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Intermediate Time-Scale Response of Atmospheric CO_2 following Prescribed Fire in a Longleaf Pine Forest

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Key Points:

1) The impact of prescribed fire on local carbon cycle is not limited to the period of fire but may extend several weeks beyond the fire.
2) Micrometeorological impacts were limited to 1-2 days or less but the impacts to the CO_2, particularly to the flux of CO_2 lasted longer.
3) Large initial changes in the net ecosystem exchange between the pre- and post-burn periods were no longer observed 60-90 days following.

Abstract

Fire plays an essential role in maintaining the structure and function of longleaf pine ecosystems. While the effects of fire on carbon cycle have been measured in previous studies for short periods during a burn and for multi-year periods following the burn, information on how carbon cycle is influenced by such changes over the span of a few weeks to months has yet to be quantified. We have analyzed high-frequency measurements of CO_2 concentration and flux, as well as associated micrometeorological variables, at three levels of the tall Aiken AmeriFlux tower during and after a prescribed burn. Measurements of the CO_2 concentration and vertical fluxes were examined as well as calculated net ecosystem exchange (NEE) for periods prior to and after the burn. Large spikes in both CO_2 concentration and CO_2 flux during the fire and increases in atmospheric CO_2 concentration and reduced CO_2 flux were observed for several weeks following the burn, particularly below the forest canopy. Both CO_2 measurements and NEE were found to return to their pre-burn states within 60-90 days following the burn when no statistical significance was found between pre-burn and post-burn NEE. This study examines the micrometeorological conditions during a low-intensity prescribed burn and its short-term effects on local CO_2 dynamics in a forested environment by identifying observable impacts on local measurements of atmospheric CO_2 concentration and fluxes.

Introduction

Over the past century human influences have altered the fire regime of many of the world's ecosystems. The longleaf pine ecosystem in the southeastern United States is a key ecosystem for the sequestration of CO_2 from the atmosphere. Historically, fire has played an essential role in controlling the structure and function of this terrestrial ecosystem (Bonds and Keeley 2005, Mitchell et al. 2014). The longleaf pine ecosystem has evolved with frequent fires, leading to the development of specific plant traits associated with this cyclic disturbance (Keeley et al. 2011). These plant traits along with the ecosystem's large distributional range have promoted the longleaf ecosystem to be an ecological "hot spot" for biodiversity.

The longleaf ecosystem, once a substantial part of the landscape in the southeastern United States, has been reduced to 3% of its original size with much of the remaining forests in a state of disarray (Noss 1990, Gilliam and Platt 1999). A variety of methods have been suggested to account for the degradation, including prescribed fire. However, anthropogenic influence, including climate change, continues to threaten this ecosystem despite increasing awareness of the critical ecosystem services provided by the longleaf systems and the subsequent public and scientific support for their restoration and maintenance (Mitchell et al. 2014).

One such ecosystem service is the sequestration and retention of CO_2 from the atmosphere. Although fire maintains this ecosystem, it also returns a substantial amount of carbon back to the atmosphere while changing local meteorological conditions for periods of days to weeks (Whelan et al. 2013; Starr et al. 2015; Whelan et al. 2015). The impact of fire on the carbon cycle has been studied on timescales ranging from monthly to annual to decadal cycles and for regions with large burns (Amiro 2001; Amiro et al. 2003; Starr et al. 2015; Whelan et al. 2013; Whelan et al. 2015; Wirth et al. 2002). With expanding interest in continuous carbon cycle measurements, the density of flux towers is increasing, including in forested regions where prescribed burn practices are often used. While many studies have focused on long-term climate trends, the literature on how short-term changes may impact the carbon cycle at a particular site is virtually non-existant.

Previous studies investigating meteorological variables and carbon cycling in response to fire have identified altered carbon fluxes between the canopy and the atmosphere, as well as effects on surface temperatures as the primary impacts of fire (Hope and McDowell 1992, Clements et al. 2006). Impacts on near-surface temperature and heat fluxes have been attributed to albedo changes resulting from surface darkening following a burn, dramatically altering the radiation budget (Myhre et al. 2005, Bremer and Ham 1999). However, such studies have focused on the long-term changes on annual to decadal timescales.

Studies which have characterized meteorological conditions or carbon cycling during a prescribed burn or low-intensity fire have generally not extended beyond the burn period of a few hours. Studies by Clements et al. (2007) and Seto et al. (2014), for example, provide detailed measurements of meteorological conditions within the burn area but have ignored potential impacts beyond a few hours. Similarly, Virkkula et al. (2014) shows measurements of CO_2 during a prescribed burn but does not show potentially altered conditions which may exist beyond the day of the burn. Clements et al. (2006) reported measurements from a study of micrometeorological conditions within a burn which exhibited increases of temperature by 20°C, 400-500% increases in CO_2 concentration, heat flux exceeding 1000 W m^{-2}, CO_2 flux near 200 mg m^{-2} s^{-1}, and a 30% increase in water vapor during the burn compared to ambient atmospheric conditions. However, few studies have focused on measurements following the burn. One such study by Whelen et al. (2013) suggested that CO_2 fluxes following a low-intensity, prescribed burn may not return to their pre-burn levels for 30-60 days.

On January 19, 2013, a low-intensity burn was performed in the region surrounding the Aiken AmeriFlux tower. The intent of the burn was to remove understory fuel, primarily consisting of pine litter, to limit the potential for widespread wildfire. Measurements from the tower were used to describe the meteorological conditions present during a prescribed burn and the short-term effects of prescribed fire on local CO_2 dynamics to address the following questions:

1) What are the observable impacts of small-scale prescribed burns on CO_2 concentration and flux measurements? Characterization of these values is important for accurate assessment of the carbon cycle and how it relates to examining re-growth of vegetation after small-scale burns and during the regeneration period.

2) What is the recovery time of the forest carbon cycle? This is important for data analysis so that changes in the carbon cycle can be properly attributed to either small-scale burns or other environmental or biological impacts.

3) Do these impacts extend to other micrometeorological measurements? While CO_2 is the focus of this paper and a prime atmospheric component impacted by fire, it is expected that other variables such as

vertical wind velocity, air temperature or turbulence kinetic energy collected at typical flux towers will be impacted as well.

To adequately attribute periodic or short-term changes in the carbon cycle to prescribed fire near an instrumented tower is important to ensure that these changes are not mistakenly attributed to other factors such as impacts due to disease or insect infestations (Girousse et al. 2005; Amiro et al. 2010; Hicke et al. 2012) or natural year-to-year variations in growing conditions. This study thus fills a gap in our body of knowledge on short-term post-fire carbon cycle components by providing insight on short-term effects of prescribed fire on local CO_2 dynamics in a forested environment.

Methods

Site description

The study was conducted in a longleaf pine forest located at the Department of Energy's Savannah River Site (SRS) near Aiken, SC, USA (33° 23'N; 81° 40' E). This forest stand is dominated by *c*. 50 year-old longleaf pine (*Pinus palustris*) with an average canopy height of 23 m. In addition to the dominant longleaf pine that comprises the forest canopy, the stand also contains a small number of slash pine (*Pinus elliottii*) and white oak (*Quercus alba*). The soil is mainly Blanton sand with loamy subsoil more than 1.2 m below the surface (Rogers 1990). The surface fuel is dominated by longleaf pine leaf litter, but some grasses, such as dog-fennel (*Eupatorium compositifolium*) and broomsedge (*Andropogon* spp.) are also present (Wike et al. 2006). The USFS-SR does not allow extensive understory growth as a precautionary measure to limit the potential for extensive wildfires. Characteristics of the longleaf pine stand in the vicinity of the flux tower are presented in Table 1.

Measurements

At the center of the study site is the Aiken AmeriFlux tower, a 30 m walk-up tower equipped to measure micrometeorological variables at 2 m (below the pine canopy), 18 m (within canopy), and 28 m (above canopy). Each level of the tower is instrumented with a sonic anemometer (CSAT3; Campbell Scientific, Logan, Utah, USA) to measure three dimensional winds and virtual temperature along with an open-path CO_2/H_2O gas analyzer (LI-7500; Li-Cor Biosciences, Lincoln, NE, USA) to measure CO_2 and water vapor concentrations. All measurements were sampled at 20 Hz.

Using measurements from the Aiken AmeriFlux tower prior to, during, and after a prescribed burn conducted around the tower on 19 January 2013, we examined the changes in atmospheric CO_2 concentration and flux during the burn and the lasting impacts over the weeks following the burn as the ecosystem returns to its previous state. Measurements of CO_2 and related meteorological properties are presented at three heights (2m, 18m and 28m) for the week prior to the burn, during the burn period, and for 30 days after the burn.

Measurements from the week preceding the prescribed burn (i.e., pre-burn) were used as a baseline from which to compare measurements during (i.e., burn), and for 30 days after the burn (i.e., post-burn) for most CO_2 descriptions with larger periods (45 days prior to the burn through 90 days after the burn) used to assess changes in NEE. Measurements during periods of rain, as determined by a rain gauge located approximately 100 m from the tower, were removed from the analysis because water can obstruct the optical path of the gas analyzer and produce erroneous data. To account for errors related to the tilt of the sonic anemometers as well as moderately sloping topography, a planar fit was applied to the measurement data prior to analysis. The planar fit was performed following Wilczak et al. (2001) which imposes a coordinate transformation to ensure that the mean vertical velocity is zero. Additional corrections to account for density fluctuations were applied following Webb et al. (1980). Pressure measurements for performing the corrections were taken from 15-minute averages from a sensor located approximately 10 km away.

Prescribed burn

A prescribed burn was conducted on 19 January 2013. The burn began at 1510 UTC using solid strip ignition with subsequent ignitions at 40 m intervals lasting through 1910 UTC and active burning until approximately 2000 UTC. The initial ignition was done along the northeast side of the burn region and subsequent ignitions were set along lines placed 40m southwest of the previous line. Each of the fire fronts backed to the northeast toward the previous line of ignition, where it would burn out upon reaching the previously burned material. This created a low-intensity fire which consumed ground-level fuels but minimized impacts to the overstory trees. Pine needles within 2 m of the AmeriFlux tower were raked away to prevent damage to instrumentation or to the tower itself. After the burn, no scarring or noticeable flame damage was present on the overstory trees.

A summary of the characteristics of the fuel available for the prescribed fire calculated using the National Fire Danger Rating System are given in Table 2. The values of 1, 10 and 100 hour dead fuel moisture depict the timelag with which various plant types respond to ambient meteorological conditions, and can be tied to the thickness of the plants available for fuel with larger lags correlating with larger plant stem diameters. The Keetch-Byram drought index (KBDI; Keetch and Byram 1968) describes the available water and ranges from 0 to 800, with higher numbers indicating extremely dry conditions where loss of control may be an issue. The Burning Index describes the difficulty of controlling a fire (Burgan 1988) with a typical range of 0 to approximately 100, with low numbers representing low risk. The values of 255 for KBDI and 10 for the Burning Index suggest that conditions were good for conducting the prescribed burn on this day. The fire itself had average flame lengths of ~0.5 m and spread at a rate of 20 m hr^{-1}, meaning it generally took about 2 hours for each fire front to burn from its ignition location to the previous ignition location 40 m away.

Prevailing near-surface winds measured at a meteorological tower located in a small clearing 18 km from the burn site showed light winds throughout the burn period (< 3 m s^{-1} at heights of 2, 18, 36 and 61m) from the northeast before shifting to southeast and then southwest during the burn. Winds above the canopy were initially from the northeast, but shifted to flow from the northwest early in the burn period.

Statistical analysis

For similar studies, averaging times for meteorological variables have ranged from 0.1 seconds to 30 minutes (Amiro 2001; Clements et al. 2006). Given the short duration of the burn (~ 5 hours), most measurements were averaged over 1-minute periods to ensure sufficient detail in trends and variations. The averaging period was selected to show variations in the measurements over small time periods during the burn. The same averaging period was used in pre- and post-burn analysis for consistency. Averages were calculated using

$$\overline{X} = \frac{1}{1201}\sum_{n=-600}^{600} X_n \quad (1)$$

where X_n is the value of the variable being averaged. The range of -600 and 600 describe the time periods 30 seconds prior to and after the point in time the averaging is occurring (30 seconds · 20 measurements per second). For some measurements, the standard deviation over the 1-minute periods was used to estimate their variability and was calculated as

$$\sigma_X = \left(\frac{1}{1200}\sum_{n=-600}^{600}\left(X_n - \overline{X}\right)^2\right)^{0.5} \qquad (2)$$

To determine whether the measurements recorded after the burn were significant, a two sample, two sided, unequal variance, unequal sample size t-test was performed. Differences were tested between a burned and an unburned year for 45 days pre burn, 0-30 days post burn, and 60-90 days post burn at 2 m and at 18 m. Differences were also tested at 2 m and at 18 m for the burned year between the 45 days pre burn and the two post burn periods (0-30 days, and 60-90 days). For each test a null hypothesis of $\mu_1=\mu_2$ and an alternative hypothesis of $\mu_1\neq\mu_2$ are used and tested with statistical significance defined as $\alpha<0.05$. The t-value was calculated as:

$$t = \frac{\bar{x}_1 - \bar{x}_2}{s_{\bar{x}_1-\bar{x}_2}}$$

where x_1 and x_2 are sample means and

$$s_{\bar{x}_1-\bar{x}_2} = \sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}$$

where s_1 and s_2 are the sample standard deviations, and n_1 and n_2 are the number of samples in each mean.

Results & Discussion

Burn patterns

While monitoring micrometeorological and carbon cycle conditions during the burn are not the primary goal of this study, a summary of the conditions and measurements taken during the burn are presented so that comparison with other burn studies can be performed. The burn was ignited at 1510 UTC on January 19, 2013 at the upwind boundary of the burn region relative to the AmeriFlux tower (Fig. 1) with subsequent ignitions moving to the southwest past the tower. By design, the flame heights were relatively low (1 m or less). With the lowest level of instrumentation on the flux tower at 2 m, the instruments were adequately protected from air temperatures above the operating range of the sensors (323 K) and from reflections of heat from the flames themselves. Spikes in the temperature and carbon flux data are likely caused by smoke crossing the open path of the flux sensors. Two distinct time periods centered at approximately 1630 and 1710 UTC were identified when plume impacts on the tower were strongest. The first spike occurred as the smoke plume from the upwind fire strip located nearest to the tower was ignited. The second spike is attributed to the subsequent fire line ignited slightly downwind of the tower which burned back past the tower, passing the tower at approximately 1650 UTC.

Mean [CO_2] increased 17-25% during the burn period compared to the pre-burn period with the greatest increase occurring within the canopy (Table 3). The increase in CO_2 was primarily noted with larger increases within and above the canopy rather than below the canopy (Fig. 2). The increase in [CO_2] was larger with the second fire front below and above the canopy, and comparable with the first plume within the canopy. After the second fire front passed the tower, [CO_2] began to diminish down to its pre-burn conditions, but continued to show greater variability than was present prior to the burn, particularly within and above the canopy.

The effects of the burn on $\overline{w'c'}$ only exhibited large increases when the fire fronts were near the tower (Fig. 3) where stronger convective activity driving the changes in $\overline{w'c'}$ was present. This is supported by measurements of vertical velocity which show substantial increases in variability near the 1630 and 1710 UTC times noted above when smoke plumes impacted the tower (Fig. 4). Also noted in the vertical velocity data were weak downdrafts surrounding the strong upward convective motions as ambient air was drawn into the burn to replace rising air at the flame front. This matches the fire /behavior noted by Sun et al. (2006) and Clements et al. (2007) where cooler air was drawn down both ahead of and behind the fire front in response to the rising warm air in the smoke plume.

Turbulence kinetic energy (TKE) during the burn was found to steadily increase ahead of the burn as smoke plumes affected the tower (Fig. 5). The 28m level shad its highest TKE ahead of the burn reaching the tower when smoke plume from fire lines further upwind had the greatest influence. As the fire lines closer to the tower were ignited, the smoke plumes would have had less influence on the 28 m level and increased influence on lower levels. This is reflected in the peak values of TKE at 18m and 2m occurring when the fire lines were near the tower. After the fire lines passed, TKE slowly decreased as the fires to the northeast of the tower burned out. Late in the burn period, between 19 and 20 UTC, TKE again increased at all levels. This is attributed to the shifting winds from northeast to southeast and southwest during the burn period which would have blown smoke plumes from the last fire lines, located southwest of the tower, back towards the tower.

While some of these measurements exceeded the measurement bounds and operating temperature conditions the instruments are designed for, no data was removed from this part of the analysis since conditions prior to and after the burn were the primary focus of this study.

Comparison of Pre- and Post-Burn Conditions

The patterns of the carbon cycle are documented for sites in the southeastern United States similar to the one we are studying. For example, Whelan et al. (2013) examined trends in carbon cycle for longleaf pines in the Joseph W. Jones Ecological Research Center in southwestern Georgia, USA and Powell et al. (2008) studied trends in the Austin Cary Memorial Forest in northern Florida, USA. In both studies, the forest was determined to be a net source of CO_2 during nighttime hours and become a sink during daytime hours following the established diurnal cycle of tree and plant growth. The same pattern is observed in our forest, with a diel pattern with higher concentrations during the night when CO_2 has a tendency to accumulate near the surface due to weaker nighttime turbulence and lower concentration during the day when CO_2 uptake by vegetation was occurring (Fig. 6). The diel pattern was most evident near the surface where [CO_2] decreased and remained steady during the day and then increased and exhibited greater variability at night. Variations in [CO_2] were quite small above the canopy, slightly higher within the canopy, and much larger below the canopy. Variations in [CO_2] below the canopy were much higher at night when CO_2, whereas variations within the canopy were higher during the day. Variations above the canopy were very small, regardless of the time of day. Following a cold front passage on 17 Jan 2013, [CO_2] increased approximately 2 mmol m^{-3} and the nighttime variation near the surface was reduced.

At night, $\overline{w'c'}$ showed low magnitude positive fluxes, indicating a slow transport of CO_2 from within the canopy upwards to the atmosphere above the canopy (Fig. 7). During the day, $\overline{w'c'}$ exhibited the opposite behavior with a net transport of CO_2 from the atmosphere above the forest into the canopy layer, illustrated by the large negative fluxes occurring above the canopy and, to a lesser extent, within the canopy.

Following the burn, [CO_2] decreased from its peak values during the burn, but remained 4-8% higher than prior to the burn, with the greatest increase in [CO_2] occurring below the canopy level (Fig. 8). At 2 and 18 m, these increases varied over the 30 days following the burn, with [CO_2] remaining higher at lower canopy levels, but the level of [CO_2] above the canopy remained unchanged at 28 m for the three post-burn sampling periods. It is also worth noting the difference in [CO_2] between the 2m and 28 m levels 30 days after the burn had returned to the same level as the pre-burn difference, though mid-canopy levels of CO_2 remained elevated.

The CO_2 concentration remained elevated, particularly in the first 48 hours post-burn. Compared to pre-burn concentrations (i.e., Jan 14-17), [CO_2] in the first 48 hours following the burn increased *c*. 10%, 10% and 20% above the canopy, within the canopy, and below the canopy, respectively. [CO_2] within the canopy also exhibited increased variability compared to pre-burn conditions. The [CO_2] remained elevated for about 10 days following the burn before a cold front passed and [CO_2] temporarily dropped to near pre-burn levels before a slight increase in [CO_2] was observed two days later and remained steady through the 0-30 day post-burn period.

Variation in [CO_2] remained small in the weeks after the burn except during the frontal passages or around periods of rain. The standard deviation tended to be higher at the 2m level than at the 18 or 28 m levels which can be attributed to greater carbon sources and sinks within the forest than above it while the 28m level was consistently mixed with the free atmosphere above the canopy, leading to less variation of [CO_2] on short time scales. The trend of $\overline{w'c'}$ was similar to its pre-burn trends, but the magnitude of $\overline{w'c'}$ was reduced from its pre-burn values (Fig. 9). This was noted at all levels, but was most pronounced within the canopy layer. The reduction in magnitude remained for the following weeks, indicating a reduced rate of transport of CO_2 between the canopy levels. This may be attributable to the removal of near-surface vegetation which diminished the carbon uptake/respiration signal that was present prior to the burn.

In the days following the burn, the ground remained altered as smoldering occurred and the albedo was reduced through blackening of the surface material. During the four days prior to the burn, the average temperature difference between the canopy level and the lower forest level ($T_{18m} – T_{2m}$) was -0.01 ± 0.70 K, indicating no clear tendency for the air near the surface to be warmer or cooler than air within the tree canopy. Following the burn, the temperature difference was found to be -0.11 ± 0.83 K two days after the burn, -0.48 ± 0.75 K fifteen days following the burn and -0.51 ± 0.98 K thirty days following the burn, indicating a tendency for air near the surface to be warmer following the burn. Examination of this tendency after 60 days was -0.05 ± 0.74 K, indicating a return to pre-burn conditions.

Trends in NEE

Looking at larger trends in Net Ecosystem Exchange (NEE) over the forest, we expanded our analysis to conditions beginning 45 days prior to the burn and lasting 90 days after the burn. Conditions were then compared to the previous un-burned year to identify changes in NEE that may be directly attributed to the burn (Table 4). Direct comparisons are shown for the 2 and 18m level; at the 28m level, data was available during the burn year, but not for the year before, so no data comparisons are presented in Table 4, but the available data is discussed below.

In the 45 days prior to the burn, the 2m and 18m levels showed similar behavior that is consistent both in the burn and the un-burned year. In both years, the NEE indicates a slight sink of CO_2 on average at the 18 m level, but within a standard deviation of being neutral. The 2m level indicates a slightly positive NEE. After the burn, the forest is a sink for CO_2, with the magnitude of the NEE sink approximately 5 times greater in the burned year at 18 m than in the un-burned year. At the 2m level, the magnitude of the NEE source has been reduced by 40% compared to the un-burned year.

Examining calculated NEE during the 0-30 day period and during the 60-90 day period following the burn shows a steadily decreasing value of NEE following the burn. During the first 30 days post-burn, NEE values were lower at both 2 and 18 m. The forest remained a net source at 2 m, but the magnitude of NEE was reduced by 74%. At 18m, the forest became a greater sink, with a magnitude nearly three times greater than the pre-burn values. However, how much of this change is the result of the burn is uncertain because similar trends were noticed in the unburned year, with the value of NEE only half its magnitude at 2m during the same period and three times greater in magnitude at 18m. This suggests that the burn had only a limited impact on the NEE in the first few weeks following the burn and that the changes reflected during this period may have more to do with the natural carbon cycle of the forest during this period.

The trends in NEE during the 60-90 days post-burn period exhibit differing behaviors between the two years. At 2m, the NEE during the unburned year increased so that it was higher during the 60-90 day period than it was during the corresponding pre-burn period. Following the burn, NEE was higher during the 60-90 day period than it was during the 0-30 day period, but was still substantially reduced compared to the pre-burn period. While the increase in NEE from the 0-30 to the 60-90 day periods is likely reflective of natural progression of the carbon cycle, the reduction in magnitude from the pre-burn period may reflect the substantial carbon loss that occurred during the burn. While the values of NEE during the burn year were notably lower than the unburned year to begin with, we might still expect a value of NEE approximately three times larger at 2m than was observed if the behavior of NEE would otherwise be expected to follow what occurred during the unburned year. At 18 m, the value of NEE became much more negative during the 60-90 day period, indicating a much greater sink of NEE. While the strength of the sink is larger to begin with in the burn year, this conflicts with the trend in the unburned year when the sink became weaker during this same period.

Some variation may be due to differences in meteorological conditions. However, the changes reported in NEE as a function of wind speed and PAR reported by Whelan et al. (2013) indicate changes on the order of 0.01 – 0.10 g C m^{-2} s^{-1} which are an order of magnitude smaller than the changes we are reporting, so the changes in our data are not expected to be due solely to changing weather conditions between the unburned and burned years or from the pre-burn to post-burn periods.

At the 28 m level, the average NEE leading up to the burn was -2.93 g C m^{-2} d^{-1} with a standard deviation of 3.28 g C m^{-2} d^{-1}, indicating the forest was acting as a carbon sink but remained nearly carbon neutral. After the burn, the NEE remained nearly unchanged for the first 30 days following the burn before becoming decidedly negative beginning in late February. The steady decline in NEE is attributed to forest re-growth, though whether it was enhanced due to fire or represented natural springtime growth in unclear as there was no data available from the previous year at the 28 m level.

To test whether the changes in NEE between years and between pre- and post-burn periods were statistically significant, a two sample, two sided, unequal variance, unequal sample size t-test was performed (Table 5). Comparing values between the pre-burn periods in each year, only the 2m conditions were found to be significant while comparison of post-burn periods in each year produced statistically significant results for both 0-30 and 60-90 days post burn at both 2 and 18m. Comparison of different periods in the burn year yielded significance only when comparing the 0-30 day period at 2 m.

Previous results reported by Whelan et al. (2013) indicated that NEE values returned to pre-burn conditions after 1-2 months and also observed that pre-burn conditions were generally re-established approximately 90 days after the burn. This behavior was seen during the unburned year, suggesting that we may expect this to be the natural cycle when the forest is undisturbed. However, during the burn year, the results we've reported suggest that greater differences in NEE were observed 60-90 days following the burn than were observed in the first 30 days. Like the previous studies by Sun et al. (2006), Clements et al. (2007) and Wehlan et al. (2013), this was a low-intensity burn which did not affect the overstory of the forest, so the differences must be attributable to changes in the understory or possibly soil conditions. Limited data was available during this period for soil data, so no conclusions can be drawn what changes occurred in the soil across the burned region. Soil moisture, as measured by a COSMOS probe located approximately 60 m from the AmeriFlux tower, indicated that soil moisture was only 5-10% lower in the 5-10 days following the burn (not shown), but no soil temperature data was available for the burn period.

Data Limitations

This study examines micrometeorological conditions during a low-intensity prescribed burn and the carbon dynamics observed following the burn with the goal of identifying how the carbon cycle and NEE may be impacted by the burn. While the data presented provides a good base for future work, there are improvements in data collection and processing that would benefit the quality of additional studies. The use of an off-site pressure sensor in the calculation of our WPL corrections likely hinders the quality of the data being taken during the burn itself when pressure at the burn location would be expected to have a substantial spatial variation. Also, the short data record available following the burn hinders the extent to which this particular case can be used to quantify the effects of the burn on forest characteristics and carbon cycle, particularly with regard to the effects of a small-scale burn on annual NEE. These limitations are expected to be addressed in future prescribed burn studies.

Conclusions

Fire has been documented to influence the local carbon cycle as well as other micrometeorological variables with effects that may last for at least a month. The presence of flux sites in regions where prescribed fires may be routinely used to manage the forest environment requires a knowledge of how fire directly impacts measurements related to monitoring carbon cycle and how long these effects may be expected to last to ensure that changes in the local carbon cycle are not attributed to other factors such as disease, insect infestation or simply natural inter-annual variations.

The results of our study supported results from previous studies by Whelan et al. (2013) which observed fire impacts which could impact the carbon cycle for up to and beyond 30 days. In our results, [CO_2] remained higher at all levels and $\overline{w'c'}$ showed decreased variability, particularly at the lowest level of the forest, 30 days following the burn. While these changes are likely linked to the burn and resulting changes in vegetation structure along the forest floor, it is unclear how much natural seasonal variation could play in these results. Future work in this area would benefit from being able to compare carbon cycle components at nearby sites to assess what portion of the measured changes are due to natural variations in the local ecosystem. Additional characterization of fuel types and corresponding flux measurements in a non-burned area would improve future *in situ* fire studies.

While the greatest impacts were to micrometeorological variables and were generally limited to a few hours to 1-2 days, the impacts to the CO_2, particularly to the flux of CO_2 into or out of the forest lasted much longer. Comparison of NEE values from the burn year of 2013 to the previous un-burned year showed differences in averages and standard deviations that are statistically significant. While some of the differences reflect differences in meteorology and biology within the forest between the two years, there is greater significance in the post-burn periods compared to the pre-burn periods, which suggests that the fire plays a role in the difference of measurements between the two years.

The prescribed burn examined here was small in scale and focused only on removing understory but still impacted the carbon cycle in the forest for out to 90 days or more after the burn. While other burns or wildfires may be larger and have greater impacts, a lack of understanding regarding how a nearby small or prescribed burn can impact short-term carbon cycles may lead to unexplained or misinterpreted measurements. We expect to use this study as a basis for examining future prescribed fires to develop a greater understanding of how fire influences local carbon measurements and what secondary influences, such as fuel characterization or atmospheric conditions, may also play a role. Understanding these impacts is important when examining CO_2 trends using towers in regions where prescribed burns are routinely used.

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References

Amiro, B. D., 2001: Paired-tower measurements of carbon and energy fluxes following disturbance in the boreal forest. Global Change Biology. **7**, 253-268.

Amiro, B. D., MacPherson, J. I., Desjardins, R. L., Chen, J. M., and Liu, J., 2003: Post-fire carbon dioxide fluxes in the western Canadian boreal forest: evidence from towers, aircraft and remote sensing. Agricultural and Forest Meteorology. **115**, 91-107.

Amiro, B. D., et al., 2010: Ecosystem carbon dioxide fluxes after disturbance in forests of North America. J Geophys. Res. **115**, G00K02, doi:10.1029/2010JG001390.

Bonds, W. J., and Keeley, J. E., 2005: Fire as a global 'herbivore': the ecology and evolution of flammable ecosystems. Trends in Ecology and Evolution. 20(7), 387-394.

Bremer, D. J., and Ham, J. M., 1999: Effect of spring burning on the surface energy balance in a tallgrass prairie. Agricultural and Forest Meteorology. **97**, 43-54.

Burgan, R. E., 1988: 1988 revisions to the 1978 national fire-danger rating system. Research Paper SE-273. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 39pp.

Clements, C. B., Potter, B. E., Zhong, S., 2006: In situ measurements of water vapor, heat, and CO_2 fluxes within a prescribed grass fire. International Journal of Wildland Fire. **15**, 299-306.

Clements, C. B., Zhong, S., Goodrick, S., Li, J., Potter, B. E., Bian, X., Heilman, W. E., Charney, J. J., Perna, R., Jang, M., Lee, D., Patel, M., Street, S., Aumann, G., 2007: Observing the dynamics of wildland grass fires: Fireflux – a field validation experiment. Bulletin of the American Meteorological Society. **88**, 1369-1382.

Gilliam, F. S., Platt, W. J., 1999: Effects of long-term fire exclusion on tree species composition and stand structure in an old-growth *Pinus palustris* (Longleaf pine) forest. Plant Ecology. **140**, 15-26.

Girousse, C., Moulia, B., Silk, W., Bonnemain, J.-L., 2005: Aphid infestation causes different changes in carbon and nitrogen allocation in alfalfa stems as well as different inhibition of longitudinal and radial expansion. Plant Phys. **137**, 1474-1484.

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

Hope, A. S., and McDowell, T. P., 1992: The relationship between surface temperature and a spectral vegetation index of a tallgrass prairie: effects of burning and other landscape controls. International Journal of Remote Sensing. **13**, 2849-2863.

Keeley, J. E., Pausas, J. G., Rundel, P. W., Bond, W. J., Bradstock, R. A., 2011: Fire as an evolutionary pressure shaping plant traits. *Trends in Plant Science*. **16**, 406-411.

Keetch, J. J., Byram, G. M., 1968: A drought index for forest fire control. Research Paper SE-38. Asheville, NC: U.S. Department of Agriculture, Forest Service, Southeastern Forest Experiment Station. 35pp.

Mitchell, R.J., Y. Liu, J.J. O'Brien, K.J. Elliott, G. Starr, C.F. Maniat, J.K. Hiers (2014). Future Climate and Fire Interactions in the Southeastern Region of the United States. Forest Ecology and Management. http://dx.doi.org/10.1016/j.foreco.2013.12.003

Myhre, G., Govaerts, Y., Haywood, J. M., Berntsen, T. K., and Lattanzio, A., 2005: Radiative effect of surface albedo change from biomass burning. Geophysical Research Letters. **32**, L20812.

Noss, R. F., 1990: Indicators for monitoring biodiversity: a hierarchical approach. *Conservation Bio.*, **4**, 355-364.

Powell, T. L., Gholz, H. L., Clark, K. L., Starr, G., Chopper Jr, W. P., and Martin, T. A., 2008: Carbon exchange of a mature, naturally regenerated pine forest in north Florida. *Global Change Biology*, **14**, 1-16.

Rogers, V. A., 1990: Soil survey of Savannah river plant area, parts of Aiken, Barnwell, and Allendale counties, South Carolina. USDA Soil Conservation Service, Washington DC

Seto, D., Strand, T. M., Clements, C. B., Thistle, H., Mickler, R., 2014: Wind and plume thermodynamic structures during low-intensity subcanopy fires. Agricultural and Forest Meteorology. **198-199**, 53-61.

Starr, G., Staudhammer, C. L., Loescher, H. W., Mitchell, R., Whelan, A., Hiers, J. K., and O'Brien, J. J., 2015: Time series analysis of forest carbon dynamics: recovery of *Pinus palustris* physiology following a prescribed fire. *New Forests*, **46**, 63-90.

Sun, R., Krueger, S. K., Zalauf, M. A., Jenkins, M. A., Charney, J. J., 2006: Wildfire evolution in the convective boundary layer. Preprints, *17th Symposium on Boundary Layers and Turbulence*, San Diego, CA, American Meteorological Society, CD-ROM, 1.8A.

Virkkula, A., Pohja, T., Aalto, P. P., Keronen, P., Schobesberger, S., Clements, C. B., Petaja, T., Nikmo, J., Kulmala, M., 2014: Airborne measurements of aerosols and carbon dioxide during a prescribed fire experiment at a boreal forest site. Boreal Environment Research. **19**, 153-181.

Webb, E. K., Pearman, G. I., and Leuning, R., 1980: Correction of flux measurements for density effects due to heat and water vapor transfer. *Quart. J. R. Met. Soc.*, **106**, 85-100.

Whelan, A., Mitchell, R., Staudhammer, C., and Starr, G., 2013: Cyclic occurrence of fire and its role in carbon dynamics along an Edaphic moisture gradient in longleaf pine ecosystems. PLoS One 8(1): e54045.

Whelan, A., Starr, G., Staudhammer, C. L., Loescher, H. W., and Mitchell, R. J., 2015: Effects of drought and prescribed fire on energy exchange in longleaf pine ecosystems. *Ecosphere*, **6(7)**:128. http://dx.doi.org/10.1890/ES15-00111.1

Wike, L. D., Martin, F. D., Nelson, E. A., Halverson, N. V., Mayer, J. J., Paller, M. H., Riley, R. S., Serrato, M. G., Specht, W. L., 2006: SRS Ecology Environmental Information Document. WSRC-TR-2005-00201. Accessed on May 16, 2016. http://sti.srs.gov/fulltext/WSRC-TR-2005-00201.pdf

Wilczak, J. M., Oncley, S. P., and Stage, S. A., 2001: Sonic anemometer tilt correction algorithms. Boundary Layer Meteorology. **99**, 127-150.

Wirth, C., Czimczik, C. I., and Schulze, E.-D., 2002: Beyond annual budgets: carbon flux at different temporal scales in fire-prone Siberian Scots pine forests. Tellus. **54**, 611-630.

Table 1. Characteristics of the forest stand that comprises the footprint of the flux tower. Data were derived from an aerial LiDAR scan conducted in 2009. Data presented are the mean values with the total range (minimum and maximum values) fom each LiDAR grid cell immediately below in parentheses.

Height (m)	Density (tree ha^{-1})	Basal Area (m2 ha-1)	Volume (m3 ha-1)	Biomass (Mg ha-1)
19.7 (8.3-21.4)	525.8 (81.0-973.9)	19.7 (1.6-39.4)	178.7 (4.3-428.9)	91.6 (1.2-218.3)

Table 2. Fire and fuel characteristics of the burn region surrounding the Aiken AmeriFlux Tower

1-hr Fuel Moisture	10%
10-hr Fuel Moisture	10%
100-hr Fuel Moisture	17%
Drought Index (KBDI)	255
Burning Index	10
Surface Rate of Spread	20 m hr^{-1}
Flame Length	0.5 m

Table 3. Mean (± 1 standard deviation) CO_2 concentration [mmol m^{-3}] before, during, and after the prescribed burn conducted on January 19, 2013. Starting and ending times were 00 UTC except for the burn period on 01/19.

	Averaging Period				
Height	01/14-01/18	01/19 16Z-18Z	01/20-01/22	02/01-02/03	02/17-02/19
28 m	15.88 ± 1.60	19.53 ± 4.02	16.79 ± 0.76	16.60 ± 1.02	17.14 ± 0.44
18 m	16.20 ± 0.90	20.30 ± 5.14	18.12 ± 1.88	16.81 ± 0.83	17.46 ± 0.62
2 m	16.81 ± 1.62	19.61 ± 4.71	18.56 ± 1.99	16.84 ± 1.21	17.31 ± 0.70

Table 4: A comparison of NEE (g C m^{-2} s^{-1}) averages and standard deviations during the burn period and the previous unburned year.

		Un-burned Year (2012)		Burned Year (2013)	
		Average NEE	Standard Deviation of NEE	Average NEE	Standard Deviation of NEE
45 Days Pre-Burn	18 m	-0.226	2.726	-1.249	2.751
	2 m	4.145	2.083	2.470	1.602
0-30 Days Post-Burn	18 m	-0.797	1.303	-3.677	3.792
	2 m	2.366	1.514	0.630	1.053
60-90 Days Post-Burn	18 m	-0.525	2.656	-6.758	4.650
	2 m	5.478	1.859	0.963	1.384

Table 5: P-Values calculated to determine statistical significance in the changes of NEE between various burn periods. μ_1 is the null hypothesis and μ_2 is the alternative hypothesis. Values that are considered statistically significant are in bold.

μ_1	μ_2	P-Value
Unburned Year 45 Days Pre-Burn 18 m	Burned Year 45 Days Pre-Burn 18 m	0.081
Unburned Year 45 Days Pre-Burn 2 m	Burned Year 45 Days Pre-Burn 2 m	**< 0.0001**
Unburned Year 0-30 Days Post-Burn 18 m	Burned Year 0-30 Days Post-Burn 18 m	**0.0002**
Unburned Year 0-30 Days Post-Burn 2 m	Burned Year 0-30 Days Post-Burn 2 m	**< 0.0001**
Unburned Year 60-90 days Post-Burn 18 m	Burned Year 60-90 Days Post-Burn 18 m	**< 0.0001**
Unburned Year 60-90 days Post-Burn 2 m	Burned Year 60-90 Days Post-Burn 2 m	**< 0.0001**
Burned Year 45 Days Pre-Burn 18 m	Burned Year 0-30 Days Post-Burn 18 m	0.1999
Burned Year 45 Days Pre-Burn 2 m	Burned Year 0-30 Days Post-Burn 2 m	**0.0477**
Burned Year 45 Days Pre-Burn 18 m	Burned Year 60-90 Days Post-Burn 18 m	0.0775

Burned Year 45 Days Pre-Burn 2 m	Burned Year 60-90 Days Post-Burn 2 m	0.533

Figure Captions

Figure 1: Aerial photo of the study site. Ignition began north and northeast of the AmeriFlux Tower at 1510 UTC with subsequent ignitions spaced approximately 40 m of the previous ignition, producing a backing fire in which each subsequent fire front spread toward the northeast. The Aiken AmeriFlux tower is identified as the green triangle

Figure 2: 1-minute averaged CO_2 concentration during the prescribed burn period at a) 28, b) 18 and c) 2 m. The solid vertical lines represent the start and stop times of the burn; the dashed vertical line indicates the passage of the fire at the site of the AmeriFlux tower. The dashed horizontal line shows the trend in [CO_2] during the previous day for the same time period for comparison.

Figure 3: 1-minute averaged vertical CO_2 flux during the prescribed burn period at a) 28, b) 18 and c) 2 m. The solid vertical lines represent the start and stop times of the burn; the dashed vertical line indicates the passage of the fire at the site of the AmeriFlux tower. The dashed horizontal line shows [CO_2] during the previous day for the same time period for comparison.

Figure 4: 1-minute averaged vertical wind speed during the prescribed burn period at a) 28, b) 18 and c) 2 m. The solid vertical lines represent the start and stop times of the burn; the dashed vertical line indicates the passage of the fire at the site of the AmeriFlux tower. Positive *w* indicates rising motion while negative *w* indicates sinking motion.

Figure 5: 1-minute averaged turbulence kinetic energy during the prescribed burn period at a) 28, b) 18 and c) 2 m. The solid vertical lines represent the start and stop times of the burn; the dashed vertical line indicates the passage of the fire at the site of the AmeriFlux tower.

Figure 6: 1-minute averaged CO_2 concentration in the days leading up to the prescribed burn at a) 28, b) 18 and c) 2 m. Gaps in the data occur during rainfall events.

Figure 7: 1-minute averaged vertical CO_2 flux in the days leading up to the prescribed burn at a) 28, b) 18 and c) 2 m. Gaps in the data occur during rainfall events.

Figure 8: 1-minute averaged CO_2 concentration after the prescribed burn period at a) 28, b) 18 and c) 2 m. The dashed vertical lines represent the start and stop times of the burn. Gaps in the data occur during rainfall events.

Figure 9: 1-minute averaged vertical CO_2 flux after the prescribed burn period at a) 28, b) 18 and c) 2 m. The dashed vertical lines represent the start and stop times of the burn. Gaps in the data occur during rainfall events.