

Project Title: The Influence of Prescribed Fire and Understory Fuels Mastication on Soil Carbon Respiration Rates in Flatwoods Forests

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I. Abstract

Soil CO₂ efflux (R_s) is a significant flux of carbon dioxide from ecosystem soils to the atmosphere and is a critical component of the total ecosystem carbon budget. R_s fluxes are comprised of autotrophic (R_a) sources of CO₂ produced by plant roots and associated rhizosphere fungi and heterotrophic (R_h) sources of CO₂ produced by aerobic soil microbes. A variety of forest management activities, including prescribed fire and mechanical fuels mastication treatments have been shown to significantly influence R_s rates in forests of the Western United States (US), yet these relationships are not well known for southeastern US forests. Prescribed fire is one of the most prevalent forest management tools employed in the southeastern US, and mechanical fuels treatments are becoming more common in the region as efforts to mitigate potential wildfire behavior in the wildland urban interface grow. Given that many of these forests provide habitat for endangered species, understanding the implications of management activities on ecosystem carbon dynamics may allow landowners to capitalize on future alternative revenue streams for carbon sequestration services while maintaining their properties in conserved states. This study investigated the influence of prescribed fire and mechanical fuels mastication treatments on R_s rates in longleaf / slash pine flatwoods of the Osceola National Forest in North Florida. In the flatwoods forests, neither mechanical fuels treatments nor prescribed fire significantly altered monthly mean R_s rates. Prescribed fire, mechanical fuels mastication, and mechanical fuels mastication followed by prescribed fire were found to significantly increase mean soil temperature within the flatwoods sites. Future research is needed to understand whether the changes in soil temperature will ultimately lead to altered decomposition rates and soil carbon fluxes. Our results however, found no evidence of elevated soil CO₂ fluxes within one-year of mastication treatment. Our results suggest that future methods to model soil carbon fluxes in the region should account for the impacts of land management activities on soil temperature, a key driver in soil carbon dynamics.

II. Background and Purpose

Managing forests to increase carbon sequestration and decrease carbon emissions has been suggested as a method for reducing global atmospheric CO₂ concentrations that have increased over the last century (IPCC, 1995; Lal, 2005; Woodbury et al., 2007). As the southeastern United States (US) has over 81 million ha of forested land, there exists significant potential for public and private forest landowner compensation for carbon sequestration services (“Cap and Trade” programs) (USFS/FIA 2006; Maier et al., 2012).

It has been suggested that the understanding of soil carbon pools and fluxes are the weakest links in assessing carbon in southeastern US forests (Raich and Schlesinger, 1992; Johnson et al., 2001). This is important as much of the carbon sequestered in temperate forested systems are found within the soils (50-60%), with soil CO₂ efflux comprising a significant portion (50-60%) of temperate forest total ecosystem carbon budgets (Post et al., 1982; Raich and Schlesinger, 1992; Lal, 2005; Noormets et al. 2010). At landscape scales, given that soils contribute such large fluxes to atmospheric CO₂, even small changes in soil CO₂ efflux rates over broad regions could have significant impacts on overall atmospheric CO₂ concentrations (Raich and Schlesinger, 1992; Bond-Lamberty and Thomson, 2010). Because of the importance of soil

CO₂ efflux rates in local, regional, and global carbon cycles it is important to understand how forest management practices influence soil CO₂ efflux rates.

Soil CO₂ efflux (R_s) is a combination of CO₂ respired by plant roots and associated rhizosphere fungi (R_a) and heterotrophic soil microorganisms (R_h) (Luo and Zhou, 2006; Subke et al., 2010). Soil CO₂ efflux is the product of a multitude of interrelated biogeochemical factors that govern the production of CO₂ by plant roots (and associated mycorrhizal fungi) and soil micro and macro biota, including: soil temperature, soil moisture content, aboveground vegetative composition and belowground carbon allocation, phenology, soil carbon and nutrient content, and disturbance processes (Raich and Tufekciogul, 2000; Ryan and Law, 2005; Luo and Zhou, 2006). In addition a suite of physical factors including soil porosity, CO₂ pressure gradients, surface wind speed, and surface air turbulence influence the evolution of CO₂ to the soil surface (Luo and Zhou, 2006).



Figure 1. Prescribed fire in mechanically treated pine flatwoods in north Florida.

Prescribed fire is one of the most prevalent forest management tools employed in the management of conserved lands in the southeastern US, with over 2.4 million ha burned in 2011 (Waldrop and Goodrick, 2012). While prescribed fire in the southeastern US is an obvious source of atmospheric carbon in the short-term, investigations of the rapid response of vegetation following prescribed fires suggest that the ecosystem recovery and sequestration of carbon lost via emissions is relatively fast (1-2 years), especially in comparison to other regions of the US (Wiedinmyer and Neff, 2007; Lavoie et al., 2010). It is known that variations in the frequency or season of prescribed fire management regimes can result in significant changes in forest vegetation structure and composition in the southeastern US (White et al., 1990; Waldrop et al., 1992; Knapp et al., 2009; Glitzenstein et al., 2012). What are not so well known are the effects of such management regime variations on the biotic and abiotic factors that drive forest soil carbon fluxes.

Mechanical fuels mastication treatments are becoming more common in the southeastern US as wildfire prone forests and urban areas intermix (Mitchell et al., 2006; Menges and Gordon, 2010). Mechanical fuels mastication is used to reduce understory fuel heights which has been

shown to reduce wildfire behavior in many systems (Agee and Skinner, 2005; Glitzenstein et al., 2006; Kobziar et al., 2009; Kreye, 2012). In many wildland urban interface areas in the southeastern US, prescribed fire has become difficult for land managers to implement due to concerns from adjacent and nearby landowners over smoke and wildfire risk and as such, many land managers and agencies are opting to use mechanical fuels treatments in place of prescribed fire (Miller and Wade, 2003; Long et al., 2004; Menges and Gordon, 2010). As the implementation of mechanical fuel treatments has increased, it is important to understand the influence of such practices on forest carbon dynamics. Previous studies of mechanical fuels mastication in Western US systems have shown that treatments can significantly alter soil CO₂ efflux rates (Kobziar and Stephens, 2006; Ryu et al., 2009) as well as soil environmental factors known to influence long-term soil carbon dynamics (Concilio et al., 2005; Kobziar and Stephens, 2006; Xu et al., 2011). Given the increased use of mechanical fuels mastication treatments in place of or in combination with prescribed fire in the southeastern US, it is important to understand the effects of such activities on forest soil carbon fluxes and soil abiotic and biotic conditions.

A variety of forest management activities, including prescribed fire, and mechanical fuels mastication treatments have been shown to significantly influence soil CO₂ efflux rates in the Western US, yet these relationships are not well known for southeastern US forests (Concilio et al., 2005; Tang et al., 2005; Kobziar and Stephens, 2006; Ryu et al., 2009; Xu et al., 2011). To address this knowledge gap, this study sought to evaluate the effects of mechanical fuels mastication treatments, prescribed fire, and mechanical fuels mastication treatments followed by prescribed fire on soil CO₂ efflux rates and soil abiotic conditions in pine flatwoods forests.

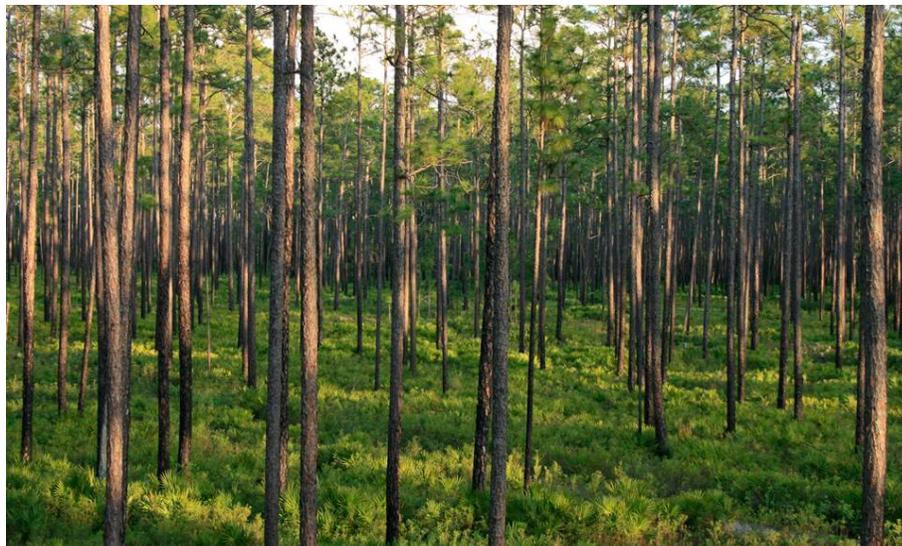


Figure 2. Frequently burned pine flatwoods in north Florida.

Flatwoods are the most common forested ecosystem in Florida totaling over 5.2 million ha (Myers and Ewel, 1990). Given the prevalence of this forest type, public and private interest in the effect of forest management activities on forest carbon dynamics are expected to be significant (Law and Harmon, 2011). With the possibility of future federal land management goals including carbon sequestration, understanding the effects of federal forest management

regimes on carbon dynamics is critical (Exec. Order No. 13,513, 2009). In flatwoods managed for conservation, prescribed fire is one of the most frequently utilized management tools for maintaining ecosystem composition and structure and reducing wildfire risk (Outcalt and Wade, 1999). For wildfire risk reduction in flatwoods forests, prescribed fire is typically applied on a 3-5 year interval to remove the accumulation of saw palmetto (*Serenoa repens* (Bartr.) Small) and other understory vegetative fuels that tend to drive fire behavior in these systems (Brose and Wade, 2002). Given the importance of prescribed fire in these forests and the potential ecological and economic benefits of carbon credits for carbon sequestration, it is important to understand the influence of these management fires on soil CO₂ efflux rates.

Mechanical fuels mastication treatments and prescribed fire can influence soil CO₂ efflux rates by altering soil and environmental physical, chemical, and abiotic factors that affect the sources of heterotrophic and autotrophic R_s. For example, fire has been shown to alter forest floor litter and duff loads, carbon and nitrogen pools, soil temperature, pH, and microbial activity in multiple ecosystems (Neary, 1999; Debano, 2000). In addition, mechanical fuels mastication treatments have been shown to influence forest floor litter and duff loads and average soil temperature and moisture content which can also influence sources of R_s through biogeochemical processes (Luo and Zhou, 2006; Kobziar, 2007). Finally, both prescribed fire and mechanical fuel treatments have clear impacts on understory forest vegetation through physical mastication or damage, combustion, injury, or competitive release that can alter vegetative activity and belowground carbon allocation. Such manipulation of vegetation can alter sources of R_s through direct impacts on autotrophic R_s sources and indirect impacts on R_s heterotrophic sources.

Numerous studies have investigated carbon dynamics in flatwoods and similar commercial slash pine forests of the southeastern US, however none known have specifically addressed the effects of mechanical fuels mastication treatments and prescribed fire management regimes on soil CO₂ efflux rates (Ewel et al., 1987a; Ewel et al., 1987b; Fang et al., 1998; Clark et al., 2004; Powell et al., 2008; Meigs et al., 2009; Lavoie et al., 2010; Bracho et al., 2012). By investigating prescribed fire, mechanical fuels mastication, and mechanical fuels mastication followed by prescribed fire in the context of flatwoods ecosystems managed for conservation and multiple-use purposes, this study sought to address the following research questions: (1) How do prescribed fire and understory fuels mastication treatments influence monthly, seasonal, and annual soil CO₂ efflux rates, and, (2) How do prescribed fire and mastication treatments affect forest conditions that will likely influence long-term site level soil CO₂ efflux rates and soil carbon dynamics? For managers and researchers alike, this study provides insight into linkages between forest management, soil carbon storage and flux, and the physical and biotic variables influencing those fluxes that are likely to be influenced by global climate change.

III. Study Description & Location

The study sites were located within the 80,000 ha United States Forest Service (USFS) Osceola National Forest (Osceola) in Columbia County, FL, USA approximately 20 km from the town of Lake City. The area is within the Gulf Coastal Plain region and has little to no perceptible slope. Average annual precipitation was 132 cm with the majority falling during the summer months of June, July and August (National Climate Data Center 2009). Vegetation

across all sites consisted of an overstory mixture of naturally regenerated slash pine (*Pinus elliottii* Engelm) and longleaf pine (*P. palustris* P. Mill) and an understory composed of saw palmetto (*Serenoa repens* (W. Bartram) Small), gallberry (*Ilex glabra*), and deerberry (*Vaccinium stamineum*) shrubs (Myers and Ewel 1990). Across the study area, stand age averaged 80 years (Osceola National Forest staff pers. comm.). Prior to the start of the study, all plots had been unburned for at least 11 years (Jesse Kreye, pers. comm.).

Sampling Design

The study consisted of twelve sample plots representing four treatment types: prescribed fire (burn), mechanical fuel mastication (mow), mechanical mastication + prescribed fire (mow+burn), and unburned control (control). Plots were established in three 2 ha experimental treatment blocks, with each block containing a representative plot of each treatment. One sampling plot was randomly located within each treatment type in each block. Mechanical fuel mastication in the mow and mow+burn plots took place during the summer of 2010. Prescribed burning in the mow and mow+burn plots took place in February, 2011, with two blocks burned on one day and one block burned the next day.

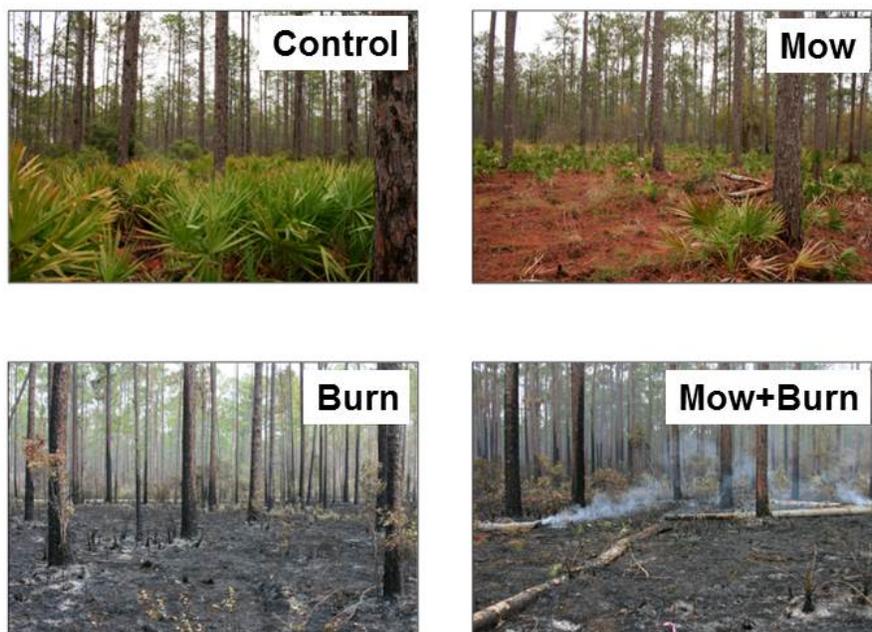


Figure 3. Treatment types in the Osceola National Forest, Florida.

Field Measurements

Soil CO₂ efflux sample plots were established in the early winter of 2010. Each sample plot consisted of nine permanently installed 20 cm diameter independent PVC collars arranged in a 3 x 3 grid with 5 m separation following Kobziar and Stephens (2006). A LI-COR Biosciences LI-8100 Automated Soil CO₂ Flux System attached to a 20 cm survey chamber was used to measure soil CO₂ efflux rates (R_s) ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ sec}^{-1}$) at each collar (LI-COR Biosciences, Inc., Lincoln, NE). Concurrently with soil CO₂ efflux measurements, soil temperature at 10 cm depth ($^{\circ}\text{C}$) (T_s) and soil volumetric moisture content ($\text{m}^3 \times \text{m}^3$) (M_s) at 5 cm depth were recorded

onboard the LI-8100. Soil temperature was measured using an Omega 8831 type E T-Handle temperature probe, while soil moisture content was measured using a Decagon Systems EC-5 soil moisture probe (Omega Inc., Stamford, CT; Decagon Systems Inc., Pullman, WA). To assess temporal and seasonal variations in R_s rates, T_s , and M_s , collars were sampled monthly over the course of two days on an approximately four-week rotation. To account for diurnal variations in R_s , T_s , and M_s , measurements were taken twice per day between 0800 and 1700 local time. Collars were sampled from March 2011 to February 2012. Plot stand characteristics and vegetative sampling were conducted in the winter of 2011.

Analysis

Treatments were analyzed as a randomized complete block design with fuel treatment type as the main treatments. Two-way repeated measures analysis of variance (ANOVA) were used to test for differences in monthly means of R_s , T_s , and M_s among treatments at each study site. To assess differences between site physical and vegetative characteristics by treatment at each study site, one-way ANOVA tests were used. Where significant differences were identified in the ANOVA, differences among treatments were analyzed using Tukey's HSD test. Additional linear and nonlinear regression models were developed per treatment and measurement season (growing vs. dormant) to assess the influence of treatments on the relationships between monthly per plot mean R_s rates and T_s , M_s , and the field parameters. Non-linear models of the relationships between R_s rates and T_s and monthly mean ambient air temperature (M Temp) per entire study period and season were explored using an exponential equation frequently used to describe the response of R_s rates to soil temperature (Lundegardh, 1927; Samuelson et al., 2004; Concilio et al., 2005; Kobziar and Stephens, 2006). Multiple regression using a forward step-wise procedure was used to develop models per treatment of monthly mean R_s rates, utilizing measured parameters that best explained the observed variability in R_s rates (using R^2 and p-value). All statistical analyses were performed using JMP 9.0 (SAS Institute, Cary, NC, USA).

Results

Treatment Effects

Vegetative conditions varied significantly ($p < 0.05$) by treatment within the study areas. Prescribed burning was shown to significantly reduce litter depth in the burn (1.57 cm) and mow+burn (1.18 cm) treatments relative to the mow (3.50 cm) and control (4.50 cm) treatments. No significant treatment effects were observed for soil organic matter or total soil carbon, for either sample depth.

Repeated measures ANOVA found monthly mean soil CO_2 efflux rates were not significantly different between treatments ($F = 0.86$ $p = 0.4985$). Soil CO_2 efflux rates did vary significantly by month ($F = 35.69$ $p < 0.0001$) but did not show an interaction between treatment effect and time (treatment x month) ($F = 0.66$ $p = 0.9123$). While no significant differences in M_s were observed between treatments, mean overall soil temperature was significantly higher in all treatments relative to the control, with no other significant differences between treatment types observed ($F = 11.42$ $p < 0.05$).

Overall Drivers of Soil CO_2 Efflux.

Pearson's Correlation coefficients and linear regressions were used to identify broad overall relationships between R_s , T_s , and M_s and plot vegetative and meteorological conditions.

Pearson's Correlation coefficients indicated positive relationships between R_s and T_s (0.63) and R_s and monthly mean ambient air temperature (M Temp) (0.52). Pearson's Correlation coefficients also indicated that T_s and M Temp were strongly correlated (0.77). Vegetative conditions were shown to have a small influence on overall R_s rates as litter depth (0.06), duff depth (0.08), stand density (0.00), and basal area (0.11) were only weakly correlated with R_s rates.

Linear regressions of pooled monthly mean values, soil temperature ($R^2 = 0.40$ $p < 0.0001$) and M Temp ($R^2 = 0.27$ $p < 0.0001$) were also positively linearly correlated with overall mean R_s rates, while plot level vegetative characteristics such as basal area ($R^2 = 0.01$ $p = 0.1772$), stand density ($R^2 = 0.00$ $p = 0.9991$), distance to nearest tree ($R^2 = 0.00$ $p = 0.4682$), and distance to nearest palmetto ($R^2 = 0.03$ $p = 0.0274$) were not correlated with R_s rates .

Treatment Specific Drivers of Soil CO₂ Efflux.

To assess the influence of T_s , M_s , and vegetative and meteorological conditions on monthly mean R_s rates within treatments, simple linear regression models were developed for each parameter and treatment. Simple linear regression models by treatment identified significant positive relationships between soil CO₂ efflux rates (R_s) and soil temperature (T_s) ($R^2 = 0.33 - 0.58$) and monthly mean ambient air temperature ($R^2 = 0.24 - 0.34$). A weak linear relationship was identified between R_s rates and soil moisture content (M_s) ($R^2 = 0.02 - 0.12$), with one treatment having a positive relationship with M_s (Control) and the remainder having a negative relationship with M_s (Burn, Mow, Mow+Burn).

Seasonal Drivers of Soil CO₂ Efflux.

To assess seasonal variations in the relationships between R_s and T_s , M_s , and plot vegetative and meteorological characteristics, additional simple linear and nonlinear regression models were developed per treatment and season (growing and dormant).

Linear and nonlinear models of all treatments found that the relationships between R_s and T_s and R_s and M_s varied seasonally. Positive linear models of T_s explained much more of the variability in R_s rates during the cooler dormant season ($R^2 = 0.69 - 0.79$) than during the warmer growing season ($R^2 = 0.30 - 0.60$). Similarly, positive non-linear models of T_s explained much more of the variability in R_s rates during the dormant season ($R^2 = 0.64 - 0.76$) than during the growing season ($R^2 = 0.30 - 0.58$). For either season or modeling type (linear or non-linear), the burn treatment recorded the weakest relationship between R_s and T_s , while the mow treatment recorded the strongest relationship. In the soil moisture content linear models, monthly mean R_s was more closely correlated (negatively) with M_s during the dormant season ($R^2 = 0.24 - 0.67$) than during the growing season ($R^2 = 0.09 - 0.53$) in all treatments except for the burn treatment. In the burn treatment, R_s was more closely correlated with M_s during the growing season ($R^2 = 0.44$) than the dormant season ($R^2 = 0.11$).

Multiple Regression Models.

Multiple linear regression models were developed per treatment and season to identify the influence of treatment and season on the drivers of soil CO₂ efflux rates. Models were developed using a forward step-wise approach (minimum parameter input and retention $p < 0.05$) using the stand and plot characteristics as potential parameters. Models were developed to minimize BIC score and parameter multicollinearity while maximizing model coefficient of variation (R^2).

The amount of variation in R_s rates explained by the all-season multiple linear regression models varied by treatment and ranged from ($R^2 = 0.36 - 0.72$). Similar to the linear and non-linear models, the mow+burn treatment model explained the least amount of the variation in R_s ($R^2 = 0.36$ $p = 0.0006$) while the control treatment model explained the greatest amount of the observed variation in R_s rates ($R^2 = 0.72$ $p < 0.0001$). The season specific models explained more of the variation in R_s rates during the cooler dormant season ($R^2 = 0.85 - 0.93$) than during the warmer growing season ($R^2 = 0.53 - 0.85$). During both the growing season and the dormant season the mow+burn treatment models explained the least amount of observed variation in R_s ($R^2 = 0.53$ and $R^2 = 0.85$, respectively) while the control model explained the most in the dormant season ($R^2 = 0.93$) and the burn treatment model explained the most during the growing season ($R^2 = 0.84$). The season specific multiple linear regression model terms identified as significant during the forward step-wise process, differed by treatment type and season. During the growing season T_s was significant only in the control and mow models, while the other treatment models included M_s , monthly mean air temperature, precipitation, and distance to nearest palmetto. During the dormant season T_s explained the majority of the variation observed in R_s rates in all models with subsequently added parameters explaining much less of the variation in R_s . The model parameters other than T_s identified as significant (tree density, basal area, soil moisture content, and distance to nearest tree) provided evidence for the roles of additional drivers of R_s beyond T_s and M_s ; although overall patterns in the relationships were not clear.

Estimated Carbon Flux.

During the growing season, soil carbon flux was greatest in the control sites and lowest in the burn only treatments and mow+burn treatments. During the cooler dormant season months of December, January, and February, monthly total soil carbon flux in the control treatments reduced to lower than the other three treatment types. When soil carbon fluxes were totaled for the entire year, estimated annual soil C flux was greatest in the control units ($1.89 \text{ kg C m}^{-2} \text{ yr}^{-1}$), and lowest in the mow+burn treatment ($1.64 \text{ kg C m}^{-2} \text{ yr}^{-1}$), with the burn ($1.69 \text{ kg C m}^{-2} \text{ yr}^{-1}$) and mow treatments falling in between ($1.67 \text{ kg C m}^{-2} \text{ yr}^{-1}$).

Q_{10} Model Results

Model parameters were used to estimate the Q_{10} value per treatment following Kobziar and Stephens (2006). The Q_{10} value is often reported in studies of R_s to describe the response of R_s to a 10°C change in soil temperature (Luo and Zhou, 2006). Estimated Q_{10} values in the all-seasons models were highest in the control ($Q_{10} = 2.14$) and lowest in the mow+burn treatment ($Q_{10} = 1.65$). The Q_{10} values in the season specific models ranged from $Q_{10} = 1.63 - 2.51$. Q_{10} values in all treatment types and control were higher during the dormant season than the growing season.

IV. Key Findings

Soil CO_2 Efflux Rates Unaffected by Fuels Treatment

This project found that neither prescribed fire nor mechanical fuels mastication treatments, nor mechanical fuels mastication followed by prescribed fire significantly influenced mean soil CO_2 efflux rates in the relatively short-term. Prescribed fire and mechanical fuels

mastication treatments were however found to significantly increase monthly mean soil temperature. Measured soil CO₂ efflux rates in all treatments varied seasonally and were largely correlated with soil temperature. Soil temperature was generally the strongest assessed driver of soil CO₂ efflux rates in our study. These results, while indicating no direct influences on soil CO₂ efflux rates, suggest that prolonged periods of continuous management may affect soil carbon dynamics through persistent changes in the abiotic conditions (i.e. soil temperature) that influence heterotrophic and autotrophic sources of soil carbon efflux. Further research is needed to understand the long-term implications of increased soil temperature in these systems, particularly in sites where mechanical fuels mastication treatments have occurred, as the fate and duration of vegetative and biogeochemical effects of masticated fuel treatments are not well known.

Soil CO₂ Efflux Coupled to Seasonal Trends

This project presents inconclusive evidence that seasonal variations, as well as prescribed fire and mechanical fuels mastication treatments, may influence the relative contributions of heterotrophic and autotrophic sources of soil CO₂ efflux. Although this was not a specific partitioning study, our estimated Q₁₀ values support the findings of others who suggest that the contributions of heterotrophic and autotrophic sources of soil CO₂ efflux vary seasonally (Lee et al., 2003; Xu et al., 2011). Our results suggest that future studies would benefit from both short and long-term sampling intervals that capture the daily, monthly, and seasonal variability in soil CO₂ efflux rates.

V. Management Implications

The results of this project may inform further management and policy recommendations by providing details on the impacts of prescribed fire and mechanical fuel mastication programs on Florida pine flatwoods carbon cycles. This project demonstrates that, while prescribed fire and mechanical fuel mastication treatments have no significant impacts on short-term CO₂ soil efflux rates, these management activities can have significant and prolonged impacts on soil temperature conditions. Future attempts at carbon accounting and or management policies that require documentation of ecosystem carbon budgets can thus more precisely discuss short term implications of prescribed fire and mechanical fuel mastication treatments on soil efflux rates. Furthermore, ecosystem carbon modeling efforts in pine flatwoods can now incorporate more treatment specific models of the relationships between soil CO₂ efflux rates and soil / ambient air temperature.

VI. Relationship to Recent Findings and Ongoing Work on this Topic

The range of monthly mean soil CO₂ efflux rates ($\mu\text{mol CO}_2 \text{ m}^{-2} \text{ sec}^{-1}$) recorded at the Osceola (1.16 - 8.73 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ sec}^{-1}$) study sites were similar but higher than those reported in many other published studies of R_s rates. In a similar study of mechanical fuels mastication treatments, prescribed fire, and mechanical treatments followed by fire in a mixed conifer plantation in California, USA, Kobziar and Stephens (2006) reported growing season R_s rates

ranging from 2.37 - 4.55 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ sec}^{-1}$. In another California study, Tang et al. (2005) also reported similar mean R_s rates (3.26 - 3.78 $\mu\text{mol CO}_2 \text{ m}^{-2} \text{ sec}^{-1}$) for thinned and un-thinned ponderosa pine plantations. The ranges of R_s rates reported in the Osceola were also similar to those reported by Fang et al. (1998) and Ewel et al. (1987a) for mature slash pine plantations in north central Florida. The higher R_s rates recorded in our studies relative to those mentioned previously from the western USA, were likely related to the relatively high mean annual temperatures, frequent precipitation, and long growing seasons in our sites.

Effects of Prescribed Fire and Mechanical Fuels Mastication

At the Osceola study site neither mechanical fuels mastication, prescribed burning, nor mechanical fuels mastication followed by prescribed burning significantly altered overall mean soil CO_2 efflux rates relative to control. These results are similar to Kobziar (2007) who found that a single mechanical fuel mastication treatment had no significant effect on soil CO_2 efflux rates in a Sierra Nevada mixed conifer plantation in California, USA. In a similar western US study, Concilio et al. (2005) found no significant effect of prescribed burning on soil CO_2 efflux rates in the mixed conifer Teakettle Experimental Forest. In a related study of the effects of forest thinning on soil CO_2 efflux rates and soil conditions, Tang et al. (2005) also found no significant changes in overall mean soil CO_2 efflux rates following treatment. The lack of a treatment effect on R_s rates at either of our study sites was surprising given the multiple effects that prescribed fire and mechanical fuels treatments can have on the autotrophic (R_a) and heterotrophic (R_h) sources of soil CO_2 efflux. Both mechanical fuel treatments and prescribed fire kill, consume, or damage live understory vegetation thereby reducing sources of root respiration (R_a). At the same time, such treatments provide heterotrophic soil microorganisms with fresh labile carbon in the form of dead plant roots, potentially increasing R_h contributions to R_s .

The lack of a detected R_s response to the treatments could be due to the inability of the monthly sampling protocol employed in this study to capture short-term treatment responses. This is supported by a recent dissertation study of the Florida Everglades by Medvedeff (2012) that found a soil microbial response (in the form of altered R_h) was detectible only within two days of prescribed burning. The Medvedeff (2012) study reported that subsequent post-burn sampling of R_h in burned and unburned sites weeks and months following treatment revealed no significant differences between treatments. Other studies including a ^{13}C isotope tracing experiment in a coniferous forest in northern Sweden, Ekblad and Hogberg (2001) and a ^{13}C tracing experiment in a 15-year-old loblolly pine plantation in North Carolina, USA (Andrews et al. 1999) have reported soil CO_2 efflux responses to treatments in as little as 1-4 days. We suggest, similar to Medvedeff (2012), that future R_s sampling protocols employ more temporally intensive measurements in the period immediately following treatment while maintaining monthly long-term sampling to capture annual and seasonal variability. Quantifying short-lived responses may seem insignificant at the ecosystem level, but over broad spatial scales even transient CO_2 fluxes may be important for future landscape level carbon budgeting and modeling.

Our results found that while prescribed burning and mechanical mastication treatments did not have a significant effect on soil CO_2 efflux rates, they did result in increased soil temperature relative to control sites. Previous studies of forest management practices have documented similar effects on soil conditions. In a study of a mixed-conifer forest in California, USA, Ryu et al. (2009) reported that prescribed burning and forest thinning treatments increased

soil temperature and moisture content while simultaneously reducing soil CO₂ efflux rates. In another example, following a heavy thinning treatment in a ponderosa pine plantation in California, USA, Tang et al. (2005) found that thinning increased forest soil temperature and soil moisture while having no clear overall effect on mean R_s rates.

Soil CO₂ Efflux Response to Temperature Fluctuations

Soil temperature was generally the strongest assessed driver of soil CO₂ efflux rates in our study at both study sites. When treatment types were ignored and all data pooled in the Pearson's Correlation coefficient tests of all parameters, T_s had the highest correlation with R_s (0.63). These results are similar to three previously published studies of slash pine plantations in north central Florida, Clark et al. (2004) (R² = 0.49 - 0.78), Ewel et al. (1987a) (R² = 0.75), and Fang et al. (1998) (R² = 0.96). The burn and mow+burn treatments tended to reduce the amount of variability in R_s rates explained by T_s in linear and non-linear models in comparison to the control and mow treatments. This may have been due to reductions in the relative importance of temperature in governing R_s production, as plants and soil microorganisms responded to changes in microsite conditions and nutrient availability following fire (Medvedeff, 2012). Further study may show whether additional time since fire in the burned treatments leads to an increase in the amount of R_s variability explained by T_s.

Additional Research

The establishment of the sampling and monitoring plots installed during this study provides the opportunity for a much-needed longer-term assessment of the ecosystem, fuel, and carbon cycle implications of prescribed fire and mechanical fuel mastication treatments in pine flatwoods. Only through long-term research will a comprehensive understanding of the biogeochemical effects of these management programs be attained. While ongoing and future monitoring and data analysis within these sites will be contingent upon internal and external funding sources, the information provided by such research may be critical in modeling ecosystem responses to changing environmental conditions and management regimes.

VII. Future Work Needed

There exist many gaps in our current understanding of the interactions between forest management practices, natural disturbances, and ecosystem carbon cycles. Continuing research is greatly needed as such knowledge gaps are directly tied to global climate change impacts and mitigation. The following research needs and questions were identified during this course of study:

- To better predict the effects of global climate change on soil CO₂ efflux rates, more research is needed to understand how autotrophic and heterotrophic sources of CO₂ respond to forest management practices, as well as to changes in elevated atmospheric CO₂ concentrations, temperature, moisture regimes, and forest vegetation.
- Research is needed to develop cost-effective methods that allow for the partitioning of the components of heterotrophic and autotrophic sources of soil CO₂ efflux *in-situ* without disturbing site biotic or abiotic factors.

- Little is known about the fate of masticated fuel beds in southeastern US forests. How quickly these fuels are decomposed and cycled remains an open and important question for modeling carbon cycles local and landscape levels.
- Similarly, the short, medium, and long-term impact of fuels mastication on soil temperatures should be addressed. Previous research (covered in section VI) has identified the important role of soil temperature on soil CO₂ efflux rates. Future research is needed to understand whether the changes in soil temperature will ultimately lead to altered decomposition rates and soil carbon fluxes.

VIII. Deliverables Crosswalk

Proposed	Delivered	Status
Present research results and conclusions at an international scientific research conference.	Presented at AFE 2012 Fire Congress	Completed
Present research results to the Osceola National Forest management and staff.	Presentation to ONF staff in coordination with field workshop.	Completed
Plan and participate in field workshop for managers held at the ONF in conjunction with existing JFSP project	Workshop presented at ONF.	Completed
Publish research results and conclusions in an appropriate scientific research journal.	Manuscript in preparation.	In prep.
Publish research briefs on the University of Fire Science Lab and Southern Fire Exchange JFSP Regional Consortium websites.	Research brief and video on SFE website. See citations.	Completed
Publish research results as a portion of the Co-PI's PhD dissertation work.	Dissertation complete. See citations.	Completed

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X. Oral Presentations

- Departmental Exit Seminar (November 2012 – Gainesville, FL) Oral Presentation "The Effects of Prescribed Fire and Mechanical Fuels Mastication on Soil CO₂ Efflux in Two Southeastern Naturally Regenerated Pine Forest Ecosystems".
- 5th International Fire Ecology and Management Congress (December 2012 - Portland, OR) Oral Presentation "The Influence of Prescribed Fire and Mechanical Fuels Mastication Treatments on Soil CO₂ Efflux Rates in Pine Flatwoods".
- Conserved Forest Ecosystems Outreach and Research (CFEOR) Osceola National Forest Field Workshop (September 2011 - Lake City, FL) Oral Presentation and Field Discussion "Preliminary Soil Carbon Efflux Results".

XI. Poster Presentations

- University of Florida School of Forest Resources and Conservation Symposium (2011 - Gainesville, FL) Poster Presentation "Effect of Prescribed Fire and Mechanical Fuel Treatments on Soil Carbon Respiration in Pine Flatwoods" Godwin D.R. and Kobziar L.N.

XII. Publications

Godwin, D.R., Kobziar, L.N. Effects of prescribed fire and mechanical fuel mastication on soil respiration in flatwoods forests. *Fire Ecology* (In preparation).

Godwin, D.R., Kobziar, L.N. and Zipperer, W.C. 2012 "The influence of prescribed fire and understory fuels mastication on soil CO₂ efflux rates in flatwoods forests" Annual research report to the USDA Forest Service. 78 pg.

Kreye, J., Godwin, D.R. Field Workshop Guide and Handout Publication. 2011 "Mechanical fuels reduction treatments effects on fire behavior, fuel loads, and forest ecology" http://www.southernfireexchange.org/Archive/Kobziar_Osceola_Workshop_Handout1.pdf).

Godwin, D.R. "The influence of prescribed fire and understory fuels mastication on soil CO₂ efflux rates in two North Florida flatwoods forests" Dissertation chapter in: "The influence of prescribed fire and mechanical fuels mastication on soil CO₂ efflux rates in two southeastern U.S. Ecosystems". University of Florida. 2012.

XIII. Multimedia

Edited Video Recording "Field Workshop: Landscape-scale mechanical fuels reduction treatment effects on fire behavior, fuel loads, and forest ecology" Recorded 2011. Edited by David Godwin (2012). 1 hour 18 mins. <http://www.youtube.com/watch?v=mqgAF9touFE>

Original Video Recording and Animation "Flatwoods Fuel Loading: 22 Months of Forest Growth Following Mechanical Fuel Treatments" Created by David Godwin (2013). 1 min 22 secs. <http://www.youtube.com/watch?v=Tg3H6b6TJDc>

Website "Forest Management and Soil Carbon Respiration in Pine Flatwoods" Created by David Godwin (2012). <http://davidrgodwin.com/research/forest-management-and-soil-carbon-respiration-in-pine-flatwoods/>