carboeurope-IP flux stations (forests, green diamonds; grasslands, blue circles; crops, red triangles). The histogram bars show the fractional distribution of stations numerically (left bar) and the distribution of European land area and biological production between wetlands,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

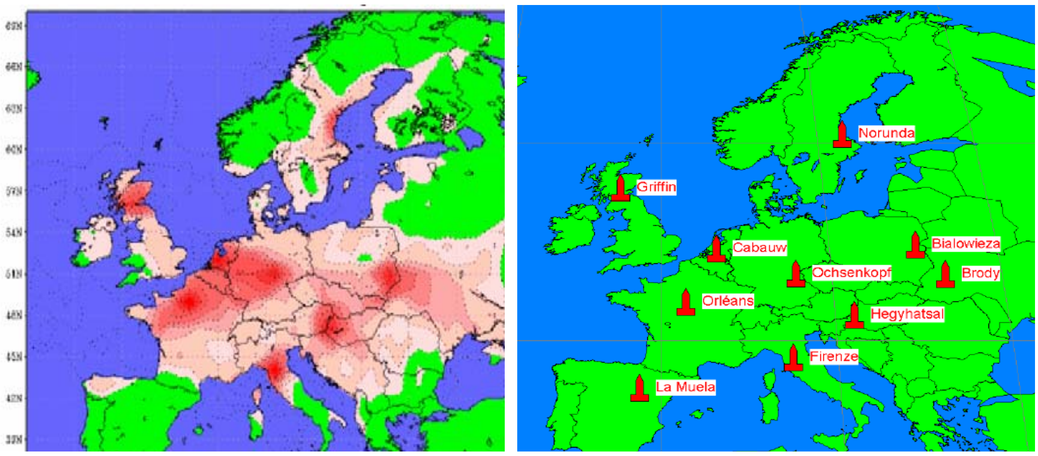


Figure 5-5 Coverage of Europe by the Carboeurope system of tall towers. Tall towers 'see' the signal from about 100 km around them as an increase or decrease in concentration. Note the coverage of the northern part of GB by the tower in Fife Scotland and the weaker coverage of the southern part of UK, 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.

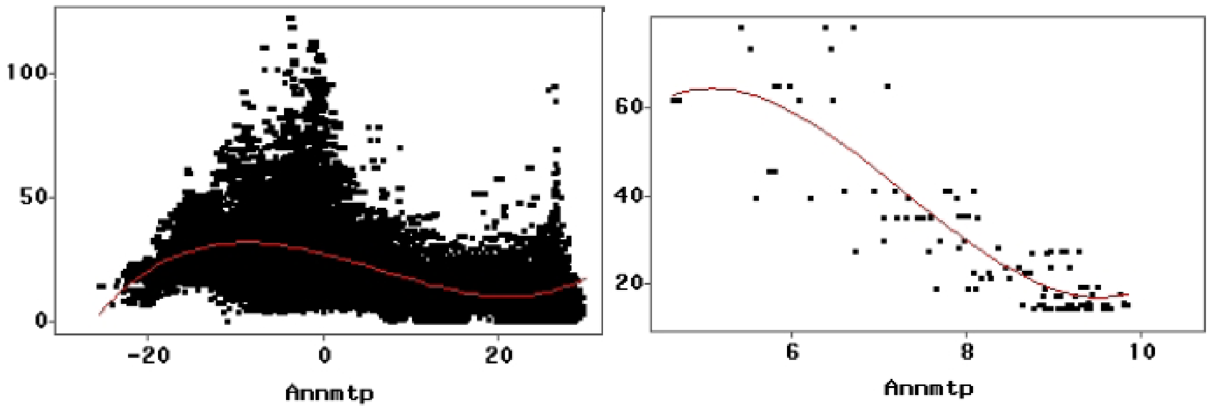


Figure 5-6 Relationship between soil carbon (kg m^{-2}) and annual mean temperature (Celsius). Soil is to 150 cm in depth and data are ISLSCP II. The graphs show global relationships (left) and UK relationships (right).

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.

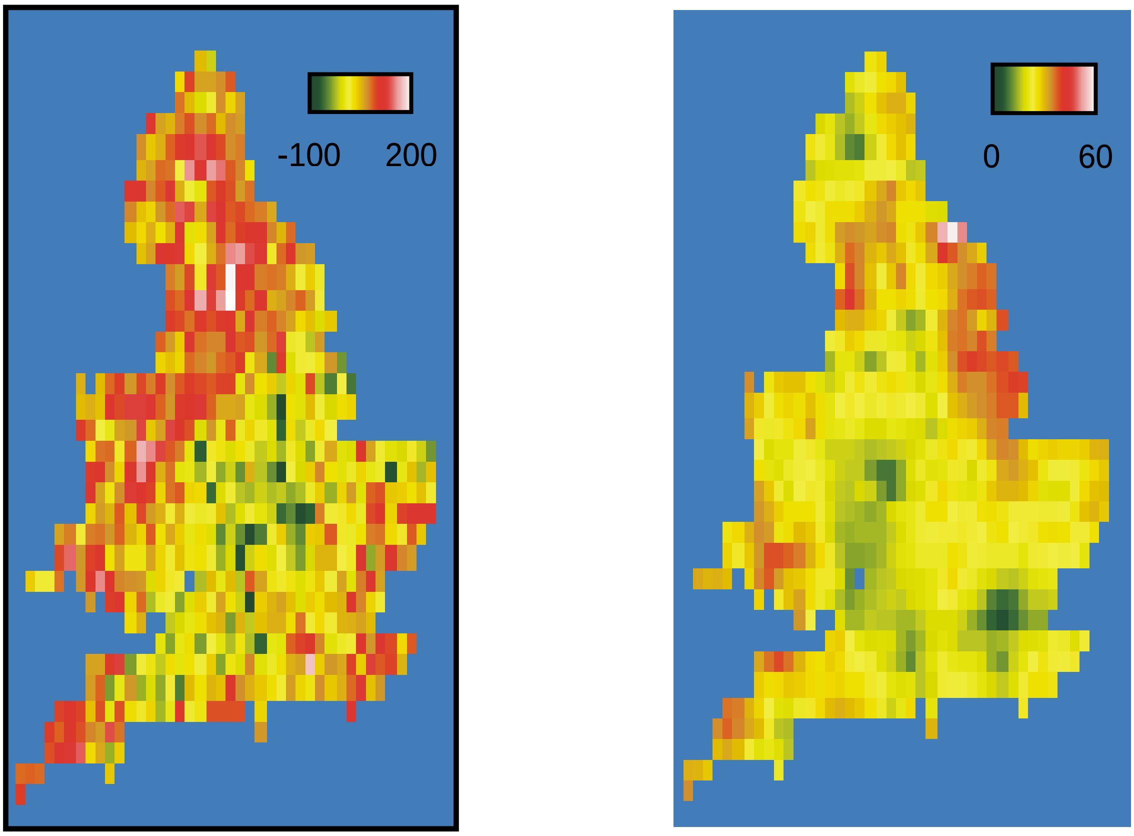


Figure 5-7 Maps of (left) best estimates of the biogenic uptake of CO_2 for England and Wales for 2000 (C-sinks are shown as positive and sources are negative) and (right) the standard deviation of the estimates, arising from uncertainty in the Plant Functional Types and soil parameters. The units are 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.

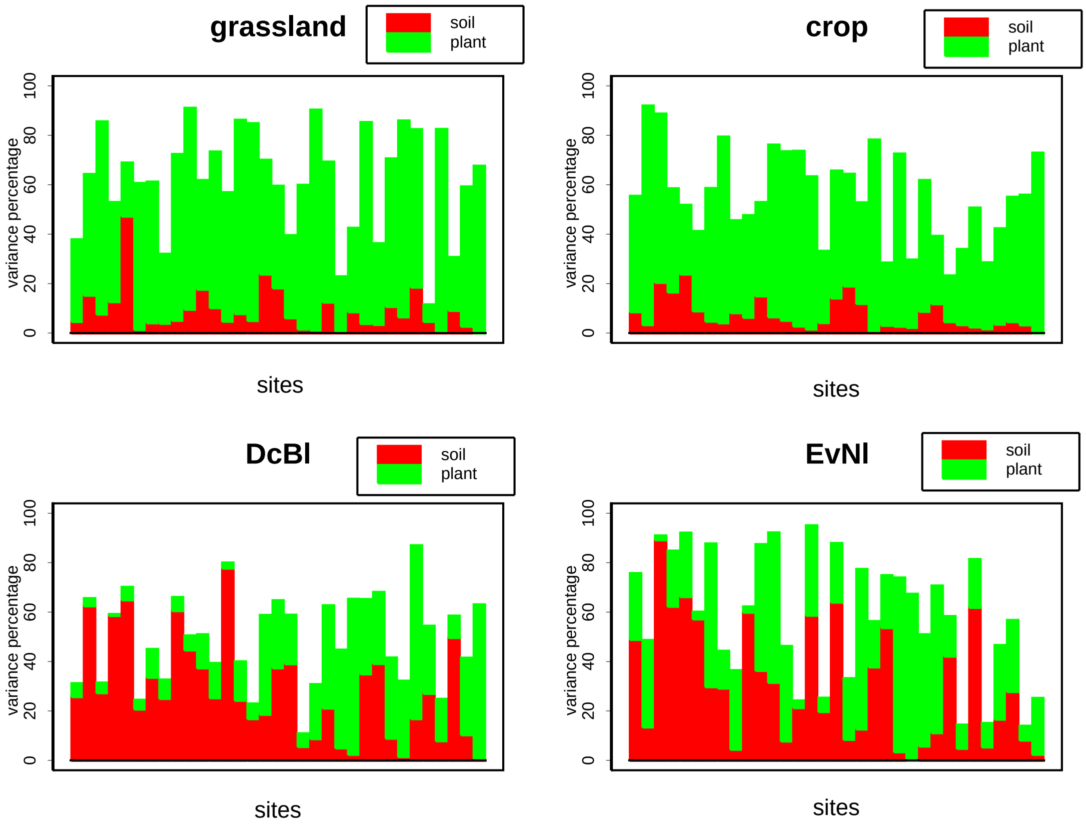


Figure 5-8 Percentages of uncertainty in NBP output from SDGVMd (for grasslands, croplands, Broadleaved Trees and Evergreen Trees) at 33 test sites due to PFT parameter uncertainty (green) and soil parameter uncertainty (red). Note that these do not sum to 100% because of interaction effects.

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:

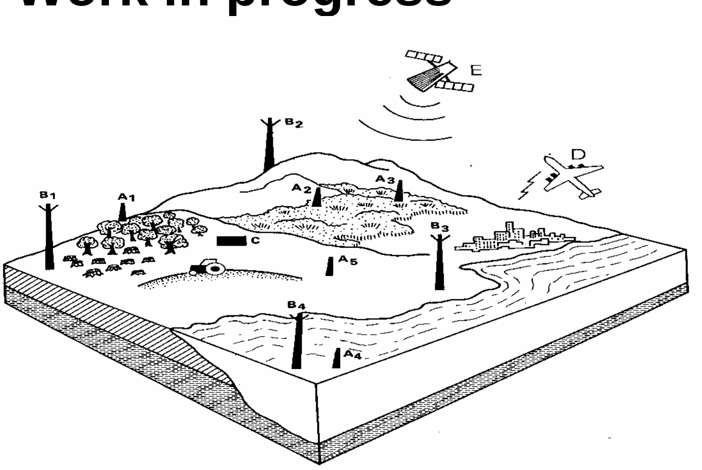
1. In the UK we are fortunate to have an excellent map of land cover (through the CEH Countryside Survey and Land Cover Map 2000) which is due for an update soon. We have shown that using moderate resolution satellite-based land cover products leads to biases in estimates of the UK net carbon uptake, 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

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