Cover page

Final Report for the Project DE-FG02-03ER63640

Title: Understanding the Influences of Seasonality and Interannual Variability on Biosphere-Atmosphere $^{13}CO_2$ Exchange

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1.0 Executive Summary

The carbon isotope ratios of carbon dioxide fluxes from terrestrial ecosystems are key measurements needed to constrain interpretations of carbon sinks in North American carbon cycle analyses. The completed research was a multi-faceted effort addressing photosynthetic and respiratory isotope exchanges across the biosphere-atmosphere boundary at five AmeriFlux sites (Harvard Forest, Howland Forest, Rannalls Ranch, Niwot Ridge Forest, and Wind River Crane Site), spanning the dominant ecosystem types of the United States. The sampling and analysis protocols developed in this project have become the fundamental analytical approach for all sites measuring ecosystem isotope studies across the United States and Canada. It is the first network of long-term observations to characterize the isotopic composition of the biosphere-atmosphere CO_2 flux. We focused on understanding the magnitude of changes in the carbon isotope ratio of respiration and of photosynthetic discrimination on seasonal and interannual bases. Focusing at AmeriFlux sites provided a direct link to NEE measurements associated with studies of the North American carbon cycle and an opportunity to provide mechanistic insights relating observed isotope changes and the controls over carbon sequestration and loss on seasonal and interannual bases. An additional component of our research linked directly with eddy covariance monitoring to partition NEE into assimilation and respiratory components. The completed project promoted cross-site analyses and resulting publications applicable at AmeriFlux and other long-term carbon cycle research sites. Lastly, the online monitoring of carbon dioxide in the Salt Lake Valley and the intermittent monitoring of absolute carbon dioxide concentrations at different AmeriFlux sites contributed public awareness and data sets that can be used in public education and as a basis for public policies related to carbon dioxide.

2.0 Accomplishments of the Project

2.1 Relationship of the completed project to DOE carbon cycle research goals

Stable isotope ratios (δ) of CO_2 are recognized as a key element in improving our interpretations of the carbon cycle at the ecosystem, regional, and global scales. The $\delta^{13}C$ and $\delta^{18}O$ values of CO_2 have been critical measurements in the global CO_2 flask network for over a decade, where these data are essential in partitioning fluxes within the global carbon cycle. Stable isotope analyses are integrated into regional and ecosystem carbon cycle studies, because photosynthesis and respiration have large and opposite impacts on diurnal and seasonal patterns on CO_2 concentration and isotope ratios. This isotopic variation contains information about the functioning of different terrestrial ecosystems and is filtered out in a flask network that is largely focused at marine sampling sites. The U.S. Carbon Cycle Science Plan (1999) recognized the need to expand atmospheric monitoring over terrestrial surfaces and the need to have a stronger characterization of the isotopic composition of CO_2 in terrestrial biosphere-atmosphere exchange. In that regard, the Terrestrial Carbon Processes (TCP) Program specifically identifies the need to "... obtain isotopic data that pinpoints source and seasonality of CO_2 fluxes". Our project directly addresses the isotope needs identified by both the U.S. Carbon Cycle Science Plan and the TCP Program. In addition, the TCP Program calls for research at the AmeriFlux sites, thereby bringing together many facets of carbon cycle research to common locations.

This proposal incorporates stable isotope measurements at six AmeriFlux sites, spanning C_3/C_4 dominated ecosystems and coniferous/deciduous forests. We will focus on the influences of seasonality and interannual variation on the isotopic composition of atmospheric CO_2 exchange between the biosphere and the atmosphere. We propose also to use isotopic methods to partition net ecosystem exchange (NEE) into photosynthetic and respiratory components, providing a complementary approach which is independent of other partitioning methods.

We propose further integration of the existing isotope ratio studies at other AmeriFlux sites that are part of the Biosphere Atmosphere Stable Isotope Network (BASIN), providing a basis for AmeriFlux cross-site comparisons. Site-based studies are particularly useful for understanding functioning of individual ecosystems, but a cross-site integration is a key element in assessing any continental or global effect. BASIN provides a mechanism for data sharing and a platform for linking site-based and planetary boundary layer carbon cycle efforts.

The TCP products derived from this proposed research will include (a) a continent-scale map of the $\delta^{13}C$ of ecosystem respiration and photosynthetic discrimination, (b) an understanding of how seasonal and interannual changes in the environment influence these two parameters that contribute to both ecosystem- and continental-scale carbon cycle modeling, and (c) an improved understanding of NEE partitioning and of the autotrophic versus heterotrophic contributions to ecosystem respiration.

2.2 Tasks Proposed and Completed

Task 1 - Monitoring $\delta^{13}C$ of CO_2 exchange with the atmosphere

If the carbon isotope ratio of ecosystem respiration ($\delta^{13}C_R$) and of photosynthetic discrimination (Δ_{eco}) are not constant, what is the magnitude of these variations on seasonal and interannual bases? What is the role of weather variation on these values? Which ecosystems exhibit a strong seasonal signal and should receive more attention and which ecosystems exhibit limited ^{13}C variation? How different is the seasonal variation in organic matter versus the atmospheric ^{13}C moving between the biosphere and the atmosphere?

These questions were addressed as initially proposed by monitoring the $\delta^{13}C$ of CO_2 within canopies using our established atmospheric air sampling systems (Schauer et al., 2003a) in place at each of the 5 sites. Based on $\delta^{13}C$ data, $\delta^{13}C_R$ and daytime $\delta^{13}C_{a-o}$ values exhibited strong seasonal dynamics that reflect changes in stomatal limitations at the leaf level in response to variations in sunlight and vapor pressure deficit. With weekly atmospheric sampling during the growing season and monthly during the winter, we had sufficient data to calculate $\delta^{13}C_R$ and Δ_{eco}. We maintained a very good working relationship with onsite personnel to ship flasks biweekly and maintain autosamplers.

Flasks were analyzed at our Utah lab (SIRFER) for the $\delta^{13}C$, $\delta^{18}O$, and concentration of CO_2, as originally proposed The precision of our analyses were ± 0.02 ‰ for $\delta^{13}C$, ± 0.03 ‰ for $\delta^{18}O$, and ± 0.2 ppm for [CO_2] (Schauer et al., 2003b) using a Finnigan MAT XL operated in CF mode in conjunction with our manifold and GC. All CO_2 gas standards were calibrated against NOAA-CMDL standards.

From these near continuous data, we looked for changes in $\delta^{13}C_R$ and Δ_{eco} that are related to changes in water availability (precipitation, plant water potential, transpiration rates) and changes in community structure (LAI development, understory and overstory development) and NEE. We linked these isotope data with NEE data from the AmeriFlux sites for calculations of *iso*fluxes and partitioning the assimilation and respiratory fluxes. We maintained a very good working relationships with the AmeriFlux PIs at each site and with technical assistance at each site.

Task 2 – Dissecting $\delta^{13}C_R$ into above- and belowground components

The isotope ratio of ecosystem respiration ($\delta^{13}C_R$) is composed of two components: CO_2 effluxing from the soil and CO_2 effluxing from aboveground vegetation, each of which has different turnover rates and therefore responds to current climatic conditions differently:

$$\delta^{13}C_R = \delta^{13}C_{R\text{-canopy}}(f) + \delta^{13}C_{R\text{-soil}}(1 - f) \, , \qquad (8)$$

where the subscripts R-canopy and R-soil refer to aboveground (stem and leaf) canopy and belowground soil respiration components, respectively, and f represents the fraction of the total respiratory flux coming from aboveground canopy sources.

We examined the difference between $\delta^{13}C_{R\text{-canopy}}$ and $\delta^{13}C_{R\text{-soil}}$ fluxes by separate measurements of the two components. A closed, soil-respiration chamber placed over the soil accumulated CO_2 over a period of minutes. Repeated sample collection of CO_2 into flasks were used to reconstruct a Keeling curve as is typically done for $\delta^{13}C_R$ (Flanagan et al., 1999; Ometto et al., 2002). These measurements provided a direct measure of the disequilibrium between aboveground and soil ^{13}C respiratory fluxes. These measurements allowed us to better understand timing in the short-term substrate-input sensitivity of ^{13}C soil respiration.

Task 3 - Modeling of canopy CO_2 fluxes and discrimination

Modeling efforts were carried out in the current study, using existing mathematical models. A biophysical canopy gas exchange model (Lai et al. 2000) was modified to include calculations of photosynthetic discrimination based on knowledge of leaf-level plant physiology. The current version of the model include a second order closure model to characterize the velocity statistics inside plant canopies, providing sufficient information to describe scalar transport within the canopy. The model showed reasonable agreement in predicting CO_2, latent and sensible heat fluxes above the canopy and CO_2 concentration gradient inside the canopy. By adding the isotopic fractionation principles and our understanding of physiological and environmental controls on the dynamics of isotopic discrimination, we used the model to predict the $\delta^{13}C$ and $\delta^{18}O$ in the canopy air and to predict temporal variations in Δ during photosynthesis. Modeled Δ values were used in the partitioning of season-long NEE flux measurements into photosynthetic and respiratory components. Our $\delta^{13}C_{i\text{-}o}$, $\delta^{13}C_R$ and Δ_{eco} measurements were used directly to validate model calculations. Model inputs (leaf area density profile, mean wind speed, photosynthetically active radiation, air temperature and humidity) were supplied from the ecological and meteorological database managed by the site PIs.

3.0 Project Activities

3.1 Hypotheses

(a) The isotope ratio of ecosystem respiration will vary among ecosystem types on both a geographical and temporal basis.

(b) The isotope ratio of ecosystem respiration will be dependent on environmental water status, described either as atmospheric vapor pressure deficits of soil moisture content.

(c) The midday levels of atmospheric carbon dioxide measured over an annual basis can be used through inversions to calculate region ecosystem-level fluxes.

3.2 Approaches

Field flask collection for the measurement of $\delta^{13}C_{a-i}$ and $[CO_2]_{a-i}$ in canopy air. We collected dry atmospheric air from different heights into 100-ml flasks using an automated sampling system at each of the 6 AmeriFlux sites. CO_2 from canopy air is collected for isotopic analyses ($\delta^{13}C_{a-i}$, $\delta^{18}O_{a-i}$) at 2 heights within and 1 height at the top of the vegetation canopy ($\delta^{13}C_{a-o}$, $\delta^{18}O_{a-o}$). Air was sampled through Dekoron (Saint Gobain Performance Plastics) tubing attached to the eddy-covariance towers already established at the sites.

The field flask collection system consisted of 2 coupled elements: an automated measurement and control component and a flask-solenoid component. The system was designed to fill (a) 10 flasks at selected periods through the night that will be used for $\delta^{13}C_R$ analyses and (b) 5 flasks at selected periods during a 2-day period to be used for Δ_{eco} analyses. Technical assistance is required only once weekly at each of the AmeriFlux sites to (a) install new flasks and switch out flasks after they have been filled and (b) replace magnesium perchlorate and reference gas.

A data logger (CR23X, Campbell Scientific) was used to control (a) solenoids for atmospheric inlet selection, (b) a multi-position trapping flow path valve (Valco Instruments Inc.) for sample flask selection and isolation, (c) a pump, and (d) to measure the output from an infrared gas analyzer (Li-800, Li-Cor Inc) (Schauer et al., 2003a). The infrared gas analyzer was coupled to the datalogger to provide a rough estimate of the atmospheric $[CO_2]$ (precision of 3-10 ppm). Only approximate $[CO_2]$ are needed in the field as accurate $[CO_2]$ measurements occur back in the laboratory. Using either AC or DC power, air is drawn through the tubing at a flow rate of 25 ml/s and dried using magnesium perchlorate.

Once the nighttime air samples have been collected, the datalogger is directed to collection of daytime air samples from the top of the canopy over the next 2 days. The first day's sampling will be at 9, 11, and 13 hours solar time. The second day's sampling will occur at 12 and 14 hours solar time. Dried air from the top of the canopy will first pass through a 2-liter buffer so that the 100-ml flask contains an integrated measure of atmospheric [CO_2] over the previous 15-minute period. These daytime samples will be used in calculations of Δ_{eco}.

Field collection and measurement of $\delta^{13}C_{R\text{-}soil}$. Soil respiration rates are measured with a Licor Photosynthesis System (LI-6200) and soil cuvette, operating in a closed-loop mode and with a minimal pressure gradient between the chamber and outside. We use a plexiglass cuvette which covers 0.37 m^2 soil surface in place of the standard Licor soil-respiration chamber in order to (i) increase the sample area, (ii) reduce heterogeneity associated with patchy root distributions, and (iii) reduce chamber-edge effects. The chamber has a total volume of 100 L.

A precise estimate of the isotope ratio of soil respiration ($\delta^{13}C_{R\text{-}soil}$) is essential for partitioning $\delta^{13}C_R$ into above- and below-ground components. Analyzing soil organic matter (SOM) is not a satisfactory approach to estimating $\delta^{13}C_{R\text{-}soil}$ because the fluxes of CO_2 from microbial components decomposing SOM and root respiration need not be the same as overall mass, especially since a fraction of the soil carbon is recalcitrant (Ehleringer et al., 2000). Minimizing disruption of the soil [CO_2] and soil δ profiles during a soil respiration measurement reduces errors in the estimate of $\delta^{13}C_{R\text{-}soil}$.

Following a soil respiration measurement, the chamber will be opened to equilibrate with atmospheric air. The cuvette top will then be closed to allow CO_2 levels to slowly increase as soil respiration continues. A series of 100-ml evacuated flasks will be attached to the soil cuvette. As the [CO_2] rises, dry air is subsampled 7 times sequentially at 40 ppm [CO_2] intervals between 370 and 650 ppmV, each time filling a separate flask. The flask volume is small relative to the chamber volume, resulting in negligible changes in overall pressure within the system. These 100-ml flasks are then shipped back to SIRFER at the University of Utah for stable isotope analyses. From the sequence of 7 carbon isotope ratios and concentration values (measured and analyzed as described above), we will calculate $\delta^{13}C_{R\text{-}soil}$ from a Keeling-plot analysis. Using this approach, one obtains high-precision estimates of $\delta^{13}C_{R\text{-}soil}$ that are not influenced by air pressure or concentration errors associated with introducing atmospheric gas concentrations that deviate significantly from normal background values (and thus influence diffusion rates).

Field collection and laboratory measurement of $\delta^{13}C_p$. Sun-lit leaves will be collected, dried and ground to a homogeneous mixture. A 2-mg subsample will be combusted to produce CO_2 using an elemental analyzer coupled to a delta S isotope ratio mass spectrometer in the SIRFER facility (Ehleringer, 1991). The same procedure will be used for acid-washed litter and soil organic analyses after they have been subdivided by layers.

3.3 Key personnel involved

Principal Investigator: James Ehleringer
Postdoctoral investigator: Chun-Ta lai
Technician: Andrew Schauer
Undergraduate: Timothy Jackson

3.3 Problems encountered

None

3.4 Component studies

We have made significant progress during the first five years of our two DOE TCP awards. The long-term $\delta^{13}C$, $\delta^{18}O$, and mixing ratio observations of CO_2 have been extremely useful, revealing patterns that are clear on an interannual basis, but would not be evident with only a single year of sampling. We highlight several key progresses here by summarizing results that contribute to our understanding of terrestrial carbon processes from ecosystem to regional to global scales, including (a) development and construction of automated trace gas samplers and their installation at 7 AmeriFlux sites, (b) development of a new automated analytical method for high-precision CO_2 isotope ratio and concentration measurements with an isotope ratio mass spectrometer in continuous flow mode (GC-IRMS), (c) weekly flask measurements at 7 AmeriFlux sites, providing a database with longest records of $\delta^{13}CO_2$ exchange linking NEE measurements since 2001, (d) disclosure of multi-seasonal and interannual variability of $\delta^{13}CO_2$ signature in the US major biomes, (e) identification of key environmental drivers that influence carbon isotopic composition of CO_2 fluxes, (f) separation of NEE into photosynthetic and respiratory components (g) inferring regional CO_2 fluxes from daytime mixing ratio data, and (h) providing constraints for global carbon models. 17 manuscripts have been published, are in press, in review or in preparation related to our research during the current funding period. These manuscripts are noted with an asterisk in the literature-cited section.

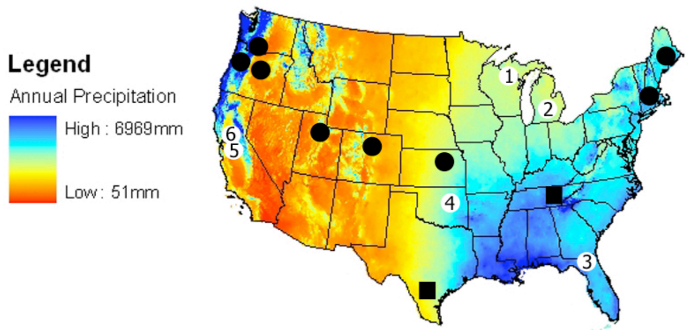

Figure 1. AmeriFlux sites with ongoing flask-based isotope measurements for Keeling plot analysis. Color shading shows spatial gradients of total annual precipitation for the US. Solid circles indicate our proposed study sites. Squares indicate two southeast sites separately proposed by Lai for NICCR support, and open circles indicate studies conducted by (1) deciduous forest, Berry (2) deciduous forest, Curtis (3) slash pine, Chanton (4) grassland, Berry (5) grassland, Dawson (6) oak savanna, Dawson.

Long-term, consistent $\delta^{13}CO_2$ measurements reveal multi-seasonal and interannual variability in contrasting USA ecosystems

Figure 2 shows weekly measurements of carbon isotope ratios of ecosystem respiration ($\delta^{13}C_R$, ± S.E.) at 3 USA temperate forests and 1 urban site. Measurements of $\delta^{13}C_R$ show substantial intra-seasonal variation at all 4 sites, with the greatest fluctuation in urban ecosystems (Salt Lake City), followed by coniferous forests (Wind River and Howland) and deciduous forests (Harvard). Despite the fundamentally different mechanisms and emission sources that predominantly control the CO_2 mixing ratio, these 4 contrasting ecosystems appear to suggest a great similarity in the seasonal $\delta^{13}C_R$ pattern. Generally speaking, the most negative $\delta^{13}C_R$ values occurred in early spring, which became progressively more positive towards late summer before decreasing again in the fall. These carbon isotope variations far exceeded any observed variations in the leaf organic ^{13}C content, which had varied insignificantly with time. These seasonal $\delta^{13}C_R$ fluctuations are expected to substantially contribute to temporal and spatial distributions of global atmospheric $\delta^{13}C$ content, as nighttime respiration was recently suggested to account for 40-60% of the ecosystem-atmosphere CO_2 exchange (Mathieu et al., 2006; Cooper et al., 2006).

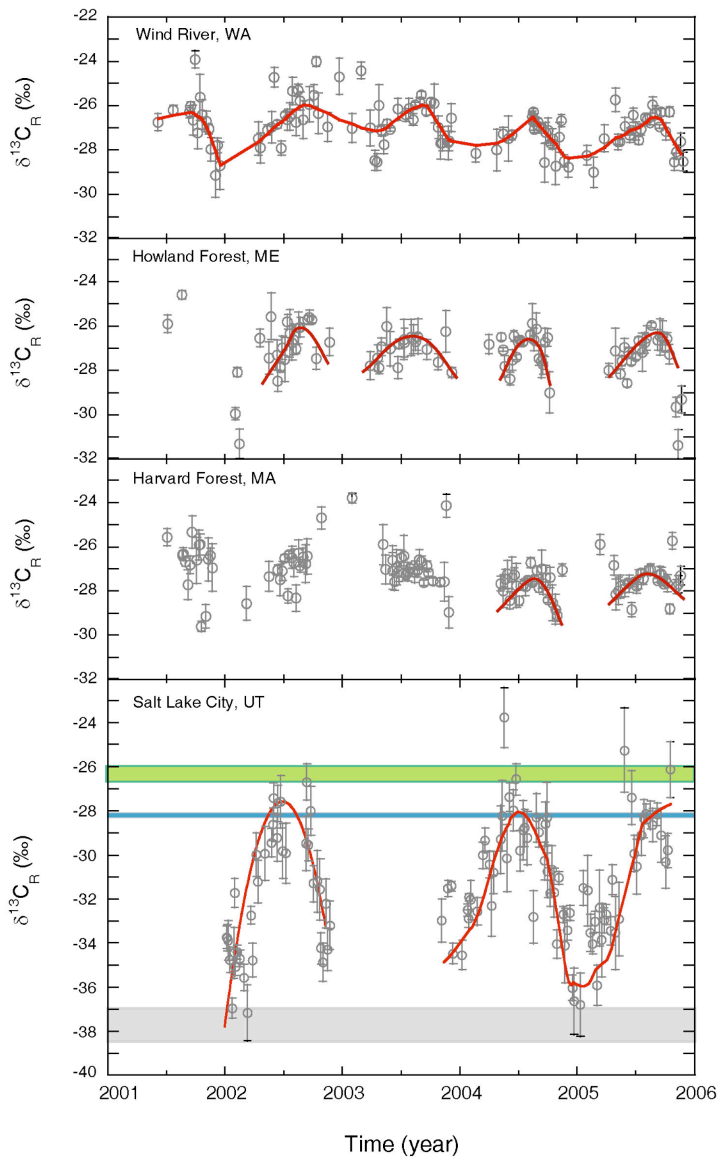

Figure 2. Weekly measurements of carbon isotope ratio of ecosystem respiration ($\delta^{13}C_R$, ± S.E.) at 3 US temperate forests and 1 urban site. Smooth curves are superimposed on weekly values to highlight seasonal patterns. Intra-seasonal $\delta^{13}C_R$ variations are greatest in urban ecosystems (Salt Lake City), followed by coniferous forests (Wind River and Howland) and deciduous forests (Harvard). This multi-seasonal $\delta^{13}C_R$ observation also reveals a long-term decreasing trend in $\delta^{13}C_R$ values that would not be evident with a single-year observation. $\delta^{13}C_R$ measurements in the forest sites are from Lai et al. (unpublished data). For the urban site, the shaded bars show the 95% confidence interval for the $\delta^{13}C_R$ values due to emissions from respiration (green), gasoline combustion (blue) and natural gas combustion (gray). 2002 data are redrawn from Pataki et al. (2003).

Identifying key environmental drivers that influence carbon isotopic composition of CO_2 fluxes

Temporal variations of $\delta^{13}C_R$ values at ecosystem level are expected because of environmental effects on leaf gas exchange and associated carbon isotope discrimination. The exact mechanism that influences primary $\delta^{13}C_R$ variation differs, however, in contrasting ecosystems. In urban ecosystems, a seasonal swing of nearly 10 ‰ were observed for $\delta^{13}C_R$ with values approaching that resulting from natural gas combustion in winter and natural biogenic respiration in summer (Figure 2). Using both carbon and oxygen isotope measurements, Pataki et al. (2003) showed that natural gas combustion contributes substantially to the CO_2 mixing ratios in winter, whereas contributions from biogenic respiration became more significant in spring, summer and early fall. Their study nicely demonstrates stable isotope a powerful tracer technique that can be used to characterize sources of CO_2 emission in urban ecosystems.

By contrast, natural ecosystems exhibit relatively smaller seasonal $\delta^{13}C_R$ variation due to the absence of direct impacts from fossil fuel emission. Considering the $\delta^{13}C$ of global atmosphere changes by 0.02 ‰ yr^{-1}, the potential impact of these seasonal changes (~ 2 ‰) on atmospheric ^{13}C contents should not be ignored. The temporal $\delta^{13}C_R$ variation in natural ecosystems largely results from biological processes. Figures 3 and 4 illustrate how changes in natural forcing may influence seasonal variability of $\delta^{13}C_R$ in forests and grassland. Figure 3 suggests that leaf gas exchange responds strongly to water availability in the two coniferous forests, which results in corresponding changes in carbon discrimination and reflects such changes in the carbon isotope ratios of ecosystem respiration. The correlation in Figure 3 is robust and has been shown based on observations from multiple years. Figure 3 demonstrates a strong coupling between the hydrological forcing and terrestrial carbon dynamics.

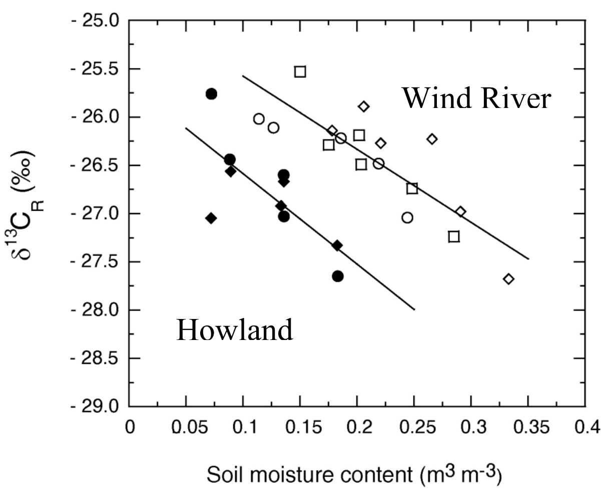

Figure 3. Relationship between $\delta^{13}C_R$ and soil moisture content in two coniferous forests. Different symbols represent measurements from multiple years. Redrawn from Lai et al. (2005).

In grassland ecosystems with vegetations of both C_3 and C_4 photosynthesis, eco-physiological response is often superimposed by the effect of photosynthetic pathways on the seasonal $\delta^{13}C_R$ variation. Figure 4 shows (a) monthly averages of $\delta^{13}C_R$ and (b) the fraction of C_4 contribution over 3 growing seasons in the Rannells Prairie. The contrasting seasonal pattern between the 3 years reflects changes in ecosystem composition from C_3 to C_4 photosynthesis and their respective tolerance to drought. $\delta^{13}C_R$ values in 2002 showed a lagged shift from C_3 to C_4 production in this tallgrass prairie. That is because in spring 2002 a severe drought limited the growth of C_4 grasses while C_3 forbs, which have deeper rooting distribution, were able to continue carbon uptake due to their ability to access deeper soil waters.

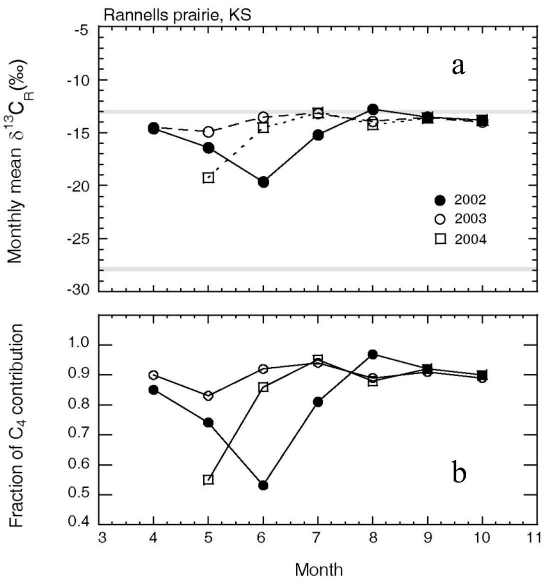

Figure 4. (a) Monthly averages of $\delta^{13}C_R$ and (b) the fraction of C_4 contribution in Rannells Prairie, KS. The gray lines indicate measured $\delta^{13}C$ boundaries based on leaf organic matter from dominant C_3 (-27.9 ‰ ± 0.54 S.E.) and C_4 (-12.3 ‰ ± 0.19 S.E.) species. Redrawn from Lai et al. (2006a).

Partitioning NEE into gross flux components

Carbon isotopes have been shown as a powerful tool for partitioning NEE into photosynthetic (F_A) and respiratory (F_R) fluxes (Yakir and Wang, 1996; Bowling et al. 2001, 2003; Lai et al. 2003; Ogée et al. 2003, 2004; Knohl and Buchmann, 2005). The separation of NEE into gross flux compartments is critical because the two opposing processes respond differently to climatic perturbations. Carbon models need to consider these separate processes exclusively in order to predicting future atmospheric CO_2 levels. Figure 5 shows diurnal patterns of modeled F_A and F_R with the $\delta^{13}C$ approach in a C_3-C_4 tall grass prairie. The isotopic approach agreed reasonably well with chamber-based measurements when the system is not in isotopic equilibrium state. This research is an excellent example of a joint effort linking isotope technique with the AmeriFlux community.

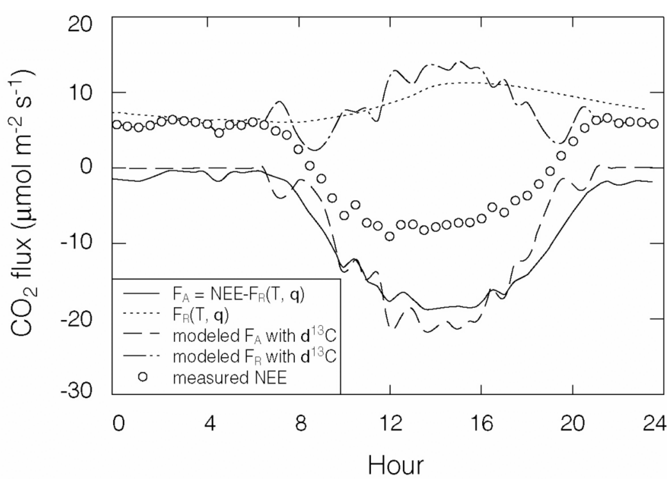

Figure 5. Partitioning NEE into photosynthetic and respiratory components in Rannells prairie. Carbon isotope measurements allow for deciphering net CO_2 fluxes at AmeriFlux sites, which is critical for understanding mechanisms controlling carbon exchange rates between the atmosphere and terrestrial ecosystems. From Lai et al. (2003).

Inferring regional CO_2 fluxes from mixing ratio data

Reliable methods that are capable of quantifying annual carbon budgets at regional scales are needed in order to understand distributions of carbon sources and sinks on land that were thought to be responsible for the additional atmospheric uptake (Tans et al., 1990; Conway et al., 1994; Ciais et al., 1995; Keeling et al., 1996; Battle et al., 2000). Accurate CO_2 mixing ratio measurements can be used to infer regional CO_2 flux due to the large source area that affects mixing ratio data (Gloor et al., 2001). In addition to nighttime respiration measurements, we collected whole-air samples in the mid-afternoon on weekly intervals. These mid-afternoon samples provide integrated information between synoptic-scale transport, surface CO_2 production and troposphere-boundary layer exchange. On a monthly basis, the balance between these processes allows one to view the atmospheric boundary layer (ABL) as approaching an equilibrium state (Betts, 2000; Betts et al., 2004). We applied this equilibrium ABL approach to model regional CO_2 fluxes and compared the results to tower-based eddy covariance NEE flux measurements in a grassland (Figure 6). The boundary layer budget approach appeared to be fairly robust based on the comparison between modeled and measured NEE. Complete agreement between measured NEE and calculated net CO_2 fluxes was not expected because of the difference in spatial scales the two quantities represent. Given the heterogeneity of land uses in the area (mixtures of natural tallgrass prairie with agricultural crop fields), it is not too surprising that regional and local estimates of NEE fluxes do not fully agree in magnitude. Yet, the ABL approach reasonably captures the timing of the NEE transition from a positive rate of change to a negative rate of change and vice versa for three years of contrasting water conditions (2002 being the driest year). The timing of the NEE transition is determined primarily by biotic factors (e.g. bud break and senescence), as well as anomaly in weather patterns. It is important to identify whether such biotic controls occur at a large spatial scale. Such agreement suggests that our mid-afternoon samples are potentially very useful for characterizing regional CO_2 fluxes.

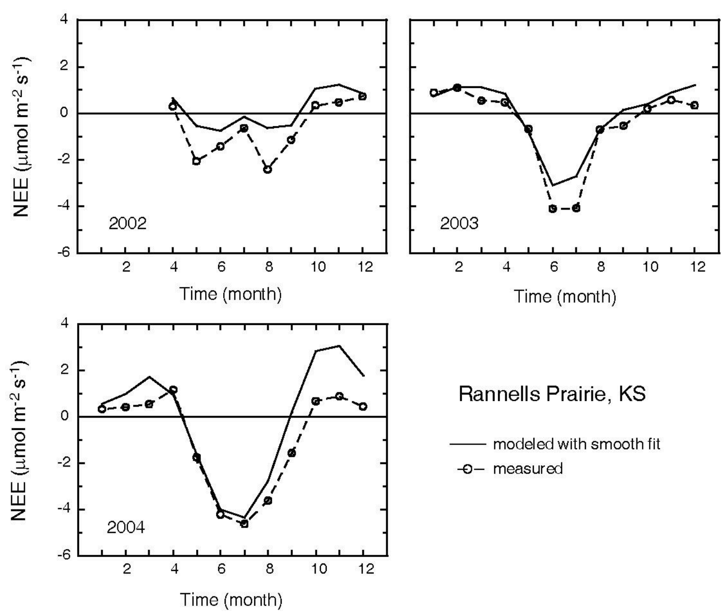

Figure 6. Comparison between modeled regional CO_2 fluxes and local eddy covariance flux measurements. Both modeled and measured CO_2 fluxes were presented as monthly averages. Modeled CO_2 fluxes were calculated using CO_2 differences between troposphere and those measured during midday in the surface layer. The boundary layer budget approach appeared to be fairly robust based on the comparison between modeled and measured NEE for three years of contrasting water conditions. Redrawn from Lai et al. (2006b).

Providing constraints to global carbon models

A continental network of $\delta^{13}C$ measurements provides linkage to global carbon cycle studies. Figure 7 shows the comparison between measured $\delta^{13}C$ of net ecosystem exchange CO_2 fluxes ($\delta^{13}C_{bio}$) from this study and that of Miller et al. (2003). Our estimates of $\delta^{13}C_{bio}$ at C_3 forest sites differ from those reported by Miller et al. (2003). Such discrepancy may be consequences of different footprints represented by the two analyses. Nevertheless, these experiment-based estimates were very useful to constrain modeled estimates. For example, Figure 8 compares measured $\delta^{13}C_{bio}$ with modeled photosynthetic $\delta^{13}C$ signatures ($\delta^{13}C_A$) produced by several global carbon models (Fung et al. 1997; Lloyd and Farquhar 1994; Still et al. 2003; Suits et al. 2005). As three-dimensional global inversion analyses of CO_2 and $\delta^{13}C$ become available, longitudinal variations of terrestrial ^{13}C discrimination need to be considered as well. Our AmeriFlux-isotope network provides the only dataset available to constrain model calculations in terrestrial ecosystems across the North American continent.

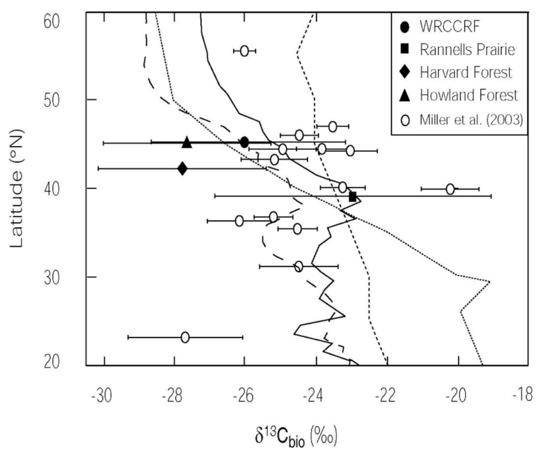

Figure 7. Latitudinal distribution of the annual mean, flux-weighted $\delta^{13}C$ of net ecosystem exchange CO_2 fluxes ($\delta^{13}C_{bio}$). The dash line, dotted line, solid line and broken line represent modeled $\delta^{13}C_A$ from Still et al. (2003), Fung et al. (1997), Lloyd and Farquhar (1994) and Suits et al. (2005) respectively. Redrawn from Lai et al. (2004)

4.0 Products of the Project

4.1 Publications

Alstad, K., C.-T. Lai, L. Flanagan, and J.R. Ehleringer, Carbon isotope ratio of respired CO_2 in temperate and boreal forests of North America. Tree Physiology (in press).

Hollinger, D.Y., C.-T. Lai, and J.R. Ehleringer, J. Munger, and S. Wofsy. Estimating net CO_2 fluxes from mixing ratio data – comparisons between IRGA and flask measurements, in preparation.

Lai, C.-T., W. Riley, C. Owensby, J. Ham, A. Schauer, and J. Ehleringer. 2006d. Seasonal and interannual variations of carbon and oxygen isotopes of respired CO_2 in a tallgrass prairie: Measurements and modeling results from three years with contrasting water availability, Journal of Geophysical Research-atmosphere, in press.

Lai, C.-T., J. Ehleringer, B. Bond, and K.T. Paw U 2006e, Contributions of evaporation, isotopic non-steady state transpiration, and atmospheric mixing on the $\delta^{18}O$ of water vapor in Pacific Northwest coniferous forests, Plant, Cell and Environment, 29(1), 77-94, doi: 10.1111/j.1365-3040.2005.01402.x.

Lai, C.-T., J. Ehleringer, A. Schauer, P. Tans., D. Hollinger, K.T. Paw U, J. Munger, and S. Wofsy. 2005. Canopy-scale $\delta^{13}C$ of photosynthetic and respiratory CO_2 fluxes: observations in forest biomes across the United States, Global Change Biology, 11, 633-643, doi: 10.1111/j.1365-2486.2005.00931.x.

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4.2 Website reflecting project results and publications

http://ecophys.biology.utah.edu
http://co2.utah.edu

4.3 Network collaborations fostered

This project was associated with the development and activities of two carbon-cycle networks:

- AmeriFlux, http://public.ornl.gov/ameriflux/
- BASIN, the Biosphere-Atmosphere Stable isotope Network, http://basinisotopes.org

4.4 Pattens and inventions

None