ENVIRONMENTAL AND ECONOMIC RESEARCH AND DEVELOPMENT PROGRAM

Observing Carbon Fluxes and Potential Climate Change Impacts from Forest Land Management

Final Report
December 2013

PREPARED BY:

ANKUR R DESAI, DEPT. OF ATMOSPHERIC & OCEANIC SCIENCES
UNIVERSITY OF WISCONSIN-MADISON

focus on energy[sm]
Partnering with Wisconsin utilities

This report was funded through the Environmental and Economic Research and Development Program of Wisconsin's Focus on Energy.

Executive Summary

Wisconsin's energy choices and policies influence the trajectory of global greenhouse gas emissions. Forests cover nearly half of the state and pulp, paper, lumber, bioenergy, and outdoor recreation are all important economic sectors in Wisconsin that benefit from having a robust and healthy forest in Wisconsin. Choices made in the management of these forests by federal, state, local, and private actors can influence the long-term health and adaptability of these forests to a changing climate and also provide an opportunity for enhanced climate mitigation by improved sequestration of fossil fuel carbon dioxide emissions.

This project focused on one key aspect of forest ecosystems in Wisconsin – the sensitivity of forest carbon uptake to climate variability and management decisions. While numerous projects have provided regional modeling and inventory-based assessments of forest yields and ecosystem services, direct, long-term ecosystem-scale observational evidence of whole forest net carbon uptake are difficult to acquire.

The objective of this project was to understand how land management and climate variability alters the carbon cycle of forest ecosystems in Wisconsin and investigate how well we can predict carbon cycle impacts of differing land management options. The primary activity involved intensive study of a single forest site where measurements of ecosystem carbon cycle have been made since 1998 (Cook *et al*., 2004) and where intensive forest management and harvest are planned by the U.S. Forest Service and being used here as an experiment to test hypotheses of changes to the carbon cycle. There is large uncertainty in how models simulate harvest and climate sensitivity, hence the need for direct observations. Further, a primary goal of this project was to build a greater research and policy community to engage this question more deeply, which was accomplished through focused workshop with scientists and forest managers.

Results and activities from our research study site located in the Chequmegon-Nicolet National Forest has led to many peer-reviewed publications, presentations, and public outreach. In summary, our major findings are:

- Many of the mature temperate northern hardwood forests of Northern Wisconsin are at a peak for net carbon exchange and sequester more carbon on a per area basis then wetland, grassland, and lake ecosystems in the region.
- These carbon sinks are moderately sensitive to climate. Extensions in the growing season length have counteracting effects on net carbon uptake. While earlier springs increase net carbon uptake and can counterbalance the effect of summer droughts, later autumns tend to decrease net uptake by extending the period of decomposition and respiration.
- Soil respiration is dominated by newly photosynthesized carbon that is introduced to soil through roots, but when roots are removed, microorganisms can switch to

consuming older carbon. Consequently, we anticipate that removing trees could cause a pulse of older soil carbon to be released, as microorganisms switch from consuming root-derived, new carbon to older soil carbon.

- Partial and selective harvesting with moderate rotation intervals can enhance net carbon uptake in the ecosystem compared to more intensive harvesting. Also, increases in harvest intervals could enhance carbon sinks on top of any enhancement of sinks that may arise from increasing atmospheric CO_2 or counterbalance declines in carbon sequestration from increased respiration in warmer climates.

While these findings will be enhanced from the planned pre- and post-thinning experiment, the observation, modeling, and coordination components of the project has already led to several policy implications:

- Carbon mitigation in northern Wisconsin forest ecosystems through enhanced sequestration is viable, but this sink is expected to decline with increasing age of the region's forests beyond their peak period of uptake.
- These forests are climate sensitive, and forest management that emphasizes climate adaptation, specifically to changes in autumn climate and summer drought, is warranted.
- Shifts in the type soil carbon respired may be significant with forest harvesting and methods for soil carbon stabilization during harvest need to be considered.
- Focused workshops, data sharing, and model comparisons jointly with forest managers and scientists can significantly improve the scientific basis for forest management for carbon in a changing climate.

Observing carbon fluxes and potential climate change impacts from forest land management

Introduction

Wisconsin's energy choices and policies influence the trajectory of global greenhouse gas emissions. Forests cover nearly half of the state and pulp, paper, lumber, bioenergy, and outdoor recreation are all important economic sectors in Wisconsin that benefit from having a robust and healthy forest in Wisconsin. Choices made in the management of these forests by federal, state, local, and private actors can influence the long-term health and adaptability of these forests to a changing climate and also provide an opportunity for enhanced climate mitigation by improved sequestration of fossil fuel carbon dioxide emission.

This project focused on one key aspect of forest ecosystems in Wisconsin – the sensitivity of forest carbon uptake to climate variability and management decisions. While numerous projects have provided regional modeling and inventory-based assessments of forest yields and ecosystem services, direct, long-term ecosystem-scale observations evidence of forest net carbon uptake (photosynthesis minus respiration and decomposition) are difficult to acquire. Additionally, direct observation of these before and after a management prescription is even rarer.

The objective is to understand how land management alters the carbon cycle of forest ecosystems in Wisconsin and investigate how well natural resource managers can predict carbon cycle impacts of differing land management scenarios. Instead of a general framework, the primary activity here involved intensive study of a single forest site where measurements of ecosystem carbon cycle have been made since 1998 (Cook *et al*., 2004) and where intensive forest management and harvest are being used as an experiment to test hypotheses of changes to the carbon cycle.

In this particular case, planners of the forest harvest specifically highlighted this study site to better understand the emerging science of carbon management and the use of selection harvest policies that could potentially increased the carbon sink capacity of forests in Wisconsin and elsewhere, while maintaining or improving the economic and environmental services of Wisconsin's forests. Unfortunately, environmental impact assessment and review took longer than anticipated, so that the harvest is now marked and ready to cut for winter 2013. Nonetheless, a variety of observational and modeling experiments were conducted that provided a strong basis for conclusions on the climate sensitivity and management response to harvest scenarios.

Our key project hypothesis was that carbon cycle sensitivity to a selection harvest and management exceeds that of interannual climate variability. I expected harvest would initially cause the ecosystem to release carbon, but soon sequester carbon at rates larger than pre-management. In the next section, I review the key science that leads to these justifications. The remaining sections outline the project approach, key findings from published papers and reports, and implications for Wisconsin energy and environmental policy.

Forests in the Global Carbon Cycle

Global fossil fuel emissions have reached 9.5 billion metric tons of carbon in 2011, 54% greater than 1990 (Fig. 1a, from Le Quere *et al*., 2013). However, the atmosphere has growth rate in carbon dioxide is nearly half the fossil fuel emissions, because of the role of ocean and terrestrial net carbon uptake (Fig. 1b, from Le Quere *et al*., 2013). Terrestrial ecosystems, for example, absorb nearly 30% of fossil fuel emissions. In particular, northern hemisphere forests have been shown to provide numerous ecosystem and climate services, including high productivity (Bonan, 2008).

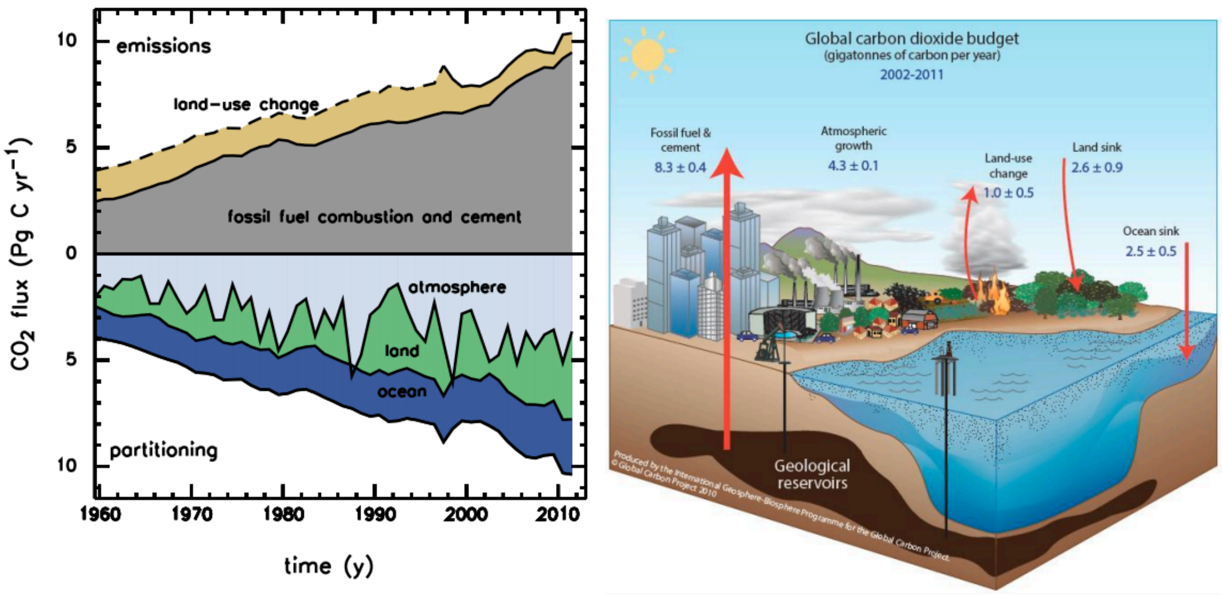

Figure 1. Figure from the Global Carbon Project 2012 synthesis of carbon cycle changes and net global flows from Le Quere *et al*., 2013. a) Fossil fuel combustion emissions have continued to rise steadily for the past several decades, with half of those emissions staying in the atmosphere owing to the efficiency but large variability of land and ocean carbon sinks. b) The land and ocean sinks for carbon are each roughly ¼ of the fossil fuel emission rates.

Fig. 1a also highlights the key difficulty in improving prediction of this terrestrial ecosystem “carbon sink” or understanding the role of land management. The year-to-year variation in land uptake as seen in Fig 1a. is very large, exceeding all other fluxes of the carbon cycle. Thus, carbon sequestration prediction is difficult because ecosystems are strongly sensitive to climate variability and human land management. Simulation models, such as global earth system climate models, have high spread in prediction of the land carbon sink, leading to large uncertainty in carbon emissions reduction scenarios.

In the U.S., in particular, forests are 1/3 of the U.S. landscape and almost half of that is publicly managed by agencies such as the U.S. Forest Service (USFS). Land management by humans is endemic to virtually all ecosystems globally, so understanding how changes in management practices influence the carbon cycle is a key uncertainty for global climate models. The USFS has a goal to improve science-based management decisions in light of future climate uncertainty.

The impact of harvest on gross photosynthesis (GPP), ecosystem respiration (ER) and the net carbon uptake (the difference of ER and GPP, termed Net Ecosystem Production (NEP)) is significant and has wide variation with time, as presented in a paper that included data from the Wisconsin sites studied here (Amiro *et al*., 2009). The largest periods of variability occur for very young (recently harvested) and mature/old sites (pre-harvest) (Fig. 2).

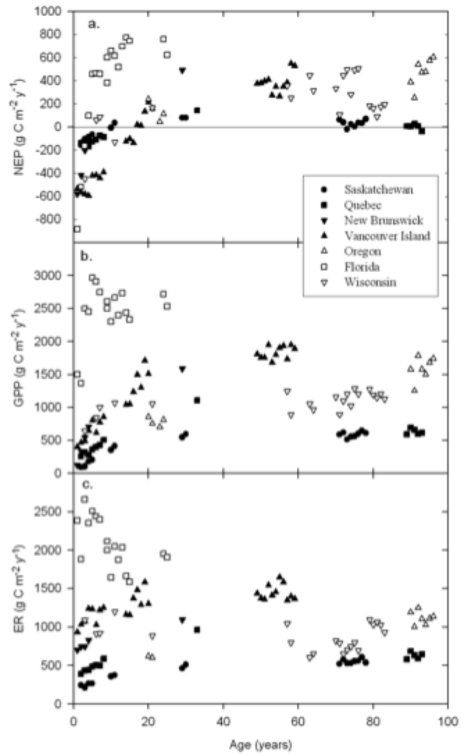

Figure 2. Synthesis of forest harvest and fire chronosequences across North America from sets of eddy covariance flux towers as published in Amiro et al (2010) show that a) net ecosystem production, b) gross primary production and c) ecosystem respiration follow mostly predictable trajectories with age since disturbance, but highest variability exists for recently disturbed sites. Sites from this project contributed to the study (upside down clear triangles)

Natural disturbances, including biotic disturbances (Hicke *et al*., 2011), also form a major source of variation in net carbon uptake and can be occurring in conjunction with larger scale disturbances like harvest and fire.

Carbon in the Northwoods

Northern Wisconsin has extensive forest cover and derives much economic activity from its public and private forests. Climate and topographic variations leads to a range of southern boreal forests mixed with northern temperate hardwoods. A significant fraction of the landscape is also wetland, including wet forests and carbon rich peat bogs. A synthesis and model calibration study was published with several colleagues for the Northern Highlands Region of Wisconsin, where we showed that forests are the dominant carbon flux in the region, while wetlands have the largest carbon stores (Fig. 3)

On net, the Northwoods region appears to be a net carbon sink, reflective of the productive forests but also the legacy of 19th and early 20th century land clearing. Typical mature northern hardwood forests, like those studied here, sequester 200-400 grams of carbon per every square meter. However, year-to-year variation is nearly 50% of the mean and variation with forest age suggests decreased carbon uptake with both younger and older forests (Desai *et al*., 2008). An overarching research question for North American carbon cycle researchers is whether changes in climate and atmospheric CO_2, trends in extreme disturbances, and current forest management regimes today are enhancing this carbon sink or hastening its eventual expected long-term decline with age. Given the importance of the terrestrial carbon sink and North American and Midwest carbon uptake to carbon emissions policy for the energy industry, adaptation and mitigation options for forest management and its impact on net carbon exchange require better constraint.

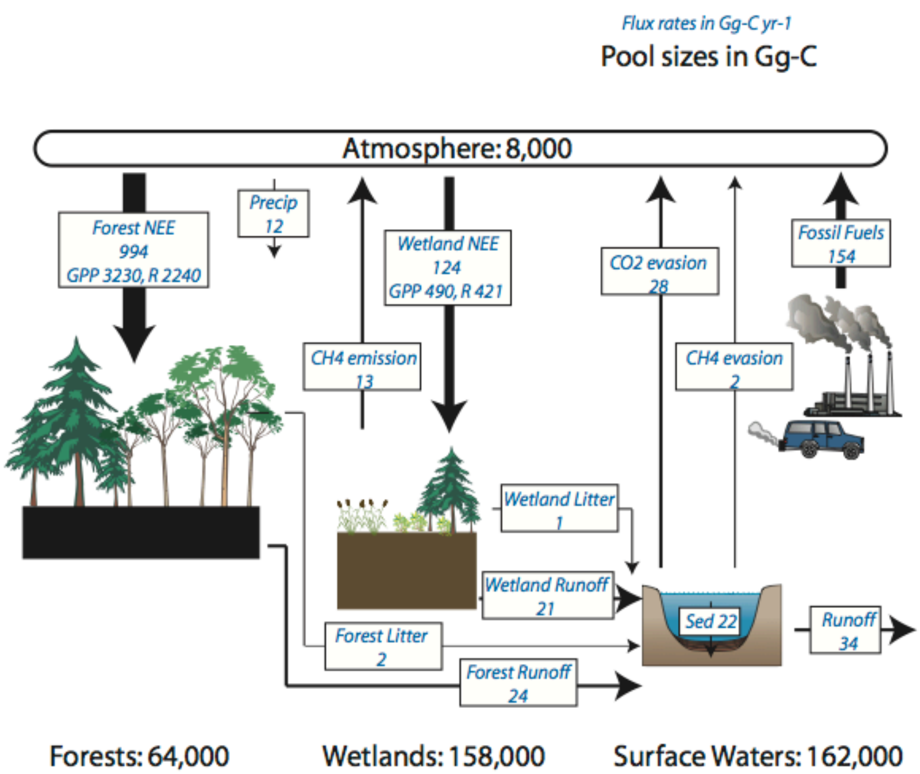

Figure 3. *Synthesis from Buffam et al. (2011) of carbon flows among forests, wetlands, and lakes in the Northern Highlands lake district of Wisconsin. The flux tower sites from this study were used for calibration of the model.*

Forest Management in Wisconsin

Virtual all Wisconsin forests are managed to some extent for recreation, timber, wildlife, and more generally multiple uses. Recently, there is growing interest in management for carbon sequestration and climate adaptation. For example, the USFS has recently produced the Northwoods Climate Change Response Framework (CCRF) that addresses current known science on adaptation and mitigation potential of forests in Wisconsin, Michigan, and Minnesota.

One of the largest tracts of forest in Wisconsin is the 1.5 million acres of land managed by the Chequamegon-Nicolet National Forest (CNNF). The USFS CNNF is currently executing a commercial harvest and thinning activity in the Medford-Park Falls ranger district in Northern Wisconsin. The activities of this project were designed to coincide with this proposed action. The proposed action included selective harvest and thinning of a 16,000 ha region of northwoods forest. The region is at a successional turning point as it continues to recover from large-scale forest clearing during European settlement in the late-1800s. Over the past several decades, active management of these forests has been limited. One major purpose of the CNNF action is to maintain forest health by increasing biodiversity of the forest as it ages. These actions include decreasing the area of early successional forest, reducing density in overstocked stands, increasing diversity of forest age structure, restoring wind and disease damaged forests, and removing some ash trees to lessen the susceptibility to emerald ash borer (Fig. 4).

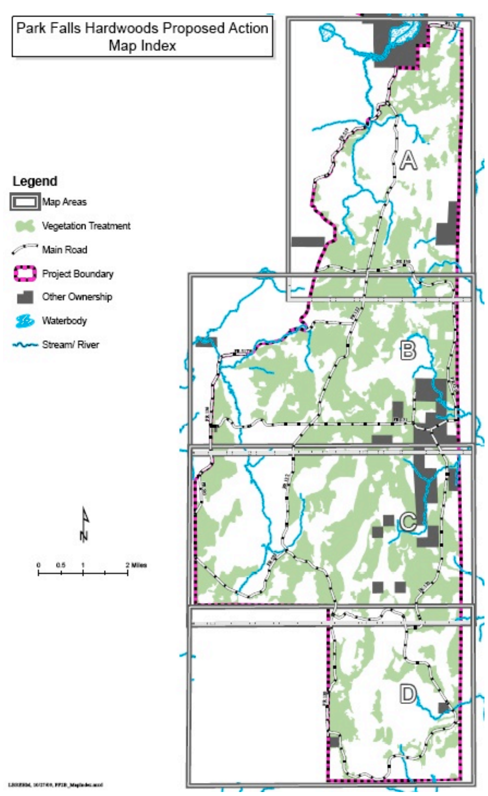

Figure 4. *Areas of Park Falls hardwood harvest. The study site in this project is located in section B.*

The USFS forest plan for this region is for uneven-aged northern hardwoods that mimic old-growth conditions including complex stand structure (a greater diversity of tree ages, greater amounts of downed woody debris, more gaps) and late-successional plant communities (increased dominance of maple and basswood, decreased dominance of ash, aspen, and birch). The research site studied here included management for "relatively continuous mid to late successional uneven-aged northern hardwood and northern hardwood-hemlock forest. Large patch conditions and a relatively continuous canopy is to be maintained or recreated with hardwood patch sizes in the thousands of acres", which will be accomplished by creating four to eight 25 to 40 foot gaps per acre and harvesting groups of pole sized trees or 1-2 large crowned trees. Species diversity will be encouraged through the use of one 60-foot gap for every two acres.

A unique feature of this study is the existence of a research site that has studied net carbon uptake in a hardwood stand since 1998 using the eddy covariance method (as described in the approach). The large scale of the management and the existence of long baseline carbon flux measurements led the USFS to include the carbon management activities of this study in its scoping study. The integration of research and management is partly in response to the USFS Northern Research Station Climate Change Response Framework and Model Forest Initiative. Like this project, the Model Forest Initiative also seeks to understand how forest carbon sequestration varies with management and climate.

Table 1. *USFS existing and desired forest cover for the management tract (source: CNNF)*

Type	Existing %	Desired %
Aspen	25	0-10
Fir	1	0-3
Birch	2	0-2
Jack pine	0	0-2
Red/white pine	1	0-10
Northern hardwoods	69	50-80
Oak	1	0-3
Permanent openings	1	0-1
Other upland forest	1	1-15

Approach

This project opted to use the planned harvest as an experimental manipulation to better understand the effects of climate variability and land management on forest carbon sequestration. This approach can provide strong observational evidence of how the forest carbon cycle responds to manipulation and to what extent this effect can be simulated by forest ecosystem models. There is large uncertainty in how models simulate harvest and climate sensitivity, hence the need for direct observations. Further, a primary goal of this project was to build a greater research and policy community to engage this question more deeply. Thus, our approach rested on three pillars: observe, simulate, and coordinate.

Observations were centered on the Willow Creek research study site. At this site, a 24 m meteorology and flux research was instrumented in 1998 and operated from 1998-2006 and then, with funding from this grant and the USDA, restarted in 2009 for continuous operation (Cook *et al.*, 2004). A key observation of the carbon cycle is acquired through the use of the eddy covariance method (Baldocchi, 2008).

Eddy covariance flux towers measure high-frequency (> 10 Hz) fluctuations of atmospheric trace gases and vertical velocities. These measurements can be applied to CO_2 and estimate total net ecosystem production (NEP) on scales of ~1 km^2 and time resolution of 30 min. This is a well-studied technique with hundreds of towers globally. Earlier work has shown how the Willow Creek tower was a large carbon sink compared to nearby older forests (Fig. 5., from Desai *et al.*, 2005) and that leaf defoliating insect disturbances influence short-term but not necessarily long-term productivity (Cook *et al.*, 2008)

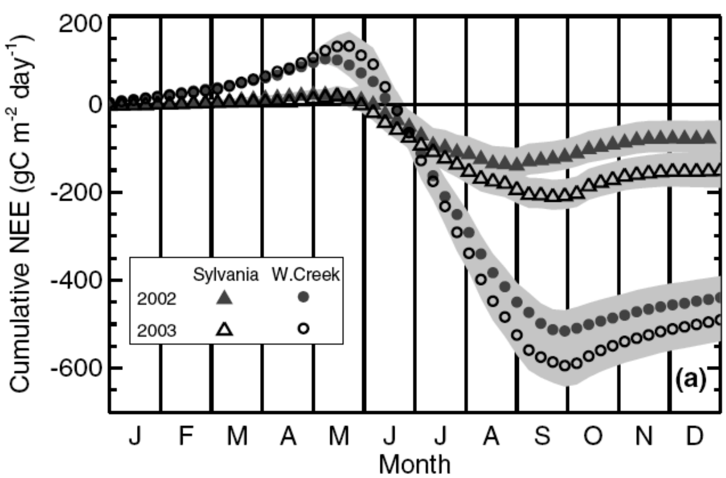

Figure 5. *Cumulative annual net carbon uptake at WC (circles) over two years compared to a nearby old-growth forest (triangles). Reprinted from Desai et al. (2005)*

In addition to flux tower observations, micrometeorological observations of temperature, radiation, precipitation, humidity, wind speed, soil temperatures, and ecological observations of component (soil, tree, etc…) fluxes were made to tease apart the NEP signal into its component processes and estimate their climate sensitivity. Originally, the proposal called for measurement of pre and post harvest fluxes. Unfortunately, because of the harvest delays, to date there are only pre-harvest measurements. However, additional funding from the Dept of Energy will keep the tower running starting this summer and the harvest is now scheduled for winter 2013.

Ecosystem models quantitatively encapsulate theories of ecological systems and how nutrient cycling and energy use responds to climate and biotic variability. The proposal included use of the LANDIS forest demography model. However, an additional simpler model based on CENTURY was also added to better test forest management impacts over long time integrations. A variety of harvest scenarios were tested in these models to estimate both the immediate and long-term response of the forest carbon cycle to harvest.

Finally, the project sought to coordinate a community of researchers and forest managers to understand the role of carbon management. Research collaborators added several additional measurements to the project as described in the findings. The site's data has been used in global syntheses of the carbon cycle. Project results have been presented at a number of scientific conferences and also incorporated into discussions with the USFS forest harvest plans and the USFS climate change response framework and model forest initiatives. Additionally, a workshop focused on improved modeling and observation of forest management carbon cycling was held in 2012.

This approach was executed through a number of activities conducted by the Principal Investigator (PI), several post-doctoral scholars, and a site technician. All were involved in the maintenance and operation of the eddy covariance tower, processing and archiving of data in near real-time, support and collaboration of research partners for radiocarbon, phenology, soil carbon, and ecosystem modeling analyses, and joint co-authorship of manuscripts and presentations. Additionally, the post-doctoral scholar focused on development and testing of a forest ecosystem model with realistic forest management scenarios. The PI additionally led the collaboration aspects with USFS and development of the forest management workshop.

Findings and Activities

Large consistent seasonal patterns of carbon cycling appear require long-term near real-time eddy covariance tower carbon cycle observations

The primary activity of the project was to restart and continued observation and maintenance of the Willow Creek Ameriflux tower (US-WCr), which had been out of operation for several years due to lack of funding, so as to build a carbon flux baseline prior to harvest. The site is located in the northwoods and there are several other Ameriflux sites that have operated in the past or currently in the region that collectively form the Chequamgeon Ecosystem-Atmosphere Study (ChEAS) research cooperative (Fig. 6)

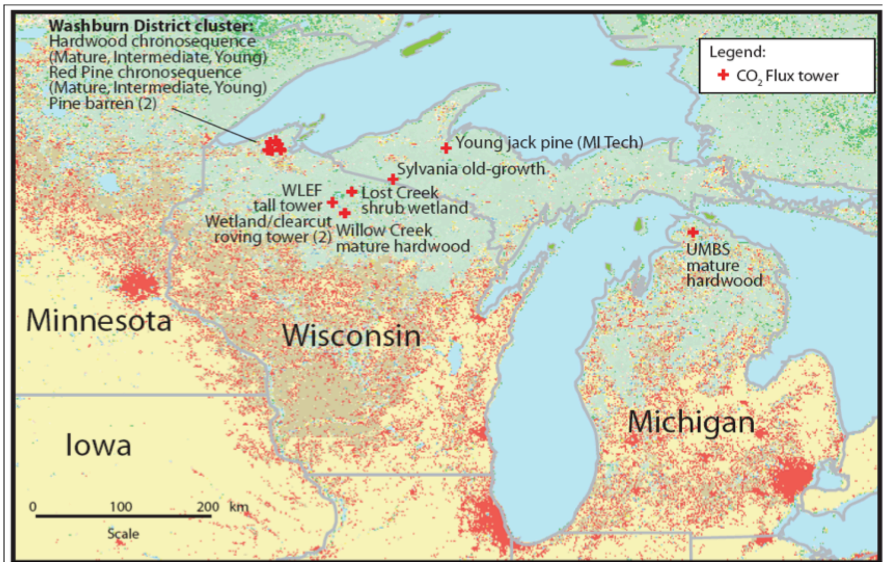

Figure 6. *Map of ChEAS sites. Study site is listed as "Willow Creek mature hardwood"*

In 2010, we were able restart the site and started collecting 10 Hz flux observations and 1 second meteorology observations. A real-time data access system based on cellular uplink to the site was installed and a web-based real-time web interface was added the same year to allow for viewing of raw data and to ensure high uptime (Fig. 7)

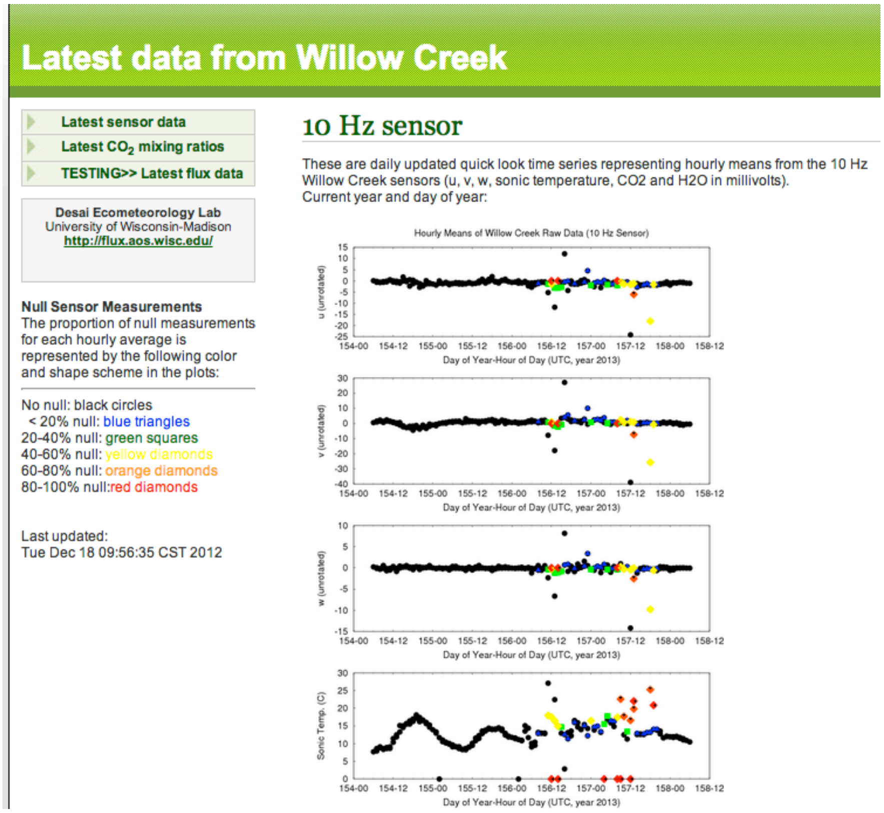

__Figure 7__. Snapshot of real time flux tower interface including flagging of suspect values shown from 7 June 2013 located at [*http://flux.aos.wisc.edu/~bjorn/willow_creek/*](http://flux.aos.wisc.edu/~bjorn/willow_creek/)

The legacy and current data set was intensively quality controlled, harmonized, and instrument drifts were corrected (Fig. 8). These data are now available to the public on the PI web server (http://flux.aos.wisc.edu/twiki/bin/view/Main/ChEASData) and also at the Ameriflux and Fluxnet project pages.

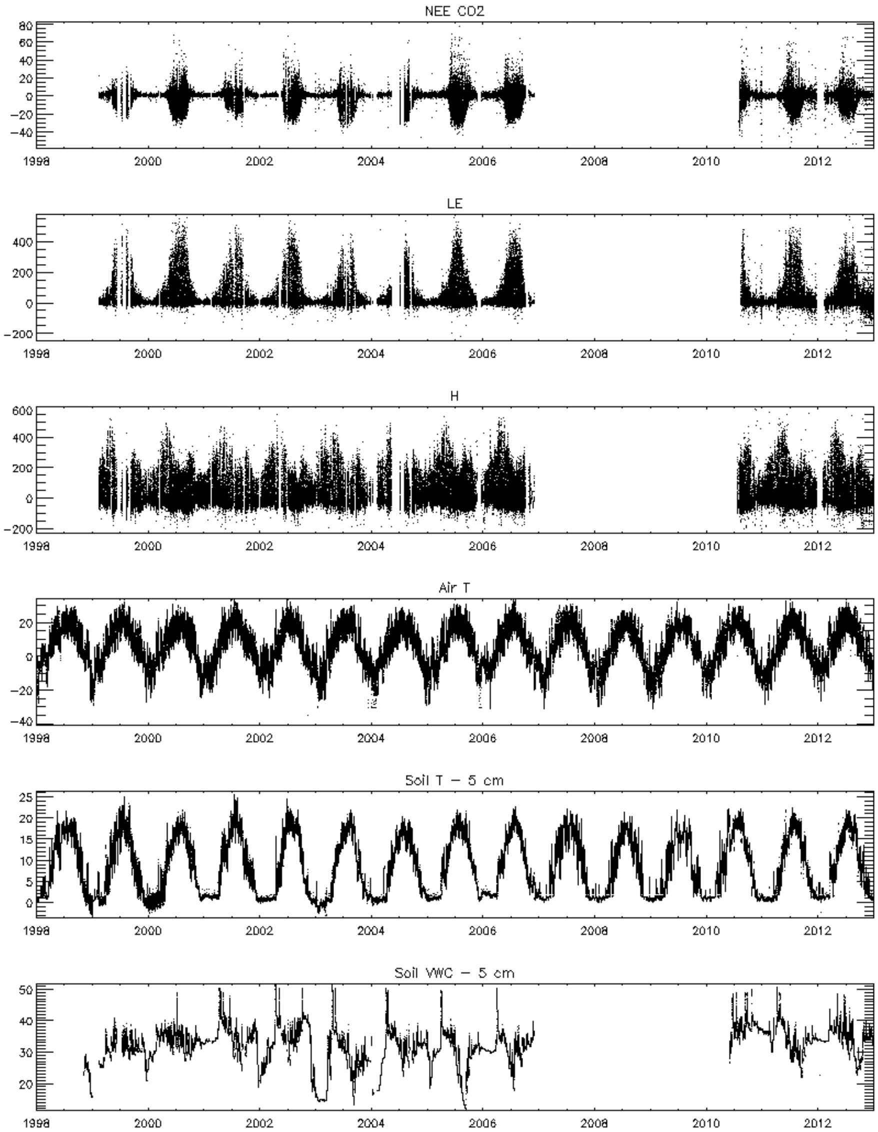

Figure 8. *Example of quality-controlled harmonization of several variables including half-hourly net CO_2 flux, evapotranspiration flux (LE), sensible heat flux (H), air temperature, soil temperature, and soil moisture observed from 1998-2012. Several of these data streams were also gap-filled with nearby sensors.*

Several collaborator experiments were also added to the site, included a real-time web camera for monitoring of plant phenology (Fig. 9), continuous soil respiration chambers for soil flux measurement, and vegetation census surveys. All of these data are available on the PI web server, too.

Figure 9. *Recent web camera automated photo from the PhenoCam network camera from 7 June 2013. A new image is taken every hour and archived at the PhenoCam network website.*

Forest carbon sequestration has moderate climate and moisture sensitivity

The data discussed above was analyzed to understand what drives the climate sensitivity of NEP of carbon in temperate hardwood forests in Wisconsin and globally. Annual carbon fluxes show that the mature hardwood forest is the largest carbon sink among the ChEAS network of towers (Fig. 10), which include a regional tall tower in a mixed forest, a shrub wetland, and an old-growth forest. This large carbon sink (seen as a negative number (-NEP, also dubbed Net Ecosystem Exchange or NEE) to reflect the loss of CO_2 from the atmosphere) comes with large interannual variability, reflective of sensitivity to temperature, moisture, light, and biotic disturbances, in the specific case of 2001 (Hicke *et al*., 2011).

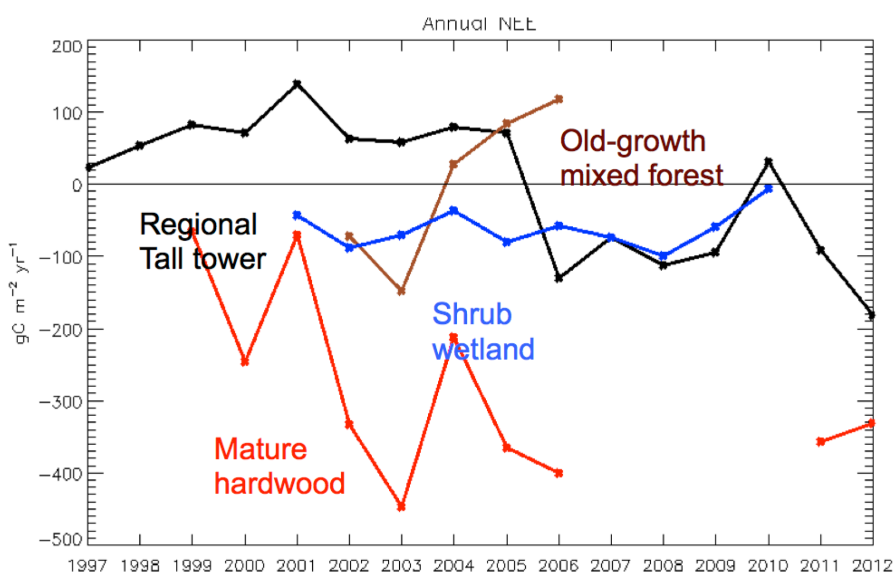

Figure 10. *Annual net ecosystem exchange of carbon among four long-running eddy covariance flux tower sites. The study site is the red line. Negative numbers indicate net carbon assimilation by the ecosystem.*

The drivers of this interannual variability are difficult to diagnose, but coherent variability among the sites points to regional climate drivers (Desai, 2010), the most significant of which is the length and timing of the growing season. Growing season length is defined by the period of active photosynthesis and for deciduous forests starts with leaf emergence and ends with leaf senescence. Many sites across the northeastern US show a strong sensitivity to the start of spring and net carbon uptake. However, a global synthesis analysis that included this study site showed that net carbon accumulation in boreal and sub-boreal forests is more strongly controlled by anomalies in the end of the growing season. Climate changes that enhance periods of warm, sunny conditions in fall tend to reduce total carbon uptake as any enhanced photosynthesis is dwarfed by increased decomposition activity (Wu *et al*., 2013; Fig. 11).

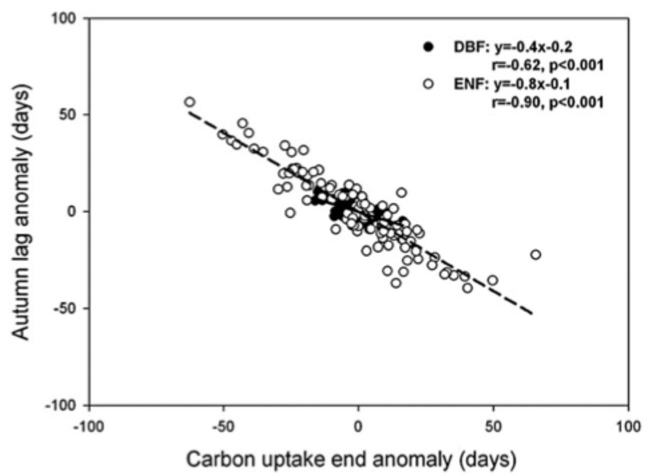

Figure 11. *From Wu et al. (2013), the relationship of when net carbon uptake finishes in fall (x-axis) and a metric of the length of the autumn senescent period.*

The newly installed phenology camera is also providing direct high-resolution observations of plant life cycle. A forest canopy mask is applied to the imagery and used to extract the mean green chromatic value. As seen in Fig. 12., a very clear pattern of spring flush and autumn senescence can be seen in 2012 as well as the start of spring in 2013. There is more than a two-week difference in start of spring from 2012 (early) to 2013 (late) and it is to be seen how much these extreme shifts in spring phenology, as opposed to the more typical subtle year to year shifts in phenology, affect carbon cycling.

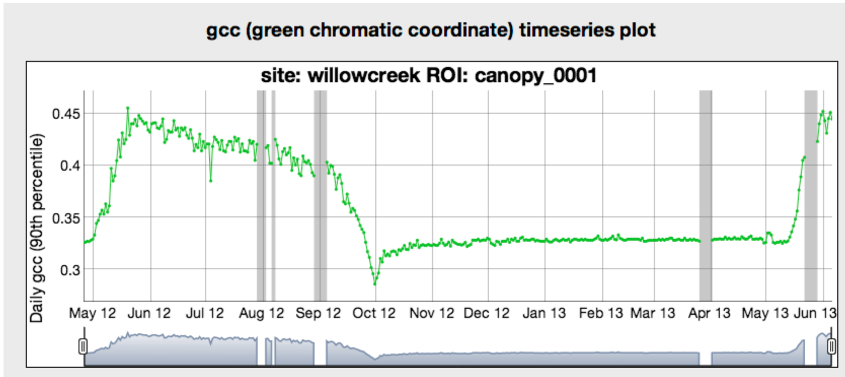

Figure 12. *Green chromatic metric from the phenology camera at the Willow Creek tower from late April 2012 to early June 2013.*

Beyond growing season length, another surprising finding is how important variations in moisture are to the relatively mesic ecosystem. A sensitivity analysis of anomalies of carbon uptake to climatic anomalies at a nearby regional mixed forest shows high correlation between carbon uptake extremes and extremes in evapotranspiration and water use efficiency at time scales from daily to annual (Desai, 2013; Fig. 13). These sensitivities persist even when accounting for lags, and exceed those for temperature. Moisture stress has a negative impact on forest productivity in the region.

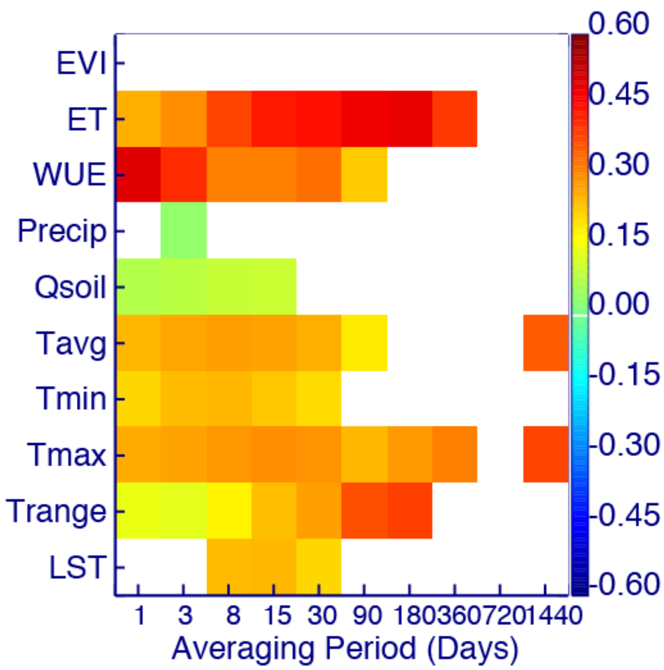

Figure 13. *Correlation between anomalies in regional plant photosynthesis and climatic variables (EVI = vegetation greenness, ET = evapotranspiration, WUE = water use efficiency, Precip = precipitation, Qsoil = soil moisture, Tavg = Mean temperature, Tmin = Minimum temperature, Tmax = maximum temperature, Trange = Diurnal temperature range, LST = land surface temperature)., from Desai (2013).*

However, caution is warranted in over-interpreting these sensitivities. Fig. 14 shows the cumulative net carbon exchange at the regional tower and the Willow Creek site. The black line represents 2011, red line, a drier year, 2012. For both sites, while the dry year had reduced carbon uptake in the late summer, this was more than cancelled out by the early spring. Also shown is 2001 (blue line), which experienced a large forest tent caterpillar outbreak followed by a particularly warm summer. Complete defoliation in early spring was followed by re-flush and continued uptake, but at reduced capacity. Clearly, the intersection of disturbance and climate is different than the sensitivity of forests to climate variability alone. A larger scale global synthesis of drought sensitivity is currently in preparation (Wolf *et al.*, in prep).

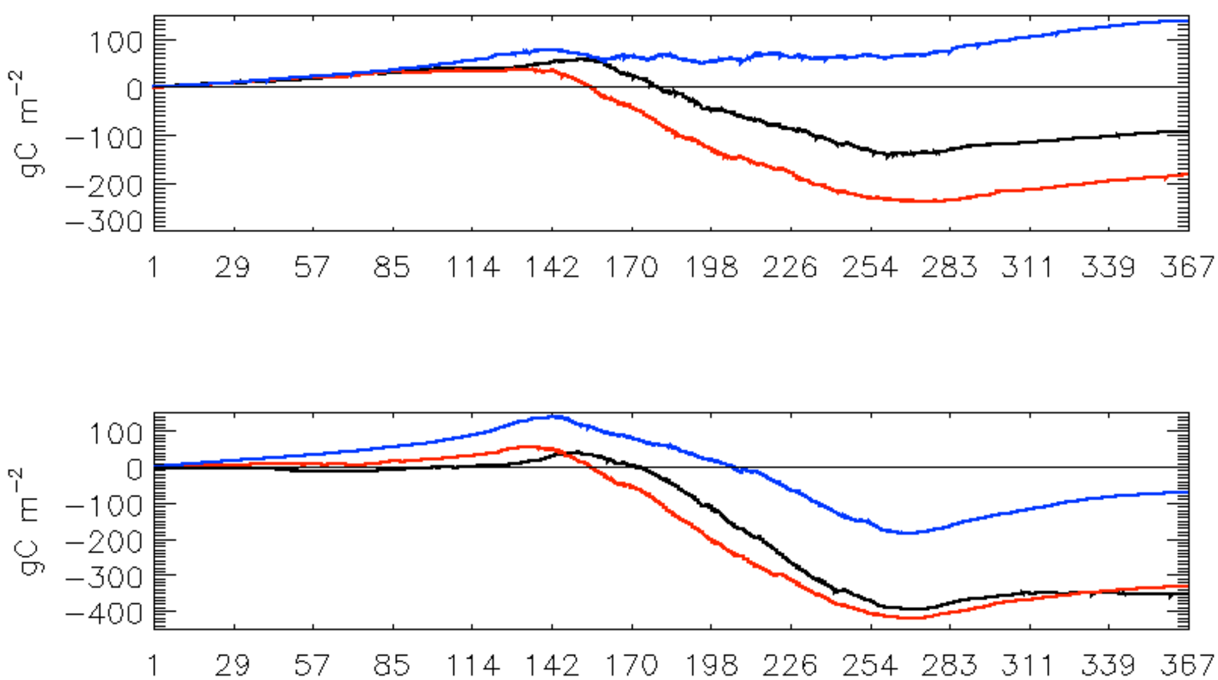

Figure 14. *Time series of cumulative net carbon exchange at the hardwood forest study site (top) and the regional tall tower (bottom) for 2011 (black), 2012 (red), and 2001 (blue).*

Carbon and water fluxes and meteorological observations from the Willow Creek site are made public usually within months of collection. As a result, the tower site has been used in a number of syntheses to advance global change and carbon cycle science. Studies include a review of the potential for carbonyl sulfide measurements to improve monitoring of ecosystem photosynthesis (Blonquist *et al.*, 2011), satellite remote sensing of canopy light use efficiency of photosynthesis (Wu *et al.*, 2012), evaluation of satellite based phenology metrics (Shen *et al.*, submitted), and a global evaluation of representation of canopy layers in ecosystem photosynthesis models (Sprintsin *et al.*, 2012). Additional studies that have documented specific improvements to modeling global climate controls on terrestrial carbon cycles where this study site was used include a study of new satellite algorithms for carbon cycle net ecosystem exchange (Tang *et al*., 2012, 2013; Fig. 15), an evaluation of modeled phenology processes (Richardson *et al*., 2012) and photosynthetic processes (Schaefer *et al*., 2012), and an assessment of processes that determine thermally optimum conditions for photosynthesis (Niu *et al*., 2012; Yuan *et al*., 2011).

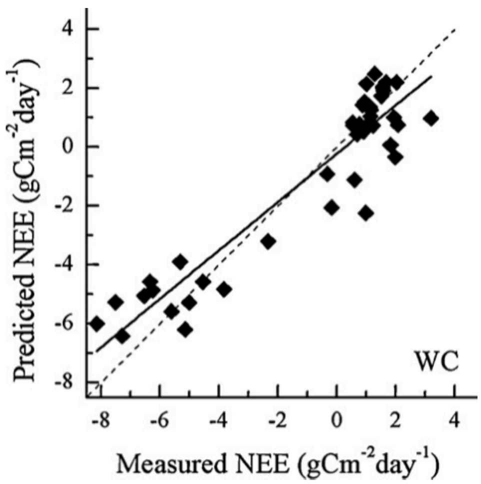

Figure 15. *Comparison of a satellite remote sensing algorithm for bi-weekly net ecosystem exchange against observations at the Willow Creek hardwood forest site, from Tang et al., 2013.*

While many of these findings reflect technical advances to the state of the carbon cycle, they all feed larger implications for energy use and policies. In summary, northern hardwood forests of Wisconsin are currently modest to large carbon sinks, but are sensitive to variations in the length of the growing season, drought, and disturbance. Carbon management policies need to consider the complicated nature of climate sensitivity when assessing total carbon sequestration potential of forests.

Soil carbon storage and emissions provide a quantitative picture of how harvest will modify soil carbon respiration

With collaboration from Dept of Energy Lawrence Livemore National Laboratory (LLNL), in 2011-2012 we conducted a soil study to understand how forest management impacts storage and turnover of soil carbon (Phillips *et al*., 2013). Carbon in soil accounts for about two-thirds of the total carbon present at Willow Creek, in the form of plant litter, roots, and microorganisms that are alive or in stages of decay. Root activity and decomposition of soil C produces large amounts of CO_2 that annually account for about 60-80% of total forest respiration (Bolstad *et al*., 2004). To better quantify rates of soil carbon storage and turnover, we used LLNL's Center for Accelerator Mass Spectrometry, where soil samples can be radiocarbon-dated to determine how long organic matter resides in soil before being decomposed. In addition to measuring solid soil, at Willow Creek we measured ^{14}C in soil CO_2 to assess whether emissions were from relatively new plant material or older material that had been residing in the soil for some time. We established four soil plots about 30m from the base of the eddy covariance tower, and sampled soil CO_2 approximately every through weeks through the 2012 growing season.

The ^{14}C abundance ($\Delta^{14}C$) of soil C and soil-respired CO_2 was measured to 75cm depth. Solid soil C had a large range in ^{14}C abundance, corresponding with an age range of >2500 years old at 75cm depth to contemporary ages at the soil surface (Fig. 16). Below approximately 15 cm soil ^{14}C abundance dropped off steeply. The 0-15 cm depth is where most root growth occurs at Willow Creek, where most inputs of contemporary carbon also occur, and as described below it is where most of the emitted CO_2 derives from.

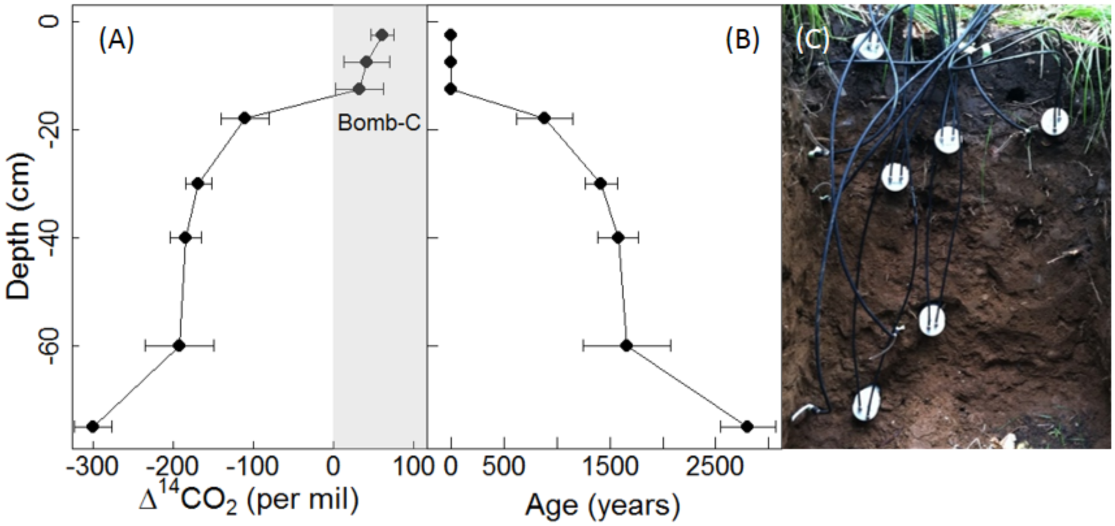

Figure 16. *(A) ^{14}C abundance in solid soil (more negative values indicate less ^{14}C), (B) equivalent ^{14}C age, and (C) photo of a soil profile to 75 cm depth, showing gas wells inserted into profile wall for soil CO_2 sampling.*

The top 15cm of soil also contained elevated ^{14}C levels associated with thermonuclear weapons testing that took place in the early 1960s. Generally, ^{14}C is constantly produced in the upper atmosphere, and when CO_2 is fixed into plant tissue the amount of ^{14}C in the tissue gradually declines due to radioactive decay. In the early 1960s, however, nuclear weapons testing created an additional source of ^{14}C in the atmosphere (Fig. 17). This bomb-C has gradually decreased since a 1968 ban on aboveground testing, and has helped make it possible to age C materials from the last 50 years with better resolution.

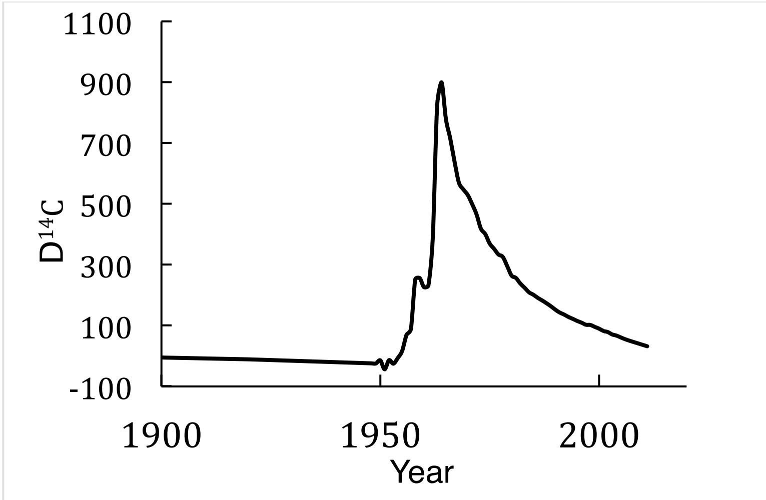

Figure 17. *Atmospheric ^{14}C abundance in the northern hemisphere, 1900-2010. The spike in ^{14}C due to thermonuclear weapons testing in the early 1960s (i.e. bomb-C) is presently declining at a rate of 4-5.5‰ per year. This makes it possible to date C that was fixed in the last fifty years to within a resolution of ± 2 years. Materials containing bomb-C have a $D^{14}C$ value >0‰, whereas pre-bomb C has a $D^{14}C$ value <0‰.*

Our next step was to examine ^{14}C abundance in CO_2 to assess its age and sources. Fig. 18 shows ^{14}C abundance in CO_2 respired from the soil surface in four plots: three that were intact, and one that was trenched on all sides to 1 m depth to cut off live roots. (The trench was lined with plastic film to prevent re-growth of roots into the plot, and then back filled with soil.) This trenched plot served to simplify the metabolic activity in the soil; normally soil CO_2 is produced by both roots and microorganisms decomposing soil C, and by cutting off roots we could observe microbial activity alone, in the absence of live roots. In both the trenched plot and the intact plot we found respired CO_2 contained more bomb-C than the atmosphere. This indicated that respired CO_2 was older than atmospheric CO_2, and had been retained in the soil for several years before being emitted. The CO_2 from the trenched plot also had more bomb-C than CO_2 from the intact plots, indicating that microbial respiration was 6 to 8 years older than total respiration from intact plots.

We also found distinct seasonal patterns in the intact and trenched plots. Over the course of the 2012 growing season the $\Delta^{14}C$ of respiration gradually decreased in the intact plots, whereas in the trenched plot it remained comparatively high (Fig. 18). By cutting off roots in the trenched plots and preventing inputs of new C to the soil, we caused respiration to contain older C than if we allowed roots to continue growing.

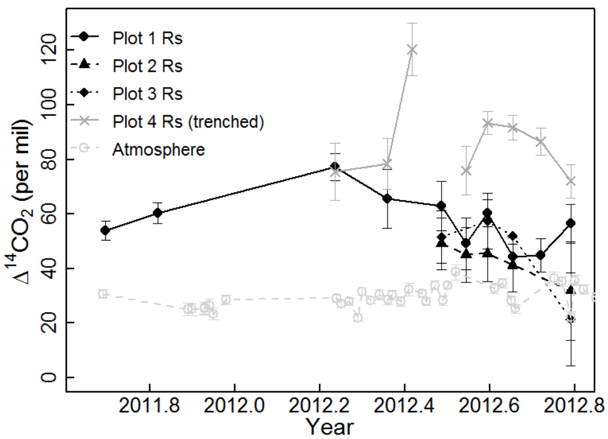

Figure 18. *Δ14CO$_2$ of soil surface flux, and atmospheric Δ14CO$_2$ (collected from the eddy covariance tower at 21 m) for the same period.*

These results suggested that under normal conditions soil respiration is heavily dominated by new C that is introduced to soil through roots, but than when roots are removed, microorganisms can switch to consuming older C. This theory was further corroborated by a laboratory test: when we picked roots out of soil and incubated them in the lab to collect the CO_2 they produced, the CO_2 contained much older C than if dead roots were left in place (Fig. 19). In the trenched plot where dead roots were left in place to decay, respired ^{14}C had a modern composition and was enriched with bomb-C throughout the profile. In contrast, when these same soils had the roots picked out and were incubated in the lab, they produced CO_2 with C hundreds to thousands of years older.

These data collected in 2011-2012 provided baseline information on the spatial and seasonal variability of soil C age. We hope to compare these baseline data to measurements following thinning, and anticipate that removing trees could cause a pulse of older soil C to be released, as microorganisms switch from consuming root-derived, new C to older soil C. Pre- and post-thinning comparisons will be important for advising policy makers on the impacts of thinning on long-term forest C storage.

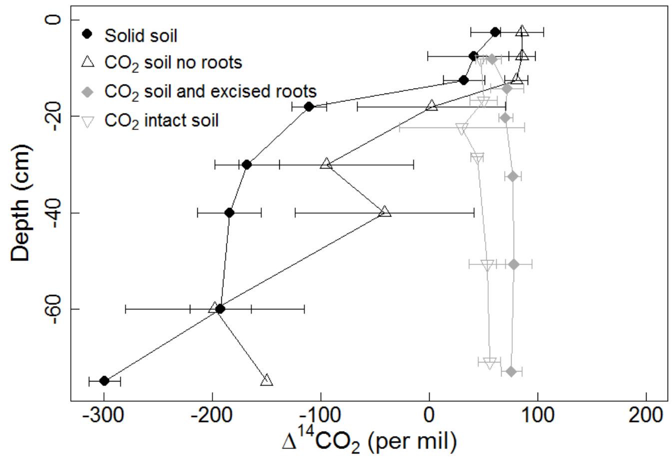

***Figure 19**. $\Delta^{14}C$ of bulk solid soil, CO_2 respired from same soil in laboratory incubations (no roots present), soil air CO_2 from trenched plot (dead roots left in place), and soil air CO_2 from intact soil plots (live roots present). Incubated soils had similar ^{14}C profiles as solid soil, with a positive bias that reflects microorganisms' preference for younger materials within the bulk soil. CO_2 collected from the trenched plot had higher ^{14}C abundance than lab incubations and contained bomb-C, likely due to the presence of decaying roots. CO_2 collected from intact plots had less bomb-C than the trenched plot, which reflects new C inputs from roots.*

Simulated harvest type affects long-term forest carbon accumulation

A primary activity of this project was to observe the effects of harvest disturbance on the carbon cycle to improve computer simulations of this, as a tool to understand management and policy decisions regarding carbon sequestration. While the observational post-harvest component of the experiment has been delayed to 2013-2014, that does not prevent us from considering several options for model simulation and initial model parameterization.

Initially, the project focused on collaboration with Prof. David Mladenoff at the University of Wisconsin on their well-established LANDIS-II forest demography model. The model can well simulate the successional trajectory of northern hardwood forests (Fig. 20) and has recently been coupled to a belowground carbon cycle component. In our experiment, we investigated the relative sensitivity of the carbon cycle in LANDIS-II to CO_2 fertilization on primary productivity, changes in disturbance frequency (to simulate changes in rotation interval), and changes of temperature on decomposition rates. Surprisingly, relative changes in each had nearly equivalent effects on carbon uptake, and these effects were independent and linear (Fig. 21). These results do suggest that increases in harvest intervals could be used to enhance carbon sinks on top of any enhancement of sinks by increasing atmospheric CO_2 or counterbalance declines in carbon sequestration form increased respiration. However, the model does require continued evaluation by observation.

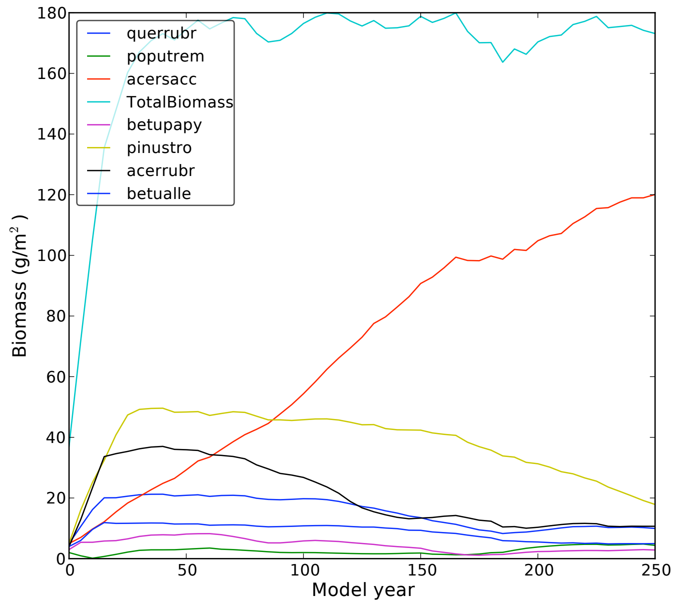

Figure 20. Relative biomass abundance of tree species after disturbance in the study site by age as simulated by LANDIS-II. Early successional species are eventually replaced by sugar maple (Acer sacc.), leading to a maximum attainable biomass after 75 years.

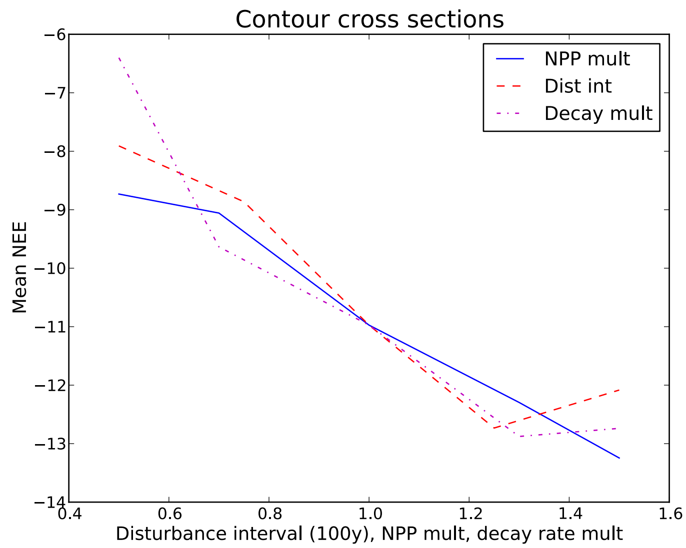

Figure 21. Relative response of CO2 fertilization (blue line, represented as a multiplier on net primary production), rotation interval (red dashed line, represented as a multiplier on disturbance interval), and decomposition rate (red dotted line, reversed to be overlaid with the other two) on net ecosystem exchange in the forest system simulated in Fig. 20.

Recently, post-doctoral scholar Dong Hua has developed a simpler and faster simulation of the core carbon cycle component of the forest succession model with an eye toward long run simulations across an ensemble of harvest types. In these simulations, information about forest management prescriptions from the Park Falls hardwood project have been incorporated into the model. A sample run (Fig. 22) reveals that the long-term carbon cycle consequences of clear cut versus two types of planned partial harvesting with similar rotation intervals is relatively minimal with respect to net carbon exchange. However, during the harvest intervals, partial harvesting increases carbon sequestration in the model. Also, differences appear by harvest type in total biomass, nitrogen retention, and other factors. These results are currently being synthesized into a manuscript for publication (Hua *et al*., in preparation).

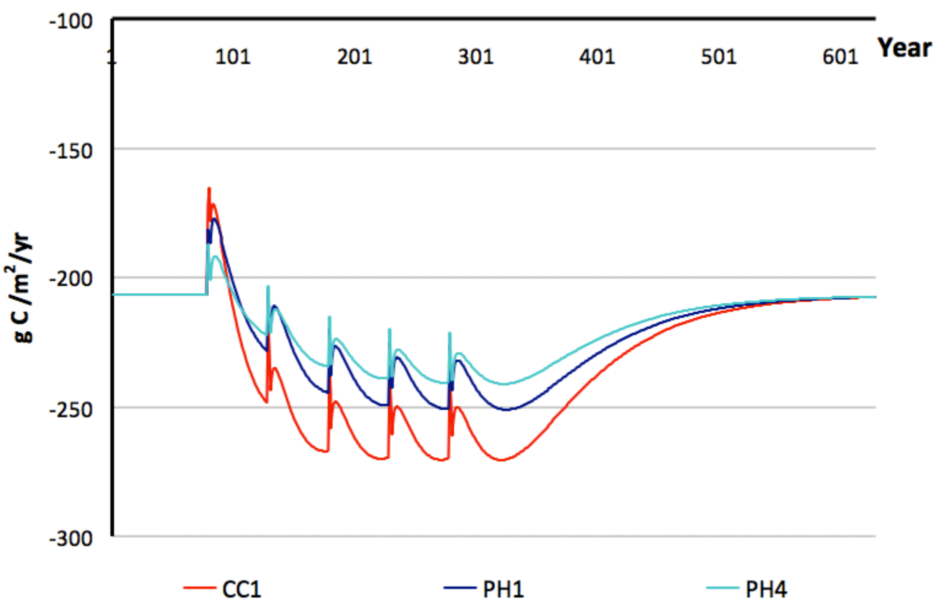

Figure 22. *Net carbon exchange (negative implies sequestration) for clear cut (CC1) and two partial harvesting scenarios (PH1 and PH4) for a 50 year rotation cycle over a 600 year run. After year 300, harvesting is stopped and in all three cases, net carbon exchange returns to a similar state, though with different time constants.*

Regional and global efforts are underway to better incorporate carbon management

The final goal of this project was to coordinate scientists and forest managers in Wisconsin to better discuss how scientific findings on carbon cycle can be incorporated into forest planning and similarly how detailed planning decisions can be better incorporated into scientific assessment and models. Since the study site was in the Chequamegon-Nicolet National Forest, the project team has worked closely with the forest in discussing the flux tower. The Park Falls hardwood scoping and analysis documents specifically included discussion of the Willow Creek site as an experimental research area to understand carbon management for forest harvesting (http://www.fs.usda.gov/projects/cnnf/landmanagement/projects). We also have held a discussion and tour with a national group of forest planners at the U.S. Forest Service, Region 9 EMS Planning, Appeals, and Litigation Meeting on 19 May 2010. Also, the PI has conducted outreach programs with the College of Menominee Nation, including talks and flux tower tours to discuss sustainable forestry.

The lead PI, Desai, is also a member of the Chequamegon-Nicolet National Forest Climate Change Science Roundtable and has participated in the Climate Change Science Mitigation and Adaptation Needs Workshop, Madison, WI, Apr. 27-28, 2010, which led to a report published by USFS Northern Institute of Applied Climate Science (NIACS), http://www.nrs.fs.fed.us/niacs/climate/. Recently, NIACS has initiated teleconferences on forest climate adaptation and mitigation, in which Desai participates.

The largest coordination activity occurred in 2012 for the Chequamegon Ecosystem-Atmosphere Study Workshop: Observing and simulating carbon cycle impacts of forest management and climate variability in heterogeneous landscapes, http://flux.aos.wisc.edu/twiki/bin/view/Main/ChEASMeeting2012

Researchers and foresters both locally and nationally (Table 2) met in northern Wisconsin, discussed state of the science through a series of short talks, focused discussion topics, and field trips. The workshops focused on identifying key uncertainties in carbon cycle science for forest management and included: “Remote sensing of land management, disturbance, and ecosystem properties”, “Challenges in ecosystem modeling and model-data fusion”, “Characterizing observational and model uncertainty”, “Understanding drivers and patterns of land management in the region”, and “Dealing with in situ observations of carbon cycle components in models”. A number of cross-cutting activities have occurred since, including training on use of USFS geographic information system (GIS) resources, development of satellite and airborne remote sensing data cutouts for the study sites, and an ecosystem model intercomparison.

Table 2. List of attendees of the ChEAS 2012 workshop

NAME	AFFILILATION
Ankur Desai	University of Wisconsin
Erika Marin-Spiotta	University of Wisconsin
Linda Parker	USFS CNNF
Claire Phillips	DOE LLNL
Mike Dietze	UIUC / BU
Shawn Serbin	UIUC
Bjorn Brooks	UIUC
Peter Curtis	Ohio State
Aditya Singh	University of Wisconsin
Alex Fotis	Ohio State
Bruce Cook	NASA GSFC
Erica Smithwick	Penn State
Doug Baldwin	Penn State
Kusum Naithani	Penn State
Robert Kennedy	Oregon State
Ken Davis	Penn State
Jonathan Thom	University of Wisconsin
Dong Hua	University of Wisconsin
Mark Kubiske	US Forest Service
Seyed Hossein Kia	Penn State / U. Southampton

Recommendations

The carbon sequestration capacity of Wisconsin's forests is a major natural asset in the state. How government agencies and private property owners manage these forests can impact this capacity. This project intensively measured the carbon sequestration capacity of a typical mature northern hardwood forest and assessed the impacts of forest management on its long-term sequestration capacity. The importance of this study is in how it addresses the relative lack of strong observational evidence for total net carbon uptake rates, including productivity and decomposition. Observations provide the base to parameterize and evaluate predictive simulation models of how forest harvesting practices can influence carbon sequestration and forest ecosystem response to climate change.

The study thus affords an opportunity to consider both climate change mitigation and adaptation options for Wisconsin ecosystems. Regardless of the energy choices made by Wisconsin, environmental impacts attributable to fossil fuel use will lead to consequences for forest ecosystems and requires research to improve policy options and management decisions for forest planning.

The proposal was written to be responsive to the request for proposal component "Environmental and Economic Impacts of Climate Change in Wisconsin Potentially Attributable to Electric or Natural Gas Use", specifically to "understand the flux of carbon within Wisconsin's environment, and the ramifications of this understanding for policy development"

We conducted a long-term observational and modeling study of carbon fluxes immediately preceding a forest harvest to establish the baseline carbon sequestration capacity of Wisconsin forests. Our research study site, part of the Chequamegon Ecosystem-Atmosphere Study, has led to many peer-reviewed publications, presentations, and public outreach to further this goal. In summary, our major findings are:

- Many of the mature temperate northern hardwood forests of Northern Wisconsin are at a peak for net carbon exchange and sequester more carbon on a per area basis then wetland, grassland, and lake ecosystems in the region.

- However, these large carbon sinks are moderately sensitive to climate variability. Extensions in the growing season length have counteracting effects on net carbon uptake. While earlier springs increase net carbon uptake and can counterbalance the effect of summer droughts, later autumns tend to decrease net uptake by extending the period of decomposition and respiratory processes. Additionally, the forest is also surprisingly sensitive to moisture deficits.

- Soil respiration is dominated by newly photosynthesized carbon that is introduced to soil through roots, but when roots are removed, microorganisms can switch to consuming older carbon. Consequently, we anticipate that removing trees could cause a pulse of older soil carbon to be released, as microorganisms switch from consuming root-derived, new carbon to older soil carbon.

- Partial and selective harvesting with moderate rotation intervals can enhance net carbon uptake in the ecosystem compared to more intensive harvesting, while maintaining steady carbon export from productive forests. Over the very long period, model simulations suggests that forest ecosystems are relatively insensitive to harvest type with respect to equilibrium carbon uptake after cessation of harvesting. However, the time to recovery is longer with intensive harvesting.

- Changes in harvest intervals could be used to enhance carbon sinks on top of any enhancement of sinks that may arise from increasing atmospheric CO_2 or counterbalance declines in carbon sequestration form increased respiration in warmer climates. Large uncertainty in parameters requires that these models be confronted with intensive evaluation by observation.

Pre- and post-thinning comparisons will be important for advising policy makers on the impacts of thinning on long-term forest C storage. However, the observation, modeling, and coordination components of the project to date already leads to several policy implications:

- Carbon mitigation in northern Wisconsin forest ecosystems through enhanced sequestration is viable, but this sink is expected to decline with increasing age of the region's forests beyond their peak period of uptake.

- These forests are climate sensitive, and forest management that emphasizes climate adaptation, specifically to changes in autumn climate and summer drought, is warranted.

- Shifts in the type soil carbon respired may be significant with forest harvesting and methods for soil carbon stabilization during harvest need to be considered.

- Focused workshops, data sharing, and model comparisons jointly with forest managers and scientists can significantly improve the scientific basis for forest management for carbon in a changing climate.

We emphasize that enhancing carbon sequestration by forest management is not a silver bullet. The magnitude of fossil fuel emissions in Wisconsin far exceeds the total carbon sink capacity of northern Wisconsin forests. Further, climate changes have been shown here to strongly influence the magnitude of this carbon sink. This project was not focused on harvest exports, economic decision-making, or policy scenarios. Instead, the primary conclusion here is that observations in this forest support that carbon sequestration is viable, has strong climate sensitivity, and will respond in numerous ways to harvest. As the selection harvest occurs in Willow Creek, Wisconsin, additional continued observation, with new funding from the Dept of Energy, will allow us to refine the conclusions noted above.

List of Acronyms

CCRF	Climate Change Response Framework
CENTURY	Century Soil biogeochemistry model
ChEAS	Chequamegon Ecosystem-Atmosphere Study
CNNF	Chequamegon-Nicolet National Forest
DOE	U.S. Dept of Energy
ER	Ecosystem Respiration
GIS	Geographic Information System
GPP	Gross Primary Production
H	Sensible heat flux
LANDIS	Landis-II Forest demography and ecosystem model
LE	Latent heat of evapotranspiration flux
LLNL	Lawrence Livermore National Laboratory
NEE	Net Ecosystem Exchange of CO_2
NEP	Net Ecosystem Production of CO_2
NIACS	Northern Institute of Applied Climate Sciences
PI	Principal Investigator
US-WCr	Willow Creek, Wisconsin Ameriflux site
USDA	U.S. Dept of Agriculture
USFS	U.S. Forest Service

Works Cited

Amiro, B., Barr, A.G., Barr, J.G., Black, T.A., Bracho, R., Brown, M., Chen, J., Clark, K.L., Davis, K.J., Desai, A.R., Dore, S., Engel, V., Fuentes, J.D., Goldstein, A.H., Goulden, M.L., Kolb, T.E., Lavigne, M.B., Law, B.E., Margolis, H.A., Martin, T., McCaughey , J.H., Misson, L., Montes-Helu, M., Noormets, A., Randerson, J.T., Starr, G., and Xiao, J., 2010. Ecosystem carbon dioxide fluxes after disturbance in forests of North America. *Journal of Geophysical Research-Biogeosciences*, 115, G00K02 , doi:10.1029/2010JG001390.

Baldocchi, D., 2008. 'Breathing'of the terrestrial biosphere: lessons learned from a global network of carbon dioxide flux measurement systems. *Australian J Botany*, 56:1-26.

Blonquist, J.M., Montzka, S.A., Munger, J.W., Yakir, D., Desai, A.R., Dragoni, D., Griffis, T.J.,Monson, R.K., Scott, R.L., and Bowling, D.R., 2011. The potential of carbonyl sulfide as a tracer for gross primary productivity at flux tower sites. *Journal of Geophysical Research-Biogeosciences*, 116, G04019, doi:10.1029/2011JG001723.

Bonan, G.B., 2008. Forests and Climate Change: Forcings, Feedbacks, and the Climate Benefits of Forests. *Science*, 320:1444-1449, doi:10.1126/science.1155121.

Buffam, I., Turner, M.G., Desai, A.R., Hanson, P., Rusak, J., Lottig, N.R., Stanley, E.H., and Carpenter, S.R., 2011. Integrating aquatic and terrestrial components to construct a complete carbon budget for a north temperate lake district. *Global Change Biology*, 17(2): 1193-1211, doi:10.1111/j.1365-2486.2010.02313.x.

Cook, B.D., Bolstad, P.V., Martin, J.G., Heinsch, F.A., Davis, K.J., Wang, W., Desai, A.R., and Teclaw, R.M., 2008. Using light-use and production efficiency models to predict forest production and carbon exchange during canopy disturbance events, *Ecosystems*, 11: 26-44, doi:10.1007/s10021-007-9105-0.

Cook, B.D., Davis, K.J., Wang, W., Desai, A.R., Berger, B.W., Teclaw, R.M., Martin, J.G., Bolstad, P.V., Bakwin, P.S., Yi, C., and Heilman, W., 2004. Carbon exchange and venting anomalies in an upland deciduous forest in northern Wisconsin, USA. *Agricultural and Forest Meteorology*, 126(3-4): 271-295, doi:10.1016/j.agrformet.2004.06.008.

Desai, A.R., 2013. Influence and predictive capacity of climate anomalies on daily to decadal extremes in canopy photosynthesis. *Photosynthesis Research*, doi:10.1007/s11120-013-9925-z, in press.

Desai, A.R., Bolstad, P.V., Cook, B.D., Davis, K.J., and Carey, E.V., 2005. Comparing net ecosystem exchange of carbon dioxide between an old-growth and mature forest in the upper Midwest, USA. *Agricultural and Forest Meteorology,* 128(1-2): 33-55, doi:10.1016/j.agrformet.2004.09.005.

Hicke, J.A., Allen, C.D., Desai, A.R., Dietze, M., Hall, R., Hogg, E.T., Kashian, D., Moore, D., Raffa, K., Sturrock, R., and Vogelmann, J., 2012. Effects of biotic disturbances on forest carbon cycling in the United States and Canada. *Global Change Biology*, 18, 7-34,doi:10.1111/j.1365-2486.2011.02543.x.

Hua, D., Desai, A.R., in prep. Simulating the Impacts of Woody Biomass Harvesting on North Temperate Forest Carbon and Nitrogen Cycling and Storage, *Forest Ecology and Management*

Le Quéré, C., *et al*., 2012. The global carbon budget 1959–2011, *Earth Syst. Sci. Data*, 5, 165-185, doi:10.5194/essd-5-165-2013

Niu, S., *et al*., 2012. Thermal optimality of net ecosystem exchange of carbon dioxide and underlying mechanisms. *New Phytologist*, 194(3), 775-783, doi:10.1111/j.1469-8137.2012.04095.x.

Phillips, C., McFarlane , K.J., Risk, D., and Desai, A.R., 2013. Biological and physical influences on soil 14CO2 seasonal dynamics in a temperate hardwood forest. *Biogeosciences*, 10, 7999-8012, doi:10.5194/bg-10-7999-2013.

Richardson, A.R., Anderson, R.S., Altaf Arain, M., Barr, A.G., Bohrer, G., Chen, G., Chen, J.M., Ciais, P., Davis, K.J., Desai, A.R., Dietze, M.C., Dragoni, D., Garrity, S., Gough, C.M., Grant, R., Hollinger, D.Y., Margolis, H.A., McCaughey , H., Migliavacca, M., Monson, R.K., Munger, J.W., Poulter, B., Raczka, B.M., Ricciuto, D.M., Sahoo, A., Schaefer, K., Tian, H., Vargas, R., Verbeeck, H., Xiao, J., and Xue, Y., 2012. Terrestrial biosphere models need better representation of vegetation phenology: results from the North American Carbon Program Site Synthesis. *Global Change Biology*, 18(2), 566-584, doi:10.1111/j.1365-2486.2011.02562.x.

Schaefer, K. *et al*., 2012. A model-data comparison of gross primary productivity: Results from the North American Carbon Program Site Synthesis. *J. Geophys. Res.*, 117, G03010, doi:10.1029/2012JG001960.

Shen, M., Tang, Y., Richardson, A., Chen, J., and Desai, A.R., 2012. Evaluation of MODIS land surface phenology using phenology of canopy photosynthesis derived from AmeriFlux . *International Journal of Remote Sensing*, #TRES-PAP-2012-0429, submitted.

Sprintsin, M., Chen, J.M., Desai, A.R., and Gough, C.M., 2012. Evaluation of leaf-to-canopy upscaling methodologies against carbon flux data in North America. *Journal of Geophysical Research-Biogeosciences,* 117, G01023, doi:10.1029/2010JG001407.

Sulman, B.N., A.R. Desai, and R.M Scheller, 2010: Sensitivity of regional forest carbon budgets to continuous and stochastic climate change pressures, American Geophysical Union Fall Meeting, Abstract B42B -06, San Francisco, CA, Dec 13-17, 2010.

Tang, X., Wang, Z., Desai, A.R., Jia, M., Dong, Z., Liu, X., and Liu, B., 2013. Monitoring the seasonal and interannual variation of the carbon sequestration in a temperate deciduous forest with MODIS time series data: A novel approach. *Forest Ecology and Management*, 306, 150-160, doi:10.1016/j.foreco.2013.06.032.

Tang, X., Wang, Z., Liu, D., Song, K., Jia, M., Dong, Z., Munger, J.W., Hollinger, D.Y., Bolstad, P.V., Goldstein, A.H., Desai, A.R., Dragoni, D., and Liu, X., 2012. Estimating the net ecosystem exchange for the major forests in the northern United States by integrating MODIS and AmeriFlux data. *Agricultural and Forest Meteorology*, 156, 75-84, doi:10.1016/j.agrformet.2012.01.003

Wolf, S. *et al*., 2013. Carbon cycle impacts of the 2012 Drought. In preparation.

Wu, C., Chen, J. M., Black, T. A., Price, D. T., Kurz, W. A., Desai, A. R., Gonsamo, A., Jassal, R. S., Gough, C. M., Bohrer, G., Dragoni, D., Herbst, M., Gielen, B., Berninger, F., Vesala, T., Mammarella, I., Pilegaard, K. and Blanken, P. D., 2013. Interannual variability of net ecosystem productivity in forests is explained by carbon flux phenology in autumn. *Global Ecology and Biogeography*, doi:10.1111/geb.12044, in press.

Wu, C.,Chen, J.M., Desai., A.R., LaFleur , P.M., and Verma, S.B., 2013. Positive impacts of precipitation intensity on monthly CO2 fluxes in North America. *Global and Planetary Change*, 100, 204-214, doi:10.1016/j.gloplacha.2012.10.019.

Yuan, W., Luo, Y., Liang, S., Yu, G., Niu, S., Stoy, P., Chen, J., Desai, A.R., Lindroth, A., Gough, C., Ceulemans, R., Arain, A., Bernhofer, C., Cook, B.D., Cook, D.R., Dragoni, D., Gielen, B., Janssens, I., Longdoz, B., Liu, H., Lund, M., Matteucci, G., Moors, E., Scott, R.L., Seufert, G., and Varner, R., 2011. Thermal adaptation of net ecosystem exchange. *Biogeosciences*, 8, 1453-1463, doi:10.5194/bg-8-1453-2011.