Section 7

Estimating Biogenic Carbon Fluxes from Flux tower measurements and Earth Observation data

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7. Estimating Biogenic Carbon Fluxes from Flux tower measurements and Earth Observation data

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7.1. 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 7-1, 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.

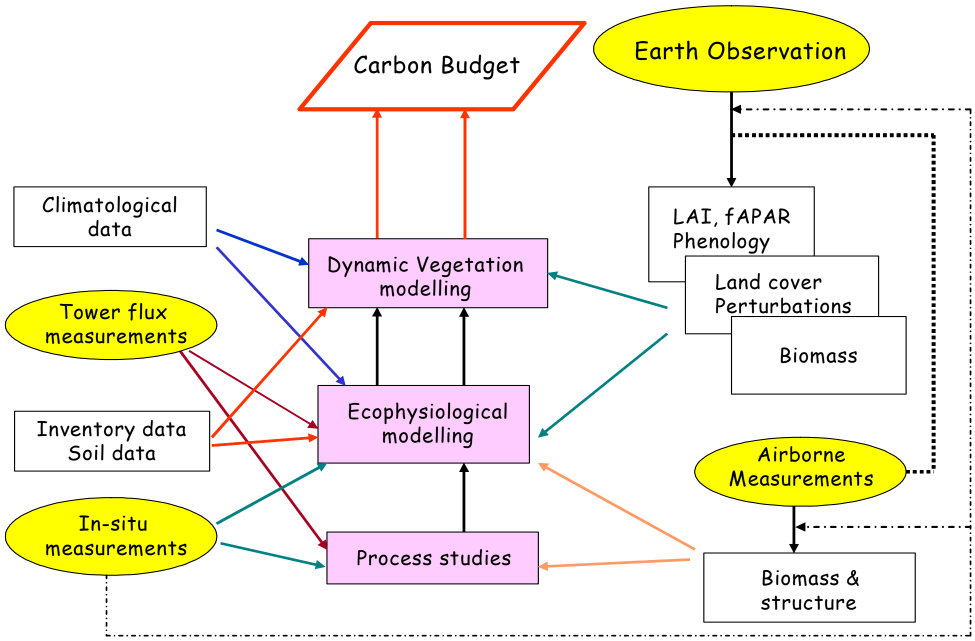


Figure 7-1: The inter-linking of models and measurements within the CTCD. Threaded through the whole structure is characterisation of uncertainty and its consequences.

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 fluxes based on three different methods.

7.2. Models and model testing

Three models to calculate carbon fluxes are in use within CTCD: SDGVM (Sheffield), SPA/DALEC (Edinburgh) and ForestGrowth (Forest Research). Tests of the models against CO_2 flux data were presented last year in our Annual Report.

SDGVM has been the main workhorse around which uncertainty methodology has been developed and tested; it has provided simulations in steps towards data assimilation and for comparison with EO models for global primary production; it has also been used to calculate uncertainty associated with simulating vegetation phenology; and it has been used in investigations of uncertainty raising from soil carbon parameters and the temperature responses of soil respiration.

SPA/DALEC is the central model for data assimilation, providing a method for spatial extrapolation and process investigation of CO_2 flux observations from flux towers.

ForestETP and **ForestGrowth** are detailed and site-specific Forest Research models used in quantifying how process generalisations in SDGVM and other models affect the reliability of the calculations. Their calculations provide critical comparisons with CO_2 flux calculations by SDGVM and SPA, and they are also the appropriate models for studying the effects of forest management on carbon dynamics. ForestGrowth provides simulations of detailed site-specific CO_2 exchanges of trees and forests suitable for driving and developing process-based soil models. In addition, ForestGrowth 3-D, with its description of dynamic canopy architecture as a function of radiance, competition and growth can and will be run to simulate radiance for comparison with EO data.

A key development has been to demonstrate that readily-available information on run-off can reduce the uncertainty in carbon flux calculations. First of all, simulated monthly and annual stream flows for the catchments were compared with long time-series observations for 29 large catchments in the United Kingdom. Figure 7-2 compares simulated stream flow by SDGVM with observations for four of these catchments ranging in annual precipitation. In 23 out of the 29 catchments, the bias between model and observations was found to be less than 10% of precipitation. In the remaining catchments, larger errors are due to unpredictable causes, in particular various human activities and measurement issues; in two cases, the causes were unidentified. Hence overall the hydrology module in SDGVM was confirmed to work reliably in the UK.

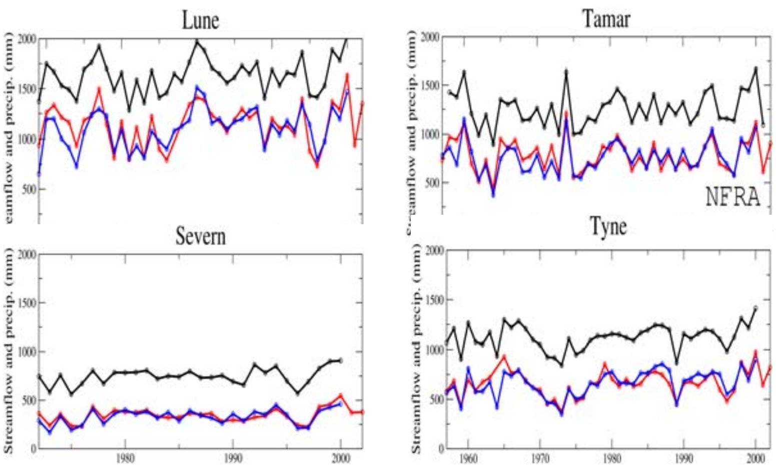


Figure 7-2: Plots of observed annual stream-flow (red line) and annual stream flow simulated by the SDGVM (blue line) using CRU climate data or NFRA climate data (NFRA is printed on the plot). Annual precipitation (black line) is also shown

While SDGVM is a generalised model designed for regional scale simulation, ForestGrowth is designed to simulate the dynamic growth of trees in semi-natural and managed landscapes, particularly at individual and stand scale, and uses species rather than the plant functional types of SDGVM. The soil-vegetation-atmosphere transfer (SVAT) model (ForestETP) at the core of ForestGrowth predicts transpiration, evaporation, the vertical and lateral water movement through the soil-plant-atmosphere continuum and gross primary productivity. This SVAT model has been extended to account for the effects of topography and the heterogeneity of surface properties on the water and carbon budget, and the impact of land cover and land change on catchment discharge. This makes it possible to simulate and partition the sub-daily and aggregated dynamics of water flow.

The ForestGrowth model is currently being integrated with the Century soil C-N biogeochemical model to allow a full assessment of C stocks and fluxes accounting for catchment hydrology, including the impacts of both climate change and N deposition on growth dynamics, and their effects on water quality and quantity at the catchment scale.

A key point of these detailed and site-specific Forest Research models is that they allow us to quantify how process generalisations in SDGVM (and other models) affect the reliability of the calculations. They are also the appropriate models for studying the effects of forest management on carbon dynamics.

One of the greatest difficulties, in modelling the carbon fluxes over forests, is the problem of accounting for age-related effects resulting from forest management. Information on the age structure of plantation forest can be inferred from ERS Tandem coherence, particularly the younger stands. The relation between age and coherence varies with weather conditions, and the SPA model was coupled with a simple scattering model to explain the temporal behaviour of coherence; the variation was reasonably well explained but not the magnitudes. This analysis showed that the high variability of the water content of the canopy makes a model-based inversion of coherence to age very unreliable, and forces a fall-back onto empirical methods. These were applied to 1995 data for the UK, where we have very good forest age information from Forest Research with which to calibrate the inversion. NEP varies strongly with age for younger stands, then becomes stable; this behaviour is matched to the age sensitivity of coherence. Coherence was used to produce estimates of the age structure and NEP from all UK forests (Forest Commission and private). The results indicate significantly different age structures between Wales and the rest of the UK, and significantly larger values of NEP than are produced by inventory methods. Jointly with Gamma Remote Sensing, we have assessed and compared the ability of L-band radar (JERS) and coherence to detect clear-cut. Accuracy levels are around 90% for both techniques. Three papers on measuring forest age and clear-cut using have been submitted.

7.3. Influence of land cover parameterisation

Our models currently impose an externally provided land cover, typically derived from EO observations, to constrain the proportion of Plant Functional Types (PFTs) within a given area. The unavoidable errors in such land cover maps introduce uncertainty into model calculations. The aims of this work-package are (i) to develop methods for assessing the uncertainty in model-predicted C budgets due to uncertainties in the land cover data; (ii) to assess the associated uncertainty, initially for the UK, then Europe, then globally.

Generic methods have been developed for this type of assessment and have been used to provide uncertainties in carbon fluxes (GPP, NPP and NEP) over the UK. The concept is very simple. For fixed land cover, the PFTs do not compete. Hence the SDGVM can be run over the region of interest populated with a single PFT. The calculation for a given land-cover then just involves linear summation of the estimated flux for each PFT, weighted by the proportions of each PFT in a grid-cell. This approach allows quick calculation of the effects of uncertainty in land cover on

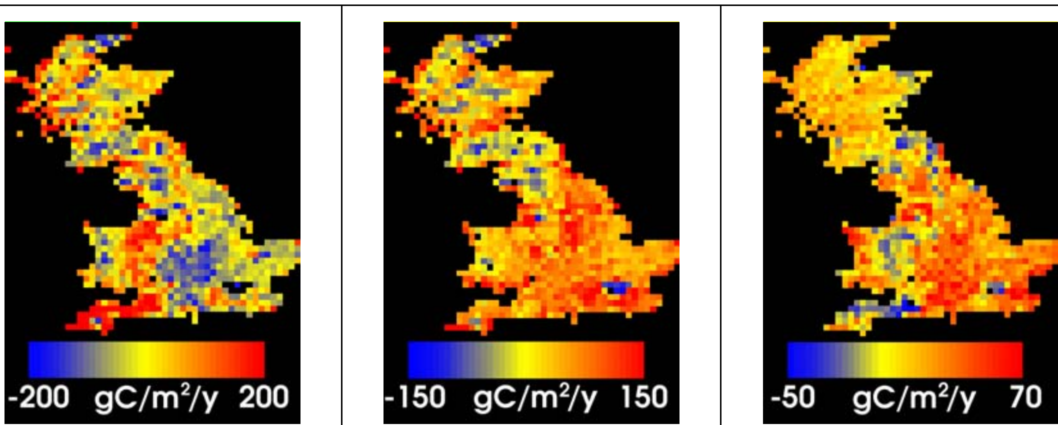
C fluxes. For the UK, the uncertainty in GPP is estimated using a high spatial resolution land cover map (LCM2000), an independent assessment of the error in LCM2000 (a 'confusion matrix'), and a coarser spatial resolution global land cover map (GLC2000).

Figure 7-3 shows the differences in flux estimates between the GLC2000 and the LCM2000 for the UK. Positive values (red) indicate an overestimate by the GLC2000. The mean difference in GPP for the whole of the UK is close to zero, but there is a strong positive bias in the estimates of NPP and NEP derived from the GLC2000. Table 7-1 shows the mean UK fluxes derived from the two different data sets.

Many of the discrepancies between the two data sets can be explained by the effects of heterogeneity. The base resolution for the GLC2000 is 1 km whereas the LCM 2000 is a 25 m product and thus capable of describing much greater levels of complexity in the landscape. Flux in urban areas, for example, is always lower using GLC2000 than when using LCM2000, because far fewer urban green spaces are represented at the 1 km scale.

The main generic result is that the impact of uncertainty in land cover depends on how strongly the fluxes of the individual PFTs differ. For example, the GPP of crops and C3 grasses are normally very different (C3 grasses tend to have a higher GPP). Thus large uncertainties in land cover maps between these two PFTs will have a strong impact on overall uncertainty. This is especially important because the spectral signatures of these cover types are similar and are thus likely to exhibit a high degree of confusion in EO-derived land cover maps.

A journal paper for submission to Remote Sensing of Environment is nearly completed.



(a) ΔGPP	(b) ΔNPP	(c) ΔNEP

Figure 7-3: Differences in carbon fluxes calculated using the LCM2000 and the GLC2000. Areas in red are where the GLC map overestimates the flux and blue where it underestimates it in comparison to the LCM2000. Yellow denotes areas are where there is only a small difference.

Table 7-1: Mean carbon flux for UK in the year 2000 derived using the LCM2000 and GLC2000 land cover data sets.

	GPP (gC/m^2)	NPP(gC/m^2)	NEP(gC/m^2)
GLC2000	1302.73	850.93	138.37
LCM2000	1290.17	800.08	119.16

7.4. Data assimilation

Our critical achievement this year has been the publication of the first paper to demonstrate how C flux and stock data can be assimilated into a terrestrial C model. We used the Ensemble Kalman filter with a simple C box model, and pool and flux observations, to generate improved estimates of C dynamics for a pine stand in Oregon, USA (Williams *et al.*, 2005) . We also showed how the assimilation of photosynthesis observations, which can be derived from EO data, generates a measurable and important reduction in error bars on the estimates of net ecosystem exchange (Figure 7-4).

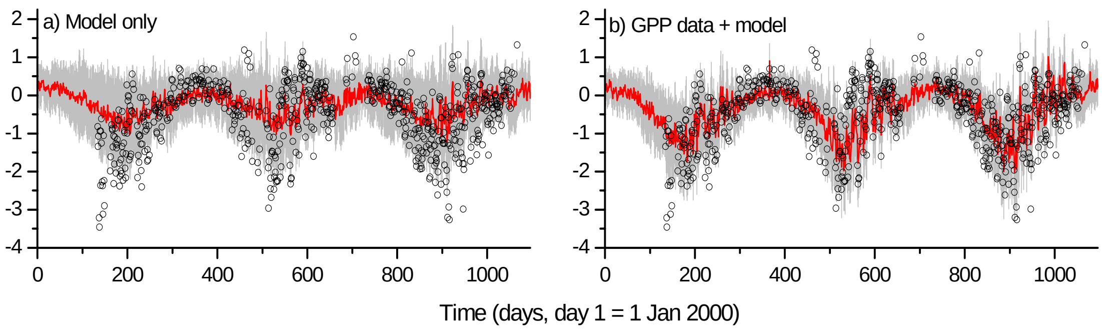


Figure 7-4: The panels show daily analyses (red lines) over three years of net ecosystem carbon exchange (NEE) for a young ponderosa pine stand in central Oregon. These were generated using (a) model only, no observations; b) model plus GPP (derived from sap flow data) estimates only. NEE observations from an eddy flux station are shown as open circles. Grey lines indicate the standard deviation around the mean of the ensembles used in the data assimilation.

We know from experimental data that the pine stand is drought stressed during late summer. The box model used in the DA scheme did not relate photosynthesis to soil moisture, which forced shedding of leaf area in the summer to reduce photosynthesis, in line with the alteration in the flux data. We were able to identify this inconsistency because leaf area data contradicted this change. Consistency checking of this type is a key strength of DA. To overcome this drought problem, we have constructed a new version of the DALEC model with coupled carbon and water fluxes (Figure 7-5). The coupled model has been tested over three years at the pine site, and produces realistic simulations of the development of drought stress (Schwarz *et al.*, 2004). However, the lack of a snow model in DALEC causes some inconsistencies, and we are now investigating a simple snow model. Once complete, DALEC will be a globally applicable, simple, coupled C-water model that can be used in the twin experiment. The advantage of DALEC is that the majority of its state variables are simply related to observations, meaning that it is optimally constructed for use in assimilation schemes.

To predict photosynthesis (GPP) and evapotranspiration (ET), the DALEC model uses components called emulators, which are constructed from the detailed SPA model. Using a tested aggregation scheme (Williams *et al.*, 1997) we have generated simple flux emulators of daily GPP or ET, dependent on daily drivers. These emulators are useful because they have reduced driver requirements and are 3-4 orders of magnitude faster than SPA. The emulators allow us to include realistic representations of the multi-dimensional response surfaces of GPP and ET.

Other progress has been an exploratory coupling of the SPA model with a model of the planetary boundary layer. This will allow us to test the consistency of flux data at the land surface with measurements of CO_2 concentration from tall towers or aircraft, and is a first step in being able to assimilate concentration data. In preparation for the regional assimilation experiment in central Oregon, we have begun to assemble and generate the relevant spatial data sets. This is an area with a rich array of flux towers, stand-level surveys and EO data, spanning a major precipitation gradient, and with significant fire disturbance, so an ideal test arena for our DA scheme. Finally, we are using frequency domain analysis of the DALEC model to determine the necessary sampling rate for effective data assimilation (i.e. how often and over what period should observations be available?).

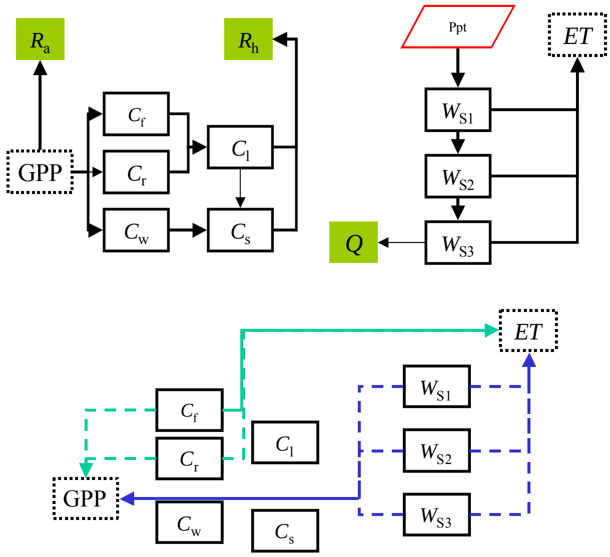


Figure 7-5: The Data Assimilation Linked Ecosystem Carbon (DALEC) model, version 2. The original DALEC model simulated C dynamics alone. We have now added a simulation of soil moisture dynamics, and coupled the carbon and water fluxes. The left half of the figure shows the state variables, both stocks (solid boxes; C = carbon, r: root, f: foliage, w: wood, l: litter, s: soil, Ws: soil water content in numbered soil layers), emulated fluxes (dashed boxes; GP: photosynthesis, ET: evapotranspiration), input fluxes (red rhombus; Ppt: precipitation), and fluxes exchanged across system boundaries (green boxes; R: respiration, a: autotrophic, h: heterotrophic, Q: discharge). The right half shows the influences (dashed lines) that connect state variables with the emulators of GPP and ET, generating feedbacks.

7.5. Incorporating new data

7.5.1. Flux data

CarboEurope-IP is continuing to collect and archive new data from forest, grassland and farmland, as itemised in our 2004 Report, which are now coming available to modellers.

We deployed the short ‘roving’ tower for making new measurements at a heather *Calluna /Sphagnum* bog within Harwood Forest in Northern England. This heather-dominated vegetation covers much of northern Britain, and constitutes the native vegetation on which plantations have been established. The data show fluxes that are usually one-third to one-half of those observed for Sitka spruce, and the ecosystem appears to be a very weak C sink. Figure 7-6 shows the light response curves of uptake of CO_2 for midsummer: in bright sunlight (over 1000 μmol photons m^{-2} s^{-1}) spruce accumulates carbon at a rate of about 15 μmol CO_2 m^{-2} s^{-1} whilst heather accumulates only at 5 μmol CO_2 m^{-2} s^{-1}. The data so far suggest that the bog is only a very weak carbon sink.

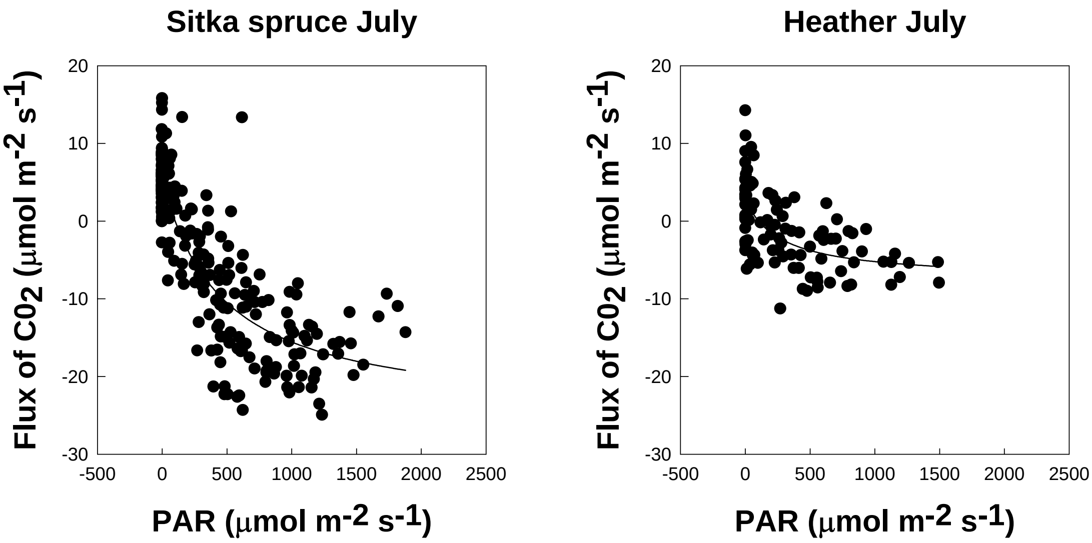


Figure 7-6: Eddy covariance flux data of spruce and heather compared at the Harwood site. Fluxes are plotted (y-axis) against the incoming photosynthetically active radiation (x-axis). The data points are half-hour averages and the fitted line is a rectangular hyperbola. Uptake from the atmosphere is shown as negative, by convention. Ecosystem respiration (from the fitted hyperbola) was 5.5 ± 0.5 µmol CO_2 m^{-2} s^{-1} and 2.7 ± 0.7 µmol CO_2 m^{-2} s^{-1} respectively for spruce and heather.

7.5.2. Reducing uncertainty in carbon stocks of soil

Information on soil is a core requirement of the CTCD, affecting all model calculations of C fluxes. Soil texture databases are basic inputs to the models; soil C maps allow model testing; measurement and differentiation of C fluxes from soils provide insights into processes and form part of our intensive site-based measurement programme; these insights will hopefully lead to improved representations of processes for incorporation in the models; and more fundamental models based on soil biology provide the future of understanding what drives C fluxes in soils. Figure 7-7 compares the most recent CTCD UK 'best estimate' of soil C stocks at two grid scales, based on field data, vs. SDGVM model outputs (far right). Any discrepancies in modelled soil C stocks amplify through to major uncertainties in predicting terrestrial C fluxes; a principal generic failing in all DGVMs is their inability to accurately model organic soils. The central theme of soil research within CTCD is to identify and reduce these uncertainties.

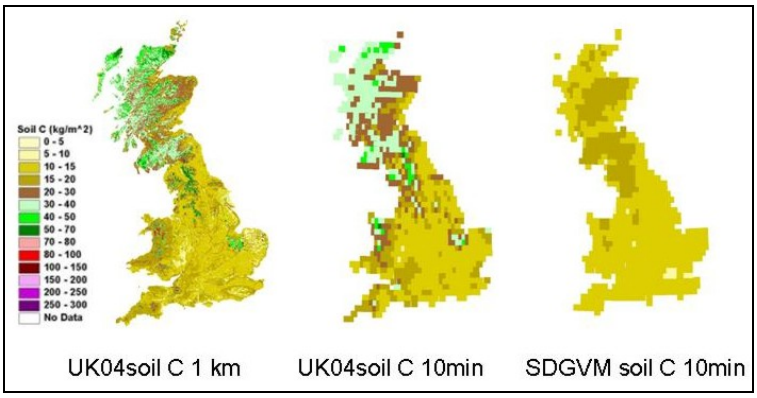


Figure 7-7: Observed and calculated soil stocks

An important, substantial and unanticipated task arose when the basic soil C stock dataset, obtained from DEFRA, via Silsoe and MLURI, was found to contain many important errors and regional inconsistencies. Working with the data providers, the dataset was carefully examined to identify and rectify errors (e.g. incorrect bulk density values, misclassified grid squares, etc). We now have an acceptable UK dataset, where any further improvement would not deliver any significant improvement in comparison to the additional effort required. These data were provided to the CTCD data manager in mid 2004 and a full list of necessary corrections has been returned to the data providers to enable them to modify the original dataset.

A similar effort was required to identify and correct errors in the UK soil texture data. However, this is limited to texture data from England, Wales and Northern Ireland. Data from Scotland are excluded because of major unresolved problems with access to these data and this compromises all models and maps which we produce for the UK.

In collaboration with the statisticians at Sheffield, the LCM2000 land cover database and UKCIP/BADC data are being used with the latest soil C database to investigate relationships between contemporary UK climate and current soil C stocks. This involves Bayesian methods to deal with censored data (i.e. maximum C densities within a fixed soil depth). We find that contemporary mean annual air temperatures are the best predictor, being inversely correlated with soil C stocks. These results are currently being compared with soil C estimates generated from SDGVM and European data.

7.6. Overall biogenic carbon fluxes and uncertainty calculations

SDGVM was used to make uncertainty calculations of the Net Ecosystem Productivity for England and Wales. The calculations took into account uncertainties in (a) soil texture and bulk density (b) uncertainties in the parameters defining Plant Functional Types, but currently we have ignored uncertainties in climate data, land cover and model structure. The uncertainty limits for parameters including ‘budburst limit’ and ‘evergreen leaf lifespan’ were defined by elicitation of the experts’ knowledge by the modellers.

Figure 7-8 maps the results of the uncertainty analysis of NEP, accounting for uncertainty in PFT parameters, soil texture and bulk density. It does not yet account for uncertainty in land cover (work reported in Strand 3 suggests that this may not affect total NEP much, but there will be local effects on both best estimates and their uncertainty), in monthly climate data (and its disaggregation to daily data by the SDGVMd weather generator), or in model structure.

On the left of Figure 7-8 is a map of the correction that should be applied to the SDGVMd NEP output that is obtained by running it with the ‘best estimates’ of all parameters. The correction arises as a combination of uncertainty in those estimates and the nonlinearity of the model. The right hand side of Figure 7-8 maps the standard deviation of the NEP estimates due to uncertainty in soil and PFT parameters.

Two papers describing this work are in draft form.

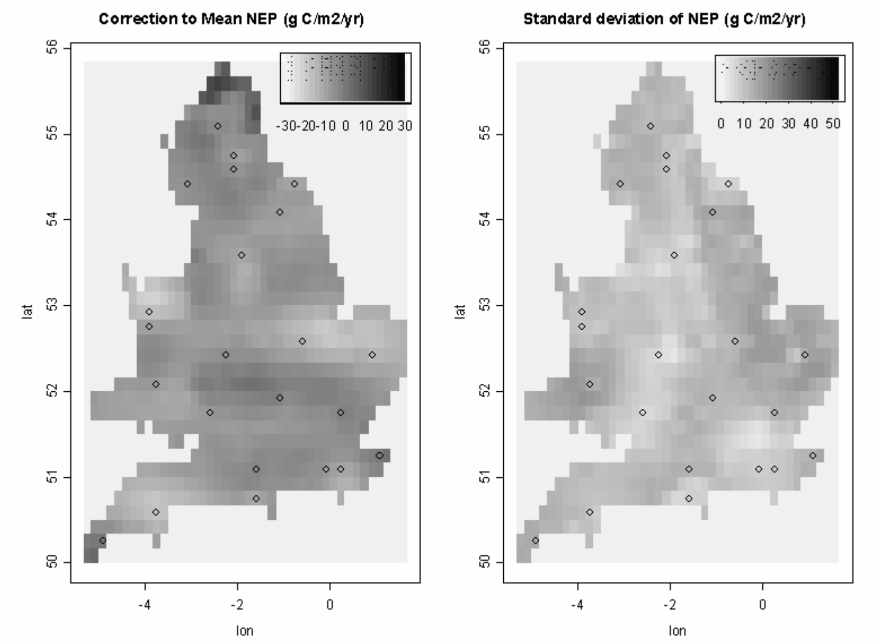


Figure 7-8: Uncertainty analysis correction to SDGVM (see text).

For England and Wales the uncertainties in carbon fluxes are shown in Table 7-2. The aggregate estimate for the carbon flux is 3.63 +/- 0.49 MtC per year, of which the forest component is 0.56 MtC. This is smaller than the corresponding inventory values. Cannell & Dewar (1995) used forest inventory to calculate a carbon sink of 2.5 MtC for the UK; of this, we may estimate a figure of 1.1 MtC for England and Wales. Inventory data produced last year by CEH were essentially the same as Cannell & Dewar's published result based on a somewhat more advanced approach (8444 Gg of CO_2 is 2.30 Mt C). A third independent estimate, albeit a rough one at present, can be obtained from eddy covariance measurements: productive plantation forests may be expected to have a NEP of 4-6 tC ha^{-1} yr^{-1} when in their middle age, but only 2-3 when considered over their entire life cycle. Allowing for some forests to be less productive, we think an average for UK forests is likely to be a sink of 2 tC ha^{-1} yr^{-1}. Multiplying this by the land area of England and Wales suggests a forest sink that is higher than any of the above values, of 2.6 MtC.

Table 7-2 Estimated carbon flux obtained from running SDGVM. The uncertainties ascribed to the estimates are based on a preliminary uncertainty analysis. In the case of the 'crops' component, consumption of the production is not accounted for.

	Estimate (MtC)	**Range (+/- as a percent)**
Crops	2.24	20
Grasses	0.83	6
Deciduous	0.41	8
Evergreen	0.15	8
Total	3.63	14

7.7. Priorities for next year

(i) A top priority is to reconcile the differences in estimates of the carbon sink from different methods, and to extend the CTCD estimate to include Scotland.

(ii) To utilise new data sets coming available from CarboEuropeIP

(iii) to make new estimates of the biogenic fluxes using atmospheric measurements (from tall towers and aircraft)

7.8. Glossary

BADC	British Atmospheric Data Centre
CRU	Climatic Research Unit
DALEC	Data assimilation linked ecosystem carbon
EO	Earth Observation
ERS	Series of satellite missions (1991, 1995) by the European Space Agency
ET	Evapotranspiration
GLC2000	Global Land Cover 2000 is a remote sensing product from the European Space Agency
JERS	Series of satellites from the Japanese Space Agency (Japanese Earth Resources Satellite) from 1992
LCM2000	Land Cover Map 2000 is a high resolution land cover map of the UK
NBP	Net Biome Productivity, an expression of carbon flux which includes disturbance and is relevant for regional scale budgets
NEE	Net Ecosystem Exchange is a high resolution measure of carbon flux, using the sign convention whereby gains by the atmosphere are positive
NEP	Net Ecosystem Exchange is a high resolution measure of carbon flux, using the sign convention whereby gains by the atmosphere are negative
NPP	Net Primary Productivity is photosynthesis minus plant respiration
PAR	Photosynthetically Active Radiation, is the radiation between 400 and 700 nm, usually expressed as μmol photons m^{-2} s^{-1}. A mol of photons is Avagadros number of photons.
PFT	Plant Functional Type (eg deciduous tree, C4 grass)
SDGVM	Sheffield Dynamic Global Vegetation Model
SVAT	Soil Vegetation Atmosphere Transfer Scheme
UKCIP	UK Climate Impacts Programme, established 1997.

7.9. References

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