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FluxLetter

THE NEWSLETTER OF FLUXNET

A focus on a few of the FLUXNET network's sites where scientists have multi-year measurements of methane emissions from wetlands and peatlands across the world.

In this issue of the FLUXLETTER, we profile a few of the sites that are measuring methane on a long-term basis. These include a managed wetland in California, temperate wetlands in Europe and a remote arctic wetland in Siberia. We also profile a young scientist working in the Florida Everglades, and provide a list of sites from an informal survey where methane measurements have been recently initiated, and others where measurements are more long-term.

In This Issue:

Methane Flux Measurements, New Opportunities for FLUXNET

An Editorial by Dennis Baldocchi and Laurie Koteen

Over the past decade we have been experiencing a quiet revolution in the development of trace gas sensors. Technical advances in fiber optics communications have led to the development of cheap and stable infrared lasers that correspond with spectral wavebands associated with methane. Hence companies, like Aerodyne, Campbell Scientific, Los Gatos Research and Picarro, are supplying researchers with a new generation of tunable diode laser spectrometers (TDLs) that are suitable for continuous and long-term eddy covariance flux measurements—these sensors are capable of sampling ambient methane concentrations (1700 to 5000 ppb), five to ten times per second, with low enough noise (< 5 ppb) and stable calibrations to detect the natural range of small and large methane fluxes (5 to 500 nmol m^{-2} s^{-1}) that are expected in flooded environments, like peatlands, fresh water marshes, rice paddies and estuaries.

This issue of the FLUXLETTER highlights activities associated with methane flux measurements by our community. As we publish this issue, there are already a handful of teams with four or more years of methane flux measurements (Rinne, Laurila, Vesala et al, Finland; Dolman et al, Netherlands; Friborg and Christenson, Denmark/ Sweden; Baldocchi et al., California). An informal poll of the FLUXNET community discovered that 50 or more teams are currently measuring methane fluxes with eddy covariance, or will start soon (Table 1).

The eddy covariance method has numerous strengths for measuring methane fluxes, as compared with chambers. It can measure fluxes *in situ*, continuously, across broad areas and without artifacts. These strengths are espe-

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cially important for ecosystems where methane transport occurs through bubbles (ebullition), via xylem through tall plants and diffusion through soils and water columns. Hence, new advances in methane instrumentation help augment the previous knowledge on methane exchange that has been produced by hundreds of studies that used small chambers.

From a historical perspective, these new instruments are democratizing our ability to measure methane fluxes routinely and at diverse sites. The earliest methane flux studies were conducted in the 1990s by a few groups (Verma et al., Nebraska; Fowler et al, CEH-Edinburgh; Thurtell et al. Guelph; Miyata et al., Japan) using finicky TDLs that required continuous monitoring by highly-trained spectroscopists, frequent cooling of detectors with liquid nitrogen and access to AC power to run the pumps and sensor electronics. Today's methane sensors don't require liquid nitrogen or frequent adjustment of lasers. However, closed path sensors still rely on power hungry pumps, that tie us to power lines or diesel generators. New open-path configurations allow us to measure methane fluxes in remote locations like tule wetlands, the Everglades and the tundra with the aid of solar panels. Yet, they remain susceptible to moisture, which occurs frequently in tropical and Arctic areas where methane may be a large source.

We expect great growth in methane fluxes in the coming decade and this issues heralds a new avenue for a subset of FLUXNET scientists, whom have plans underway to form a methane network. For a snapshot on current activities we profile activities by Finnish, German and U.S. groups working in wetlands, and by the German group working in Siberia. We also profile a young scientist working in the everglades of North America.

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Table 1: A list of sites, PIs, and instruments taking methane flux measurements through the eddy covariance method, as compiled through a recent informal survey.

Institute name	Site name	Site Country	Site type	Start year	Site PI	Sensor
Finnish Met. Instit.	Lompolojänkkä	Northern Finland	Fen	2006	Tuomas Laurila	Los Gatos, RMT-200
Finnish Met. Instit.	Kaamanen	Northern Finland	Fen	2008	Tuomas Laurila	Los Gatos, RMT-200
Finnish Met. Instit.	Tiksi	Russia, Siberia	Tundra	2009	Tuomas Laurila	
Univ. Helsinki	Siikaneva I	Southern Finland	Fen	2005	Timo Vesala/ Janne Rinne	Los Gatos, RMT-200
Univ. Helsinki	Siikaneva II	Southern Finland	Bog	2011	Timo Vesala/ Janne Rinne	Los Gatos, RMT-200
GFZ, German Research Center	Lena River Delta	Russia, Siberia	Tundra		Torsten Sachs, Lars Kutzbach	Campbell TGA-100
GFZ, German Research Center		Germany	re-flooded wetland site	2012	Torsten Sachs, Lars Kutzbach	Campbell TGA-100, Los Gatos RMT 200
Universities of Lund, Stockholm, Copenhagen	Stordalen	Northern Sweden	Mire	2006	Torben Christensen, Thomas Friborg	
ISPRA	Castellaro	Italy	Rice/maize rotation	2009	Alessandro Cescatti/ Seufert	Los Gatos, RMT-200
Univ. Antwerp	Lochristi	Belgium	Poplar bioenergy plantation	2010	Ivan Janssens, Reinhart Ceulemans	
ECN, Energy Research Centre of the	Reeuwijk	Netherlands	Peat meadow	2008	Arjan Hensen	
CEH	Auchencorth moss	Scotland, UK	Drained bog	2010	Ute Skiba/ Helfter	
Univ Copenhagen	Skjern Meadows	Denmark	Restored wetland	2008	Thomas Friborg/ Henrik Soegaard/ Herbst	Los Gatos, RMT-200
Innsbruck	Neustift	Austria	meadow	2010	Wohlfarht	Aerodyne

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Institute name	Site name	Site Country	Site type	Start year	Site PI	sensor
Innsbruck	Neustift	Austria	meadow	2010	Wohlfarht	Aerodyne
University of Lund		Sweden	clear cut forest		Lindroth	gradient
Vriej University	Horstermeer site	Netherlands	pasture	2006	Dolman	Los Gatos, RMT-200
Vriej University	Chokurdagh / Kytalyk Siberia	Russia	wetland		Dolman	Los Gatos, RMT-200
UC Berkeley	Twitchell Island	US-California	rice	2009	Baldocchi/ Hatala	Los Gatos, RMT-200
UC Berkeley	Sherman Island	US-California	peatland	2007	Baldocchi/ Hatala	Los Gatos, RMT-200
UC Berkeley	Sherman Island	US-California	wetland	2010	Baldocchi/ Hatala	Licor, LI-7700
USGS	Twitchell Island	US-California	wetland	2010	Anderson	Los Gatos, RMT-200
University of Lethbridge	Alberta	Canada	peatland	2007	Flanagan	Campbell, TGA-100
San Diego State	Barrow	US-Alaska	tundra		Oechel/Zona	
Alabama	everglades	US-Florida	wetland	2011	Starr	
North Carolina State	Alligator River	US-North Carolina	wetland	2012	Noormets	
Minnesota	Marcell expt station	US-Minnesota	bog	2009	Griffis	Campbell TGA-100
Illinois	central Florida	US-Florida	grazed pastures	2011	Bernacchi	Licor, LI-7700
Wisconsin	Park Falls, WI	US_Wisconsin	mixed forest	2010	Desai	Picarro, GF 1301

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Institute name	Site name	Site Country	Site type	Start year	Site PI	sensor
Toledo	Ohio	US	coastal marshland	2010	Jiaquan Chen	Licor, LI-7700
Toledo	Ohio	US	(corn-soybean)	2010	Jiaquan Chen	
USFS/Harvard	Howland	US-Maine	mixed forest	2011	Hollinger/ Richardson	Picarro, GF 1301
Carelton	Mer Bleue, Ontario	Canada	bog	2010	Humphries	Los Gatos, RMT-200
KIT/IMK-IFU, Garmisch-Partenkirchen	Bavaria	Germany	bog	2012	Schmid	Licor 7700/ Aerodyne
LBL/ANL	ARM North Slope AK site	US-A;aska	Tundra	2011	Fischer/Cook	
University of Tuscia	Ankasa	Ghana	Tropical Rain forest	2011	Valentini	Licor, LI-7700
Fudan University	Fudan	China	estuary wet-land	2011	Zhao	Licor, LI-7700
Goettingen		Indonesia/ Sumatra	oil palm	2012	Knohl	
ISPRA	Castellaro	Italy	rice	2009	Suefert/ Magliulo/ Meijide	Los Gatos, RMT-200
ETH Zurich	Früebüe	Switzerland	grassland	2011	Merbold	Los Gatos, RMT-200
ETH Zurich	Chamau	Switzerland	grassland	2012	Merbold	Aerodyne
Umea	Degero Stormyr	Sweden	boreal minerogenic mire	2012	Nilsson	Los Gatos, FMT-200
INRA	F-Laq 1 and 2	France	grazed pas-ture	2009	Klumpp	Los Gatos, RMT-200
Centre for Forestry & Climate Change	Farnam	UK	oak forest	2009	Yamulki	
Univ Edinburgh		Peru		2011	Grace	
Wageningen		Netherlands	shallow lake	2011	Moor/Kruijt/ Elbers/Jacobs	Licor, LI-7700
CSIRO	Arcturus	Australia		2012	Zegelin	Licor, LI-7700
Peking University	Haibei	Tibet	grassland	2011	He	Licor, LI-7700

Methane flux measurements at Siikaneva wetland complex

Janne Rinne & Eeva-Stiina Tuuttila

Siikaneva is a boreal open wetland located in Southern Finland. Fluxes of carbon dioxide, water vapor, and methane have been measured there continuously by the eddy covariance method since 2005. The site is operated as a satellite site of the SMEAR II flagship station of the University of Helsinki, (see FluxLetter Vol.4, iss. 2) and is a part of ICOS, the Integrated Carbon Observation System, Fluxnet, InGOS, the Integrated non-CO2 Greenhouse gas Observing System, and GHG-Europe.

From humble beginnings

The eddy covariance flux measurements started at the Siikaneva wetland in 2004 as a collaborative project between the University of Helsinki and the Finnish Meteorological Institute. In the first year, only fluxes of carbon dioxide and water vapor were measured.

However, by the end of that first year, we realized that our Campbell TDLAS with nitrous oxide and methane lasers did not have any commitments for years 2005 and 2006. As there was already line-power, road access, and most of the equipment needed for flux measurements, we started toying with the idea of measuring the full annual cycle of methane fluxes with eddy covariance at Siikaneva.

"Has this been done before?" was the only question of Timo Vesala, the head of the micrometeorology group in the University of Helsinki, when introduced with the idea. To our answer "Not to our knowledge", his reply was simply "Then, go ahead". Thus, the "project" started without any funding, but somehow the expenses (e.g. the liquid nitrogen cost of 10 000 € per year) were footed.

The TDLAS was installed at the Siikaneva flux site in February 2005. The reason to start the measurements in the middle of boreal winter was logistic rather than scientific, as it is easier to sledge the 80 kg instrument, that is also the size of a coffin, over snowpack, rather than carry it along narrow walkways. After the TDLAS had been hauled to the site, installed, and a couple of startup hiccups had been resolved, came the time to wait for the snow and ice to melt and for the show to start.

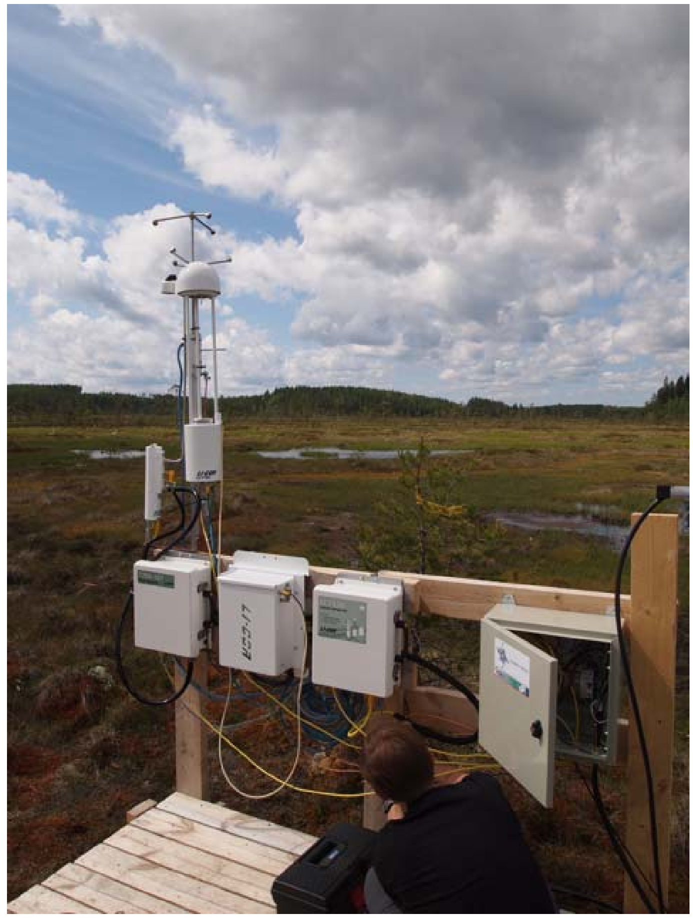

Figure 1: Sami Haapanala installing the measurement systems at the ombotrophic Siikaneva II site. This site is run by batteries, and is charged from time to time by a diesel generator.

First results and some surprises

After a month of measurements, our colleague from the Finnish Meteorological Institute, called and told us that there was a clear covariance peak to be found in the methane data. So, even though we didn't really think we would be able to measure anything but noise before snow melt, the instrumentation was able to resolve the methane emission seeping through ice and snow.

As we later analyzed the flux data some surpris-

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ing features were found. First, the methane was important not only to for global warming potential (GWP) type calculations, but also for quantifying the carbon balance of the fen. We found that nearly 20% of the carbon assimilated annually from CO_2 was released back to the atmosphere as methane. Another surprise was that even though we expected methane fluxes to be controlled partly by water table depth, we could not find any such dependence for the temporal behavior of the fluxes. This is in contrast with the spatial behavior of methane emission as observed with the manual chambers. The ecosystem scale methane emission seem to be controlled mostly by peat temperature.

Figure 2: Ombotrophic Siikaneva II site.

Towards consolidation, intensification, and expansion

Fast forward to summer 2010 and there are four methane flux instruments running in parallel at the Siikaneva fen site. In between the onset of measurements and the present, we had continued the methane flux measurements mainly as a "hobby", i.e. with no official funding. The technical assistance, for example, which amounted to two site visits per week and which was required in order to keep the liquid nitrogen dewar of the TDLAS topped-up, was provided by the SMEAR II station located just an 8 km drive from Siikaneva. Thus the Siikaneva site was annexed as a satellite site of the SMEAR II, where eddy covariance fluxes of CO_2 and H_20 have been conducted above an up-land Scots pine forest since the mid 1990's. Then came the ICOS project in which one task, among others, assigned to the University of Helsinki was, to produce a recommendation for methane flux instrumentation.

After the instrument inter-comparison was performed in response to the ICOS project needs, we had settled upon instruments that could be used for intensification and expansion of our measurement scheme. In late 2010, scouts were sent out to find a bog type flux measurement site in the Siikaneva wetland. They were successful, and in summer 2011 Siikaneva II was in operation (Figure 2). Currently in the pipeline, are

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additional measurements that would serve to enhance our understanding of methane emission dynamics and development of numerical models.

Siikaneva in nutshell

With 12 km^2 area Siikaneva is one of the largest wetlands in Southern Finland that survived the forestry drainage programs of the 1950s and 1960s. The formation of the peatland goes back 9000 years. With peat accumulation, some parts of the peatland have reached an ombotrophic stage in their development where all the additional nutrients are received only from rain water (the bog parts) but some parts have stayed minerotrophic (the fen parts) and reserve nutrients from surrounding mineral soils. The peat depth is up to 7 meters, corresponding to carbon stock of 200 kg C m^{-2}. The average annual temperature is 3.3°C and annual precipitation 713 mm.

In addition to eddy covariance flux measurements, manual chambers have been used for measurements of CO_2 and CH_4 exchange. In order to upscale the results of manual chamber studies, the vegetation around the Siikaneva fen site has been systematically inventoried. To better understand the biology behind methane emissions, the microbial communities responsible for methane production and oxidation have also been studied in Siikaneva fen site. Also emissions of volatile organic compounds (VOCs) have been conducted in the Siikaneva fen. We measure

Figure 3: Minerotrophic Siikaneva I site during snow melt period. The yellow box houses LiCor for carbon dioxide and water vapor and Los Gatos for methane. The diaphragm pump for LiCor is housed on top of its own pole to isolate the analyzers from vibration. Supporting data is collected by two Campbell data loggers.

Table 1: Typical values for carbon exchange between Siikaneva fen and the atmosphere. A positive sign denotes an upward flux. i.e. emission to the atmosphere.

Compound	Annual carbon balance	Reference
Carbon dioxide	-56 gC m^{-2}	Aurela et al. 2007
Methane	9.4 gC m^{-2}	Rinne et al., 2007
Isoprene	0.1 gC m^{-2}	Haapanala et al., 2006

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VOCs because the air chemistry in remote northern areas can be significantly affected by these emissions, even though they have only a minor effect on the carbon balance. For paleoecological purposes, peat cores taken from the wetland have been analyzed and the peat depth mapped.

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Young Scientist Profile: Sparkle Malone

Growing up in Miami, I never gave much thought to the Everglades. My interests in the outdoors didn't extend too far from Miami's beaches. I took a long meandering path through my undergraduate education, with a long stop in New York City at the Dance Theatre of Harlem, before finding a good fit in Forest Resources Conservation at the University of Florida. My name is Sparkle Malone, and I am studying carbon cycling in the Everglades sawgrass (*Cladium jamaicense* Crantz.) ecosystem, (Figure 3).

While studying at Florida, I also found that I enjoyed statistics, so my Bachelors of Science, which I received in 2009, has a focus in Informatics. During my undergraduate education, I worked with the U.S. Forest Service using GIS for forest management and planning activities. This spurred my interest in using GIS for forest conservation and I decided to pursue a masters. In the fall of 2009, I was awarded a Conserved Forest Ecosystems Outreach and Research fellowship to work with Dr. Leda Kobziar, a fire ecologist, and Dr. Christina Staudhammer, a forest biometrician at the University of Florida. My research focused on modeling burn severity in a pine flatwoods forest in north Florida. To determine the impact of previous fire on the severity level of subsequent fire, we used 11 years of fire history data from the Osceola National Forest to develop Landsat-based differenced normalized burn ratios and logistic regression methods to model burn severity.

My research interests include modeling carbon fluxes in wetland ecosystems, spatial and temporal modeling of ecosystem processes in forested landscapes, and remote sensing and spatial analysis. I have been fortunate to attend the two-week course on flux measurements and advanced modeling at the University of Colorado. I also joined the Rocky Mountain Re-

Figure 2: Chamber-based and eddy covariance methane measurements are currently underway at the Florida Coastal Everglades (FCE) LTER site by Sparkle and others.

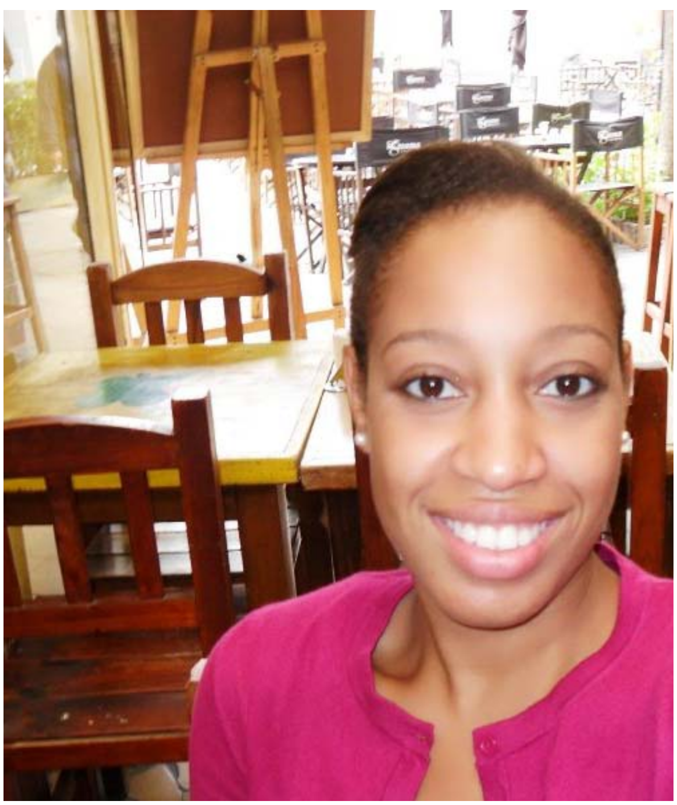

Figure 1: Sparkle Malone

Young Scientist Profile: Sparkle Malone

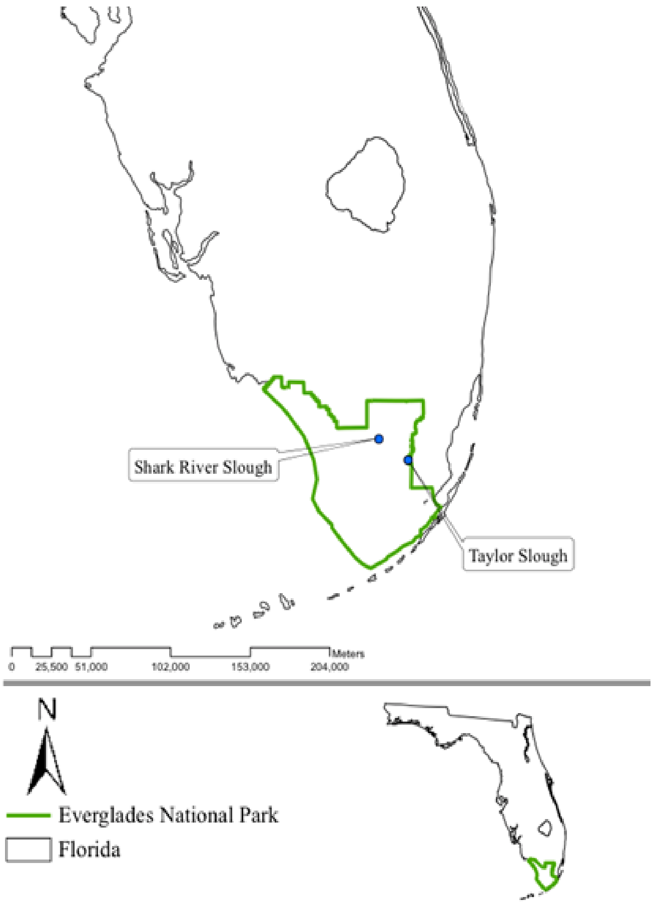

Figure 3. Tower locations in Taylor Slough and Shark River Slough.

search Station (RMRS) in 2011 through their Research Scientist Initiative program, and plan to transfer there as a Research Scientist after completing my PhD. I am currently working under the direction of Dr. Mike Ryan, Research Ecologist in Fort Collins, CO who also serves on my PhD committee with Dr. Hank Loescher (National Ecological Observatory Network) and Dr. Julia Cherry (UA Department of Biological Science, Wetland Ecologist).

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Methane flux measurements in pristine arctic and degraded temperate peatlands of Eurasia

Lars Kutzbach

Carbon in Peatlands

Peatlands store enormous amounts of organic carbon (globally about 600 Gt) which accumulated over past centuries to millennia. Peat accumulates in non-degraded peatlands as long as the build-up of soil organic matter is faster than its decay due to water-saturated and anoxic soil conditions. The huge peatland carbon pool is closely coupled with the atmospheric carbon budget by the exchange of the greenhouse gases carbon dioxide (CO_2) and methane (CH_4). While peatlands are typically long-term net sinks of atmospheric CO_2, they are important net sources of CH_4, which has a 25times higher global warming potential per mass compared to carbon dioxide.

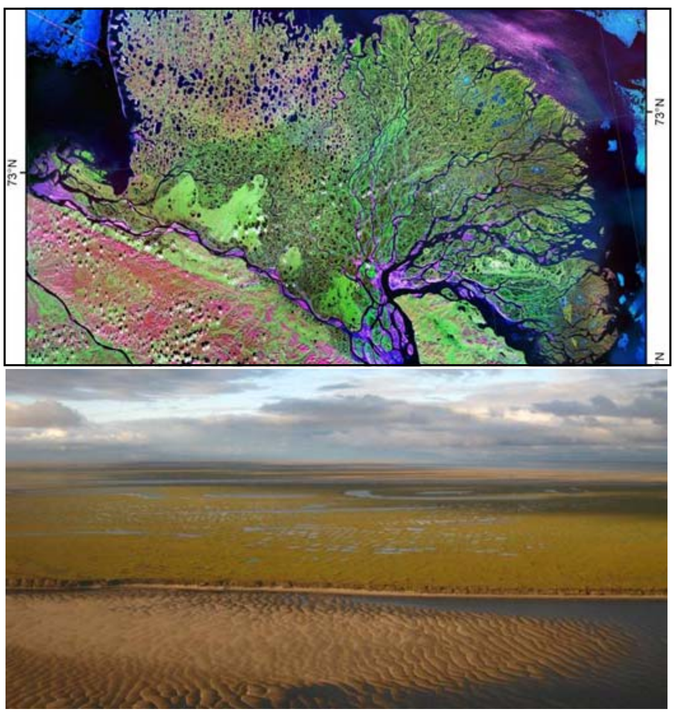

Figure 1. Upper panel: The Lena River Delta in the Siberian Arctic, location of methane flux measurement site Samoylov Island (data from GeoCover 2000, Landsat-7 ETM+/NASA; map by G. Grosse). Lower panel: Landscape in the Lena River Delta (photo by I. Preuss).

As long as peatlands are stable sinks for atmospheric carbon dioxide, they can be considered to have a net cooling effect on the atmosphere over long time scales. However, peatlands and their ecosystem functions and services are severely threatened by climate and land use changes. Most pristine peatlands are situated in the arctic and boreal zones where they face the most pronounced climate changes on Earth due to a set of strong feedback effects which lead to the so-called polar amplification of climate warming. However, due to the high structural diversity and the complex interactions that control the hydrology and biogeochemistry in peatlands, the effects of climate changes are still highly uncertain and need to be investigated more comprehensively. On the other hand, it is evident that the peatlands degraded by intensive land use, which are concentrated in the temperate and tropical zones, have already lost their carbon sink and climate cooling function. In these regions, the main question must be how best to restore peatland functioning.

Objectives

Our working group "Regional Hydrology in Terrestrial Systems" which is based at the Institute of Soil Science at the KlimaCampus of the University of Hamburg studies the coupled water and carbon dynamics of pristine peatlands in the arctic and boreal climate zones as well as of degraded peatlands in temperate oceanic and mediterranean climates. We have a strong focus on quantifying CH_4 land-atmosphere fluxes by means of closed chamber measurements and application of the eddy covariance methodology.

Here, I want to describe our CH_4 eddy covariance flux measurements at a pristine polygonal tundra mire in the Siberian Arctic and a degraded cutover bog under restoration near Hamburg, Germany. While the latter site is very convenient for educational purposes and for testing new instruments because of its relative proximity to our institute, at the remote Arctic site the primary challenges to the use of the eddy covariance CH_4 flux measurements are still at the stage of tuning instru-

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mentation to survive the harsh site conditions and providing for continuous power generation.

Arctic tundra mire

Our arctic investigation site is located in the Siberian Lena River Delta at 72° 22' N, 126°30' E. This largest arctic delta which is situated at the interface of the Eurasian continent and the Laptev Sea is a stunningly beautiful, nearly pristine lowland tundra landscape. The fan-shaped delta is a maze of tributaries which surround more than 1,500 islands of various sizes (Fig. 1). At this amazing but really remote place, our group's engineer Christian Wille, my supervisor Eva-Maria Pfeiffer and I started measuring land-atmosphere fluxes of CH_4 using the eddy covariance methodology in the summer of 2002, as part of my Ph.D. project at the Alfred Wegener Institute for Polar and Marine Research in Potsdam.

Our eddy covariance set-up at this time consisted of a sonic anemometer (Solent R3, Gill Instruments, UK), a closed-path infrared CO_2/H_2O analyzer (LI-7000, LI-COR Biosciences, USA) and a TGA-100 closed-path trace gas analyser (Campbell Scientific, USA) based on tuneable diode laser infrared absorption spectroscopy for measuring the CH_4 fluctuations (Fig. 2, upper panel). Sample air was drawn from the intake through the gas analysers, which were arranged in series in the sample gas line, via a heated tube at a flow rate of 20 standard liters per minute by a vacuum pump. Before entering the TGA-100, the sample air was dried by a gas dryer relying on the principle of reversed flow (PD-200T-48 SS, Perma Pure, USA).

The operation of the TGA-100 required a stable and relatively large power supply to run the vacuum pump and a cryocooler compressor for cooling the laser. In fact, running a closed-path eddy covariance system at such a remote place like the Russian Arctic means that a substantial part of the working time has to be devoted to the operation and maintenance of the indispensable generator.

After the normal teething troubles of the first expedition, the TGA-100 trace gas analyser turned out to be a very robust and reliable instrument, and we were able to obtain high-quality CH_4 flux data from two expeditions during the vegetation periods of 2003 and 2004. Further successful CH_4 flux campaigns were conducted by Torsten Sachs in 2005 and 2006 during his Ph.D. project at the Alfred Wegener Institute in cooperation with me and Christian. The two of us were then affiliated at the University of Greifswald where we worked on boreal peatlands in the research group of Martin Wilmking.

From empirical analysis of the flux time series we obtained from the four expeditions, we were able to deduce the main controls of temporal variability of CH_4 fluxes between the polygonal tundra mire and the atmosphere over the thaw season: While season-

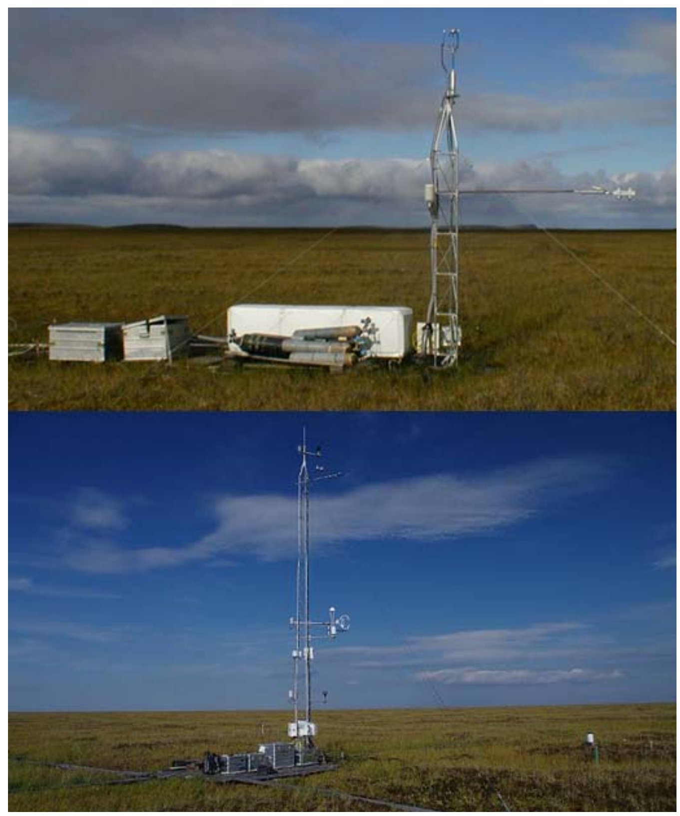

Figure 2. Eddy covariance systems for measuring CH_4, CO_2, H_2O and energy fluxes in the Lena River Delta, Northern Siberia. Upper panel: set-up 2002-2006 (photo by C. Wille); lower panel: set-up from 2010 on (photo by P. Schreiber).

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al variability was mainly controlled by the ground temperature, day-to-day variability was strongly affected by near-surface atmospheric turbulence and air pressure changes. We think that turbulence and pressure changes are major controls of the CH_4 fluxes in polygonal mires because these landscapes are characterised by a mosaic of many small ponds in which CH_4 transport by ebullition, which is the gas transport by ascending bubbles, is important. Increased turbulence could lead to the release of gas bubbles that adhere to surfaces below the water table, such as submerged plant shoots, roots, or shallow sediments through wind induced turbulence in the water, agitation of plants, or wave action. Decreasing atmospheric pressure can also lead to the destabilization of gas bubbles. The CH_4 emissions from the investigated polygonal tundra mire were at the lower end of summer emissions observed by other flux studies in arctic or sub-arctic wetlands. Over the snow-free period from June to September, the integrated CH_4 emission amounted to about 1.9 g m^{-2}.

Figure 3. Some problems encountered during Siberian winter (upper two photos by P. Schreiber, lower photo by G. Stoof.) .

In 2009, I started my research group at the KlimaCampus in Hamburg, and we resumed our work in the Lena River Delta in the same year, after a two-year break. Within the framework of the Ph.D. project of Peter Schreiber, we set up a completely new eddy covariance system on Samoylov Island. The new system (Fig. 2, lower panel) consists of a sonic anemometer (CSAT, Campbell Scientific, USA), a closed-path analyser (LI-7000, LI-COR Biosciences, USA) and an open-path analyser (LI-7500, LI-COR Biosciences, USA) for measuring CO_2 and H_2O fluctuations, and of a closed-path fast CH_4 analyser (RMT-200, Los Gatos Research, USA) and an open-path CH_4 analyser (LI-7700, LI-COR Biosciences, USA).

Presently, Peter works on comparing the performances of the different gas analysers under the harsh arctic conditions as well as on testing the proposed procedures for correcting biases introduced by instrument heating effects. A further focus of his Ph.D. work will be the analysis and quantification of CO_2 and CH_4 fluxes during the autumn and spring shoulder-seasons and the long arctic winter. Preliminary results show the emissions of these gases proceed for a long time into the early winter even at air temperatures below minus 30 °C.

Temperate cutover bog

Our temperate site is the degraded bog Himmelmoor which is located about 20 km north-east from the centre of Hamburg. While the marginal areas of this 600 ha bog were used for centuries for fuel peat mining, the central part of this bog has been used over the last decades until today for harvesting gardening peat. Since 2009, half of the peat

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harvesting area has been successively re-wetted with the aim to restore peatland functions, especially with respect to biodiversity and greenhouse gas emission reduction goals. In 2009, our group and the group of Eva-Maria Pfeiffer have started a multiyear project that aims to monitor the effects of the large-scale re-wetting on the ecology and biogeochemistry of the severely degraded bog. The project includes hydrological, soil-scientific, biogeochemical and biometeorological measurements. Our goal is to evaluate the changes of the balances of water, carbon, nitrogen and other elements in response to the "landscape-scale hydrological experiment".

An important part of our monitoring concept is an eddy covariance system for measurements of fluxes of CH_4, CO_2, H_2O and energy. This system is established at the border between the still-harvested peatland area and the recently re-wetted peatland area. The monitoring of CH_4 emissions over the next few years is of special interest because an increase of CH_4 emissions could offset the positive effects of reduced CO_2 emissions in response to higher water levels. As CH_4 fluxes from water-saturated or even flooded soils are known to be highly variable in time and space due to ebullition, the application of the eddy covariance methodology offers great advantages as it provides a quasi-continuous flux time series that integrates over the often pronounced micro-scale variability of CH_4 fluxes in natural wetlands.

Our set-up in the Himmelmoor (Fig. 4) is composed of a sonic anemometer (R3, Gill Instruments, UK), an enclosed CO_2/H_2O analyser (LI-7200, LI-COR Biosciences, USA) and an open-path CH_4 analyser (LI-7700, LI-COR Biosciences, USA). The Institute of Soil Science and our research group cooperates closely with the company LI-COR Biosciences. As partners, we work together to test new instruments in the field and to train students and scientists in the eddy covariance methodology.

Future directions

Since November 2011, our working group has participated in the collaborative project "Changing Permafrost in the Arctic and its Global Effects in the 21st Century PAGE21" which is funded by the 7th Framework Programme of the European Union. Our Arctic tundra flux measurement site is one of the most intensive study sites of the circumpolar network at which measurements of vertical fluxes of CO_2, CH_4, N_2O and lateral fluxes of carbon and nitrogen will be studied. In the framework of this four year-long project, we aim for multiannual and ideally year-round flux measurements to be able to study the inter-annual variability of land-atmosphere fluxes in response to changing environmental controls. Another important task of this collaborative project is the development of harmonized best practices protocols for CH_4 and N_2O flux measurements and analyses.

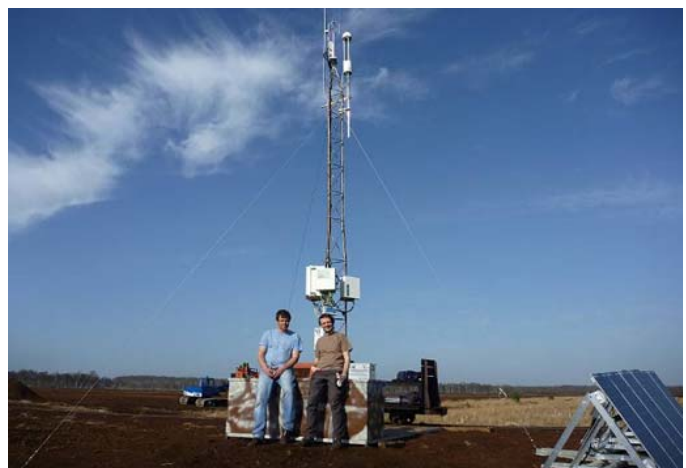

Figure 4. Eddy covariance research and education site at the temperate cutover bog Himmelmoor near Hamburg (upper photo by P. Schreiber, lower photo by UHH/KlimaCampus).

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In another project, submitted to the German Federal Ministry of Education and Research, we and other German institutes proposed to extend our CH_4 flux measurements from the polygonal tundra to other relevant landscapes of the Lena River Delta. We hope to learn more about the spatial variability of CH_4 fluxes on different scales and the possibilities for up-scaling local flux estimates. This approach will be complemented by airborne trace gas concentration and flux measurements on the regional scale which will be conducted within a recently funded research project of our cooperation partner, Torsten Sachs (Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences).

Regarding the many research projects on CH_4 fluxes, the necessity of a global initiative for compiling and synthesizing the existing CH_4 flux measurements is apparent. We aim to contribute our experience to this urgent process.

Figure 5. Research Group "Regional Hydrology in Terrestrial Systems". From left to right: Ph.D. Student P. Schreiber, group leader L. Kutzbach, chemical engineer S. Kopelke, scientific engineer C. Wille, Ph.D. student A. Avagyan, Postdoc B. Runkle, Ph.D. student F. Beermann

Acknowledgements

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Observations of the Atmospheric Carbon Cycle in Restored Wetlands

Frank Anderson, Brian Bergamaschi, Lisamarie Windham-Myers, Robin Miller, Roger Fujii

Study Overview

The Sacramento – San Joaquin Delta is a mosaic of 57 islands (polders) and river ways at the confluence of the Sacramento and San Joaquin rivers that serves as a point source of fresh water for 22 million Californians (DWR 1995). The rich organic (peat) soils of the Delta region have developed primarily from historic wetlands over the past 7,000–10,000 years (Atwater, 1980). The product of decayed marsh plants and periodic sediment deposition resulted in areas of the Delta with peat soils up to 18 meters thick (Drexler et al. 2009). The nutrient-laden peat soils, abundance of water, and Mediterranean-type climate make the Delta excellent for agriculture. Settlers recognized this in the late 1800s and systematically adapted the existing wetlands for crop production by constructing levees and draining the peat soils. Unfortunately, the newly established aerobic conditions resulted in the rapid loss of the organic soils and concomitant subsidence of land so that most Delta islands are currently several meters below sea level. With approximately 1,700 kilometers of protective levees in the Delta, levee maintenance is costly and flooding is an ongoing threat to the regional agriculture and California's water supply (Mount and Twiss 2005). Consequently, the re-establishment of wetlands in the Delta is a plan under consideration to mitigate land surface subsidence and protect the fresh water supply.

In 1997, two 3 hectare wetlands were established on Twitchell Island, in the heart of the Sacramento – San Joaquin Delta (Figure 1), to experimentally test how rapidly peat could be produced and develop a better understanding of the balance between documented long-term sequestration of carbon and the release of more potent greenhouse gases (GHG). The wetlands were constructed and maintained at two different water depths: 25cm in the West wetland and 55cm in the East wetland. By 2002, planted hardstem bulrush or tule (*Schoenoplectus acutus*), and volunteer cattails (*Typha* spp.) covered the majority of the West wetland, but only the southern portions of the East wetland, as shown in Figure 2.

Over a ten-year period (1997-2008), the range of accreted organic soil from the emergent wetlands ranged from 28 - 47 cm (Miller et al. 2008). These high rates of subsurface biomass (peat) accretion continue today (Robin Miller, USGS, written com-

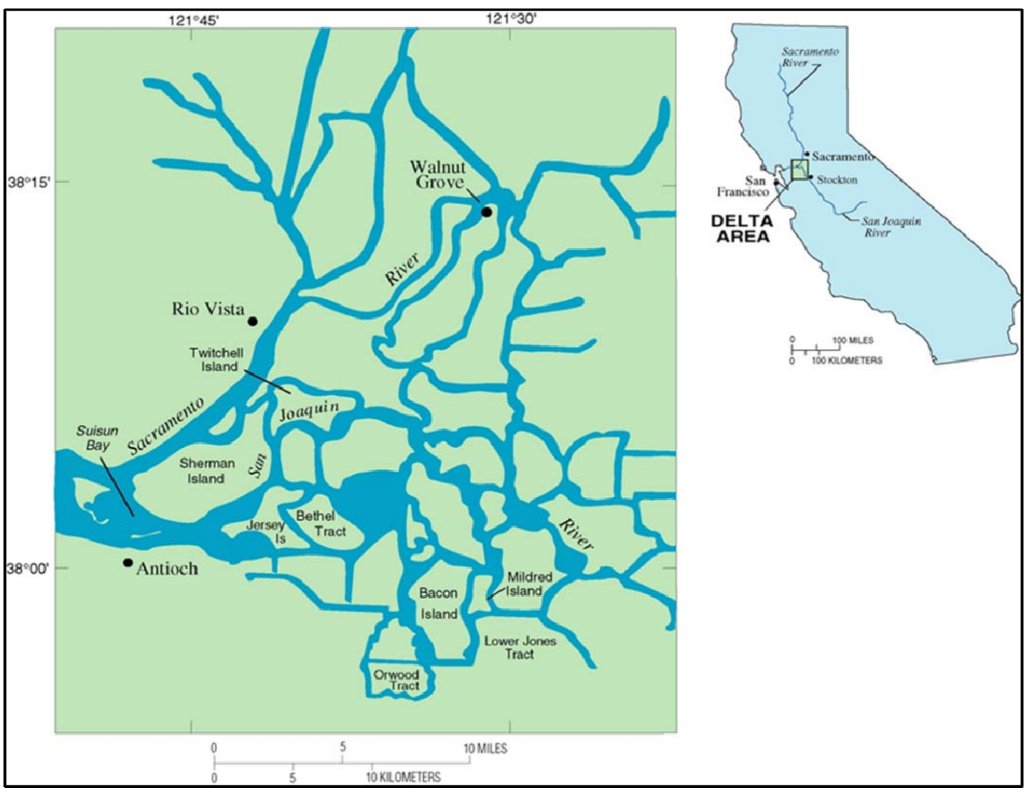

Figure 1: An expanded view of the Sacramento-San Joaquin Delta. Twitchell Island is located to the southeast of Rio Vista, and has an average elevation of 5 meters below sea level.

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Figure 2: A 2002 aerial photograph looking west, showing a fully covered West wetland and mostly-covered East wetland, center.

munication, 2011), and with annual rates of carbon sequestration in this peat averaging ~1 kg C m^{-2} yr^{-1}, these types of restored wetlands are important due to their potential for carbon sequestration. However, the anaerobic conditions that promote this carbon accumulation have been observed to produce high rates of methane fluxes. In 2010, we installed an eddy covariance tower to measure carbon dioxide and methane fluxes to investigate the extent that methane emissions from these temperate wetlands may offset the high levels of carbon dioxide uptake and biomass storage. Preliminary flux measurements indicate both carbon dioxide uptake and methane emissions at this site are among the highest rates compared to other flux studies in the Delta and to ecosystems globally.

Balancing Productivity and Greenhouse Gas Emissions

Both wetlands have shown high productivity and one reason may be the region's Mediterranean climate and long growing season. Additionally, during summer afternoons, a cool, moist breeze filters into the Sacramento – San Joaquin valleys from the San Francisco Bay, known as the "Delta Breeze". This localized weather pattern is not considered a true land-sea breeze, but is the result of the changing synoptic atmospheric pressure patterns in the Eastern Pacific Ocean. The amount of cooling that occurs from the Delta breeze depends on the depth of the fog layer formed near the California coast. We hypothesize that both the Mediterranean climate and the "Delta Breeze" create conditions where plants are highly productive during the day and exhibit limited respiration during the cool

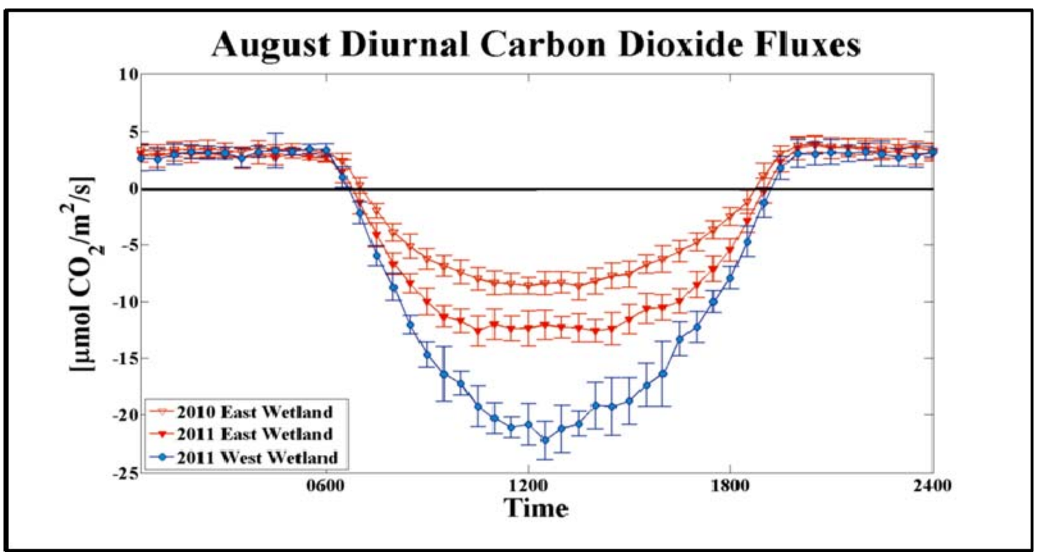

Figure 3: August mean half-hour CO_2 fluxes from the East (2010 and 2011) and West wetlands (2011). The diurnal plots were created from all available half hours for the month. Error bars indicate +/-one standard deviation

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nighttime hours.

Carbon dynamics within the wetlands are highly variable. Whole-plant-enclosed chamber measurements, despite similarities in the amount of soil carbon sequestration, showed peak daily methane production varied between locations based primarily on water depth and position along the wetland's water flow path from marsh inlet to marsh interior (Miller 2011). The maximum values of atmospheric gas exchange occur during the peak growing season when daily maximum temperatures are greatest and plant and microbial metabolisms are most active. Miller (2011) found significant vegetation effects on methane fluxes, in that 1) plant-mediated methane release was nearly an order of magnitude greater than surface-water diffusion alone, and 2) stem density was correlated with methane fluxes during the growing season. With large cumbersome plants playing such a significant role in GHG fluxes, and with replicated whole plant chambers illustrating significant variability in GHG fluxes by site, a continuous spatially integrated approach using an eddy covariance tower was necessary to assess temporal variability and address larger scale GHG emissions.

Continuous eddy covariance flux measurements give us the ability to integrate daily-annual patterns over larger areas of the wetlands, providing a better picture of the net GHG benefits of peatland restoration. We measured carbon dioxide and methane fluxes in the East wetland during 2010 and 2011 and the West wetland in 2011. The instruments

Figure 4: Plantcam picture from the East wetland flux tower, August 1, 2010, showing the large amounts of senescent material.

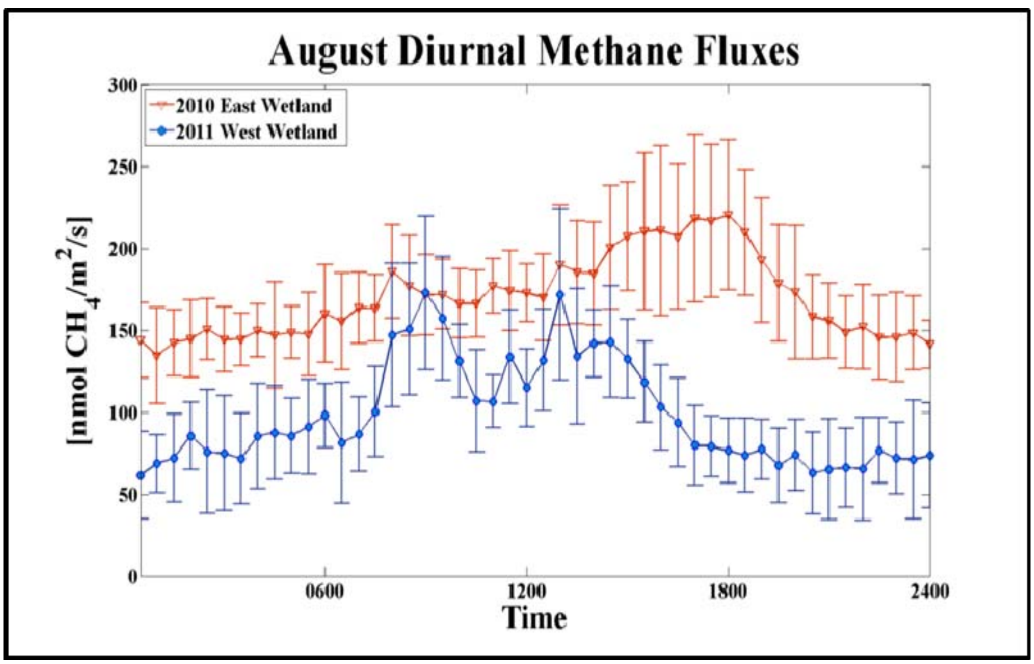

Figure 5: August mean half-hourly methane fluxes from the East wetland in 2010 and the West wetland in 2011. The diurnal plots were created from all available half hours for the entire month. The error bars indicate one standard deviation from the mean.

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used to collect carbon and energy flux measurements included: a CSAT3 or a Gill Windmaster Pro sonic anemometer; a LI-7500 open-path CO_2/H_2O infrared gas analyzer; a LGR Fast Greenhouse Gas Analyzer or a LI-7700 open-path CH_4 analyzer; a Kipp & Zonen 4-channel net radiometer; a Visala HMP45c Temperature and Relative Humidity Probe, a Delta-T SPN1 Sunshine Pyranometer; and up and downward facing LI-190 Quantum Sensors.

What We Are Learning from the Flux Measurements

Initial chamber and eddy covariance measurements both showed that the East wetland was more productive during the earlier stages of the wetland restoration. Between 2002 and 2004, peak midday net ecosystem exchange (NEE) rates exceeded -40 μmol m^{-2} s^{-1}, whereas in 2010 and 2011, the peak midday NEE rates ranged from -8 to -11 μmol m^{-2} s^{-1} (Figure 3). Preliminary results suggest that the presence of aboveground senescent material affects the rates of NEE as the wetland ages, and that additional biotic factors affect Net Primary Production (NPP) on an inter-annual basis. We look to two sources of evidence that could help explain the differences in productivity between the wetland's early stages and what we observed in 2010 and 2011. First, there are now areas within the East wetland, within the 2010 eddy covariance footprint, where >55 cm of accumulated dead plant or senescent biomass exist (Figure 4); an aspect that was not present from 2002 to 2004. Second, we see that the rates of midday NEE increased from 2010 to 2011 and are correlated with a 90% increase in the Normalized Difference Vegetation Index (NDVI) from July 2010 to 2011 (Stefania Di Tommasso, USGS Menlo Park, written commun., 2011). This may suggest an oscillation pattern in NEE that correlates with inter-annual fluctuation in macrophyte production; a pattern that was also observed by Rocha and Goulden (2008) in a freshwater marsh of similar emergent vegetation in Sothern California.

Figure 6: Plantcam picture from the West wetland flux tower, August 1, 2011. Green vegetation is dominant in this photo compared to the August 1, 2010, photo from the East pond.

Similar to the carbon dioxide emissions, the East wetland methane emissions

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were also higher early on in the wetland's development. Chamber results show median midday plant-moderated methane emissions were approximately 320 nmol m^{-2} s^{-1} from 2000 to 2003 (Miller, 2011, table 1), whereas, in August 2010, midday half-hour averaged methane fluxes were approximately 175 nmol m^{-2} s^{-1} (see Figure 5). Interestingly, peak mean half-hour fluxes during this period were approximately 225 nmol m-2 s-1 and occurred in the late afternoon, coinciding with maximum air and water temperatures. This is different from other wetland studies where midday peak methane fluxes coincide with bulk or pressurized convective flow through the emergent vegetation (Chanton et al., 1993; Kim et al., 1998; Garnet et al., 2005). We hypothesize that the presence of senescent material may also play a role in methane release. Despite the decline over time, methane emissions from the East wetland are in the upper range of flux measurements compared to other global studies (2011 American Geophysical Union Fall Meeting: B11G. Natural Wetlands: Observations and Modeling of Distributions and Methane Dynamic I).

Work in Progress: West Wetland Eddy Covariance Fluxes

In 2011, we focused our attention on the West wetland and found that rates of daytime NEE were greater than the East wetland in both 2010 and 2011 (see Figure 3) and that methane emission rates were lower compared to the East pond in 2010 (see Figure 5). An August 1, 2011, Plantcam photo taken at the West wetland (Figure 6) shows that the aboveground green biomass dominates the West wetland and may exemplify why NEE values are greater than the East wetland, where green biomass cover is lower. Furthermore, the aboveground green biomass may also be influencing the methane emissions as the emergent marsh vegetation provides a pathway for advective venting through aerenchyma tissue. Figure 5 shows peak methane rates occurring during midday morning, a characteristic of pressurized convective flow via the emergent vegetation. The timing of the peak rates is similar to midday peak emissions measured by other wetland studies with emergent wetland vegetation, as mentioned in the previous section. The West wetland seems to have less dependence on temperature compared to the timing in peak methane emissions from the East wetland in 2010.

Observations from both the East and West wetlands indicate an ability to sequester carbon. One of our research goals is to understand how the global warming potential of methane production offsets this ability. We have found that the rates of NEE were higher during the early stages of the East wetland and have decreased by approximately 75% in August 2010 and 2011, while methane emissions have remained high through the entire period. Based on this pattern, the East wetland has become less of a negative net forcing to global climate change over time. On the other hand, the shallower West wetland may show a more consistent pattern of interannual NEE and lower methane production, which would result in a more consistent negative net forcing to global climate change over time. We look to NEE, which is strongly influenced by NPP from aboveground biomass, for changes in the balance of GHG net forcing and observe that it varies across site, season, and year. Future publications will present quantitative tests of these patterns to suggest methodological benefits and limitations in understanding the processes behind carbon sequestration and net GHG fluxes.

Contact

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