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Effects of Prescribed Fire on Soil Respiration in a Longleaf Pine Forest.

Caroline E. Paxton

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by

Caroline E. Paxton

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Approved by:

Micheal A. Davis, Ph.D.,
Thesis Advisor,
School of Biological, Environmental and Earth Sciences

Jake F. Schaefer, Ph.D., Director,
School of Biological, Environmental and Earth Sciences

Ellen Weinauer, Ph.D., Dean
Honors College

ABSTRACT

Prescribed fire is a common tool used to increase the herbaceous diversity in longleaf pine forest understories and to eliminate competition from undesirable mid-canopy species. Little is known about the effects of these fires on the soil respiration rates within these forests. A study of the effects of prescribed fire on soil respiration was conducted within a longleaf pine stand at the Lake Thoreau Environmental Center to examine soil respiration across seasons and before and after a prescribed fire. Soil CO_2 efflux rates were measured using a LICOR LI-8100A gas flux system with long-term chambers from October 2020 to March 2021. Initial analyses showed a sharp decrease in soil respiration after the prescribed fire. However, closer examination of the data revealed distinctive seasonal temperature variations. Subsequent analyses using daily high temperature as a covariate and eliminating the warmer months of October and November showed that there was no significant effect of prescribed fire on soil respiration. This study highlights both the value of long-term data collection for examining soil respiration and the danger of not considering other environmental parameters when analyzing soil respiration data.

Keywords: soil respiration, prescribed fire, longleaf pine, forest management

DEDICATION

This paper is dedicated to my parents, Michael and Jennie Paxton, who raised me to view this world with profound wonder and joy. For your love and support, and for putting up with my own special brand of weirdness, thank you.

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LIST OF ABBREVIATIONS

DF	Degrees of Freedom
EP	Eubanks Preserve
IRGA	Infra-red gas analyzer
LLP	Longleaf Pine Preserve
LLPS	Longleaf Pine Savanna(s)
LTEC	Lake Thoreau Environmental Center
PLSD	Protected Least Significant Difference
PVC	polyvinyl chloride
SR	soil respiration
USM	University of Southern Mississippi

CHAPTER I: INTRODUCTION

Prior to European settlement, much of the southeastern United States was dominated by longleaf pine (*Pinus palustris*) ecosystems (Oswalt, 2012). These communities were shaped by, and adapted to, natural fires that occurred every two or three years (White and Harley, 2016). This recurring fire frequency resulted in an open landscape that allowed herbaceous understory diversity to flourish and provided habitat for many bird and animal species (Aschenbach et al., 2010; Clinton et al., 2011; Jose et al., 2007; Whelan et al., 2013). By the early 1900s, logging and conversion of forests to agricultural or urban land use began to reduce the original range of these ecosystems. The subsequent replanting of cleared areas with loblolly (*Pinus taeda*) or slash pine (*Pinus elliottii*) and the widespread practice of fire suppression prevented longleaf pine savannas (LLPS) from recovering, subsequently leading to a ~97% loss of original LLPS habitat (Bizzari et al., 2015; Jose et al., 2007; Wright et al., 2020). Recent reintroduction of prescribed burns and other efforts to restore longleaf pine habitats have been successful in returning portions of the remaining ecosystem to its natural state.

The balance of carbon on earth is not static; rather, it is in a constant state of change, or flux, as carbon travels among terrestrial environments (above- and belowground), the oceans, and the atmosphere. Individual ecosystems can serve as carbon sources or sinks, meaning that their community composition and combined photosynthetic and respiration rates contribute to either a net gain in atmospheric carbon or a net loss through immobilization and sequestration (Maier et al., 2011). The largest source of natural terrestrial CO_2 efflux (i.e., return to the atmosphere) comes from soil respiration (SR) and is a combination of all autotrophic and heterotrophic processes during carbon cycling within the soil (Bloemen et al., 2012; Bond-Lamberty & Thomson, 2010; Giasson et al., 2013; Raich & Tufekcioglu, 2000; Ryan & Law, 2005). While microbial respiration and organic matter decomposition play a large role in SR dynamics, the metabolic activities of plant roots and mycorrhizal networks generate the greatest percentage of soil CO_2 (Giasson et al., 2013; Plaza-Álvarez et al., 2017; Schlesinger & Andrews, 2000). The rate at which that carbon is released into the atmosphere via SR depends on the amount of belowground biomass as well as other environmental factors (e.g., precipitation, temperature) discussed below.

Soil temperature is an influential factor governing ecosystem SR dynamics. This is evidenced by the relationship that exists between SR and temperature, wherein efflux rates increase or decrease as temperature rises or falls. This correlation is largely dictated by season, with SR rates generally at their lowest during winter months and at their highest in summer (Lellei-Kovács et al., 2011; Maier et al., 2011; Reichstein et al., 2003; Samuelson & Whitaker, 2012). Soil moisture content and nutrient availability can also impact SR. Saturated soils release more CO_2 than those that are dry, thus xeric and drought-prone areas often have lower rates of SR than more mesic habitats (Cook & Orchard, 2008; Giasson et al., 2013). Similarly, nutrient-poor soils also have lower SR rates due to ecosystem wide shifts in growth patterns. In such instances, plant communities will often allocate more resources to above-ground biomass production than subsurface root production, leading to lower SR (Giasson et al., 2013; Maier et al., 2011). In ecosystems dominated by herbaceous species, as is the case in LLPS, the opposite is true, and SR rates will typically be higher in comparison.

There are certain difficulties and challenges present in quantifying the release of gaseous carbon from the ground. Most estimates of ecosystem productivity are based on stand biomass or remote sensing methods, which are unable to provide a direct measure of soil efflux (Bond-Lamberty & Thomson, 2010; Matson & Harris, 2009; Zhang et al., 2012). Respiration rates are instead determined using specialized chambers that read and record changes in ground to atmospheric CO_2 over time. Such systems may be either steady- or non-steady state and are often further classed as static or dynamic based on the level of interaction between the chamber and atmosphere (Matson & Harris, 2009). Steady-state chambers are usually open to the air and calculate CO_2 concentrations based on the difference between the inlet and outlet sources. Non-steady state systems determine concentrations based on the rate of CO_2 increase within isolated, closed chambers (Liang et al., 2004; Pumpanen et al., 2003) Long-term chamber systems are often paired with infrared gas analysis (IRGA) techniques and pre- or post-measurement CO_2 purges to reduce sources of error inherent to such systems (Liang et al., 2004). In the present study, a non-steady state, dynamic setup consisting of a LI-8100A flux system and corresponding LI-8150 multiplexer was used to quantify SR.

Given that root density and rates of litter deposition and decomposition are naturally higher near the soil surface, any changes to the composition or characteristics of this horizon will also lead to changes in SR (Raich & Tufekcioglu, 2000). Fire in any ecosystem represents a sudden and direct change to nutrient cycling and soil surface dynamics. In LLPS ecosystems, fire is a frequent source of dramatic but relatively low-level disturbances that are necessary to maintain the overall structure and diversity characteristic of this habitat (Bizzari et al., 2015; Jose et al., 2007; Plaza-Álvarez et al., 2017; Thaxton, 2003; Whelan et al., 2013). However, the impact a fire has on SR dynamics specifically within LLPS remains unclear. Earlier, Flowers (2016) showed a decrease in SR in a LLPS ecosystem following a prescribed fire, when compared to corresponding unburned sites. This decrease in SR continued for at least one year post-fire. This study, however, focused more on comparing the SR rates in burned and unburned sites rather than tracking long-term SR patterns within the burned areas.

The aftereffects of both high-intensity wildfires and low-intensity prescribed burns have been well documented in some forest ecosystems. During a fire, there is an immediate and large release of CO_2 in the form of smoke and ash as well as a dramatic reduction in understory biomass. The sudden decrease in community-level photosynthetic capacity and organic matter in the soil leads to a decline in SR and efflux rates immediately following the burn (McCarthy & Brown, 2006; Scharenbroch et al., 2012; Whelan et al., 2013). However, ash deposition and canopy clearing provide nutrient resources and habitat space necessary for a major resprouting event of herbaceous understory species, which in turn increases root biomass and organic litter. As a result, SR rates typically rise within months after a burn (McCarthy & Brown, 2006; Scharenbroch et al., 2012). Given this recovery, a similar pattern should occur in fire-maintained LLPS as shorter burn intervals result in reduced fuel accumulation and lower-intensity disturbances. Damage to the canopy and subsurface soil and the resulting shift in LLPS SR flux should therefore be minimal compared to ecosystems that experience infrequent, high-intensity fires (Agee, 2005; Akburak et al., 2018; McCarthy & Brown, 2006; Thaxton, 2003; Wright et al., 2020). In the present study, I measured SR in a single longleaf pine stand for at least two months prior to a prescribed fire and two months post-fire to provide a fine scale analysis of how fire affects SR patterns. I hypothesized that SR would drop significantly following the fire and begin to recover in the following months. This study will hopefully provide a greater understanding of the impact of frequent fires on LLPS SR dynamics.

CHAPTER II: METHODS

This experiment was conducted between October 2020 and mid-March 2021 at the Lake Thoreau Environmental Center (LTEC) at The University of Southern Mississippi (USM) near Hattiesburg, MS in Forrest and Lamar Counties. Two preserves comprise this property, the Eubanks Preserve (131 acres) and the Longleaf Pine Preserve (160 acres). The Longleaf Pine Preserve (LLP) was donated to USM in 1916 by the J.J. Newman Lumber Company and the Eubanks Preserve (EP) was donated by the estate of Mason Leon Eubanks, a former USM English instructor, in 1999. Management of the LLP was undertaken by the Mississippi Forestry Commission from the time of the university's acquisition of the property to the late 1980s, after which the site was left undisturbed. Most of the forest in the EP had not been significantly managed prior to acquisition by USM. In 2008, USM's Department of Biological Sciences (now School of Biological, Environmental, and Earth Sciences) took on management responsibilities for the property and reintroduced a regular fire regime to control fuel loads the following year. Since that time, portions of both the LLP and the EP have been burned every two years, alternating between the growing and dormant season fires. The fire for this experiment occurred in December 2020.

The field site for this study was located within a portion of the EP that had been previously used for gopher tortoise (*Gopherus polyphemus*) hatchling experiments and an ongoing experiment examining the response of gallberry (*Ilex glabra*) to fire (Filliben, 2018; Price, 2018). The site is an uneven-aged longleaf pine stand with the larger trees approaching 40-50 years old. The stand is included in the prescribed fire management routine at LTEC, and the last fire prior to the experiment was in October 2018.

Soil respiration, specifically CO_2 flux, was measured using a LI-8100 (LiCor, Lincoln, NE) infrared gas exchange (IRGA) analyzer attached to LI-8150 multiplexer and four long-term chambers (LI-8150-104) (Figure 1). Each long-term chamber was positioned over a polyvinyl chloride (PVC) soil collar (soil area= 317.8 cm^2) inserted approximately 1-3 cm into the soil. Respiration data were collected at 30-minute intervals during a minimum 24-hour time frame in order to better represent diel fluctuations in SR rates. Each observation length was set at three minutes to minimize the effect of CO_2 buildup within the chambers. Before each reading, the chambers were sealed for thirty seconds to mitigate sources of CO_2 influx and purged for an additional thirty seconds following data collection to return chamber levels to a baseline (Welles et al. 2001). Measurements were collected daily from October 2, 2020 to March 16, 2021, although some dates were excluded due to equipment malfunction and battery failure.

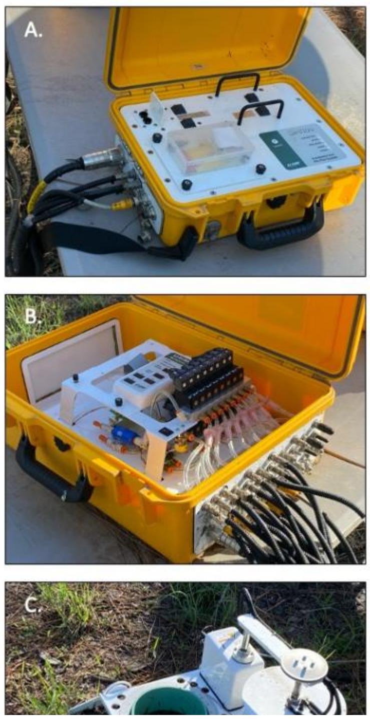

Figure 1. SR measurement equipment. A. LI-8100, IRGA, B. LI-8150, multiplexer, C. LI-8100-104, long-term chamber

All data were collated and sorted using SoilFluxPro software (LI-COR, Lincoln, NE). Prior to analysis, data were examined for anomalies, and values > 2 standard deviations from the mean were excluded. Anomalous values can be caused by several environmental factors including rainfall accumulation within the soil collars (e.g., abnormally low values) and animals (e.g., rodents, spiders, insects) entering the soil collars or chambers (e.g., abnormally high values). Occasional battery failure also caused some data to be excluded. One chamber consistently malfunctioned, thus all data from that chamber were excluded. Values for each day were averaged, and only days that had usable data for all three functional chambers were included in the data analyses. Overall, out of 166 possible days of data collection, only 113 days were used in the final analyses. Data were analyzed using Past 4.04 software (Hammer et al., 2001). Monthly means were calculated and used for examining larger scale patterns. Data were analyzed using a repeated measures ANCOVA comparing pre- and post-burn daily means and using daily high temperature as a covariate. Linear regressions were performed to examine relationships between daily high/low temperatures and precipitation, which were subsequently used to determine the covariate that explained the most amount of variance. Temperature data were collected from the USM Polymer Sciences Building weather station (ID# KMSHATT1I7) archived at Weather Underground (https://www.wunderground.com).

CHAPTER III: RESULTS

A total of 7,466 SR CO_2 measurements were collected from the three functional chambers over the study period. After discarding anomalous readings (see above), 7,308 measurements were used in the data analyses. Daily means ranged from 5.41 µmol $m^{-2}s^{-1}$ to 0.02 µmol m^{-2} s^{-1} (Figure 2).

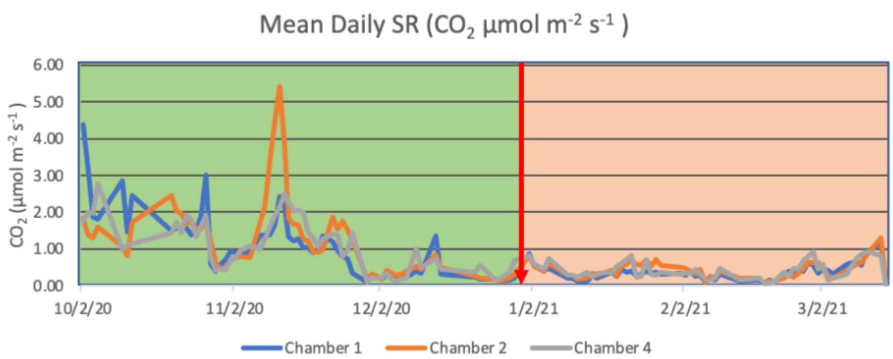

Figure 2. Mean daily SR. Green-shaded and orange-shaded portions represent pre-fire and post-fire measurements, respectively. The red line marks the date of the prescribed fire, December 29, 2020.

Prior to full data analysis, data from each chamber were compared using a repeated measures ANOVA to verify that all chambers were functioning. No significant differences were detected among the CO_2 measurements collected by each chamber (p = 0.7822, Figure 3).

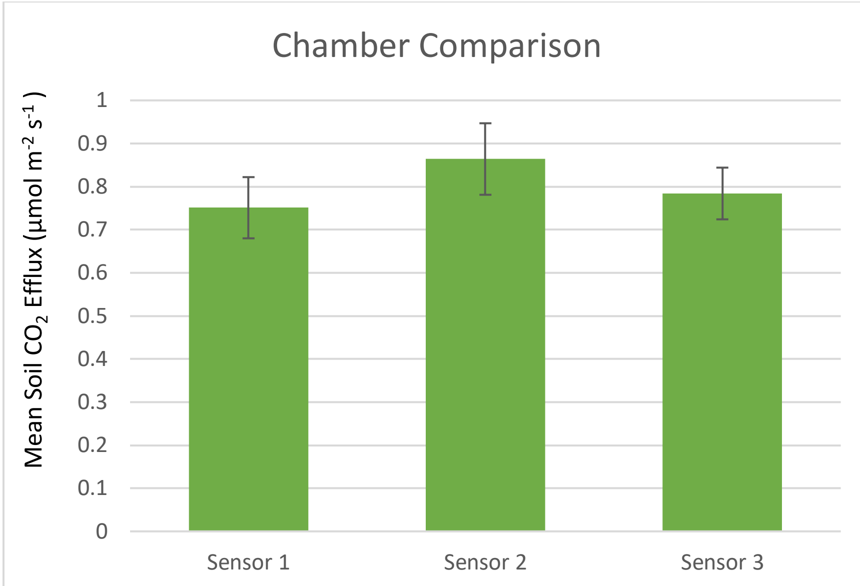

Figure 3. Mean daily SR by chambers. No significant differences were detected among chambers.

Results indicated fire significantly affected SR and that temperature does have an effect on variance ($p < 0.0001$, Table 1). To determine the directionality of that effect, a simple linear regression was performed comparing SR rates and average daily high temperatures (Y = -0.255 + 0.01 * X, Figure 4). Daily high temperature positively influenced SR rates (p-value = 0.0018, Figure 4) but only explained a small portion of variation ($R^2 = 0.239$).

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Fire	1	16.406	0.105	61.276	<.0001
Daily High Temperature	1	45.479	1.565	169.867	<.0001
Fire * High Temperature	1	23.616	0.085	88.207	<.0001
Residual	335	89.691	0.268		

Table 1. ANCOVA table for the effects of prescribed fire with daily high temperature as a covariate.

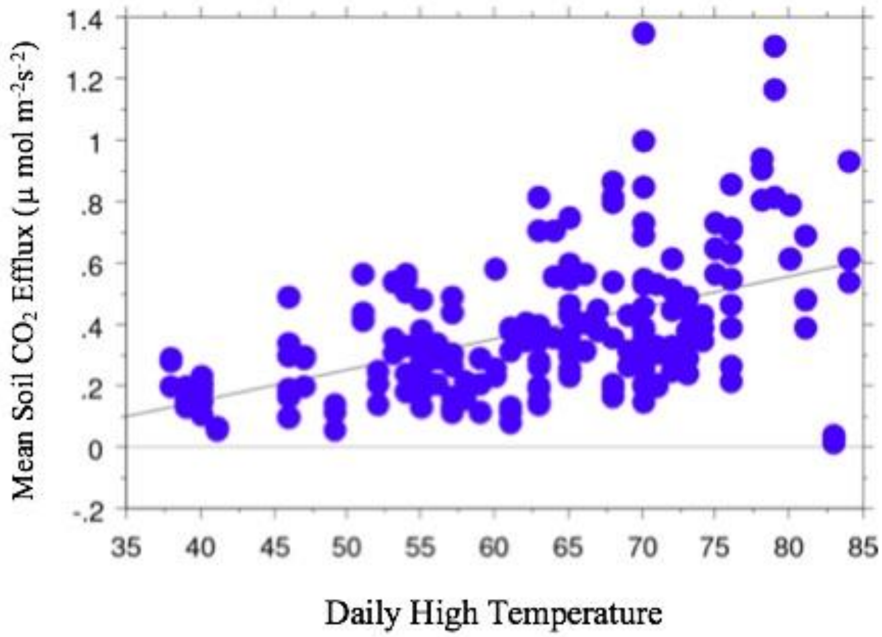

Figure 4. Linear regression showing the relationship between daily high temperature and SR. ($p < 0.0001$, $Y = -0.255 + 0.01 * X$, $R2 = 0.239$).

Soil CO_2 efflux was 65.5% lower post-fire than before the fire (Figure 5), and the Fisher's PLSD conducted on the ANCOVA results indicated that this difference in SR was significant ($p < 0.0001$). Upon closer examination, however, results appear to indicate a tight relationship with ambient temperature, and more significantly, the seasonality of temperature fluctuations.

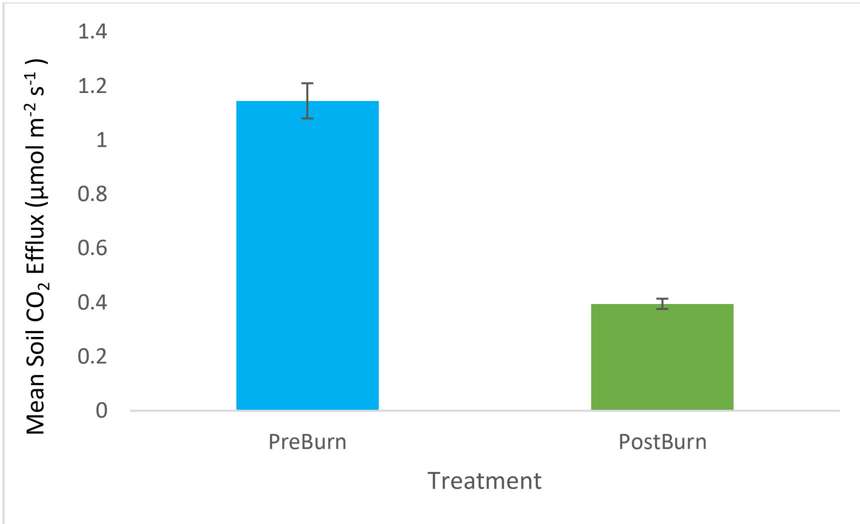

Figure 5. Fisher's PLSD results on pre- vs. post-burn SR. ($p < 0.0001$).

To examine the effects of seasonality on soil CO_2 efflux, an ANOVA was conducted to compare monthly soil CO_2 effluxes. This analysis showed that CO_2 monthly temperatures were significantly different ($p < 0.0001$, Table 2). Post-hoc Fisher's PLSD analysis showed that soil CO_2 efflux was not significantly different ($p = 0.861$, Figure 6) between October and November. However, soil CO_2 efflux for both October and November were significantly different from every other month ($p < 0.0001$ for all comparisons of October and November with other months). For this reason, another ANCOVA was conducted that excluded data from October and November to better isolate the effect of fire from the effect of season on CO_2 flux. This new ANCOVA showed that post-burn SR increased by 17%, but this increase was not statistically significant ($p = 0.1148$, Figure 7).

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Month	5	95.268	19.054	61.866	< 0.001
Residual	333	102.558	0.308		

Table 2. ANOVA table for the effects of month on SR.

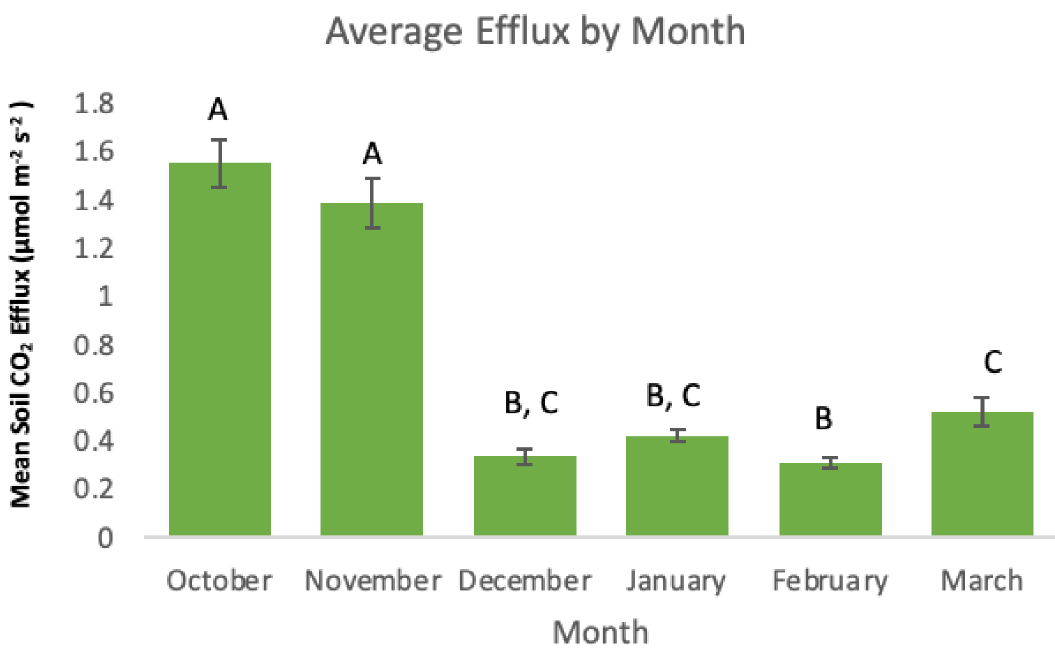

Figure 6. Fisher's PLSD results on effect of month on SR. Months with the same letter are not significantly different.

	DF	Sum of Squares	Mean Square	F-Value	P-Value
Fire	1	0.105	0.105	2.509	0.1148
Daily High Temperature	1	1.565	1.565	37.347	<.0001
Fire * High Temperature	1	0.085	0.085	2.017	0.1571
Residual	203	8.507	0.042		

Table 2. ANCOVA table for the effects of prescribed fire with daily high temperature as a covariate. Data for October and November were excluded from this analysis.

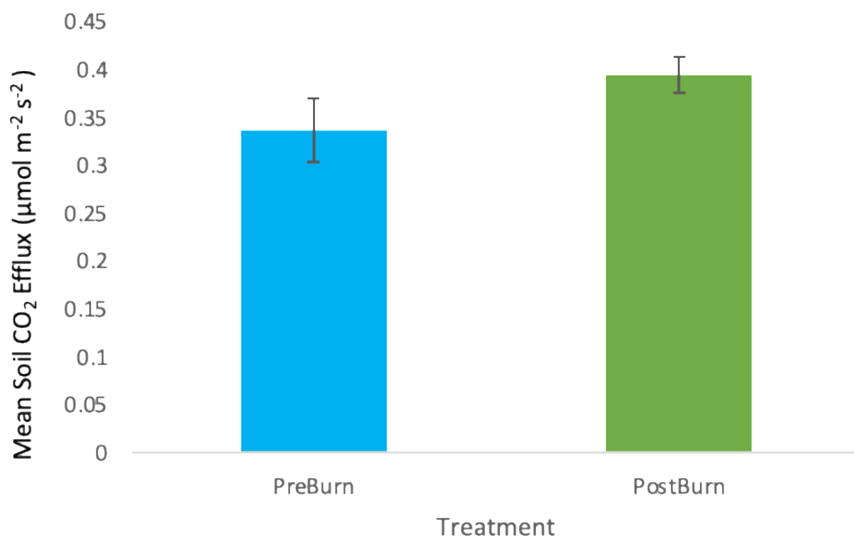

Figure 7. Pre-burn vs. post-burn SR excluding October and November data (p = 0.1148).

CHAPTER IV: DISCUSSION

Initial analysis of the results indicated that fire resulted in a strong reduction of SR rates. At first glance, these results are consistent with a previous study that showed reductions in SR following a fire (Flowers, 2016). However, the previous study focused on comparing burned vs. unburned sites at discrete measurement periods in various seasons. This study tracked the same precise sites through time and collected pre- and post-fire data within days of each other.

While the effect of fire on SR seems to be inconsistent between the two studies, two factors may explain these apparent differences. First, seasonal variability in temperature plays an important role in SR. As expected, SR rates (in the northern hemisphere) are generally lower during winter months and greater in the summer and early fall (Giasson et al., 2013; Lellei-Kovács et al., 2011; Reichstein et al., 2003). Flowers (2016) compared SR among burned and unburned sites in spring and summer but did not compare SR within burned sites throughout seasons. Thus, pre- and post-fire differences in that study may simply be due to seasonal variability.

Secondly, SR rates have been shown to decrease due to the loss of surface leaf litter following a burn (McCarthy & Brown, 2006 Plaza-Álvarez et al., 2017; Scharenbroch et al., 2012). In the present study, soil leaf litter was removed prior to installation of the soil collar, thus any variability due to soil litter was removed prior to collection of SR measurements.

As measurements were recorded during the shift between the growing and dormant seasons, some data were excluded from the study to reduce the apparent effects of season and focus on the effects or prescribed fire. The result of this isolation showed that SR rates did not appear to be affected by prescribed fire. Further studies into dormant versus growing season prescribed fires may be necessary to expand this finding. The effect precipitation had on SR during this study was likewise unclear, as the exact climatic conditions corresponding to each recorded measurement were unknown and precipitation levels and hourly temperatures were estimates. A more comprehensive examination of climatic data and SR measurements may be useful in better understanding this effect.

The effect of leaf litter on respiration rates was not examined in this study as the measurement chambers were placed on cleared soil in order to minimize external sources of carbon (e.g., litter organisms and variability in litter biomass). The removal of that organic matter may explain why there was no significant difference between pre- and post-burn SR rates.

The hypothesis that SR would decrease following a prescribed fire was not supported by the results of this study. These results highlight the need for caution when making broad assumptions from data collected across various seasons. Our initial analysis supported the hypothesis that SR would decrease, however, this result was an artifact driven by higher SR rates during the warmer months of October and November. Further research is needed to determine if there is truly no effect of prescribed fire on SR in these forests and to clarify other factors that may influence ecosystem SR rates.

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