

SMOLDERING FIRE IN LONG-UNBURNED LONGLEAF PINE FORESTS:  
LINKING FUELS WITH FIRE EFFECTS

By

J. MORGAN VARNER, III

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL  
OF THE UNIVERSITY OF FLORIDA IN PARTIAL FULFILLMENT  
OF THE REQUIREMENTS FOR THE DEGREE OF  
DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

2005

To Julian M. Varner, Jr. (1941-2004).

## ACKNOWLEDGMENTS

Many people and organizations assisted me with this work, primary among them the Chair of my committee, Jack Putz. His inquisitiveness, energy, enthusiasm, and belief in me and my work inspired me through trying life events. Doria Gordon acquired funding and had faith in my abilities to balance logistical issues that tend to accompany fires in remote locations. Alan Long, Tim Martin, and Bob Mitchell helped me to better understand fire and the trees they affect. My friends and colleagues Kevin Hiers, Neil Pederson, and Ben Poulter stimulated and challenged my thinking and provided encouragement.

Research involving the use of fire requires incredible logistical support. Pete Jerkins, Kevin Hiers, James Furman, Kevin Mock, and many others provided assistance with fires at Eglin Air Force Base. Fires at the Carl Swisher-Katharine Ordway Preserve were accomplished with the help and energy of Steve Coates. Field support was provided by many at Eglin Air Force Base Jackson Guard. Assistance with data collection and study design was provided by Diana Olson, David Wright, Roger Ottmar, Bob Vihnanek, and many others at the USDA Pacific Northwest Research Station's Pacific Wildland Fire Sciences Laboratory. Joe O'Brien helped with small-scale experimental fire temperature measurements and advice on study design and analysis. Data collection throughout this project was assisted by Elise Owens and her quick wit. Over the course of

this project, Rich Fonda, Dale Wade, and John Kush and many others provided advice and helpful criticisms.

This research was supported by funds provided to the USDA Forest Service, Southern Research Station, Asheville, North Carolina, from the Joint Fire Science Program of the Departments of Agriculture (Forest Service) and Interior (Bureau of Land Management) with supplementary support from the University of Florida School of Natural Resources and Environment, The Nature Conservancy, and Eglin Air Force Base Jackson Guard. I appreciate the time, patience, and support over the last year from the Department of Forestry and Watershed Management at Humboldt State University.

Over the course of this project, I experienced personal tragedies amidst newfound bliss. Without the support of my family and friends, this project would have never been completed. In addition to surveying burned forests, excavating roots, and reviewing manuscript drafts, Rachel Seman-Varner helped keep me focused and joyful. Slaton Wheeler assisted with field research through lightning storms and humidity. Special thanks are also due to Geoff Parks, Adam Watts, Tova Spector, Eddie Watkins, Claudia Romero, Alex Varner, Bob Dylan, Maynard Hiss, and many others in McCarty, Carr, and Bartram Halls.

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Abstract of Dissertation Presented to the Graduate School  
of the University of Florida in Partial Fulfillment of the  
Requirements for the Degree of Doctor of Philosophy

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By

J. Morgan Varner, III

December 2005

Chair: Francis E. Putz

Major Department: School of Natural Resources and Environment

Historically, frequent fires maintained low fuel loads in many temperate coniferous forests. Widespread 20<sup>th</sup> century fire exclusion altered community structure and species composition while facilitating the accumulation of fuel. Organic matter accumulations on the forest floor have been poorly studied and have major implications for the restoration of historically fire-maintained ecosystems.

A major restoration strategy for historically fire-maintained ecosystems in general, and *Pinus palustris*-dominated ecosystems in the southeastern USA in particular, is to reintroduce fire. The results of reintroducing fire into longleaf pine ecosystems have been appalling; post-ignition smoldering fires generate noxious smoke and kill remnant large pines. The potential mechanisms of fire-induced pine mortality are long-duration heating to vascular tissues in the stems and roots, or a combination of factors increasing tree stress.

In landscape-scale experimental fires in long-unburned pine forests, four replicated treatments based on lower forest floor (duff) moisture content were applied: dry burns were ignited at 55% duff moisture content (DMC); moist burns at 85% DMC; wet burns at 115% DMC; and there was a control treatment that was not burned. Pine mortality was delayed up to 18 months following burning, and was highest ( $P < 0.05$ ) in the dry burns. The likelihood of mortality was predicted by duff consumption and canopy scorch; only duff consumption consistently predicted mortality across all burning treatments.

Isolation of the effects of stem and root heating were tested in an experiment using small-scale fires designed to heat stem, root, stem and root, or neither tissues. Depth of lethal temperatures in the mineral soil across all treatments was highly related to post-fire radial growth and root nonstructural carbohydrates. Mineral soil heating, not duff or basal bark temperatures, decreased latewood growth in the year following fire ( $P = 0.07$ ). Coarse root (2-5 mm diameter) carbohydrates were also linked to duration of lethal heating of the mineral soil ( $P < 0.01$ ;  $R^2 = 0.59$ ).

Given the conclusions from both small- and large-scale experiments and a simulation model-based comparison, current knowledge and research needs are reviewed. Future research should focus on determining spatial patterns of forest floor moisture and combustion dynamics. Research linking forest floor fuels to fire behavior and subsequent fire effects will increase ability to manage and restore long-unburned forests.

## CHAPTER 1 INTRODUCTION

In fire ecology research, limited understanding of mechanistic links among pre-fire conditions, fire characteristics, and subsequent ecosystem effects results in a poor understanding of fire effects (Johnson and Miyanishi 1995, 2001; Dickinson and Johnson 2001, 2004). Knowing the linkages among pre-fire fuel characteristics (types and amounts), fire characteristics (types, temperatures, and durations), and post-fire ecological outcomes (e.g., tree damage or death) will provide an increased understanding of the ecology of fire and its effects on species, communities, and ecosystems (Ryan and Frandsen 1991, Swezy and Agee 1991, Ryan 2000, Johnson and Miyanishi 2001, Dickinson and Johnson 2001).

Development of a mechanistic fire ecology will require several lines of inquiry for southern pine ecosystems. First, a review is needed of fuel characteristics, fire behavior and damage, and resulting post-fire tree mortality in southern pine-dominated ecosystems. To date, most work in coniferous ecosystems has focused on pre-fire and subsequent post-fire communities, with little emphasis on the fuel and fire characteristics that influence the structure and composition of the latter (Figure 1-1). Specifically, lack of research on the role of forest floor fuels (organic soil horizons) is troubling; especially considering their role in smoldering fire, smoke generation, and tree mortality in coniferous ecosystems worldwide (Flinn and Wein 1977, Ryan and Frandsen 1991, Swezy and Agee 1991, Hungerford et al. 1995, Miyanishi 2001).

Following this logic, descriptive work is needed on forest floor fuels in fire-excluded coniferous ecosystems. Forest floor fuel depth, distribution, structure and composition are topics that deserve study, with particular reference to their roles in smoldering fire and fire-induced tree mortality. The forest floor fuel complex has been little studied (but see Brown 1966, Brown 1970; Miyanishi 2001; Stephens et al. 2004; Hille and Stephens 2005). Given the diversity of its physical and chemical characteristics, the forest floor fuel complex warrants experimental study on fire behavior and determinants of combustion. With a better empirical understanding of the forest floor fuel complex and its combustion characteristics, we can then incorporate pre-fire forest floor fuel loading into theoretical models of fire-caused tree mortality (Dickinson and Johnson 2001, Miyanishi 2001).

This study evaluated the effects of varying burning treatments on overstory tree mortality in relation to forest floor combustion. In a large field experiment, long-unburned longleaf pine stands were burned at different duff moisture contents. After these fires, post-fire damage and tree mortality were monitored for 3 years to capture delayed mortality. To explore the mechanisms for the observed patterns of tree mortality in stand-level fires, individual pines were burned so as to damage stem, roots, both stem and roots, or neither tissues. Temperatures on the basal bark, within the duff, and at 5, 10, and 20 cm depths in the mineral soil were monitored to determine heating effects on tree stress, growth, and mortality. These experiments, in concert with field and laboratory smoldering experimentation, strengthen our understanding of the mechanistic linkages among forest fuels and fire behavior with tree damage and mortality.

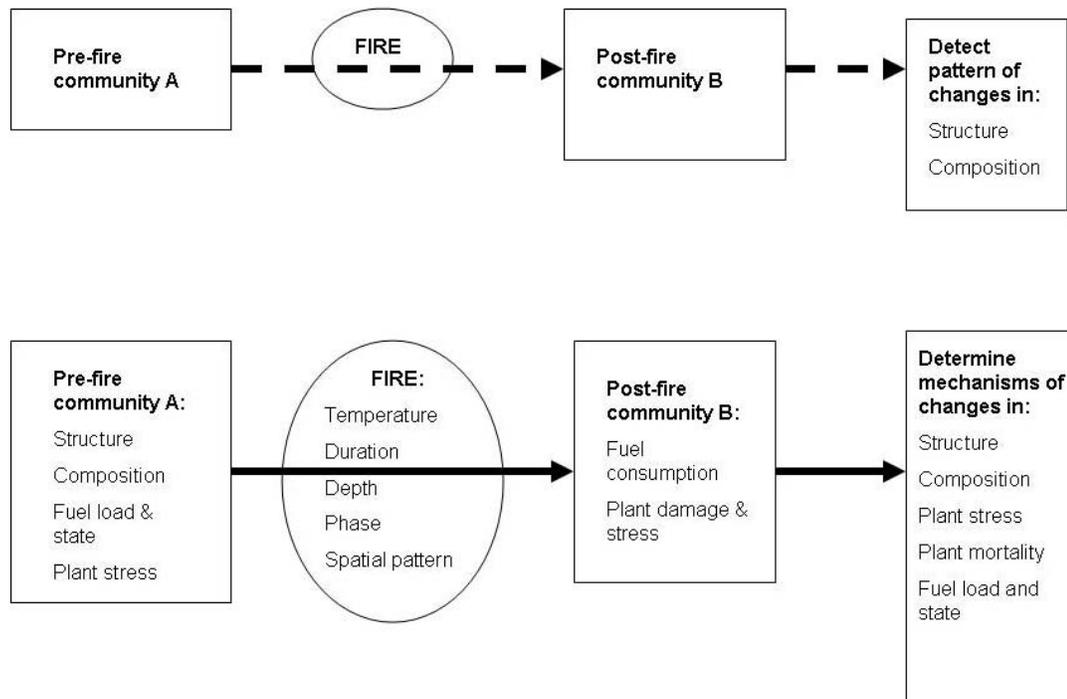


Figure 1-1. Many traditional models in fire ecology research have neglected fuel and fire characteristics and instead employed simplistic and often misleading pre-fire environment + fire = post-fire environment models. The objective of this study is to build a more rigorous approach to understanding fire effects and the mechanisms of fire ecology, particularly in relation to longleaf pine dominated ecosystems of the southeastern USA.

CHAPTER 2  
RESTORING FIRE TO LONG-UNBURNED PINUS PALUSTRIS ECOSYSTEMS:  
NOVEL EFFECTS AND CONSEQUENCES<sup>1</sup>

**Introduction**

Southeastern USA pine forests and savannas dominated by *Pinus palustris* (longleaf pine) and a biologically diverse understory covered an estimated 37 million ha before European settlement (Frost 1993). During ensuing centuries, southeastern forestlands have been logged, farmed, subdivided, and planted with faster-growing southern pines (Croker 1987). Remnant areas not converted have been degraded by several decades of fire suppression (Croker 1987, Frost 1993). In these areas, such landscape changes caused a 97% decline in the area of longleaf pine ecosystems, making them among the most imperiled ecosystems in the United States (Noss et al. 1995).

Of the remnant area of longleaf pine ecosystems, only about half is frequently burned (Outcalt 2000), leading to substantial alterations in ecosystem structure and composition. Presettlement fire regimes were typified by short fire-return intervals (ranging from 1 to 5 years), and by low-intensity surface fires ignited by lightning and late Holocene Native Americans (Christensen 1981). Fire suppression transforms these once open savanna-woodland ecosystems into closed canopy forests, with reduced understory plant species richness, and heavy accumulations of surface fuels (Heyward 1939, Engstrom et al. 1984, Mushinsky 1985, Ware et al. 1993, Gilliam and Platt 1999,

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<sup>1</sup> A version of this chapter was published as Varner, J.M., D.R. Gordon, F.E. Putz, and J. K. Hiers. 2005. Restoring fire to long-unburned *Pinus palustris* ecosystems: Novel fire effects and consequences. Restoration Ecology 13:536-544.

Kush and Meldahl 2000, Kush et al. 2000, Varner et al. 2000, Provencher et al. 2001b). Overstory density, tree species richness, and basal area increase in response to fire suppression (Ware et al. 1993, Gilliam and Platt 1999, Varner et al. 2000), while understory species richness and cover decrease (Gilliam and Platt 1999, Kush et al. 2000, Varner et al. 2000). Whereas organic matter on the forest floor was scarce in presettlement ecosystems, in the absence of frequent fires there are substantial accumulations of surficial organic horizons, particularly around the bases of large pines (Heyward and Barnette 1936, Brockway and Lewis 1997, Varner et al. 2000, Kush et al. 2004).

To reverse or reduce the further decline of southeastern longleaf pine ecosystems, many fire-excluded stands with remnant mature pine overstory have been targets for ecological restoration (Hermann 1993, Landers et al. 1995, Wade et al. 1998, Provencher et al. 2001b). In long-unburned pinelands, the objectives of restoration (Wade et al. 1998, Varner et al. 2000, Provencher et al. 2001b) are typically:

- Maintain the remnant pine overstory
- Reduce the hardwood midstory
- Enhance or re-establish native plants and animals
- Reduce accumulated fuels
- Reduce native and non-native invasive species populations.

Efforts at restoring community structure and composition have generally included the complementary actions of altering species composition by removing invasive species, reducing stand density, and reducing fuel loads. In highly altered systems, reintroduction of understory species is increasingly common (Bissett 1996, Cox et al. 2004, Jenkins et al. 2004). The most common approach to restoration of long-unburned southern pine communities has been the reinitiation of historical fire regimes with prescribed fires.

The objectives for this review were:

- Describe the effects of fire exclusion on southern pine ecosystems
- Review the outcomes of fire reintroduction and restoration
- Review the hypothesized causes of restoration fire mortality of overstory pines in the Southeast and in analogous ecosystems worldwide
- Present a fuels-based perspective for setting restoration priorities that minimizes catastrophic overstory mortality.

## **Effects of Fire Exclusion on Longleaf Pine Ecosystems**

### **Overstory responses to fire suppression**

With fire exclusion, Southeastern pinelands have experienced structural and compositional shifts from open savanna-woodlands to closed canopy forests. Frequently-burned savanna structure is typified by a spatially variable but mostly open canopy, with stand densities of 130 to 250 trees/ha > 10 cm dbh, and basal areas of 12 -20 m<sup>2</sup> ha<sup>-1</sup> (Wahlenberg 1946, Platt et al. 1988, Boyer 1990, Palik and Pederson 1996, Varner et al. 2003a; Figure 2-1). Throughout its range, longleaf pine is mono-dominant or occurs with scattered fire-resistant oaks (primarily *Quercus geminata*, *Q. incana*, *Q. laevis*, *Q. margaretta*, and *Q. marilandica*) and hickories (*Carya tomentosa* and *C. pallida*; Peet and Allard 1993, Varner et al. 2003b). With the cessation of fire-induced mortality, the cover and density of shrubs and trees increase in the midstory and canopy (Gilliam et al. 1993, Brockway and Lewis 1997, Gilliam and Platt 1999, Kush et al. 2000, Varner et al. 2000, Provencher et al. 2001a, 2001b; Figure 2-2). The species that benefit from fire suppression include many fire-susceptible species (e.g., *Q. hemisphaerica*, *Q. nigra*, *Acer rubrum*, *Liquidambar styraciflua*, *Magnolia grandiflora*, and *Nyssa sylvatica*) that alter stand structure by increasing tree densities, leaf areas, and basal area. Stand composition is degraded as canopy species richness increases.

### **Understory responses to fire suppression**

Without fire in longleaf pine ecosystems, understory communities undergo radical shifts in cover and richness. Frequently-burned pineland understory communities are among the most species-rich outside of the tropics (Peet and Allard 1993, Kirkman et al. 2001, Provencher et al. 2003). Typical burned understories contain 20 to 30 species  $m^{-2}$ , with dominance by bunch grasses (*Aristida stricta*, *Schizachyrium scoparium*, and *Andropogon* spp.), asters, legumes, and other forbs including several rare and endemic plant species (Hardin and White 1989, Peet and Allard 1993). Without fire, increased overstory and midstory canopy cover (and leaf litter deposition) reduce sunlight reaching the forest floor; leading to the loss of light-demanding understory grasses, forbs, and pine seedlings (Provencher et al. 2001a, 2001b, Waters et al. 2004). After several decades of fire suppression, herbaceous species richness is often  $<2$  species  $m^{-2}$ ; pine seedlings are lacking, and the understory becomes dominated by woody species (Varner et al. 2000, Kush et al. 2004).

### **Midstory responses to fire suppression**

A marked change in fire-excluded pinelands is the advent of a woody midstory. Most frequently-burned pinelands (particularly on sites with high net primary productivity) lack a well-developed midstory stratum (Peet and Allard 1993, Landers et al. 1995). The few native shrub and tree species present in frequently-burned pinelands include oak and hickory sprouts, *Ilex glabra* (gallberry), *Vaccinium* spp., *Serenoa repens* (saw palmetto), and isolated patches or “domes” of *Quercus geminata* (Guerin 1988, Peet and Allard 1993). Without fire, hardwoods and shrubs ascend into the midstory, where they increase cover and stem density dramatically (Provencher et al. 2001b).

### **Forest floor characteristics after fire suppression**

Frequently-burned pinelands have very little organic matter on the forest floor, except some litter (Oi horizon); but this condition is altered radically by fire exclusion. Without frequent surface fires, leaf litter, sloughed bark, fallen branches, and other organic necromass accumulate and decompose into fermentation (Oe) and humus (Oa) horizons absent in frequently-burned communities (Figure 2-3 Heyward 1939, Switzer et al. 1979). Roots and mycorrhizal hyphae exploit these “duff” horizons, especially near the bases of large pines, where duff can accumulate to depths of 25 cm or more (Varner et al. 2000, Gordon and Varner 2002, Kush et al. 2004). Litter accumulation and duff formation further block light from reaching the forest floor (Waters et al. 2004) and may play a significant role in driving changes in nutrient cycling (Wilson et al. 2002).

### **Responses to Fire Reintroduction: Restoration Case Studies**

#### **Flomaton Natural Area**

The Flomaton Natural Area is a 27 ha remnant old-growth longleaf pine stand in Escambia County, Alabama (31°01' N, 87°15' W). Fire had been suppressed in the stand for 45 years until 1993, when a small trash fire ignited a 3-ha stand isolated by a dirt road. The wildfire was allowed to burn out on its own with no observed canopy scorch and limited stem char (all trees < 1 m char height). For several days after the fire, smoldering continued in the deep duff that had accumulated around the large remnant pines. Smoke from these fires was problematic for local residents particularly because emissions from smoldering fires are much more hazardous to human health than relatively benign flaming-phase fire emissions (McMahon et al. 1980, McMahon 1983). Additionally, the danger of re-ignition remained high as long as smoldering continued. During the first 2 years after the fire, heavy mortality was observed in the overstory

longleaf pines (Kush et al. 2004). Mortality was highest among large pines: 91% of the trees >35 cm dbh died. Survival was higher among small (10 to 20 cm dbh), longleaf, slash (*P. elliotii* var. *elliotii*), and loblolly pines (*P. taeda*). Most of the small trees of fire-susceptible hardwood species (primarily *Liquidambar styraciflua*, *Prunus serotina*, and *Acer rubrum*) that invaded during the fire-free period also survived the fire (Kush et al. 2004).

In response to the loss of a high proportion of the old growth pines during the 1993 fire, an aggressive ecological restoration program was initiated on the adjacent 24 ha unburned site. The restoration process began with the mechanized harvesting of all hardwood stems (primarily *Quercus* spp.) > 10 cm dbh with a Morbark three-wheeled feller-buncher (Morbark Inc., Winn, Michigan). Beginning in 1994, prescribed fires were re-introduced at a FRI of 1 to 3 years (Varner et al. 2000, Kush et al. 2004). All fires were ignited when duff moisture content was high (typically within 2 to 4 days after large rain events) and were lit to minimize fire residence time and fireline intensity. Canopy scorch was low (<20% of trees) in all fires. Even though the Oe and Oa horizons in the duff were moist when the fires were ignited, smoldering was initiated in deep duff accumulations near tree stems. Occurrences of smoldering continued to be detected for several days post-ignition, requiring repeated extinguishing with backpack, ATV, and tractor-mounted water sprayers. As a result of these efforts to control fire intensity and to extinguish duff smoldering when detected, mortality of pines in the 4 years after the fire was reduced to an annual average of 4.2% (Varner et al. 2000), still much higher than typical longleaf pine mortality (Boyer 1979, Palik and Pederson 1996), but most death occurred in trees < 20 cm dbh. The fires killed several pines 50 to 80 cm dbh, but losses

of these old pines did not exceed 2 trees ha<sup>-1</sup> year<sup>-1</sup> (Varner et al. 2000, J.S. Kush, Auburn University, unpublished data).

### **Eglin Air Force Base**

Eglin Air Force Base is a 188,000 ha military reservation in Okaloosa, Walton, and Santa Rosa Counties in the Panhandle of Florida (30°38' N, 86°24' W). Among the many natural plant communities at Eglin, longleaf pine communities cover approximately 130,000 ha. Many of Eglin's pinelands have experienced prolonged fire-free periods (McWhite et al. 1999, Hiers et al. 2003), leading to ecosystem conditions similar to those observed at Flomaton.

Reintroduction of fire has been the major method for restoration of longleaf pine ecosystems in Eglin (McWhite et al. 1999), but results have been mixed. As a result of fire re-introduction at Eglin, some stands suffered 75 to 100% overstory pine mortality; whereas in other stands pine mortality was 10% or less (McWhite et al. 1999, Gordon and Varner 2002). Aside from the need to understand the mechanisms of variation in this phenomenon, these novel fire effects in such fire-dependent forests are alarming. The huge scale of the restoration efforts at Eglin (Hiers et al. 2003) preclude the individual tree treatments used at Flomaton (Kush et al. 2004). This situation is relevant to many fire-excluded areas in the Southeast, as natural resource managers must operationally manage landscapes, rather than individual trees.

### **Other examples**

Throughout the pinelands of the Southeast, managers have experienced problems with excessive tree mortality resulting from reintroduction of fire (Table 2-1; Gordon and Varner 2002). As observed at Flomaton and Eglin, pine mortality after reintroduction of fire is usually concentrated in the largest diameter classes with greatest pre-fire duff

accumulations (Varner et al. 2000). Resulting pine mortality combined with vigorous resprouting of competing hardwoods, prolonged fire dangers, and smoke emissions plague restoration of stands throughout the southeastern US. These unintended outcomes are major deterrents to additional restoration burning region-wide.

### **Causes of Pine Mortality after Fire Re-Introduction**

Hypothesized mechanisms for mortality of large trees after reintroduction of fire involve the direct effects of fire, such as root damage (Ryan and Frandsen 1991, Swezy and Agee 1991); vascular tissue damage (Martin 1963, Ryan 2000); leaf scorch (Ryan 2000, Menges and Deyrup 2001); or canopy damage (Menges and Deyrup 2001; Figure 2-4). Increased insect and pathogen attack of fire-stressed trees has also been suggested as an indirect cause of post-fire mortality in these communities (Ostrosina et al. 1997, Ostrosina et al. 1999, Menges and Deyrup 2001).

Where fires have been reintroduced, tree death is reportedly correlated with damage to canopy foliage and branch meristems (Herman 1954, van Wagner 1973, Wade and Johansen 1986, Menges and Deyrup 2001, McHugh et al. 2003). Foliage scorch is considered less stressful than foliage consumption, which is generally associated with damaged branch cambia (Wade and Johansen 1986). Foliage consumption has been correlated with fire-caused mortality of slash pine in the Southeast (Johansen and Wade 1987, Menges and Deyrup 2001). Nevertheless, pine mortality after reintroduction of fire has been observed without canopy damage (Varner et al. 2000, Kush et al. 2004). Regardless, canopy damage is one of many stressors to a tree, exacerbating stem or root damage, and ultimately contributing to excessive pine mortality rates after reintroduction fires.

Post-fire tree decline and mortality can also result from fire-caused root damage (Wade and Johansen 1986, Swezy and Agee 1991, Busse et al. 2000). Lateral roots of longleaf pines are concentrated in the top 30 cm of mineral soil (Heyward 1933, Wahlenberg 1946) and in long-unburned longleaf pine forests, numerous branch roots grow up into duff horizons (Gordon and Varner 2002). In frequently-burned pinelands, soil heating and resulting root mortality are negligible (e.g., Heyward 1938). With fire suppression and duff accumulation, in contrast, pine roots in duff and in the surface mineral soil can be heated, damaged, or consumed in long-duration smoldering fires where temperatures can exceed lethal values for hours (Flinn and Wein 1977, Wade and Johansen 1986). Smoldering fires spread three orders of magnitude slower than surface fires and are typically concentrated in the lower duff (Oa horizon) beneath a thermal blanket of overlying Oe material (Hungerford et al. 1995). Although localized and small, the smoldering front transmits lethal heat loads (hours > 60°C) to 10 to 20 cm deep in the mineral soil (J.M. Varner, unpublished data). A similar mechanism of duff root heating was proposed as a cause of tree death and decline in ponderosa pine stands (*P. ponderosa*; Swezy and Agee 1991, Busse et al. 2000). Given the potential physiological impairment posed by large-scale root heating and consumption, mechanisms involving root damage deserve further study.

Basal cambial damage is another proposed mechanism of tree mortality after fire reintroduction. Basal damage in tree stems can occur during surface fires and during residual smoldering of duff. During surface fires, combustion of litter causes large amounts of heat to be released close to tree stems, leading to stem char (Wade and Johansen 1986, Dickinson and Johnson 2001). Bark, especially the thick accumulations

on long-unburned trees, usually insulates the cambium sufficiently against heat damage (Spalt and Reifsnyder 1962, Fahnestock and Hare 1964, Hare 1965, Reifsnyder et al. 1967, Vines 1968, Dickinson and Johnson 2001). In contrast, long-duration heating during smoldering of duff around tree bases can raise temperatures to lethal levels and cause cambial death and tree mortality (Dixon et al. 1984, Ryan et al. 1988, Ryan and Rheinhardt 1988, Dunn and Lorio 1992, Ryan 2000, Dickinson and Johnson 2001). Duff smoldering often continues for hours or days after ignition (Covington and Sackett 1984, Hungerford et al. 1995), long enough to kill the cambium under even thick layers of bark. Cambial damage, even when it does not entirely encircle the stem, is correlated with fire-caused tree mortality in other conifers (e.g., Ryan et al. 1988, Ryan and Rheinhardt 1988, Ryan 2000). Given the long-duration heating observed in reintroduction fires and the potential damage to whole-tree physiology, basal cambial damage appears to be an important mechanism of overstory pine mortality when fires are reintroduced.

Indirect effects of fire re-introduction are reflected in tree physiological stress that, in turn, renders pines susceptible to pests or pathogens. Overall tree stress may be indicated by changes in carbon balance, as indicated by stem or root tissue carbohydrate levels, by reduced resin exudation pressure, or by reduced radial growth (Kozlowski et al. 1991). Past work on southeastern (Davidson and Hayes 1999) and western USA conifers (Covington et al. 1997, Ryan 2000, McHugh et al. 2003, Wallin et al. 2003, Wallin et al. 2004) shows that increased physiological stress renders trees more susceptible to pest and pathogen attack. Re-introducing fire to long-unburned slash pine stands in south Florida led to sharp increases in both *Ips* and *Platypus* spp. beetles and subsequent overstory mortality (Menges and Deyrup 2001). It follows that if restoration burning in longleaf

pinelands increases tree stress, then growth and defenses would decline and pest and pathogen attacks would increase. In many restoration treatments (burning and thinning, thinning alone, and burning alone), however, resulting physiological condition varies, as does susceptibility to decline and disease. Resin exudation pressure, a correlate of a tree's ability to defend itself from bark beetle attack (Raffa and Berryman 1983, Dunn and Lorio 1992), increases after fire re-introduction in ponderosa pine ecosystems. Tree physiological condition and growth also increase after thinning, raking, and burning in long-unburned ponderosa pine forests (Feeney et al. 1998, Stone et al. 1999, Wallin et al. 2004). However, reduced radial growth has been correlated with restoration burning in other ponderosa pine forests (Busse et al. 2000). To what degree restoration treatments in southern pine stands are effective in maintaining, improving, or reducing tree physiological conditions deserves further study, but arguably only within a mechanistic framework that links physiological response to specific tree damages and characteristics of the fuels and fire that caused the damage (i.e., heat damage from smoldering duff fire to stem vascular tissues that causes physiological impairment and reduced defense capability).

Evidence supports a mechanistic link between tree mortality and stem and root damage after fire reintroductions. Thus an understanding of smoldering combustion is needed to understand the mechanism behind tree mortality in long-unburned southern pine forests. Smoldering differs from flaming combustion by being controlled mostly by oxygen availability (as opposed to fuel availability), by lower temperatures ( $< 500^{\circ}\text{C}$  versus higher temperatures in flaming combustion), and by longer residence times (Hungerford et al. 1995, Miyanishi 2001). Smoldering elevates temperatures in duff, in

the underlying mineral soil horizons, in roots located within these horizons, and in nearby tree stems (Wade and Johansen 1986, Ryan and Frandsen 1991, Swezy and Agee 1991, Hungerford et al. 1995, Schimmel and Granstrom 1996, Haase and Sackett 1998, Dickinson and Johnson 2001, Miyanishi 2001).

### **Smoldering Duff Fires and Southeastern USA Restoration**

Determining the correlates and mechanisms of tree mortality following fire reintroduction should be a high priority for southeastern restoration efforts. Given that 50% of all remnant longleaf pinelands are unburned (Outcalt 2000), successful restoration burning could double the area of functioning longleaf pinelands. Landscape scale fire suppression has similarly affected other southern pinelands (dominated by *P. taeda*, *P. elliotii* var. *elliotii*, *P. elliotii* var. *densa*, and *P. echinata*; Noss et al. 1995). A better understanding of restoration burning has the potential to restore the ecological integrity of these important communities. Without a more rigorous understanding of the effects of restoration, continued reintroduction of fire will inevitably lead to more catastrophic overstory mortality and hasten the decline in southeastern pine-dominated ecosystems (Landers et al. 1995, South and Buckner 2003).

Smoldering duff and tree decline and mortality is a familiar phenomenon in ecosystems maintained by frequent fires outside of the southeastern US where, in response to fire suppression, deep organic horizons accumulate around large conifers, creating a potential for mortality when fire is re-introduced (Ryan and Frandsen 1991, Swezy and Agee 1991, Haase and Sackett 1998, Stephens and Finney 2002, McHugh and Kolb 2003). It is likely that as native ecosystems continue to be degraded by fire suppression and restoration efforts ensue, we will experience other novel disturbances that will challenge future conservation and restoration.

It is ironic that southeastern USA pinelands are imperiled by fire suppression but the reintroduction of fire often results in the death of a large portion of the residual pines. Clearly, if fire is to be a useful tool for restoring the remnant stands from which it has been excluded for decades, the fire-induced mortality problem needs to be solved. As described, consumption of novel fuels in fire excluded stands play a major role in contributing to fire-induced pine mortality. Reducing these novel fuelbeds, characterized by well-developed forest floor horizons, should be a primary restoration objective for managers attempting to reintroduce fire into excluded stands. Multiple fires over many years may be necessary for the gradual elimination of these novel fuels prior to meeting ancillary restoration objectives such as midstory reduction or understory restoration. At small scales, extinguishing duff fires can save many of the large old trees for which these ecosystems are valued, but such efforts are expensive and thus unlikely to be viable over large areas. Nevertheless, understanding the patterns and processes of duff fire-induced mortality represents an important step towards restoring and maintaining southeastern pine ecosystems as viable components in our conservation landscape.

Table 2-1. Reports of excessive overstory longleaf pine mortality following re-introduction of fire into pine ecosystems after decades of fire suppression.

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<b>Federal Agencies</b>	
USDA Forest Service	
Ocala National Forest, FL	<sup>a</sup>
Talladega National Forest, AL	<sup>b</sup>
US Fish and Wildlife Service	
Mountain Longleaf National Wildlife Refuge, AL	<sup>b</sup>
Department of Defense	
Eglin Air Force Base, FL	<sup>c</sup>
Fort Gordon, GA	<sup>b</sup>
Fort Jackson, SC	<sup>b</sup>
<b>State Agencies &amp; Institutions</b>	
Austin Cary Forest, FL	<sup>b</sup>
Autauga Demonstration Forest, AL	<sup>b, h</sup>
Florida Division of Forestry	<sup>b, d</sup>
Florida Fish and Wildlife Conservation Commission	<sup>c</sup>
Florida Park Service	<sup>e</sup>
Georgia Department of Natural Resources	<sup>c</sup>
North Carolina Division of Parks & Recreation	<sup>c</sup>
University of Florida	<sup>f</sup>
<b>NGO Land Management Agencies</b>	
The Nature Conservancy	
Alabama Chapter	<sup>c</sup>
Florida Chapter	<sup>f</sup>
Georgia Chapter	<sup>c</sup>
Louisiana Chapter	<sup>g</sup>
<b>Forest Industry</b>	
International Paper, Cantonment, FL	<sup>c</sup>

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A- Harold G. Shenk, personal communication, September 2001

B- Personal observations

C- Varner and Kush 2004

D- Jim Meeker, personal communication, April 2001

E- Erik Johnson, personal communication, November 2003

F- Walt Thomson, personal communication, March 2003

G- Nelwin McInnis, personal communication, November 2000

H- John McGuire, unpublished data



Figure 2-1. A frequently-burned longleaf pine ecosystem reference condition at the Katharine Ordway Preserve-Swisher Memorial Sanctuary in northern Florida. Pristine pinelands are increasingly rare in current landscapes of the southeastern USA.



Figure 2-2. Typical long-unburned (37 years since fire) longleaf pine forest at the Katharine Ordway Preserve-Swisher Memorial Sanctuary, Florida. Many pinelands throughout the southeastern USA have undergone decades of fire suppression, leading to increases in the midstory, organic forest floor soil horizons, and decreases in plant and animal species richness.

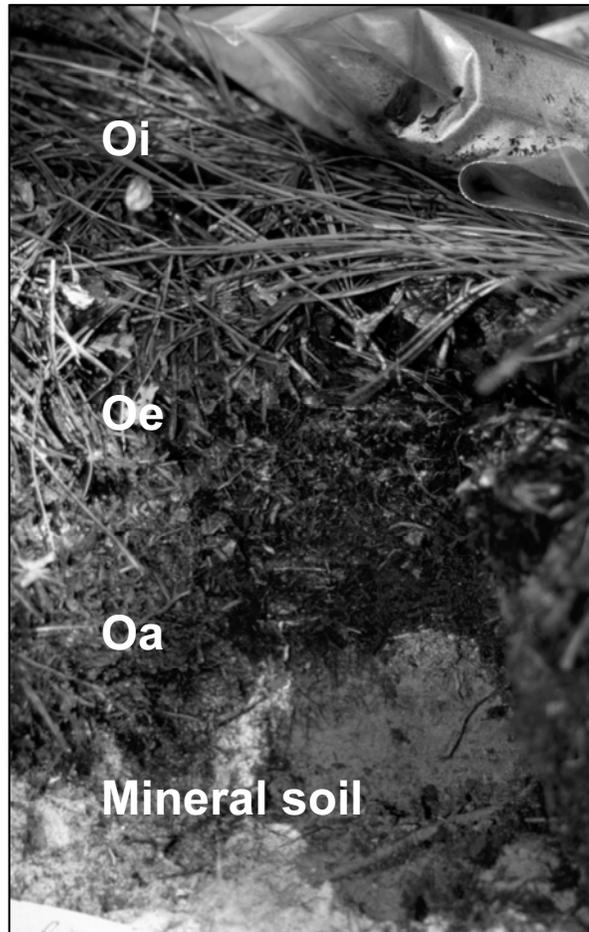


Figure 2-3. Forest floor development in a long-unburned (ca. 40 years since fire) longleaf pine forest at Eglin Air Force Base, Florida. In frequently-burned pinelands, only a thin Oi horizon forms; Oe and Oa horizons are signs of prolonged fire suppression. In many long-unburned pinelands organic soil accumulations surrounding large pines can exceed 25 cm in depth.

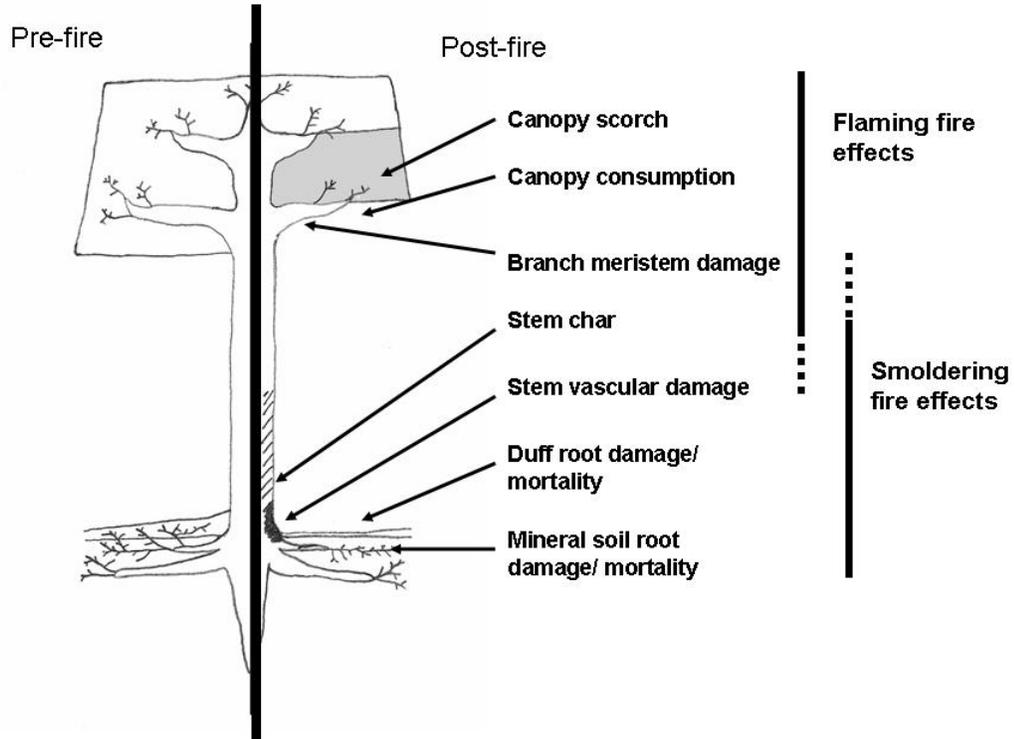


Figure 2-4. Restoration fires in long-unburned longleaf pine forests damage canopy, stem, and root tissues often leading to excessive tree mortality. Flaming and smoldering fire can cause direct damage to canopy, stem, and root tissues. Pine mortality has been linked to smoldering combustion of duff near trees, perhaps caused by damage to root and/or stem tissues, or from indirect effects due to increased physiological stress.

CHAPTER 3  
TREE MORTALITY RESULTING FROM REINTRODUCING FIRE TO  
LONG-UNBURNED LONGLEAF PINE FORESTS: THE ROLE OF DUFF  
MOISTURE

**Introduction**

The frequency, intensity, and severity of fires have been drastically altered in many contemporary landscapes (Agee 1993, Minnich et al. 1995, Ottmar et al. 1998, Outcalt 2000, Busse et al. 2000, Barton 2002, Wright and Agee 2004). In ecosystems historically maintained by frequent fires, fire exclusion leads to increased tree and shrub density, changed species composition, altered nutrient cycles, and fuel accumulation (Heyward 1939, Cooper 1960, van Wagtenonk 1985, Ware et al. 1993, Covington and Moore 1994, Minnich et al. 1995, Gilliam and Platt 1999, Everett et al. 2000, Varner et al. 2000, Keane et al. 2002, Wright and Agee 2004, Chapter 2). When fires do occur after a prolonged period of suppression, these legacies in fuel structure and composition result in altered fire behavior and effects (Johnson and Miyanishi 1995). Although reinitiation of historic fire regimes is a major component of most approaches to restoring fire-suppressed forests, woodlands, and savannas worldwide, burning these previously fire-suppressed ecosystems often fails to achieve the desired results (Fulé et al. 2004, Chapter 2).

Among the impediments to restoration of fire regimes after long periods of fire suppression is the excessive tree mortality resulting from reintroduction of fire (Wade et al. 1997, Varner et al. 2000, Stephens and Finney 2002, McHugh and Kolb 2003, Fulé et al. 2004, Chapter 2). In ecosystems maintained by frequent low-intensity fires, the

likelihood of fire-induced mortality generally decreases with increasing tree diameter (e.g., Ryan and Reinhardt 1988, Peterson and Ryan 1985, Wade and Johansen 1986, Ryan et al. 1988). In restoration fires, in contrast, tree mortality follows varying patterns, sometimes increasing with increasing tree diameter (Kush et al. 2004) and occasionally with bimodal peaks of mortality in small and large diameter trees (Swezy and Agee 1991, Varner et al. 2000, McHugh and Kolb 2003). The mechanism responsible for increased mortality caused by restoration fires is unclear, with different investigators emphasizing damage to canopy (Wyant et al. 1986, Ryan and Reinhardt 1988, Menges and Deyrup 2001), stem vascular tissue (Ryan and Frandsen 1991, McHugh and Kolb 2003), and root tissues (Swezy and Agee 1991, McHugh and Kolb 2003), as well as indirect effects of these damages on tree stress and defense against pathogens (Ostrosina et al. 1997, Ostrosina et al. 1999, Menges and Deyrup 2001, Feeney et al. 1998, Wallin et al. 2003, McHugh et al. 2003). Determining causes of fire damage should help managers predict fire-caused mortality and inform burn prescriptions to avoid or reduce post-fire tree mortality.

Restoration of longleaf pine (*Pinus palustris* Mill.) ecosystems in the southeastern USA after long periods of fire suppression is a major conservation and management goal (Hermann 1993, Landers et al. 1995, Wade et al. 1997, Johnson and Gjerstad 1998, Chapter 2). Reference longleaf pinelands have park-like stand structure, are often mono-dominant, and have a fire return interval of 1 to 5 years (Christensen 1981, Robbins and Myers 1992). Since European settlement, 97 % of longleaf pinelands have been lost (Frost 1993) and only half of all remnant pinelands are burned regularly (Outcalt 2000). Overstory mortality in restoration fires can be as high as 75 to 95%, causing radical shifts

in ecosystem structure and composition (Varner et al. 2000, Chapter 2) and defeating restoration goals. This conflict between restoration objectives and outcomes has confounded pineland restoration efforts region-wide (Chapter 2).

In 2001, a large-scale restoration experiment was initiated to examine the correlates of mortality in long-unburned longleaf pine forests. Motivated by the reported correlations of conifer mortality with duff consumption (Swezy and Agee 1991, Ryan and Frandsen 1991), varying duff volumetric moisture contents were used as treatments. We hypothesized that overstory pine mortality would increase with duff (Oe+Oa) consumption and decrease with day-of-burn duff moisture content. Additionally, damage to canopy, stem, and roots were examined at the stand and individual tree levels as they related to tree mortality. The effects of tree, fuel, and burn characteristics were tested as predictors of overstory pine mortality in restoration fires.

## **Methods**

### **Study Area**

Experimental burns were conducted in four blocks in long-unburned (35 to 45 years since fire) longleaf pine forests at Eglin Air Force Base on the Florida Panhandle, USA (N 30° 38', W 86° 24'; Figure 3-1). All blocks had heavy downed woody and duff fuel loading (ranging from 3.14 to 7.63 kg m<sup>-2</sup>), remnant longleaf pine overstory (45-200 trees > 10 cm DBH ha<sup>-1</sup>), and the altered midstory and canopy tree species composition typical of long-unburned pine forests on the southeastern Coastal Plain (Heyward 1939, Peet and Allard 1993, Gilliam and Platt 1999, Kush and Meldahl 2000). All sites are within the Southern Pine Hills District of the Coastal Plain Physiographic Province with deep, well-drained sandy soils (Brown et al. 1990). Soils of the study sites were all typic Quartzipsamments of the Lakeland series with mean depth to water table exceeding 200

cm (Overing 1995). The climate of the area is subtropical, characterized by warm, humid summers and mild winters, with mean temperatures of 19.7°C and mean annual precipitation of 1580 mm, most of which falls from June to September (Overing et al. 1995). Elevations of the study sites are 52 to 85 m asl and all sites have typical sandhill topography with minimal effects of slope and aspect (Myers 1990).

Stands at each of four sites were randomly assigned to one of four burning treatments based on collected day-of-burn volumetric duff moisture content (vdmc; percent of dry weight): dry (60% vdmc); moist (90% vdmc); wet (120% vdmc); and an unburned control. Moisture contents of forest floor (Oi, Oe, and Oa horizons) and woody fuels were calculated based on day-of-burn collections (Table 3-1.) For each experimental fire, fire weather and fire behavior were recorded periodically (Table 3-1). All prescribed burns were ignited during the late dormant season (February to April). To minimize variation in fire behavior, all fires were ignited using narrow strip head fires or spot-grid ignition (10 to 30 m between strips or spots; Wade and Lunsford 1989), with ignition managed to minimize variation in flame lengths and rate of spread.

### **Field Data Collection**

Characteristics of ground fuels and vegetation were measured in each 10 ha stand prior to burning. Forest floor depth was measured by horizon (litter [Oi horizon] and duff [Oe and Oa horizons]) at the base of each of 50 randomly selected pines, 15 to 60 cm dbh (dbh = stem diameter at 1.37 m), per plot. Forest floor depth was measured at each tree using eight 20 cm pins buried flush with the litter surface and offset from the stem approximately 10 cm at cardinal and ordinal directions. Total woody fuel loading was estimated for each plot using Brown's (1974) planar intercept method. For all overstory

pinus (> 15 cm dbh), their dbh, total height, crown height, and distance and direction to plot centers was recorded.

Initial post-burn measurements on all plot trees were made 3 to 4 weeks following the experimental fires. Stem char heights were estimated with a height pole at four cardinal directions. Scorch height and maximum height of needle consumption were estimated using a clinometer. Percent of canopy volume scorched was estimated by the same two trained observers on all trees. Post-fire reductions in forest floor depth at individual trees were measured as the average difference between the pre- and post-fire exposure of duff pins. Basal damage and evidence of pathogens were noted for all plot trees. Following initial post-burn surveys, tree mortality and any signs of decline or disease 6, 12, 18, and 24 months post-burn were noted to capture the temporal patterns of mortality.

### **Data Analysis**

The study was designed as a randomized block design with four treatments and four replicates per treatment. The four treatments were based on day-of-burn volumetric duff moisture content (wet, moist, dry and a no-burn control, as described above), collected on the morning of each burn (Table 3-1).

At the burn block level, analysis of variance was used to detect effects of treatment duff moisture (wet, moist, dry, control) on pine mortality. If differences were detected, a post-hoc Tukey-Kramer HSD test was used to detect differences between treatments. The same design was used to test for effects of duff moisture treatments (wet, moist, dry) on forest floor reduction (cm and %), stem char height, and canopy damage (scorch %, scorch height, and % canopy consumption). When necessary, non-normal data were transformed to meet the assumptions of parametric analyses. Fuel environment

parameters tested in the multiple regressions were: relative humidity (%); air temperature; moisture contents of litter (Oi), fermentation (Oe), and humus horizons (Oa); and, moisture contents of 10-, 100-, and 1000-hour fuels. The role of crown scorch (plot means of scorch height and percent of canopy volume scorched), height of stem char, and duff consumption on pine mortality were also evaluated.

Given the substantial within-plot variation in fire effects and post-fire tree mortality, individual tree post-fire mortality was modeled using the nested logistic regression approach employed in a similar study by Stephens and Finney (2002). Probability of pine mortality was modeled as a function of pre-burn fuel characteristics (dbh, pre-fire duff depth, crown height, and total tree height), duff moisture treatment, and fire effects (% duff consumed, duff depth reduction, char height, % crown scorch, and scorch height). When variables were highly correlated (e.g., crown scorch height and % crown scorch), the less correlated variable was removed from subsequent model iterations. Akaike's Information Criteria (AIC) were utilized to rank competing regression models.

## **Results**

Duff consumption, stem char, and canopy damage varied among the 12 experimental fires (Table 3-2). Across all twelve burns, mean duff consumption at the bases of the pines ranged from 2 to 63% (0.2-6.2 cm). Duff consumption in the dry burns was six times greater than in wet burns and three times greater than in moist burns (Table 3-2). Mean height of stem char was 2.24 m across all burns; individual plot means ranged from 0.9 to 5.1 m with no apparent treatment effect (Table 3-2). Mean percent of pine canopy scorched and scorch height ranged from 4.3 to 71.7 % and 3.5 to 16.7 m, respectively, across all burned plots and was independent of treatment (Table 3-2). Due

to the low intensity of all the prescribed burns, only 3 trees (< 0.7% of all burned trees) suffered any needle loss during the fires (crown “consumption” in contrast to crown “scorch,” where needles are heated, not combusted) during the fires; needle consumption did not exceed 10% of the total canopy volume of any tree and was therefore not included in the analyses.

Overstory longleaf pine mortality for all plots during the first two years after the fires ranged from 0 to 42%, with only three plots exceeding 10% mortality (Table 3-2). Variation in mortality rates was greatest among the four dry burns, where overstory pine mortality ranged from 8 to 42%. Soon after the fires, all pines in the burned blocks produced new foliage and none showed obvious signs of decline; mortality generally lagged 12 to 18 months after fires. All of the pines that died showed signs of bark beetle attack (primarily *Dendroctonus terebrans* and, *Platypus spp.*), as did several surviving pines. Overstory pine mortality during the first two years after fires differed among treatments; dry burns averaged 20.5% mortality, moist burns averaged 3.0 %, and both wet and control burns suffered < 1% mortality over the two years post-burn (Figure 2;  $F=10.56$ ,  $df = 12$ ,  $p < 0.001$ ).

Univariate linear regressions using plots as replicates revealed that pine mortality was related to various parameters describing the fuel environment and fire effects. Among fuel environment variables, ambient air temperature was positively related to tree mortality ( $p = 0.04$ ), while 100-hour and both Oe and Oa horizon fuel moisture were all negatively related to mortality ( $p < 0.05$ ; Table 3-3). The best fuel environment predictors were Oa and 100-hour fuel moisture, respectively explaining 50 and 47% of variation in pine mortality. Among fire effects variables, consumption of forest floor

(litter plus duff), duff consumption, and stem char were positively related ( $p < 0.05$ ) to overstory pine mortality (Table 3-3). Forest floor reduction alone explained 71% of the variation in overstory pine mortality.

At the whole plot level, fuel environment and fire effects variables were related to pine mortality (Table 3-4). Among fuel variables, lower duff (Oa) moisture content was negatively related to probability of tree mortality. Among fire effects variables, as bole char and duff consumption increased, so did the tree death. When all fuel environment and fire effects variables were included in a variety of single and multiple regression models (Table 3-4), the model with the highest  $R^2$  (0.57) and lowest AIC (5.1) included only duff consumption ( $p < 0.01$ ):

$$\log \text{ pine mortality (\%)} = -2.93 + 0.15 (\% \text{ duff consumption}).$$

The results of the logistic regression of individual tree mortality supported the importance of fire effects parameters demonstrated in the plot-based analyses. Combining trees from all of the treatments in a nested logistic regression model revealed that the likelihood of a tree dying was related to a combination of canopy scorch and duff consumption (Table 3-5;  $R^2 = 0.34$ ,  $p < 0.001$ ). This analysis revealed that while duff consumption was an important factor across all treatments, canopy scorch was significant only in the dry burning treatment. No fuel environment parameters were incorporated into this model because fuel environment variables were measured at the plot level, not at individual plot trees, which may explain the low  $R^2$  value.

### **Discussion**

In this study, maximum fuel reduction was linked strongly to the greatest loss of overstory pines (Figure 3). Restoration of long-unburned southeastern pine forests is complicated by the often opposing goals of reducing fuels while retaining mature

overstory pines. Further, although most models of fire-caused mortality assume that as tree size, bark thickness, and canopy height increase, so does resistance to fire damage (e.g., Martin 1963, Ryan et al. 1988, Dickinson and Johnson 2001), fire-caused longleaf pine mortality rates in this study increased with tree size. This pattern appears related to the deeper accumulations of forest floor fuels around the bases of large trees. Given that work on other conifers has also found post-fire reductions in survival (Stephens and Finney 2002, McHugh and Kolb 2003) and growth (Busse et al. 2000, Elliott et al. 2002) with fire-caused reductions in forest floor and duff, these results may be more generally relevant.

Fire-induced overstory pine mortality lagged 12 to 18 months after the burns, consistent with reports in other conifers (e.g., Wyant et al. 1986, Stephens and Finney 2002) and observations by longleaf pine resource managers (Chapter 2). This lag may have been due to the fact that the large, old trees had several predisposing mortality factors (i.e., reduced physiological condition, high root volumes in drought-prone duff, greater duff fuel accumulation, high stand density resulting from fire exclusion) in addition to the direct fire injuries to roots, cambia, and canopy meristems. Kelsey and Joseph (2003) suggest that the fire-caused root damage may lead to water stress and subsequent declines in tree defenses. Delayed mortality may have also been caused by reduced allocations to defense leading to attack by beetles or susceptibility to fungal pathogens, both common after fires (Ostrosina et al. 1997, Ostrosina et al. 1999, Menges and Deyrup 2001, Kelsey and Joseph 2003) and detected in our study area. This work, however, suggests more proximate causes of the lags in tree mortality. Future work is

needed on the physiological mechanisms of decline and mortality in response to fire damage (see below).

### **Mortality and Fire Damage to Stem, Canopy, and Roots**

Duff consumption due to smoldering combustion was the only fire effect consistently related to pine mortality across scales and treatments (Tables 3-3 to 3-5). Lower duff (Oa) percent fuel moisture explained 78% of variation in duff consumption ( $p < 0.0001$ ), consistent with results from other coniferous forests (Frandsen 1987, Brown et al. 1991, Ottmar et al. 1991, Sandberg et al. 2001). Duff is consumed by smoldering combustion, causing long-duration heating to stems and organic and mineral soil (Swezy and Agee 1991, Hungerford et al. 1995). The long duration (often many hours post-ignition) of moderately elevated soil temperatures can damage or kill roots (Swezy and Agee 1991) and stem vascular tissues (Ryan and Frandsen 1991).

Stem char has been correlated with decreased growth and increased tree mortality in studies of various conifers (e.g., van Wagner 1973, Dixon et al. 1984, Peterson and Arbaugh 1986, Wade and Johansen 1986) and char height was positively related to longleaf pine mortality in our study (Table 3-3). The exclusion of small ( $\text{dbh} < 15 \text{ cm}$ ) fire-susceptible trees in this study may also have reduced the overall effect of char height on tree mortality. It is important to note, however, that measurements of char do not capture the results of long-duration heating during the smoldering phase of combustion. McHugh and Kolb (2003) supplemented char height measurements with char severity (=stem damage) and found strong correlations with post-fire mortality. Given the high correlation between char height, canopy damage, and fire behavior, its ease of measurement and persistence, and its potential role in tree mortality, char height can be a

valuable post-fire measurement for understanding tree mortality (see review in Fowler and Seig 2004).

Canopy scorch was a significant predictor of longleaf pine mortality in the nested logistic regression and has been associated with post-fire mortality in many other conifers (Peterson and Arbaugh 1986, Wyant et al. 1986, Ryan et al. 1988, Menges and Deyrup 2001, Stephens and Finney 2002). The logistic regression models nested by treatment (dry, moist, wet burns) revealed that the role of scorch was confined to the dry treatment (Table 3-5), a potential explanation for the contradictory results found in restoration burns in which scorch was prevalent and a good predictor of mortality (Menges and Deyrup 2001) or absent altogether and therefore not related to mortality (Kush et al. 2004). This finding is critical in that it highlights the challenges of making sense of fire effects with an incomplete understanding of fire behavior. Understanding the dynamic role of canopy scorch in tree mortality will require a more mechanistic approach that isolates scorch from other types of fire damage.

The results of this study reinforce the need to better understand the mechanisms by which fires kill trees (Dickinson and Johnson 2001, Kelsey and Joseph 2003, Fowler and Seig 2004). Future work on fire-caused mortality should isolate the different types of fire damage (e.g., isolating fire damage to canopy tissues from damage to below-ground tissues; Carter et al. 2004) and consider their interactions (e.g., heat from smoldering duff damages vascular tissues in surficial roots and the bases of tree stems rendering trees susceptible to beetle attack). Such studies should combine whole tree physiology models with considerations of fire damage and subsequent increases in tree stress (Manion 1991, Dunn and Lorio 1992, Ryan 2000, Kelsey and Joseph 2003, Wallin et al. 2003).

### **Challenges to Restoration Using Fire**

Given the clear role of duff moisture content in causing tree mortality, efforts to understand moisture dynamics of duff should be a high research and management priority. Duff moisture content is controlled by several factors acting at different scales. At large scales, duff moisture is controlled by recent precipitation amounts and temporal distributions (Ferguson et al. 2002). Within stands, localized duff moisture can vary with forest floor composition, beneath and between tree crowns, and at small scales in basal duff accumulations (Gordon and Varner 2002, Miyanishi and Johnson 2002). Duff fuel particles vary in their physical and chemical composition (e.g., suberin-rich bark in contrast to extractive and cellulose-dominated pine needle litter), both of which affect ignition and burning characteristics at small scales.

Burning prescriptions for long-unburned forests will continue to require consideration of traditional synoptic weather variables but should be enhanced to acknowledge the important role of forest floor fuel complexes. Prescriptions should incorporate more robust estimates of time and duration of localized precipitation and drying, duff moisture (Ferguson et al. 2002), and the subsequent effects of these factors on fire behavior, particularly residence time (Frandsen 1987, Frandsen 1991, Miyanishi 2001, Miyanishi and Johnson 2002). Given the diversity in forest floor composition and structure in long-unburned longleaf pine forests, the drying, wetting, and burning behavior of this fuel complex warrant further study.

Prescriptions for fire reintroduction in long-unburned forests should be tailored to local operational scales. For example, it may be operationally feasible to use a combination of wetting (either with backpack or tractor-mounted units) and/or raking away forest floor fuels to minimize potential for long-duration heat damage to high-value

trees in small stands. Pre-fire raking has been used successfully in *P. ponderosa* burning (Feeney et al. 1998, Wallin et al. 2002) but less often in longleaf pine forests. In addition to the labor intensity of raking, a few longleaf pine forest managers have reported what they believe to be raking-induced mortality (Varner and Kush 2004). Extinguishing smoldering duff fires with tractor, ATV, or backpack-mounted water or foam has been successfully employed in small (< 20 ha) restoration fires (Kush et al. 2004).

Unfortunately, none of these labor-intensive treatments are appropriate for large-scale restoration burning (Chapter 2). Managers of large forests throughout the southeastern USA are faced with burning large areas with limited staff and increasing limitations on smoke production (Hiers et al. 2003). For large areas, utilizing duff moisture and optimizing burn resources to priority stands must be the rule. In these situations, acceptable thresholds of tree mortality must be balanced with duff and woody fuel consumption and placed in the context of landscape objectives.

In restoration fires, managers and forest and fire scientists must recognize the increasingly important role of forest floor fuels and the unintended damage they can cause. Traditional fire effects such as canopy scorch and stem char are readily observed and modeled. While more subtle, the relationships between duff consumption and overstory mortality deserve increased attention and additional small and large-scale experimentation. The reason for this oversight may be that this phenomenon was formerly rare but getting more common as fires are being reintroduced after long periods of suppression (e.g., Ryan and Frandsen 1991, Swezy and Agee 1991, Haase and Sackett 1995, Stephens and Finney 2002, McHugh and Kolb 2003). While duff smoldering is problematic, land managers are left with the conundrum of having to reduce duff fuels

while maintaining a living overstory. Incorporating fuel moisture thresholds in burn prescriptions that include measures of the forest floor fuel complex may help managers avoid widespread overstory tree damage and mortality and successfully reduce fuels when they reintroduce fires after long periods of exclusion.

Table 3-1. Fire weather and fuel moisture values for each 10 ha experimental prescribed burn in long-unburned longleaf pine forests at Eglin Air Force Base in northern Florida, USA.

Site	Treatment <sup>1</sup>	Burn Date	Rel. Hum. (%)	Air Temp. (°C)	Wind Speed (m sec <sup>-1</sup> )	Fuel Moisture Content (% dry wt.) <sup>2</sup>					
						Oi	Oe	Oa	10-hr	100-hr	1000-hr <sup>3</sup>
RT01	Wet	Feb 18/01	26	17	0.45	18	69	102	26	54	83
RT02	Wet	Mar 05/02	24	12	0.89	27	70	125	43	61	--
RCX	Wet	Mar 14/02	64	20	1.34	22	76	133	42	45	77
RCM	Wet	Mar 04/02	21	8	0.89	35	91	137	52	66	86
<i>Wet Treatment Means</i>			34 a <sup>4</sup>	14 a	0.89 a	26 a	76 a	124 a	41 a	57 a	82 a
RT01	Moist	Mar 27/01	24	16	0.45	14	41	117	20	44	119
RT02	Moist	Feb 22/02	43	17	1.34	17	43	79	25	45	--
RCX	Moist	Mar 08/02	35	24	1.79	16	45	112	22	28	70
RCM	Moist	Feb 22/02	37	18	0.45	14	27	102	18	39	64
<i>Moist Treatment Means</i>			35 a	19 ab	1.01 a	15 b	39 b	103 a	21 b	39 b	84 a
RT01	Dry	Apr 26/01	43	32	0.45	16	18	40	18	15	92
RT02	Dry	Mar 24/02	39	23	0.89	12	27	87	13	22	--
RCX	Dry	Apr 07/02	60	19	1.34	11	46	64	9	13	33
RCM	Dry	Apr 24/02	53	28	0.89	7	11	59	14	18	47
<i>Dry Treatment Means</i>			49 a	26 b	0.89 a	12 b	26 b	62 b	14 b	17 c	57 a

<sup>1</sup> Prescribed fire treatments were based on day-of-burn volumetric duff moisture content.

<sup>2</sup> Fuel moisture content for each fuel category was calculated based on day-of-burn collections of 5 samples per fuel category.

<sup>3</sup> 1000-hour fuel moisture contents are based on an average of both sound and rotten downed fuels (R. Ottmar, unpublished data).

<sup>4</sup> Different letters following treatment means denote significant differences among column means determined with ANOVA followed by post-hoc Tukey's HSD with  $\alpha = 0.05$ .

Table 3-2. Effects of 10 ha prescribed burns in long-unburned longleaf pine forests at Eglin Air Force Base in northern Florida, USA.

Site	Treatment <sup>1</sup>	Forest Floor		Duff		Stem Char	Canopy Scorch		Pine Mortality <sup>2</sup>
		cm loss	% loss	cm loss	% loss	m	m height	% SC	%
RT01	Wet	1.3 (1.0) <sup>3</sup>	24 (8)	0.2 (0.3)	2 (4)	1.0 (0.6)	--	--	0
RT02	Wet	3.7 (2.3)	33 (15)	0.5 (1.3)	5 (15)	1.4 (0.8)	4.5 (5.6)	5.8 (11.3)	0
RCX	Wet	3.2 (2.3)	33 (13)	0.3 (1.3)	4 (13)	0.9 (1.7)	4.1 (4.2)	4.3 ( 5.2)	0
RCM	Wet	7.9 (4.9)	49 (14)	1.2 (2.9)	9 (17)	2.1 (1.4)	10.3 (6.1)	23.6 (26.7)	2
<i>Wet Treatment Means</i>		4.0	35 a <sup>4</sup>	0.6	5 a	1.4 a	6.3	11.2 a	0.5 a
RT01	Moist	3.4 (3.2)	28 (17)	0.9 (1.8)	9 (17)	1.2 (1.0)	--	--	0
RT02	Moist	3.3 (2.8)	31 (19)	1.0 (2.2)	11 (20)	1.0 (0.8)	3.5 (4.3)	8.8 (15.4)	4
RCX	Moist	7.8 (5.0)	52 (16)	2.3 (2.7)	22 (20)	3.1 (1.5)	10.2 (4.7)	35.9 (32.7)	6
RCM	Moist	7.4 (4.7)	56 (16)	1.4 (3.0)	16 (23)	5.1 (2.8)	16.7 (3.4)	71.7 (29.7)	2
<i>Moist Treatment Means</i>		5.5	42 a	1.4	14.5 a	2.6 a	10.1	38.8 a	3.0 a
RT01	Dry	10.3 (4.7)	73 (26)	6.2 (4.0)	63 (34)	1.2 (1.0)	--	--	22
RT02	Dry	6.9 (3.2)	63 (14)	1.6 (2.0)	25 (23)	2.8 (1.6)	8.4 (6.3)	34.3 (36.6)	10
RCX	Dry	6.7 (3.6)	72 (11)	2.8 (2.6)	49 (18)	3.1 (1.4)	11.9 (3.1)	58.4 (31.4)	8
RCM	Dry	9.6 (5.0)	73 (17)	4.6 (3.9)	49 (27)	4.1 (2.2)	15.3 (3.7)	70.4 (33.7)	42
<i>Dry Treatment Means</i>		8.4	70 a	3.8	46.5 b	2.8 a	11.9	54.4 a	20.5 b

<sup>1</sup> Prescribed fire treatments were based on day-of-burn volumetric duff moisture content.

<sup>2</sup> Percent tree mortality is cumulative mortality of all pines > 15 cm dbh. Mortality values for 2001 burns include surveys 36 months post-burn; mortality values for all 2002 burns include surveys 24 months post-burn.

<sup>3</sup> Values in columns are plot means (n=50 trees per plot), with standard deviations noted parenthetically.

<sup>4</sup> Different letters following treatment means denote significant differences among column means determined with ANOVA followed by post-hoc Tukey's HSD with  $\alpha = 0.05$ .

Table 3-3. Univariate linear regression results for correlates of individual pine mortality (n=450 trees) resulting from prescribed restoration burns in long-unburned forests at Eglin Air Force Base in northern Florida, USA.

Dependent Variable	Independent Variable	$R^2$	$P$
<i>Day-of-Burn Variables</i>			
log Pine Mortality (%)	Ambient Air Temperature (C)	0.36	0.04
log Pine Mortality (%)	Relative Humidity (%)	0.11	0.30
log Pine Mortality (%)	10-hour Fuel Moisture (%)	0.26	0.09
log Pine Mortality (%)	100-hour Fuel Moisture (%)	0.47	0.01
log Pine Mortality (%)	1000-hour Fuel Moisture (%)	0.31	0.12
log Pine Mortality (%)	Oi (litter horizon) Fuel Moisture (%)	0.17	0.19
log Pine Mortality (%)	Oe (fermentation horizon) Fuel Moisture (%)	0.36	0.04
log Pine Mortality (%)	Oa (humus horizon) Fuel Moisture (%)	0.50	0.01
<i>Fire Effects Variables</i>			
log Pine Mortality (%)	Forest Floor (litter+duff) Reduction (%)	0.71	<0.001
log Pine Mortality (%)	Duff Reduction (%)	0.57	0.04
log Pine Mortality (%)	Canopy Scorch Volume (%)	0.43	0.06
log Pine Mortality (%)	Stem Char Height (m)	0.38	0.03

Table 3-4. Step-wise multiple regression results for predictors of block-level longleaf pine mortality caused by prescribed restoration burns in long-unburned pinelands at Eglin Air Force Base.

Dependent Variable	Parameters			R <sup>2</sup>	P	AIC <sup>1</sup>
	$\beta_0$	$\beta_1$	$\beta_2$			
<i>Fuel Environment Variables</i>						
log Pine Mortality (%) =	6.26	- 0.07 (Oa% moisture)		.45	0.04	19.8
<i>Fire Effects Variables</i>						
log Pine Mortality (%) =	-1.01	+ 0.23 (char height)	+0.03 (% duff reduction)	.82	< 0.001	15.9
<i>Combined Model (Fuel Environment + Fire Effects)</i>						
log Pine Mortality (%) =	-2.93	+ 0.15 (% duff reduction)		.57	< 0.01	5.1

<sup>1</sup> AIC (Akaike's Information Criteria) values rank competing regression models; models with lower AIC values approximate modeled responses better than models with higher AIC values.

Table 3-5. Modeled nested logistic regression of post-fire individual tree longleaf pine mortality at Eglin Air Force Base in northern Florida, USA.

Fire Effects Nested within Treatments		Parameter Estimate	$\chi^2$	<i>P</i>	<i>R</i> <sup>2</sup>
<b>Tree Status (alive/dead)</b>					
	Intercept	3.16	21.29	<0.001	
Dry Treatment	% Canopy Scorch	-0.03	11.65	<0.001	
Moist Treatment	% Canopy Scorch	-0.01	0.32	0.57	
Wet Treatment	% Canopy Scorch	-0.03	1.39	0.24	
Dry Treatment	% Duff Consumption	-0.04	15.44	<0.001	
Moist Treatment	% Duff Consumption	-0.03	7.29	<0.01	
Wet Treatment	% Duff Consumption	-0.07	5.03	<0.01	
<b>Whole Model</b>			<b>96.35</b>	<b>&lt;0.001</b>	<b>0.34</b>

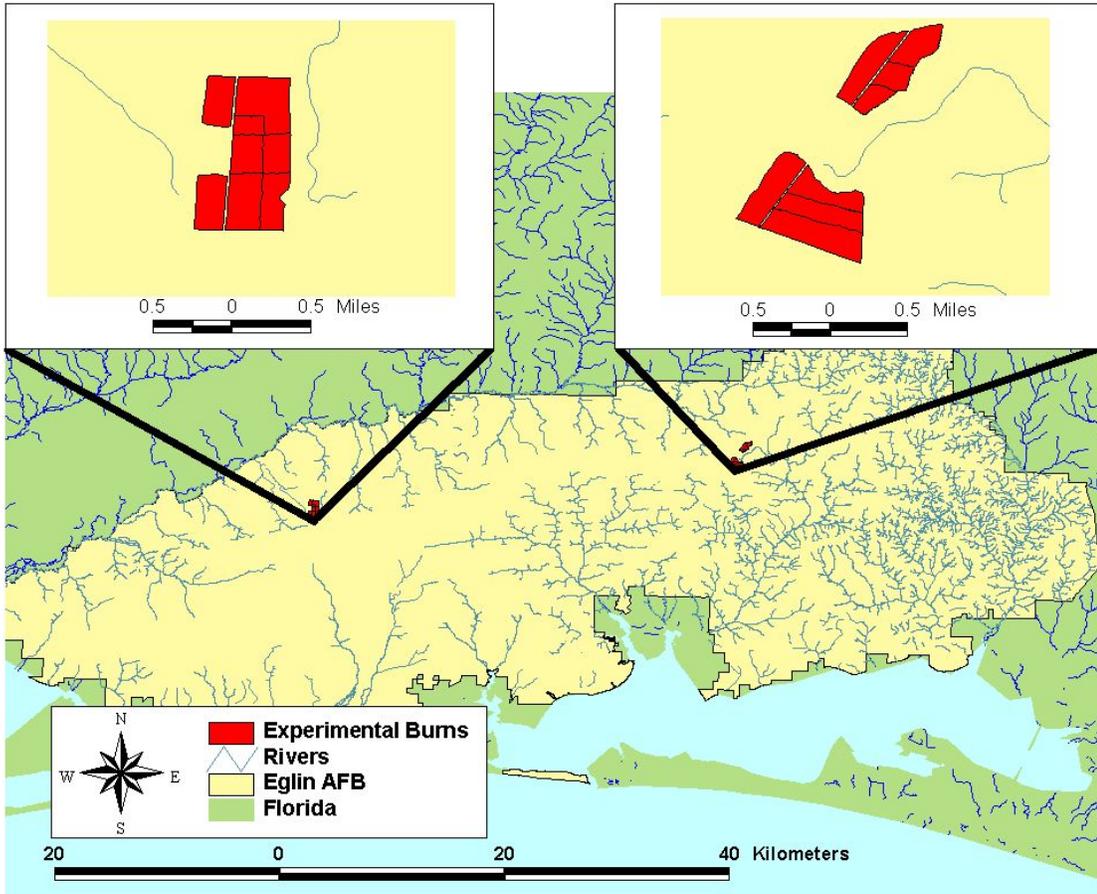


Figure 3-1. Study site locations of experimental prescribed fires to examine correlates of mortality resulting from reintroduction of fire into fire-suppressed (ca. 35 – 45 years since fire) longleaf pine (*Pinus palustris*) forests.

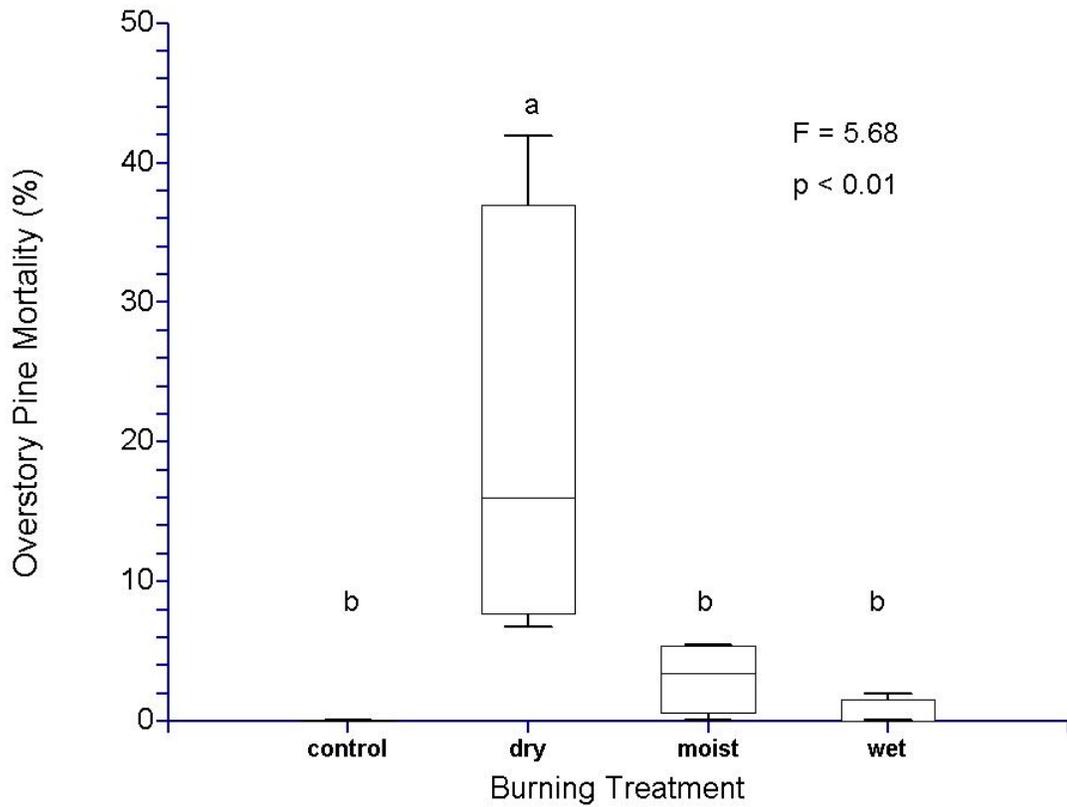


Figure 3-2. Effects of burning treatment on cumulative overstory longleaf pine mortality at Eglin Air Force Base, Florida. Treatments were based on day-of-burn duff moisture contents, where wet = 115% duff moisture content (DMC), moist = 85% DMC, dry = 55% DMC, and an unburned control. All treatments were replicated 4 times over the two years of the study.

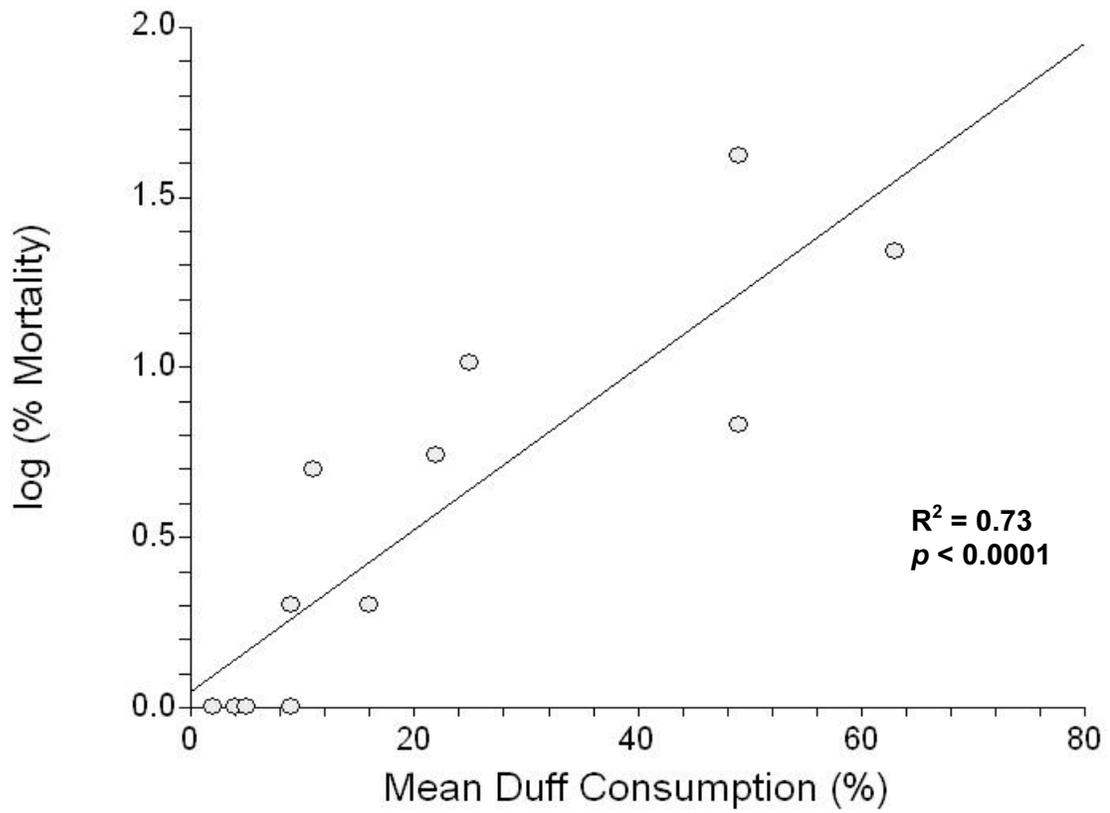


Figure 3-3. Relationship between duff consumption and cumulative post-fire mortality of overstory longleaf pines at Eglin Air Force Base, Florida.

CHAPTER 4  
EFFECTS OF BASAL BARK, DUFF, AND SOIL TEMPERATURES ON POST-FIRE  
TREE STRESS AND GROWTH

**Introduction**

Although frequent fires are necessary for the maintenance of many conifer-dominated ecosystems, when fires are reintroduced after long periods of exclusion they can stress, reduce the growth of, and kill even large trees. Increasing our understanding of fire induced conifer mortality is important given on-going efforts to reintroduce fire to areas that have suffered long periods of fire exclusion (Swezy and Agee 1991, Covington et al. 1997, Wade et al. 1997, Haase and Sackett 1998, Stephens and Finney 2002, McHugh and Kolb 2003, Agee 2003, Varner et al. 2005). Fires reintroduced following fire exclusion can damage root, stem, and canopy meristems and lead to stresses that reduce the abilities of trees to defend themselves against pathogens or weather periodic climatic stress (Feeney et al. 1998, Kolb et al. 1998, McHugh et al. 2003). A major deficiency in our understanding of post-fire tree mortality concerns the linkages between fuels and fire behavior.

Understanding the causes of fire-induced mortality of conifers characteristically resistant to fire damage is critical to the management of fire, fuels, and forest health. While several of the proposed mechanisms of fire-induced mortality (i.e., damage to stem, canopy, and root meristems and second-order effects related to pathogen susceptibility) have received attention, the link between consumption of forest floor fuels and tree mortality has increasing support (Swezy and Agee 1991, Stephens and Finney

2002, Chapter 3). For example, fire damage to surface and duff-bound roots (i.e., roots in the mor humus) was proposed as a cause of mortality in *P. ponderosa* (Swezy and Agee 1991). But fire damage to stem vascular tissue also can also cause *P. ponderosa* death (Ryan and Frandsen 1991, Ryan 2000). In the case of *P. elliotii*, canopy scorch has been linked to post-fire mortality (Dixon et al. 1984, Wade and Johansen 1987, Menges and Deyrup 2001). Combinations of fire-caused damage affect tree survival, and several investigators report the strongest correlates of post-fire mortality are those that include damages to multiple tissues (Wyant et al. 1986, Ryan and Reinhardt 1988, Ryan et al. 1988, Saveland and Neuenschwander 1990, Haase and Sackett 1998, Ryan 2000). Distinguishing the actual causes of mortality will help managers modify their actions to avoid or minimize post-fire tree mortality. Second-order fire effects such as bark beetle infestations (Dixon et al. 1984, Menges and Deyrup 2001, McHugh et al. 2003) and fungal infections (Ostrosina et al. 1997, Ostrosina et al. 1999) are cited as causes of post-fire decline and mortality, but are likely linked to compromises in tree defenses caused by fire-caused damages to stem, canopy, or root tissues. The inability to establish a relationship among the responses of trees, the characteristics of the disturbing fire (i.e., temperatures and duration of lethal heating), and the fuels that fed them is a major shortfall in our understanding of the ecology of fire as a disturbance and inhibits restoration of fire-excluded ecosystems.

The objectives of this study were to link fuels, specific types of damage to individual trees, and fire behavior to the subsequent growth, carbohydrate storage, and mortality of mature *Pinus palustris* in replicated small-scale burns. Specifically, the following hypotheses were tested:

- Changes in first-year post-fire earlywood growth in response to burning are minimal given that earlywood reflects the previous year's growing conditions in longleaf pine (Meldahl et al. 1999).
- Given that latewood in longleaf pine responds to current year stresses (Meldahl et al. 1999), decreases in latewood growth are greatest with greater duration of lethal (>60°C) heating of basal bark, and roots in duff and mineral soil.
- Changes in fine root non-structural carbohydrates in response to fire are minimal because fine roots are either killed and replaced and/or are sinks for carbohydrates from more coarse sources (stem and coarse roots; Guo et al. 2004).
- Coarse root non-structural carbohydrate concentrations following burns decrease with increasing duration of lethal (>60°C) heating to basal bark and roots in duff and mineral soil.
- Tree mortality increases with greater durations of duff smoldering and with more severe fire damage.

This work was designed to inform regional restoration efforts and to contribute to our understanding of the larger issue of post-fire overstory tree decline and mortality common to many North American coniferous ecosystems.

## Methods

### Study Site

This experiment was conducted in a long-unburned (37 years since fire) longleaf pine stand at the Katharine Ordway Preserve-Swisher Memorial Sanctuary near Melrose (Putnam County), Florida, USA (N 29° 40', W 81° 74'; Figure 4-1). The stand was dominated by an overstory of longleaf pine, with a thick midstory of oaks (*Quercus laevis*, *Q. geminata*, and *Q. hemisphaerica*), a patchy remnant groundcover dominated by *Aristida stricta*, and a thick forest floor (depths to 15 cm) typical of long-unburned xeric southeastern pine ecosystems (Chapter 2). Soils of the site are deep, excessively well-drained hyperthermic, uncoated Lamellic Quartzipsamments in the Candler series (Readle 1990). The topography is gentle, with north-facing slopes < 5% and elevations

averaging 36 m above msl. The climate is humid, warm temperate with long, warm, and humid summers and short, mild winters with annual temperatures and precipitation averaging 20° C and 1432 mm, respectively (Readle 1990).

One hundred mature (30 – 50 cm DBH) individual longleaf pines across a 2 ha area were randomly selected as experimental units for examination of fire-induced stress and mortality. Five treatments (20 replicates per treatment) were assigned to trees in a simple random design. The treatments allowed comparison of three hypothesized causes of post-fire mortality: 1) root damage (ROOT); 2) root and stem damage (ROOT+STEM); and , 3) stem damage (STEM). Two control treatments were installed to compare background mortality and stress: a control treatment that burned but smoldering phase combustion was prevented (CONTROL) and a control treatment that was not burned (NO BURN). Individual pines formed the center of 1 m radius plots in which measurements were focused (Figure 4-2). Each tree was ring-ignited with a drip torch from a raked line 1 m from the tree base over a 34-day period beginning 25 September and concluding 4 November 2003. In the ROOT+STEM treatment, fires were allowed to consume the forest floor without protection, thereby heating both basal bark and underlying roots (Figure 4-2). ROOT treatments were accomplished by first moving a 5 cm radius of basal forest floor away from the stem, then protecting the stem with insulating material (Cleveland Laminating Corp., Cleveland, OH, USA). In the STEM treatments, basal bark was heated by burning a 20 cm radius area surrounding each tree base; the adjacent forest floor was protected with the insulating material as described above. CONTROL burns were extinguished with a flapper once flaming combustion ended.

## Tree Measurements

One measure used to estimate post-fire tree stress was change in stem radial growth following burns (Busse et al. 2001). Radial stem growth (mm) of all 80 burned treatment trees was measured using increment cores (2 per tree, 90° apart) extracted one year post-burn (January-February 2005). Cores were air-dried, mounted, and sanded according to standard dendrochronological methodology (Stokes and Smiley 1968). All cores were measured using a binocular microscope with both earlywood and latewood measured to the nearest 0.01 mm.

Another metric used to estimate tree stress following burns was change in non-structural carbohydrate concentrations in fine and coarse roots (Wargo et al. 1972, Marshall and Waring 1985, Kozłowski and Pallardy 1997). Within a randomly selected subset of 8 trees in each treatment (n=40), total non-structural carbohydrate concentrations (starch + sugar) in roots were sampled within 10 days and again at 4 months post-burn (hereafter, “tnc<sub>10</sub>” and “tnc<sub>120</sub>”). The tnc<sub>10</sub> trees were sampled within 3 to 10 days post-fire to minimize transformations of carbohydrates from their pre-treatment pools (Kozłowski and Pallardy 1997). For each root carbohydrate sample, 3 g (dry weight) of fine (1-2 mm diameter) and 3 g of coarse (2-5 mm diameter) longleaf pine roots were unearthed from the top 20 cm of mineral soil within a 50 cm radius surrounding treatment trees. All roots were bagged and immediately stored on dry ice. Immediately upon removal from chilling, the roots were rinsed and oven-dried at 100° C for 2 h, followed by drying at 70° C to a constant mass to minimize post-harvest carbohydrate losses (Caldwell 1989).

Root non-structural carbohydrate samples were analyzed using a modified phenol-sulphuric acid method (Buysee and Merckx 1993). From each fine and coarse

diameter dry root sample, 80 mg was extracted for 12 h in 10 ml 80% ethanol then centrifuged at 2200 rpm for 15 minutes. The resulting supernatant was removed and placed in a 50 ml flask. The residue was centrifuged a second time in 5 ml 80% ethanol for 5 minutes, and the supernatant was transferred to the same volumetric flask. The residue from the ethanol extractions was transferred to a glass tube, dried, and then boiled for 3 hours in a 5 ml 3% HCl. The filtrate was adjusted to 50 ml in a volumetric flask and used for the starch analysis. For total sugar and starch determinations, 1 ml of a solution containing 20 to 80  $\mu\text{g}$  sugar was transferred into a glass tube and 1 ml of a 28% phenol in 80% ethanol was added. Five ml of concentrated sulfuric acid was immediately added directly to the liquid surface. The tube was agitated for 1 minute and allowed to stand for 15 minutes prior to measuring absorbance at 490 nm in a Shimadzu UV spectrophotometer (Shimadzu Corporation, Kyoto, Japan).

Pines from all 4 treatments ( $n=80$ ) were surveyed for signs of decline and mortality at 4, 8, 12, and 24 months after the burns. Because fire-induced mortality is often delayed for 18 to 24 months (Chapter 2, 3), no initial mortality was expected; annual sampling will continue in order to capture any delayed mortality.

### **Fuel Sampling**

To understand the effects of fuels on fire intensity and tree damage, we measured forest floor consumption surrounding each burned tree. Eight 20 cm tall steel pins were installed flush with the forest floor 8 cm from the stem in cardinal and ordinal directions. Following all burns, pins were measured for duff depth reduction [(initial depth - post-fire depth) / initial depth]. To estimate moisture contents, forest floor fuels were collected by horizon on each burn day from trees proximal to treatment trees. Samples were divided along horizons, with Oi removed first, then Oe material, concluding with

Oa fuels. Since pine cones are likely vectors of duff ignition (Fonda and Varner 2005), six cones (3 recent, 3 decomposing) within the drip line of each neighbor tree were collected and sealed in polyethylene bags. In the laboratory, fresh mass of all fuels was determined and were then oven-dried at 70°C to a constant weight to determine moisture content and biomass.

### **Fire Measurements**

Fire temperatures were measured on a subset of all treatment trees (6 trees per burning treatment, n=24) during fires using Type J (range 0° to 1200°C; Omega Laboratories, Stamford, CT) thermocouples connected to a Campbell Scientific CR10X datalogger (Campbell Scientific, Logan, UT). Temperatures were measured on the bark surface at three points 120° apart at approximately 10 cm above the mineral soil surface (near the forest floor-bark interface; Figure 4-3). To assess root and soil heating, thermocouples were buried 120° apart in the lower duff (Oa horizon) ca. 10 cm from the tree base, and directly beneath these points in the mineral soil at 5, 10, and 20 cm depths (Figure 4-3). To minimize soil disturbance, thermocouples were inserted into the soil in narrow openings created by slicing into the soil at a slight angle with a machete and then inserting the thermocouple lead at the predetermined depth. Maximum and mean temperatures were stored every 2 minutes from 15 minutes pre-ignition to 1700 h when the fires were required to be extinguished according to prescription and burn permits from the Florida Division of Forestry. While truncated, this artificial burn extinction was applied equally to all treatments and also fits with regional land management practices.

Fire behavior, weather, and fuel consumption were recorded for each experimental fire. Fire measurements included maximum flame height (cm; ocularly estimated), flame time (sec), and residual smoldering time (sec). Fire weather (2-m wind speed, air

temperature, and relative humidity) was recorded periodically during all fires (Table 4-1). Post-burn forest floor consumption was estimated by measuring the difference in pin exposure following fires.

### **Data Analysis**

The experiment was a completely randomized design with 4 burning treatments (ROOT, STEM, ROOT+STEM, CONTROL) with 20 replicates in each treatment. The NO BURN trees were only used to monitor background stand mortality and root carbohydrate changes, but future plans are to sample their radial growth and include these trees in the larger analyses. ANOVA was used to detect overall treatment effects, with any pair wise differences among treatments determined using a post-hoc Tukey-Kramer HSD test ( $\alpha=0.05$ ). The effects of treatments were tested on forest floor consumption (%), duration (minutes) of heating  $>60^{\circ}\text{C}$  (a good approximation of lethal temperature for plants; Byram 1958), changes in 1-year post-burn radial growth (earlywood and latewood increment; %), mortality 2 years post-burn (%), and short-term post-burn changes in root non-structural carbohydrates (fine and coarse diameter; %). In addition to the ANOVA, we used a step-wise multiple regression to examine relationships between fuel moisture contents ( $O_i$ ,  $O_e$ ,  $O_a$ , cones, 0-5 cm mineral soil) as predictors of fire behavior response variables. Step-wise regressions were also used to relate heating duration in the different strata (bark, duff, and mineral soil depths) to tree mortality (%), 1-year radial growth (% change in earlywood and latewood increment, 2003-2004), and changes in root non-structural carbohydrates (fine and coarse diameters,  $tnc_{10} - tnc_{120}$ ) post-burn response variables. To meet assumptions of parametric analyses, any non-normal data were transformed prior to analysis according to convention (Zar 1996). Finally, given the correlations among strata (i.e., the burning of duff fuel provides heat to underlying

mineral soil horizons that subsequently heat lower horizons), regression model iterations were evaluated for their multicollinearity (Hintze 2004).

## Results

### Fire Behavior

Flame heights during the experimental burns ranged 0.4 to 3.0 m (mean = 1.52 m  $\pm$  0.70 m, n=80), did not vary with treatment and were within the range of large restoration fires (Chapter 3). Fire temperatures on the instrumented trees (n=24) during experimental burns were highest above-ground, with average maximum basal bark temperatures in individual fires ranging up to 476° C, average maximum duff temperatures to 304° C, and average maximum mineral soil temperatures at 5, 10, and 20 cm below the surface to 134°, 117°, and 80° C, respectively. Lethal heating durations were longest in duff (mean = 74  $\pm$  168.8 min), next longest on basal bark (mean = 36  $\pm$  73.9 min), and then decreased with increasing mineral soil depth (27  $\pm$  4.8, 7  $\pm$  14.4, 1  $\pm$  2.5 min at 5, 10, and 20 cm depths, respectively; Table 4-2). Following ignition, basal bark temperatures increased first, then duff, then sequential depths in the mineral soil. After initial heating, basal bark temperatures across all treatments dropped below 60° C. As intended, basal bark temperatures were higher in ROOT+STEM and STEM treatments than in ROOT and CONTROL treatments (P = 0.06, df=3, F= 2.91). Duff and mineral soil temperatures at all depths, in contrast, did not differ among treatments (Table 4-3). Average forest floor consumption at the base of treatment pines differed among treatments (P < 0.001, df=3, F= 6.69; Table 4-3), with the ROOT+STEM treatment having the greatest fuel consumption. Smoldering time also differed among burning treatments (P= 0.018, df=3, F= 5.49; Table 4-3), with all smoldering treatments (ROOT, ROOT+STEM, and STEM) differing from the CONTROL treatment.

Temperatures on the basal bark and within the duff, and at 5, 10, and 20 cm deep in the mineral soil were related to several fuel moisture parameters. In a step-wise regression with day-of-burn fuel moistures and weather observations as independent variables, the duration (min) of basal bark temperatures  $> 60^{\circ}\text{C}$  was best predicted by lower duff (Oa horizon) moisture content ( $P=0.05$ ,  $R^2=0.16$ ). The best step-wise fit for duration of duff temperatures  $> 60^{\circ}\text{C}$  was a function of Oe moisture (fermentation horizon or “upper duff”) moisture content ( $P=0.01$ ,  $R^2=0.24$ ). None of the fuel moisture predictors (including mineral soil moisture) were related to heating duration in the underlying mineral soil (5, 10, and 20 cm depths; Table 4-4).

### **Radial Growth and Mortality**

In the first year following fires no trees died in any treatment, and only two trees died in the first 24 months. Of these two dead trees, one occurred in the ROOT+STEM treatment, the other tree was in the UNBURN control treatment and appeared to be struck by lightning. Neither earlywood nor latewood growth differed among treatments. In a regression with instrumented trees ( $n=32$ ) as replicates, radial growth (% change from 2003 ring radius) decreased with greater heating duration  $> 60^{\circ}\text{C}$  in the top 5 cm of mineral soil ( $P=0.08$ ,  $R^2=0.16$ ; Table 4-5). Earlywood increment was apparently insensitive to heating durations, but the regression marginally related latewood growth to duration of 10-cm mineral soil temperatures  $> 60^{\circ}\text{C}$  ( $P=0.069$ ;  $R^2=0.17$ ).

### **Root Nonstructural Carbohydrates**

As with radial growth, changes in root nonstructural carbohydrates did not vary among the burning treatments (Table 4-3). There were differences, however, when trees from all burning treatments were combined. While fine (1-2 mm diameter) root carbohydrates were insensitive to lethal heating durations, coarse pine root carbohydrates

decreased precipitously with greater burning duration (Table 4-5). Lethal heating duration at 5 cm depths in the mineral soil significantly reduced coarse root carbohydrates ( $P < 0.01$ ), explaining 59% of the variation in post-burn changes in coarse root carbohydrates (Figure 4-4).

### **Discussion**

Fire effects research suffers from a poor understanding of mechanistic linkages between fire damage and post-fire stress and decline (Ryan 2000, Dickinson and Johnson 2001, 2004). In this study, post-fire stress, as indicated by reductions in coarse root carbohydrates, was linked to the duration of mineral soil heating caused by overlying smoldering duff. Additionally, post-burn radial latewood growth rates during the first year following the fires declined with greater duration of lethal heating in the upper 5 cm of mineral soil (Table 4-5). These radial growth results suggest that damage from mineral soil heating decreases radial growth in the year following fire. These data support a multiple damage (i.e., root plus stem damage) cause, though weak, for post-fire tree decline. Further, in contrast to the preceding years, the post-fire year (2004) was the wettest year in the previous decade and terminated the longest sustained drought in northern Florida recorded history (National Climate Data Center 2005), potentially concealing or delaying the effects of damage.

Changes in coarse root carbohydrates found in this study support the role of mineral soil heating as a primary cause of post-fire tree stress. Whereas stem radial growth in longleaf pine represents an aggregate result of both the current and preceding year's conditions (Meldahl et al. 1999), carbohydrate supplies are metrics of current tree stress (Wargo et al. 1972, Marshall and Waring 1985, Dunn and Lorio 1992, Kozlowski and Pallardy 1997, Guo et al. 2004). Long duration lethal heating at 5 cm depths in the

mineral soil explained 59% of the variation in post-burn losses in coarse root carbohydrates (Table 4-5), which is strong support for root heating as a cause of overstory tree stress, and potentially the cause of widespread mortality reported following restoration fires region-wide (Chapter 2).

As has been reported in several other studies of fire effects on North American conifers (e.g., Ryan 2000, Stephens and Finney 2002, Agee 2003, McHugh and Kolb 2003, Chapter 2), there was little mortality within the first two years following fires. The reason for such low mortality may be the short duration of the experimental fires or other causes (e.g., wet climate during two years following burns). As periodic post-burn surveys continue at this site, it will be interesting to evaluate the impacts of observed short-term changes in carbohydrates (120 days post-burn) and radial growth (1 year) on subsequent radial growth and mortality. To detect “delayed mortality” (Agee 2003, Chapter 2, 3), plans are to survey the trees burned in this study for several years.

One important shortcoming of this work was the lack of differences among the burning treatments. None of the fire damage treatments (ROOT, ROOT+STEM, STEM, or CONTROL) differed in radial stem growth, root carbohydrate drain, or tree mortality (Table 4-3). Durations of lethal temperatures across all treatments varied (Table 4-2), but lethal heating durations generally followed the expected pattern: CONTROL durations of heating  $> 60^{\circ}\text{C}$  in all strata (bark, duff, 5-, 10-, and 20 cm depths) were the shortest; STEM durations were low below-ground; ROOT durations  $> 60^{\circ}\text{C}$  were lowest on the bark; and ROOT+STEM durations were consistently longer across all strata. Future sampling will determine if treatment differences in growth and mortality materialize, as observed in other post-fire studies (Busse et al. 2000, Ryan 2000, Stephens and Finney

2002, Agee 2003, McHugh and Kolb 2003, Chapter 2). Future research should seek to segregate heating more vigorously, perhaps with the use of torches (to focus heating) and more elaborate heat exclusion materials (to exclude heat from non-target tissues).

Fire research is fraught with operational problems; one problem with this experimental methodology was that the fires surrounding treatment trees were artificially extinguished prior to their “natural” extinction. All burns were extinguished with water according to prescription. Even though small amounts of water (less than 750 L of water were used to extinguish the 80 experimental fires) were used to extinguish experimental fires, these inputs may have confounded results by alleviating some of the post-fire moisture stress (Ryan 2000). Nevertheless, the small volumes of water used were unlikely to have greatly influenced the initial post-fire stress period, especially given the very wet year following the fires. Failure to consider the role of the post-fire watering in cooling and abatement of temperature stress in response to soil heating may have been a bigger oversight. In the future, researchers should allow smoldering to burn to extinction to avoid these problems.

Among the most striking results of this experiment was the depth and duration of heating in the lower duff and surface mineral soil (Table 4-2). In the ROOT and ROOT +STEM treatments, mineral soil temperatures were elevated well above ambient down to 20 cm below the mineral soil surface for long durations. This finding seems important given that in long-unburned longleaf pine stands targeted for restoration; most fine roots grow within basal duff and the upper few centimeters of mineral soil (Heyward 1933, Wahlenberg 1946, Gordon and Varner 2002). Mineral soil heating, the most prominent predictor of reductions in growth and stored carbohydrates, exceeded 60°C in the top 5

cm in 58% of all burns (75% of treatments designed for root-only heating), as well as at lower depths: 42% and 25% of all burns had temperatures  $> 60^{\circ}\text{C}$  at depths of 10- and 20-cm below the surface, respectively. Data from an extended overnight burn (4 November 2003; only temperature data prior to 1700 were included in the analyses) reveal temperatures in the mineral soil can exceed lethal values for  $>19$  hours (these burns were extinguished at 0900 h), perhaps indicative of how other trees would have burned if not extinguished and how fuels smolder in many large landscape fires. Duff and soil heating, even with the artificially truncated durations in this study, suggest substantial root heating and fire-caused root mortality in smoldering fires. Prolonged heating kills small pine roots, but also damages or kills higher-order roots (Guo et al. 2004) that connect large numbers of smaller roots to the tree, cascading localized effects into more substantial whole-tree damage. Given the observed link between the duration of lethal heating in the soil and carbohydrate drain, it appears that prolonged smoldering exacerbates post-fire stress and may cause tree death. Root damage may not be the sole cause of tree decline and mortality, but the links among duration of lethal temperatures, reduced stem radial growth, and root carbohydrate drain underscore our need to understand fire damage and the physiological response to fire-caused injury (Ryan 2000, Johnson and Miyanishi 2001).

The findings of this study provide a mechanism for delayed post-fire mortality observed in longleaf pine (Chapter 2, 3) and other conifers (Stephens and Finney 2002, Agee 2003). Coarse root carbohydrate concentrations in this study were reduced drastically by smoldering-induced heating of mineral soil (Figure 4-4). Fine root carbohydrate concentrations were unaffected by heating duration. This pattern

(carbohydrate drain in coarse roots while fine root carbohydrate pools remain unchanged) in concert with findings from landscape fires (Chapter 3) where duff consumption was strongly linked to tree mortality is provocative. These findings support a model of post-fire mortality where damaged trees use available carbohydrate storage to replenish killed or damaged fine roots while source carbohydrate reserves are depleted, weakening the tree. If stressed further, these fire-weakened trees then could succumb to second-order pests and diseases. There is a strong need for finer scale attempts at reconciling tree death in response to stresses associated with smoldering fires.

Regardless of mechanism (root or basal damage), one major shortcoming in our understanding of smoldering fires is linking the fuel (basal duff) to tree damage. Basal duff is compositionally and structurally complex (Gordon and Varner 2002; Chapter 6), hence the determinants of its ignition, smoldering duration, and extinguishment are poorly understood. In this study, the best predictive model explained only 19% of the variation in duration of duff temperatures  $> 60^{\circ}\text{C}$  (Table 4-4). Given the importance of duff smoldering and its implications for conifer mortality throughout North America, future work should focus on better characterizing duff fuels, the variation in duff moisture content, and determinants of duff ignition and combustion. With continued large-scale fire exclusion in southeastern pine forests and in coniferous forests elsewhere in North America, problems with duff smoldering are sure to continue.

Table 4-1. Fire weather observations and time-of-ignition fuel moistures from 80 experimental single-tree burns at the Katharine Ordway Preserve-Swisher Memorial Sanctuary, Florida, USA. All experimental fires burned between 25 September and 4 November 2003.

Weather variable	Mean $\pm$ s.d.	Maximum	Minimum
Air Temperature ( $^{\circ}$ C)	27.8 $\pm$ 2.37	32.0	25.3
Relative Humidity (%)	58.3 $\pm$ 6.19	67.0	51.0
Wind Speed (m sec <sup>-1</sup> )	0.9 $\pm$ 0.41	1.3	0.4
Oi moisture (%)	14.9 $\pm$ 3.4	19.1	9.4
Oe moisture (%)	64.5 $\pm$ 59.9	186.3	11.6
Oa moisture (%)	55.9 $\pm$ 23.3	100.4	36.2
Cone moisture (%)	21.0 $\pm$ 18.4	47.7	6.5
A horizon moisture (%)	7.1 $\pm$ 3.1	12.7	3.8

Table 4-2. Durations of lethal heating (i.e., temperatures >60°C) to basal bark, duff, and mineral soil during individual tree burns at the Katharine Ordway Preserve-Swisher Memorial Sanctuary in northern Florida, USA.

Treatment <sup>a</sup>	Duration of temperatures >60°C (minutes)				
	basal bark	basal duff	5 cm soil	10 cm soil	20 cm soil
STEM (n=6)	44.3 ± 77.1	42.9 ± 47.3	7.9 ± 14.1	7.3 ± 17.9	--
ROOT (n=6)	10.1 ± 7.0	145.6 ± 283.7	41.0 ± 90.5	4.6 ± 9.9	0.7 ± 0.8
ROOT + STEM (n=6)	82.2 ± 121.8	95.7 ± 187.3	56.1 ± 122.2	12.8 ± 20.9	2.1 ± 4.8
CONTROL (n=6)	9.4 ± 2.6	10.6 ± 24.6	2.7 ± 5.9	1.4 ± 3.5	0.2 ± 0.5
Means	36.5 ± 73.9	73.7 ± 168.8	26.9 ± 74.8	6.5 ± 14.4	0.8 ± 2.5

<sup>a</sup> Treatments were intended to isolate long-duration heating to either roots (ROOT), basal stems (STEM), both roots and stem tissues (ROOT+STEM), or surface fuels burned with no long-term smoldering (CONTROL).

Table 4-3. Effects of individual tree experimental burning treatments on smoldering time, mean floor consumption, longleaf pine stem radial growth, and root nonstructural carbohydrates in northern Florida, USA.

	Burning Treatment <sup>a</sup>				N	P
	ROOT	ROOT+STEM	STEM	CONTROL		
Smoldering time (minutes)	6.9 ± 6.7 <i>A</i> <sup>b</sup>	8.9 ± 8.6 <i>A</i>	6.8 ± 6.8 <i>A</i>	1.1 ± 2.2 <i>B</i>	8	0.018
Forest floor consumption (cm)	6.3 ± 1.8 <i>AB</i>	9.1 ± 3.1 <i>A</i>	7.0 ± 3.0 <i>AB</i>	4.6 ± 2.0 <i>B</i>	8	< 0.001
Radial growth (% change 2003-04)	-17 ± 19	-19 ± 36	-28 ± 33	-22 ± 19	8	0.582
Fine root carbohydrates (% change 2003-04)	6.3 ± 16.6	12.6 ± 14.3	-9.3 ± 16.5	8.1 ± 26.3	8	0.246
Coarse root carbohydrates (% change 2003-04)	-5.6 ± 27.1	-12.8 ± 46.8	-3.3 ± 44.1	9.9 ± 16.2	8	0.584

<sup>a</sup> Treatments were intended to isolate long-duration heating to either roots (ROOT), basal stems (STEM), both roots and stem tissues (ROOT+STEM), or surface fuels burned with no long-term smoldering (CONTROL).

<sup>b</sup> Values followed by a different letter indicate significant differences among treatments, determined using a post-hoc Tukey-Kramer HSD with  $\alpha=0.05$  prior to analysis.

Table 4-4. Regression results for the analysis of fuel and soil moisture effects on basal bark, duff, and mineral soil temperatures in smoldering fires in a long-unburned longleaf pine stand in northern Florida, USA.

Dependent variables	$\beta_0$	$\beta_1$	$R^2$	$P$
<i>log</i> (basal bark temperatures > 60 C; min)	3.86	- 0.019 (% Oa moisture)	0.16	0.053
<i>log</i> (duff temperatures > 60 C; min)	3.61	- 0.018 (% Oe moisture)	0.24	0.015
5-cm mineral soil temperatures > 60 C (min)	n/a			NS
10-cm mineral soil temperatures > 60 C (min)	n/a			NS
20-cm mineral soil temperatures > 60 C (min)	n/a			NS

Table 4-5. Effects of basal bark, duff, and mineral soil temperatures on longleaf pine stem radial growth and root nonstructural carbohydrates following individual tree fires in northern Florida, USA.

Dependent variable <sup>a</sup>	$\beta_0$	$\beta_1$	$R^2$	$P$
Radial growth (% change 2003-2004)	-0.22	0.045 <i>log</i> (5-cm min > 60)	0.16	0.08
Earlywood growth (% change 2003-2004)	n/a			NS
Latewood growth (% change 2003-2004)	21.7	- 19.4 <i>log</i> (10-cm min > 60)	0.17	0.07
Fine root carbohydrates (% change 2003-2004)	n/a			NS
Coarse root carbohydrates (% change 2003-2004)	7.1	- 36.7 <i>log</i> (5-cm min > 60)	0.53	0.02

<sup>a</sup> Results are based on step-wise linear regressions with minutes of basal heating > 60° C, duff heating > 60°, 5-cm mineral soil > 60°, 10-cm mineral soil > 60°, and 20-cm mineral soil > 60° as potential predictor variables.

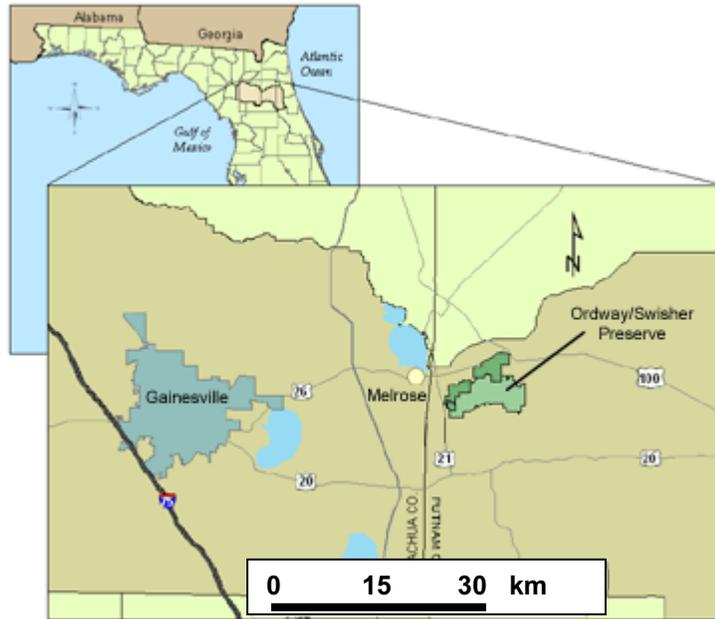


Figure 4-1. The Katharine Ordway Preserve-Swisher Memorial Sanctuary in Putnam County, Florida.



Figure 4-2. Experimental fire treatments to individual pines in a long-unburned *Pinus palustris* forest in northern Florida, USA. The treatments were, clockwise from top left: ROOT, ROOT+STEM, STEM, and CONTROL. Treatments were designed to isolate heating to target tissues (i.e., ROOT treatments were designed to heat only root tissues, while STEM treatments were designed to isolate heating on stem tissues).

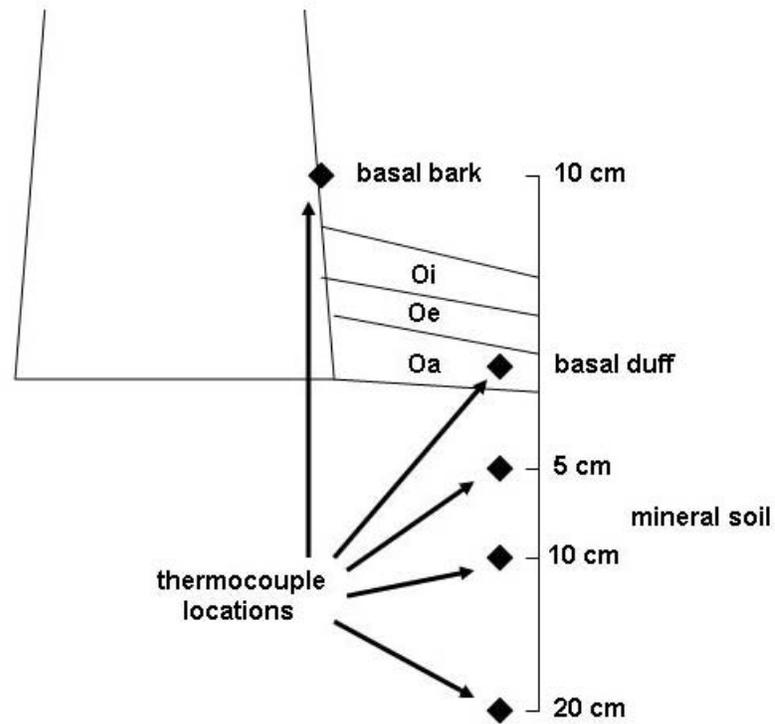


Figure 4-3. Locations of thermocouples during experimental fires surrounding the base of an individual long-unburned *Pinus palustris* tree. At each measured tree (n=8 per treatment), thermocouples were attached at three locations 120° apart in each strata: on the basal bark, inserted into lower duff (Oa horizon), and inserted at depths of 5-, 10-, and 20-cm in the mineral soil. Thermocouples measured temperatures from 15 minutes prior to ignition until 1700 extinguishment.

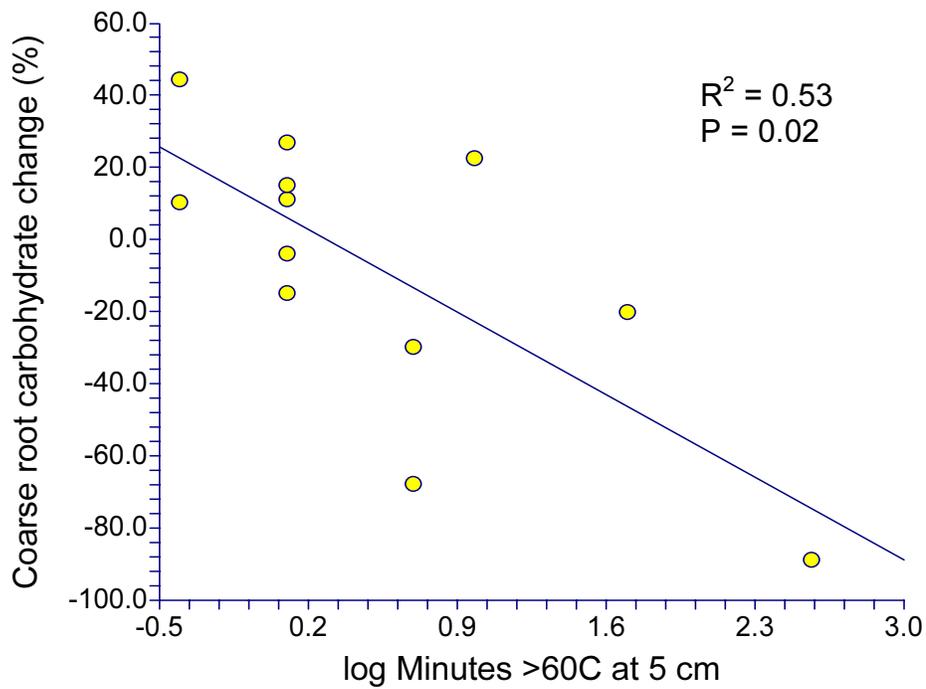


Figure 4-4. Relationship between the change (2003-2004) in coarse root non-structural carbohydrates in mature *Pinus palustris* and duration of heating >60°C at 5 cm below the surface of the mineral soil in experimental individual tree fires in northern Florida.

CHAPTER 5  
MODELED VERSUS OBSERVED FIRE EFFECTS IN LONG-UNBURNED *PINUS*  
*PALUSTRIS* ECOSYSTEMS

**Introduction**

In most historically fire-maintained temperate coniferous forests, woodlands, and savannas, frequent surface fires maintained fuel loads at low levels, often with no forest floor development (i.e., no Oe and Oa horizon or “duff” formation) and little coarse woody debris retention (Heyward 1939, Agee 2002, Stephens 2004). With widespread fire exclusion in many temperate coniferous ecosystems, fuels have accumulated, leading to uncharacteristically high fuel loads (van Wagendonk 1985, Keane et al. 2002, Chapter 2) that smolder for long periods following ignition, heating both stems and root vascular tissues. One result of these smoldering fires is a high mortality rate for large trees (Ryan and Frandsen 1991, Swezy and Agee 1991, Haase and Sackett 1998, Varner et al. 2000, Stephens and Finney 2002, Agee 2003, McHugh and Kolb 2003, Chapter 2), a phenomenon uncharacteristic of what are normally fire-resistant conifers.

Researchers and fire managers commonly use simulation models to predict effects of fire or fuels and silvicultural treatments (Stephens 1998, Brose and Wade 2002, Agee 2003). Because prescribed fires are often expensive, operationally demanding, and unforgiving, these models have great utility. Among other models (e.g., BehavePlus, Andrews and Bevins 2003; CONSUME, Ottmar et al. 1993; FARSITE, Finney 1998), fire effects predictive models (e.g., NEXUS, Scott 1999; FOFEM, Reinhardt 2003; FMA Plus, Carlton 2005) have great value for planning prescribed fires and managing

lightning-ignited fires (so-called “wildland fire use” fires), as well as for determining post-wildfire management priorities (e.g., salvage of dying timber, installing erosion control treatments). Fire effects models also offer promise for use in predicting outcomes of reintroduction of fire into fire-suppressed ecosystems.

The need for reintroduction of fire is mounting in many places in North America (e.g., van Wagtenonk 1985, Covington et al. 1997), particularly in southeastern *Pinus palustris* (longleaf pine) ecosystems (Hermann 1993, Landers et al. 1995). Fire exclusion in longleaf pine ecosystems leads to decreased plant and animal species richness (Heyward 1939, Engstrom et al. 1984, Mushinsky 1985, Aresco and Guyer 1999, Gilliam and Platt 1999, Kush and Meldahl 2000, Provencher et al. 2003, Chapter 2), increased overstory tree density (Gilliam and Platt 1999, Varner et al. 2000), and heavy accumulations of surface organic material (hereafter “forest floor”; Chapter 2). Restoring fire to long-unburned longleaf pine stands has been surprisingly problematic; among the negative outcomes that include excessive long-duration smoke emissions and weedy species proliferation, large-scale overstory pine mortality looms large. Examples of this mortality of large, old longleaf pine trees are abundant across the region (Varner and Kush 2004, Chapter 2).

The objectives of this study were to compare the predictions of the most frequently-used (Miller and Landres 2004) fire effects model, the First-Order Fire Effects Model (FOFEM; Reinhardt 2003) with empirical results from large landscape fires and small individual tree burns in long-unburned longleaf pine forests. I expected that the currently available version of this model, developed using data from well-managed ecosystems maintained by frequent fires, would perform poorly when applied to the often

more common areas where fire has been suppressed for decades (Outcalt 2000). FOFEM 5.2.1 was used since it has been used by managers and researchers to test effects of treatments (e.g., Agee 2003, Reinhardt 2003). Specific hypotheses were:

- The model estimates for mortality are poor in formerly fire-excluded stands, because they focus on damage caused by flaming fires, with little focus on residual smoldering (Chapter 2).
- The modeled duff consumption would underestimate observed consumption because FOFEM and other models typically have difficulty modeling the spatially patchy smoldering combustion of duff.
- Modeled soil heating underestimates observed soil heating because traditional models have not included soil heating caused by prolonged smoldering duff combustion.

These results of these analyses will be useful to restorationists and managers of fire-excluded longleaf pine ecosystems and potentially help identify patterns that may hold in other fire-excluded areas. Furthermore, this work should be useful for evaluating the utility of current predictive models and for elucidating alterations for improving these important decision-support tools.

## Methods

### Study Sites

Empirical data for tree mortality and fuel consumption were gathered from experimental fires at both stand- and individual tree scales in northern Florida. Large operational prescribed fires were ignited in two long-unburned sites dominated by *Pinus palustris* at Eglin Air Force Base in Okaloosa County (N 30° 38', W 86° 24'; Figure 5-1). Both stands had undergone ca. 40-45 years of fire exclusion prior to reintroduction of fire. The stands were dominated by a remnant canopy of longleaf pine (45-200 trees > 10 cm DBH ha<sup>-1</sup>), with scattered sand pine (*P. clausa* var. *immuginata*), turkey oak (*Quercus laevis*), sand live oak (*Q. geminata*), sand post oak (*Q. margaretta*), and a woody

midstory dominated by yaupon holly (*Ilex vomitoria*), littlehip hawthorn (*Crataegus spathulata*), and scattered laurel oaks (*Q. hemisphaerica*) with little herbaceous species cover (Chapter 3). Soils at both sites are deep, excessively well-drained coated Typic Quartzipsamments of the Lakeland series with mean depth to water table exceeding 200 cm. Slopes are gentle (0 to 5%) and elevations range between 50 and 60 m (Overing et al. 1995). The climate of the area is subtropical, characterized by warm, humid summers and mild winters, with mean temperatures of 25° C and mean annual precipitation of 1580 mm, most of which falls from June to September (Overing et al. 1995).

Twelve 10 ha blocks in each of the two sites at Eglin were randomly assigned to one of three burning treatments based on collected day-of-burn duff moisture content (DMC; percent of dry weight): dry (60% DMC); moist (90% DMC); and wet (120% DMC; Chapter 3). For each experimental burn, fire weather (wind speed, air temperature, and relative humidity), fuel moisture, and fire behavior were recorded (Table 5-1). All prescribed burns were ignited during the spring, from late February to April. To minimize among stand variation in fire behavior, all fires were ignited using strip head fires or spot-grid ignition (Wade and Lunsford 1989), with distance between strips adjusted between 10 and 30 m to minimize variation in flame lengths and rate of spread.

Detailed data on soil heating, which are difficult to collect in large operational fires, were based on individual tree fires. Given that smoldering duff fires are small, propagate slowly, and behave in response to small-scale controls (mineral content and bulk density; Frandsen 1991), these small fires should have emulated the same patterns observed in large fires. The individual tree study site was near Smith Lake in the Katharine Ordway Preserve-Carl Swisher Memorial Sanctuary (hereafter, “Ordway”) in Putnam County (N

29° 40', W 81° 74; Figure 5-1). The Smith Lake Tract was last burned 37 years prior to the study (personal communication, T. Perry). The area is dominated by a canopy of longleaf pine, turkey oak, sand live oak, laurel oak, and a remnant understory of southern wiregrass (*Aristida stricta*) with patches of Florida rosemary (*Ceratiola ericoides*), all typical of fire-suppressed north Florida sandhills. Soils of the site are deep, extensively well-drained hyperthermic, uncoated Lamellic Quartzipsamments of the Candler series (Readle 1990). The topography is gentle, with gentle north-facing slopes < 5% and elevations averaging 36 m.

Individual tree fires at Ordway were ignited 1 m away from the base of each of 16 randomly selected mature (30 – 50 cm DBH) pines. Using methods described earlier (Chapter 4), three treatments were installed that subjected pines to root, stem, or both root and stem heating. Using collected duff moisture contents, we divided the burns into three moisture regimes that fit within the treatment fuel moistures at Eglin (wet, moist, and dry). In all burns, duff and mineral soil temperatures were measured using Type J thermocouples (range 0° to 1200° C; Omega Laboratories, Stamford, CT) connected to a Campbell Scientific CR10X datalogger (Campbell Scientific, Logan, UT). Temperatures were measured at three locations 120° apart in the lower duff (Oa horizon) ca. 10 cm from the tree base, and directly beneath each of these points in the mineral soil at 5, 10, and 20 cm depths, for a total of 12 measurement points per tree. Maximum temperatures were recorded every two minutes at all points from 15 minutes prior to ignition through the duration of the burning day (termination was required by 1700 hours on all burn days). This constrained fire length is consistent with typical prescribed fire policies in Florida and the region (Wade and Lunsford 1989). As a result, however, both duff

consumption and soil heating (both temperatures and duration) are underestimates of potential fire effects.

### **Simulation Modeling**

To model fire effects, we used the First-Order Fire Effects Model (FOFEM 5.2.1; Reinhardt 2003). FOFEM simulates soil heating depth and duration, fuel consumption (by timelag category and forest floor horizon), and overstory tree mortality. Fuel and vegetation data were gathered from the Eglin and Ordway plots and supplemented with data from Eglin (Ottmar and Vihnanek 2000, Ottmar et al. 2003; Table 5-1). Fuel moisture inputs were derived from day-of-burn collections of timelag and forest floor fuels. For fuel model input, SAF Cover Type 70 (longleaf pine; Eyre 1980) with 15 years since fire (15 years was the maximum period of fire exclusion allowable in FOFEM) was used, appropriate for the xeric longleaf pine stands at both sites. Flame height inputs into FOFEM were derived from observations in the prescribed fires at Eglin (ignition patterns described above; weather in Table 5-1).

### **Results**

Pine mortality in the long-unburned stands at Eglin differed from FOFEM estimates across all fuel moisture scenarios (Table 5-2). FOFEM predicted 35 % overstory mortality across all moisture scenarios (Table 5-2). In the large prescribed fires at each of the three duff moisture levels, there was no overstory pine mortality during the first year following burns but during the second year, mortality was 0.5, 3.0, and 20.5 % in the wet, moist, and dry scenarios, respectively (Table 5-2). In FOFEM simulations across all moisture scenarios, probability of tree mortality decreased with increasing tree diameter (Table 5-2). In contrast, observed tree mortality varied by treatment; mortality

was uniform across all size classes in wet burns, concentrated in smaller trees in moist burns, and concentrated in larger pines in dry burns (Table 5-2; Chapter 3).

Observed duff consumption and smoldering times were substantially greater than predicted in FOFEM simulations (Table 5-2). FOFEM predicted no duff consumption in the wet and moist burns, and only 8.1% in the dry scenario. In contrast, field burns resulted in some duff consumption across all moisture scenarios; duff consumption averaged 5.0% in wet burns; 14.5% in moist burns; and 46.5% in dry burns (Table 5-2; Chapter 3). FOFEM simulations predicted brief durations of smoldering across all moisture treatments (6.8, 17.0, and 18.3 minutes in the wet, moist, and dry scenarios, respectively), but observed smoldering durations, even with premature extinguishment, were greater than FOFEM predicted, with increases of 38, 137, and 883% in the wet, moist, and dry treatments, respectively (Table 5-2; Chapter 4).

Although FOFEM did not predict any mineral soil heating above lethal temperatures ( $>60^{\circ}\text{C}$ ; Table 5-2), individual tree fires resulted in substantial mineral soil heating (Chapter 4). Across all moisture treatments, mineral soil was heated to depths of 20-cm in mineral soil (Table 5-2). The dry field burns resulted in lethal temperatures ( $>60^{\circ}\text{C}$ ) at 5 cm (mean duration = 61.3 min), 10 cm (mean duration = 9.7 min), and 20 cm below the surface (mean duration = 1.7 min). Again, since field burns were extinguished at 1700 h on the day of ignition, heating duration values were conservative.

### **Discussion**

Among the differences between predicted and observed results of fires in long-unburned longleaf pine ecosystems, the discrepancy in tree mortality is of great importance. In this study, observed pine mortality differed from model predictions across all fuel moisture regimes. Whereas FOFEM predicted equal mortality across all duff

moisture content treatments, observed mortality increased as fuel moisture decreased. This increase in mortality is important, given that prescribed burning prescriptions are written within narrow fuel moisture parameters (Wade and Lunsford 1989). Because they use empirical data (based on frequently burnable stands) and predict only first-order fire effects, FOFEM and other fire effects models (e.g., FMA Plus; Carlton 2003) are generally poor predictors of mortality of large trees. This problem is not restricted to longleaf pine ecosystems. For example, in FMA Plus (Fire Program Solutions 2003) simulations of post-fire Sierra Nevada mixed-conifer mortality, Stephens and Moghaddas (2005) estimated minimal mortality of large conifers (21% of all trees > 25 cm DBH) but observed post-fire conifer mortality under similar conditions was much higher (between 64 and 100 %; Haase and Sackett 1998, Stephens and Finney 2002). These errors in mortality prediction should be addressed in future versions of these models and others that utilize their equations (e.g., FVS-Fire and Fuels Extension, Reinhart and Crookston 2003).

Overstory pine mortality in this study varied with duff moisture content; there was a minimal effect of tree diameter on mortality in wet and moist burns, whereas in dry burns mortality was highest in largest trees (Table 5-2). Other investigators have found that mortality increases with increasing tree diameter, or follows a U-shaped probability distribution (McHugh and Kolb 2003). Because first-order fire effects on overstory trees are based on equations incorporating bark thickness and canopy height as the sole predictors of mortality, they underestimate the role of basal damage caused by smoldering duff. Given that prolonged lethal soil heating has been linked to overstory stress and mortality (Swezy and Agee 1991, Haase and Sackett 1998, Chapter 4), duff

consumption and soil heating should be incorporated into these models to more accurately estimate post-fire mortality in long-unburned forests.

The durations and temperature maxima of soil heating predicted by the FOFEM simulations were much lower than observed in the field. The failure of FOFEM to capture this impact is of general concern since long-duration mineral soil heating due to duff smoldering has been observed in many mesocosm and stand scale experiments (Frandsen 1987, 1991; Swezy and Agee 1991; Haase and Sackett 1998; Chapter 4). None of the simulations in this study resulted in lethal heating in mineral soil whereas lethal heating (minutes  $> 60^{\circ}$  C) was recorded in field burns across all moisture treatments (Table 5-2). Even in the wet burning treatment, duff smoldering heated surface soil (5 cm) above the lethal threshold for an average of three minutes. These observations of long-duration lethal heating suggest that there was substantial root and mycorrhizal damage (Flinn and Wein 1977), potentially the cause of high large tree mortality in restoration fires. Given that duff fuels are the ultimate source of long duration soil heating, better models of duff ignition and consumption are needed (Frandsen and Ryan 1985, Hungerford et al. 1995, Frandsen 1997). Improved understanding of duff-soil heating should improve the predictions of fire effects models and more accurately predict the outcomes important to restorationists and fire managers.

Duration of duff smoldering increased with decreasing duff moistures in both simulated and observed burns (Table 5-2), a result consistent with previous duff smoldering research (Brown et al. 1991). The fact that simulations underestimated smoldering times is alarming, particularly given the magnitude of differences (duration of smoldering in the predicted dry scenario = 18.3 minutes; observed = 179.8 minutes;

Table 5-2) and the finding that smoldering duration and consumption are strongly related to tree mortality (Chapters 3 and 4). This non-linear increase in duff smoldering with decreases in moisture content supports results of heavy overstory mortality in dry prescribed fires and wildfires (Varner and Kush 2004, Chapter 3).

Given that fuel consumption is a product of the duration of combustion (Brown et al. 1991), it is not surprising that the differences between modeled and observed duff consumption followed the same patterns as duration of duff smoldering. FOFEM simulations predicted no duff consumption (linked to the absence of smoldering) under wet and moist scenarios, and only minimal (8.1%) consumption in the dry scenario (Table 5-2). In contrast, duff consumption was observed across all moisture treatments in prescribed burns. Observed duff consumption was greatest in dry burns (Table 5-2), with decreases in duff moisture corresponding to large increases in duff consumption. Given that duff consumption is a major objective of restoration burns in long-unburned southeastern pine forests (Hiers et al. 2003), the prediction errors reduce the utility of FOFEM for land managers. Simulation models still suffer from their reliance on solely empirical data. Future duff consumption models based on fundamental fuel characteristics (Sandberg et al. 2001) and process-based approaches (Miyanishi and Johnson 2002) are important links filling this understanding gap.

Although we did not measure smoke emissions from the landscape-scale fires, the results of FOFEM simulated emissions are worth noting. The production of smoke emissions is linked to their phase in combustion, and is therefore sensitive to durations of flaming and smoldering during fires (Sandberg et al. 2002). Smoldering phase combustion is responsible for dominant fractions of particulate matter ( $PM_{10}$  and  $PM_{2.5}$ ),

CH<sub>4</sub>, and CO. In FOFEM simulations under a dry scenario, 75.7 and 75.8 % of PM<sub>10</sub> and PM<sub>2.5</sub> emissions were generated during the smoldering phase. If FOFEM calculations were adjusted to fit the longer smoldering durations observed, smoldering phase emissions (i.e., PM<sub>10</sub>, PM<sub>2.5</sub>, CH<sub>4</sub> and CO) should increase substantially. In the dry scenario the duration of smoldering was nearly 10X that of the simulated burn (Table 5-2), potentially a critical difference given the human health hazards of particulate matter emissions (Sandberg et al. 2002) and increasing concern over greenhouse gases. Future attempts at simulating emissions should more accurately account for duration of duff smoldering and the emissions it generates.

This study indicates the need to validate fire effects models across the variation in fuel loadings present in contemporary landscapes. The weaknesses of current versions of FOFEM and others using similar algorithms (e.g., FVS-FFE and FMA Plus) help reveal gaps in our knowledge of how to manage fire in ecosystems. Incorporation of additional empirical data across the variation in time since fire and future adaptations of process-based approaches will improve the utility of simulation models in the restoration and management of fire-excluded ecosystems.

Table 5-1. Model inputs for simulations of fire effects (FOFEM 5.2.1) across three different moisture regimes in fire excluded longleaf pine stands in northern Florida, USA. Values were based on replicated operational prescribed burns at Eglin Air Force Base, Florida used in subsequent comparisons.

	Moisture Scenario		
	Wet	Moist	Dry
Weather variables			
Relative Humidity (%)	34	35	49
Air Temperature (°C)	14	19	26
Wind speed (at 6.1 m; m sec <sup>-1</sup> )	0.89	1.01	0.89
Fire behavior observations			
Flame length (m)	1.3	1.3	1.3
Fuel moisture variables <sup>A</sup>			
O <sub>i</sub> (litter; %)	26	15	12
O <sub>e</sub> (fermentation; %)	76	39	26
O <sub>a</sub> (humus; %)	124	103	62
10-hour (%)	41	21	14
100-hour (%)	57	39	17
1000-hour (%) <sup>B</sup>	82	84	57
Fuel loading (kg ha <sup>-1</sup> ) <sup>C</sup>			
1-hour	-----	0.40	-----
10-hour	-----	0.66	-----
100-hour	-----	0.84	-----
1000-hour	-----	1.15	-----
Litter	-----	3.03	-----
Duff	-----	4.24	-----
Live herbaceous	-----	0.09	-----
Shrub	-----	0.35	-----
Foliage	-----	0.00	-----
Branch	-----	0.00	-----
Total loading (kg ha <sup>-1</sup> )	-----	10.76	-----
Soil Inputs			
Soil texture <sup>D</sup>	-----	Coarse-Silt	-----
Soil moisture (A horizon; %)	12	8	4
FOFEM season of burn	-----	Spring	-----

<sup>A</sup> Fuel moisture data are from collected field data (R.Ottmar, unpublished data from Eglin Air Force Base).

<sup>B</sup> 1000-hour fuel moisture contents are based on averages of collected sound and rotten downed fuels (R. Ottmar, unpublished data from Eglin Air Force Base).

<sup>C</sup> Fuel loading data are a composite of collected field data (1-, 10-, 100-, and 1000-hr; litter and duff) and data from Ottmar and Vihnanek (2000) and Ottmar and others (2003) for live herbaceous, shrub, foliage, and branch fuels.

<sup>D</sup> Allowable soil textures are limited in FOFEM; coarse-silt approximated local sites better than alternative soil selections.

Table 5-2. Comparison of results from simulated (FOFEM 5.2.1) and actual fires for fire-excluded longleaf pine forests at Eglin Air Force Base and the Katharine Ordway Preserve-Swisher Memorial Sanctuary in northern Florida, USA. Data on soil heating and duration of smoldering were collected during individual tree fires at the Katharine Ordway Preserve-Swisher Memorial Sanctuary and tree mortality and duff consumption data were collected in replicated prescribed fires at Eglin.

Parameter	Model predictions			Observed effects		
	Wet	Moist	Dry	Wet	Moist	Dry
Soil heating (minutes)						
Duration > 60°C 5-cm	0	0	0	3.0	11.6	61.3
10-cm	0	0	0	0.8	9.2	9.7
20-cm	0	0	0	0.3	0.3	1.7
Fuel reduction						
Duff (% consumed)	0.0	0.0	8.1	5.0	14.5	46.5
Duration of smoldering (minutes)	6.8	17.0	18.3	9.4	40.4	179.8
Pine mortality probability (%)						
Overall	35	35	35	0.5	3.0	20.5
10 – 20 cm dbh	69	69	69	0.0	0.0	6.7
20 – 30 cm dbh	47	47	47	0.0	17.9	13.4
30 – 40 cm dbh	30	30	30	3.2	3.3	30.0
40 – 50 cm dbh	18	18	18	0.0	6.8	13.4
50 – 60 cm dbh	12	12	12	3.2	3.3	30.0

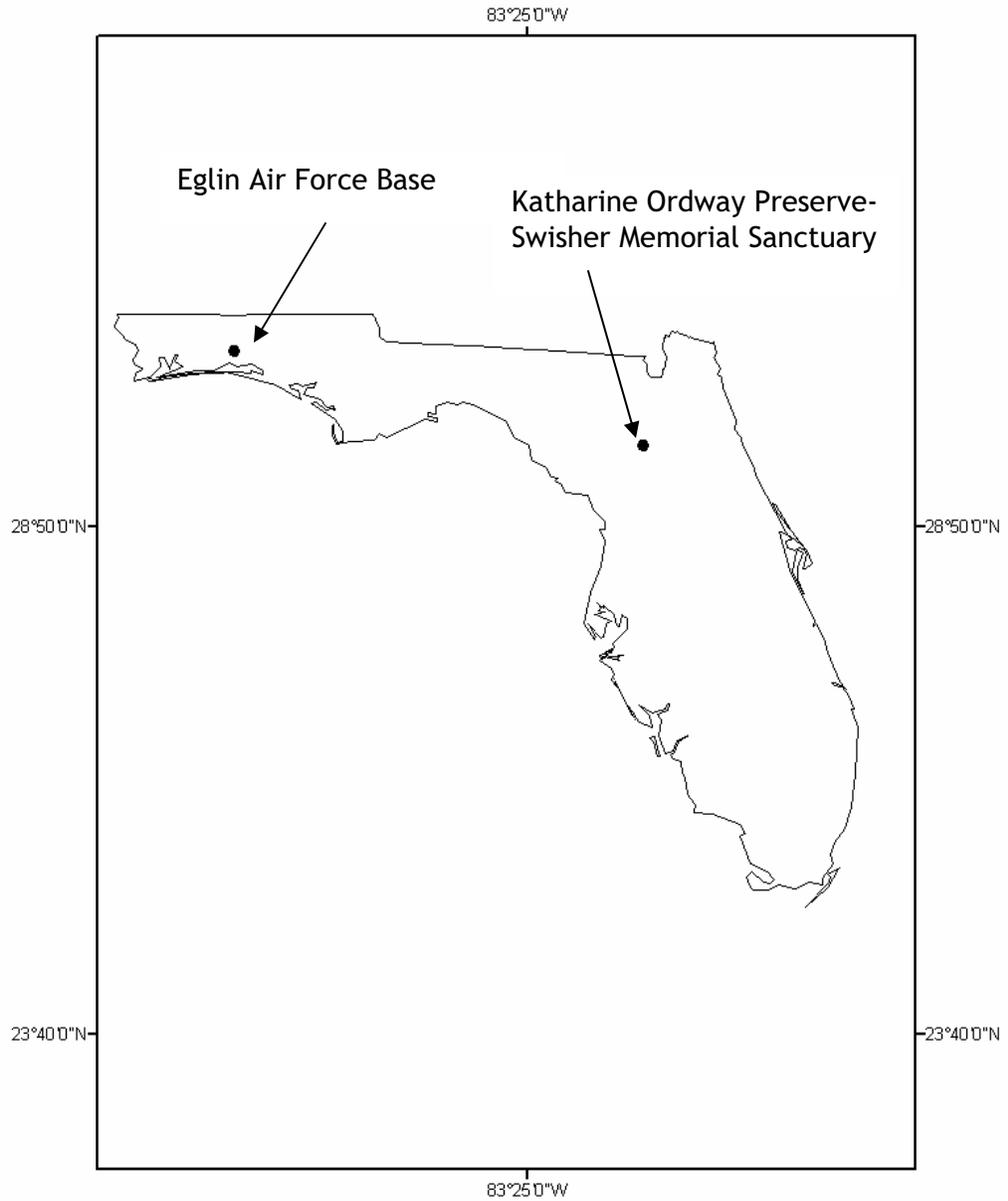


Figure 5-1. Locations of study sites in northern Florida, USA. Both sites had undergone 37-45 y of fire exclusion prior to prescribed and simulated fires. Large prescribed fires were conducted at Eglin Air Force Base. Individual tree centered fires to evaluate mineral soil heating were conducted at the Katharine Ordway Preserve-Swisher Memorial Sanctuary.

CHAPTER 6  
LINKING FOREST FLOOR FUELS WITH FIRE BEHAVIOR AND EFFECTS: A  
REVIEW

**Introduction**

Although foresters and ecologists have long recognized the role of fire in temperate coniferous forests (e.g., Harper 1913, Chapman 1928, Stoddard 1931, Cooper 1960), fire exclusion is ongoing in many temperate savanna, woodland, and forest ecosystems. Excluding fire results in drastic alterations in ecosystems including: increased overstory density (Cooper 1960, Covington and Moore 1994, Gilliam and Platt 1999, Varner et al. 2000, Keane et al. 2002); altered overstory, midstory, and understory species composition (Heyward 1939, Gilliam and Platt 1999, Kush and Meldahl 2000, Varner et al. 2000, Keane et al. 2002, Provencher et al. 2003); altered vertebrate habitat (Stoddard 1931, Leopold et al. 1963, Engstrom et al. 1984, Mushinsky 1985, Aresco and Guyer 1999); and, changes in the distribution and loading of surface and ground fuels (van Wagtenonk 1985, Swezy and Agee 1991, Haase and Sackett 1998, Stephens 2004, Varner et al. 2005). Among these changes resulting from fire exclusion, the development of deep organic matter accumulations on the surface of the mineral soil (hereafter, “forest floor”) and the ecological implications of this alteration have received little attention.

In ecosystems maintained by frequent low-intensity fires, recently fallen litter is typically consumed by solid-phase combustion, reducing inputs into surface organic soil horizons (Oe and Oa, collectively termed “duff”). As a result of successful fire suppression over the last century, many fire-prone temperate savannas, woodlands, and

forests currently have well-developed duff horizons (Switzer et al. 1979, Swezy and Agee 1991, van Wagendonk et al. 1998, Varner et al. 2000, Stephens et al. 2004, Hille and Stephens 2005; Chapter 2). With re-introduction of fire, duff accumulations represent novel forest fuels that, in contrast to surface flaming combustion in frequently burned ecosystems, support smoldering combustion (Chapter 2). Smoldering duff consumes the roots it contains and concentrates long duration heating on basal meristematic tissues and surficial roots near the mineral soil surface (Flinn and Wein 1977, Ryan and Frandsen 1991, Swezy and Agee 1991, Hungerford et al. 1995, Schimmel and Granstrom 1996, Haase and Sackett 1998, Dickinson and Johnson 2001). Smoldering duff fires often kill trees, alter stand structure and species composition, and generate noxious smoke emissions (Ryan and Frandsen 1991, Swezy and Agee 1991, Hungerford et al. 1995, Chapter 2).

Smoldering combustion has received relatively little attention in fire research (but see Frandsen 1987, Frandsen 1991, Frandsen 1997, Miyanishi 2001), even though smoldering fires are commonly associated with elevated fire severity (e.g., soil damage and plant mortality; Ryan and Frandsen 1991, Swezy and Agee 1991, Schimmel and Granstrom 1996). Downed woody debris (100-, 1000-, and 10,000-hour downed woody material) is often linked to smoldering and localized fire severity (Ottmar and Sandberg 1985, Brown et al. 1991, Ottmar et al. 1993, Costa and Sandberg 2004). If forest floor accumulations surrounding trees (“basal accumulations”; Sandberg et al. 2001) ignite, although their temperatures are modest (<500°C), they are a major cause of post-fire conifer mortality (Swezy and Agee 1991, Ryan and Frandsen 1991, Hungerford 1995, Haase and Sackett 1998). Deep forest floor accumulations smolder for long periods

(Covington and Sackett 1984, Swezy and Agee 1991, Hungerford et al. 1991, Haase and Sackett 1998, Miyanishi 2001, Chapter 4), raising soil temperatures (Haase and Sackett 1998) and damaging surficial roots (Swezy and Agee 1991) and stem vascular cambia (Ryan and Frandsen 1991, Ryan 2000).

Here, I summarize the available information on forest floor fuels with emphasis on their accumulation, ignition, combustion, and role in fire effects on long-unburned ecosystems. Research interest in duff smoldering is increasing due to the mounting backlog of areas that have undergone decades of fire exclusion and the increasing emphasis on restoring these communities (Parsons et al. 1986, Landers et al. 1995, Covington et al. 1997, Chapter 2). Particular subjects of interest are spatial patterns of accumulation, physical and chemical composition of duff accumulations, determinants of ignition and combustion, and moisture retention.

### **Forest Floor Accumulation Patterns**

In contrast to the continuous blankets of duff in many boreal forests (Miyanishi and Johnson 2002) and peat-dominated forested wetlands (Hungerford et al. 1995), duff in temperate coniferous forests tends to be patchy, usually accumulated near the base of source trees (Ryan and Frandsen 1991, Swezy and Agee 1991, Gordon and Varner 2002, Varner et al. 2005, Hille and Stephens 2005). In two long-unburned *Pinus palustris* stands in Florida, for example, mean duff depths in one study reportedly decreased rapidly away from pines from 20.4 cm near the stem to 16.1 and 11.9 cm at 100 and 200 cm from the stem, respectively (Gordon and Varner 2002; Figure 6-1).

Given the variation in fire effects associated with duff combustion, foresters and ecologists need a better understanding of the spatial pattern of forest floor accumulations. Accumulated duff supports localized smoldering near the base of conifers (Ryan and

Frandsen 1991, Swezy and Agee 1991), with one or more isolated actively smoldering areas (ranging from ca. 1 to 100 cm<sup>3</sup>) rather than a unified smoldering front (Hungerford et al. 1995, Miyanishi 2001, Miyanishi and Johnson 2002; Figure 6-2). Basal smoldering is facilitated by the increased depth, bulk density, reduced moisture content, and composition of duff and its fuel particles. Prolonged duff smoldering has been linked to the presence of thermal cover provided by overlying Oi and Oe horizons (Miyanishi and Johnson 2002). Thicker surface forest floor insulates the underlying smoldering front in the Oa, aiding with distillation and volatilization of adjacent fuel particles. Duff bulk density varies spatially, which should alter burning behavior substantially (Stephens et al. 2004). Above-ground canopy cover also adds variation: duff moisture content is lower beneath canopies due to their role in the interception of precipitation (Miyanishi and Johnson 2002, Hille and Stephens 2005) and perhaps, inhibition of dew formation (Miyanishi and Johnson 2002). The fact that duff moisture is lower near the stems is interesting given the assumption that this location should receive substantial stemflow. Another potential cause of localized smoldering at tree bases is that bark slough is concentrated near stems whereas needle litter dominates the duff elsewhere beneath the canopy (Gordon and Varner 2002; Figure 6-1).

A better understanding of mechanisms responsible for the observed patterns of forest floor development in the absence of fire is needed. Duff accumulation near conifer stems may be linked to the resistance to decomposition of the high phenolic and suberin content of bark slough (Susott 1982, Rogers et al. 1986, van Wagendonk et al. 1998). High C: N ratios in Oi and duff horizons and high remnant phenolics and incorporated mineral soil in the duff horizons inhibit decomposition (Berg et al. 1982, Lee et al. 1983,

Gholz et al. 1985; Table 6-1). Decomposition may also be slowed beneath coniferous canopies, due to reduced moisture contents (Keane et al. 2002, Miyanishi and Johnson 2002, Hille and Stephens 2005). Given the variation in contemporary fire regimes across forest types, we should be able to determine at least the correlates, if not the mechanisms responsible for the amounts and spatial patterns of duff accumulation in coniferous ecosystems.

### **Forest Floor Composition**

Forest floor fuels contain particles that differ in characteristics that influence ignition, burning, and extinction of surface and ground fires. Forest floor fuels can be subdivided into Oi, Oe, and Oa horizons and at finer scales by their composition (e.g., chemistry or moisture holding capacity) and structure (e.g., depth, particle size, and bulk density). Forest floor fuels are often treated as either “litter layers” or “litter and duff layers;” seldom are the complex strata and components that typify coniferous forest floor accumulations differentiated.

Litter (Oi) horizons contain recently fallen and only slightly decomposed necromass (Pritchett 1979). Oi horizons contain particles with large surface area:volume ratios and large air spaces (low bulk density) resulting in the Oi having the wide fluctuations in moisture characteristic of 1-hour timelag surface fuels (Byram 1959, Nelson 2001, Stephens et al. 2004). Oi horizons also contain fine woody debris, cones and cone fragments, some broadleaf litter, and coarse bark slough. Freshly fallen litter contains the highest extractive contents of the forest floor (Table 6-1) and consequently lowers ignition temperatures and increases fire intensity. The low moisture contents, low bulk density, high volatile content, and high surface area:volume of Oi horizons support flaming combustion fronts of high intensity but short duration (Fonda et al. 1998, Fonda

2001). Considering both the potential fire intensity created by Oi fuels and the diversity of particles found in Oi, this topic deserves additional study both from mesocosm (e.g., Fonda 2001) up to ecosystem scales.

With partial decomposition and an extended period without fire, an Oe (fermentation) horizon forms underneath the Oi. Oe horizons are absent in frequently burned coniferous forests; their presence is indicative of a prolonged fire-free interval. The Oe is typified by decomposed but recognizable plant parts, reduced air space, stable moisture contents, abundant fungal hyphae, and many fine roots (Pritchett 1979, Harvey et al. 1994). The tightly-packed and abundant roots and hyphae result in the Oe being the most fire-resistant of the horizons. Decomposition decreases necromass particle size, structural integrity, and cellulose-to-lignin ratios (Table 6-1). Oe horizons generally have higher moisture content than Oi or Oa horizons. The high moisture content and smaller particle sizes results in smoldering combustion, allowing the Oe horizon to burn independent of wind direction and at very slow rates (Byram 1959, Hungerford et al. 1995, Nelson 2001, Miyanishi 2001). In smoldering fires, Oe accumulations insulate and often conceal underlying Oa smoldering. Of all the forest floor horizons, Oe is the most enigmatic because it resists water loss. Research is needed to understand the linkages between the fermentation horizon, its imbedded roots and hyphae, and its resistance to desiccation.

With continued decomposition, an Oa (humus) horizon forms beneath the Oe and overlying the mineral soil surface in fire-excluded longleaf pine forests. In many temperate coniferous forests growing on acidic sandy soils, a mor humus or Lentar ectogranic layer is created (Heyward 1939, Mader 1953, Wilde 1966). As with

decomposition to a fermentation horizon, particle sizes in the Oa are small litter structures not macroscopically recognizable, cellulose-to-lignin ratios are low, and air space is greatly reduced (van Wagtenonk et al. 1998, Stephens et al. 2004). Mineral ash content in Oa is high due to both the admixture of mineral soil from the underlying mineral horizon and as remnant products from decomposition (van Wagtenonk et al. 1998). The Oa horizon consists of fine organic matter and numerous plant roots (Pritchett 1979, Harvey et al. 1994). Oa horizons are dessicated by the underlying mineral soil, so they are often drier than the overlying Oe (Nelson 2001, Varner, *unpublished data*). As with Oe, the Oa behaves as a ground fuel (Byram 1959, Hungerford et al. 1995, Nelson 2001, Miyanishi 2001) and its presence is an indicator of prolonged periods of fire exclusion. Oe and Oa horizons, collectively termed “duff,” are often treated together in fire management and research despite the fact that the two horizons differ substantially in water relations, ignition, and burning behavior. Given the contrast between the two horizons, the treatment of “duff” as a homogenous stratum may preclude understanding of fuel moisture, ignition, and combustion dynamics.

The composition of basal forest floor accumulations varies over spatial scales of meters and less (Figure 6-2). This variation in forest floor composition is likely critical to fire behavior, with the ignition, combustion, and smoldering of these contrasting parts varying widely (Fonda 2001, Miyanishi 2001, Fonda and Varner 2005). Despite this obvious diversity, commercial peat has been used frequently as a standard to test for effects and determinants of duff ignition, combustion, and effects on soil heating (Frandsen 1987, Hungerford et al. 1995, Miyanishi and Johnson 2002). The combustion of forest floor fuels ranges from short-duration needle litter (Fonda et al. 1998, Fonda

2001) to long-duration cones (Fonda and Varner 2005) and woody material (Costa and Sandberg 2004). Substantial work is needed to describe spatial variation in forest floor composition and the role that composition plays in combustion.

Given that duff accumulations near many conifers contain a large proportion of bark slough, it is important to understand their chemical and physical characteristics. Bark of many conifers contains high temperature suberin and lignin compounds that are difficult to ignite, but burn with great intensity (Susott 1982, Rogers et al. 1986). Basal accumulations in long-unburned *Pinus palustris* stands in Florida are dominated by bark slough and other forests have similar patterns (R. Ottmar, *unpublished data*). Conifer cones are also clumped around individual trees and likely serve as localized sources of both high intensity and long duration combustion (Fonda and Varner 2005). Hille and Stephens (2005) provide the only published data on spatial variability (i.e., thickness, moisture content) of forest floor fuels. Insufficient research, therefore, has focused on the variability in fuel depth, structure, and composition and the outcomes for fire effects. Increased attention to this relationship would enhance our understanding and prediction of fire effects in fire-excluded forests.

While the complexity of forest floor fuels is now beginning to be appreciated, their relative importance in fire behavior and effects has not been rigorously examined. One need is to determine the relative importance of fuel composition and structure on forest floor ignition and combustion. This could be accomplished in laboratory mesocosms with contrasting fuelbeds or perhaps in an ordination framework using more elaborate pre-fire data in field burning conditions. Developing a process-based model incorporating fuel heterogeneity may help suggest viable future research directions.

### Controls of Duff Moisture Content

Moisture content is the primary determinant of duff ignition and combustion probability (Sandberg 1980; Frandsen 1987, 1991; Hungerford et al. 1995; Miyanishi 2001). Both empirical (Anderson et al. 2003) and process-based (Miyanishi 2001, Miyanishi and Johnson 2002) models of duff moisture variation exist. More empirical work is necessary before generalization across fire-managed ecosystems is possible. In addition to their structural and compositional complexity, duff fuels are located above and below dynamic adsorptive surfaces (O<sub>i</sub> and O<sub>e</sub> above; mineral soil below) and contain active living roots and mycorrhizae (Harvey et al. 1994). Root and mycorrhizal activity within O<sub>e</sub> and O<sub>a</sub> duff drain these fuels of moisture but may also all substantial wetting in response to hydraulic lift of subsurface moisture (Dawson 1993, Horton and Hart 1998, Espeleta et al. 2004). To what degree the latter is responsible for localized increases in moisture is yet to be determined, but the influence of active root uptake of water surely affects forest floor moisture dynamics. There is obviously substantial room for inquiry into duff moisture dynamics.

Although substantial work has been focused on duff combustion (Sandberg 1980; Frandsen 1987, 1991, 1997), many questions remain. In restoration burning in *Pinus ponderosa* forests in southern Oregon, for example, Agee and collaborators (Swezy and Agee 1991, Agee 2003) observed abundant duff smoldering beyond threshold moisture contents. Similar observations have been recorded in large field studies (Chapter 3) and in small single-tree fires (personal observation, Flamelot Hammock, March 2002). Mechanisms for wet duff ignition may be linked to the presence of dry duff vectors such as 10-hr woody timelag fuels and fallen cones common in long-unburned stands. Cone fuels have very low field moisture contents (contents lower than litter in longleaf pine

sites, Varner, *unpublished data*) and burn with both high intensity (maximum flame lengths of individual *Pinus palustris* cones at field moisture contents averaged 87.1 cm) and long duration (individual cones burned for an average of 52.8 min; Fonda and Varner 2005). Cones and small timelag fuels dry much faster than underlying duff and, as they burn, preheat and eventually ignite underlying duff. Given that we have a poor grasp on vector moisture dynamics and the mechanisms of duff ignition, substantial research on these topics seems warranted.

### **Conclusions**

Forest floor fuels are an often overlooked component of fuel loading, and accumulations around the bases of trees even more so. Given the proximity of basal accumulations of duff to heat-sensitive tree tissues, and the potential for long-duration smoldering fires, understanding the implications of changes in these fuels is critical to understanding the mechanisms and severity of fire effects. The effects of fire exclusion obviously have far-reaching effects on forests beyond changing stand structure, species composition, and habitat availability (Keane et al. 2002, Chapter 2). Incorporation of a greater understanding of fire exclusion on fuels, fire behavior, and fire effects will invigorate our ability to restore and manage rapidly changing ecosystems.

Table 6-1. Carbon fractions from basal fuel accumulations in a long-unburned longleaf pine forest floor at Smith Lake, Ordway-Swisher Preserve, Florida, USA.

Forest Floor Component	N	Mean Percent of Sample					
		Extractives	Hemicellulose	Cellulose	Lignin	Ash	
Litter (Oi horizon)	5	28.4	13.3 b <sup>1</sup>	31.3 b	26.3 a	0.6	b
Fermentation (Oe)	5	28.2	11.6 b	28.1 b	31.5 b	0.6	b
Humus (Oa)	5	29.6	6.3 a	21.5 a	35.4 b	7.2	a
Intact bark	5	26.0	6.7	28.7	38.0	0.5	
Sloughed bark	5	30.9	6.2	28.6	33.9	0.5	
Recently fallen cones	5	<i>18.9</i> <sup>2</sup>	<i>15.4</i>	<i>34.6</i>	<i>30.7</i>	<i>0.4</i>	
Weathered cones	5	<i>22.7</i>	<i>8.3</i>	<i>28.3</i>	<i>38.6</i>	<i>2.0</i>	

<sup>1</sup> Percentages followed by different letters denote significant differences (p < 0.05) among forest floor components determined using post-hoc Tukey-Kramer HSD test.

<sup>2</sup> Italicized percentages denote significant differences (p < 0.05) determined using paired t-tests.

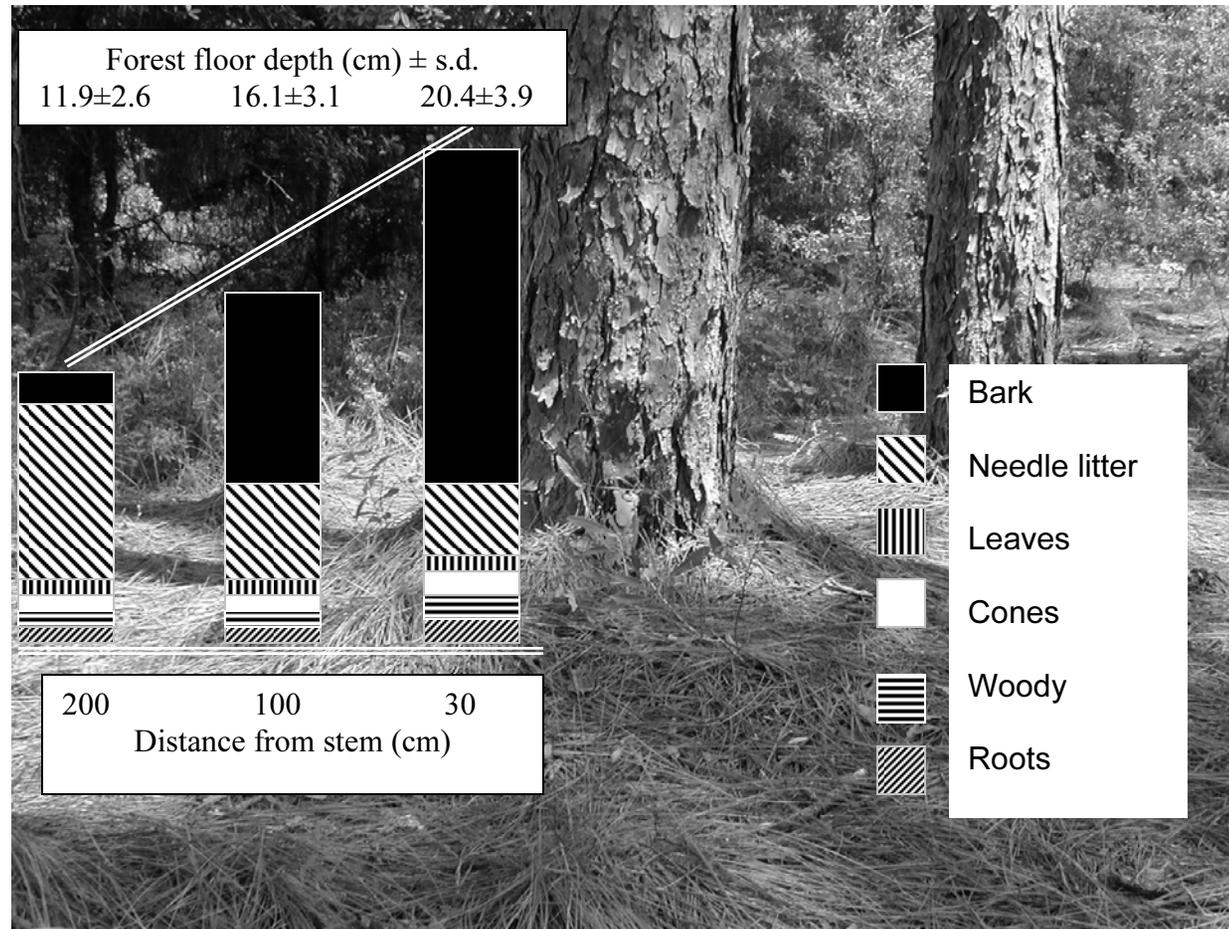


Figure 6-1. Basal forest floor depths and composition in a long-unburned longleaf pine forest (n=60 trees) in northern Florida, USA. Accumulations of forest floor are deepest near the stem. Composition of forest floor material changes with distance from the stem.



Figure 6-2. Basal smoldering near a mature longleaf pine at the Katharine Ordway Preserve-Swisher Memorial Sanctuary in northern Florida, U.S.A. Smoldering in long-unburned longleaf pine forests is typically patchy, with small, localized smolder cavities (arrow above) common near large pines.

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## BIOGRAPHICAL SKETCH

J. Morgan Varner, III was born in Columbus, Georgia on February 3, 1971. A seventh-generation Alabamian, he grew up in several towns throughout Alabama. Before receiving his Bachelor of Science degree in forest management from the University of Idaho in 1997, he worked as a research assistant at the J.W. Jones Ecological Research Center (Newton, GA). In the landscape surrounding the Jones Center, he became inspired to understand more about open-canopied pine forests and their conservation. His master's work at Auburn University focused on the composition, structure, and conservation of old-growth longleaf pine communities in northern Alabama. During this work and in similar projects in lower Alabama, he was confronted with the effects of fire exclusion and its implications for southern pine forests, the subject of his dissertation research. He entered the University of Florida's doctoral program in 2000. In August 2004 he accepted a one-year lectureship at Humboldt State University (Arcata, CA). In July 2005, he was named Assistant Professor of Wildland Fire Management in the Department of Forestry and Watershed Management. He is married to Rachel and has three daughters, Zoe, Maya, and Clara.