Introduction

We are in the midst of a grand global experiment that presents unprecedented challenges for ecosystem science and environmental policy. To fully understand the impacts on ecosystems of ensuing global changes in climate and land use, we need to link global climatic process affecting atmospheric composition, chemistry, and radiative balance to local ecological processes affecting biosphere-atmosphere interaction. The emerging subfield of regional (10s-1000s of km) biogeochemistry has arisen to meet this need (Blankinship *et al.*, 2008), developing new methodologies to bridge the gap from meteorology to ecology and in process discovering new insights into functions of ecosystem-atmosphere interaction (Baldocchi, 2003). While significant progress has been made to this end in carbon dioxide (CO_2), the same cannot be said other greenhouse gases, including methane (CH_4) (Beswick *et al.*, 1998; Wofsy and Harris, 2002). Similarly, carbon balance studies to date have been generally focused on forested uplands, with limited research in lowland and wetland regions.

Quantifying carbon balance, estimating net radiative forcing, and predicting future changes in vegetated landscapes with significant quantities of wetlands requires understanding *both* CO_2 and CH_4 cycles. In addition, the interaction of carbon cycles with the hydrologic cycle cannot be neglected in these landscapes. Complex upland-lowland landscapes are characteristic across temperate latitudes, especially in sub-boreal and boreal regions. **This CAREER proposal addresses the scientific need to understand the joint regional balance of CO_2 and CH_4 in these sub-boreal landscapes, their environmental controls, and future trajectories in the face of global change**. Additionally, I seek to integrate this research into education activities that emphasize local ecological impacts of global change and prepares next generation environmental scientists and managers to bridge local and global concerns.

Though global level carbon cycle inversions have largely been successful (e.g., Chen and Prinn, 2006), even with the added complexity of OH chemistry for CH_4, these inversions are limited in their application at the regional scale (Bousquet, 2006); a similar argument can be made for plot level studies (Potter *et al.*, 2006). There are many reasons to suspect that studying the interaction of CO_2 and CH_4 at regional scales can reveal subtleties in earth system biogeochemistry that are not captured by simple scaling of plot level data or downscaling of global data. Emergent regional properties such as CO_2 and CH_4 emissions from lake sediments (e.g., Bastviken *et al.*, 2008; Repo *et al.*, 2007), CH_4 ebullition in saturated landscapes (e.g., Sachs *et al.*, 2008; Strack and Waddington, 2008), CO_2 or CH_4 hot spots (e.g., Flessa *et al.*, 2008), or ecological and micrometeorological edge effects at forest-wetland boundaries are likely to be missed.

I propose to adapt an existing tall tower regional observatory (WLEF, Park Falls, WI) for simultaneous observations and analysis of regional CO_2 and CH_4. To adequately constrain CH_4 and CO_2 budgets, I will utilize what Mike Goulden of UC-Irvine has coined "method-hopping"– the integration of multiple observation techniques at multiple scales (Blankinship *et al.*, 2008). I will instrument the first long-term tall-tower observatory of regional CH_4 using recently developed high-precision, fast response, self-calibrating CH_4 analyzers and a combination of innovative footprint-weighted eddy covariance flux tower (Desai *et al.*, 2008; Wang *et al.*, 2007b), surface layer Bowen ratio similarity (Werner et a., 2003), and convective boundary layer tracer budget techniques (Helliker *et al.*, 2004). These analyses, along with the existing nearly decade long CO_2 observations, plot level CH_4 observation, and soil, hydrologic, and meteorological regional observation networks will be used to analyze and contrast the regional environmental controls on CO_2 and CH_4 exchange and parameterize and test sensitivity of a next-generation hydrological-biogeochemical model of regional carbon exchange (Mackay *et al.*, 2003a,b, 2007).

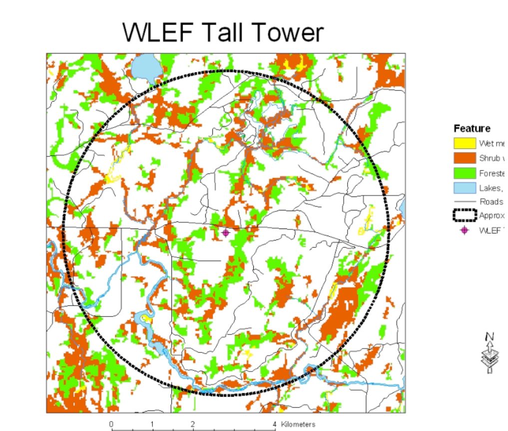

Figure 1. Wetland (colors) vs upland (white) delineation in a 4-km radius around the WLEF tower. (Courtesy of R. Teclaw, USFS)

There are several compelling reasons to conduct this study at the WLEF site. First, the existence of the 447-m WLEF tall flux tower, operating since 1996 and studies occurring in the region have provided a rich existing database on landscape properties and atmospheric trace gases (Chen *et al.*, 2008). Second, the footprint of the tower is a complex, mixed landscape, that is more than 30% wetland, ideal for this study (Fig. 1). Finally, a long term decline in water table elevation has been observed at several pizeometers around the region and corroborated by stream flow and precipitation records (Mackay *et al.*, 2007) (Fig. 2). This trend has been shown to affect stand scale wetland CO_2 flux (Cook *et al.*, 2008; Sulman *et al.*, 2008). The water table effect provides a natural regional scale manipulation that can be analyzed for its effects on regional carbon balance and hypothesized shifts from CH_4 flux to CO_2 flux.

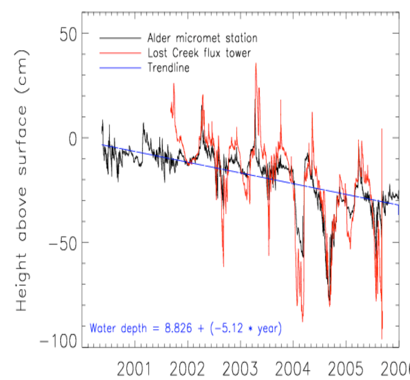

Figure 2**.** Trend of declining water table elevation at two independent wetland sites. (Courtesy of B. Cook, U. MN)

Relevance

Natural emission of methane from wetlands is the largest source of uncertainty in quantifying sources/sinks of atmospheric CH_4 (Mikaloff Fletcher *et al.*, 2004), contributing 25-40% of global CH_4 emissions and dominating the interannual variability signal (Bousquet *et al.*, 2006; Chen and Prinn, 2006; Crill *et al.*, 1992) Significant anthropogenic warming is predicted to dominate natural variability in the climate signal in as little as 5-10 years (Smith *et al.*, 2007). These climate changes are bound to affect regional water tables and wetland soil temperatures (Roulet *et al.*, 1992). Given the close coupling of CH_4 to CO_2 and H_2O cycles and the sensitivity of wetlands to hydrology and climate, wetlands are expected have regional and global significance in future atmospheric trajectories of CH_4 and CO_2.

To date, based on review of the literature, only a few other continuous annual CH_4 eddy covariance flux measurements has been made, and only at short towers (Rinne *et al.*, 2007; Will *et al.*, 2008). Shorter term CH_4 flux observations have also been made (e.g., Fowler *et al.*, 1995; Friborg *et al.*, 2003; Kim *et al.*, 1998; Shurpali and Verma, 1998; Suyker *et al.*, 1996). None of these measurements have been made at the regional scale from a tall tower and few have had simultaneous CH_4, CO_2 and H_2O flux measurements. This proposal also targets the aims of the U.S. Carbon Cycle Interagency Working Group North American Carbon Program (NACP) to develop infrastructure for long-term surface fluxes of CO_2 and CH_4 and improve the next generation of ecosystem models to assimilate data from these observational platforms to derive regionally resolved fluxes of CH_4 (Wofsy and Harriss, 2002).

Next-generation research will be tied to next-generation place-based education. Outreach activities are integral to this CAREER proposal and will be used to increase exposure of STEM disciplines and the local impacts of global change research with programs aimed at Native American community college students, high-school students, the general public, international undergraduate lab interns, non-science major students in my global change class, and a Ph.D. student to be recruited to work on this project. Detailed descriptions of these activities are noted in the *Broader Impacts* section below.

I believe this proposal has potential to be transformative to the field of regional biogeochemistry by moving beyond a CO_2-only to a more inclusive greenhouse gas perspective and with better consideration of complexity in landscapes. Innovations in regional observation methods will also help shape the future of the emerging tall tower network. This CAREER proposal also strengthens my existing ties with the network of ecologists, hydrologists, meteorologist studying carbon and water cycles in the upper Midwest and with whom I have been acquainted for the past seven years. I have been building expertise in observing and modeling regional CO_2 cycles in heterogeneous regions and have identified the need to better understand wetlands, hydrologic cycles, and CH_4. Since starting at the University of Wisconsin-Madison (UW-Madison), I have started on this latter path by starting new collaborations in wetland observation and CH_4 modeling and incorporating elements of such into my education and outreach. Funding this proposal would significantly jumpstart these efforts in both my research and education.

Background

Global Atmospheric View: CO_2 and CH_4

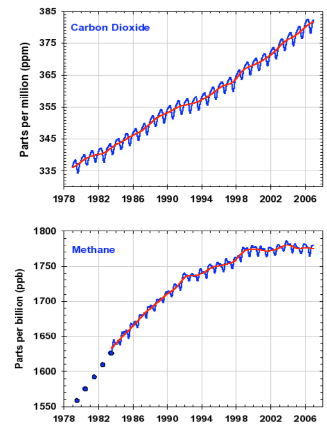

Figure 3. Global average CO_2 and CH_4 from 1978-2007 (source: NOAA).

Magnitudes and future source/sink strengths of terrestrial ecosystem exchanges of carbon dioxide (CO_2) and methane (CH_4) to the atmosphere are highly uncertain, subject to large interannual variability, and responsible for a long term trajectory of the atmospheric greenhouse effect (Friedlingstein *et al.*, 2003, 2006; Shindell *et al.*, 2004; Zhuang *et al.*, 2004). Atmospheric CH_4 has tripled since pre-industrial times (Houghton *et al.*, 2001). In addition to being a potent greenhouse gas with 62x greenhouse gas warming potential at 20 year times scales and 23x at 100 year time scales when compared to CO_2 (Houghton *et al.*, 2001; Lelieveld, 2006), CH_4 is also an important sink for atmospheric OH and plays an important role in tropospheric water vapor and stratospheric ozone chemistry (Keppler *et al.*, 2006).

While the growth rate of atmospheric CO_2 has been a positive trend of 1-2 ppm yr^{-1} (Conway *et al.*, 1994), the growth rate for CH_4 is less defined, slowing from 10-15 ppb yr^{-1} in the 1980s to 0-5 ppb yr^{-1} in the 1990s (Dlugokencky *et al.*, 2003) (Fig. 3). Currently, CH_4 is increasing 0.5% per year and responsible for 15% of the 2.5 W m^{-2} increase in atmospheric longwave radiative forcing (Chen and Prinn, 2006; Collins *et al.*, 2006). Globally, atmospheric CH_4 concentration is approximately 4850 Tg (doCarmo *et al.*, 2006) with a typical net annual emission to the atmosphere of 600 Tg CH_4 yr^{-1} (Prather *et al.*, 2001).

Local Ecological View: CH_4 and The Role of Wetlands

North temperate regions play a large role in the wetland carbon cycle, given their relatively large area and carbon in wetlands (Dahl, 2006) and significant expected regional climate change (Heitmann *et al.*, 2007; Urban *et al.*, 1989); moreoever, these emissions are poorly constrained and highly variable (Cao *et al.*, 1998, Panikov *et al.*, 1999). Much activity has focused on the large carbon stores under thawing permafrost in wetlands north of the 0C isotherm (Christensen *et al.*, 2004; Johansson *et al.*, 2006), though carbon release is also likely to be significant in warming and drying temperate mid-latitudes.

Two pathways exist to convert buried organic carbon into the form of major greenhouse gases. CO_2 is produced mainly due to aerobic oxidation of organic matter; CH_4 is produced only in anaerobic environments (Segers, 1988) from a balance of production and consumption in the soil due to reduction of CO_2 (Heitmann *et al.*, 2007) or fermentation of acetate. Controlling factors on this balance are the difference in rates of methanogenesis and methanotrophy and modes of transport (Conrad, 1995; Holzapfelpschorn *et al.*, 1985; Oremland & Culbertson, 1992; Schimel & Gulledge, 1998; Zinder, 1993).

Water table and temperature have both been shown to be controlling environmental factors for CO_2 and CH_4, but results on their dominance have been inconclusive. Thus, changes in water table are expected to have strong impact on temperate wetland CH_4 and CO_2 emission ratios, though with great uncertainty (Davidson and Janssens, 2006). Numerous studies have attempted to correlate CH_4 observations to environmental parameters such as water table depth, temperature, vegetation type, CO_2 fixation/respiration rates, atmospheric O3, and/or microbe/organic matter quality (e.g., Aerts and Ludwig, 1997; Bellisario *et al.*, 1999; Blodau *et al.*, 2007; Bubier *et al.*, 1995; Christensen *et al.*, 2003; Dunn *et al.*, 2007; Freeman *et al.*, 1992; Friborg *et al.*, 2000; Giradin *et al.*, 2001; Grant and Roulet, 2002; Gulledge and Schimel, 2000; Hargreaves *et al.*, 2001; Kettunen *et al.*, 1996; King *et al.*, 2002; Kruger *et al.*, 2001; Laine *et al.*, 1996; Lelieveld, 2006; Moore and Roulet, 1993; Mörsky *et al.*, 2008; Shannon *et al.*, 1996; Shaver *et al.*, 2006; Strack and Waddington, 2007; Updegraff *et al.*, 2001; vonFischer and Hedin, 2007; Whalen and Reeburgh, 2000), but these plot-level chamber, modeling, or meta-analysis based studies have had mixed results. A review paper noted that most studies point to water table and temperature as strong controlling factors, and the authors note that latitudinal trends show that anaerobic and aerobic decomposition are both important in boreal regions (Jungkust and Fiedler, 2007).

Moving Forward To Regional CO_2/CH_4 Biogeochemistry

Lessons learned from regional CO_2 studies

My collaborators and I have conducted several studies attempting to primarily understand regional CO_2 balance in upper Midwest upland ecosystems. Before discussing how I will incorporate CH_4 and wetlands into this picture, I review major findings relevant to this proposal.

Regional CO_2 fluxes

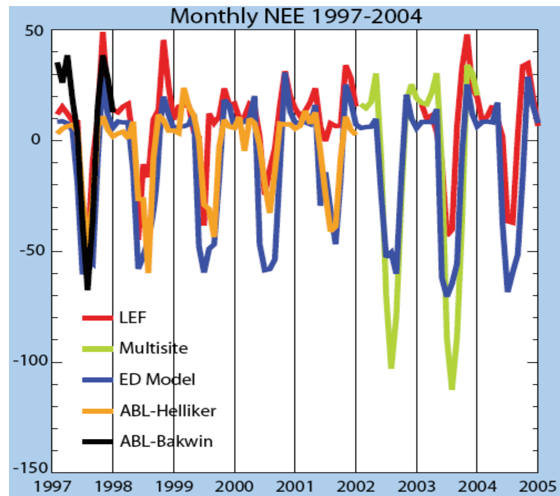

Figure 4. Regional CO_2 NEE at WLEF estimated from five different methods (Desai *et al.*, 2006).

We have attempted to quantify regional CO_2 net ecosystem exchange (**NEE**) flux around the WLEF tall tower using several independent techniques (Desai *et al.*, 2006), including tall tower eddy covariance (Davis *et al.*, 2003), a forest inventory based model (Desai *et al.*, 2007), biometric budgets (Tang *et al.*, 2008), an ecosystem model tuned to 16 nearby flux towers (Desai *et al.*, 2008; Wang *et al.*, 2006b), and CO_2 boundary layer budgets (Bakwin *et al.*, 2004; Helliker *et al.*, 2004) (Fig. 4). Unlike upscaling of forest evapotranspiration (Ewers *et al.*, 2007, 2008; Mackay *et al.*, 2002, 2007; Tang *et al.*, 2006), there is not strict convergence of upscaled CO_2 fluxes among the methods due to differences in region footprints, error in model inputs, and error in model processes. Nevertheless, the results are encouraging and suggest that regional flux quantification is possible if errors and footprints are properly accounted. For example, we've learned that footprint "bias" in the raw WLEF EC data requires a model to deconvolve the EC sampled landcover against the true regional landcover, which significantly improves comparison against the multiple flux tower model (Desai *et al.*, 2008).

Environmental controls of CO_2 exchange

A number of studies in the region, focused mostly on the stand-scale flux towers have studied environmental and anthropogenic controls on upland CO_2 ecosystem respiration (**ER**) and gross primary production (**GPP**) (e.g., Bolstad *et al.*, 2004; Cook *et al.*, 2004; Desai *et al.*, 2005; Yi *et al.*, 2004) and more recently wetland CO_2 GPP or ER (Cook *et al.*, 2008; Sulman *et al.*, 2008). Short-term controls on flux are largely temperature, shortwave radiation, and for wetlands, water table elevation. Longer-term controls vary by site, but typically include site age and growing season length. Interannual variability is notoriously hard to model (Ricciuto *et al.*, 2008). Lags in biogeochemical responses to environmental controls exist and need to be accounted when regressing or modeling fluxes. The region-wide declining water table and trends in temperature and precipitation provide a natural experiment for testing these controls. These studies have led to installation of significant infrastructure in water table elevation pizeometers and micrometeorological and soil observations systems that are currently in operation.

Flux modeling and prediction

A number of ecosystem models and parameter estimation techniques have been successfully applied at individual tower sites (E.g., Pridhoko *et al.*, 2008), but short-term (years) prediction of CO_2 fluxes using tuned ecosystem models have generally been confounded by the difficulty in capturing interannual variability. I have done some initial work suggesting that incorporating a dynamic start of growing season and site disturbance history can significantly improve this. Long-term regional prediction has mostly focused on forest succession (e.g., Gustafon *et al.*, 2000), and less on biogeochemical cycling. Emerging ecological data assimilation and parameter optimization techniques have potential for providing a better picture of future regional carbon cycle (Riccituo *et al.*, 2008; Sacks *et al.*, 2006). Linking CO_2, CH_4, and H_2O cycles for regional biogeochemistry has not been done.

Some initial findings on wetlands and CH_4

Preliminary findings by my lab and collaborators on CH_4 and the role of water table in the upper Midwest form my basis for suspecting that a better picture of controls on regional biogeochemistry can be had by simultaneous observations of CH_4 and CO_2 fluxes from a regional perspective. Some of these findings are briefly reviewed here.

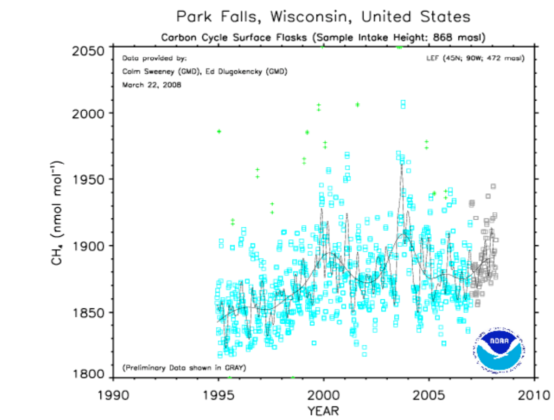

Figure 5. Monthly flask observations of CH_4. Gray squares are preliminary data. Green squares are those identified as significantly above the regional background. (source: NOAA)

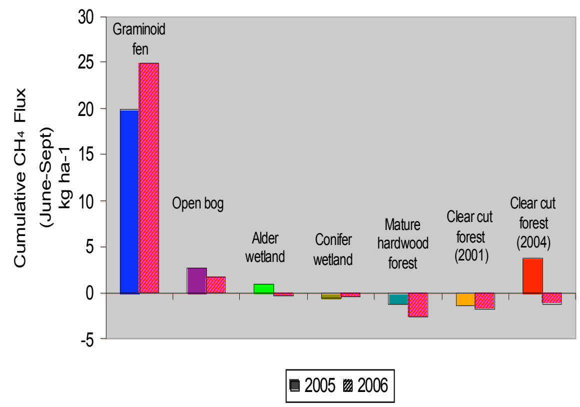

Figure 6. Methane flux in seven different vegetation cover types in a northern Wisconsin landscape. Fluxes are estimated from approximately tri-weekly growing season measurements (courtesy of P. Weishampel).

Tall tower CH_4 flask observation

The National Oceanic Atmospheric Administration (NOAA) Earth Systems Research Lab (ESRL) monitors greenhouse gases at the WLEF tower including weekly single level flask observations of CH_4. These observations show periods of higher than background CH_4 concentrations in the region (Fig. 5). Given the small amount of anthropogenic CH_4 emissions, these data suggest a significant natural flux of CH_4 in the region with large temporal variability. Werner *et al.* (2003) attributed these emissions to wetlands based on a simple land cover analysis, but uncertainty on this remains high.

Soil chamber observations of CH_4 flux

A colleague (P. Weishampel, see letter) recently made some CH_4 chamber flux observations in the footprint of the WLEF tower to complement the larger number of CO_2 chamber flux observations made in the past (e.g., Bolstad *et al.*, 2004). These measurements were made with standard static chamber techniques (Healy *et al.*, 1996; Hutchinson *et al.*, 2000; Livingston and Hutchinson, 1995) and deployed over soil, low-growing vegetation, or floated on water. Measurements made at various times over the growing season in 3 lowlands and 3 uplands showed the largest CH_4 emissions in a fen, smaller in a bog, neutral in forested wetlands and generally methane consumption in forests (Fig. 6). Results also showed pulses of CH_4, such as a large pulse of CH_4 in the recent clear cut in one year but not the following. Only continuous observations, such as those from eddy covariance, will be able to regularly observe pulses of CH_4 (e.g., after a rainstorm or during ebullition events (Strack and Waddington, 2008) along with non-growing season fluxes, which may also be substantial (Pelletier *et al.*, 2007; Yu *et al.*, 2007).

Water table-carbon interaction in wetlands

My graduate student and I have recently analyzed six years of shrub wetland eddy covariance CO_2 and water table data to reveal a strong relationship of water table elevation to ER, but a weak relationship to GPP (Sulman *et al.*, 2008). We also found preliminary evidence of changing water use efficiency (WUE) at the site in the face of a deepening water table elevation, possibly hinting at plant succession.

Fig. 7 shows that depending on soil temperature, CO_2 emissions have a sharp decline as water table approaches the surface, at roughly -20 to -40 cm. This result has been corroborated at two other wetland EC sites. The picture for GPP to date has been more mixed. Without CH_4 observations, however, the total carbon balance of this wetland with change in water table is unknown.

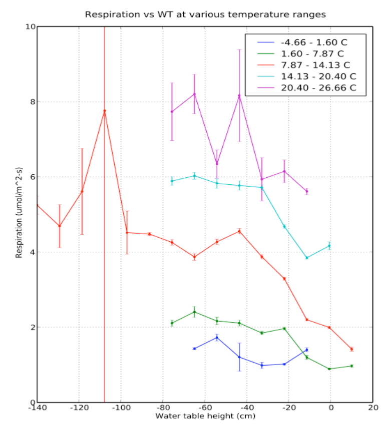

Figure 7. Declining CO_2 respiration with increasing water table for different temperature classes from 6 years of flux observations at a shrub wetland site. (courtesy of B. Sulman, U.WI)

Lingering questions and proposal objective

The initial findings suggest that there are significant CH_4 sources in the region that have large spatiotemporal variability and potentially share environmental controls with CO_2 fluxes, in both uplands and wetlands, for decomposition and photosynthesis. These findings provide motivation for my **objective** of *observing and analyzing regional (10s-100s km) CH_4 flux* and *understanding the combined carbon-climate feedbacks of CO_2 and CH_4 under conditions of declining water table elevation and rising temperature*. I ask:

1.) How is our understanding of regional controls on greenhouse gas uptake/emissions by natural vegetation skewed by our lack of observation of the fuller carbon cycle beyond CO_2?

2.) Are there emergent regional responses in CO_2 and CH_4 cycling that are not observed by plot-level and stand-scale observations?

I intend to meet our objective by quantifying regional CO_2 and CH_4 flux in a mixed upland-wetland landscape, investigating environmental controls on them, and parameterizing these results in ecosystem models to test sensitivity of regional biogeochemistry to future climate. These goals can be subdivided into the these questions and hypotheses:

1.) **Can we quantify regional CO_2 and CH_4 flux?**

> Hyp. 1: Independent observations of regional CO_2 and CH_4 flux will converge on magnitude, trends, and interannual variability within the estimated uncertainty for each technique.

2.) **Is there a simple way to estimate CH_4 fluxes from CO_2 fluxes?**

> Hyp. 2: Interannual variability of CO_2 and CH_4 are correlated, thus allowing for derivation of a region CH_4 emission:CO_2 uptake ratio useable for remote sensing of regional CH_4 (e.g., Potter *et al.*, 2006), similar to the global scale ratio proposed by Whiting and Chanton (1993).

3.) **What are the primary environmental controls on CO_2 and CH_4 flux and the implication for climate sensitivity?**

> Hyp 3a: Land cover distribution (upland vs wetland), water table elevation, soil/air temperature, soil moisture, and photosynthetic active radiation (PAR) explain most of the diurnal, season, and interannual patterns in regional CO_2 and CH_4 flux.

> Hyp 3b: The net effect on carbon fluxes from increasing air/soil temperature is a smaller CO_2 sink and greater CH_4 emission, due to increased soil aerobic and anaerobic decomposition and reduced net primary production of vegetation.

> Hyp 3c: The net effect on carbon fluxes from a decreasing (deeper) water table is a smaller CO_2 sink and smaller CH_4 emission, due to increased ER of CO_2 and decreased ER of CH_4 in wetlands, decreased CH_4 consumption in uplands, and decreased GPP in uplands.

The confounding effects of CO_2 and CH_4 will be considered together using CH_4 and CO_2 climate forcing factors to assess the net radiative and chemistry impacts of these changes in regional carbon cycling.

Research Methods

General approach

To answer my questions and test my hypotheses on the differences in environmental controls of regional CO_2 and CH_4 fluxes, I intend to intensively observe regional biogeochemical cycling across a mixed upland-wetland landscape in northern Wisconsin using a number of innovative techniques, analyze their environmental controls, and adapt a joint CO_2-CH_4-H_2O model to test regional carbon cycle sensitivity to climate, hydrology, and land management. I propose to:

1) Quantify regional CH_4 and CO_2 flux: I intend to produce the first long-term record of continuous regional CH_4 observations in a mixed landscape using both tall tower eddy covariance and boundary layer budget techniques. These observations complement the existing long-term records of CO_2 flux at the field site. The five-year funding cycle will allow generation of a sufficiently long dataset so as to analyze both short-term and interannual controls on CH_4 and CO_2 flux. Regional flux will be computed using 1.) "footprint weighted" tall tower eddy covariance, 2.) single tower convective boundary layer budget technique, and 3.) a modified Bowen ratio technique. **Applies to questions 1, 2, and 3**.

2) Analyze environmental controls of CH_4 and CO_2 flux: The regional fluxes will be used to test hypotheses on how CO_2 and CH_4 regional carbon fluxes are simultaneously affected by changes in water table, temperature, PAR, etc… at hourly to interannual timescales. The existing water table elevation network and previously collected plot-level chamber and flux data will be used to clarify and identify processes leading to the observed results. **Applies to questions 2 and 3**.

3) Predict future CH_4 and CO_2 flux: The quantified regional flux and the analyzed environmental controls will be used to refine an existing hydrological and biogeochemical model that a collaborator and I are currently building for a wetland site. Parameter and model optimization techniques will be employed and simple scenarios of future climate, hydrology, and land use will be applied to this model to quantify future changes in biogeochemical cycling and net radiative forcing and atmospheric chemistry effects of regional landscapes. **Applies to question 3.**

Details of the site and the approaches are provided below.

Site description

The proposed area of study is the region surrounding the WLEF-TV tall tower in Park Falls, WI USA. The tower is located with the Chequamegon-Nicolet National Forest. This region is lightly populated and heavily forested. The terrain is characterized by undulations in elevation of about 20m forming a heterogeneous landscape of wetlands and uplands. The region was heavily logged in the early 20th century and is currently managed for hardwoods, red pine, aspen, and forest wetlands (e.g., alder, cedar) (Mackay *et al.*, 2002).

The 447-m tall WLEF TV tower is an Ameriflux eddy covariance site producing eddy covariance observations of CO_2, H_2O, temperature and momentum flux at 30, 122 and 396 m since mid-1996 (Bakwin *et al.*, 1998; Davis *et al.*, 2003). The heterogeneous flux footprint provides direct observations of regional flux. A large database of ecological *in situ* and remotely sensed data are also available for the tower footprint. My lab is involved in operating the flux and CO_2 tracer instrumentation at this site in collaboration with NOAA and The Pennsylvania State University.

The measurements and analysis conducted to date has fallen mostly under the auspices of the Chequamegon Ecosystem-Atmosphere Study (ChEAS; http://cheas.psu.edu), a multi-investigator consortium of investigators studying carbon and water balance in the region. Plot, stand and regional data, primarily focused on CO_2 fluxes, H_2O fluxes, carbon stocks, and land cover, have been collected by nearly one dozen independently funded investigators.

Task 1: Quantify Regional Flux of CH_4 and CO_2

I will use three independent techniques, described below, to quantify the regional fluxes of CH_4 and CO_2 in the region. All three rely on the existing infrastructure of the WLEF tower. Installation of a recently acquired high-precision CO_2/CH_4 analyzer and the acquisition of a fast-response CH_4 analyzer will be initiated under this proposal to allow for CH_4 flux analysis. Previously collected plot-level chamber flux and stand-scale flux tower (as many as 16 in the region in the past) data will be scaled and compared to these fluxes for comparison.

Task 1a: Footprint weighted eddy covariance from a very tall tower

The eddy covariance technique relies on transport of scalars in the turbulent atmospheric surface layer. By conservation of mass, measuring the sum of scalar advective flux, below sensor scalar accumulation, and most importantly the turbulent covariance of vertical wind velocity and scalar yields the net flux into or out of the surface (Loescher *et al.*, 2006). Typically, the advective flux is ignored, which is a reasonable assumption in flat terrain with homogenous landcover (Goulden *et al.*, 1996). Thus, single tower measurements of scalar profile and high frequency (>5 Hz) vertical wind and scalar can be used to yield NEE. High frequency wind velocity is typically measured with an ultrasonic anemometer, which uses pulses of ultrasonic sound to gauge wind velocity. There are many sensor related corrections related to measuring the flux (Berger *et al.*, 2001). An advantage of the tall tower is that the homogenous landcover requirement is relaxed, given the mixing in the boundary layer. My collaborators and I have successfully measured CO_2, H_2O, temperature, and momentum fluxes on the WLEF tall tower and several other sites in this way for the past decade (Davis *et al.*, 2003).

The top levels (122m and 396m) of the tower sample a mixed landscape of uplands and lowlands that is representative of the larger region as a whole, "seeing" roughly 2 km^2 in unstable conditions, larger in stable conditions (Desai *et al.*, 2007a; Wang *et al.*, 2006a). The 122m and 396m level have similar flux footprints, but the 122m is also more likely to be in the nocturnal boundary layer, increasing its usability at night. However, because the heterogeneous landscape sampled changes with wind direction and atmospheric stability, the hourly flux "footprint" is not always measuring the same regional flux. To overcome this issue, my colleague, Weiguo Wang, developed a novel technique to deconstruct the flux use a micrometeorological footprint model (e.g., Horst and Weil, 1992) for the convective boundary layer (Wang *et al.*, 2006a) that is then convolved with a land cover map, an empirical minimal parameter ecosystem model, and the observed fluxes. Though the problem is nonlinear and underconstrained, there is sufficient oversampling to solve for land cover based fluxes at monthly and seasonal timescales with acceptable uncertainty. By sampling many hours and applying the footprint model, a consensus (by multivariate optimization such as Monte Carlo simulation) emerges on the net fluxes (specifically, emission/uptake factors) from each land cover type.

I have applied this method and developed a reconstruction technique to then observe the regional "footprint-weighted" flux (Desai *et al.*, 2008). Initial use of this technique will be improved in this proposal by using a more recent landcover map with detailed wetland delineation (a deficiency noted by Wang *et al.* (2006b)), a better ecosystem model (with water table consideration), and run over a longer (interannual) time periods. Additionally, the joint use of CO_2 and CH_4 flux in this optimization should significantly improve detection of wetland fluxes as the covariance between the two fluxes is likely to change with amount of wetland in the footprint. Finally, this technique may be valuable for detecting any possible sources of hypothesized CH_4 production from upland vegetation (Frankenburg *et al*., 2005; Houweling *et al*., 2006; Keppler *et al*., 2006;).

This proposal supports the acquisition of one of the recently developed fast-response, high-precision, self-calibrating, continuous CH_4 analyzers (Kroon et al., 2007). The analyzer will be calibrated and installed at the WLEF tower to acquire CH_4 fluxes at the 122m level. Using the existing sonic anemometer and data acquisition system at the WLEF tower reduces costs. Storage flux will be computed using the high-precision CH_4 profiling analyzer (see Task 1b). These observations will allow for direct observation of regional scale continuous CH_4 over interannual timescales, which has never been done before.

Typical CH_4 turbulent fluxes at WLEF are expected to be 1 mg m^{-2} h^{-1} (0.5 ppb m s^{-1}) (Werner *et al.*, 2003), which requires that eddies with deviations of 2 ppb must be detected by the sensor at hourly averaging scales. The instrument I plan to acquire that can accomplish this is the Picarro, Inc. Envirosense 3000f high frequency cavity ringdown CH_4/CO_2 analyzer, currently in the final phase of testing and slated for sale in late summer 2008 (E. Crosson, 2008, pers. comm.). Unlike traditional single-pass infrared gas analyzers, as are used for CO_2, this analyzer relies on integrating the decay curve (ringdown) as photons are lost from the highly reflective cavity and subsequently counted. Thus, the sensor is very precise and does not require reference calibration. Line and pressure broadening effects are minimized by scanning and integrating across the entire absorption spectra of interest. The lines being scanned by the Picarro sensor also includes CO_2, allowing for an additional measure of CO_2 flux at the site. The instrument will collect 10 Hz CH_4 flux data at 122m by drawing down air from that level to a trailer located at the WLEF base. Eddies at this height are large, therefore relaxing the frequency response required to ~0.1 Hz. However, the higher altitude increases the averaging time needed to capture the largest eddies to one hour (Berger *et al.*, 2001). Drawing air samples down to the surface via long tubes at high flow rates has been shown to have little effect on fluxes because mixing of the eddies that transport scalars is minimized by turbulent flow in the tubes. High-frequency spectral losses for CO_2 fluxes at 122m are roughly 5% (Berger *et al.*, 2001). Errors due to systematic advection are modest (Davis *et al.*, 2003; Ricciuto *et al.*, 2008; Yi *et al.*, 2000). Some research will be needed on applying Webb-Pearman-Leuning density corrections to CH_4 (Webb *et al.*, 1980). These potential systematic errors primarily influence flux magnitude, and have little influence on temporal variability; therefore, questions that hinge on temporal variability can be addressed with great confidence via micrometeorological flux measurements.

Task 1b: Trace gas boundary layer budget

I have recently acquired a Los Gatos, Inc. high-precision CO_2/CH_4 analyzer with my University start-up funding. The instrument is currently in use for lab calibration of CO_2 and CH_4 gas standards. I plan to install this instrument at the WLEF tower and sample the existing high-precision CO_2 profiling lines (Bakwin *et al.*, 1998) to acquire six-level two-minute average samples of CH_4 concentration. The instrument is based on integrated cavity output spectroscopy (ICOS). ICOS is a multi-path cavity-enhanced absorption spectroscopic technique with a precision of < 0.7 ppbv CH_4 and < 0.2 ppm CO_2 at 0.5 Hz (Bear *et al.*, 2002). The unique cavity uses high reflectivity mirrors to create an effective path length of ~10km within a 40cm cavity, significantly increasing detection of CH_4 in the near IR at room temperature. The device is also relatively insensitive to vibration, small changes in cavity length, temperature and alignment. The device is calibrated and line locked against a reference cell and a baseline loss value from a cavity ringdown measurement at the end of each scan.

Several papers have shown that, when averaged over synoptic cycles, CO_2 mixing ratio time rate of change, corrected for boundary layer entrainment, is strongly correlated to the tall tower CO_2 flux as measured by eddy covariance (Bakwin *et al.*, 2004; Helliker *et al.*, 2004). Entrainment at the boundary layer top is estimated by 1) extracting vertical velocity measurements from reanalyzed meteorology models and applying a zero-order jump model to tower and NOAA weekly aircraft profiles or 2) relying on a water vapor similarity approach that relates water vapor vertical derivatives, water vapor eddy covariance flux, and NOAA water vapor soundings to free troposphere entrainment. I propose to extend this analysis to the continuous CH_4 observations that will be acquired by the CH_4 profiling system. This tracer approach also has a larger footprint (10-100 km upwind fetch) than the tall tower flux (1-10 km fetch) and so will be investigated for extrapolating from the tower footprint to the larger region.

Task 1c: Modified bowen ratio

An alternative approach to estimating large region CH_4 flux from CH_4 tracer profile has also been tested at the tall tower for a short time period (Werner *et al.*, 2003). This method, termed the Modified Bowen Ratio (MBR) technique relies on similarity of diffusion for CO_2 and CH_4. By combining first-order diffusion equations for CO_2 and CH_4 and equating the diffusion coefficients, one can derive an equation for CH_4 flux as a function of CH_4 tracer profile, CO_2 tracer profile, and CO_2 flux. This method was tested on two growing seasons at the tall tower. In this proposal, I will extend the analysis to the entire data record of available CH_4 profiles and compare to the eddy covariance and tracer budget techniques.

Task 2: Understand Environmental Controls of CH_4

Regional fluxes from Task 1, the network of meteorological and hydrological observations, nearby stand-scale fluxes towers, and plot-scale chamber fluxes will be analyzed at the diurnal, monthly, seasonal and annual timescales for patterns and correlations of CO_2 and CH_4 emissions in the region and the mechanisms responsible for these patterns. Correlation analysis, both direct and lagged, will be performed at the hourly, daily, synoptic (weekly), monthly, seasonal, and interannual timescales as appropriate for each measurement. Primary environmental variables that will be tested are soil and air temperature, water table elevation, precipitation, soil moisture, and PAR. CH_4 pulse fluxes will be compared to atmospheric pressure and turbulence variables to test for ebullition effects (e.g., Sachs *et al.*, 2008). ANOVA and related tests will be used to test for significant interactions across the entire regional observation network.

Of particular interest is whether there is consistency in relationships of environmental variables to CO_2 and CH_4 flux, even if the magnitude of regional flux varies among the methods (which is likely given the different spatial/temporal scales of measurement). The goal is to provide more confidence that observed correlations are robust against flux uncertainty. Interannual analysis will also be valuable to estimate regional CH_4:CO_2 emission factors and their spatiotemporal variability.

Another compelling way to analyze these is to use the footprint weighting model mentioned in Task 1a and essentially run it in reverse. The key here is recognizing that that the patterns and parameters derived from the simple ecosystem model embedded in the footprint model can be used to test hypotheses on the sensitivity of wetland and upland GPP and ER to water table, temperature, moisture, light, and cover type. Model selection, tuning, and sensitivity tests will be the primary activities used to test the hypotheses.

Task 3: Predict Future CH_4 and CO_2 Flux

While the simple model to be developed for the footprint model of Task 1a and the environmental control analysis of Task 2 can be used for interpreting data, it does not have value for extrapolation and prediction. A biogeochemical process model is needed for this task. While several wetland and CH_4 models exist (e.g., Cao *et al.*, 1996; Petrescu *et al.*, 2008; Potter *et al.*, 1997; Sonnentag *et al.*, 2008; Walter *et al.*, 2001; Zhang *et al.*, 2002; Zhuang *et al.*, 2004), many only weakly constrain hydrology, only a few also include upland biogeochemistry, and therefore most are not suited for regional application. Here, I propose to remedy that by building on work being done by a collaborator (D. Scott Mackay, SUNY-Buffalo) and I on an independently funded proposal (see "Current Support" and letter). We are adapting the Terrestrial Regional Ecosystem Exchange Simulator (TREES) ecohydrology model (Mackay *et al.*, 2003a,b; Ewers *et al.*, 2008) to incorporate wetland biogeochemistry and hydrology. The TREES model has been successfully used to model transpiration and leaf level CO_2 fluxes across the region (Mackay *et al.*, 2003). Non-vascular plant processes and peatland respiration models will be added to TREES to incorporate wetland CO_2 and CH_4 biogeochemistry. Regional processes will be connected by a hydrology model based on a finite difference groundwater model and constrained by the water table peizometer network and previously collected canopy LiDAR ground return data that will be used to construct a high resolution hydraulic gradient map.

CH_4 regional flux data to be collected by this proposal will be synthesized and provided as constraint to the TREES model. A Markov Chain Monte Carlo (MCMC) parameter estimation routine is being implemented for TREES (Samanta *et al.*, 2007) to constrain model parameters with CO_2 flux tower assimilation. Here, I will investigate data assimilation of CH_4 flux into this framework after the TREES model CH_4 biogeochemistry and wetland hydrology have been incorporated. The constrained model can then be fed a variety of scenarios on future temperature and water table to test the effects on upland, wetland, and regional variability in biogeochemical cycling and land-atmosphere exchange.

Once regional flux predictions are produced, simple analyses can be done on the climate impact on CH_4 versus CO_2 fluxes using radiative balance models (Frolking *et al.*, 2006) and tracer transport/chemistry models. For example, tradeoffs in CH_4 emissions versus CO_2 respiration with a changing climate can be quantitatively examined by comparing across years with different mean temperatures and precipitation. This kind of analysis would provide added insight at the large region impact and role that subboreal regions play in carbon balance, air quality, and climate.

Prior, Current, and Future Support

Carbon and water cycle studies have been funded in the ChEAS-region for over a decade, though none have focused on the entire region across water, CO_2, and CH_4 interactions. The most relevant funded project was a NASA Carbon Cycle project (PI: P. Bolstad) that focused extensively on collecting high resolution land cover data around the tall tower corroborated with many intensive biometric sampling plots, LiDAR based tree canopy mapping, roving portable flux tower wetland CO_2 fluxes, and mechanistic modeling with a modified Biome-BGC model (Bond-Lamberty *et al.*, 2006). These data are available and provide a thorough snapshot of the state of the regional landscape that will be used to initialize the proposed mechanistic models.

Currently, I am funded on two projects relevant to this proposal. I have recently initiated a project to measure and model wetland carbon fluxes funded by a Department of Energy (DOE) National Institute of Climate Change Research (NICCR) Midwest region grant (Lead PI: Ankur Desai, UW-Madison; co-PI: D. Scott Mackay, SUNY-Buffalo). The goal of that proposal is to understand water table controls on wetland CO_2 flux and develop a hydrological-biogeochemical model for wetlands. This CAREER proposal builds on the expertise gained here and extends the TREES model developed by the NICCR grant to incorporate CH_4 and regional landscape hydrology.

I am also currently funded by NSF as co-PI on collaborative proposal OCE-0628560 (with lead PI G. Mckinley, C. Wu, UW-Madison; and N. Urban, Michigan Tech.), 10/1/06-9/31/10, *Carbon balance of Lake Superior.* This project is in year 2. We have successfully built a biological and physical model of Lake Superior and estimated initial regional atmospheric CO_2 emission rates. I have focused on incorporating atmospheric CO_2 observations into the model and comparing results to land flux towers in the region. Presentations have been made at the American Geophysical Union and the American Society of Limnology and Oceanography. We have also recruited and trained a minority post-doc and a female Ph.D. candidate. A workshop on the Lake Superior carbon cycle is planned for August 2008.

This proposal helps tie my current research and education activities, and potential future projects into a coherent whole focused on understanding wetland biogeochemistry, atmospheric CO_2/CH_4 variability, and carbon-climate interaction in regional settings using micrometeorological and ecological techniques. At UW-Madison, I have formed new collaborations with Frank Keutsch (see letter) on methane instrumentation; Ishi Buffam, Monica Turner, Jon Foley, and Tim Krantz to better understand regional carbon cycling in the lake-studded Northern Highlands region of Wisconsin and the North Temperate Lakes Long Term Ecological Research Site (LTER); and Phil Townsend and Shawn Serbin on biomass and wetland cover sampling from high-resolution hyperspectral remote sensing. I have submitted an NSF proposal with Chuixiang Yi., CUNY-Queen's, to investigate advection across wetland-upland gradients.

Research initiated by this proposal also has potential for generating new collaborations and projects. I have currently initiated discussions with Randy Kolka, USFS (see letter) on comparing methane eddy covariance observations; Peter Weishampel, U. Minnesota (see letter) on scaling plot-level chamber CH_4 observations; Dylan Millet, U. Minnesota on the potential for VOC eddy covariance at the WLEF tall tower; Gregg Starr, U. Alabama on open-path methane sensors and water table studies, and Nic Saliendra, USFS and D. Scott Mackay, SUNY-Buffalo on how to model human behavior and incorporate land and water management actions into biogeochemical models. Support of this proposal would significantly improve the likelihood of converting these discussions into new formal collaborations.

It is likely that other projects and new research questions will also emerge from continued analysis of the wealth of data from the WLEF tall tower observatory and the newly acquired methane instrumentation. The CH_4 instrumentation will form a significant new facility for the Desai lab and the Ameriflux flux tower network. I also foresee future acquisition of a currently in-development low-power open-path CH_4 flux sensors (e.g., Li-Cor, Inc. LI-7700) to do targeted studies at wetland sites in the tower footprint that lack A/C power. Finally, I note that the NSF-support National Ecological Observatory Network (NEON, Inc.) has located its Great Lakes core facility at the nearby (< 100 km) University of Notre Dame Environmental Research Center (UNDERC) and based on my discussions and site visits with them, they are planning to leverage the data collected by ChEAS (including this proposal if funded) to understand spatiotemporal variability of carbon cycling and local future sensing platforms or sites for this region.

Broader Impacts

Global climate change is a topic on many people's minds today. Of course, local weather and climate are always a topic of interest. However, much misinformation is passed around when the latter is attempted to be tied to the former (e.g., recent extreme weather, frequency of hurricanes, change in planting dates). In my research, I am fundamentally interested in making both global change and local observations relevant to regional scale concerns about ecosystems. Consequently, I believe, as University faculty, that my education and outreach should also be similarly directed. I would like to use this CAREER proposal to further some of my current efforts and establish new ones, in the realm of tieing together global change, local observations, and regional ecological change. Moreover, I prefer that these education and research activities do not stand alone, but form an integrated whole. Here, I outline several broader impact activities that connect the research in this proposal to education and outreach activities, and vice versa.

The activities below target 1.) community college science students at a Wisconsin tribal college seeking more knowledge about 4-yr degrees in STEM, 2.) Wisconsin rural high school students and the local public interested in learning about local impacts of global chance, 3.) UW undergraduate non-science majors interested in global change, and 4.) international undergraduates considering attending graduate school in the U.S. A graduate student interested in education and outreach activities will also be recruited to assist in these activities. Although this is an ambitious list, it should be noted that only the first two activities will be completely new endeavors, with the majority effort focused on the tribal college.

Each of the plans share some common goals and themes. For each group, I want to **motivate interest in the sciences and global change by appealing to the research we are doing in their backyards**, namely northern Wisconsin. Too often, as scientists, we gain greatly by doing research in various field locations, but for the local populace, the reverse is not necessarily true. I have been working on research in northern Wisconsin for almost a decade, and I would like to ameliorate my own deficiency here. Moreover, local outreach is well received by the University of Wisconsin due to the enshrinement of the Wisconsin Idea, which states that "the boundaries of the university should be the boundaries of the state, and that research conducted at the University of Wisconsin System should be applied to solve problems and improve health, quality of life, the environment and agriculture for all citizens of the state". The idea is well tied to the NSF CAREER program aim to integrate research and education.

The proposed activities are also aligned with recent calls to improve STEM education, provide teacher education, and develop summer institutes as noted in the recent National Academy of Science document, "Rising Above the Gathering Storm" (National Academy of Sciences, 2007). The education plans here are aimed to promote STEM careers, provide hands-on activities that utilize STEM skills, and propagate STEM awareness in underserved populations. To do this, activities also need to follow published national guidelines on science standards, incorporating research into education, and assessment (e.g., National Research Council, 1996, 2001, 2002). The outreach here targets national science standards on the state of current local, national and global Earth system scientific and technical challenges.

Preparing for college degrees in STEM: College of Menominee Nation

Through a collaborative opportunity with the NSF-supported multi-college consortium Wisconsin Alliance for Minority Participation (WiscAMP, see letter), I intend to develop, implement, and assess a 12 day summer science inquiry and career exploration program for 2-yr college students at the College of Menominee Nation (CMN), in cooperation with their VP of Academic Affairs, Donna Powless (see letter). The **goal** of this activity is to provide greater exposure to research careers in STEM to students. The **expected outcome** is to increase enrollment in 4-yr STEM degrees, which will be **assessed** by longitudinal tracking through WiscAMP.

CMN is an accredited 2-yr tribal college on the Menominee Reservation in Keshena, WI. Menominee County is the poorest county in the state of WI, located within the same general region as the proposed field study, and less students here pursue STEM careers. At the same time, the Menominee Tribe have been pioneers (since before the 20th century) in the development of sustainable forestry techniques (Davis, 2000; Pecore, 1992; Wood and Dewhurt, 1998) and consequently CMN offers AA degree programs in Natural Resources, Sustainable Development, and Biology & Physical Sciences. I intend to target this pool of students, introduce them to topics on global change and regional biogeochemistry via inquiry-based projects at our field sites, and attempt to interest some to pursue baccalaureate and graduate degrees in the sciences. CMN also has some connections with the Menominee Indian School District, and the opportunity to recruit advanced high school students into the program will also be considered in consultation with CMN.

WiscAMP is committed to increasing the pipeline of underrepresented minority students who receive bachelor's degrees in STEM fields. Native Americans do not receive a share of degrees in STEM in proportion to their share of population (age 20-24) at any degree level (Babco, 2003, 2005). Though Native Americans have now increased to 0.7% of all STEM degrees in 2000, compared to 0.4% in 1987 (Babco, 2003), poverty, poor educational systems, and lack of exposure of science research continues limit the appeal of STEM degrees (Lin *et al.*, 2007). I would like to increase exposure to the breadth of global change research that can provide viable careers and an opportunity to improve the livelihoods (e.g., forestry in a changing climate) of the local community. Summer science enrichment programs with other tribes have been done (Dalbotten *et al.*, 2004; Lin *et al.*, 2006, 2007) and lessons learned here on unique cultural, family, and educational backgrounds of many Native American students places additional requirements on what should be included in an educational program.

The summer program will take place at CMN, a field station, and the field study site. The first part (2 days) at CMN will take place during the day, and will focus on basic earth system science topics such as biogeochemical cycling, climate change, and energy. Much of these materials will be adapted from an undergraduate global change class that I currently teach (see below). For the last two parts, participants will be transported to Kemp Natural Resources Station (NRS) and reside there for the remainder of the project. Kemp NRS is an experimental field station run by the University of Wisconsin-Madison, College of Agriculture and Life Sciences. I have had a long relationship with Kemp NRS, since it is my primary base for research studies in northern Wisconsin. In addition to lab, lodging, and kitchen space for researchers, classroom and outdoor meeting space are available for outreach and Kemp NRS encourages researchers who utilize the facility to also conduct outreach (see letter). Kemp NRS provides affordable dormitory lodging ($12/pp/night), classrooms, lab facilities, and a computer lab with internet access.

In the second part (5 days), participants will visit field sites, learn about local land-atmosphere datasets and dataset tools. Simple measurements will be made at the field sites to demonstrate scientific measurement techniques. Students, in teams of three, will then meet with me and other colleagues. Each student group will develop a short, simple inquiry-based project on regional land-atmosphere change based on the existing data (with possible limited opportunity for more data collection). National Research Council (2002) provides insight into how to incorporate scientific research into education, and the guidelines there on education of research conduct, presentation, and ethics will be incorporated here.

After students have selected projects, the final portion (5 days) of the class will consist largely of free time dedicated to pursuing the project in close cooperation with my lab and other colleagues available for consultation. Typically, many field researchers also stay at Kemp in the summer, and a few will be recruited to assist in research mentoring. At the end of the program, each group will write a scientific abstract describing their project and produce a 20-minute presentation with graphics as part of a mini-conference. Particularly compelling projects may possibly lead to incorporation into the proposed research or used as a motivator to recruit participants to UW-Madison and my lab.

Assessment and evaluation are integral to any educational endeavor. The National Research Council (2001) notes that assessment in science needs to gauge student cognition, observation, and interpretation skills. Timely feedback is needed to improve student metacognition (reflecting and direction one's own thinking). I extensively use "clicker" instant-response classroom technology in my undergraduate courses and I will investigate the potential to use these in the course. Student evaluation will be driven by use of a pre-test prior to start of the program, short self-graded quizzes and journaling activities during the course, and post-course evaluation and self assessment. A rubric and written assessment will be provided for the presentations. Evaluation of the overall program logistics and content will be scrutinized to improve future runs of the course. These assessments will be used by Kemp NRS and CMN as part of its review process of outreach programs. The potential to offer CMN credit for this class will also be considered.

To optimize the time commitment of this activity, the first year of this proposed activity will be devoted entirely to course development and recruitment of the first class in collaboration with WiscAMP, CMN, Kemp NRS, and my lab. The graduate student to be supported by this proposal will be recruited with express notice that an education component involving assistance to this course will be part of professional development (see below). Thus, a side benefit of this course is to provide instructional experience for a graduate student, something that is typically lacking in most science Ph.D. programs. Additionally, there is a Menominee student currently considering majoring in Atmospheric & Oceanic Sciences at UW-Madison. Supplemental NSF REU, minority participation funding, or UW internal grants will be used to recruit him or other interested undergraduates to work on both research and education components. In years 2-5, a program for 15-20 students will be held. Selection will be by application. This proposal includes funding to cover transport, lodging ($12/pp/night at Kemp), meals, and incidentals to all participants. The possibility of stipends (which may be necessary for many or most participants) will be explored through internal WiscAMP grant competition and other funding mechanisms.

K-12 and public outreach on STEM careers at Kemp NRS

Kemp NRS routinely welcomes researchers who are lodging at Kemp to present research to the public. I will present two talks per year at Kemp NRS targeted to high school students from the surrounding mostly rural school districts and the general public. The **goal** of this activity is to disseminate knowledge about global change, local impacts, local research to residents in the area, and provide education about science careers and STEM degrees to high school students. The **expected outcome** is increased understanding about local research and science careers which will be **assessed** by participant evaluation and follow-up surveys. I will develop two sessions per year. One will likely focus on global climate change and the connection to local land use, biogeochemical cycling, and environmental science careers. The other will focus our local research activities and provide hands-on access to instrumentation that we use to measure land-atmosphere exchange and micrometeorology by installing these sensors at the Kemp property. Access to research grade instrumentation is one way to engage people on how science actually works and connecting the message scientists communicate with the methods they develop to acquire the results. Publicity and school district contact for these events will be coordinated with Kemp NRS.

Undergraduate global change course development

I currently teach an undergraduate course in the Atmospheric & Oceanic Sciences department (and cross listed in Environmental Studies) at UW-Madison titled "Global Change: Atmospheric Issues". This undergraduate introductory level elective has fulfills a University writing intensive course requirement needed by all undergraduates, most of whom are from Wisconsin. I cover topics on climate change, stratospheric ozone, acid rain, and basic earth system science. Regional climate and land-atmosphere data generated by this proposal will be incorporated into existing written homework assignments that currently rely on article response papers to include more analysis and discussion of *in situ* data. Student evaluations in the past have shown that the data-driven writing assignments were the most well received. The **goal** of this activity is to connect the relatively abstract concepts of global change to regional change and scientific data analysis. The **expected outcome** is increased understanding of global change as **assessed** by tracking expected improved results on final exams and the final term paper.

International student lab exchanges: The Khorana Program

The Khorana Program for Scientific Exchange has been recently established at UW-Madison and is focused on increasing interaction and research between universities in India and UW-Madison (see letter). Every year, undergraduates from top institutions in India are accepted into a summer lab internship program via the program. I am currently listed as a faculty mentor and if this proposal is funded, I plan to leverage the funding to recruit an undergraduate from India to work in my lab via the Khorana program. The proposed research lends naturally to many opportunities for lab, computational and/or field research. The **goal** of this activity is to build a pipeline for future Indian environmental scientists and increase opportunities for international collaboration with India. The **expected outcomes** are increased enrollment in graduate programs in biogeosciences by participants and future international research proposals, which will be **assessed** by participant tracking through Khorana and reporting on research collaborations by me.

Graduate student education

A graduate student will be funded on this proposal and will focus on the burgeoning fields of regional biogeochemistry, land-atmosphere interaction, and carbon cycle. The student will also be directly involved in the education activities outlined here as part of his or her professional development. To assist this, I will leverage the Delta program, the UW-Madison implementation of the NSF-funded Center for the Integration of Research, Teaching, & Learning (CIRTL) (see letter). Delta offers courses in instructional materials development and classroom diversity. These courses will be taken by the student. The student will also have the opportunity to engage in a "teaching-as-research" internship and obtain a certificate offered by Delta which acknowledges this student as a next generation scholar committed to integration of teaching and research, the **goal** of this activity. The **expected outcome** is that the Ph.D. student will not just participate but lead some of the proposed education activities and upon graduation, have better career opportunities, which will be **assessed** by student follow-up.

Management Plan

Personnel

I (Ankur Desai), will be the PI and am in my 2nd year as Assistant Professor of Atmospheric & Oceanic Sciences at University of Wisconsin-Madison. I have extensive experience in eddy covariance flux measurement, trace gas calibration, and scaling land-atmosphere fluxes. I also have significant ecosystem modeling experience. This proposed project, if funded, will help broaden my current CO_2 and upland focused research to CH_4 and wetlands. I will supervise the technician and graduate student on the project and oversee project management. Also, I will interact with the numerous outreach partners identified in this proposal. Last year, I organized an NCAR/NSF sponsored 50 graduate student summer regional biogeochemistry colloquium in Boulder, CO and have organized other workshops in the past. Thus, I feel I have the experience necessary to develop, implement, and assess the proposed education programs.

This proposal supports an associate researcher who will act as lead field technician and will be trained in maintenance of eddy covariance flux towers, micromet stations, and water table depth stations and continue to provide these services for the WLEF tall tower and the surrounding sensors. This person will also lead purchase, calibration, installation and data collection of the CH_4 flux instrumentation and work with colleagues at the U.S. Department of Agriculture (USDA) U.S. Forest Service (USFS) Northern Research Station in Rhinelander, WI who will visit sites weekly to collect data, perform simple maintenance, and troubleshoot problems (see letter).

This proposal supports training of a Ph.D. student in Atmospheric & Oceanic Sciences. He or she will work with me to develop a Ph.D. thesis around the research topics proposed here. The student will also collaborate on field measurement and on the education component as part of his or her professional development as previously described.

Timeline

Year 1: *Research*: Acquisition, calibration and installation of CH_4 flux sensor; continued operation and maintenance of CO_2 flux observations and CH_4 trace gas measurements; acquisition and maintenance of existing water table, soil temperature, land cover data; analysis of CH_4 camber data; recruiting of personnel; presentation at regional meeting. *Education*: One Kemp NRS presentation and contact of local schools; Khorana student recruiting; meeting with CMN and WiscAMP to develop course.

Years 2-4: *Research*: Continued operation of CH_4 and CO_2 systems; grad student training; flux tower data analysis; regional flux computation; CH_4/CO_2 model development, data assimilation, and sensitivity study; development of proposals to support supplementary observations (e.g., targeted CH_4 fluxes); publication and presentation at national meetings. *Education*: Two Kemp NRS talks, undergraduates in the lab; operation of summer course; global change course improvement.

Year 5: *Research*: In addition to above, a decommissioning of systems if needed; and regional workshop on CH_4 and CO_2 biogeochemistry and dissemination of data. *Education*: Continuation of programs plus overall assessment of outreach program and evaluation of opportunities for sustaining them.