Upscaling Peatland Diversity and Carbon Dynamics to the Ecosystem Level

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Reliable estimates of peatland carbon fluxes, as carbon dioxide (CO_2) and methane (CH_4), are vital for quantifying feedbacks between climate change and the substantial peatland carbon reservoir. However, the complex spatial and temporal variability of peatland carbon dynamics represents a key source of uncertainty. Upscaling carbon fluxes from the microscale to the landscape scale is a way of resolving uncertainty, vital for the inclusion of peatland carbon feedbacks in models of future climate change.

Peatlands are highly heterogeneous environments, composed of a mosaic of microhabitats: hummocks, gullies, lawns, and pools. These are colonised by distinctive plant communities, representing collections of Plant Functional Types (PFTs); pools are dominated by sphagnum species, lawns by ericoids such as Calluna vulgaris, and hummocks and gullies by graminoids including Eriophorum sp.. Plant species with particular functional traits affect the quality and quantity of organic material entering the soil, and are important regulators of the soil microbial communities responsible for aerobic and anaerobic decomposition (producing CO_2 and CH_4) (Bardgett et al., 2008).

Mapping PFTs provides a means of modelling the spatial variability of potential carbon dynamics. Small-scale spatial heterogeneity is significant in peatland carbon fluxes; McNamara et al. (2008) used GIS to quantify the contribution of gully hotspots to ecosystem CH_4 fluxes. Increasing availability of high resolution remotely-sensed datasets such as QUICKBIRD and LiDAR, in addition to geostatistical techniques such as Kriging, allow microscale modelling of peatland carbon flux interactions.

This project will combine a GIS approach, incorporating extensive vegetation and peat depth survey data with experimental work focussing on the influence of PFTs on soil microbial biodiversity and terrestrial carbon fluxes. Here we present a novel methodology for upscaling microhabitat (i.e. 10^0-10^1 metres; (Baird et al., 2009)) biodiversity and carbon dynamics linkages to the landscape scale, and provide initial conclusions derived from survey work conducted on the blanket bog at Moorhouse National Nature Reserve, north Pennines, UK.

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Permafrost Dynamics in a Changing Climate: Implications for Northern Peatlands

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Peatlands cover about 3 Mio km^2 north of 40° N (Matthews & Fung, 1987). It is estimated that about one-third of northern peatlands are in zones of continuous permafrost, with another 40% of northern peatlands in discontinuous, sporadic, and isolated permafrost zones (Smith et al., 2007). Permafrost formation in peatland areas impacts a number of hydraulic, hydrological, and biogeochemical processes in peatlands.

Anticipated changes in the formation and distribution of permafrost regions as a result of a warming climate (e.g., Osterkamp and Romanovsky, 1999; Zhang et al., 2008) can therefore impact the carbon dynamics in peatlands and thereby influence the peat net accumulation rates and methane emissions.

We assess the changes in permafrost formation in Northern regions using a coupled, large-scale, grid-based water balance/permafrost model that simulates hydrological budgets, the distribution of soil temperature dynamics and permafrost thawing and freezing, using a number of projections of future climate for the next century. The model takes into account the geographic distribution of organic soils and peatlands, vegetation cover and soil properties, and is tested against a number of permafrost records for the last century. We test the sensitivity of the model on parameters, present maps of the future geography of peatlands and permafrost regions, and report results of simulations for a number of different climate drivers derived from climate model outputs for a set of IPCC scenarios.

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Exceptionally High Summer Methane Emissions from a Boreal Peatland Ecosystem in the Republic of Komi, Russia

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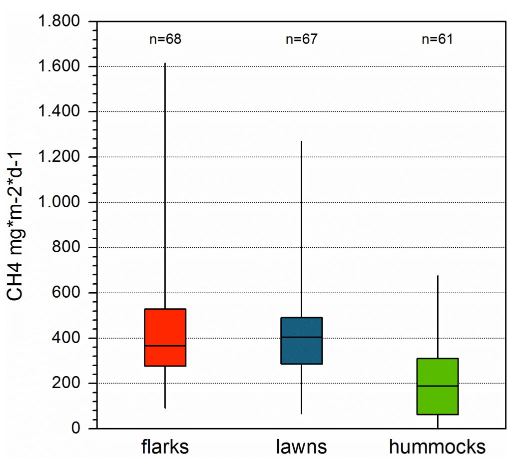
Wetlands of the northern high latitudes play a crucial role in the global methane cycle (Christensen et al., 2003). Here, we present CH_4 flux data from 18th of June to 22nd of August 2008 measured in a boreal peatland ecosystem located in the southern part of the Republic of Komi (61°56'N, 50°13'E), European Russia. Closed chamber CH_4 measurements were carried out on replicates of hummocks, lawnsm and flarks that represent the different microrelief situations. On lawns and flarks, aerenchymatous plants *(Carex limosa, C. rostrata, Scheuchzeria palustris)* occur. In addition to the closed chamber CH_4 measurements, once per month soil water for analysis of dissolved CH_4 and dissolved organic carbon was sampled. Green area index (GAI) was also measured several times during the growing season. Slightly more than half of all measured flux values were in the range of 150 – 440 mg m^{-2} d^{-1}, thereby being more than three times higher than the average of CH_4 fluxes in boreal regions (Blodau, 2002). The median-value was 323.5 mg m^{-2} d^{-1} (mean: 345.9 mg m^{-2} d^{-1}) that is more than twice as high as the average reported from the boreal zone. Extraordinary peaks above 1000 mg m^{-2} d^{-1} were identified for flarks and lawns. Differences in emission rates among different microsite types could be figured out (see figure below). No clear correlation with environmental parameters was found. However, for hummocks and lawns a linear correlation with water table and soil temperatures (5 and 10 cm) was observed. There is no evidence that high or low CH_4 surface fluxes coincide with high or low values of dissolved CH_4 in the soil water. The influence of different vegetation cover on CH_4 dynamics will be studied using the GAI. It remains unclear why this peatland is such a strong CH_4 emitter. This has to be unravelled in the future for less uncertain CH_4 up-scales for the boreal zone.



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Haul Roads, *Sphagnum* and Hydrology: How Roads in Peatlands May Change the Community Structure, Hydrology, and Water Chemistry

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Close relationships are known to exist between *Sphagnum* spp., the water table and water chemistry (Vitt and Chee 1990; Gignac et al., 1991). We examined a 0.5 x 0.5 km poor fen in the Wabasca region of northern Alberta, Canada to gain an understanding of the relationship between the bryophyte community, water chemistry, and water level fluctuation. We also examined an arm of the fen where a road has been built and examined how the road influences the seasonal variation in the water table, and water chemistry. Our preliminary data indicates that there is approximately a two fold difference in the slope of the water table upstream compared to downstream (~1:100 vs 1:200) and that there is a greater seasonal variation in the water table downstream of the road compared to the upstream side of the road (Figure 1). We also found higher pH and elevated base cation concentrations (Ca^{++}, K^{+}, Mg^{++}, Na^{+}) near the road compared to main body of the fen. We hypothesize that the changes in water chemistry and water table profile are driving changes in the bryophyte communities.

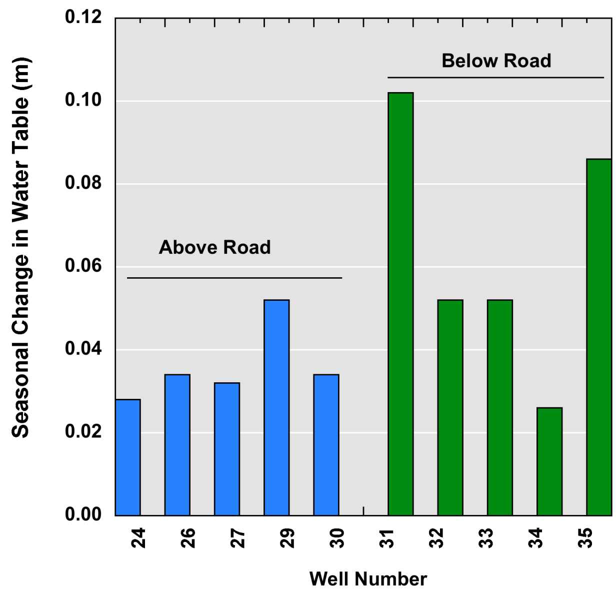

Figure 1. Seasonal Change in the water table (July 23 – Sept. 28) upstream (wells 24-30) compared to down-stream (wells 31-35). All wells are within 50 m on each side of the existing haul road.

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The Potential for Carbon Storage in UK Peatlands

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Upland peat soils represent a large terrestrial carbon store and as such have the potential to be either an ongoing net sink of carbon or a significant net source of carbon. In the UK many upland peats are managed for a range of purposes but these purposes have rarely included carbon stewardship. However, there is now an opportunity to consider whether management practices could be altered to enhance storage of carbon in upland peats. Furthermore, there are now both voluntary and regulated carbon trading schemes operational throughout Europe that mean stored carbon, if verified, could have an economic and tradeable value. This means that new income streams could become available for upland management. The 'Sustainable Uplands' RELU project has developed a model for calculating carbon fluxes from peat soils that covers all carbon uptake and release pathways (e.g., fluvial and gaseous pathways). The model has been developed so that the impact of common management options within UK upland peats can be considered. The model was run for a decade from 1997-2006, and applied to an area of 550 km^2 of upland peat soils in the Peak District. The study estimates that the region is presently a net sink of –62 Ktonnes CO_2 equivalent at an average export of – 136 tonnes CO_2 equivalent/km$_2$/yr. If management interventions were targeted across the area the total sink could increase to –160 Ktonnes CO_2/yr at an average export of– 219 tonnes CO_2 equivalent/km2/yr. The model suggests which management interventions would be most effective and given present costs of peatland restoration and value of carbon offsets the study suggests that 51% of those areas, where a carbon benefit was estimated by modelling for targeted action of management interventions, would show a profit from carbon offsetting within 30 years

The Success of Peatland Restoration for Improving Carbon Storage – the Case of Bleaklow

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The peats of the Peak District represent some of the most marginal and damaged upland peat soils and then in April 2003 the summit of Bleaklow was devastated - a wildfire that removed large areas of vegetation. Subsequently the area has been targeted for extensive restoration involving a range of techniques including: reseeding, brashing, geotextiles, and liming. For the last two years, a range of sites have been monitored for water table, soil and runoff water quality, net ecosystem exchange of CO_2, and CH_4 flux. The study sites included a range of restored sites and controls including: pristine, unburnt sites, sites never restored, and sites under managed burning. The results of the study shows that although a carbon benefit has been achieved by restoration, this was only achieved where the greatest effort in restoration was applied and the most extensive revegetation occurred. However, this carbon benefit was in terms of an avoided loss and no restored site was restored to net carbon sink. In terms of water quality restoration achieved dramatic declines in particulate losses but the picture for DOC was more mixed. The results of this study will be compared to modelling results for restoration of the same area enabling validation of regional models to be conducted.

The Production of Black Carbon During Managed Burning of UK Peatlands: Could Managed Burning of Peatlands Lead to Enhanced Carbon Storage?

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Peatlands are the UK's largest single terrestrial carbon store with more carbon stored in UK peatlands than in forests of Britain and France combined. Unlike most northern peatlands, the peat soils of the UK are heavily managed for recreation and agriculture and due to their proximity to major centres of population are under more anthropogenic pressure than most peatlands. A typical management strategy on UK upland peats is the use of managed fire to restrict vegetation. Fires are used upon a 10-25 year rotation and are described as "cool" as they are designed to remove the crown of the vegetation without scorching the litter layer or the underlying soil. In this case the fire destroys primary productivity and limits litter production but produces char. Char is a low volume, highly refractory, high carbon content product while litter is a high volume, decomposable, lower carbon content product. Therefore, the question is if there are fire conditions under which the production of char causes more carbon to be stored in the peat than would have been stored if no fire management had been employed. This study combines field studies of recent managed burns and wildfires along with detailed vegetation studies from a long term monitoring site in order to assess litter, biomass, and black carbon production. In the laboratory experimental burns were undertaken in order to assess the amount and controls upon char production and the carbon content of that char. Results of field and laboratory observations are used to model carbon accumulation under a series of fire management scenarios and the modelling shows that cool burns at long rotations could lead to higher carbon storage than if no fire had occurred; further, in several cases more carbon accumulation occurred even if less depth of peat was generated.

A 15-year Nitrogen Budget of Upland Peat Catchment in Comparison to its Carbon Budget

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This study considered records of atmospheric deposition, stream, and soil water from an upland, ombogotrphic, peat-covered catchment over a period of 15-years. The time series of nitrogen inputs and outputs was examined in the context of carbon fluxes within and from the soil as well as CHN analysis of vegetation and peat cores from the site. The study shows that when in-stream losses of nitrogen are accounted for the site is not always a net sink of nitrogen relative to atmospheric deposition, in four out of the 15 years of the study the soil released more nitrogen to the stream than it received in deposition. An examination of the C:N ratio of soil showed that the process of humification at the site released nitrogen. Furthermore, the comparison of C:N ratios between the dissolved organic carbon (DOC) and the soil shows that DOC production also resulted in the release of nitrogen. Coupled with a knowledge of the respiration of CO_2 from the soil at this site it is possible to estimate the

extent of internal cycling of nitrogen within the peat soil. However, in comparison with measured primary productivity at the site the external and internal sources of nitrogen are still insufficient and the extent of nitrogen fixation can be quantified.

Carbon Fluxes Across a Nutrient Gradient in a Domed Tropical Wetland

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Tropical peatlands are a significant source of atmospheric carbon dioxide (CO_2) and methane (CH_4). Therefore,-better knowledge of CO_2 and CH_4 fluxes in tropical wetlands and the factors that control them, are needed to predict the impact of climate change and/or land-use change upon these systems and their ability to store carbon. We investigated CO_2 and CH_4 fluxes along a nutrient gradient in San San Pond Sock wetland, Panama. The study was conducted at three locations on an established transect that bisected five distinct phasic communities. Community types studied were; *Raphia taedigera* (Rafia) palm swamp, *Campnosperma panamensis* (Orey) dominated forest and a *Cladium jamaicense* (sawgrass) swamp.

At all sites annual CO_2 and CH_4 surface fluxes were quantified to determine the seasonal pattern. Surface fluxes showed a significant variation between sites with a seasonal influence also being significant. With greater CO_2 fluxes found during the dry season and vice versa for CH_4 fluxes. Additionally, peat soil cores were taken at each site, four to a depth of 1 m, with one continued to a depth of 2 m to explore the potential for trace gas production at depth. CO_2 and CH_4 fluxes were measured down each core-along with; pH, organic carbon, total nitrogen, and total phosphorous (from both porewater and soil), percentage moisture and microbial enzyme activity. Results showed that CO_2 was significantly affected by depth ($P<0.05$) and by site ($P<0.05$) whilst no depth or site—effects were found for CH_4.

Annually it can be seen that CO_2 and CH_4 vary at site level and a between site variation that is relatively continuous over the course of a year. It is apparent that there is a potential for CO_2 and CH_4 production with also at depth and C trace gases—produced throughout the peat profile may contribute to surface fluxes.

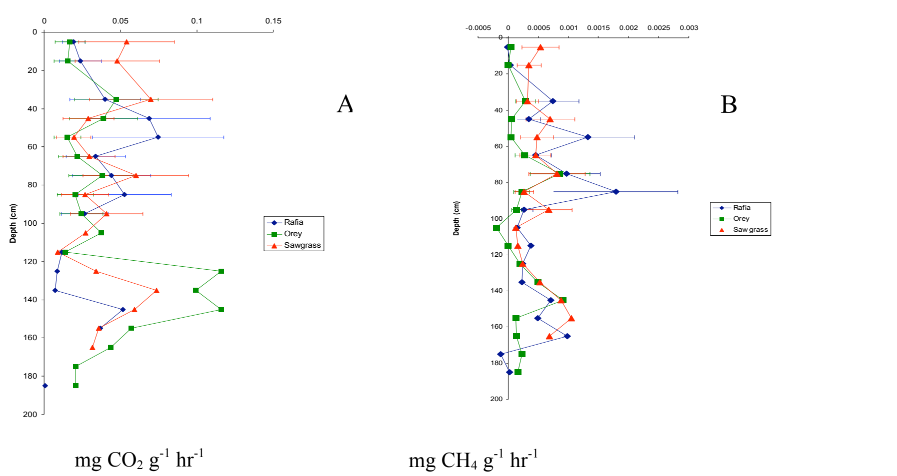

Fig.1: A) Mean CO_2 fluxes +/- SE through the peat profile. Mean at all sites shown for the first 1m depth.
B). Mean CH_4 fluxes+/- SE through the peat profile. Mean at all sites shown for the first 1m depth.

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Modeling the Sensitivity of the C Cycling in Northern Peatlands to the Projected Climate Change

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Northern peatlands have functioned as carbon (C) sinks for thousands of years and as a result stored ~ 25% the world's terrestrial C. Hydrology and the biogeochemistry of northern peatlands are tightly coupled to climate, raising concern that the C function of peatlands will change with a warmer and generally wetter north. To examine the possible changes in the biogeochemical C functioning of northern peatlands we coupled a wetland C model, McGill Wetland Model, with the wetland version of Canadian Land Surface Scheme (referred to as CLASS3W-MWM) and then simulated a number of future climate scenarios. The study peatlands we have selected are an ombrotrophic bog in eastern Canada and Degero Stormyr, a minerotrophic poor fen in northern Sweden. Four IPCC climate change scenarios are used, A1B, A2, B1 and commitment, and three time slices, 2030, 2060 and 2100, were chosen for analysis. By comparing with the present time simulated baseline C fluxes, we found that the bog has a significantly different response to climate change than the fen. Specifically, the fen was much more sensitive to climate change than the bog. Gross primary production (GPP) at Mer Bleue increased by 25-43% by 2100 for all scenarios except commitment, while GPP at Degero Stormyr decreased by 34% and 39% for A1B and A2, respectively, and increased slightly (9% and 5%) for the B1 and commitment. Total ecosystem respiration (TER) for both peatlands increased: 38-57% for the bog and 11-33% for the poor fen by 2100 for all scenarios except commitment. Net ecosystem exchange (NEE) decreased in both peatlands, because the magnitude of the increase for TER exceeded that of GPP. Mer Bleue bog, however, became a smaller C sink up to 2100, for all scenarios but Degero Stormyr, switched from a C sink to a source for the A1B and A2 scenario. From our preliminary analyses it appears that fens, while being generally wetter peatlands than bogs, are more sensitive to the range of changes expected over the next century. We are now conducting a three factorial analysis on moisture, temperature, and CO_2 to determine the relative importance of each stressor on the simulated change.

Trace that Nitrogen: Responses of Canadian Boreal Bogs to Addition of Nitrogen

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We studied the effects of increased nitrogen deposition on Canadian boreal bogs by monitoring various carbon and nitrogen pools including peat, roots, aboveground vascular plants, microbes, and fungi. Doubled labeled $^{15}NH_4{}^{15}NO_3$ was applied in 2005 in doseages of 5, 10, 15, and 20 kg ha^{-1} yr^{-1} in four bogs in northern Alberta, Canada followed by addition of regular NH_4NO_3 in the same concentrations in 2006 an 2007. We used crankwires to measure moss growth and found higher growth of moss with increased nitrogen deposition as a result of high bulk density of stems and capitula rather than linear incremental growth. Growth responded quickly to the addition of nitrogen in the first year and slowed down in 2006 and 2007. Microbial biomass N increased with nitrogen additions while ergosterol content (a surrogate measurement of fungal biomass) did not show strong response. Aboveground vegetation responded strongly and quickly to the nitrogen addition. We found high concentration of ^{15}N and declining C:N ratio in tissues of *Vaccinium oxycoccos*, *V. vitis-idaea* and *Ledum groenlandicum* with increasing N deposition. Bulk peat retained ignificant amounts of applied nitrogen in the top 10 cm but the percentage of retention declined when nitrogen addition exceeded 15 kg N ha^{-1} yr^{-1}.

The Response of a Middle and High Latitude Peat Bog to Predicted Climate Change: Fluxes of CO_2 and Methane

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Peatlands contain one third of the total soil carbon. Their response to climate change is largely unknown. Here we present the results of a comparative study of how peat collected in central and northern Europe will respond to warmer and drier conditions predicted for the 21st century. We collected peat cores (10 cm in diameter, 30 cm deep) from two sites differing in mean annual temperature, Velke Darko (VD, Czech Republic, 7.2°C), and Stor Amyran (SA, Sweden, 4°C). For 12 months, the cores were incubated in growth chambers. The effects of warming and drying were determined by periodical measurements of CO_2 and CH_4 concentrations at the peat surface.

Under present-day summer condition the warmer, lower-latitude site VD produced seven times more methane compared to the colder, higher-latitude site SA. The lower production of CH_4 found in our study at the colder boreal site SA may be explained by poor litter quality, i.e., *Sphagnum fuscum* that decomposes very slowly.

Two different warming scenarios were used, temperatures of incubation were 11°C versus 16°C, and 16 versus 22°C. No temperature control on CO_2 production rate was found after four months of incubation. A temperature control on CH_4 production was found. No effect on CO_2 production rate was observed after an 8-month incubation of peat cores under drying conditions (decreasing water table level from –2 to as much as -14 cm below surface). In contrast, the CH_4 production decreased. The combined effect of simultaneous warming and drying at 11 and 22°C was studied. Despite no individual effect of either warming or drying on CO_2, the combination resulted in a three times higher CO_2 production rate.

Moreover, the following site-specific features of peat exposed to changing environmental conditions was observed:

- **[i] We found peaks of CH_4 production peaks at 16°C and 11°C for the warmer VD and the colder SA site, respectively.**
- **[ii] Regardless of the water table level, warming led to higher CO_2 production rate at the warmer site VD. SA peat showed no significant changes in CO_2 production rate.**
- **[iii] Drying conditions led to a steeper reduction in CH_4 production at VD, compared to SA.**
- **[iv] The combined effect of simultaneous warming and drying at 11 and 22°C led to different reduction of CH_4 productions. We observed 100 fold and 33 fold reduction at the warmer VD and the colder SA sites, respectively.**

The warmer site VD responded more strongly to the simulated climate change than the colder SA site. Lower availability of labile forms of organic carbon at the colder site SA limits the response of the peat to changes in temperature and moisture. Considering the measured concentrations and the known relative contributions of CO_2 and CH_4 to the greenhouse effect, the combined effect of warming and drying at our sites would be a net 7 fold and 13 fold decrease in direct and indirect greenhouse effect, respectively, at the warmer site VD.