RECENT ADVANCES IN UNDERSTANDING DUFF CONSUMPTION AND POST-FIRE LONGLEAF PINE MORTALITY

J. Morgan Varner, Jesse K. Kreye, J. Kevin Hiers, and Joseph J. O'Brien[1]

Abstract—Many longleaf pine stands across the range have suffered decades of fire exclusion, leading to declines in plant and animal biodiversity and complicating restoration and management efforts. Recent research on this topic has focused on the physiological response of overstory longleaf pines and the fuel characteristics of the surrounding forest floor. In small-scale and operational prescribed fires, post-fire pine mortality is tightly linked to basal duff (lowermost fermentation and humus forest floor horizons) consumption and, where present, crown scorch. Pines with substantial duff consumption suffered coarse root carbohydrate drain, a decline in sap flux, and reduced leaf chlorophyll content. Duff consumption in prescribed fires has been linked to duff moisture content, a difficult to predict variable in prescribed fire planning. Duff moisture varies tremendously across the forest floor and within typical burn units. Basal duff dries more rapidly than within-stand conditions. This heterogeneity in duff characteristics is further complicated by the presence of ignition vectors in the forest floor, including woody fuels and intact pine cones. When pine cones are present, ignition of underlying duff is facilitated well beyond assumed moisture thresholds of these fuels. Operational prescribed burns in long-unburned sites should focus efforts on balancing duff consumption with the need to retain overstory longleaf pines.

INTRODUCTION

Over the past two decades, forest and fire managers across the southeastern United States have reported cases of unexpected heavy overstory tree mortality following prescribed and wildfires. Mortality has been observed in several southern pines (Varner and others 2005), most notably in the normally fire-resistant longleaf pine (*Pinus palustris*). Reports of longleaf pine mortality have exceeded 75 percent, with the greatest losses occurring in larger pines (Varner and others 2005). The cause of these mortality events have been linked to long-duration heating of accumulated forest floor fermentation and humus horizons, so-called "duff" (Varner and others 2005, 2007, O'Brien and others 2010). To date, no synthesis has occurred on the cause of these duff fires and their consequences for pine survival.

Fire has been an important factor for millennia in southern pine forests in general, and longleaf pine forests and woodlands in particular. With European settlement and subsequent land use changes over the 20th century, fire diminished in its use in remnant longleaf pine forests (Jose and others 2006). Without fire, senesced leaves, bark slough, cones, and woody branches accumulate on the forest floor. This accumulated debris forms distinct forest floor horizons: surface litter (L or Oi horizon); fermentation (F or Oe horizon); and humus (H or Oa horizon). The lower, heavily decomposed fermentation and humus horizons are collectively termed "duff." The presence of duff in longleaf pine stands suggests long periods without fire (Varner and others 2005).

DUFF AND FIRE

Duff contrasts markedly with litter fuels. Whereas litter burns with rapidly spreading, intense surface fire (Fonda 2001), duff burns via smoldering combustion. Smoldering is a solid-phase or glowing form of combustion where char is generated by the thermal degradation of the fuel (Miyanishi 2001). This char mantle then ignites and glows as the smoldering front progresses. Smoldering is characterized by lower intensity, but protracted duration burning. Duff fires are capable of smoldering for hours to days following the passage of the flaming front, thereby heating the surface mineral soil, imbedded roots, and potentially tree basal cambium (Varner and others 2009).

Although widely assumed to be homogenous (the literature is replete with text describing "deep litter"), the composition and structure of duff is diverse. Duff tends to "mound" around source trees; larger trees reveal this pattern (fig. 1). These basal mounds are markedly

[1]J. Morgan Varner, Assistant Professor, Virginia Tech, Blacksburg, VA 24061; Jesse K. Kreye, Post-doctoral Research Scientist, Mississippi State University, Mississippi State, MS 39762; J. Kevin Hiers, Director of Environmental Stewardship, Sewanee- The University of the South, Sewanee, TN 37383; Joseph J. O'Brien, Research Ecologist, U.S.D.A. Forest Service, Southern Research Station, Athens, GA 30602

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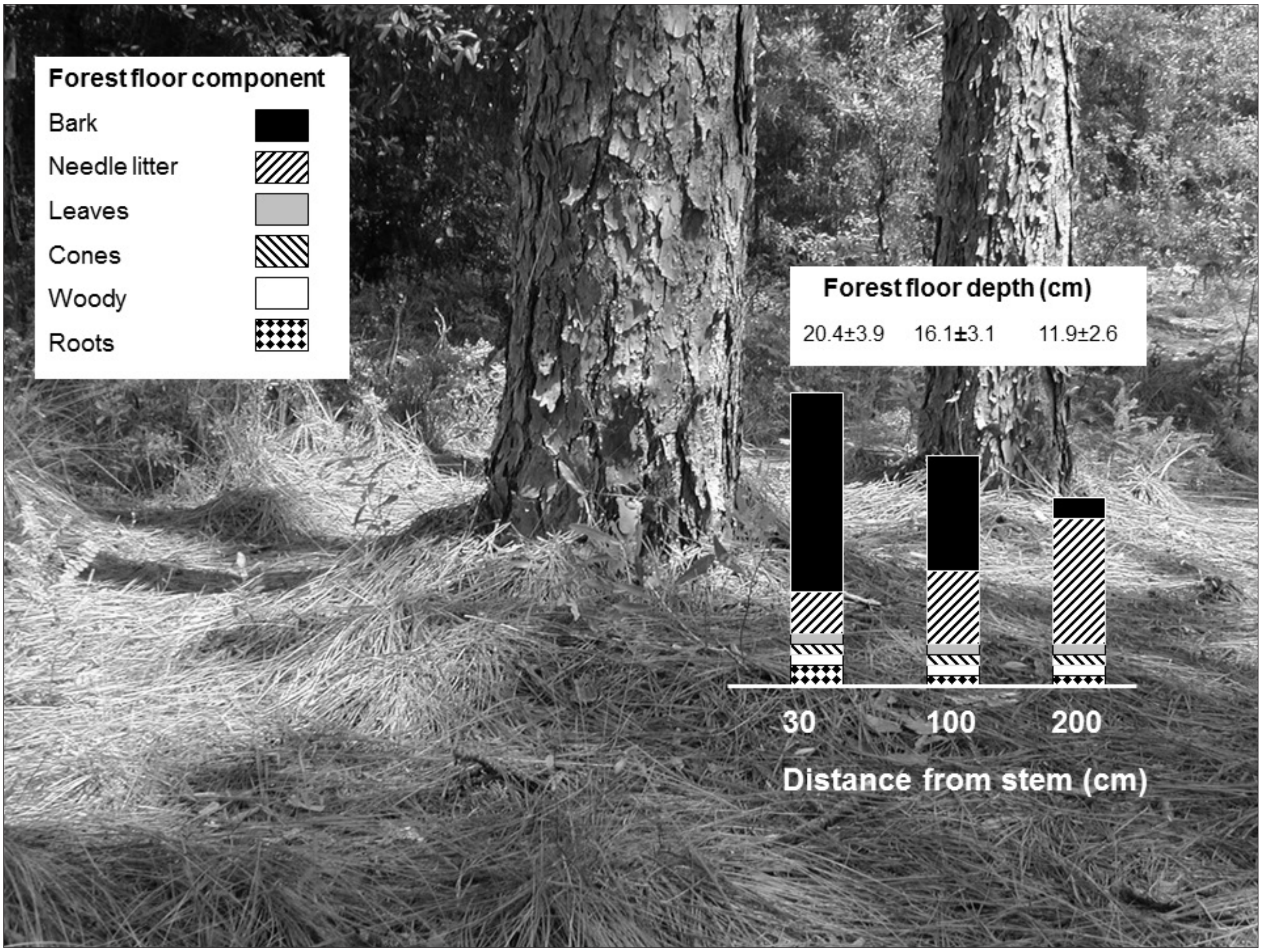

Figure 1—Forest floor accumulations in a long-unburned longleaf pine stand in northern Florida. Forest floor duff is concentrated at tree bases. The composition of duff differs with distance from stem, consisting primarily of bark slough near the bole and becoming increasingly dominated by needle litter with distance from source trees.

deeper than elsewhere in the stand, with depths near tree bases exceeding 20 to 30 cm in long-unburned stands (Varner and others 2005, Kreye and others 2014). The composition of basal mounds is dominated by sloughed bark, with senesced needle litter, cones, woody fuels, and imbedded roots comprising the remainder (fig. 1). As distance from the source tree increases, needle litter dominates the composition.

While pine and oak litter burning characteristics are somewhat understood (Fonda 2001, Kane and others 2008), there is considerably less known about duff burning. The ignition and spread rates of smoldering duff fires are controlled by moisture content, bulk density, mineral content, and depth. Ignition is limited primarily by fuel moisture (Miyanishi 2001), which is spatially heterogeneous in longleaf pine forest floor fuels (Kreye and others 2014). Duff moisture contents above 60 percent (dry-weight basis) resist ignition unless vectors are present. Ignition vectors include woody fuels and pine cones (Fonda and Varner 2004, Kreye and others 2013) that are often elevated and thus drier that the surrounding duff (Varner and others 2009). Cones, in particular, are capable of burning for long periods (mean burning time for longleaf pine cones = 49 minutes; Fonda and Varner 2004) thereby drying and pre-heating adjacent duff. Kreye and others (2014) found that the presence of cones enabled duff to ignite and smolder even when above presumed ignition thresholds.

CONSEQUENCES OF DUFF FIRES

Restoration fires across longleaf pine's range have resulted in substantial tree stress and mortality (Varner and others 2005). The cause of tree stress and mortality has been linked to duff consumption near the base of trees (Varner and others 2007, 2009, O'Brien and others 2010). In southeastern Georgia longleaf pine stands, duff consumption diminished sap flux and reduced leaf chlorophyll (O'Brien and others 2010). The duration of duff and underlying mineral soil heating in north Florida was linked to reductions in coarse root carbohydrate storage, presumably due to the drain to replenish killed or injured fine roots (Varner and others 2009). Latewood radial growth the year following duff fires was likewise related to durations of heating (Varner and others 2009).

The proximate mechanism of these injuries is unclear. Because duff burns so slowly and can form a mantle over the underlying heated mineral soil, heat is retained for long durations following ignition (Varner and others 2009). The high density of fine roots (O'Brien and others 2010) in basal duff and in the uppermost mineral soil places these tissues at risk of fire-caused injury or consumption. This hypothesis is corroborated by results for diminished sap flux and drained carbohydrates in coarse storage roots. The limited data we have on basal heating suggests that the thick bark of longleaf pine insulates underlying cambium. Other possible contributing mechanisms include post-fire climatic water deficits, interactions with bark beetles, and root diseases (Ostrosina and others 1999, Menges and Deyrup 2001, Varner and others 2009). This blurred linkage between cause and effect, combined with the uncertainties of future climate change in the region (Mitchell and others 2014), is a hindrance to understanding and managing these ecosystems.

There are widespread examples of duff fires resulting in pine mortality. Varner and others (2005) reported cases of duff fire-caused mortality across the range of longleaf pine and across a suite of ownerships and manager experience. Using replicated prescribed fires in northwest Florida, Varner and others (2007) found that stands burned with lower duff moisture suffered markedly greater tree mortality than those burned under moist or wet duff moisture contents. In sites with heavy mortality, tree death was concentrated in the largest size classes, contrary to typical fire-caused tree mortality predictive models (Varner and others 2007). The same result of large tree mortality has been observed in other reintroduction fires in south Alabama (Kush and others 2004).

BALANCING DUFF CONSUMPTION AND OVERSTORY MORTALITY

A primary challenge for managers faced with long-unburned longleaf pine stands is to balance duff consumption with overstory pine mortality (Varner and others 2007). Burning when duff is too wet to ignite results in minimal tree mortality but a residual duff hazard. Burning when the duff is too dry results in maximal duff consumption but heavy overstory pine mortality. The balancing act between these extremes is simple in concept, but difficult in practice. One reason for the difficulty is the spatial heterogeneity of duff moisture (Kreye and others 2014) and the difficulty of measuring duff moisture (Engber and others 2013).

In spite of the difficulty, there are cases of small- and large-scale restoration treatments that achieve the balance between duff consumption and overstory pine mortality. In a series of prescribed fires in south Alabama, Kush and others (2004) burned following recent soaking rains and then extinguished (via backpack sprayers and ATV-mounted sprayers) individual pines for two days following fires. This careful burning and mop-up was successful in reducing forest floor depths (due to repeated fires) and resulted in minimal overstory pine mortality. At the large-scale, Eglin Air Force Base used operational prescribed fires in northwestern Florida to reduce duff. Using a similar prescription and data from nearby meteorological stations (Ferguson and others 2002), managers were able to consume duff, while having minimal overstory pine mortality. In a replicated prescribed fire experiment with three duff moisture treatments (dry, moist, and wet), Varner and others (2007) found that burning when duff was moist (85 percent average duff moisture content) reduced forest floor depths while resulting in minimal (less than 5 percent) overstory pine mortality. At dry duff moistures below this range, mortality was high and peaked in large pines; at wet duff moistures above this range, little duff was consumed (Varner and others 2007). There are other examples of operational prescribed fires with minimal overstory pine mortality in southern Georgia and northern Florida (Hiers and others 2005).

Finding site-specific prescriptions that result in balances between duff consumption and pine mortality is clearly possible, but larger issues impede success. The impediments to using prescribed fire in southeastern pine ecosystems are well-established (Hiers and others 2003, Kobziar and others 2015). Long-unburned stands are problematic due to the presence of deep duff, but also suffer diminished plant and animal diversity (Jose and others 2006). Prioritizing burning for sites with deep duff is possible without substantially compromising other high priority sites for burning (Hiers and others 2003).

CONCLUSIONS

The ecological consequences of fire exclusion and subsequent reintroduction of fire is a primary issue in longleaf pine ecosystem management. Current understanding of this issue suggests that the forest floor is a much more complex fuel stratum than earlier appreciated. The consequences of fires cause a cascade of physiological injuries that can result in heavy tree mortality, particularly in large pines. There are examples of successful efforts balancing duff consumption with overstory tree mortality, but challenges remain.

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