Estimation of Carbon Sequestration in a Restored Tallgrass Prairie Ecosystem in Eastern Missouri

B. Jason West and Danelle Haake
Litzsinger Road Ecology Center, a division of the Missouri Botanical Garden

Abstract

We measured the net primary productivity (NPP) and soil respiration of restored prairies at the Litzsinger Road Ecology Center, managed by the Missouri Botanical Garden and located in eastern Missouri, in the period between July 2013 and May 2014. Productivity was measured using a biometric approach and soil respiration was measured using the soda-lime method. NPP measurements agreed well with results reported by similar studies, and soil respiration followed similar trends for months when data were available. NPP and respiration were used to calculate net ecosystem productivity (NEP), as well as an estimate for net biome productivity (NBP) based on estimated carbon lost during prescribed burns. The NEP and NBP for the study site in 2013 were found to be positive (794 g C/m^2/yr and 403 g C/m^2/yr, respectively), indicating that the site functions as a carbon sink. The results support the idea that restored prairies can be significant carbon sinks, which will be useful as governments and other entities search for ways to reduce net carbon dioxide emissions into the atmosphere.

Introduction

Global climate change is being driven in large part by increased atmospheric CO_2 concentration, and has serious consequences for humans and ecosystems [Pachauri 2007]. Policy frameworks, such as the Kyoto protocol and many local government initiatives, encourage the reduction of net anthropogenic carbon emissions, which constitute one of the strongest drivers of climate change. Restored prairies can be significant carbon sinks and may thus be used in carbon credit trading by governments, non-profit organizations, and businesses [Cahill 2009, Davidson 2011]. The restoration community has been aware of these climate-related benefits at least since the 1990s [Packard 1997], but case studies of specific sites remain relatively rare.

Litzsinger Road Ecology Center (LREC), established in 1989 and managed by the Missouri Botanical Garden, consists of 34 acres of restored prairie, woodland, and savanna in eastern Missouri, of which 12 acres are prairie. While the primary goals of LREC are educational and research-focused, the site provides important ecosystem services to the region, including contributions to climate regulation via the carbon sequestered in the soil and plant matter. As long as the site land use is preserved, the site could potentially serve as a carbon sink into the future. This project's goal was to estimate the annual carbon sequestration potential in the prairies at LREC through the net ecosystem productivity and net biome productivity metrics, both to investigate the carbon-related benefits of prairie restoration, and to serve as a site benchmark should such an estimate be repeated in the future.

The Carbon Cycle

Carbon is one of the most abundant elements on earth, and is a critical building block of life. The atmosphere, biosphere, hydrosphere, pedosphere, and lithosphere all play key roles in the global carbon cycle, where carbon is continuously transported and changed in form through various chemical and physical processes. This study was concerned specifically with the carbon-related processes occurring between the atmosphere, the biosphere, and the pedosphere. The three primary processes driving the terrestrial carbon cycle in those spheres are photosynthesis, respiration, and decay. Plants require solar radiative energy, CO_2 from the air, H_2O from the soil and the air, and nutrients from the soil for photosynthesis, and generate organic matter (as plant biomass) and oxygen as the products. This process can be conceptually described as such:

$$\text{Solar energy} + CO_2 + H_2O + \text{nutrients} \rightarrow \text{Organic matter} + O_2$$

Conversely, respiration and decay processes convert the organic matter contained in the plant biomass (which includes above-ground and below-ground biomass) back into its original constituent components [Burch 2013]:

$$\text{Organic matter} + O_2 \rightarrow \text{Energy} + CO_2 + H_2O + \text{nutrients}$$

Respiration is accomplished by plants through leaf transpiration into the atmosphere, and by soil microbes, which respire CO_2 into the soil and air. The equations above depict the transfer of carbon in a completely balanced system, where the amount of carbon incorporated into plant matter is equal to the amount of carbon returned to the atmosphere through respiration and decay. However, real-world systems are often unbalanced and either store excess carbon in the soil (indicating a carbon sink) or release it into the atmosphere (indicating a carbon source). It is estimated that about 2,300 gigatons of carbon are semi-permanently stored in the world's soils as a result of millions of years of carbon cycling--almost a quarter of the carbon stored in the earth's fossil pool [Burch 2013].

The annual net direction of carbon flow, into or out of the soil, can be measured as the difference between the carbon stored in plant mass at the peak of the growing season and the carbon respired by soil microbes throughout the year [Cahill 2009]. This is conventionally expressed as net ecosystem productivity (NEP), which is a function of above-ground net primary productivity (ANPP), below-ground net primary productivity (BNPP), and heterotrophic soil respiration (R_h):

$$NEP = ANPP + BNPP - R_h$$

Cahill’s [2009] literature search of grassland carbon sequestration studies found that managed grasslands consistently had positive NEP values ranging between 150 g $C/m^2/yr$ and 631 g $C/m^2/yr$. In managed prairies where prescribed burns are common, it is also necessary to adjust the NEP value to account for carbon lost to the atmosphere during burning [Brye 2002, Kucharik 2006, Suyker 2001]. The IPCC describes the resulting metric as net biome production (NBP) [IPCC 2006]:

$$NBP = NEP - \text{Carbon losses from disturbance/land-clearing/harvest}$$

The purpose of this study was to estimate the NEP and NBP of the prairies at LREC, and thus determine the extent to which they are carbon sources or sinks.

Methods

Site selection

Between July 2013 and May 2014, data were collected from eight sites (shown in Figure

1) located in the two largest prairies on the property, and were selected using a random number generator. Though the sites were randomly selected, they were confirmed to include most of the key plant species typically present in the LREC prairies, including *Silphium perfoliatum* (cup plant), *Andropogon gerardii* (big bluestem), and *Rudbeckia subtomentosa* (sweet coneflower).

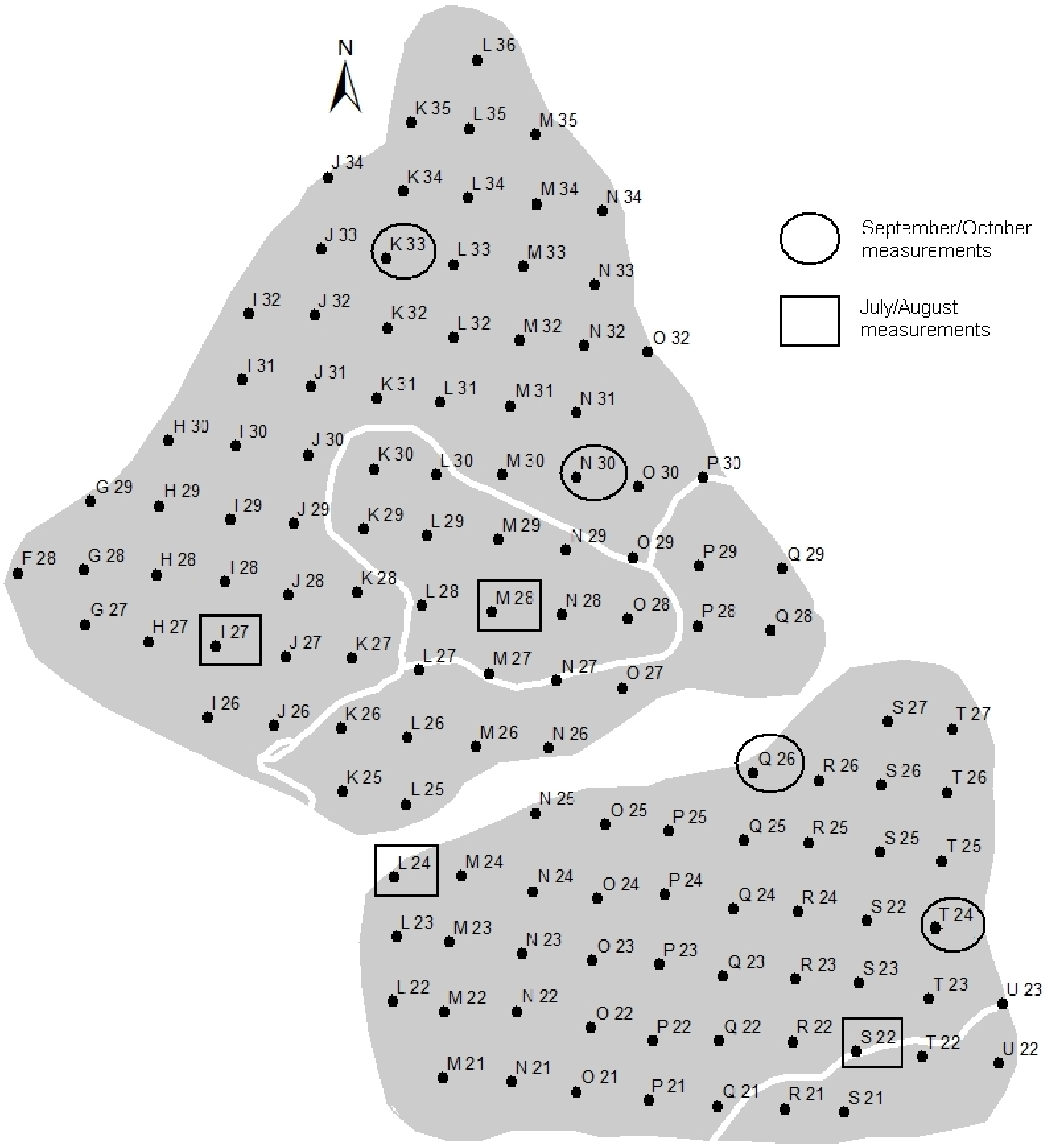

Figure 1: Data collection sites

Measurement of above-ground net primary productivity (ANPP)
ANPP measurements were taken only for the eight samples collected in July and September 2013. Following similar methods to those described by Cahill et al. [2009], all live above-ground plant matter was clipped from 0.25m x 0.25m sample plots located within two meters of site markers. The exact sampling location was selected based on

there being a representative density and distribution of plants in the surrounding area. Site markers were already in place for monitoring purposes prior to the experiment. Clipped plant material was cut into small sections, transported to the lab, oven-dried at 65°C (150°F), periodically weighed, and removed from the oven when the mass stabilized. ANPP was normalized to units of g/m^2.

Measurement of below-ground net primary productivity (BNPP)

BNPP measurements were taken only for the four samples collected in July 2013. Following similar methods to those of Cahill et al. [2009], and Tufekcioglu et al. [1999, 2001, and 2003], one soil sample was collected from each sample plot. Because of a lack of deep soil sampling equipment (the aforementioned studies included samples at various depths up to 125 cm), soil samples were taken to depths between 27 cm and 38 cm, depending on local soil conditions. Standard landscaping shovels were used to excavate a trench around a plug of soil, after which the plug was loosened and removed. This was done directly following the removal of above-ground plant matter from each sample plot. To allow for partial sample degradation during transport and processing, larger samples were removed from the ground than needed, and were shaped, using a hand saw, into square columns with widths between 7 cm and 12 cm, upon return to the lab.

Samples were then labeled, covered, and placed in a refrigerator to preserve the roots until further processing was possible. Each sample was then gently crumbled by hand to extract the roots. Live and dead roots were not separated because of the difficulty in identifying them. The extracted roots were gently washed with water over a sieve to remove any remaining soil. The cleaned roots were then oven-dried at 65°C, periodically weighed, and removed from the oven when the mass stabilized. BNPP was normalized to a depth of 35 cm, to compare the samples at a consistent depth, by multiplying the measured BNPP by 35 cm and dividing by the measured core depth (e.g., for a 38 cm-deep sample, the BNPP would be multiplied by a factor of 35/38). BNPP was then normalized to units of g/m^2 by dividing by the soil sample cross-sectional area.

Measurement of total soil respiration[1]

Soil respiration chambers were deployed at the sample sites after the collection of above-ground and below-ground plant biomass was complete. The soda-lime method was used to measure soil respiration [Keith et al. 2006 and Tufekcioglu et al. 1999, 2001, 2003]. Soil respiration chambers consisted of black plastic buckets 19 cm in diameter and 16 cm in height (above soil level, resulting in a cross-sectional area of 2.84×10^{-2} m^2 and an interior volume of ~4500 cm^3), with the bottoms removed. Chambers were initially placed approximately 1 cm into the soil, with tops open. Chambers were left open in the field for at least 24 hours to account for soil disturbance and any resulting CO_2 flush. During this period, 20 g of soda lime (Carolina Biological Supply Company; indicating, reagent grade, 4-8 mesh) was measured and placed into 9 cm-diameter petri dishes and pre-dried in an oven at 105°C until the mass stabilized.

Once the 24-hour soil disturbance period had elapsed (for the first set of measurements only; subsequent measurements were taken after many days or weeks), petri dishes

---

[1] Measurement methods were refined in the September 2013—May 2014 period, but the general methodology was similar enough that August 2013 respiration data are still included in the results. Specific differences between measurement methods can be found in the Appendix.

containing dried soda lime were covered with tops, sealed with electrical tape to prevent CO_2 absorption, and transported to the field. At each site, above-ground plant mass was clipped from the inside of the open respiration chamber (for the first set of measurements; subsequent measurements used the same chambers with vegetation already clipped). A 9.5 cm-square plywood platform with 4.5 cm-high posts, and the petri dish of soda lime, were then placed inside the respiration chamber so that they were elevated above the soil surface. The petri dish was then opened and approximately 3 mL of water was added to the petri dish with a spray bottle to allow the soda lime reaction to begin. The petri dish was then set atop the platform and the respiration chamber top was fastened. One "blank," or control, chamber with the bottom left intact and not exposed to the soil, was concurrently placed in the field for each round of respiration measurements, to account for CO_2 absorbed during oven drying, transport, and field setup.

For the January through May 2014 respiration measurements, soil temperature was concurrently measured at each site using a digital thermometer. The thermometer used here was only capable of measuring temperatures at and above freezing, so results showing "0°C" may have in fact been colder. We were primarily interested in the dependence of respiration on temperature after soil thawing in the spring, so this was not a concern for this study.

The petri dishes were collected after 24 hours, re-sealed with electrical tape, transported back to the lab, opened, and once again oven-dried to remove the moisture. The dried soda lime was weighed, compared to the initial dry mass, and corrected for the blank chamber mass gain. Respiration was recorded in g $C/m^2/day$, using calculations reported by Keith et al. [2006] to convert change in soda lime mass to grams of carbon absorbed, and dividing by the respiration chamber cross-sectional area.

Calculation of net ecosystem productivity and net biome productivity

Net ecosystem productivity (NEP), the difference between sequestration of carbon by plants and respiration of carbon by soil microorganisms, was calculated by adding ANPP and BNPP, and subtracting R_h. Following the formula in the literature, NEP was estimated on an annual basis (in g $C/m^2/yr$). Before calculating NEP, several corrections were made to productivity and respiration measurements, as follows:

ANPP and BNPP were assumed to be close to annual values as-measured, because annual plant-based carbon sequestration reaches its maximum at the time of peak growth, which was known to occur near the sampling dates. ANPP and BNPP were converted from g of dried biomass/m^2/yr to g $C/m^2/yr$ by multiplying by a carbon fraction of 0.40, as reported by Cahill [2009] and Tufekcioglu [2003]. BNPP was then multiplied by a series of three correction factors. First, a deep-root correction factor of 1.20 was applied to account for roots below 35 cm-depth that were not measured. We based this conservative estimate on the lower end of measurements reported by Tufekcioglu [2003]. Second, a live-to-total root fraction of 0.60, as reported by Gill [2002], was applied because live roots were not separated from dead roots during soil core processing and only live roots are typically counted in annual productivity estimates. Third, a root turnover coefficient of 0.56 was applied, based on an exponential relationship with mean annual temperature (MAT=14.4°C for the site and year of this study) of $0.2884e^{0.046MAT}$/yr [Gill 2002, republished by Cahill 2009].

To estimate soil respiration, data are typically collected at a site throughout the entire year, but this project was limited to the time period between August 2013 and May 2014.

To account for the lack of measurements spanning an entire year, data collected in a similar mid-latitude-Missouri, Ozark-border tallgrass prairie [Kucera 1971], as well as data collected in a switchgrass-dominated plot in central Iowa [Tufekcioglu 2001] were used as a simple model to estimate respiration behavior throughout the year (peak respiration time and shape of the curve). The LREC respiration data from 2013 were used with the model assumptions to estimate annual respiration, and heterotrophic respiration was estimated by multiplying total respiration by 0.70, the midrange of tallgrass prairie values reported by Cahill [2009].

An estimate for carbon released to the atmosphere during prescribed burns was then subtracted from the NEP result (in the literature, the result is sometimes reported as NEP, and sometimes as NBP). The convention in the literature for making such an estimate is to collect above-ground plant biomass samples before and after a burn and measure the amount of carbon in each sample [Brye 2002, Kucharik 2006, Suyker 2001]. However, these measurements were not possible during this study, so carbon loss estimates from Kucharik [2006] were used. The mid-range of carbon loss values (as a fraction of ANPP) from that study was approximately 0.75, and half of LREC’s prairies are burned each year, so the carbon loss term was calculated by multiplying ANPP by (0.75/2).

Results

A summary of ANPP and BNPP estimates is shown in Table 1. ANPP varied from 307 g/m^2 (123 g C/m^2) for a plot dominated by *Tripsacum dactyloides* and measured in July, to 10,294 g/m^2 (4,118 g C/m^2) for a plot dominated by *Silphium perfoliatum* and measured in September 2013. The average ANPP of the eight sample plots, including measurements taken in July and September 2013, was 2,608 g/m^2 (1,043 g C/m^2). BNPP varied from 505 g/m^2 (202 g C/m^2) to 960 g/m^2 (384 g C/m^2), with an average of 745 g/m^2 (298 g C/m^2).

Table 1: Summary of data for ANPP and BNPP estimates.

	Location	**I27 (north)**	**M28 (north)**	**L24 (south)**	**S22 (south)**
	Dominant plant	*Pycnanthemum tenuifolium*	*Veronicastrum virginicum*	*Tripsacum dactyloides*	*Elymus canadensis*
Above-ground plant mass (July measurements)	**Date (plant clipping)**	07/16/2013	07/26/2013	07/18/2013	07/19/2013
	Total above-ground plant mass, dry (g)	47.5	65.6	19.2	71.6
	Total above-ground plant mass (g/m^2)	760	1,050	307	1,146
	ANPP (g C/m^2/yr)	**304**	**420**	**123**	**458**
Below-ground plant mass (July measurements)	**Date (soil core extraction)**	07/16/2013	07/26/2013	07/19/2013	07/19/2013
	Soil core dimensions	27cm x 7cm (cylinder)	38cm x 10.25cm x 11.25cm (rectangular column)	33cm x 10.5cm (square column)	30cm x 10cm (square column)
	Below-ground plant mass, dry (g)	3.7	29.7	24.1	12.2
	Below-ground plant mass, dry (g/m^2)	1,246	2,372	2,318	1,423
	BNPP (g C/m^2/yr)	**202**	**384**	**375**	**230**

	Location	**T24 (south)**	**Q26 (south)**	**K33 (north)**	**N30 (north)**
	Dominant plant	*Silphium perfoliatum*	*Andropogon gerardii*	*Rudbeckia subtomentosa*	*Rudbeckia subtomentosa*
Above-ground plant mass (September measurements)	**Date (plant clipping)**	09/09/2013	09/09/2013	09/11/2013	09/11/2013
	Total above-ground plant mass, dry (g)	643.4	177.7	118.3	160.3
	Total above-ground plant mass (g/m^2)	10,294	2,843	1,893	2,565
	ANPP (g C/m^2/yr)	**4,118**	**1,137**	**757**	**1,026**

An examination of soil respiration data from the literature (as described in the Methods), as well as two measurements taken in January and February 2014, resulted in the model assumption that respiration in January and February were near-zero (due to freezing soil temperatures), the peak respiration time occurred in early-to-mid-August, and respiration increased and decreased approximately linearly throughout the year. In reality, the curve is nonlinear, but the linear approximation fit Kucera's [1971] data from a similar tallgrass prairie in central Missouri with an R^2 value of 0.96 for both halves of the year and Tufekcioglu’s [2001] data from a switchgrass-dominated plot in central Iowa with R^2 values of 0.97 and 0.98 for the first and second halves of the year, respectively (not including January and February). Those two datasets, as well as minimum, maximum, and mean daily soil respiration rates measured from August—October 2013 and January—May 2014 in this study, are shown in Figure 2. While data were not collected in the first half of 2013, the five data points collected between August and October 2013 yielded an R^2 value of 0.97 to a linear fit and were thus used to estimate

2013 soil respiration (the 2014 data are shown for comparison only and were not included in the NEP calculations). Integrating the area under the respiration trend lines yielded an annual soil respiration value of 780 g C/m^2, close to Cahill's [2009] mean value between C_3 and C_4 grass-dominated plots in southern Wisconsin of 881 g C/m^2, lower than Tufekcioglu's [2001] range of 1030—1220 g C/m^2 for perennial grass plantings in central Iowa, but significantly higher than Kucera's [1971] reported value of 450 g C/m^2.

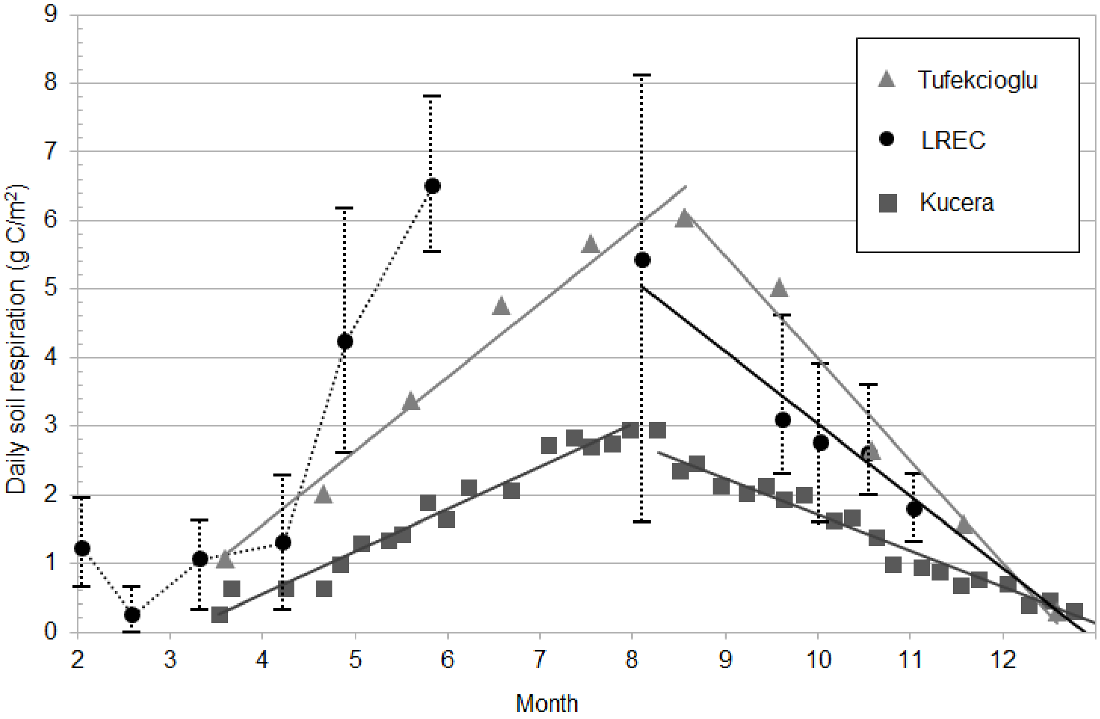

Figure 2: Soil respiration measurements and linear fits to data collected at LREC in August—October 2013 and similar grassland sites in central Missouri [Kucera 1971] and central Iowa [Tufekcioglu 2001], excluding January and February values. LREC data from early 2014 are also included for comparison, without a linear fit (the dashed line is only a visual guide). LREC range bars depict the minimum and maximum measured values for each date, not the measurement error.

The average NEP (not corrected for burning) was 794 g C/m^2/yr, and the NBP (NEP corrected for burning) was 403 g C/m^2/yr, a third less than the maximum value measured by Cahill et al. of 603 g C/m^2/yr and near the mid-range value from their literature search of managed grassland NEP estimates (391 g C/m^2/yr). Assuming the average estimated NBP is representative of the LREC prairie as a whole, the estimated NBP for the two prairies included in the study, which together constitute 7.2 acres (29,000 m^2) is approximately 11.7 Mg (megagrams, or metric tons) C/yr.

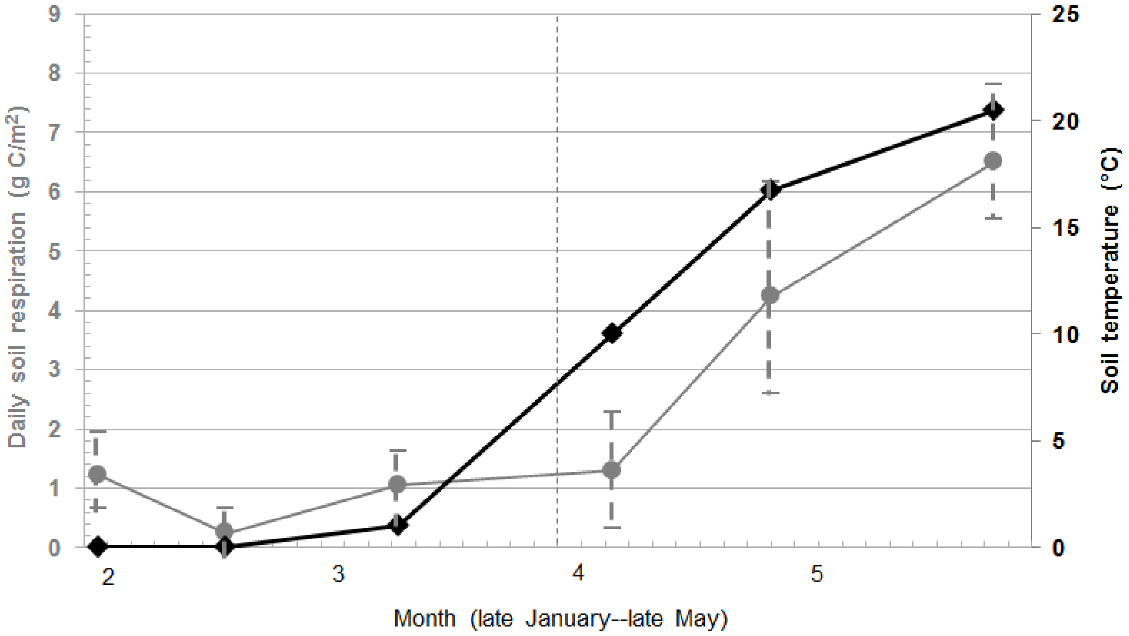

Figure 3: LREC average soil respiration and soil temperature measurements in 2014. Solid lines are visual guides to distinguish the two data sets; they are not curve fits. Dashed lines extending from respiration measurements show the minimum and maximum values for a given measurement day, not the measurement error. The dashed line at the end of March indicates the date of a prescribed burn in the north prairie.

Soil respiration measurements taken at LREC from January 2014 through May 2014 are shown separately in Figure 3. Soil respiration at LREC in the first half of 2014 was significantly higher than respiration in the second half of 2013; the average respiration in late May 2014 was already 6.5 g C/m^2, while the average 2013 respiration was 5.4 g C/m^2 near the peak, which was assumed to occur in August. Furthermore, respiration was near-zero in January, February, and early March, but rapidly increased between March and May. This increase followed a similar rapid increase in soil temperature by ~2-3 weeks; Kucera's [1971] study, in contrast, showed respiration rates more or less directly correlated with soil temperature changes.

Discussion

Comparison of measured NEP to similar sites

In general, temperate grasslands (prairies) fall in between other temperate biome types in terms of productivity: prairie NPP is approximately four times that of temperate desert and half that of temperate forest, while prairie NEP is approximately three times that of temperate desert and half that of temperate forest[2] [Schlesinger 1997]. Among prairies where NEP has been measured, results vary widely, from sites representing major sources to major sinks of carbon, though managed prairies tend to be carbon sinks

---

[2] Schlesinger does not specifically cite NEP when comparing biomes, rather long-term accumulation of soil organic carbon.

[Cahill 2009]. The fact that the estimated NEP in this study was nearly halfway between the minimum and maximum values from Cahill's literature search of managed grasslands might suggest that the LREC site has similar features (management techniques, plant communities, climate and soil conditions, etc.) to those managed grasslands. However, the geographic locations and physical conditions of grasslands in the literature vary significantly. The closest study known to the authors, in terms of geographic location and site management [Kucera 1971], reported annual soil respiration data that was less than two-thirds of the 2013 value, and less than half of the 2014 value reported here. Studies conducted at higher latitudes with significantly lower mean annual temperatures and precipitation levels [Cahill 2009, Tufekcioglu 2001] nonetheless reported higher annual soil respiration values, compared to 2013 LREC data, but lower values compared to 2014 LREC data.

The interannual variation in respiration at LREC highlights some of the difficulty in producing a site estimate for NEP. Differences in weather and site management practices from year to year can have a significant impact on carbon cycling. Furthermore, Cahill et al. caution that the measurement uncertainties involved in such estimates may be of the same order of magnitude as the differences in site conditions, so the accuracy of the estimates must be carefully considered.

Major sources of uncertainty:
Cahill's [2009] investigation of the biometric approach to carbon sequestration estimation revealed that the uncertainties associated with such an approach strongly affect the magnitude, and even the sign, of the overall result. Because this study was modeled largely after methods described in the aforementioned study, those uncertainties apply here, and will not be repeated. However, there were additional limitations to this project's scope which may have increased the uncertainty of the results. Sources of uncertainty stemming from those limitations are described here.

- *Spatial heterogeneity in the prairie*
  ANPP measurements were made at eight sites throughout the LREC prairies and included all key species present (based on data from biannually conducted plant monitoring). However, results were not weighted to reflect the distribution of plant species. ANPP values varied by a factor of 33, with the minimum occurring in a sparsely vegetated, upland, near-edge plot containing *Tripsacum dactyloides*, and the maximum occurring in a dense streamside plot with a stand of *S. perfoliatum*. Though the *S. perfoliatum*-dominated stand included in the study was closer to a typical height for the species (~8 ft.) than the typical height found on-site (~12 ft.)[3], the ANPP measurements (4118 g C/m^2/yr) were nonetheless 33 times higher than those of the plot with *T. dactyloides*, and about four times higher than the second-highest sample plot, dominated by *Andropogon gerardii* (1137 g C/m^2/yr). The wide range of productivity over the site would best be captured with more measurements and weighting based on the known distribution of species. Despite the lack of weighting, the eight sample sites were believed to constitute a reasonably representative sample of the landscape.
- *Incomplete soil samples*
  The literature has well documented the fact that many tallgrass prairie plants can send their roots down to depths exceeding their above-ground height, in some

---

[3] The LREC prairies are in a riparian area, with the east edges 10 m to 20 m from a stream. The soil is a rich alluvial deposit which allows many species to grow to or beyond the generally expected maximum heights.

cases beyond 10 feet-deep [Davidson 2011; Jarchow 2011; Smith 2010]. By one estimate, up to 80% of the carbon stored in prairies may be contained in the below-ground plant matter [Rice 2002]. This means that accurate estimates of below-ground productivity are only possible by measuring or estimating deep-root mass. This measurement problem may not be as serious for restored prairies as for native prairies, because plant roots in restored prairies may not have extend as far as roots in native prairie plants. However, the maximum soil core depth in this study (38 cm) was observed to be insufficient, as roots were extracted from even the deepest layer of that sample. The reason that relatively shallow soil cores were taken for this study is due to a lack of deep soil coring equipment. Future studies could address this problem by considering alternative deep soil coring methods. Additionally, soil samples were only collected in the four sample plots that yielded the lowest ANPP values, so the average BNPP value was likely lower than it would have been had soil samples been collected from the other four sample plots. Finally, the quality of the data would be improved if soil samples were collected at the beginning, middle, and end of the growing season.

- *Lack of respiration measurements for a complete year*
  In this study, for the purposes of NEP and NBP estimation, soil respiration was measured at each sample plot for 24-hour periods in August, September, and October of 2013, and in January, February, March, April, and May of 2014, providing a reasonably complete picture of respiration behavior in the second half of 2013 and the first half of 2014. Because of the differences in weather and other site conditions between the two years, only the 2013 respiration data were used in NEP and NBP estimates in this study. The simple linear model used to estimate respiration in the first half of 2013 was assumed to be accurate, based on similar studies that have documented respiration rising in the first half of the year at similar rates to the decrease in the second half of the year, such as the Kucera [1971] and Tufekcioglu [2001] studies referenced earlier in the paper. However, to increase the accuracy of the results, future studies should include measurements taken throughout at least one entire calendar year.

Effects of fire on carbon cycling

Prescribed burning is a common tool in prairie restoration and management because of the resulting benefits, such as removal of shade from the ground at the beginning of the growing season, increased availability of some nutrients to the soil, and soil warming. Indeed, in the context of carbon sequestration, such benefits have been shown to result in increased post-burn carbon flux to plant matter (i.e., faster accumulation of ANPP) during the growing season [Suyker 2001]. However, the positive effects on NEP through increased ANPP and BNPP are tempered by higher post-burn soil respiration rates [Tate 1993] and, as described earlier, carbon losses to the atmosphere during the burn itself. Despite the large amount of carbon lost to burning, this study showed a significantly positive site NBP value, a result that would support future use of prescribed burns, even in sites designed to sequester carbon.

In 2014, there was a delay between the measured increase in soil temperature, which began in early April, and the increase in soil respiration, which began in late April. The authors hypothesize that one possible cause for the delay could be a partial or temporary disabling of the soil microfauna following a prescribed burn in the north prairie (where two of the four respiration measurements were carried out) in late March of 2014, though further investigation is needed.

Conclusions

In the carbon trading and offset field, carbon cycling is typically measured in metric tons, or Mg, of CO_2 per year. Based on the measurements of ANPP, BNPP, and R_h, we estimate that the prairies studied at LREC absorb approximately 51.9 Mg C/yr and respire 22.6 Mg C/yr, resulting in a net annual sequestration, after subtracting burn losses, of 11.7 Mg C/yr. Expanding the estimate to include a third prairie area (covering 4.8 acres) at LREC that was not studied here, but contains similar plant communities, yields a total LREC site carbon sequestration estimate of 19.5 Mg C/yr. The fact that the average NEP and NBP of the site were positive, indicating that the site functions as a carbon sink, is significant. The total site carbon sequestration value of 19.5 Mg C/yr is equivalent to 71.5 Mg CO_2/yr by simple conversion using the molecular mass of CO_2 (44) and the atomic mass of carbon (12). For comparison, the total carbon footprint of the average U.S. household, including direct and embodied emissions from transportation, housing, food, goods, and services, is approximately 48 Mg CO_2/yr [Jones 2011]. Restoration site and project managers may benefit from communicating similar figures to stakeholders to illustrate the value of maintaining restored ecosystems into the future, as well as expanding the number and size of such sites onto additional parcels of land.

This study, while yielding encouraging results, nonetheless suffered from data gaps that could be filled in future studies. Namely, soil respiration measurements could be expanded to cover at least one full calendar year in order to verify the linear behavior assumption used here. Soil temperature and moisture could be measured concurrently with respiration (temperature was measured in this study beginning in 2014, but a full years' worth of data would be preferable). ANPP measurements could be repeated on more dates during the warmer months to obtain a more accurate peak plant growth time. Deeper soil samples could be collected and live roots could be separated from dead roots prior to BNPP measurements. ANPP, BNPP, and respiration results could be weighted for each sample site based on known distribution and density of plant species throughout the study site. Finally, pre- and post-burn biomass samples could be collected and measured for their carbon content to obtain a more accurate estimate for annual carbon lost due to prescribed burns.

Acknowledgments

The authors wish to acknowledge the support of the LREC staff for their direction and assistance with the project. LREC volunteers and interns also contributed their time and energy to soil core extraction and analysis, as well as general project support. Aydin Tufekcioglu provided helpful comments on a draft of the paper. Finally, this project would not be possible without the site and program established and guided by the Litzsinger Road Ecology Foundation, as well as its partnership with the Missouri Botanical Garden.

References

Baldocchi, Dennis. 'Breathing' of the Terrestrial Biosphere: Lessons Learned from a Global Network of Carbon Dioxide Flux Measurement Systems. *Turner Review No. 15, Australian Journal of Botany*. 2008. http://nature.berkeley.edu/biometlab/espm228/Baldocchi%20Turner%20Review%20v2.pdf

Brye, Kristofor R. et al. Carbon Budgets for a Prairie and Agroecosystems: Effects of Land Use and Interannual Variability. *Ecological Applications*, 12(4), 2002, pp. 962-979.

Burch, Sarah and Sara Harris. Climate Literacy: Navigating Climate Change Conversations. Course offered through the University of British Columbia and Coursera. 2013.

Cahill, Kimberly N. et al. Prairie restoration and carbon sequestration: difficulties quantifying C sources and sinks using a biometric approach. *Ecological Applications*, 19(8), 2009, pp. 2185-2201. http://www.sage.wisc.edu/pubs/articles/A-E/Cahill/Cahill_etal_2009.pdf

Davidson, Michael. Iowa: The Power of Prairies. U.S. Fish and Wildlife Service, Open Spaces Blog. June 2011. http://www.fws.gov/news/blog/index.cfm/2011/6/27/Iowa-The-Power-of-Prairies

Gill, R.A. et al. Using simple environmental variables to estimate below-ground productivity in grasslands. *Global Ecology and Biogeography*. Jan. 2002.

Intergovernmental Panel on Climate Change. Revised 1996 IPCC guidelines for national greenhouse gas inventories. 2006.

Jarchow, Meghann E. and Matt Liebman. Incorporating Prairies into Multifunctional Landscapes. Iowa State University Extension. February 2011. http://www.extension.iastate.edu/Publications/PMR1007.pdf

Jones, Christopher M. and Daniel M. Kammen. Quantifying Carbon Footprint Reduction Opportunities for U.S. Households and Communities. Environmental Science & Technology. March 2011.

Keith, H. and S.C. Wong. Measurement of soil CO_2 efflux using soda lime absorption: both quantitative and reliable. *Soil Biology & Biochemistry* 38 (2006) 1121-1131.

Kucera, C.L. and Dale R. Kirkham. Soil Respiration Studies in Tallgrass Prairie in Missouri. *Ecology* 52:912–915, 1971.

Kucharik, Christopher J., Nathan J. Fayram, and Kimberly Nicholas. A paired study of prairie carbon stocks, fluxes, and phenology: comparing the world's oldest prairie restoration with an adjacent remnant, *Global Change Biology*, Jan. 2006.

Pachauri, R. K., and A. Reisinger. "IPCC fourth assessment report." IPCC, Geneva (2007).

Packard, Stephen and Cornelia F. Mutel. The Tallgrass Restoration Handbook for Prairies, Savannas, and Woodlands. Society for Ecological Restoration. Island Press, 1997.

Rice, Charles W. Storing Carbon in Soil: Why and How? Geotimes, January 2002. http://www.geotimes.org/jan02/feature_carbon.html

Schlesinger, William H. Biogeochemistry: an analysis of global change, 2nd ed. San Diego, CA. Academic Press, 1997.

Smith, Daryl et al. The Tallgrass Prairie Center Guide to Prairie Restoration in the Upper Midwest. The Tallgrass Prairie Center. University of Iowa Press, 2010.

Sukyer, Andrew E. and Shashi B. Varma. Year-round observations of the net ecosystem exchange of carbon dioxide in a native tallgrass prairie, *Global Change Biology*, 2001.

Tate, Cathy M. and Robert G. Striegl. Methane consumption and carbon dioxide emission in tallgrass prairie: Effects of biomass burning and conversion to agriculture, *Global Biogeochemical Cycles*, December 1993.

Tufekcioglu, A. et al. Biomass, carbon and nitrogen dynamics of multi-species riparian buffers within an agricultural watershed in Iowa, USA. *Agroforestry Systems* 57: 187-198, 2003.

Tufekcioglu, A. et al. Soil respiration within riparian buffers and adjacent crop fields. *Plant and Soil* 229: 117-124, 2001.

Tufekcioglu, A. et al. Fine root dynamics, coarse root biomass, root distribution, and soil respiration in a multispecies riparian buffer in Central Iowa, USA. *Agroforestry Systems* 44: 163-174, 1999.

Appendix: Differences in soil respiration measurement methods between August 2013 data and September 2013—May 2014 data

- Measurements made in August used 50 g of soda lime, consistent with the soda lime mass reported in similar studies in the literature. For the remainder of the data collection period, the soda lime mass was decreased to 20 g based on the ratio of soda lime mass to respiration chamber cross-sectional area of approximately 625 g/m^2 as reported by Keith et al. [2006].
- The precision of August measurements was 1/10 g, whereas the measurement precision was 1/100 g for the remainder of the data collection period.
- Plastic petri dishes were used in August, while glass dishes were used for the remainder of the data collection period.
- Soda lime was pre-dried in an oven at 65°C for August measurements and 105°C for the remainder of the data collection period.
- In the respiration chamber, the posts of the square platform used to elevate the petri dish were pressed 1 cm into the soil for August measurements, and just set atop the soil surface for the remainder of the data collection period.
- Approximately 10 mL of water was added to the petri dishes during respiration chamber setup for the August measurements, while 3 mL was added during the remainder of the data collection period. The September 2013—May 2014 value was approximately proportional to that used by Keith et al. [2006].