18. Design of Greenhouse Gas Observing Systems (WP 2.15)

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18.1 Rationale

In this section, we briefly report on work within CTCD from 2006 that contributes to verification, observing systems and remote sensing methods relevant to the DEFRA LULUCF project. This includes:

- SDGVM Model Developments and analyses
- *In situ* measurements of C pools and fluxes
- Data assimilation and C modelling

18.2 SDGVM Model Developments and analyses

18.2.1 Model Development within SDGVM

The primary Dynamic Global Vegetation Model (DGVM) for estimating that we are making use of for flux estimation is the Sheffield DGVM (SDGVM). This year's major SDGVM model developments have been concerned with tracing the dynamics of individual functional type cohorts and a completely new representation of root and soil carbon dynamics. Of particular relevance to this project are:

Fully per cohort representation

Previously, although there was a per cohort representation used for yearly processes e.g. thinning, fire and biomass accumulation, the plant physiology was only computed per functional type. The system state arrays and functional type parameters have now been restructured to provide a fully per cohort representation. This is computationally burdensome but is particularly important to model the effects of young vegetation in a realistic manner.

New soil carbon/hydrology module

This provides a detailed vertical profile of soil hydrology, organic carbon and soil mineral fractions, providing a mechanism for rooting depth to evolve over time throughout a 'realistic soil profile'(Figure 18-1 and Figure 18-2). Ultimately, this will play a major role in "natural vegetation" through competition, as well as providing a physical link from the vegetation to soil moisture. The new representation has the ability to produce both organic and mineral soils with realistic soil C contents. This is achieved by controlling the mixing of soil quantities between adjacent layers, along with the decomposition rates, representing biological activity determined by soil pH, litter quality and rock/sediment (soil) substrate.

Improved coupling between stomatal conductance, transpiration and roots

Previously, the effect of reduced soil moisture on stomatal conductance was accounted for empirically. So, the 'supply', governed by stomatal conductance and soil moisture, was not directly equated to the 'demand', governed by atmospheric conditions and stomatal conductance (Penman-Monteith equation). This has been addressed by including the Penman-Monteith equation in the system of non-linear equations used to determine assimilation, stomatal conductance and internal CO_2 partial pressure. In reality, if ‘demand’ exceeds ‘supply’ a plant may incur irreversible damage.

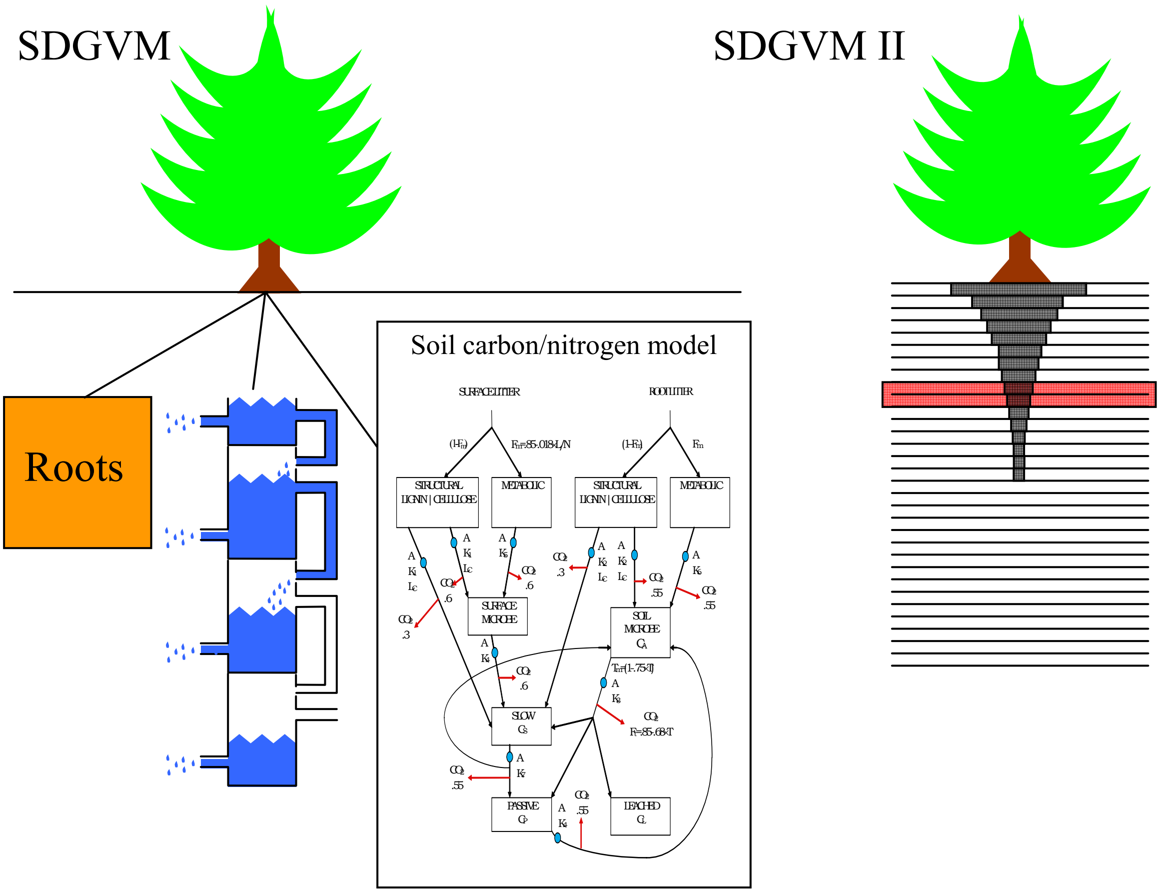


Figure 18-1: Soils representation

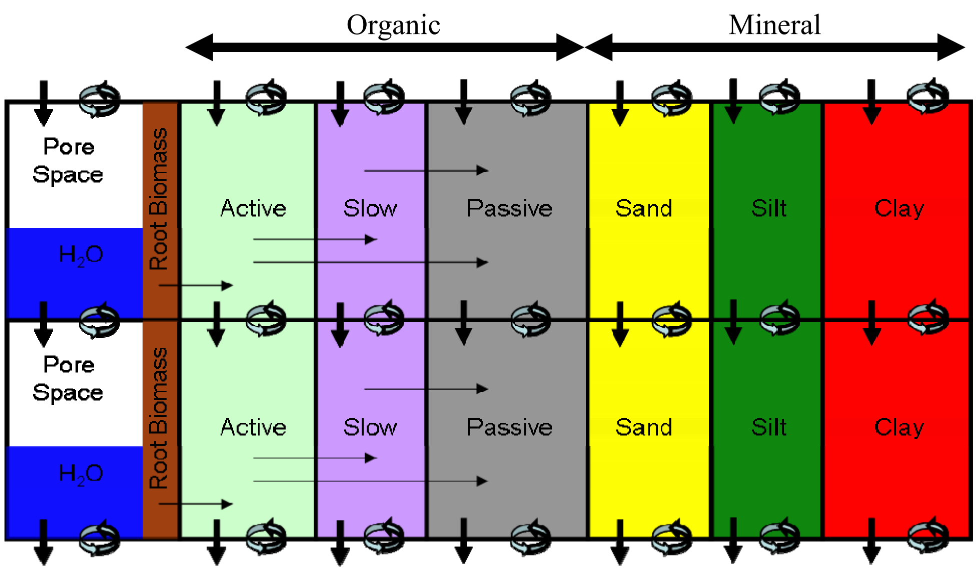


Figure 18-2: Adjacent soil layers from SDGVM II.

18.2.2 SDGVM parameter uncertainty

The work reported last year, in which we derived the uncertainty due to model parameters in SDGVM-based estimates of the England and Wales carbon flux in 2000, has been accepted for publication in the Royal Statistical Society's Journal Series A, Statistics and Society. Since then, we have been actively extending the work to incorporate uncertainty due to land cover. The previous exercise took land cover derived from LCM2000 as given, and we now account for uncertainty using a confusion matrix obtained from the Countryside Survey. This has entailed novel statistical modelling to include prior distributions for land cover and to introduce a spatial element across England and Wales. Ongoing work will propagate this uncertainty through to its implications for uncertainty in SDGVM's carbon flux estimates.

18.3 In situ measurements of C pools and fluxes

18.3.1 Characterising and reducing uncertainties in soil C stocks and fluxes, and assessing the effects on C flux models

Our research this year has addressed some key science questions, such as (i) soil carbon temperature sensitivity and potential feedback implications, (ii) soil respiration component fluxes and individual environmental responses, (iii) NEE flux methodology and modelling, (iv) restructuring existing soil carbon models for mineral and organic soils by incorporating latest science and biology, (v) advising on soils-related model uncertainty, (vi) exploring available climate and EO data (i.e. fAPAR & NDVI) for explaining global soil carbon distribution. We have successfully deployed the novel multiplexed CTCD soil respiration kit in a pine forest (Wheldrake, York) and an upland moorland site (Moor House, Pennines) in collaboration with CLASSIC (joint PhD). The system provided key science data and a novel mesh collar design led to important insight into soil respiration methodology and component fluxes, both with important implications for model process understanding. We have also adapted this system for continuous measurements of both respiration and NEE fluxes; this system is now deployed in the Arctic (ABACUS, NERC IPY), whereas the other system is at the research forest at Alice Holt (FR). Both systems are operated in conjunction with an eddy tower system, providing, for example, high quality soil flux data for crucial eddy night-time flux validation. Furthermore, through the purchase of a trace gas analyser unit linked to the multiplexed flux system, we can now provide break-through continuous trace gas fluxes (i.e. CO_2, CH_4 & N_2O) on peatland sites, whose vulnerability was pointed out by Bellamy *et al*. (2005). This has led to important links to the UKPopnet initiative measuring trace gas fluxes at catchment scale experimental plots (gully blocking) with strong science to policy implications. The flux work will provide a crucial component in validating and improving the newly developed CTCD soil carbon sub-model. Our strong position is reflected in numerous international collaborations such as the ESF (co-editorial of a book on soil respiration methodology), COST (action 639 “BurnOut”) and research links to other EU Universities (e.g. Umea with Peter Hoegberg). A very important success was the research work by the York PhD student (Iain Hartley), resulting in major publications (Heinemeyer *et al.* in press; Hartley *et al.* in press (a) and(b)); the joint CLASSIC PhD student will follow suit. We also initiated major outreach and knowledge transfer with a CTCD exhibit “The Breathing Forest” at the Royal Society summer science exhibition (July 2006) and contributed to an ABACUS science field workshop.

a) The year-long experimental work at Wheldrake Forest was exceptional and produced a major publication (Heinemeyer *et al.* in press) on field separation of soil CO_2 fluxes into three components due to roots, soil heterotrophes and mycorrhizal hyphae (Figure 18-3). Interestingly, the latter did not respond to soil temperature, as found previously (Heinemeyer *et al.* 2006); we are operating such a system at the NERC ABACUS IPY project at Abisko.

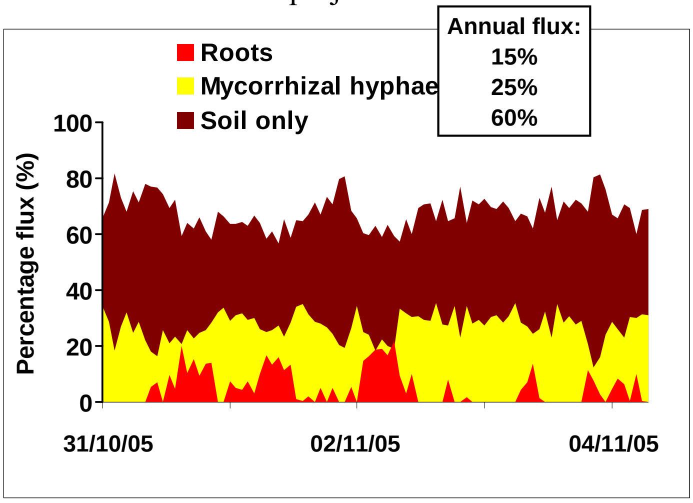


Figure 18-3: An extract from the separated soil respiration fluxes (percentage fluxes based on hourly measurements) at Wheldrake forest (pine forest) during a period in November 2005 (annually till March 2006). Note the low root but high mycorrhizal hyphal flux contribution, even annually; separation was achieved using a novel mesh collar design. This work was possible though a successful bid into the NERC CEB, enabling the construction of a multiplexed continuous soil respiration monitoring system.

b) The joint CTCD/CLASSIC CO_2 flux monitoring at the peatland site at Moor House was very successful and produced the first highly detailed soil respiration data for any UK peatland site (Figure 18-4). Importantly, hourly soil fluxes were obtained using surface collars, avoiding flux losses by cutting roots with collar insertion (see (c)). These data (NEE eddy and soil fluxes) will be crucial for model evaluation (new CTCD soils sub-model and the ECOSSE model with Pete Smith, Aberdeen). Data will be submitted to Global Biogeochemical Cycles.

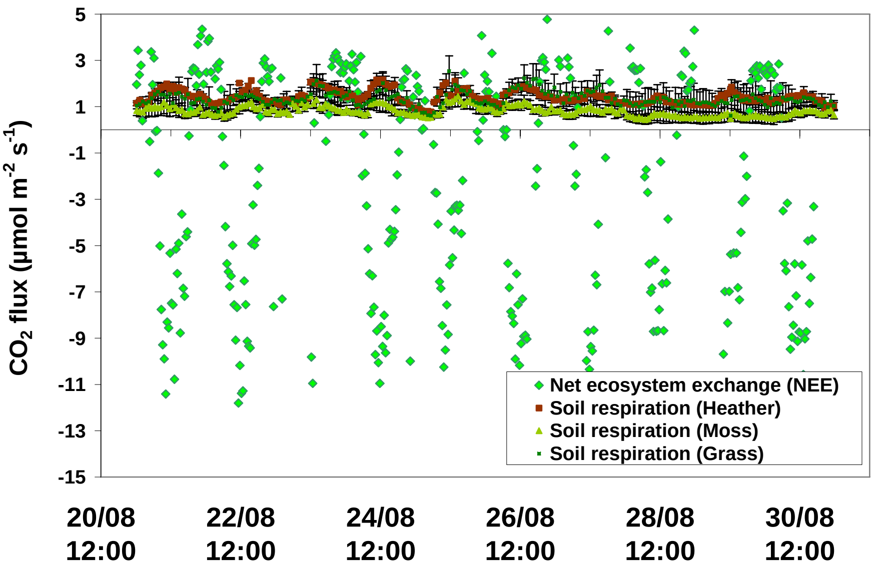


Figure 18-4: A 10-day extract from hourly Moor House NEE CO_2 fluxes (heather moorland) with soil respiration fluxes for three different vegetation types (heather, grass, moss) during a period in August 2006. The soil respiration fluxes, measured with surface collars, are around 50% of night time NEE fluxes (ecosystem respiration). Note the very high carbon uptake that could be observed during the entire very warm and sunny summer of 2006.

c) Our field work further demonstrated at two contrasting sites (Wheldrake pine forest and Moor House peatland) that conventional collar insertion of only a few cm (commonly insertion is to about 10 cm) will lead to dramatic long-term underestimation of soil CO_2 fluxes (Figure 18-5), mainly by cutting through the surface fine root and mycorrhizal layer. This has implications for global soil respiration estimates and model evaluation.

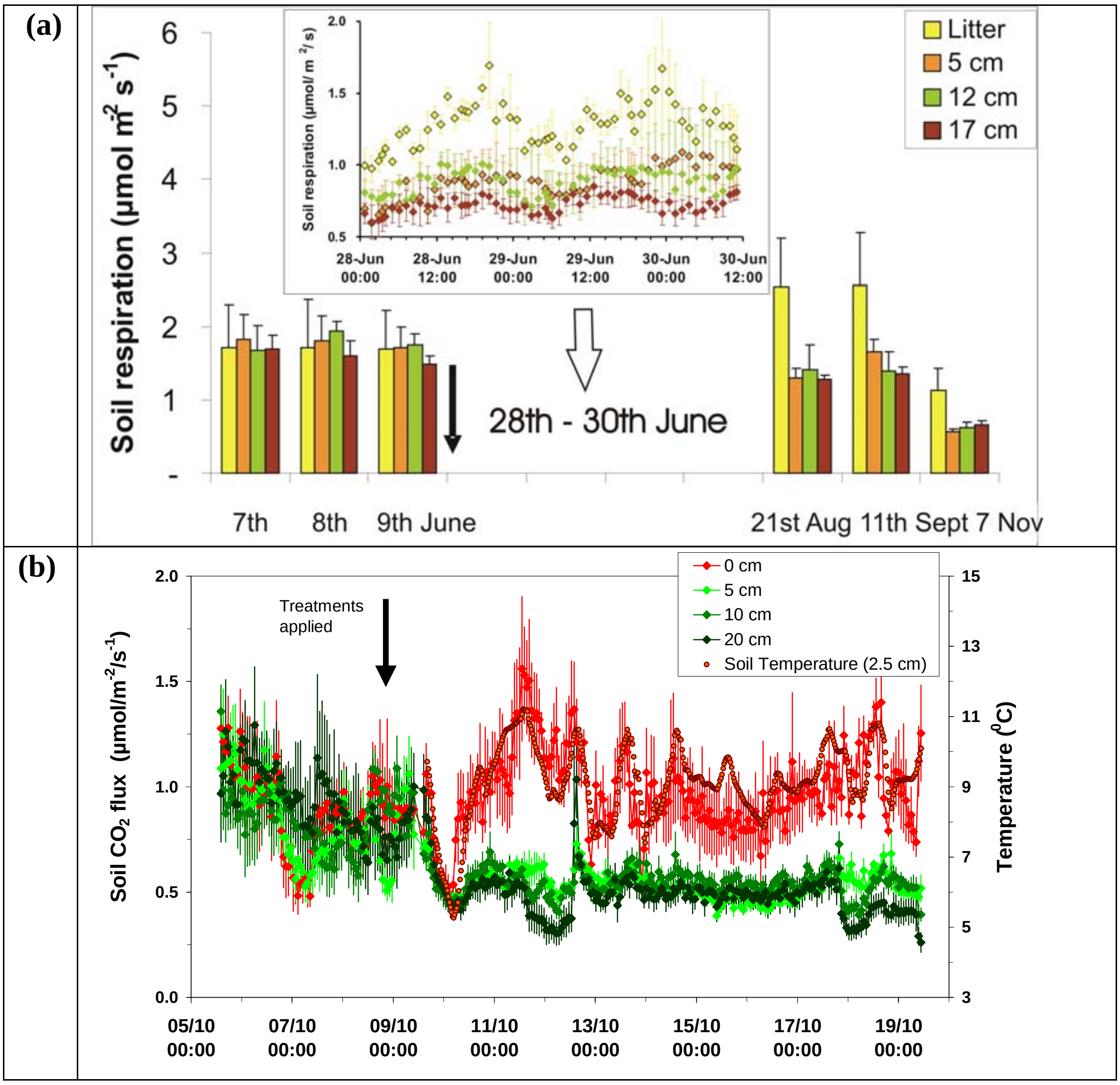


Figure 18-5: The effect of collar insertion to different soil depths on measured soil CO_2 fluxes in 2006; (a) pine forest near York and (b) heathland site at Moor House. Note the dramatic decrease in measured soil respiration after collar insertion (black arrows), even at the low insertion depths (i.e. 5 cm). The inset in a) shows hourly fluxes; both measurements included a pre-treatment period (period left of arrow).

d) The deployment of 12 soil respiration chambers at the eddy tower site at Alice Holt (since March 2007) has already produced excellent data (Figure 18-6). FR staff are available at the site and data are transferred weekly via FTP. These will be used for model improvements and development within FR/CTCD.

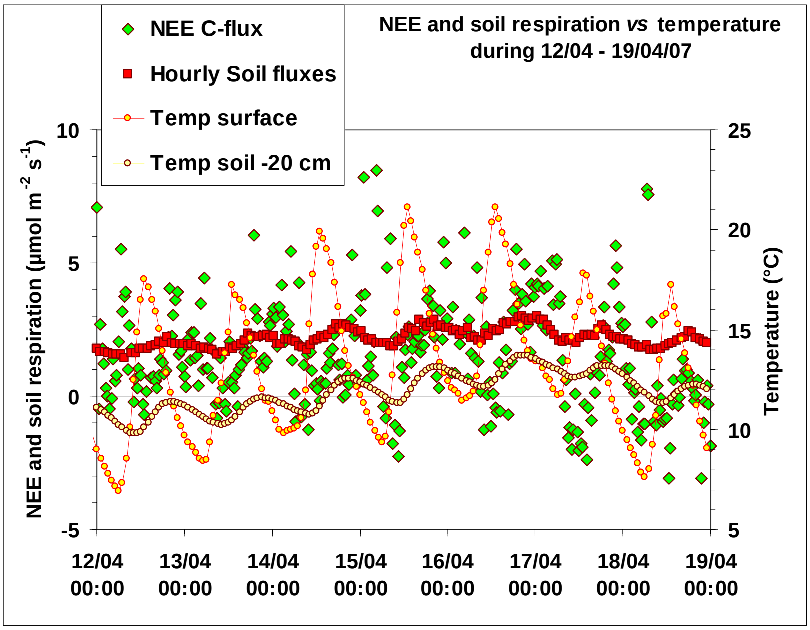


Figure 18-6: Extract from the Alice Holt (mixed oak forest) eddy and soil respiration fluxes during a weeklong period in April 2007. Hourly eddy flux data are for the same period as the soil respiration fluxes, and are about 50% of night time ecosystem respiration (i.e. night time eddy fluxes). Note how high the air and soil temperatures are (possibly heading for an interesting drought year) and the net CO_2 uptake during the day (i.e. negative NEE) just starting to kick in after observed bud burst (around 10th April).

e) A groundbreaking development was the successful adaptation of the soil respiration system for low vegetation (e.g. grassland) NEE flux work. We finished a joint CTCD/ABACUS experiment, showing that the system actually can measure NEE fluxes very accurately (Figure 18-7) and compared C-stock inventory to the C-flux based approach. The system is now deployed in the Arctic (ABACUS). The findings will be submitted to Soil Biology & Biochemistry.

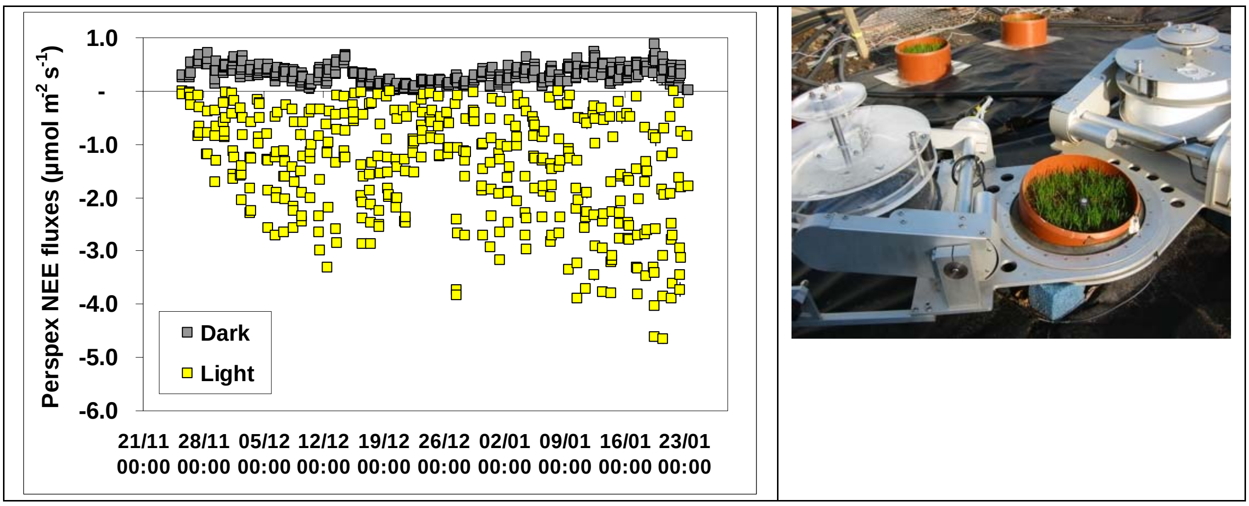
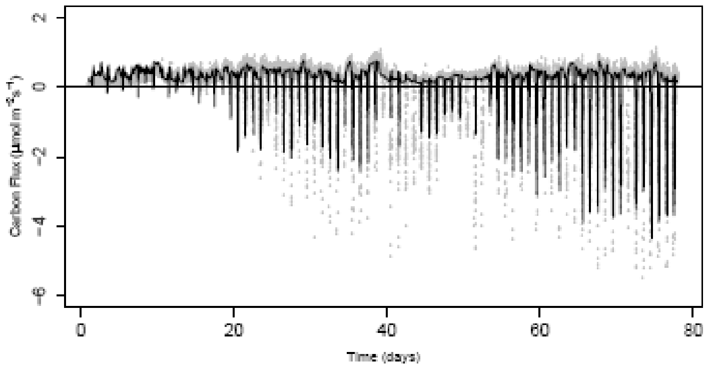


Figure 18-7: Data from the York multiplexed and continuous monitoring soil level NEE chamber system. Shown are hourly CO_2 fluxes from dark respiration (grey) and clear NEE perspex (yellow) chambers (see picture). Note the high net CO_2 uptake during the day (negative NEE values) starting immediately after seed germination (around 20th November 2006).

f) We used both the Wheldrake forest soil respiration and the York NEE perspex flux data for modelling with SPA/DALEC by 4 jointly supervised mathematics project students in collaboration with CTCD-Edinburgh (Figure 18-8 (L)). Both projects revealed important model improvement needs, such as including an autotrophic soil respiration component and a different temperature sensitivity of individual soil respiration components (Figure 18-8 (R)).



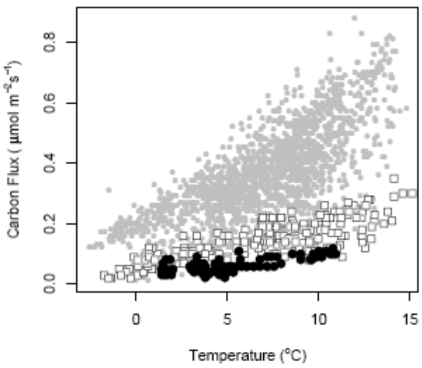


Figure 18-8: (Left) Measured (dots) vs. modelled (line) NEE fluxes from the clear NEE perspex chambers during November 06 – January 07 in the NEE flux experiment, showing net uptake (negative) during the day after germination (i.e. day 20) and net release/respiration (positive) during the night. (Right) Interestingly, we got an insight into the temperature sensitivity of different soil respiration components: soil only, root and shoot + root, from pre-seed soil only (black dots), germination (white squares) and plant growth periods (grey dots), respectively; they respond differently to temperature. Overall the model underestimates negative NEE fluxes.

g) A further crucial development was the acquisition and testing of the (INNOVA) CH_4 and N_2O analyser, coupled to the multiplexed Li-Cor soil respiration chambers. This enables fast trace gas flux measurements in the lab. In fact, we have also tested it in the field on the back of an all terrain vehicle, making it suitable for proposed phase 2 catchment scale studies. We have already used this joint system (INNOVA – Li-Cor) within a collaborative UK peatland flux project at Leeds Geography Dept., testing water-table changes on six contrasting (N and S levels) UK peatland soils (Figure 18-9). This work is currently being written for submission to J. of Hydrology.

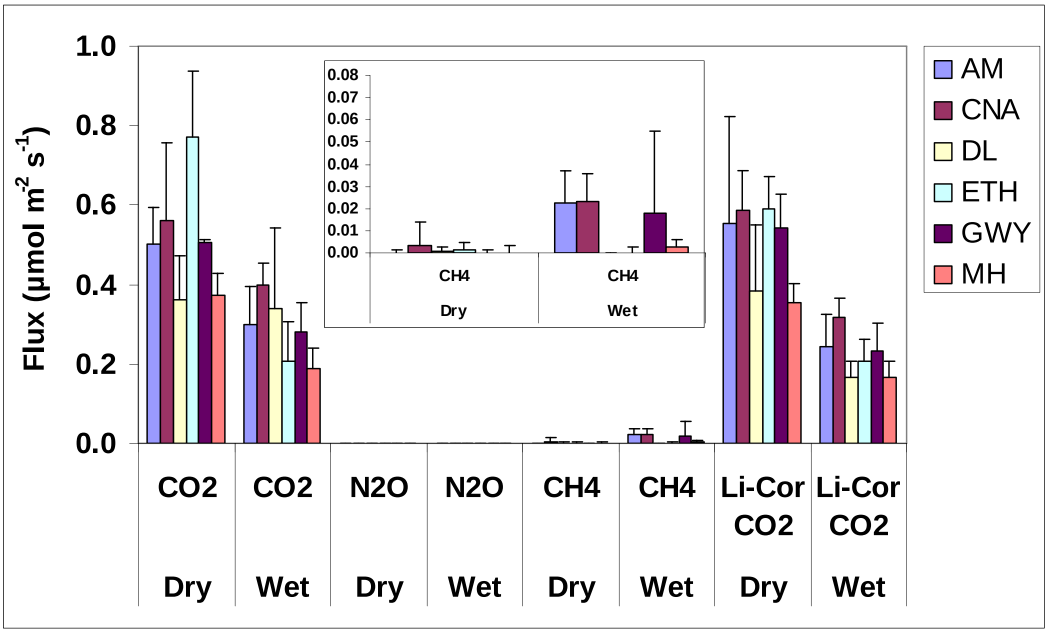


Figure 18-9: The first experimental data from the joint INNOVA and Li-Cor flux system collected during the Leeds peat water-table change study (wet: water table at surface vs. dry: at bottom of soil core) using peat from 6 UK sites; shown are the overall CO_2, CH_4 and N_2O fluxes (from the INNOVA) and also for comparison the Li-Cor CO_2 fluxes per site and treatment after 6 weeks of treatment. Note the relatively high CO_2 fluxes in the dry cores compared to the wet collars, the latter producing higher methane fluxes (also see inset) but only at some sites.

h) All the above findings are linked to the ongoing process of updating the conceptually new soil carbon sub-model for SDGVM. We are aiming to test the model this year with the high quality field data acquired from our contrasting mineral vs. organic soil sites (i.e. Wheldrake Forest and Moor House). Further ongoing work is the continuation of our advisory role within CTCD on EO related soil moisture work and an improved UK uncertainty analysis data based on a recent publication (Kennedy *et al.* in press).

18.3.2 Vulnerability of organic matter to decomposition caused by warming

The organic matter of soils is a large storage term in the carbon cycle and its breakdown could be a positive feedback in the climate system. In NW Europe we have a high component of organic matter because of the prevalence of peaty soils. Models of the carbon cycle have a simple parameterisation of the carbon cycle, possibly much too simple. Here, we carry out experimental observations on the decomposition of organic matter under a range of temperatures. Measurements have been made of the CO_2 efflux from soil material taken near the surface (5-15 cm deep) and at depth (25-35 cm) at Harwood Forest in Northumberland. The soils were removed to the laboratory and CO_2 efflux (‘soil respiration’) was measured at a range of temperatures using a Tunable Diode Laser (TDL) to examine the isotopic signal of the respired carbon, as well as to measure the overall flux. The surface samples showed respiration rates that were about four times higher than the deeper samples. The analysis of the temperature sensitivity of these data yielded Q_{10} values in the range 2.3 to 4.0, and it showed that the temperature sensitivity is greater in the surface layers than at depth. Moreover, in long term incubations, the soil respiration declined;

we think we are seeing a depletion in the supply of organic substrate from the plants. We conclude that simple Q_{10} models of soil respiration, as used in most mathematical descriptions of the carbon cycle, may not be adequate. We further investigated the response to temperature by investigating the separate efflux of $^{12}CO_2$ and $^{13}CO_2$.

It is hypothesised that this will give clues about the nature of the respiratory substrate; for example, fractions derived from woody material are rich in lignin and it is known that the carbon in lignin is more depleted than that in cellulose. The experiment clearly demonstrated the capacity of the TDL to measure the separate fluxes with good precision at the higher temperatures; however, the differences in the isotopic ratio between surface and deep soil samples were only small. It remains to check the isotopic signature of the substrates themselves, but the tentative conclusion is that most of the respired CO_2 from the deep soil is derived from non-lignin materials; it may be that the lignaceous compounds are stored in a relatively permanent way and are not vulnerable to decomposition. In April 2007 the TDL was installed in the mobile laboratory and driven to Les Landes forest in SW France, where field measurements of isotopic fluxes will be made in a contrasting type of forest in collaboration with a French group from INRA.

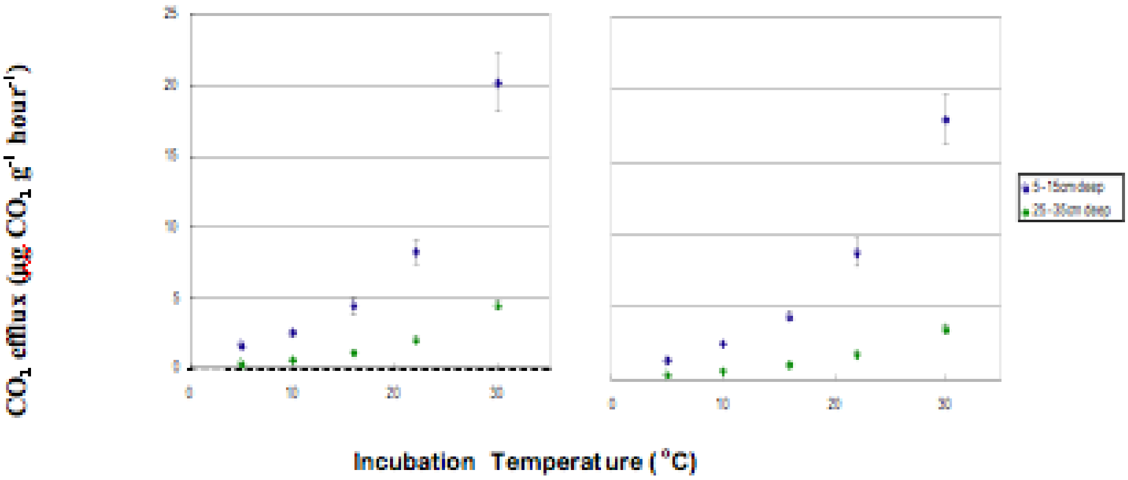


Figure 18-10: Effect of temperature on the CO_2 efflux from soils tested immediately (short term, left panel) and soils incubated for six weeks (longer term, right panel). Blue points denote surface soil samples, green denotes deep soil samples; bars represent the 95% confidence interval.

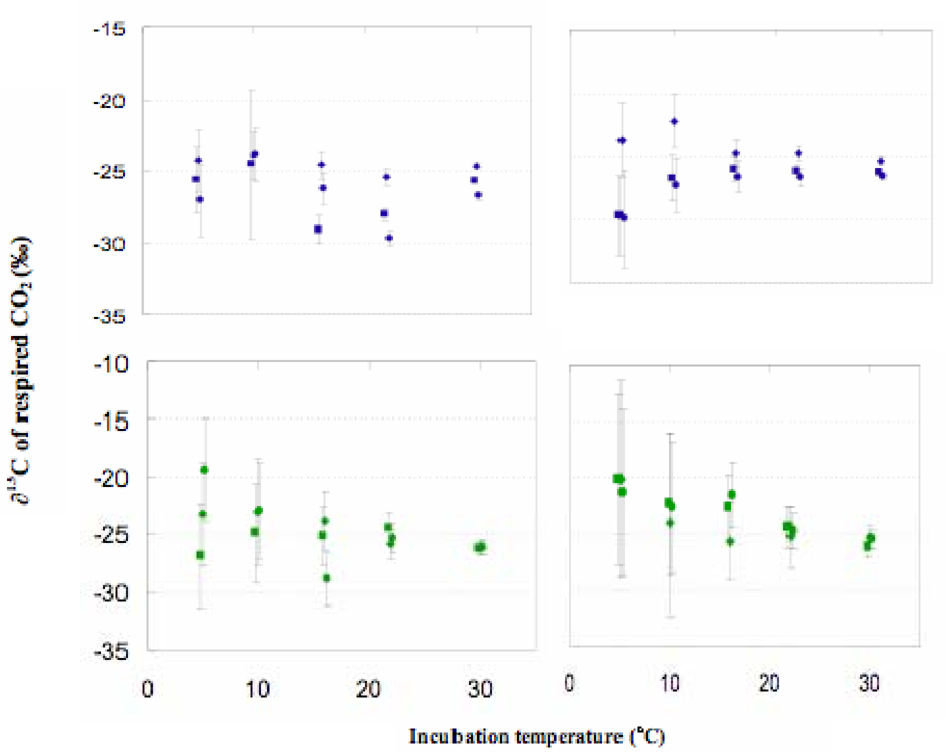


Figure 18-11: Isotopic ratio of the respired CO_2 at a range of temperatures. Symbols are as for Figure 18-10. It is notable that very precise isotopic ratios are obtained only when temperatures exceed 20 ºC.

18.4 Data assimilation and C modelling

18.4.1 DALEC development and testing

Uncertainties in coupled climate-carbon cycles models remain great as revealed by the large differences in performance in a recent model inter-comparison. This uncertainty is due in part to poorly constrained parameters, inadequate representation of ecosystem processes and a lack of strong data constraints. A key area of ongoing research within CTCD is how a wide range of available data combined with newly emerging data assimilation (DA) techniques can be utilised with C cycle models to better quantify and reduce model uncertainty. The work of Williams *et al.* (2005), who introduced a simple C cycle model (DALEC) created specifically for DA, has been further developed to ensure that it has sufficient complexity to adequately represent critical biospheric processes and then tested at a number of Fluxnet network eddy covariance measurement sites. One key advance has been in the development of a phenology module. DALEC was initially developed for use in an evergreen, needle-leaf ecosystem but to be widely applicable the model needs to be able to simulate deciduous canopies. Additionally, high level EO products (i.e. MODIS LAI) potentially provide a rich data source about phenology at a global scale, constraining GPP estimates when assimilated into the model. Adding a phenology module required a number of model modifications, including incorporating an additional, labile carbon pool and parameters to control the timing of leaf out, leaf fall and maximum foliar carbon values. Extensive testing at deciduous Fluxnet network sites in North America and Europe using ground-based and MODIS LAI estimates has produced a phenology module which uses a growing degree day scheme to successfully simulate annual variations in leaf area which strongly constrains productivity that is evaluated again flux tower NEE observations.

A main aim of DALEC is to produce a model which can be used for spatial assimilation, fully utilizing the global extent of many EO products. This will necessitate that model parameters and initial conditions, along with their associated uncertainties, be extrapolated away from the intensively studied Fluxnet sites at which they have been tested. The CTCD-led Regional Flux Extrapolation Experiment (REFLEX) is an international intercomparison of model-data fusion (MDF) techniques in C cycle models to be launched in May 2007. This has the aims of (1) comparing the strengths and weaknesses of various MDF techniques for estimating carbon model parameters and predicting carbon fluxes and (2) quantifying errors and biases introduced when extrapolating fluxes in both space and time. A full suite of ground-based and EO data from the first of 'paired' within-biome Fluxnet sites is being used to 'train' the DALEC model using a variety of MDF techniques and then model performance will be tested at a second site where only more limited (principally EO) data will be available to participants. Initial results from this experiment are expected in autumn 2007.

18.4.2 Model parameter estimation from atmospheric CO_2 measurements

Quantifying landscape C dynamics has largely been undertaken using either top-down (spatially averaged) and bottom-up (site/species specific) approaches. Top-down approaches might involve inverting global CO_2 flask measurements, whereas bottom-up methods might involved linking a series of eddy flux tower measurements. The spatial heterogeneity of C, water and energy fluxes causes difficulties when attempting to relate these different approaches to one another. The planetary boundary layer (PBL) provides a potential stepping stone between the two approaches. The PBL is in direct contact with the land surface, and dynamics within this atmospheric region are driven by ecosystem processes. Models of the PBL and biosphere provide a link between the top-down atmospheric and bottom-up ecosystem measurements by simulating processes independent of scale. The same models can be used to invert PBL observations to provide information about land surface parameters.

The Monte Carlo inversion method is just one form of analysis resulting from Bayes' theorem. Bayes' theorem allows previously held knowledge about a system (priors) to be revised using new observations. We used a simple Monte Carlo inversion scheme and a coupled atmosphere-biosphere model to investigate the interactions of the atmospheric (spatially averaged) and biosphere (site-specific) systems. A Bayesian inversion was performed using twin-data (i.e. a synthetic system for proof of concept), flat priors and a coupled PBL-biosphere model. The posterior distributions obtained for this inversion shows that information about land surface parameters can be inferred from PBL and/or eddy covariance data. However, the data resolution was not equal for all parameters and observations contain less information about foliar nitrogen, plant hydraulic conductance and albedo, and no information on the surface roughness. Combining eddy covariance and PBL observations is shown to be potentially very powerful; inverting both atmospheric and eddy covariance data improves the performance of the inversions by reducing the average uncertainty on the posterior distributions by 84% (compared to eddy covariance data only) and 74% (compared to atmospheric profile data only). In general terms, this result also shows that there is potential to make inference about the land surface from observations in the PBL alone.

18.4.3 Assimilation of EO data

Assimilation of EO data into ecosystem models provides a mechanism to constrain predictions of carbon flux away from the data-rich environments used to test and parameterise the models. The spatially synoptic nature of medium resolution EO data (MODIS, AVHRR, VGT, etc) makes it the only viable observation of global dynamics at sub-seasonal time scales for data assimilation. An attractive option for assimilating EO data into ecosystem models is to use “high-level” products such as leaf area index or GPP. Such products are linearly related to the model state vector and the construction of an observation operator is thus trivial. Two key arguments against the use of such products are: a) their error characteristics (critical for DA) are often only poorly known and, b) assumptions used in their derivation may contradict those of the ecosystem model itself. Both of these points may be addressed by using “low-level” EO products such as reflectance data. Whilst these data are still products per se, assumptions made in their derivation are independent of those made in the ecosystem model. The construction of an observation operator to assimilate such data is non-trivial however. We have replaced our previous reflectance observation operator with a hybrid geometric-optic radiative transfer model (GORT) based on the work of Ni *et al* (1999). This is more suitable for forest canopies consisting of discrete, individual crowns than the previous operator and we have demonstrated its ability to model and assimilate MODIS reflectances for a site on the Oregon transect. This work has been accepted for publication in the forthcoming special issue of Remote Sensing of Environment on Data Assimilation (Quaife *et al.* 2007). Assimilating MODIS reflectance data was shown to considerably improve the modelled NEP estimates when compared to the model running with no assimilation (Figure 18-12).

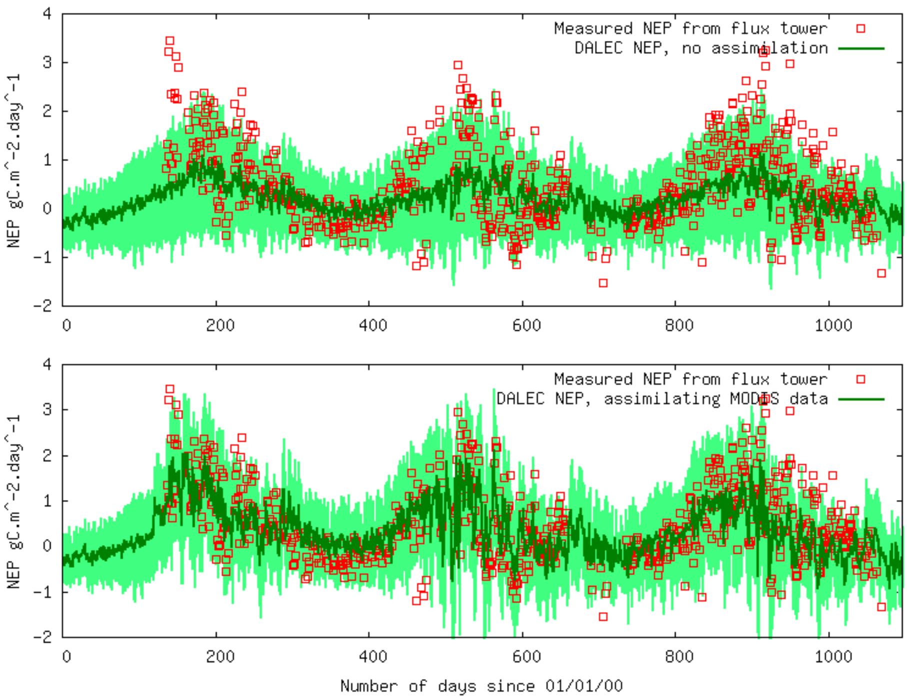


Figure 18-12: Measured and predicted net ecosystem production (NEP, positive represents a net sink) for a young ponderosa pine stand in central Oregon. Measured NEP is derived from a flux tower (data are shown in both panels). Top panel predicts NEP using an ensemble simulation of the DALEC model with an optimised parameterisation and a model error term. The lower panel uses the EnKF to assimilate MODIS reflectance data to update the model ensemble. Green bars show one standard deviation around the mean of the ensemble. Assimilation clearly reduces model bias.

18.5 References

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