FluxLetter

The Newsletter of FLUXNET

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Highlight FLUXNET site
Puechabon

Experimental Site of Puechabon, South of France
by Laurent Misson

History- In 1984, pioneer researchers François Romane started long-term ecological studies in a *Quercus ilex* forest next to the village of Puéchabon near Montpellier, south of France (Photo 1). *Quercus ilex* forests have been long ago considered as a paradigm for Mediterranean ecosystems growing on hard limestone karstic soils. It's a highly adapted species to unpredictable environments characterized by long summer droughts, storm events acting as resource pulses, and strong and frequent disturbances such as fire. *Quercus ilex* life history-strategies include some of the most prominent found in such ecosystems: it's an evergreen species with thick sclerophylous leaves; it has a diffuse-porous wood of high density providing resistance to cavitation; and it's a resprouter allocating vast amount of reserve carbohydrates to an overdeveloped root system that could extract water at more than 5-m depth. *Quercus ilex* is a strong terpenoid emitter, with VOC production accounting for 1 to 2% of GPP. This species covers millions hectares around the Mediterranean sea. As such it's a fascinating research subject and the functioning of *Quercus ilex* ecosystems have attracted many researchers for decades.

Photo 1: General view of the experimental site of Puechabon

First, studies at Puéchabon focused on forest structure, biogeochemical cycles and post-disturbance recovery. In the early nineties, with questions concerning global change arising, detailed functional studies started to understand the effects of climate on the vulnerability of

Photo 2: Flux tower at Puechabon

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Mediterranean forests. With the 1997 Kyoto protocol, European countries have been committed to report precise carbon accounting. Since 1998, Puéchabon is one of the reference sites of the European network for measurements of carbon and energy exchanges between the atmosphere and the land surface, through the Medeflux (1998-1999), Carboeuroflux (2000-2004), and Carboeurope-IP (2004-2009) projects. In 2003, several manipulative experiments started with the MIND project financed by the European Union. Rain exclusion and thinning were applied to study the effects of changing precipitation amounts and management practices on forest-atmosphere carbon and water exchange. Theses experiments culminate in 2007 with a new project testing the effects of extreme seasonal drought in spring and fall on the vulnerability of Mediterranean forest ecosystems (Drought+ project, French National Research Agency).

Infrastructure- The infrastructures at Puéchabon include several experiments. First, an eddy-flux tower and two meteorological stations record CO_2, water and energy fluxes between the atmosphere and the forest continuously since July 1998 (Photo 2). A new paper reports analyzes of seasonal and annual variation of carbon exchange (Allard et al. 2008). On average the forest acted as a net carbon sink of -250 g C m^{-2} yr^{-1}. Extreme events such as spring droughts (2005, 2006), insect-induced canopy defoliation (2005), and in a smaller proportion the 2003 heat-wave, have the effects of greatly reducing this sink capacity (Fig. 1).

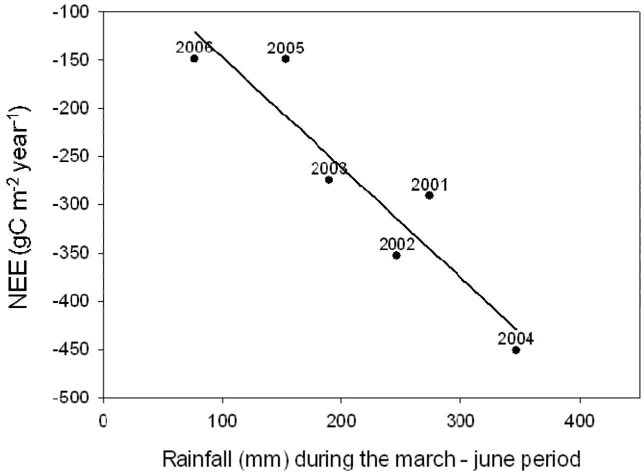

Figure 1: Relation between ecosystem annual NEE sum and rainfall during spring (March to June)

Second, a series of long-term continuous manipulative experiments started in 2003. These included 4 treatments: a control, a throughfall exclusion, a thinning, and a throughfall exclusion x thinning treatment. Throughfall exclusion was achieved using gutters under the canopy, with the aim to exclude 30% of the throughfall continuously (Limousin et al. 2008) (Photo 3). Thinning reduced the basal area by half. Scaffolds allow researchers to have access to two levels in the canopy for ecophysiological measurements of sun and shaded leaves (Photo 4).

Third, in 2007 a new manipulative experiment has been designed to simulate the effect of an extreme climatic event on the functioning and the vulnerability of this ecosystem. A rainfall shelter was installed above the canopy in order to simulate extreme drought seasonally (Photo 5). The rainfall shelter is mobile and move on two 60-m rails that are 15-m apart. Four plots are defined: an early drought plot on the south side (spring drought) and, a late drought plot on the north side (fall drought), a standby plot in the middle, and a control plot nearby. The roof will stay over the standby plot when it is not raining to avoid disturbing the

> *"The database includes long-term ecological data on forest growth, above-ground and belowground biomass, regeneration, litterfall, functional traits and phenology "*

Photo 3: Continuous rain exclusion experiment: control and dry plot

Photo 4: Second level of the scaffold in the continuous rain exclusion experiment

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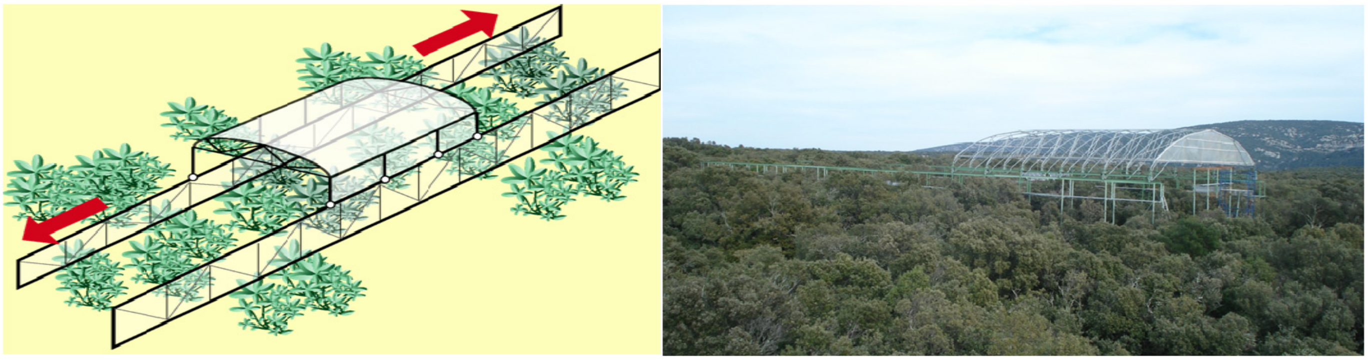

Photo 5: Mobile rainfall shelter for simulation of seasonal drought (DROUGHT + project)

micrometeorology of the drought plots.

Data- The database at Puéchabon is huge and goes back to the 1980's. It includes long-term ecological data on forest growth, aboveground and below-ground biomass, regeneration, litterfall, functional traits and phenology. Data on the main biogeochemical cycles include eddy-covariance CO_2 fluxes, soil and organ-level gas exchange data. Measurements for the water cycle include all the main fluxes, the top soil water content and discrete measurements of soil water storage across 5-m depth since the 1990's. Dry and wet nitrogen deposition started in 2007 as a companion site of the Nitroeurope UE project. Organs, soil and litter chemistry and biochemistry have been described semi-continuously. Detailed ecophysiological data and organ level VOC emission have been measured discontinuously since the 1990's.

Photo 6: Puechabon team

For further information see:

http://www.cefe.cnrs.fr/fe/puechabon/index.htm

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Editorial: FLUXNET, *Quo vadis*

Dennis Baldocchi

At this moment 510 sites are registered on the FLUXNET database. In planning for the future we must ask and assess what will FLUXNET look like in 3 to 5 years? For example, will growth continue, as we attempt to fill holes in the network in key regions like the Arctic tundra, India, Africa and Mexico, or will the network contract as funding becomes tighter and many of the original research questions get answered?

The continued operation of a global network, like FLUXNET, lies on the foundation of diverse sources of funding. Inevitably, like Death and Taxes, regional networks and independent research teams must periodically submit renewal proposals that are subject to peer-evaluation. Unfortunately, there is no guarantee of future and continued support for particular tower sites, or regional networks.

To sustain funding of regional networks and independently funded sites there are a variety of science and funding issues we need to recognize and overcome. At present, funding across the environmental sciences is highly competitive (success rates among many agencies in the U.S. ranges between 10 and 20%) and research priorities change. No doubt, the proposal/review process and competition is good because it forces us to re-evaluate our science and strive for evolving and better projects that reflect evolving research priorities. But in competing for new funding we must be conscious of and avoid becoming 'victims of our success'. We have produced an unprecedented dataset and a large body of literature. Together, they contain many exciting findings about the biophysical controls of carbon fluxes at daily to annual time scales, how carbon fluxes differ across ecosystems and climate gradients, their responses to disturbance and their interannual variability. Consequently, we face the added burden of convincing peer-review panels that continued operation of a long-term flux measurement site will produce more discoveries, rather than produce incremental findings.

Convincing arguments and rationales are needed to ensure continued funding and to help set the agenda for future research priorities. Foremost, we can't lose sight of the fact that we are measuring how the Earth's terrestrial biosphere is responding to an unprecedented change in climate and land use. This fact alone provides us with a strong opportunity, motivation and responsibility to continue making long term flux measurements across the globe. As data records get longer, we will soon have the opportunity to study how carbon fluxes change as ecosystems undergo natural succession. To emphasize this point, I submit evidence that trends in carbon fluxes are emerging from decade plus records at Harvard forest, which is recovering from disturbance in the late 1930s (Urbanski et al., 2007).

It is also noteworthy that the FLUXNET community continues to produce a treasure trove of information to a wide number and variety of stake holders. The long-term data records and future flux measurements will continue to be necessary for validating land-surface schemes in models that address problems associated with the climate, ecosystems and vegetation dynamics and biogeochemical cycles (water, carbon). Flux and meteorological data are also needed by those interested in data assimilation and model parameter inversion schemes and interpreting remote sensing indices. And in the future, I expect carbon flux data will be used by ecosystem managers, carbon traders and policy makers. At present these user communities do not bear the cost of the network, but their activities will suffer if groups of towers quit operating. At best, these stakeholder communities should be encouraged to lobby on our behalf for extending the flux measurement record into the future.

> *"Convincing arguments and rationales are needed to ensure continued funding and to help set the agenda for future research priorities "*

The investment in this global flux network may seem expensive, but it is comparable to many projects in geophysics and it is very cost effective considering the value of carbon flux data to many broad economic sectors and policy. The investment in FLUXNET represents a yearly investment, globally, of about $25M to $75M per year, if we assume that the cost of each site ranges between $50k and $150k per year, based on salaries, instrumentation, travel and discounting for teams who run multiple sites. The cost of this global flux network is small if one considers the value that information on carbon cycling will provide to emerging carbon trading markets and towards efforts to reduce carbon emissions and manage ecosystems for carbon sequestration. For instance, to stabilize and reverse greenhouse warming, efforts will be needed to reduce carbon emission 80% of current levels by 2050, if not sooner. So a $25 - 75M annual investment in a global economy, dependent on energy from fossil fuels and worth 10's of trillions of dollars, should be justified to better manage carbon sinks and sources.

This leads me to ask the question 'how big the network should be and how long individual sites should operate?' The answer depends on the scientific questions being asked of the network. Different configurations of the global and regional networks provide different services and sets of information. A small group (50 to 100) of long-term and intensive field sites spread across the globe, like Hyytiala and Harvard Forest, may prove to be adequate sentinels for assessing the impact of global change across a diverse set of ecosystems. Conversely, a larger network of cheaper and less intensive sites (300-500) may be needed to produce statistical models that are being

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FLUXNET, *Quo vadis*

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used in conjunction with remote sensing data, neural networks, inverse modeling and data assimilation schemes to perform continental and regional integrations. A large network is useful for capturing low probability climate and disturbance events like regional droughts, wind storms, fires, and pest outbreaks. An example of this function has recently been demonstrated by case studies associated with the 2003 heat spell and drought across Europe (Ciais et al., 2005) and the late spring frost across North America in 2007 (Gu et al., 2008). Data records on the order of a decade or two will be needed to detect if trends in fluxes are occurring and determine whether they are due to global climate change, natural succession or large-scale climatic oscillations (Hember and Lafleur, 2008; Magnani et al., 2007).

This editorial has been motivated because I suspect we may be near a tipping-point regarding sustained funding for the continued operation of components of the flux network. Consequently, we will need to work together and provide decision makers, potential funders, reviewers and future users of the data with compelling reasons to keep these networks and sites funded and operating. This is a lesson I have learned from reading about the trials and tribulations of David Keeling (Keeling, 1998). He had to struggle continually to keep the Mauna Loa carbon dioxide observation site running, a point re-iterated in a recent issue of *Science* by his son, Ralph:

'A continuing challenge to long-term Earth observations is the prejudice against science that is not directly aimed at hypothesis testing. At a time when the planet is being propelled by human action into another climate regime with incalculable social and environmental costs, we cannot afford such a rigid view of the scientific enterprise. The only way to figure out what is happening to our planet is to measure it, and this means tracking changes decade after decade and poring over the records. A point of diminishing scientific returns has never been realized in what is now known as the "Keeling Curve," the Mauna Loa CO_2 record'. (Keeling, 2008)

This sentiment is true for flux networks too.

FluxLetter invites the readers to contribute Editorials on emerging science and policy issues of interest to the wider community.

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What can dense Ameriflux site clusters say about spatial and temporal heterogeneity in carbon and water cycling?

Ankur Desai

Carbon and water cycling in northern forests is spatially and temporally heterogeneous. Is there any hope that we could observe, explain, and model this spatial and temporal variation in light of understanding impacts of future climatic change and human disturbances on regional biogeochemistry? Could high density observational coverage and high fidelity modeling of ecosystems across such a landscape help? What do these observations and models say about the role of ecosystem stand age, moisture sensitivity, phenology, parameter tuning/optimization, biometric measurements, transpiration variability, and boundary layer dynamics? The answers are yes, maybe, and read the articles in a 2008 special issue of Agricultural and Forest Meteorology to find out.

One of the densest cluster or mesonet of Ameriflux sites is located in the northern portions of Wisconsin and Michigan in temperate/sub-boreal forested landscapes. This is a region typical of recently glaciated sub-boreal landscapes, with abundant wetlands, heterogeneous land cover generated by fine-scale topographic and hydrologic gradients, and a history of intensive forest management in an otherwise sparsely populated area. Significant climate change is predicted for the region. Given the complex interaction of water and carbon cycles, biogeochemical impacts from climate change are poorly constrained.

Organizing a large research team to understand regional response to climate change has been tried (e.g., the BOREAS, MBL, NEESPI), when funding is available, with many lessons learned. An alternative approach is to promote interested parties through consortium development. The Chequamegon Ecosystem-Atmosphere Study (ChEAS) was initiated with the latter approach because of common interests from several groups, including Ken Davis' lab at Pennsylvania State University, Scott Denning's Biocycle research group at the Colorado State University, Paul Bolstad's forestry and remote sensing lab at the University of Minnesota, ecohydrology labs of Scott Mackay at SUNY-Buffalo and

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Ameriflux site clusters

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Brent Ewers at University of Wyoming, micrometeorology (Ankur Desai lab) and forest ecology groups (Tom Gower lab, Mark Schwartz lab) at University of Wisconsin, Jiquan Chen's Landscape and Ecosystem Science Lab at the University of Toledo, Joe Berry's lab at the Carnegie Institute of Washington at Stanford, Paul Wennberg's atmospheric chemistry lab at CalTech, the Land Cover and Land Cover Dynamics lab at Boston University, the Numerical Terradynamic Simulation Group at University of Montana, the University of Wisconsin Kemp Natural Resources Station, the University of Michigan Biological Station, biogeochemical and micrometeorological research groups at the National Center for Atmospheric Research, the NOAA Earth Systems Research Lab Carbon Cycle and Greenhouse Gas group, and the U.S. Forest Service Northern Research Station, among several others.

Together, these groups have been measuring land-atmosphere carbon and water exchange in the upper Midwest for over a decade beginning with the initiation of the Park Falls, WI WLEF-television transmitter 447-m tall tower, a NOAA carbon cycle gases tall tower observatory and one of the earliest eddy covariance flux towers in the Ameriflux network. Since then, the groups have erected nearly a dozen other flux towers with several still in operation along with many related observing sites for transpiration, biometric measurements, ecophysiology, ecohydrology, land cover assessment, soil respiration, and atmospheric chemistry. These efforts involve over a dozen Principle Investigators and dozens of post-docs, graduate students, and field technicians across many University and labs.

Over time, our lively and informal group, closely tied by many joint research agreements and the annual ChEAS meetings and workshops, have generated extremely productive collaborations leading to numerous publications, presentations, and research results funded by NSF, DOE, NASA, NOAA, USDA, and several other groups. Twelve of these publications were recently jointly published in 2008 in a special issue of Agricultural and Forest Meteorology titled "Chequamegon Ecosystem-Atmosphere Study Special Issue: Ecosystem-Atmosphere Carbon and Water Cycling in the Temperate Northern Forests of the Great Lakes Region - Great Lakes Region Special Issue" (Volume 148, Issue 2, 13 February 2008). A review editorial in that issue (Chen et al., 2008) provides an overview of the research, needs and contribution, and future work.

Figure 1: Participants at the 8th annual ChEAS meeting held in June 2005 at the University of Wisconsin, Kemp Natural Resources Station, Woodruff, WI. (Photo credit: Qinglin Li, University of Toledo)

Manuscripts in this issue include those that focus on

1) Quantifying ecological component flux budgets by Gough et al. and Tang et al.

2) Observing and modeling atmospheric surface and boundary layer properties by Denning et al. and Su et al.

3) Investigating ecohydrological and carbon-water responses of ecosystems by Ewers et al. and Noormets et al.

4) Modeling ecosystem carbon and water cycles by Ryu et al. and Sun et al.

5) Applying observational data assimilation for parameter optimization in models at multiple time-scales by Prihodko et al. and Ricciuto et al.

6) Upscaling flux tower observations by Desai et al.

One theme that arose out of several papers is the complexity that forest disturbance, stand age, and wetlands impart on spatial scaling, interannual variability, and climate sensitivity of ecosystem water and carbon cycling. Other studies, however, note that multi-year, regional scale investigations from multiple ecological and atmospheric perspectives that employ advanced model-data fusion have great potential to improve how we understand this complexity.

One of the biggest challenges for the ChEAS group and other similar groups across the Fluxnet domain is to effectively continue our collaboration as long-term data and lessons from this consortium will be non-additively increased. Toward this goal, firm commitments from both researchers and foundations are needed, including continued and increased funding for long-term ecological observation and analysis (e.g., NSF LTREB), collaborator networks (e.g., NSF RCN), and cross-disciplinary investigations. ChEAS and the related groups intend to continue their fruitful collaborations and look forward to extending to cross-group and Fluxnet-wide cooperation as we enter an era of analyzing the entire Ameriflux and Fluxnet database.

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Literature

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Highlight Graduate Student

Antje Maria Moffat

Nature has always been my fascination, and I love hiking, canoeing or just being in the outdoors. Growing up, I became increasingly aware how fragile natural ecosystems are, and this awoke a desire to understand and protect them. But when I pursued my studies in Physics, I specialized in surface science and took an opportunity to build a scanning tunneling microscope as my Master's thesis. Afterwards I started working my way up in the semiconductor industry - only to realize that this just wasn't what I wanted to do! So when my family and I moved to Jena, I took the chance to start an interdisciplinary Ph.D. in the Biogeochemical Systems Group at the Max Planck Institute in 2003.

Figure 1: Antje with her kids Leo and Anna

My research topic is data assimilation of eddy covariance data with artificial neural networks. However, since neural network models can only get as good as the dataset used for training them, I soon focused on flux data processing, quality controls, and gap filling of these data time series as a necessary first step. At the Gap Filling and Partitioning Workshop in Viterbo, Italy, Dario Papale, Markus Reichstein and I initiated a gap filling comparison which I took the lead on and extended from the Carboeurope to the Fluxnet community.

Collaborating with almost twenty researchers meant to have twenty valuable inputs but also twenty different (sometimes opposing) opinions, and the major challenge was to collect, organize, and synthesize everything into a coherent whole. After doing this by email, with me as the central node in a star network, I was glad to receive funding from the Max Planck Society to organize a workshop; it is so much easier and more effective to have round table discussions. The Gap Filling Comparison Workshop was held in Jena in 2006 and it was very positive that nearly all members of the comparison could come. The successful exchange not only helped finalize the gap filling comparison paper (Moffat et al., 2007) but also led to further collaboration resulting in three companion papers (Desai et al., 2008; Richardson and Hollinger, 2007; Richardson et al., 2008).

The main challenge for me has been to find a good balance between my work and my family. My daughter Anna is now five years old. She loves to play outside, creating worlds with sticks and strings and always collecting treasures like empty snail shells or glittering stones. My son Leo was born when the work on the gap filling comparison was at its peak, and I spent the days with him and the nights and weekends working. He is now two years old and totally excited about cars; he likes to sleep with his tractor at night.

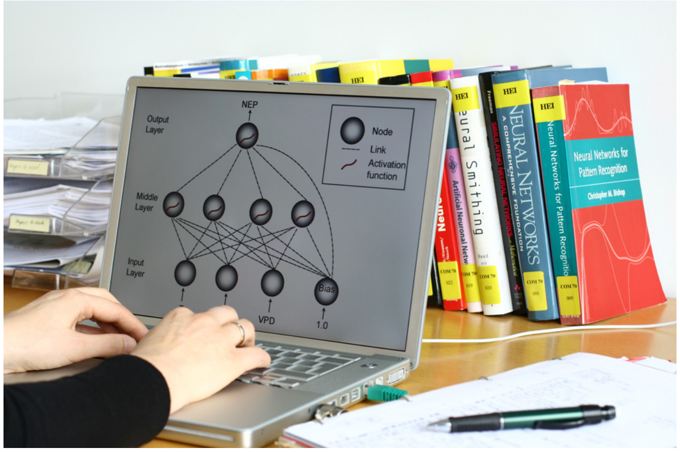

Figure 2: Antje's "site". Experimenting with artificial neural networks at her desk

Currently, I am using neural networks to explore the sensitivity of ecosystem carbon fluxes to climatic controls. This is really exciting because it employs a purely mathematical algorithm to capture the "real" ecosystem processes and connects the model world back to plant physiology. This year will be the last year of my Ph.D. and I hope to be able to continue research in environmental science in the future.

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Literature

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Highlight Young Scientist

Hans Verbeeck

My name is Hans Verbeeck. I would call myself an 'ecosystem modeller'. I am one of the guys that uses other people's data to run a model … Besides that I have been responsible for the eddy flux data collection at the Brasschaat site (Belgium) for three years. So I know how hard it is to collect reliable datasets without too many gaps… Brasschaat is a mixed coniferous-deciduous forest site with Scots pine as dominant species in the fluxtower footprint.

Figure 1: Hans Verbeeck with his son Jonas.

One year ago I finished my PhD at the Research Group of Plant and Vegetation Ecology, University of Antwerp, Belgium (www.ua.ac.be/pleco). During my PhD I mainly focussed on modelling water and carbon fluxes in temperate forests. I worked on carbon fluxes at the Hesse beech site (France) (Verbeeck et al., 2008) and on water storage in the Scots pines of the Brasschaat site (Verbeeck et al., 2007).

After finishing my PhD, I started as a post-doc at the "Laboratoire des Sciences du Climate et de l'Environnement" close to Paris (www.lsce.ipsl.fr). From the stand scale models of my PhD I moved to the global model ORCHIDEE. ORCHIDEE is a state of the art mechanistic global vegetation model. It calculates the carbon, water and nitrogen cycle in the different soil and vegetation pools and resolves the diurnal cycle of fluxes. ORCHIDEE is built on the concept of plant functional types (PFT) to describe vegetation.

I am using this model at site level, and my goal is to optimise the ORCHIDEE parameters using FLUXNET data. To do this, I am using a Bayesian optimisation approach (Santaren et al., 2007). Next month (June), I will start working on my own Marie Curie project, called POLICE: Parameter Optimisation of a terrestrial biosphere model to Link processes to Inter annual variability of Carbon fluxes in European forest Ecosystems.

During last year, I learned to use the ORCHIDEE model and the data assimilation system: ORCHIS (Orchidee Inversion System). Recently, I used the ORCHIDEE model to conduct simulations for several sites in the Amazon in the framework of the LBA-MIP project, which is a model intercomparison project using data of the LBA sites (www.climatemodeling.org/lba-mip/). The work on these tropical sites drew our attention to a very interesting problem: eddy covariance measurements at several tropical forest sites revealed an unexpected seasonal pattern in carbon fluxes which still can not be simulated by existing state-of-the-art global ecosystem models (e.g. Saleska et al., Science 2003). An unexpected high carbon uptake was measured during dry season, and in contrast, carbon release was observed in the wet season.

In order to be able to mimic the seasonal response of carbon fluxes to dry/wet conditions in tropical ecosystems we want to optimise the ORCHIDEE model using eddy covariance data. By doing this, we will try to identify the underlying mechanism of this seasonal response.

…and besides this information about my scientific activities, I can tell you very proudly that since January I became father of my first son called Jonas!

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Figure 2: View of fluxtower at Brasschaat FLUXNET site

> *"My goal is to optimise the ORCHIDEE parameters using FLUXNET data...using a Bayesian optimisation approach"*

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Integrating Airborne Lidar with Eddy Covariance and Beyond: New Research within the Canadian Carbon Program

Laura Chasmer and Valerie Thomas

The 3D structure of the canopy, understory, and ground surface topography plays an important role on the movement of mass and energy through ecosystems. Therefore, maps of canopy structure both within and beyond the source area of eddy covariance (EC) systems will improve our understanding of plant function, health, photosynthesis, and transpiration. Airborne light detection and ranging (lidar) is a powerful new remote sensing tool used for quantifying the 3D structure of forest canopies. Lidar is able to measure a variety of ecosystem properties at resolutions ranging from 0.35 m to ~5 m. In Canada, we have obtained airborne lidar data over several EC sites that were part of the Fluxnet-Canada Research Network (FCRN) and the current Canadian Carbon Program (CCP). Here we provide a brief description of how lidar works and why it has great potential for understanding and quantifying canopy, understory, and topographic influences on mass and energy exchanges. We also outline some of the challenges and limitations faced when using lidar data, and we make suggestions for getting the most out of your lidar dataset. The examples discussed include data collected over: 1) a mature mixed-wood forest located near Timmins, Ontario (the Groundhog River Flux Station (GRFS)); and 2) a jack pine chronosequence located north of Prince Albert, Saskatchewan. The jack pine chronosequence consists of a mature jack pine forest (OJP); an immature site harvested in 1975 (HJP75); a regenerating site harvested in 1994 (HJP94) and a recently harvested site scarified in 2002 (HJP02). The jack pine chronosequence has been operating as part of the Boreal Ecosystem Research and Monitoring Sites (BERMS) project. Other EC sites within the Canadian Carbon Program that have had lidar data collections include some sites in British Columbia, Quebec, and roving sites in Ontario (not discussed here).

What is Lidar?

Airborne lidar is an active remote sensing device that rapidly emits and receives discrete pulses of laser light (1064 nm) from an airborne platform to the ground surface (Figure 1). With each laser pulse that is emitted, the time of pulse emission to reception is recorded, along with the heading, pitch, and roll of the aircraft, and aircraft position. Laser pulses may be emitted at rates of 5 kHz to 160 kHz, and can record between one and four reflections (or "returns") from buildings, the ground surface, and within tree canopies. Some lidar systems can also record the full waveform of all reflections within the canopy. A scanning mirror is used to distribute the emitted pulses across the landscape in a saw-tooth pattern, known as a "scan line". The angle at which pulses are distributed can vary between 0° (nadir) and ±25° from nadir. Airborne lidar is unique because, unlike optical remote sensing methods, it can sample the structural properties of the canopy, as well as the understory and ground surface. Another type of lidar that we also use is called a terrestrial or "ground-based" lidar system. This works similarly to the airborne lidar but can be set up on a tripod and scans horizontally into a forest plot.

Figure 1: Optech Inc. ALTM 3100 lidar used for surveys

Impacts of Lidar Research and EC Integration

Many studies have shown that CO_2, water, and energy fluxes vary spatially and temporally within forested environments. The variability of these mass and energy exchanges are due to a myriad of environmental, edaphic, and vegetation drivers, including the spatial variability of forest structure and biomass, previous history (e.g. disturbance), health, topography, species type and age. Before lidar data were available, we could gain some understanding of the canopy structural characteristics and the health of vegetation using aerial photography or high resolution spectral remote sensing data. Unfortunately, these technologies are affected by shadow and cannot characterize the lower canopy. Alternatively, we can spend weeks to months measuring the structural characteristics of the forest using plot measurements or transects. To do this over large spatial areas is time consuming, expensive, and logistically prohibitive in remote areas. Lidar, on the other hand, is not influenced by solar radiation, and when surveys are optimally configured (e.g. Thomas et al. 2006; Chasmer et al. 2006b), they can provide exquisitely high resolution and accurate information on all parts of the canopy, understory and ground surface, providing us with a three dimensional picture of the ecosystem that was never before possible. The potential opportunities and new information that we can glean by combining lidar, spectral remote sensing data, and EC are almost endless!

What are some of the interesting things that we can do with lidar data to better understand ecosystem variability and mass exchanges? Some examples include:

1. Mapping canopy physiology and foliar biochemistry, as related to species and health. For example, a combina-

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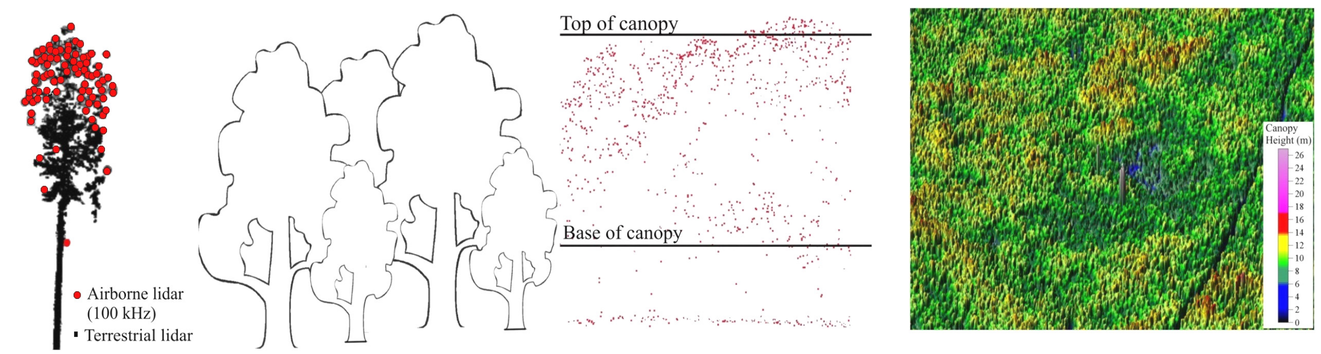

a) Integration of airborne lidar and terrestrial lidar within a single conifer tree Chasmer et al. (2006)

b) Airborne lidar "point cloud" within a plot of trees. Black lines represent top of canopy and canopy base.

c) Canopy height model (after removing topography) at OJP. EC tower located centre of image.

Figure 2: Examples of lidar point clouds within an individual tree, at the plot level, and within an ecosystem

tion of airborne lidar and hyperspectral remote sensing data were used to predict and map foliar chlorophyll and carotenoid concentrations based on reflectance properties of the canopy (derived from hyperspectral data) in combination with estimates of canopy height and density (derived from lidar data) within a mixedwood stand (GRFS) (Thomas et al. 2008). Maps of canopy chlorophyll generated with this approach reveal distinct spatial patterns within the 1 km radius surrounding the flux tower (Figure 3).

2. Improving our understanding of topography and CO_2 drainage on EC measurements in complex environments.

3. Examining the influence of within site variability in canopy structure and topography on CO_2 and water exchanges using a footprint model of the source flux areas (e.g. Chasmer et al. 2007).

4. Improving forest management practices as related to carbon budgeting by optimizing desirable species mixtures for carbon uptake under a variety of environmental conditions.

5. Mapping variability in LAI and the fraction of photosynthetically active radiation absorbed by the canopy (fPAR) (e.g. Thomas et al. 2006b; Hopkinson and Chasmer, 2007). LAI and fPAR are important inputs used in many ecosystem and hydrological models. Imagine the possibilities for understanding ecosystem processes if you combine ecosystem models with high resolution spatial estimates of LAI!

6. Up-scaling of canopy information (such as LAI, fPAR, or gross ecosystem production (GEP) from high resolutions obtained from airborne lidar for comparison and validation of low resolution satellite products. This last component is required to bridge the gap between the local scale of measurement possible at a flux tower and the large scale predictions from continental-scale carbon models. For example, Chasmer et al. (*accepted*) used lidar to model GPP at the jack pine chronosequence. These were compared with EC, and pixel level estimates of GPP from the Moderate Resolution Imaging Spectroradiometer (MODIS). The influences of within-pixel heterogeneity were then examined by scaling lidar-derived GPP from the model at resolutions of 1 m to 25 m, 250 m, 500 m, and 1000 m (Figure 4).

7. Forest inventory assessment (Thomas et al. 2006) and temporal change (Hopkinson et al. 2008).

From these few research suggestions, one can begin to see many research possibilities! We have not even mentioned the use of lidar for forest hydrology, energy balance modeling, evapotranspiration, snow distribution mapping, understory canopy mapping, laser return intensity as a potential for mapping ground cover and surface soil moisture,

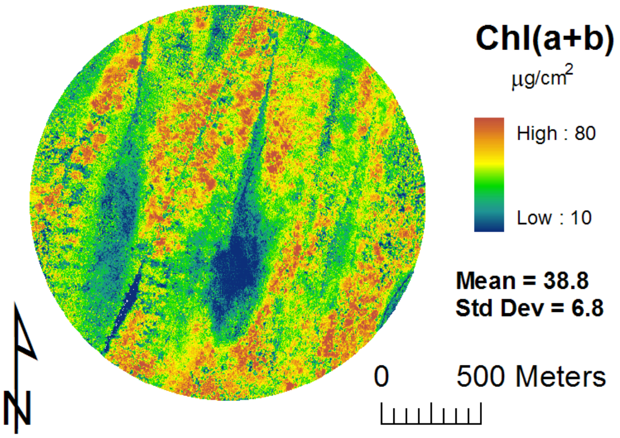

Figure 3: Average leaf chlorophyll concentration at GRFS, August, 2004 (modified from Thomas et al 2008

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and the influences of urban forests on greenhouse gases.

The Challenges

With all of the great things that we can use lidar for, there must be challenges with using the data. But what are these challenges? First of all, lidar data can be expensive to obtain because the lidar itself is an expensive piece of equipment. Lidar systems can cost between 500,000 and 2 million US$, so any service provider will want to ensure that the amount charged for the survey will cover their personnel, the cost of the equipment, the cost of the airplane, and will provide some profit to the company. Depending on the survey parameterization, a lidar survey could set you back a minimum of 10,000 US$ per hour of flying time. That would cover one or perhaps two EC sites (local to each other) and their surrounding source areas (excluding tall towers), but would require an airport nearby. Many have suggested that the cost of a lidar data acquisition is about the same or less than sending two or more students or scientists out for a few weeks of field measurements. Organizations that have publicly funded lidar systems include the AGRG and the Canadian Consortium for Lidar Environmental Applications Research (used to collect lidar data at a number of CCP sites: Hopkinson, et al. http://agrg.cogs.nscc.ca); the National Center for Airborne Laser Mapping in the USA (NCALM; www.ncalm.ufl.edu); and the National Environmental Research Council in the UK (NERC; http://www.neodc.rl.ac.uk). These groups usually work collaboratively on research projects and may charge less for lidar data than industry rates if the areas surveyed are small and funding is limited (so as not to compete with industry).

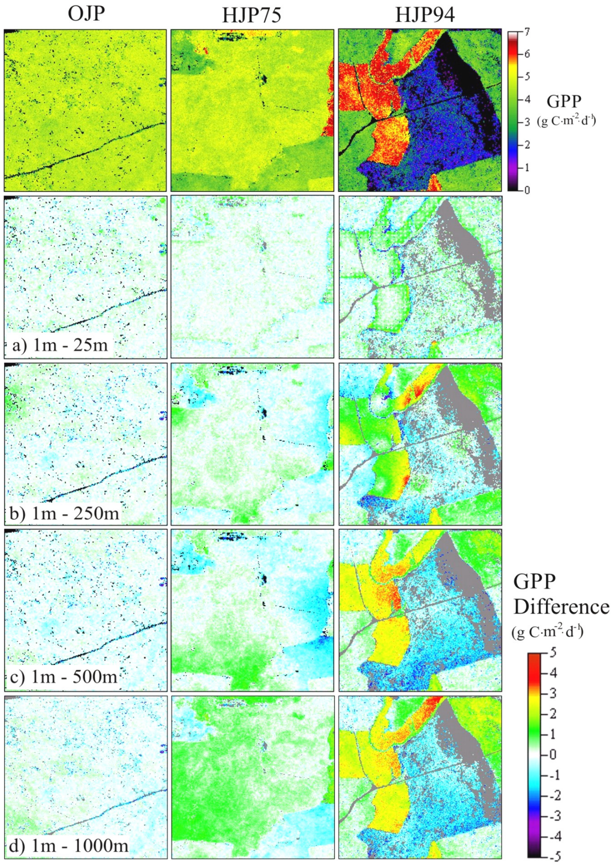

Figure 4: Influences of pixel scaling on lidar modeled GPP within MODIS pixel areas. Lower resolution pixels (e.g. 25 m) were subtracted from 1 m pixels at each site, assuming that 1 m resolution is most accurate. Positive differences indicate that lower resolutions underestimate GPP compared with 1 m resolution and vice versa for negative differences.

Another challenge is that lidar data can be difficult to work with. The data volumes can be very large, from tens of gigabytes to terabytes, often requiring very good computers and hard drive space to store and work with lidar data. The expense of good computing resources is often not considered, and in some cases lidar data are "shelved" because the users do not have the resources. Despite these issues, those who process high frequency EC data probably have the computing resources to work with lidar data.

Lidar data can also be difficult to work with because the laser return data are comprised of an "irregular" network of points which are unlike typical remote sensing data (e.g. Figure 2). Special software (e.g. Bentley MicroStation, Terrascan, and Merrick MARS, etc.) may be required to do some of the classifications of the point data (e.g. separating out ground returns from non-ground returns, and conversions from LAS binary format to ASCII). Typical remote sensing software packages such as ArcGIS, ENVI, QT Modeller, and Surfer, and coding environments (e.g. IDL, C, etc.) may also be used for analysis following classification. As lidar data becomes more popular, software is adapting, making data much easier to work with. All in all, we have seen large reductions in the costs of lidar data acquisitions, computing resources, and software making lidar data more accessible than it was ten years ago.

Getting the Most Out of Your Lidar Dataset

In all aspects of lidar data planning, collection, and analysis, it is important to first understand how your data can be or were collected. This can have an important impact on how the laser returns are distributed within the canopy. A few things to consider are: 1. Lidar systems can obtain multiple returns in forested canopies, but can only obtain one return at distances of less than approximately 1.5 m. This is important because lidar will be unable to record a return from within short vegetation *and* the ground surface (Hopkinson et al. 2005). Therefore if you were interested in knowing the height of grasses

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surrounding your EC system, this might be difficult, but the height of trees > 1.5 m (or shorter trees with large spacing between them)? No problem! 2. If you have any say in your lidar data collection and planning, ask for 50% overlap of scan lines. This ensures that both sides of each individual tree are adequately measured by the laser returns and minimizes “shadowing” or blocking of returns on the sides of trees that are not facing the direction of travel of laser pulses. 3. Flying lower (e.g. 1000 m as opposed to 3000 m) and setting the scan angle to around ±13 to 18° on either side of “nadir” will typically ensure even coverage of returns from the top of the canopy to the base and many returns from the ground surface (in open canopies). Increasing the scan angle to > ±20° will reduce the time of your survey, but will also shift pulses towards the top of the canopy. This is beneficial if you are interested in canopy height, but will result in some lack of data within the centre of the tree crowns. If you are more interested in ground surface topography (e.g. for hydrological modeling), lower scan angles are best (e.g. < ±12°) because the laser may be able to penetrate through grasses to the ground surface. A review of all survey parameterization influences on the estimation of vegetated canopy properties is provided in Hopkinson (2007). Finally, it is best to plan lidar surveys after a period of dry weather. Standing water and very wet soils absorb the near infrared radiation of laser pulses resulting in lowered laser pulse energy return (or intensity) or no return at all from the ground surface (in areas of standing water).

Figure 5: ***Laura Chasmer, Chris Hopkinson (AGRG) and John Barlow (U. of Saskatchewan) working on the AGRG lidar system during surveys in the sub-arctic, summer 2007***

The Take Home Message: Lidar has become an exciting and relatively new tool for the assessment of high resolution, 3D canopy structural characteristics. The research that has and will continue to be generated from the integration of lidar and EC has many important implications in several areas of carbon cycle science and forest management. These include forest inventory assessment, mapping canopy physiology and biochemical constituents, improving forest management practices, understanding the influence of canopy and understory structure on disturbance, forest hydrology, scaling, and satellite model validation. Accurate measurements of canopy structure from lidar also reduce time and costs associated with in situ validation, and in most cases, lidar data can be available within a few days to a month of the survey (depending on the size of the area flown).

The software tools and computing resources required to examine lidar data are also becoming less expensive and increasingly user-friendly. Finally, there are a number of online resources and short courses that have been made available so that users can efficiently understand and work with their lidar datasets. We hope that lidar will continue to make headway into carbon cycle science, and will be used increasingly as a linkage between the spatial characteristics of the vegetated landscape and measurements made by EC and meteorological sensors.

Lidar and Remote Sensing Publications at BERMS and GRFS

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Lefsky, M.A., Cohen, W.B., Acker, S.A., Parker, G.G., Spies, T.A., Harding, D., 1999. Lidar remote sensing of canopy structure and biophysical properties of Douglas-Fir Western Hemlock forests. Remote Sensing of Environment. 70, 339-361.

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Keeping an eye on the carbon balance: linking canopy development and net ecosystem exchange using a webcam

Lisa Wingate, Andrew D. Richardson, Jake F. Weltzin, Kenlo N. Nasahara and John Grace

Why observe phenology within FLUXNET?

Phenology is the study of the timing of lifecycle events, especially as influenced by the seasons and by the changes in weather patterns from year to year. The oldest phenological records, observations of cherry flowering at the Royal Court in Kyoto date back to 705 AD, and are still maintained to this day across Japan where the Japanese Meteorological Agency use these data to provide weekly forecast maps of expected blooming dates (http://www.jma.go.jp/jma/en/News/sakura.html). Robert Marsham, the father of modern phenological recording, was a wealthy landowner and amateur naturalist who recorded "Indications of spring" in Norfolk, England, beginning in 1736. His family maintained these records until the 1950s. In the modern era, phenology has gained a new impetus, as people realize that such records, if sustained over many years, can reveal how plants and animals respond to climate change. Moreover, phenological events such as the spring leaf-out and the autumn fall exert a strong control on both spatial and temporal patterns of the carbon cycle. Phenology also influences hydrologic processes, as spring leaf-out is accompanied by a marked increase in evapotranspiration, and nutrient cycling as autumn senescence results in a flush of fresh litter (nutrient) input to the forest floor. Phenology is a robust integrator of the effects of climate change on natural systems (Schwartz *et al*., 2006; IPCC 2007), and it is recognized that improved monitoring of phenology on local-to-continental scales is needed.

Historically, phenological observations were a pastime of amateur naturalists (e.g. the Marsham family) and reliable records were often dependent on the skills and effort of the observer. The increased demand for international co-operation and standardisation in this area led to the creation of many large-scale phenological monitoring networks such as the International Phenology Garden (IPG) program (http://www.agrar.hu-belin.de/struktur/institute/pfb/struktur/agrarmet/phaenologie/ipg) (founded in 1957), the Global Phenological Monitoring (GPM) program (http://www.agrar.hu-belin.de/struktur/institute/pfb/struktur/agrarmet/phaenologie/gpm) (established in 1998) as well as the recently-established USA-National Phenology Network (USA-NPN) (http://www.usanpn.org) and associated regional networks (e.g., http://www.nerpn.org). These networks have focused on developing standardized protocols for phenological observations, and ensuring overlap between plant species found across locations. Although there are obvious advantages in creating explicit linkages between these phenological networks and flux monitoring networks for the purpose of understanding patterns and processes controlling carbon budgets across a broad range of scales, explicit activities to assess the impact of phenology on ecosystem carbon balance are still somewhat lacking within the carbon cycle community. The reasons are clear: long-term observations, otherwise called 'monitoring' are not popular with those that sponsor research in this area; three or five year projects are the norm, when in practice much longer records are required to detect long-term trends and their relationships to climatic drivers. There is however, evidence for a shift in attitudes. Keeling's measurements of atmospheric CO_2 concentrations, that began in 1958, are an outstanding example of the value long-term monitoring represents in the context of a changing world (Nisbet, 2007). Moreover, continuous eddy covariance measurements of CO_2 fluxes began in the early 1990s at a handful of sites. Every year, more and more sites have been added to FLUXNET, and many of these are now providing useful long term data not only with regard to spatial patterns of carbon uptake and release, but also in relation to the influence of phenology on carbon sequestration.

One example of a synergy between phenology and flux monitoring networks in Europe has occurred between the Tharandt International Phenological Garden (also one of the 24 GPM gardens) and the nearby Carboeurope-IP site Anchor Station Tharandt over the past 12 years (Niemand *et al*., 2005; Grünwald & Bernhofer, 2007). Using the standard observations from both networks it was demonstrated that the appearance of the *Maitrieb* (May shoot) for Norway spruce is correlated with annual estimates of ecosystem gross primary productivity (GPP) and net ecosystem productivity (NEP) (with the exception of the extreme drought event of 2003 in Europe). This indicates that the earlier appearance of shoots potentially increases the length of the growing season, leading to a greater annual carbon sequestration. Mean March-April temperatures were correlated with the data of May shoot, indicating a potential scalar for GPP and NEP when coupled to longer time-series from such IPG records. Similarly, an analysis coupling budburst observations and CO_2 flux measurements at the Howland (since 1996) and Harvard (since 1992) AmeriFlux sites indicated that earlier budburst resulted in greater springtime GPP (5 g C m^{-2} per 1 day advancement of budburst date), but these increases in carbon uptake were offset by increases in springtime ecosystem respiration (RE), resulting in an uncertain effect (not significantly different from zero) on springtime

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NEP (Richardson *et al*., in preparation).

Phenological Activities within FLUXNET

At FLUXNET sites around the world that overlook forests, pastures, and wetlands, we have the opportunity of establishing precision measurements of phenological events by simply mounting networked digital cameras ('webcams') and recording daily (or even hourly) images of the vegetation canopy, as recommended by Baldocchi et al. (2005). A recent FLUXNET survey (http://www.geos.ed.ac.uk/homes/lwingate/webcam.html) has uncovered at least 26 such webcams already 'keeping an eye' on canopy development (Figure 1). Although this network is in its infancy, it appears to be growing steadily, and already represents some 58 site-years of combined flux and webcam data. A large number of these sites are in Asia where the Phenological Eyes Network was set-up in 2003 to create a much needed validation platform for remote sensing products such as NDVI (http://www.asiaflux.net/newsletter/no21_2007.pdf). It is also promising to learn that this number should continue to grow with the addition of sites in the US National Ecological Observatory Network (www.neoninc.org). However, just as phenological gardens must commit to observations in excess of ten year periods it is also necessary for this webcam activity to maintain a long-term perspective, especially when it comes to unravelling the relationships between forest carbon balance and phenology.

The opportunity presented to us is clear: webcam measurements at FLUXNET sites will reveal the link between phenology and carbon uptake; they will also provide much-needed ground verification of phenology products derived from satellite remote sensing (e.g., MODIS).

The role of the phenology network and citizen scientists

Within FLUXNET a protocol for phenological observations was also created to harmonise phenological observations across flux sites (http://www.fluxdata.org/DataInfo/Dataset%20Doc%20Lib/FLUXNET_phenophase_protocol.pdf). However, initiation of such long term monitoring requires a sustained commitment of human resources (that are typically scarce) and, as a consequence, these observations are not pursued at the majority of flux sites.

Several of the phenology networks include a substantial volunteer or "citizen science" component, wherein trained observers track the response of plants using standardized protocols, online data entry forms and visualizations designed and streamlined for the more casual observer (e.g., UK Nature Watch, US Project BudBurst and USA-NPN, and the GLOBE project (Gazal *et al*., in press). These networks of observers represent a potential bridge between phenological and flux observations, in that data collected by such "citizen scientists" can be used to (a) increase the density of observation sites and species, (b) collect information on presence/absence of

Figure 1 *Global distribution of flux sites with webcams (Agarwal et al., 2008)*

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snow, flowers or foliage undetectable to remote sensing platforms, and (c) ground-truth observations from 'near' (e.g., camera, or eddy correlation) or 'far' remote sensing platforms (e.g., AVHRR, MODIS). Development of a volunteer program for FLUXNET sites would greatly strengthen tools available for the interpretation of eddy flux data.

Towards an international canopy phenology camera network

In situ phenological observations, gas exchange and radiometric signals at the same flux sites are currently required for comparison with remotely sensed products. This is especially the case if we are to understand the apparent contradiction in findings between the CO_2, phenology and remote sensing communities with respect to the timing of canopy green up and senescence and how this relates directly to changes in the atmospheric CO_2 record, especially during spring and autumn in the northern hemisphere (e.g., Piao *et al*., 2008). This webcam network could soon be in a position to test whether the start, maximum and end of the growing season derived from satellite NDVI data really correspond to the actual start, maximum and end of the growth period of plants as observed in flux sites. Thus the webcam network presents a way to directly link on-the-ground observer records to remotely-sensed data, and moreover to link these to ecosystem physiology measured with flux towers.

The growing webcam network now represents a novel opportunity to implement both regional and global monitoring of phenology at flux sites. Thus efforts to extend the spatial coverage of phenological observations at flux sites through the simple addition of cameras on towers are now required within FLUXNET. In time this network will not only establish an archive of images documenting seasonal and inter-annual changes in forest phenology, but also capture associated variability in forest function and its potential impact on ecosystem carbon balance in response to long-term changes in climate. This multi-scale monitoring of phenology and net ecosystem exchange of CO_2 will enrich our understanding and efforts at modelling not only the impacts of climate on phenology but also the impact of phenology on climate through feedbacks on the carbon and energy cycle of the planet. Moreover, it has the potential to link the CO_2 flux community to the thousands of amateur observers, many of them school-children who will become the next generation of scientists.

BOX 1— Time-lapse animations of canopy development and net ecosystem exchange can illustrate the degree of coupling between the two signals and the additional influence of understorey and snow cover on flux measurements. A number of such animations can be observed below and at the following website (http://www.geos.ed.ac.uk/homes/lwingate/webcam.html). These observations were taken at flux sites within the Carboeurope-IP, Ameriflux and Asiaflux networks.

Howland Ameriflux Site

Takayama Asiaflux Site

Hainich Forest Carboeurope Site

Figure 2 : Time-lapse movie links for the Howland Ameriflux site (http://www.forest.sr.unh.edu/richardson/Howland2007b.avi), a *Betula ermanii* Cham. at the Takayama Asiaflux site (http://pen.agbi.tsukuba.ac.jp/~TKY/summary/dc/dc_2007_digest_TKY__y18bb/) and the Hainich Carboeurope-IP site (http://xweb.geos.ed.ac.uk/~lwingate/Hainich_forest_Flux_phenology.avi)

As we have illustrated above, webcams are an important way of tracking canopy phenology. The digital images when collected at such regular intervals can be easily assembled into time-lapse movies such as those in Box 1, providing an important product for raising public awareness on phenological and carbon cycle research. The color information of these very same images can also be analyzed to retrieve information on canopy development in both deciduous and evergreen forests as described in Box 1 and 2. If you plan to mount a camera at your flux site in the near future and have any queries for the network please do not hesitate to contact us and we will do our best to help get you started.

Acknowledgements

Many thanks to all those that took the time to respond to the recent survey on the phenology

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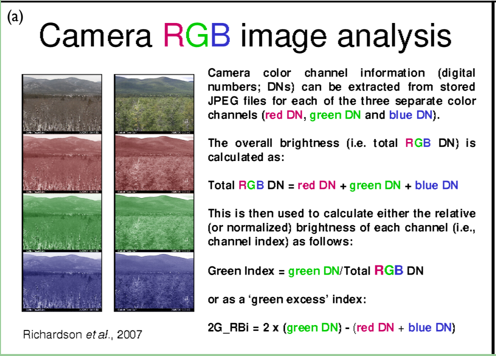
BOX 2— Coupling webcam technology with flux observations can help us understand seasonal changes in forest physiology. Recent advances in camera technology and the interpretation of digital imagery now allow the quantification of plant canopy development at flux sites automatically and without the inherent subjectivity of observer-based systems (Richardson *et al*., 2007). Besides the obvious information on snow or foliage presence at our flux sites we can also perform image analysis on the red, green and blue (RGB) colour channel brightness to obtain the information about the timing and rate of canopy green-up and senescence. Richardson *et al*. (2007) evaluated relationships between indices derived from RGB colour information and radiometric measurements of the fraction of incident photosynthetically active radiation absorbed by the canopy (f_{APAR}) and NDVI, as well as the canopy-level photosynthetic capacity (A_{max}) derived from eddy covariance measurements at a deciduous forest (Figure 3). This study showed that webcams, although they are not calibrated radiometric instruments, could provide valuable insights into canopy development and function. A more recent analysis (Fig. 3b) has shown that a "green excess" index (2 x G% - R% - B%; Richardson et al. 2007) tracks the seasonal variation in tower-based estimates of GPP at an evergreen conifer forest, offering the possibility that "near" remote sensing can provide additional insights into canopy-scale physiological activity.



Camera RGB image analysis

Camera color channel information (digital numbers; DNs) can be extracted from stored JPEG files for each of the three separate color channels (red DN, green DN and blue DN).

The overall brightness (i.e. total RGB DN) is calculated as:

Total RGB DN = red DN + green DN + blue DN

This is then used to calculate either the relative (or normalized) brightness of each channel (i.e., channel index) as follows:

Green Index = green DN/Total RGB DN

or as a 'green excess' index:

2G_RBi = 2 x (green DN) - (red DN + blue DN)

Richardson *et al*., 2007

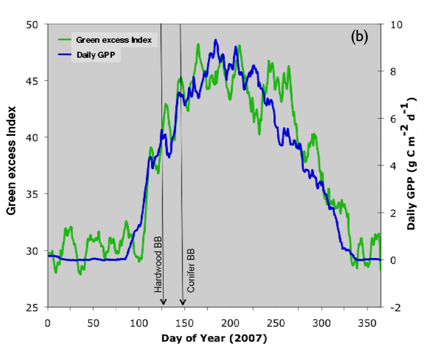


Figure 3a: *Red, green and blue image analysis of canopy development.*

Figure 3b: *Measured 'green excess index' from image analysis of webcam images of an evergreen conifer canopy alongside daily GPP estimates derived from eddy flux measurements. Data are from the Howland AmeriFlux site in Maine, USA; a movie of the camera images is available online (http://www.forest.sr.unh.edu/richardson/Howland2007b.avi). Also indicated are observed average budburst*

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We plan to make the FLUXNET newsletter a powerful information, networking, and communication resource for the community. If you want to contribute to any section or propose a new one please contact the FLUXNET Office. THANKS!!