FluxLetter

The Newsletter of FLUXNET

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Highlight FLUXNET site
Niwot Ridge

Niwot Ridge, AmeriFlux site, USA

by Russell Monson

We are ending our tenth year of flux observations at the Niwot Ridge AmeriFlux site. The site is located at 3,050 m in a subalpine forest near Nederland, Colorado, U.S.A.. The surrounding forest is approximately 100 years old, having recovered from early twentieth century logging. There are still numerous tall stumps in the forest giving testimony to past logging activities, which were predominantly carried out during the winter when deep snow carpeted the ground and forced loggers to make high cuts on the trees. The forest is dominated by subalpine fir (*Abies lasiocarpa*), Engelmann spruce (*Picea engelmannii*), and lodgepole pine (*Pinus contorta*). The understory is sparse, containing tree seedlings from all three species and patches of *Vaccinium myrtillus*, a member of the blueberry and cranberry genus. The forest slopes gently (6-7%) and uniformly, decreasing from west to east, the direction of the prevailing winds. Leaf area index for the forest ranges between 3-4.5 m^2 m^{-2}, canopy gap fraction is 17%, and canopy height is 11.4 m. Thus, as coniferous forests go, the Niwot Ridge forest is on the short side of the average. The environment is tough for tree growth, generally cold, with shallow soils and hard mid-summer droughts. Annual precipitation for the site averages 800 mm (approximately 65% falling as snow) and the mean annual temperature is 1.5 °C.

Access to the site occurs through the University of Colorado Mountain Research Station. The site lies 1.5 km east of the

Figure 1: The primary flux tower at the Niwot Ridge AmeriFlux site. .

C1 monitoring site of the U.S. National Oceanic and Atmospheric Administration, which has been the site from which the Niwot Ridge long-term atmospheric CO_2 record is constructed. This CO_2 record represents one of the longest atmospheric CO_2 records collected to date, originating in 1968. The flux tower is accessed by a pedestrian trail from the NOAA C1 site, crossing Como Creek, home to one of the last refuges of the threatened native greenback, cutthroat trout. In fact, as we walk the trail daily during the summer, we are greeted by a rather large fish in a small pool, basking in the sun dappled water. The same fish has greeted us for ten years now, making it one of the elder representatives of this species.

The site contains a primary flux tower, and three additional CO_2-profiling towers. The primary tower is operated by Russ Monson's research group at the University of Colorado, Boulder. The CO_2 profiling towers are operated by Dean Anderson of the USGS Water Resources Discipline in Lakewood. Eddy covariance fluxes, storage fluxes and estimation of net ecosystem production (NEP) are available for community use at http://urquell.colorado.edu/data_ameriflux/. A general description of fluxes at the site can be found in Monson et al. (2002).

We are using the Niwot Ridge tower site as a place to study interactions among the various processes that determine the local carbon budget of this forest. During the early years we conducted studies to understand

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Niwot Ridge, *AmeriFlux site, USA*

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and validate the micrometeorological approaches required to make accurate measurements of NEP in a site with complex topography. In a series of papers (Turnipseed et al. 2002, 2003, 2004): (1) we demonstrated that energy budget closure for our site was as good as that for sites on simpler terrain, (2) we evaluated local length and time scales for turbulent fluxes, and (3) we demonstrated that mesoscale influences from the surrounding mountains have a minimal influence on local daytime flux measurements at the site. Although our daytime fluxes exhibit robust independence from the surrounding terrain, the situation is not so straightforward for the nighttime fluxes. Our measurements show that nighttime gravitational flows, which are frequent at the site, cause the downslope loss of respired CO_2 and therefore cause systematic error in our estimate of cumulative NEP. We established a multiple-tower experiment to better quantify horizontal and vertical advective CO_2 fluxes. The results of the advection studies are just now being published (Yi et al. 2008). In the final analysis, we concluded that although nighttime advective fluxes can be of the same magnitude as daytime turbulent fluxes, the effect on the cumulative NEP is serendipitously small (e.g., a monthly mean 10% underestimation); this is due to compensation of the horizontal mean flux by the vertical mean flux. Both fluxes are of similar magnitude, opposite in sign and nearly equally dependent on atmospheric stability.

We have conducted extensive studies on the microbial controls over soil respiration at the site, including studies on both winter (beneath snow) and summer microbial communities. In a collaborative study with David Lipson (San Diego State University), we analyzed soil DNA sequences and discovered that the beneath-snow microbial community was unique in taxonomic composition. Studies of substrate-induced respiration showed that the winter microbial community was adapted to high rates of growth and respiration at low temperatures. Our observations revealed that respiration from the winter microbes was several orders of magnitude more sensitive to soil temperature than had previously been reported (Monson et al. 2006). Now, we have discovered the reason for the high sensitivity of microbial respiration to winter temperature. The most temperature-sensitive phase of winter respiration occurs in late winter when short, but repeated periods of partial snow melt occur, wetting the soil beneath the snow and facilitating the growth of several species of 'snow molds'. These snow molds exhibit exponential responses to temperature variation near 0 °C in both biomass increase and metabolic rate per unit biomass; the product of a double exponential function causes temperature sensitivity of the total respiration rate to be several orders of magnitude higher than the Q_{10} value of 2 typically used for metabolic responses alone.

“We are using the Niwot Ridge tower site as a place to study interactions among the various processes that determine the local carbon budget

We conducted studies on the nature and consequences of rhizodeposition from trees, and its influence on soil organic matter mineralization, microbial biomass and soil respiration.

Figure 2: Conducting winter flux research at the C1 NOAA site. The trailer in t he foreground houses the computers and other equipment for the Niwot Ridge AmeriFlux tower.

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Niwot Ridge, *AmeriFlux site, USA*

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Figure 3: The western fetch as viewed from the Niwot Ridge AmeriFlux tower.

Studies led by graduate student Laura Scott-Denton revealed that despite the winter dormancy of trees in this forest, a large amount of sucrose appears in the soils. This 'winter sugar' does not appear in plots with trees that were girdled the previous summer (Scott-Denton et al. 2006). This winter rhizodeposition primes the soil for increases in microbial biomass and loss of dissolved organic carbon from the site, both of which reach early season maxima during the snow melt period. In studies led by post-doc Mike Weintraub, we found that the breakdown of cellulose, lignin, chitin, and organic phosphorus were not affected by springtime increases in soil microbial biomass. In this latter study, we concluded that the priming of soil C mineralization by rhizodeposition is due to the stimulation of the microbial biomass and an increase in the breakdown of N rich proteins, but not due to increases in the degradation of plant litter constituents such as cellulose and lignin from microbial exoenzymes.

Finally, we collaborated with Dave Schimel (NEON, Inc.) to develop an ecosystem model capable of assimilating our eddy flux observations for studies of component fluxes (photosynthesis and respiration) and their response to climate variation. In our initial use of the Simple Net Photosynthesis and Evapotranspiration (SIPNET) model we were able to partition NEP into its gross photosynthetic and ecosystem respiration components in a manner that was consistent with our past leaf and soil chamber measurements (Sacks et al. 2007). In recent studies, post-doc Dave Moore worked to modify SIPNET so that it would assimilate evapotranspiration (ET) data from the tower, and partition it into its component fluxes of soil evaporation (E) and tree transpiration (T) (Moore et al. 2008). The model partitioning was validated against tree sap flux measurements and was able to replicate the tight coupling between seasonal NEP and ET that is observed in the eddy flux data.

We have initiated new studies that we hope will improve the predictions of SIPNET. In collaboration with Dave Bowling (University of Utah) we have collected a three-year set of continuous $^{13}CO_2/^{12}CO_2$ measurements along a vertical profile within and just above the forest canopy. We are hoping to modify SIPNET to be able to assimilate $^{13}CO_2/^{12}CO_2$ data from the atmosphere and inform the model respiration routine of a path toward partitioning ecosystem respiration into its autotrophic and heterotrophic components. This is just one final example of our general approach to shoot as many arrows as possible toward that elusive beast known as the local carbon budget in the hopes that we will finally tame it and coax it into a well-fenced pen.

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Further Reading

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Editorial: Citations to Published Data Sets

Robert Cook

The last issue of Fluxletter (Vol. 1, No. 3) contained an editorial with suggestions and guidelines for co-authorship of papers representing the efforts of many flux tower investigators, such as in the collection of La Thuile Synthesis papers (Baldocchi and Vargas 2008). The FLUXNET community has evolved to the point where multi-site integration and synthesis is possible and necessary to advance our science. The community has a wealth of data and information on the "breathing of the biosphere" and integrated analysis of this information across many sites and biomes helps us understand processes controlling these fluxes. How can the contributions of each of the investigators providing data to these syntheses be appropriately recognized?

One of the suggestions from the editorial was to publish data sets at a data archive. There are many advantages to this suggestion.

A permanent data archive enables users to search for, access, and download published data sets. The finalized and published data sets can be cited, giving the data producers credit. Citations to these published data sets enable a student or a researcher to obtain the actual data files from the archive to reproduce the results from papers or to conduct further analyses. The scientific method requires that the information necessary to support published results be made available to other researchers. Publication of the data themselves makes available the information necessary to reproduce the findings. Published papers in AFM, JGR, or Nature provide a description of the methods, analysis, and results, but typically do not provide a way to access the data files themselves. There are a few notable exceptions. Some disciplines (e.g., biotechnology) require publication of data before a paper is published. ESA has a journal –Ecological Archives– that publishes data papers, supplements, and digital appendices for ESA journals.

Government agencies are under increasing pressure to show the benefits of the research they sponsor, both in terms of scientific findings—published papers—as well as data products.

> *"...A permanent data archive enables users to search for, access, and download published data sets. The finalized and published data sets can be cited, giving the data producers credit. ."*

A recent US Government and Accounting Office Report summarizes the issues associated with loss of individual investigator's data and therefore the loss of some of the benefits of research, and outlines some solutions (http://www.gao.gov/products/GAO-07-1172).

Publication of scientific findings in journals has traditionally been the way the benefits were measured. In addition, publication of data sets in a long-term archive demonstrates the products of successful research. Subsequent use of the data sets in other papers as indicated by citations to these published data sets by other researchers in the coming years is also a measure of the value of sponsored research.

The ORNL DAAC, the long-term archive that houses the FLUXNET data, has a citation policy for finalized archived data: http://daac.ornl.gov/citation_policy.html

For example, this is our suggested citation for work conducted at an eddy covariance flux tower in Brazil:

Hutyra, L., S. Wofsy and S. Saleska. 2007. LBA-ECO CD-10 CO_2 and H_2O Eddy Fluxes at km 67 Tower Site, Tapajos National Forest. Data set. Available online at [http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee.U.S.A. doi:10.3334/ORNLDAAC/860

The data citation gives credit to the data providers and gives users an opportunity to locate the data files. In addition, the ORNL DAAC, as publisher, gets credit for hosting data sets that are used to advance environmental research.

In the example above, Lucy Hutyra and her colleagues get credit for a data set citation--not weighted as high as a peer reviewed publication to be sure, but important in and of itself. This credit is one incentive to get data sets archived and shared. And it is measureable, so that research sponsors can see that that LBA data archived at the ORNL DAAC have been used in peer reviewed publications.

The ORNL DAAC has recently started assigning Digital Object Identifiers (DOIs) to the DAAC's collection of published data sets. The use of DOIs facilitates the ability of authors to cite data publications in refereed journals. Many journals now require DOIs when citing online material. DOI's enable users to locate a published data set regardless of where it is stored. This immutable identifier is part of the DOI system and the Hutyra data set can be found by searching for the DOI (10.3334/ORNLDAAC/860) or by searching at the DOI System's Web site: http://dx.doi.org/10.3334/ORNLDAAC/860.

For the archived data associated with a BOREAS flux tower, we suggest the following citation:

Wofsy, S. C., and A. Dunn. 2001. BOREAS Follow-On FLX-01 NSA-OBS Derived Data - NEE, GEE, and Respiration. Data set. Available on-line at

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Citations to Published Data Sets

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[http://www.daac.ornl.gov] from Oak Ridge National Laboratory Distributed Active Archive Center, Oak Ridge, Tennessee, U.S.A.
doi:10.3334/ORNLDAAC/603

For the Wofsy and Dunn (2001) data publication, the documentation about the data set requests that users seek updated and more recent versions of the data from the individual investigators. The citation and the DOI refer to this finalized and archived version of the data from 2001. This version is archived so that a record is kept of data associated with the BOREAS study and any publications associated with the data.

We encourage investigators to add data sets to their resume. This practice will enable investigators to show a product of their research and demonstrate to sponsors that they are complying with policies to share data products. And data product authors will be able to use standard citation tools to determine how many times their data set has been used by others in future publications.

As you know, preparing data for future use is viewed as a time-consuming and heretofore thankless task that can serve as a disincentive to data sharing. The benefits to an investigator are the publication of the finalized data themselves, credit and recognition for use of data by others, and demonstrating compliance with sponsors' data sharing policies. Publishing data at an archive also takes the burden off of the investigator for maintaining the information on-line and dealing with user requests and questions.

A scientist is recognized within the scientific community, proposal review panels, and Promotion and Tenure Committees based in part on publication in the peer reviewed literature. Until recently, preparation of finalized data to share with others has not been a part of this reward structure. Many sponsors of flux tower and other environmental research are using compliance with data policies as part of their proposal evaluations and the GAO report suggests that more sponsors will do so in the future.

Publishing data products and citing those products in the literature are relatively new practices, and we are seeing more citations to published data sets. Use of a standardized citation format along with immutable DOIs will promote this practice of publishing and sharing data sets. And this practice of publishing finalized data products will promote additional flux synthesis studies, advancing our understanding of the processes that control the "breathing of our biosphere," while giving credit and recognition to those who have made the observations.

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Literature

U.S.GAO. 2007 . Climate Change Research: Agencies Have Data-Sharing Policies but Could Do More to Enhance the Availability of Data from Federally Funded Research. GAO-07-1172. Available on-line at http://www.gao.gov/products/GAO-07-1172.

Baldocchi DD, Vargas R. 2008. Whither co-authorship? FluxLetter 1(3) 3-4. Available on-line at http://www.fluxnet.ornl.gov/fluxnet/FluxLetter%20Vol1%20No3.pdf

Highlight Graduate Student

Miguel Román

My name is Miguel Román, and I was born and grew up in the tropical city of San Juan, Puerto Rico. I am currently a PhD Candidate at Boston University's Center for Remote Sensing working under the direction of Professor Crystal Schaaf and focusing on regional assessments of surface albedo and reflectance anisotropy. Land surface albedo, or the ratio of radiant energy reflected from the Earth's surface to the incident flux, is a key biophysical parameter that controls the underlying variability of the surface radiation budget. Variations in the extent of snow cover and flooding, the phenology of natural vegetation and agricultural crops, as well as other signatures from rapidly changing surface covers (e.g. burning, clearing, and tilling) are all accompanied by significant changes in surface albedo. As such, regional surface albedos with an absolute accuracy of 0.02-0.05 units for snow-free and snow-covered land have been required by the modeling community at a diverse range of spatial (from 10s of meters to 5-30 km) and temporal (from daily to monthly) scales.

Satellite remote sensing offers the only realistic means of monitoring surface albedo by providing spatially variable and temporally dynamic observations in a continental or global sense. With the launch of a number of polar orbiting sensors over the past decade, including MODIS, MISR, CERES, MERIS, and Parasol-POLDER, several routine global land surface albedo and reflectance anisotropy products are now being produced. Implementing regional assessments of remotely sensed albedo and reflectance anisotropy products will thus provide users with a pixel-specific measure of product uncertainty both in terms of the quality of the model inversions (e.g. given a limited number of cloud-free satellite observations), and their ability to capture the underlying spatial variability at the various grid scales at which ecosystem, hydrological, climate, and weather forecasting models are commonly utilized.

Figure 1 - Top: ARM-SGP Central Facility. Bottom: Boston University's Sargent Camp.

One key step in evaluating and improving the quality of our retrievals involves the production of improved methods to estimate true surface albedo (i.e. comparable to ground-based measurements taken at a point in time and under specific atmospheric conditions). In particular we want to address the specific role of the fraction of diffuse skylight under realistic scenarios of anisotropic multiple scattering. With the help from our FLUXNET colleagues, we are now evaluating our most rigorous estimates against coincident field measurements over a number of field stations with varied aerosol levels and unique landscapes ranging from croplands (e.g. Figure 1) to tundra ecosystems, to further document the ability of our satellite retrievals to capture the daily variability of surface albedo.

Another key issue in terms of using remotely sensed data for regional assessments is to quantify the intrinsic errors associated to spatial-scaling effects.

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Highlight Graduate Student

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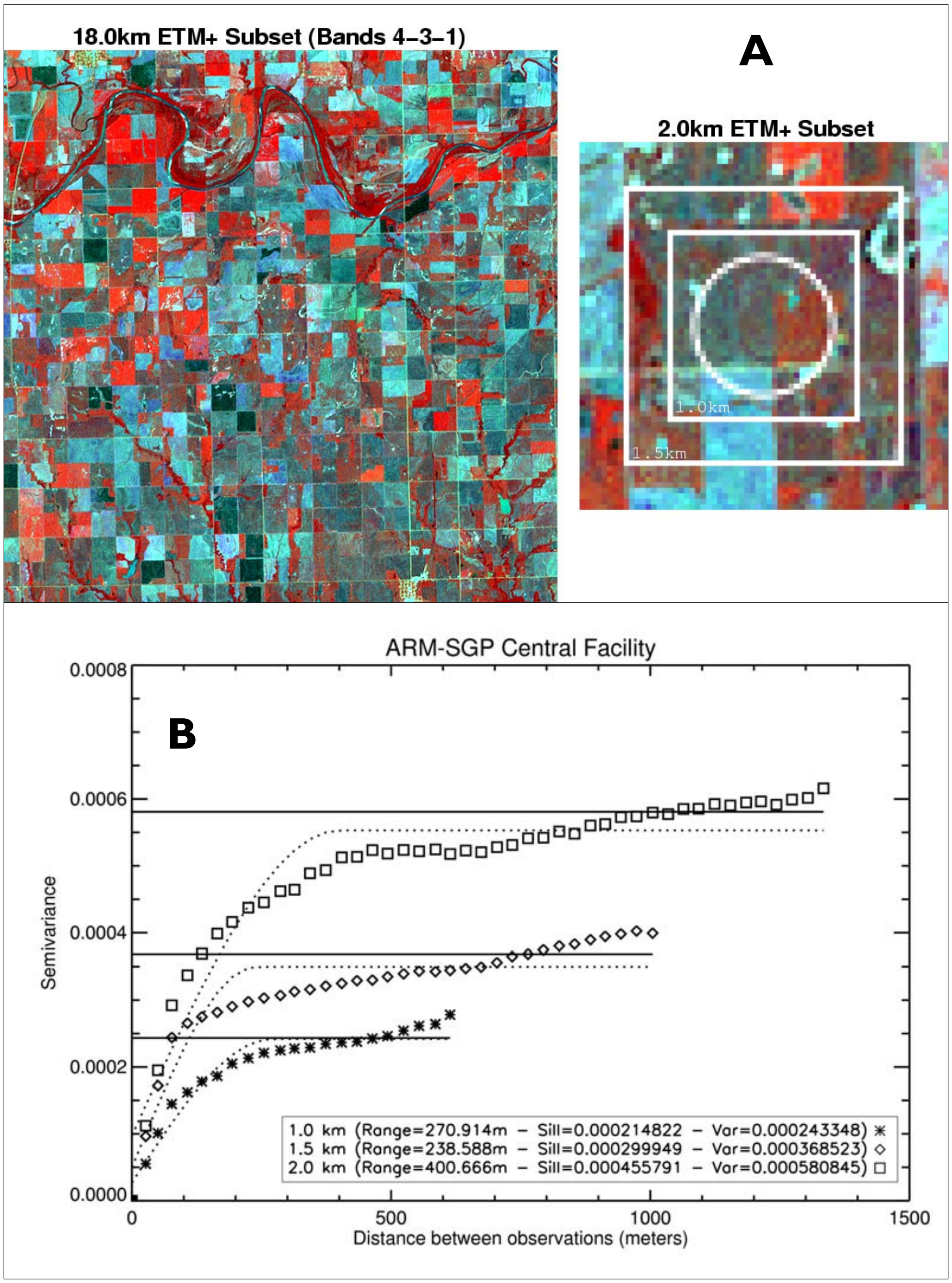

Figure 2 – (A) Top of Atmosphere Reflectance (ETM+ Bands 4,3,1) subsets at 18.0 km as well as 2.0 km, 1.5 km, and 1.0 km boundaries, all centered at the ARM-SGP Central Facility tower footprint (circular area). The region (also shown of Figure 1) shows a cluster of agricultural fields ranging from winter-wheat (including stubble) and pasture. (B) Variogram estimator (points), spherical model (dotted curves), and population variance (solid straight lines), all as a function of separation distance, obtained over the ARM-SGP Central Facility using surface albedos collected on 30 May 2001 from the same Landsat ETM+ scene.

Accordingly, we developed an algorithm that quantifies the spatial extent, structure, and strength of primary biophysical processes (including but not limited to albedo) by utilizing multispectral high-resolution imagery (e.g. 30m Landsat ETM+ or 15m Terra-ASTER) as intermediates between ground and satellite retrievals. The resulting product from this “footprint” analysis is an unbiased set of geostatistical measures derived from the principles of traditional variography that characterize the degree of spatial representativeness between the prescribed footprint and its surrounding landscape (as seen on Figure 2 for the ARM-Southern Great Plains Central Facility). Note that our goal here is to measure the overall degree of spatial representativeness, as opposed to spatial heterogeneity. One could argue that the observed landscape can be categorized as both spatially heterogeneous and spatially representative, depending on the structural consistency between the field station (be it from a small 4m flux tower or a PAR sensor overlooking a 2km circular footprint) and the surrounding region extending to a moderate resolution pixel (i.e. 500m - 2.0km).

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Further Reading

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Highlight Young Scientist

Paul Stoy

I was born in the Twin Cities and grew up in the small town of Hudson, WI. As kids we built forts in every forest and were always outside. There was a soil texture gradient in my backyard. I liked that the forest transitioned to what used to be prairie nearby, and I'm sure that some patches were remnants. Developers liked Hudson for its proximity to the Twin Cities. It's an exurb now.

I decided to become an environmental scientist as an undergraduate at the University of Wisconsin. The laboratory of Jon Foley started me on my way; it was a great place to work. I studied the effects of prairie restoration on soil carbon sequestration for my undergraduate thesis with Chris Kucharik. No significant sequestration effect was found on a restoration chronosequence with sandy soils at the International Crane Foundation (but see Brye and Kucharik, 2003).

As an undergraduate I spent a semester in Bayreuth, Germany in the lab of John Tenhunen. I measured sapflux with Markus Schmidt and Dennis Otieno in the Fichtlegebirge and in the Berchtesgadener Alps. The field sites were fantastic. Markus Reichstein graduated with his Ph.D, and we rolled out the 'Doktorwagen'.

After recovering from Markus' party I headed to Duke to work on a Ph.D in Ecology with Gaby Katul and Ram Oren. The Duke Forest was, is, and will be an outstanding place for a graduate student to do research and the Katul and Oren labs are great. The research scene at the Duke FACE site was fun, with amazing infrastructure and a revolving cast of characters working on an immense array of projects. I also snuck out when I could to help with projects in the North Carolina mountains and on the coast. The opportunity to help others with their work is critical to being well-rounded in the field.

My thesis quantified CO_2 and water and radiation flux using eddy covariance measurements in the Duke AmeriFlux old field – planted pine – hardwood forest chronosequence. Net C uptake over five years of measurements was approximately the same at the pine plantation and hardwood sites because pine C exchange was highly sensitive to drought and ice storm disturbance (Stoy et al., 2008). Conservation of mature stands may be an excellent way to sequester carbon while maintaining diverse, beautiful forests. Research outputs can be found at:

www.geos.ed.ac.uk/homes/pstoy

http://www.nicholas.duke.edu/people/faculty/katul/homepage.html

http://face.env.duke.edu/main.cfm.

Since graduating I've been working on the ABACUS project (Arctic Biosphere Atmosphere Coupling at mUltiple Scales, www.abacus-ipy.org) at the University of Edinburgh with Mat Williams and a diverse research team from a number of institutions in the UK. Four eddy covariance towers have been set up in birch forest, wetland and tundra ecosystems in Abisko, Sweden and Kevo, Finland. The ABACUS research strategy is to assimilate leaf, plant, soil, chamber, eddy covariance, remote sensing, and aircraft measurements into ecosystem models using data assimilation techniques. After completing the science plan, results can be linked to other area towers (e.g. Stordalen, Kaamanen). The flux and meteorological data will make its way into the FLUXNET database before long.

Data makes FLUXNET great and colleagues make it fantastic. Whenever I'm traveling, which tends to be often, I try to tour a flux site. Accumulating tricks and techniques from colleagues working at Puechabon, Tonzi/Vaira, Hainich, Griffin and Stordalen is invaluable for a young researcher thinking of new or different approaches. I'm writing this en route to Bartlett, NH, with Andrew Richardson to fix a wayward tower cam that revealed its erroneous position over the internet. As FLUXNET continues to grow, data streams become even more interconnected and available online, and opportunities to compare results become even more infinite, if that can be said, the best way to build collaborations is to go to a site and do a bit of fieldwork, to see how research is done elsewhere and enhance your own science accordingly.

Figure 1: Paul as a visiting scientist at the FLUXNET Office, Berkeley, CA, USA

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Literature

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Combining flux and ecosystem data with land surface models: the role of FLUXNET

Mathew Williams, Paul Stoy, Andrew Richardson, Enrico Tomelleri, Cathy Trudinger

From June 4-6, 2008, a meeting was convened in Edinburgh that combined scientists from the FLUXNET and carbon modelling communities. The objective of the meeting was to determine ways in which eddy covariance (EC) measurements might be used to improve the representation of ecosystem processes in land surface models (LSMs). Common examples of LSMs include Orchidee (Morales et al. 2005) and the Lund-Potsdam-Jena (LPJ) model (Sitch et al. 2003). The meeting focused particularly on the application of model-data fusion (MDF) techniques to bring together measurements and models in a rigorous, statistically-based analytical framework.

The participants recognized that currently model building is largely uncoordinated, and that there are no clear criteria for model improvement. Model outputs often lack assessments of error and bias, and this reduces their utility. However, large arrays of data are now available, particularly time series information such as EC data, which can provide insights into the model processes critically requiring improvement. MDF techniques provide the basis, theoretically, for linking models and observations optimally. Model-data fusion for carbon cycle science has been discussed before (Raupach et al. 2005). However, the application of MDF to ecological problems remains in its initial stages, with considerable knowledge gaps regarding practicalities.

The Edinburgh meeting addressed a series of key issues related to linking eddy covariance data to LSMs using MDF. The questions we addressed included:

1- What are the strengths and weaknesses of the various MDF approaches?

2- How should observation and model error be determined?

3- How do we assess observational and model bias?

4- What ancillary data (including Earth Observation) can and should be involved?

5- How can the LSM and FLUXNET communities best collaborate?

For accessing presentations from the meeting see www.carbonfusion.org/LSM.html. A focused discussion that addresses these questions in detail is forthcoming as a result of the meeting (Williams et al. in prep). Below we discuss in brief some of the issues raised and some background.

The principles of model-data fusion

The mathematical foundations of DA can be derived from Bayes' Theorem (equation 1). The posterior probability distribution of the model *M* given observations *O*, written $p(M\,|\,O)$ is defined as the product of the prior model state $p(M)$ and the probability of *O* given previous model state $p(O\,|\,M)$ normalized by the probability of the observations, $p(O)$ (Lorenc 1995):

$$p(M\,|\,O) = \frac{p(O\,|\,M)\,p(M)}{p(O)} \qquad (1)$$

The important concept here is that distributions are required. The terms in (1) are probability distribution functions (pdfs), not simple measurements. Every observation and model state and rate term must have an associated error term, best expressed as a pdf. Quantifying uncertainty is just as important as making the measurement, as this allows multiple data streams to be incorporated into the model estimate with correct weightings (Williams et al. 2005, Figure 1).

Error estimation

Many of the fundamental papers in the EC literature address the issue of error estimation (Goulden et al. 1996), and this area of research continues to develop. Random error in instantaneous (half-hourly) flux observations has been argued to follow a Laplacian distribution (Hollinger and Richardson 2005). However, there is evidence that flux error is normally distributed but heteroscedastic, with variance increasing with flux magnitude (Lasslop et al. 2008). This current research focus on EC error is timely for MDF studies, given the requirement by MDF for accurate assessment of flux error. While there is progress in assessing random error, systematic error is less easily evaluated. We suggest that MDF provides an opportunity to assess systematic EC error, by linking other, independent data series to EC data through the model structure.

Multiple constraints

Net flux measurements do not provide enough information to constrain the simulation and

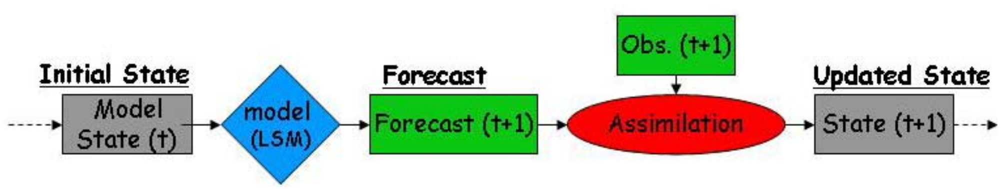

Figure 1: A schematic of sequential assimilation of data into a state-space land surface model (LSM), using an Ensemble Kalman filter (EnKF). A model ensemble (with associated error) is run forward from its initial state at time *t* to provide a forecast at time *t*+1 (likewise with associated error), and then combined with observations (again, with error) in the assimilation step (see equation 1). In the EnKF, the model error covariance matrix propagates the information from the assimilated observation(s) throughout the model state vector.

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Combining flux and ecosystem data with land surface models

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estimation of component gross fluxes – a net flux can be generated by many combinations of photosynthesis and ecosystem respiration. MDF approaches can provide useful quantification of this problem of *equifinality,* by generating pdfs of model parameters and model states. Narrow posterior pdfs can indicate that the EC data provided substantial information on the process associated with the particular parameter.

MDF can further indicate how parameter confidence intervals are reduced according to the type, amount and quality of data involved in the fusion. For LSMs, ancillary information like leaf area index, biomass, or energy fluxes, provide useful extra constraints on model processes (Williams et al. 2005). The MDF process serves to check consistency among multiple independent data types, for instance between EC and biometric data. It is also possible to assimilate earth observation (EO) data, such as MODIS time series (Quaife et al. 2008). MDF with EO data opens up possibilities for extrapolating information from FLUXNET sites to their surroundings, with assessments of uncertainty.

Model-data fusion inter-comparison

Two recent studies have focussed on comparing the capabilities of MDF techniques. The OptIC experiment used a simplified model and synthetic time series data, i.e. data generated from the model, with noise added. Multiple groups employing a range of MDF techniques attempted to estimate the parameters that were used to generate the synthetic data (Trudinger et al. 2007). The REFLEX experiment used a daily model of carbon fluxes and pools and provided both synthetic data and EC data from two FLUXNET sites. Participants used a range of MDF approaches, and attempted both to estimate parameters and determine fluxes of C and changes in stocks over multiple years (Fox et al. in review). REFLEX participants generated confidence intervals on all estimates, so it was possible to assess whether MDF approaches correctly assessed confidence by comparison with the synthetic data for which the "truth" was known. For more information on REFLEX see www.carbonfusion.org/Reflex.html.

The interaction between 'measurers' and modelers

The requirements for flux (and stock) data and error introduces a challenge for FLUXNET, which has to date excelled at reporting flux data, but less so at quantifying, reporting and organizing flux observation error, ancillary data, and particularly ancillary data error. These data requirements are heavy, and the perception may exist that delivery of data to modellers represents asymmetry in the modeller-measurer interaction (Figure 2). But measurers also benefit from LSMs, which provide a broader justification for observations and provide a mechanism to extrapolate observations to larger scales (Jung et al. 2007), to help answer the questions related to regional land-atmosphere interaction.

The future of MDF and FLUXNET

Modellers and measurers have a common goal of quantifying biosphere atmosphere fluxes (Figure 2). The meeting identified the need for a new model-data fusion exercise for LSMs using FLUXNET data. This exercise would build on previous model-data fusion projects, such as OptIC and REFLEX, using LSMs with a range of complexity, synthetic and EC data from several key biomes, including sites with long (>10 years) data time series, and with a range of auxiliary data. A major output of such an exercise would be forecasts of carbon dynamics *with confidence intervals* over multiple years beyond the period of MDF. The overarching goals of this exercise would be to identify systematic error in models and data, and to improve our skills in generating defensible and realistic model confidence intervals.

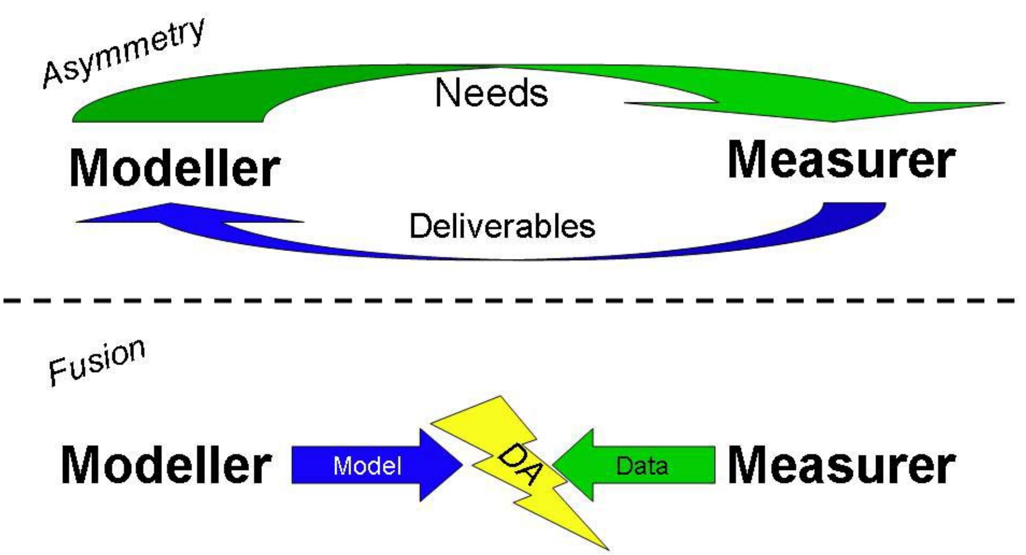

Figure 2: Asymmetry in the conventional modeller/measurer interaction can be replaced by the dual requirements for both models and measurements, with associated error terms, in a model-data fusion scheme.

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Combining flux and ecosystem data with land surface models

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Measuring and modeling CO_2 and H_2O fluxes in complex terrain

Diego A. Riveros-Iregui and Brian L. McGlynn

Photo: Riparian meadow

The feedbacks between the water and the carbon cycles are of critical importance to global carbon balances. Forests and forest soils in northern latitudes are important carbon pools because of their potential as sinks for atmospheric carbon. However there are significant unknowns related to the effects of hydrologic variability, mountainous terrain, and landscape heterogeneity in controlling soil carbon dioxide (CO_2) efflux. Mountainous terrain imposes large spatial heterogeneity in the biophysical controls of soil CO_2 production and efflux, including soil temperature, soil water content, vegetation, substrate, and soil physical properties. Further complications are introduced by the superimposed temporal heterogeneity (i.e., the asynchronous response of each variable to changes in environmental conditions). As a result, extrapolating from single- or multiple-point measurements to larger areas requires understanding of the emerging patterns controlled by the underlying spatiotemporal nature of biophysical drivers.

At the Tenderfoot Creek Experimental Forest (TCEF) in central Montana, two factors that we use to our advantage in the understanding of watershed-scale soil CO_2 efflux are 1) the temporal seasonality imposed by snowmelt and 2) the spatial redistribution of soil water imposed by topography. Snowmelt controls the timing of the most dramatic increase in water content in the soil, while landscape morphology redistributes that moisture down slope to lower areas of the landscape. Our site selection (62 soil respiration plots) targeted those areas of the landscape that offered natural biophysical gradients (Figure 1). Two eddy covariance systems were installed over the canopy of the two most important systems: a riparian meadow and a lodgepole pine forest (Figure 2). Additionally, we investigate surface water – groundwater interactions and subsurface flowpaths between different landscape positions and the stream using an array of 80+ groundwater wells and piezometers (~1-2 m depth). Our coupled water-carbon approach is based on the concept of topographic similarity [*Beven and Kirkby*, 1979], which hydrologists and biogeochemists have used to transfer process and response understanding to topographically and thus hydrologically and biogeochemically similar areas [e.g., *Creed et al.,* 1996; *Boyer et al.*, 1997; *McGlynn and McDonnell*, 2003]. This idea is conceptually intuitive because 1) many biogeochemical processes are mediated by temperature, water content, radiation, and energy balance, variables that often vary predictably with topographic position; and 2) this form of heterogeneity also depends on other abiotic factors (e.g., slope, soil type, upslope accumulated area), which can be considered static over relevant times scales [*Moorcroft*, 2006]. As such, topographic similarity can help scale soil CO_2 efflux rates from single- or multiple-point measurements to watershed scales or larger areas. Determining the minimum set of watershed measurements or variables needed to characterize soil CO_2 efflux both spatially and temporally is not trivial. However, terrain analysis techniques can help link spatial watershed patterns with biogeochemical processes, aid in transfer and interpolation, and indicate where additional field observations are needed. New process knowledge gained from such observations can help characterize the landscape, discretely or continuously, as an arrangement of response characteristics and thresholds.

Current work at the TCEF based on multiple-point measurements has demonstrated that the spatial variability of soil CO_2 efflux across the 62 sites is higher than previously thought (Figure 3). Riveros-Iregui et al.

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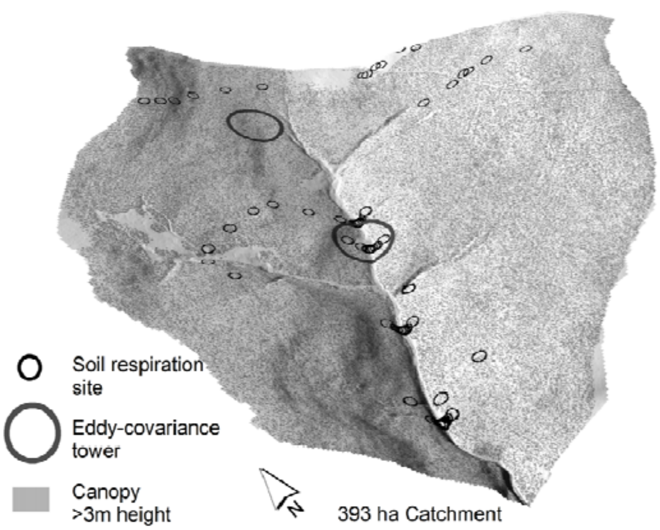

Figure 1: Tenderfoot Creek Experimental Forest (TCEF) in the Little Belt Mountains of Central Montana. Soil respiration is measured at 62 sites distributed across the catchment.

Measuring and modeling CO_2 and H_2O fluxes

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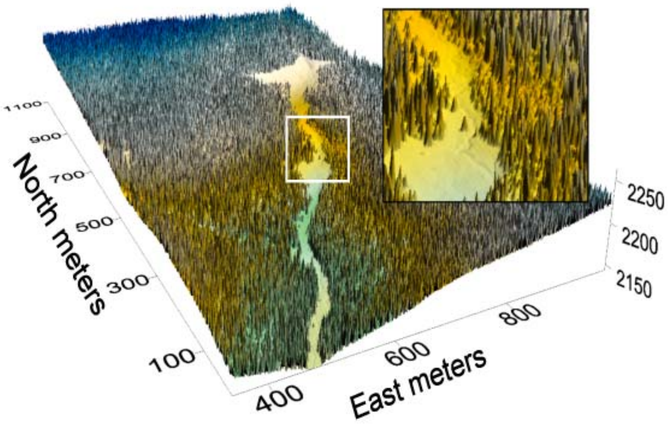

Figure 2: LIDAR-derived image of vegetation cover at the TCEF.

[in press] demonstrated that more persistent, high soil water content was the major control on the spatial difference of soil CO_2 efflux and nighttime ecosystem respiration between riparian-hillslope sites especially after snowmelt or rainfall. Pacific et al. [2008] analyzed soil CO_2 efflux measurements across riparian-hillslopes transitions based on soil gas wells and discrete chamber measurements. Their results show that soil CO_2 efflux rates differ, both in magnitude and timing, across riparian-hillslope transitions. While early in the growing season soil CO_2 efflux is higher in hillslopes than in riparian areas, later in the season soil CO_2 efflux from riparian areas becomes higher than in hillslopes. Our preliminary results demonstrate how landscape discretization and the concept of topographic similarity can help extend understanding and measurements of soil CO_2 efflux based on benchmark measurements to larger areas of the landscape. There remain great challenges in dealing with complex topography, especially transferring knowledge acquired at point/plot scales to larger spatial scales, and reconciling C fluxes measured at different levels of the ecosystem. However, based on initial results of coupled water-carbon studies in the subalpine forests of the TCEF, we recommend implementation and further investigation of the concept of "organized heterogeneity" as a responsible agent in the emergent patterns of these fluxes from the plot to the watershed to regional scales.

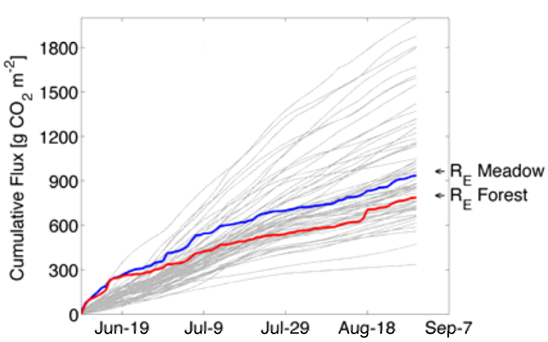

Figure 3: Comparison of cumulative CO_2 fluxes for the 2006 growing season at 62 sites (gray lines) and ecosystem respiration (R_E) measured with the EC technique over a riparian meadow (blue line) and the lodgepole pine forest (red line). Range of soil respiration varies by us much as ~600% across the catchment. Terrain analysis as well as process understanding of the organized heterogeneity are critical in up-scaling plot measurements of soil respiration to spatial scales comparable to towers.

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