Improving prediction of climate change impacts on wetland-rich landscapes:
Testing model mechanisms with flux-data assimilation at multiple sites

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ABSTRACT

Objectives
Prediction of climate change impacts on terrestrial carbon fluxes is highly uncertain. Upland ecosystem models, even when constrained with flux tower data, fail to explain interannual variability in CO₂ fluxes in the upper Midwest. One possible reason is lack of model mechanisms for wetland biogeochemistry and hydrology, where fluxes would be expected to vary with changes in depth to saturation. Wetlands are expected to be highly sensitive to climate change. We propose to develop a wetland-landscape model and assimilate long-term multiple flux tower observations to simulate wetland and upland mechanisms simultaneously, with evaluation against unassimilated flux observations. Model evaluation is typically limited to single sites and extrapolation of these results across larger regions is questionable. This research will improve understanding of carbon-rich forest-wetland landscape response to climatic change.

Hypotheses
We hypothesize that 1.) integration of wetland biogeochemistry and hydrology into a terrestrial carbon cycle model will permit observed interannual variability and trends in carbon and water fluxes to be explained for wetland landscapes and 2.) assimilation of flux data from multiple spatially co-located upland and wetland sites into a common model will lead to improved capability to predict regional scale fluxes.

Location
Northern Wisconsin, USA including Lost Creek, WLEF, and other regional Ameriflux tower sites.

Methods
We will incorporate wetland hydrology and biogeochemistry into the existing TREES model, which has been successfully used in the region to simulate transpiration. Observational data and Bayesian sensitivity analyses will investigate primary controls on wetland CO₂ flux variability. Established parameter optimization methods will incorporate data from a suite of upland and wetland flux towers to constrain parameters that control CO₂ and H₂O flux. The optimized model will be evaluated against unassimilated upland and wetland fluxes. Long-term climate change scenarios will be run to quantify the effect of constraining model predictions of vegetation responses to climate change. This proposal also supports continued maintenance of flux tower observations essential to this study.

Deliverables and Outcomes
The new model is expected to fill a major gap in mechanistic understanding of forested wetlands. It will provide 1.) tested wetland model mechanisms with multi-year, multi-site evaluation and 2.) reduction in uncertainty of wetland landscape regional flux and its response to future climatic change. Model code, parameter sets and data output will be available online. Publications detailing model development, optimization, evaluation, scaling and long-term prediction are expected. This proposal also supports training of a graduate student and postdoctoral scholar.
INTRODUCTION

Background
Future contributions by terrestrial ecosystems to atmospheric budgets of carbon dioxide (CO₂) (Friedlingstein et al., 2003; 2006) and methane (CH₄) (Zhuang et al., 2004; Shindell et al., 2004) are highly uncertain. These gases are responsible for a majority of the greenhouse effect, but the atmospheric budgets of these gases are not closed. Atmospheric CO₂ mixing ratios have been increasing at an average rate of 1-2 ppm yr⁻¹ for decades (Conway et al., 1994), but with a large degree of unexplained interannual variability. This rate would be higher were it not for the largely unexplained and highly variable net uptake of CO₂ by the terrestrial biosphere (e.g. Bousquet et al., 2000; Battle et al., 2000). Wetlands represent a large and uncertain source of global carbon emissions that are particularly sensitive to hydrology and climate, implying that wetlands potentially have regional and global significance in explaining temporal variability in atmospheric CO₂ and CH₄.

While wetlands only cover 6% of the U.S. land area (compared to 21% for forests), they are important in the extent of coverage for several regions in the U.S. (e.g., southeast, upper Midwest) (Dahl, 2006). The upper Great Lakes states (MN, WI, MI) have the largest amounts of wetland of all major U.S. regions (U.S. Dept. of Agriculture, 2000). Wetlands cover 14% of these states, but this cover is close to 1/3 within forest-wetland landscapes that dominate the northern half of the region (Desai et al., 2006).

Wetlands are expected to be especially sensitive to climate changes of both temperature and precipitation because of the close coupling of water (H₂O), CO₂ and CH₄ cycling in these ecosystems. They also are typically carbon rich, giving rise to the potential for large atmospheric carbon efflux or sequestration in response to climate change. Land use, lowland drainage and water table control can affect the extent and biogeochemical cycling of wetlands, implying that land management can potentially enhance carbon storage in these ecosystems. What’s missing, however, is a thorough quantification and mechanistic understanding of regional carbon and water fluxes in wetland rich landscapes.

Motivation
Most ecosystem models focus solely on upland, unsaturated ecosystems, and thus are unable to successfully simulate biogeochemistry and hydrology at wetland sites or predict interannual variability of CO₂ fluxes in mixed wetland-upland landscapes. Though a few wetland models exist (e.g., Bond-Lamberty et al., 2006; Cao et al., 1996; Cui et al., 2005; Potter, 1997; Zhang et al., 2002), most have not been extensively tested and parameterized against a large observational database nor specifically designed for use in a coupled upland-lowland landscape. Existing upland models, even when constrained by observation data, are unable to predict upper Midwest regional interannual variability in CO₂ flux, possibly due to lack of wetland mechanisms (Ricciuto et al., 2006). Since ecosystem models are the primary tools available to predict responses of ecosystems to climate change over the next 50-100 years, lack of wetland mechanisms and robust estimates of parameter values will limit successful prediction of ecosystem fluxes in wetland rich landscapes such as the upper Midwest.

The Chequamegon Ecosystem-Atmosphere Study (ChEAS) is an informal cooperative of scientists involved in carbon and water cycle research in mixed wetland-upland landscapes of northern Wisconsin and upper Michigan (http://cheas.psu.edu). An extraordinary wealth of ecological, micrometeorological, subsurface, trace gas, transpiration, and eddy covariance CO₂ and H₂O flux data have been collected over the past decade in uplands and lowlands by this group of investigators including regionally-integrating flux observations at a globally unique 447-m tall tower, denoted by its television station call letters, WLEF (Davis et al., 2003). These data sets together form an exceptional knowledge base from which to improve wetland model mechanisms, constrain model parameters and evaluate model simulations of regional land-atmosphere fluxes. While typical model parameterization, evaluation and upscaling relies on extrapolation of data from a single site, ChEAS allows for thorough model development, testing and generation of robust long-term predictions of climate change impacts in wetland-rich landscapes.
The plethora of ecosystem models currently in existence obviates the need for development of a new model from scratch. Instead, existing upland ecosystem models that have successfully been used in the region’s upland ecosystems can be adapted for use in wetland and mixed landscapes. Formal parameter optimization and data assimilation schemes are well-established in statistics (Metropolis et al., 1953) and are gaining rapid currency in biogeochemical research (Braswell et al., 2005). These methods provide powerful ways to constrain model parameters with observed flux data. Typically this is done with one site (e.g., Sacks et al., 2006). Constraining model parameters in a regional framework with multiple sites simultaneously has not been typically done, though it is mathematically feasible (W. Sacks, 2006, personal comm.) and holds promise to significantly improve model development and parameters. ChEAS allows for this kind of assimilation of data from multiple sites of differing ecosystems to be done, thus allowing for reduction of uncertainty in prediction of regional fluxes in mixed landscapes. Continued long-term flux data collection enables a dataset long enough for both model optimization across interannual climate cycles and evaluation of model results against unassimilated observations so as to quantify model prediction uncertainty.

Relevance
Analysis of contemporary exchanges of mass and energy, understanding biological controls of their cycles, and reducing the scientific uncertainty of climate change on regionally important ecosystems are key objectives of the Department of Energy (DOE) National Institute for Climate Change Research (NICCR) request for proposals (RFP) under focus area 3. Focus area 4 also calls for synthesis of observational datasets and development of ecosystem models. Improving existing ecosystem models to simulate both wetland and upland mass and energy exchange, testing of model wetland biogeochemistry and hydrology mechanisms with sensitivity studies, and constraining model parameters with a diverse network of ecological and flux data can lead to significant improvement in our ability to simulate regional fluxes in the upper Midwest and reduce uncertainty for prediction of 50-100 year climate change impacts on these complex and carbon-rich ecosystems. These efforts will lead to a thorough synthesis of previous and future biogeochemistry and atmospheric data collected in ChEAS and foster generation of a well-constrained regional ecosystem model. Results will fill a significant gap in understanding and predicting regional flux and aid in construction of a national carbon budget with reduced uncertainty on future impacts on climate change, a goal shared both by NICCR and the North American Carbon Program (NACP).

OBJECTIVE AND HYPOTHESES
Our ability to understand the impact of climate change on wetland-rich landscapes is limited by significant unresolved questions on key ecosystem model mechanisms and related parameters important to evaluate and predict regional CO₂ flux. We propose to use a novel biogeochemical model, built with both wetland and upland components, to test hypotheses on the 1.) value of these additional components, 2.) ability of such models to be parameterized from observational flux data and 3.) success in simulation and prediction of wetland, upland and regional fluxes in the upper Midwest and other similar upland-wetland mosaic ecoregions. The wealth of observational ecological, micrometeorological and flux data collected in the region will be used with established parameter estimation techniques to identify key model mechanisms, constrain model parameters and improve model predictions of ecosystem biogeochemical fluxes.

Objective
The general objective of this research is to improve regional modeling efforts in heterogeneous landscapes of the upper Midwest with the potential for application to many types of mixed landcover regions of North America. This objective drives the two primary questions we are interested in understanding:

1) What are the key mechanisms and related climate forcing that control interannual and longer time scale variability in CO₂ net ecosystem exchange (NEE) in upland-lowland landscapes, especially for wetlands?
2) How can a regional network with nearly a decade of biogeochemical and meteorological observations in uplands and wetlands be used to constrain model predictions of the impact of climate change in heterogeneous regions?

These questions are motivated by the inability of current models to explain interannual variability and absolute magnitude of regional CO₂ flux in the upper Midwest, even when formally constrained by half-hourly observed regional eddy covariance CO₂ fluxes (Fig. 1a). When a simple ecosystem model (Sipnet, Braswell et al., 2005) is run with default parameters at the WLEF tall tower site (blue line), the long-term net CO₂ flux, seasonal cycle amplitude and interannual variability are significantly different from observed (black line). After 11 model parameters were constrained by a parameter estimation technique (as described in the methods) with 8 years of CO₂ and H₂O NEE, the model (red line) had significant improvement in predicting long term CO₂ flux trend and the seasonal cycle (Fig. 1a). However, when comparing annual NEE deviations from the 8-year mean, the original model (blue line) does a poor job at capturing interannual variability and the assimilated model (red model) does not improve on it (Fig. 1b).

This modeling exercise and similar results (Ricciuto et al., 2006) motivate the premise that wetland mechanisms may be important in explaining this so far unexplained interannual variability. Forested, open and shrub wetlands cover roughly 30-40% of the tall tower footprint (~10² km²) and the larger region (~10⁵ km²) (Desai et al., 2006). Wetlands are expected to be more sensitive to climate variability since they respond both to temperature and water table depth/precipitation, whereas in mesic climates, interannual variability in precipitation is not expected to significantly affect upland CO₂ fluxes.

Another line of observational evidence supporting this argument of wetland control on regional interannual variability is the long term dynamics of water table depth and wetland H₂O flux (Mackay et al., 2007). Water table depth observations at two sites over the past 5 years show a declining trend in water table depth (Fig. 2a). Correlations may exist between water table depth and the shrub wetland tower CO₂ NEE (Fig. 2b) (Cook et al., 2007). This might be expected given shifts from aerobic respiration of CO₂ in unsaturated soil to anaerobic respiration of CH₄ in saturated soil (Segers, 1998). Further investigations into the mechanisms of water table control of wetland biogeochemistry are warranted given the potential for the efflux of relatively large carbon stores found in wetlands. Long-term climate change scenarios that involve significant change in precipitation patterns would be expected to have a significant effect on wetland extent and biogeochemistry, potentially leading to large changes in regional CO₂ flux that would not be well predicted by an upland-only ecosystem model.

By improving an existing ecosystem model to include wetland hydrology and soil biogeochemistry in saturated and unsaturated soils and incorporating observational data to constrain model output, we can test whether these postulates are supported in the model and data while also minimizing duplication of
effort with respect to ecosystem model development. The improved model can then be used to generate a robust regional flux estimate and produce 100-yr CO₂ flux prediction and confidence intervals on the response of the region to climate change under various IPCC scenarios. While mixed wetland-upland landscapes are endemic to upper Great Lakes region, they also share common traits with other heterogeneous systems across the globe, thus leading to results that may have global significance.

Hypotheses

In order to meet the objectives, the proposed research will be designed around the goal of statistically testing three primary hypotheses through model development and data analysis. The data analysis and hypothesis testing framework will account for parameter and prediction uncertainties using a Bayesian approach, which is described further in the sub-section entitled “Approach Details.” The analysis would begin by testing the first hypothesis against data at spatial scales containing only one dominant ecosystem type, covering one to five year time spans. The information obtained from the results of this first stage of the analysis would then be used for testing the rest of the hypotheses, related to the simulation of fluxes over larger regions with multiple ecosystem types and longer time spans of 50 or 100 years. The hypotheses are stated in their general forms below:

1) Integration of processes related to wetland hydrology and soil biogeochemistry into a terrestrial carbon cycle model leads to more accurate simulation of the interannual variability and long-term trends in carbon and water NEE for both wetland and upland landscapes, compared to models without such processes.

Because wetland hydrology and soil biogeochemistry may be incorporated in the model at different levels of detail, using different mathematical functions, or with different parameterization schemes, all potentially useful model configurations (refer to the section titled: “Implement a mechanistically predictive model of upland/wetland carbon & water cycles” for further details) will be evaluated using multiple data sets (described in section “Analyze observed regional upland and wetland CO₂ and H₂O eddy covariance flux data to discern key mechanisms and parameters”). Therefore, the general hypothesis above would be broken down into testable hypotheses comparing two specific models based on a particular data set:

a. Inclusion of the functional dependence of carbon flux on mean depth to water table in the model leads to more accurate simulation of the interannual variability of carbon flux observed at the Lost Creek shrub wetland tower.
b. Inclusion of the correlation between carbon flux and changes in water table depth leads to more accurate simulation of the seasonal variations in the carbon flux observed at the Lost Creek shrub wetland tower.

c. Improvement in the simulation of wetland carbon flux through the inclusion of interannual and seasonal water table controls in the model (assuming that H1.1 and 1.2 are accepted) is also detectable at other wetland towers (e.g., South Fork, Wilson Flowage).

Results of the comparative analysis will be utilized to identify model components and parameters that are sensitive to the locally dominant ecosystem type, and therefore, could potentially change from one location to another over large regions. This information will then be used to formulate spatially distributed models, along with various strategies for their parameterization, to test the following general hypothesis:

2) Spatially distributed models, configured and parameterized based on high resolution landcover maps, are able to more accurately and precisely model CO₂ and H₂O fluxes at regional scales, compared to models not accounting for spatial variation of ecosystem types.

The above hypothesis would be evaluated at multiple spatial scales using flux data from multiple small towers in combination, as well as independent regional flux observations made at the WLEF tall tower, by ABL budget, inverse methods and inventory/biometric techniques. The spatially distributed model and parameterization technique identified at the above stage of the analysis will then be used to generate 50-100 year predictions of CO₂ and H₂O fluxes for the wetland-rich landscape of the upper Midwest region under a variety of future climate and CO₂ scenarios based on the Intergovernmental Panel on Climate change (IPCC) report. The above predictions will be compared to the predictions from other models to evaluate the following hypothesis:

3) The long term predictions of fluxes under climate change scenarios from the spatially distributed model, conditioned on currently available observed data, are significantly different and more precise (i.e., have tighter confidence intervals) compared to those from other models, e.g., upland only model or model unconstrained on observed data.

Predicted effects of changes in temperature and precipitation on the wetlands, e.g., fluxes, extent, biogeochemistry, and the impact of such future changes in the wetlands on interannual and long-term regional fluxes will be the primary focus in the final stage of analysis.

**Comparison to other funded and proposed projects**

Complementary, but independent funded projects exist in the region. A currently funded NASA carbon grant provides funding for roving flux tower measurements in recently cut aspen and other wetland sites in the region, extensive biological measurements in ecological plots surrounding the WLEF tall tower, and high-resolution land cover characterization related to upscaling efforts. Flux, ecological and land cover data already collected by this project will be used by this proposed project to initialize the model, constrain parameters and test regional scaling methods. A decision is still pending for funding from the DOE Terrestrial Carbon Program to support flux tower infrastructure and observational data analysis of flux tower time series. This proposal supports flux tower data processing and maintenance (but not salary or long term maintenance) to two towers (WLEF tall tower, Lost Creek shrub wetland) essential to this project. Currently, most of the flux towers are unsupported, but given the long time record of data for most towers, this will not be a hindrance to successful completion of this proposal. The unique contributions of this proposal are 1.) development of a combined wetland-upland model, 2.) multiple flux tower site assimilation and parameter optimization and 3.) long-term model prediction of regional flux and impacts of climate change. Future observational studies in the upper Midwest region by other groups can be used to inform and improve model development, parameterization and testing proposed here.
METHODS

General Strategy
We propose to statistically evaluate the importance of including process details of soil biogeochemistry, wetland biogeochemistry, and wetland hydrology in physically based models for accurate and precise predictions of CO$_2$ and H$_2$O fluxes in a wetland rich landscape through tests of the hypotheses noted above. Availability of extensive flux, meteorological, and ecological data in the ChEAS region, collected by other investigators, will allow for testing the hypotheses against various ecosystem responses at multiple spatial and temporal scales. The consequences of using the extended model in terms of significant changes in predicted fluxes under long term climate change scenarios, compared to those obtained using the un-extended model, will also be examined.

Development and subsequent testing of model mechanisms, parameterization, and sensitivity analysis are the key activities central this proposal. The existing Terrestrial Regional Ecosystem Exchange Simulator (TREES; Mackay et al., 2003a,b; Ewers et al., 2006) model will be extended incrementally to include the relevant process details, using an iterative model building cycle to identify optimally complex models for upland and wetland sites supported by various sets of observed data. Though CH$_4$ biogeochemistry will be added to TREES, evaluation data is scant; therefore, parameter estimation and flux evaluation will focus on CO$_2$ and H$_2$O fluxes. Regional methane chamber flux observations (S. Frolking, 2006, personal comm.) and prior methane flux modeling (e.g., Potter, 1997; Walter et al., 2001) and observational studies (Valentine et al., 1994; Shurpali and Verma, 1998) will be used to estimate parameters and state variables.

A Bayesian approach using Markov Chain Monte Carlo (MCMC) simulations will be used to estimate parameter values, parameter uncertainty, and predictive uncertainty associated with the models conditioned on observed data. At each iterative step, parameter identifiability and model acceptability will be evaluated against data set aside for this purpose. Ecosystem specific mechanisms and parameterization schemes identified above will be combined with the data collected at multiple co-located sites, using a novel multiple site data assimilation technique, to develop and parameterize a regional model. Regional flux predictions from this model will be evaluated against independent data, as well as those from the original model.

Specific tasks of this project are listed below and discussed in more detail in the section titled “Approach Details”:

1) Identify optimal physically based model(s) of upland/wetland carbon and water cycles following these iterative steps:
   a. Analyze observed regional upland and wetland CO$_2$ and H$_2$O eddy covariance flux data to discern key mechanisms and parameters to induce models for evaluation.
   b. Implement mechanistically predictive models of upland/wetland carbon & water cycles.
   c. Apply MCMC simulations, in single or multiple site mode, to the induced models for parameter and uncertainty estimation conditioned on observed data.
   d. Perform model checking with residual analysis and evaluate model performance with unassimilated eddy covariance flux data.
   e. Use deviance information criterion (DIC) to compare the performance of the induced models to the original model.

2) Combine ecosystem specific optimal models to construct a regional flux model, parameterize the regional model with multiple site data and high resolution land cover maps of the region, and evaluate against independent regional flux data.

3) Predict future response of the region’s ecosystems to climate change and compare with the predictions obtained using other techniques.
Approach Details

1. Analyze observed regional upland and wetland CO2 and H2O eddy covariance flux data to discern key mechanisms and parameters

The Chequamegon National Forest is a lightly populated, heavily forested region of northern Wisconsin, characterized by undulations in elevation of about 20m forming a heterogeneous landscape of wetlands and uplands. The region was 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 CO2, H2O, 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 a directly observed estimate of regional flux. Three long-term stand-level flux towers, located in shrub wetland (Lost Creek), northern hardwood upland (Willow Creek), and an old-growth mixed forest (Sylvania), have operated for the past 5-7 years (Table 1). Also, a pair of roving eddy covariance flux towers has been used to observe growing season fluxes in recently cut aspen (Riley Creek, Thunder Creek) and open wetlands (South Fork, Wilson Flowage) since 2005. Ten additional stands have been observed for periods of months to years (Desai et al., 2006). Near the tall tower and coincident with many of the flux tower sites, extensive plot-level ecophysiological and biometric observations have been made in a variety of ecosystems (e.g., Bakwin et al., 2004).

Table 1. List of eddy covariance tower sites near WLEF and operated by ChEAS investigators

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Coordinates</th>
<th>Age class</th>
<th>Cover</th>
<th>Years of operation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regional</td>
<td>WLEF</td>
<td>45.95° N 90.27° W</td>
<td>mixed</td>
<td>hardwood/wetland</td>
<td>1996-</td>
</tr>
<tr>
<td>Upland</td>
<td>Willow Creek (WC)</td>
<td>45.81° N 90.08° W</td>
<td>mature</td>
<td>N. hardwood</td>
<td>2000-</td>
</tr>
<tr>
<td></td>
<td>Sylvania (SW)</td>
<td>46.24° N 89.35° W</td>
<td>old-growth</td>
<td>mixed forest</td>
<td>2002-</td>
</tr>
<tr>
<td></td>
<td>Thunder Creek (TC)</td>
<td>45.67° N 90.05° W</td>
<td>clearcut, 1yr</td>
<td>grass/aspen</td>
<td>2005-</td>
</tr>
<tr>
<td></td>
<td>Riley Creek (RC)</td>
<td>45.91° N 90.12° W</td>
<td>clearcut, 4yr</td>
<td>Aspen</td>
<td>2005-</td>
</tr>
<tr>
<td>Wetland</td>
<td>Lost Creek (LC)</td>
<td>46.08° N 89.98° W</td>
<td>n/a</td>
<td>shrub aldrew/willow</td>
<td>2001-</td>
</tr>
<tr>
<td></td>
<td>South Fork (SF)</td>
<td>45.93° N 90.13° W</td>
<td>n/a</td>
<td>ericaceous bog</td>
<td>2005-</td>
</tr>
<tr>
<td></td>
<td>Wilson Flowage (WF)</td>
<td>45.82° N 90.17° W</td>
<td>n/a</td>
<td>sedge-grass-shrub fen</td>
<td>2005-</td>
</tr>
</tbody>
</table>

a No data in 2002
b Roving tower site, growing season only

Flux data are processed using standard methods common to all sites (Berger et al., 2001). Significant variability in annual flux is seen across the sites, mainly correlated to stand type and age (Desai et al., 2006), but nevertheless complicating typical stand-scale extrapolation to regions (Fig. 3). This proposal would continue the flux data collection, maintenance, troubleshooting and data processing for the Lost Creek shrub wetland tower and WLEF tall tower, two towers central to understanding the wetland biogeochemistry and regional flux components of this proposal. Though all fixed site towers have relatively long records for Ameriflux towers in general, continued data collection at the two towers in this proposal will allow for a robust interrogation of the interannual variability signal integrated over several ENSO cycles and for sampling a range of climate variability. Wetland mechanisms can be further investigated with data collected at the open wetland

Fig. 3. Cumulative growing season net ecosystem exchange (NEE) of CO2 across ChEAS tower sites. Abbreviations are defined in Table 1.
tower sites that are part of a NASA-funded regional scaling project. Statistical data analysis linking flux variability to observed driving variables (e.g., water table depth, temperature, light, humidity) will allow for further refinement of model mechanisms and parameter priors. CO$_2$ and H$_2$O fluxes from the wetland and upland sites will be then used for model parameterization, optimization and/or evaluation as described in the following sections.

2. Implement a mechanistically predictive model of upland/wetland carbon & water cycles

For this study we will use the TREES model (Mackay et al., 2003a,b; Ewers et al., 2006; Samanta, 2005; Samanta et al., 2006, 2007). TREES has been successfully used at ChEAS for simulation of forest canopy processes (Mackay et al., 2003a,b; Ewers et al., 2006; Loranty et al., 2006). Processes within TREES are organized into canopy light environment, stomatal vapor conductance ($G_s$), boundary layer vapor conductance ($Ga$), plant CO$_2$ assimilation ($A$), canopy transpiration ($Ec$), and soil CO$_2$ efflux ($R_{soil}$).

The core of TREES consists of several classes of objects, which are used to manage state variables, flux variables, and data. Two classes of objects are used to define indexes. A data dictionary holds a collection of variable names to facilitate reference of variables by name. Time classes allow reference of properties by date and time. The data structure within TREES (data_store) uses these indexes to allow reference of states and fluxes by name and/or by time. Methods are encapsulated for reading and writing files, copying variables, and performing memory management, thereby easing the modification of existing models or constructing new models. Two additional classes of objects facilitate parameterization, uncertainty analysis, and error propagation. Parameters are defined as probability distributions of fixed, uniform, normal, grid, and Markov types. Fixed distributions are for parameters with a single value. Other distribution types invoke methods to perform Monte Carlo sampling of various types. Uniform and normal are associated with methods to randomly select a parameter value from the respective distributions. Grid samples parameter values at regular intervals within a defined range and resolution. Markov is associated with methods to perform Markov chaining of parameters. Finally, the class data is defined to hold <measured, modeled> pairs of values along with encapsulated analysis methods, including least squares regression, to support Markov chaining.

Fig. 4. Shows two instantiations of TREES (aspen/fir, alder/cedar) representing common upland and wetland systems within the ChEAS site.

The simplest instantiation of a TREES object represents a single point in space representing a soil-vegetation-atmosphere continuum (Fig. 4). However, objects may be organized hierarchically or spatially as necessary, providing the flexibility to go from a point simulation to a regional simulation. For example, an array of data_store can describe a 2-D regular grid with each grid cell containing a TREES
instantiation. This partitioning is best suited for small-scale simulations. For regional simulations such as those proposed here, we will instantiate vegetation stands based on detailed vegetation classification maps for the region so as to minimize redundancy.

**Landscape partitioning:** To represent spatial variability we can either divide the study area into uniform grids, or partition it into relatively homogeneous regions based on dominant ecosystem types. The former is computationally more intensive and assumes quite a lot of site-specific knowledge of each grid area, and so the latter is preferred. We have previously segmented the region around WLEF into regions based on species composition, computed evapotranspiration (ET) fluxes from each region, and then aggregated to the region (Mackay et al., 2002). While this approach has worked well for water fluxes, similar success with carbon fluxes remains elusive (Desai et al., 2006). We will explicitly evaluate this approach with the wetland hydrology and biogeochemistry components incorporated.

**Ecosystem Respiration:** Ecosystem respiration \((R_e)\) and \(R_{\text{soil}}\) are related by \(R_e = A - R_L - R_S - R_{\text{soil}}\) and \(R_{\text{soil}} = R_R + R_h\), respectively, where \(A\) is photosynthetic CO\(_2\) assimilation, \(R_L\) is leaf respiration, \(R_S\) is stem respiration, \(R_R\) is root respiration, and \(R_h\) is heterotrophic respiration, which is dominated by decomposition of plant residues by microbes. \(R_e\) is directly available on a continuous time basis from tower data, while \(R_{\text{soil}}\) has been measured at specific times and places across the ChEAS site with a sufficient number of observations to evaluate model logic (e.g., Bolstad et al., 2004). Component fluxes are less frequently available; therefore, their values must come from simulation.

**Photosynthesis and Transpiration:** Beam, diffuse, and scattered solar radiation (Spitters et al., 1986) are separated into photosynthetically active radiation (PAR) and near infrared radiation following Goudriaan (1977). Following De Pury and Farquhar (1997), canopy processes are separated into sunlit and shaded leaf elements. Canopy transpiration (Monteith, 1965) and photosynthesis (De Pury and Farquhar, 1997; Katul et al., 2003) are simulated at the leaf element level and then combined to yield canopy total fluxes. Half-hourly \(A\) is simulated using a hybrid of De Pury and Farquhar (1997) and Katul et al. (2003). Canopy stomatal conductance is constrained both hydraulically (Oren et al., 1999; Katul et al., 2003) at the whole tree level, and by photosynthesis at the leaf element level. This approach enables TREES to drive water loss as a function of carbon gain when photosynthesis is limiting (Ball et al., 1987; Leuning et al., 1995), and drive carbon gain as a function of leaf water potential when transpiration rates are high (Monteith, 1995). Conductance between the canopy surface and the atmosphere at a reference height is determined by assuming forced laminar flow over a hypothetical surface through the canopy with momentum and heat transfers, and diabatic corrections are solved with stability corrections. Carbon allocation routines are adopted from our previous models (Mackay and Band, 1997; Mackay, 2001). We will modify them from daily time steps to half-hourly (Ewers et al., 2006) to maximize the utilization of half-hourly (stand-scale) and hourly (WLEF) tower flux data. Carbon allocation to roots and shoots depends on limitations due to available photosynthetic, nitrogen, and water, and is governed by phenology routines, which differ among species types. Maintenance respiration costs (e.g., \(R_L\), \(R_S\)) are tied to photosynthetic rates as well as soil temperature and moisture. Short time steps are critical for diurnal fluxes at our sites (Sacks et al., 2006).

**Soil biogeochemistry:** Carbon (C) and Nitrogen (N) processes in upland soils will be adapted from Mackay (2001). \(R_h\) for soil CO\(_2\) efflux and N for vegetation growth come from soil C and N cycling routines defined in fast and slow pools within each soil layer. Both pools are updated with decomposition, net N mineralization, inputs of C and N from leaf, root, and stem drop, and N uptake by plants or loss through leaching or denitrification, atmospheric N inputs, and N fixation (e.g., in alder systems). Decomposition rates are nonlinearly related to soil moisture and temperature (Kirchbaum, 1995; Lloyd and Taylor, 1994), giving a parameterization of soil respiration that has increased sensitivity at low soil temperatures. Parameters will be derived from soil respiration data available at the site, so that site specific temperature sensitivity will be incorporated into the model. CO\(_2\) flux diffuses through successive soil layers as a function of successive steady state [CO\(_2\)] gradients. The soil is divided into layers with mid-point depths of 1, 2, 5, 10, 20, 40, and 80 cm. The 1-5 cm depths are especially important for \(R_h\), but
other depths are important for water and nitrogen uptake by plants, and lower depths provide a force-
restore constraint on soil temperature and interaction with water table. We will explicitly evaluate the
relative value of this more complex model versus a simplified approach using a single soil pool (Sacks et
al., 2006) or by just using empirical relationships based on site-specific data. We propose to initialize soil
C and N using an extensive data set we have collected as part of Mackay’s current NSF project. In
summer 2006, we measured soil C, N, and soil texture from the top 20 cm in 288 plots spanning aspen-fir,
alder, cedar, red pine, and sugar maple-basswood systems in a variety of topographic positions. These
systems represent more than 80% of the region within 40 km of WLEF (Mackay et al., 2002). Analysis
along an upland aspen to wetland transect showed a slightly increasing C:N ratio despite a 25-fold change
in C content. The sugar maple and red pine systems showed a much smaller variation in C content and no
significant variation in C:N (Traver et al., 2006). These numbers suggest that we will be able to
sufficiently constrain our C and N inputs to TREES at each of the towers and for the region as a whole.

Wetland biogeochemistry: TREES models vascular plants, so we will incorporate non-vascular
vegetation processes and heterotrophic respiration based on well-established models such as the Peatland
Carbon Simulator (PCARS; Frolking et al., 2002). TREES will be augmented with routines to handle
anaerobic decomposition, which produces both CO₂ and CH₄. Frolking et al. (2001) showed that these
processes can be modeled accurately as functions of soil moisture. CO₂ and CH₄ released from the soil
surface will be estimated using a steady-state approximation based on water table depth (Frolking and
Crill, 1994) obtained from a groundwater model, which is described in the next section. Although CH₄
data for evaluating the model will be sparse, we nevertheless compute it in the process of calculating
wetland CO₂ release. Carbon content will be constrained using wetland soils data collected in 2006 as
mentioned in the previous section.

Wetland hydrology: Wetlands within the region consist of variable
thicknesses (<0.1 m to over 3 m) of organic soils overlying highly
permeable glacial outwash sand. They generally form in three
topographic settings: (1) in connected networks or flowages in fully
vegetated, low-gradient floodplains, (2) in riparian areas around
open flowing streams, or (3) in isolated depressions. All these
wetlands have observed water table dynamics that reflect trends in
precipitation. For landscape to regional scale analysis, we must be
willing to accept that there is limited data to support sophisticated
groundwater models. Nevertheless, we believe a significant amount
of diagnostic information is available for assimilation into our
proposed framework. To incorporate water table dynamics, there
are essentially two approaches that can be used. The simplest
approach is to use head data directly from peizometers installed at a
number of wetland sites in the area. These point observations give
continuous measurements of water table height at LC since 2001
(see Mackay et al., 2007), an alder
wetland site since 2000, and at 4 additional sites within the region spanning 2000 to present. To derive
the potentiometric surface for the entire study area region, we will use a finite-difference groundwater
model, such as MODFLOW. A series of steady state potentiometric surfaces will be generated by initially
assuming a 2-D flow (one sand aquifer). ET from the surface will be based on the model by Mackay et al.
(2002). Mackay and one of his PhD students are currently collaborating with a groundwater modeler in
the UB Environmental Engineering department to construct such a model. Inputs to the model include
hydraulic conductivity parameters, hydraulic gradient, and specific water table heights to constrain the
model. LiDAR data is available to derive hydraulic gradients, and the numerous aforementioned
potentiometers, water body surface heights (ponds, rivers) estimated from LiDAR, and the USGS
continuous stream discharge station (05357335, Bear River) located 3 km downstream of the WLEF
tower, will allow us to constrain the model. Preliminary analysis shows a clear relationship between water
table height at LC and surface flow at this discharge station (Fig. 5).
3. Apply Bayesian parameter sensitivity analysis and Monte Carlo Markov Chain optimization to the model conditioned on observed data

Rigorous statistical analysis of diverse data sets using mathematically complex flux models is necessary to meet the goals of the proposed research. The complete analysis requires estimating parameter values, checking the models against independent data, and comparing the performance of various model configurations to determine whether the inclusion of wetland hydrological and/or biogeochemical processes improve the quality of flux predictions. As the parameter values are often unknown and therefore estimated from observed data, the uncertainties in the estimated parameter values and the resulting uncertainties in the model predictions should also be accounted for in the analysis. Use of Bayesian statistics provides many powerful computational techniques based on numerical simulations for analyzing mathematically complex models, which are not available otherwise. Bayesian statistics has also been successfully used previously for analyzing flux data (e.g., Braswell et al., 2005; Hargreaves and Annan, 2002; Harmon and Challenor, 1997; Ricciuto, 2006; Sacks et al., 2006; ), as well as with the TREES model (Samanta, 2005; Samanta et al., 2006, 2007). Therefore, a Bayesian approach will be used for the proposed analysis.

In a Bayesian approach, the parameters in a model are considered to be random variables, not constants with unknown values. A primary objective of Bayesian analysis is to determine the distribution of values for the parameters conditioned on observed data, which is called the posterior distribution. Therefore, the probabilistic uncertainties in the parameter values are naturally captured in the posterior distributions. The distribution of the parameter values, which is assumed based on the prior knowledge of the parameters before incorporating the information from observed data, is called the prior distribution. The model defines the density function for the observed data conditioned on the parameter values, which is called the likelihood function. According to Bayes’ rule, the posterior distribution is proportional to the product of the prior distribution and the likelihood function. Reduction in the uncertainties regarding parameters and other predictive quantities from prior to posterior indicates the usefulness of observed data and the model.

Results of the data analysis at local scales would then be used to identify appropriate model structure and parameterization technique for prediction of fluxes at regional scales. Further, the sensitivity of the long-term prediction of surface fluxes under climate change scenarios to model selection would be analyzed using the original model and the model selected based on the foregoing analysis.

Markov Chain Monte Carlo simulations for parameter estimation, model checking, and inter-comparison of models: For Bayesian analysis, the likelihood functions will be formulated by adding a stochastic error term to the deterministic process based models. The errors will be assumed independent, normally distributed, and homoscedastic with unknown variance unless severe departure from this assumption is noticed during model checking; in that case, use of heteroscedastic errors or other transformations will be explored. Initially, noninformative priors with uniform distributions within a wide but feasible parameter space will be used to minimize their roles in the posterior distributions. However, use of informative priors will be explored for the parameters that remain poorly defined in the posteriors.

For each model, the posterior distribution defined by the above prior and likelihood function will be sampled using MCMC simulations based on the Metropolis algorithm (Metropolis and Ulam, 1949). This computational technique is well developed in statistics (Braswell et al., 2005) and has been successfully used for analyzing complex hydrologic and ecosystem simulation models including TREES (Samanta et al., 2006, 2007). The algorithm can be best described as a pseudo-random walk through parameter space to define the probability density function of posterior parameter likelihoods. Bounds on parameter space priors are set to reflect the breadth of values found in literature or observation to ensure convergence on physically reasonable parameter values.

Efficient sampling of the parameter space and convergence of the chains to stationary distributions would be checked using established statistical procedures (Geyer, 1992; Gelman et al., 1995; Kass et al., 1998). The posterior samples of the parameter values would then be used to construct predictive distributions for the data reserved for model checking. Systematic structure in the residuals or inability of the predictive
intervals to contain the observations according to their posterior probabilities will indicate the need to either transform the error model or reject the model entirely.

Each model will be conditioned and tested with many data sets available in the region as described above. Multiple site or response data will also be used for conditioning models either by constructing joint density distributions or by successively using the posterior conditioned on one set of data as the prior for the next. Therefore, detailed assessments of parameter identifiability, parameter sensitivity, prediction uncertainty, and conformance to the error assumption will be available for each model. Primary data being used to constrain the parameters are flux tower observed NEE of CO₂, H₂O and temperature along with water table depth at hourly and longer timescales. Developing a likelihood function that combines monthly, seasonal and annual average data in addition to high temporal (half-hourly) frequency data will be explored as one way to use MCMC to constrain model simulation of NEE interannual variability.

This algorithm produces a collection of parameter sets that allow the model to best reproduce the data (maximum likelihood). This set can be used to generate confidence intervals around estimated parameter values. They also can be used to find parameter correlations. Forward model runs with the parameter sets allow for generation of model output confidence intervals, allowing for stronger statistical testing of the hypotheses on the relative “learning” value of the estimation algorithm and the input observed data.

**Model inter-comparison and evaluation of model complexity:** We will assess added value of a complex integrated model. Model selection is widely regarded as a problem of finding the appropriate trade-off between the fit of model output to observed data and model complexity. A model with a higher degree of complexity (e.g., diffusion versus steady state) may fit the available measurements better than a simpler model, but it is more susceptible to becoming conditioned to noise in the data (“over-fitting”). Such a model is rigid and not easily generally applied. The ideal model sacrifices some complexity for an ability to help us interpret data (Samanta and Mackay 2003).

Models not rejected based on the initial analysis will be inter-compared to identify optimal models for each ecosystem type. Model selection is widely regarded as a problem of finding the appropriate trade-off between the fit of model output to observed data and model complexity, also called the “principle of parsimony” or “Occum’s razor” (Akaike, 1974; Forster, 2000). Following this principle for inter-comparison and selection of models, we would use the deviance information criterion (DIC) (Spiegelhalter et al., 2002), which is a Bayesian measure for comparing highly complex models and accounts for posterior uncertainties. DIC accounts for prior and posterior parameter distributions, can compare models of arbitrary structure, and does not require all possible models to be specified up front. These qualities are key, as it is intractable to identify all potential configurations of an integrated model. DIC is computed using the posterior mean deviance and the deviance at the posterior estimates of model parameters. These quantities are simple to calculate by keeping track of the deviance during MCMC runs. Although DIC is used as a relative measure for comparing models, its value may be independently computed for each model, which would lend flexibility to the analysis by providing the ability to take new models into consideration without having to reanalyze already included models, thus facilitating the iterative model building approach. The results of the model inter-comparison would be used to evaluate the relative usefulness of including the proposed mechanisms in various functional forms and methods of parameterization (e.g., if a parameter should be considered spatially distributed) in various flux and ecosystem contexts. In case the analysis fails to select unique optimal models for each ecosystem type, the model averaging approach will be adopted for generating prediction uncertainties.

Samanta et al. (2006, 2007) extended TREES for Bayesian analysis and used it to diagnose DIC values for 14 different stomatal conductance models. Increased model complexity did not always improve DIC (some 7-parameter models did not improve over 5-parameter models) because of the nature of the data support for each model function. This approach objectively penalizes overly complex models, and so it will facilitate identification of appropriate simulation models. DIC determined from MCMC simulation will be used to evaluate the integrated model on ecosystem fluxes from stand-scale flux towers and landscape fluxes from WLEF tower. The results of model comparison would be used to evaluate the
relative usefulness of including the proposed mechanisms in various functional forms and methods of parameterization (e.g., if a parameter should be considered spatially distributed) in various contexts.

4. **Evaluate model performance with unassimilated eddy covariance flux data**

Comparing model simulation of land-atmosphere flux under different scenarios against eddy covariance flux data not used in the parameter optimization is a key test of the previously outlined hypotheses. Model fluxes will be compared at hourly, seasonal and interannual timescales to eddy covariance CO$_2$ and H$_2$O flux. The hypothesis that wetland biogeochemistry and hydrology improve modeled interannual variability and trends in flux will be evaluated against the Lost Creek shrub wetland tower. Data from the other two wetland sites with shorter time records will be used to test whether the model is generalizable across wetlands in terms of prediction of CO$_2$ and H$_2$O flux magnitudes. Upland towers will be used to test model prediction ability in upland forests. Both the model without and with wetland hydrology will be compared to wetland flux data to test impact of water table mechanisms on wetland flux. Also, the model will be compared with the a priori parameter set and the posterior parameter set. A salient feature of the MCMC approach is the ability to produce both an posterior parameter set and parameter probability distributions. The probably distributions can be applied to the model runs to generate confidence intervals in modeled flux and increase statistical power in the comparison to observation.

With the longest running wetland tower only having currently 5 years of flux data, it will be important to continue data collection at this tower to enable evaluation. Parameter optimization with subsets of the data are possible, but severely limit our ability to test hypotheses on interannual variability, thus losing confidence in the expected prediction capability and mechanism testing such a model would allow.

5. **Construct and evaluate regional CO$_2$ flux with a multiple site constrained model**

Ecosystem specific modeling knowledge will be utilized to develop a regional surface flux model that is capable of using high-resolution land cover data to optimally configure itself by adapting its structure and parameterization to specific site characteristics across the region. The output of this model, based on posterior predictive distributions, would be compared against flux measurements obtained using independent methods and also by using traditional models to assess the value and potential refinements for such spatially distributed modeling of regional flux.

A parameter estimation technique allowing simultaneous ingest of multiple site data will also be developed. In this approach, parameters will be divided into those that are constant for all sites (e.g., hydraulic conductivity) and those that differ between sites (e.g., CO$_2$ assimilation rate). Each site has its own constraining data set. Each site can also have its own climate forcing data or use the same climate data, allowing testing of impact of micrometeorological variability across sites. Optimization at multiple sites will modify non-spatially varying parameters in the same direction for each site. The likelihood function is rewritten to sum the likelihoods of all locations to form a single value, which is used to accept/reject parameter values. Spatially varying parameters are modified randomly at all locations and a single likelihood is used to accept/reject the set at all sites.

This proposed multiple site simultaneous upland-wetland model-data fusion approach allows for the creation of a general regional ecosystem model applicable to the area. Individual site optimization at multiple upland and wetland sites will create robust ecosystem based parameter sets. Multiple site assimilation of the full suite of upland and wetland flux data will then allow for effective constraint of parameters not expected to vary across the region. Together, when applied with high resolution information about land cover spatial variability, the modeled regional flux is expected to improve in comparison to regional flux estimated from simple upscaling methods (Desai et al., 2006) and forest inventory driven models (Desai et al., 2007) that have already been applied to the region (Fig. 6). These simpler scaling methods and the proposed model with and without wetland mechanisms can be compared to several independent regional flux estimates at timescales of hourly, monthly, seasonal and interannual to test the hypothesis that simultaneous parameter optimization and wetland biogeochemistry significantly improves modeling of observed regional flux. The WLEF tall tower is a direct measure of regional flux (Davis et al., 2003). Methods can be applied to the tall tower flux record to account for footprint sampling.
bias (Desai et al., 2006; Wang et al., 2006). Single tower CO₂ atmospheric boundary layer (ABL) budget techniques have also been applied to the WLEF tall tower as an alternative method to produce large scale regional flux (Bakwin et al., 2004; Helliker et al., 2004). The ABL budgets and tall tower serve as independent observations that can be used to evaluate model regional flux and compare to the simple scaling methods (Fig. 6).

To compute the model regional flux, regional boundary conditions/state variables, forcing, parameters and constraints have to be applied to the model. Boundary conditions of land cover will be taken from the extensive remote sensing, airborne and in situ analysis being done as part of a NASA-funded upscaling project in the region (P. Bolstad, 2006, personal communication). Ecological and inventory plot data will be used to determine variability in state variables of biomass and soil carbon. Climate and hydrologic forcing will be taken from the network of micrometeorological stations in the region. Parameters not constrained by the multiple flux tower optimization will be set to values found from the ecological plots and literature. Model regional flux will be examined at a variety of spatial scales, from the tall tower footprint (10² km²) to the ABL budget footprint (~10⁵ km²). Parameter posterior probability distributions will be used to produce model flux confidence intervals. The success of the spatial scaling will be measured using the Bayesian DIC (Spiegelhalter et al., 2002; Samanta et al., 2007), which will objectively test for significance between the simple and complex scaling.

6. Predict future response of the region’s ecosystems to climate change

After evaluating the regional model at shorter time scales, the model will be used to generate long-term predictions of fluxes in upper Midwest wetland-rich landscapes under a variety of Intergovernmental Panel on Climate change (IPCC) future climate and CO₂ scenarios (Houghton et al., 2001). The predicted fluxes would be compared to those obtained using traditional models as well as other independent studies to assess the sensitivity of long term flux estimates to the models used to predict them. As the posterior probability intervals will be calculated for each predictive quantity, we will be able to test whether the model optimization has led to more precise predictions of climate change impacts on ecosystems.

It should be noted that CO₂ fertilization effects can not been constrained by the data in the model, and so the focus will be more on the effects on changes in temperature and precipitation on interannual and longer term timescales on CO₂ and H₂O fluxes in the region and specifically in wetlands. These scenario runs can be used to test the hypothesis that wetland flux variability dominates the regional interannual flux variability signal, at least within the optimized model framework. Wetland evapotranspiration has been shown to respond to long term changes in water table depth (Mackay et al., 2007). Here we can test whether that result holds in the model and over what timescales. A salient question in this line of research is whether wetlands will emit/store large amounts of organic carbon in a drier/wetter future. Such results could have significant impact on the future trajectory of atmospheric CO₂ growth.

Anticipated Results

Development of a wetland-upland model and constraining model parameters with data from multiple years/sites will lead to a stronger ability to better evaluate biological mechanisms that control ecosystem response to climate change and improve future prediction of such. Results will be published in peer-reviewed journals and developed tools will be made available to the public. Model code will enter the public domain after suitable testing and development. An ecosystem model Bayesian parameter sensitivity and optimization code will also be provided. Parameter sets, model output and flux tower data will be published online for use by other investigators. All of these data as well as links to publications and presentations will be made publicly available at the existing ChEAS web site (http://cheas.psu.edu).
MANAGEMENT PLAN
Desai will be responsible for overall project management. Though Desai is a new assistant professor at the University of Wisconsin-Madison, he has been involved in many regional collaborative projects and has led several multi-investigator carbon cycle data analyses and publications (e.g., Desai et al., 2006). Desai has been involved with ChEAS since 2000. He has extensive experience in eddy covariance flux instrumentation, upper Midwest carbon cycle scaling and ecosystem modeling. Desai will lead 1.) collection, processing and analysis of eddy covariance data, 2.) development, implementation and evaluation of the parameter optimization methodology, and 3.) analysis of regional flux output (Table 2).

This proposal will also train the next generation of climate-carbon researchers with support for Ph.D. research of a graduate student and partial support of a post-doctoral scholar. Desai will supervise the post-doc, Sudeep Samanta, who brings expertise in Bayesian analysis, complexity analysis and parameter optimization. Samanta did his PhD on Bayesian model complexity analysis of canopy transpiration models under Mackay’s guidance. The graduate student will focus on observational data analysis and implementation of the parameter optimization techniques with model-data fusion. Shelley Knuth, a meteorological technician at the University of Wisconsin, will support tower maintenance and operation and is currently supported from other funds.

Mackay will lead TREES model development, implementation, analysis and future scenario/prediction runs (Table 2) He has experience as project director for past NASA-funded research at ChEAS and a current NSF Hydrologic Sciences project. Mackay has extensive experience with ecosystem model development and integrating field measurements with models. He has been involved with ChEAS related research for the past 8 years and has collaborated informally with Desai in the past.

To facilitate collaboration, Mackay, Desai, Samanta and the graduate student will meet during the annual ChEAS meetings held in northern Wisconsin. They will also initiate a monthly teleconference among the group. Collaboration will also extend to using field sites, data sets and developed modeling tools to generate education and outreach opportunities and presentations for local and University communities.

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Table 2. Timeline of major activities relevant to proposed project and lead PI in charge of activity
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