6 The Role of Fuels for Understanding Fire Behavior and Fire Effects

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INTRODUCTION

Fire ecology, which has emerged as a critical discipline, links the complex interactions that occur between fire regimes and ecosystems. The ecology of fuels, a first principle in fire ecology, identifies feedbacks between vegetation and fire behavior—a cyclic process that starts with fuels influencing fire behavior, which in turn governs patterns of postfire vegetative responses and the future production of fuels (Mitchell, Hiers, et al. 2009). Recent research has used this conceptual framework to understand the relationship between combustion science and ecology and to gain mechanistic understanding of fire effects (Johnson and Miyanishi 2001).

The purpose of this chapter is to synthesize research on forest fuels characterization—particularly as influenced by the overstory—and on the role that fuel heterogeneity plays in the feedback mechanisms between fire behavior and fire effects in the longleaf pine (*Pinus palustris*) ecosystems of the southeastern United States.

We begin by describing the state of the science in fire behavior within the context of ecosystem structure and function. We review advances in the modeling tools used to represent complex fuelbeds as wildland fuel cells (discrete patches of fuels). Further, we discuss model predictions of heterogeneity in fire behavior and fire effects that correspond to variations in wildland fuel cells. Our focus is on fire behavior and fire effects that influence ecosystem restoration, with an emphasis on introducing fire in sites where it has been long absent.

We also introduce an emerging concept in fire ecology that was developed in longleaf pine ecosystems: the "ecology of fuels." We review research on fuel and fuelbed characteristics including fuel accumulation rates, burning characteristics of various fuel types, and the effects of fuel moisture on fire behavior in longleaf pine ecosystems. We describe new multiscaled methods of measuring fire behavior and fuel variation that were developed to overcome the limitations of traditional approaches. We show how this emerging research can take advantage of next-generation fire-behavior prediction models to link interactions between fuel and fire behavior. We then focus on fire-fuel feedback interactions to describe an approach for fuel-based restoration of longleaf pine that transforms the traditional paradigm into one in which forest structure governs management. We conclude by discussing research directions that would advance fuel and fire ecology in longleaf pine ecosystems.

THE ECOLOGY OF FUELS

In longleaf pine and functionally analogous, frequently burned pine ecosystems, the ecology of fuels is a complex interplay among overstory structure, fuelbed heterogeneity, and ground cover vegetation (Figure 6.1) that collectively determines forest structure, composition, and functional

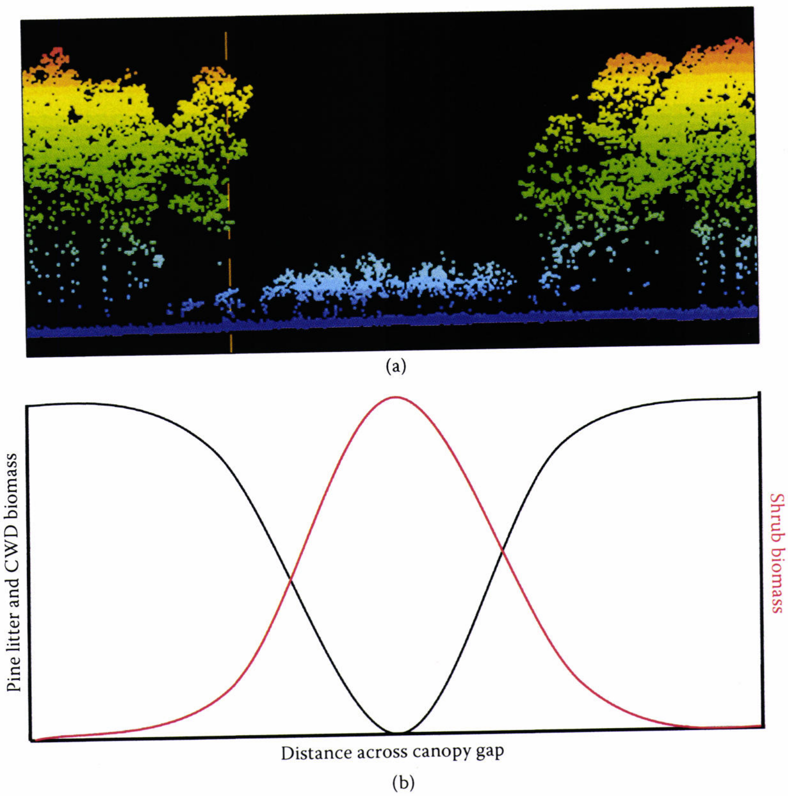


FIGURE 6.1 An illustration of the ecology of fuels as applied to overstory influences on fuel distribution in a longleaf pine sandhill habitat: (a) Cross-section from light detection and ranging three-dimensional point cloud showing encroachment or released growth of shrub in a canopy gap, and (b) changes in fuels shown directly (black line) as alterations in fuel from pine litter and coarse woody debris (CWD) distribution that were derived from the overstory and indirectly (red line) as subsequent shrub encroachment resulting from reduced fire intensity—less pine litter—and reduced belowground competition, notwithstanding interactions with grasses. Note that the biomass of each component depends on fire frequency, time-since-gap development, gap size, and habitat type; and that the dynamic conditions throughout the fuelbed create the fine-scale heterogeneity in wildland fuel cells. (From E. Rowell, unpublished data.)

processes. Moreover, these dynamics appear to vary categorically across the full range of edaphic conditions, ranging from mesic flatwoods to xeric sandhills (Wilson et al. 1999; Hiers et al. 2007). Research has focused on three aspects of fuels ecology regarding fire effects in longleaf pine ecosystems: (1) the importance of overstory canopy-derived fuels on fire behavior and resulting forest structure, (2) the mediation of biodiversity through fine-scale variations in fire behavior, and (3) the role of litter and forest floor in restoration of degraded ecosystems.

Because longleaf pine is the dominant species in the longleaf pine ecosystem, its influence on fire behavior and patterns of fire effects has been long recognized (Wahlenberg 1946; O'Brien et al. 2008; Mitchell, Hiers, et al. 2009). Overstory pines determine fuel distribution, both directly through fallen needles that support frequent fire, and indirectly through competitive interactions—largely belowground—with the less fire-tolerant hardwoods and ground cover plants that make up the complex fuelbed (Mitchell et al. 2006). The interaction between pine needles and bunchgrass produces important fine-scale variability in fire behavior, with needles adding significant residence time to fires that are propagated by grasses (Hiers et al. 2009; Loudermilk et al. 2014; Fill et al. 2016).

Fuel is the critical link between structure and function in these systems (Williamson and Black 1981; Rebertus et al. 1989; Glitzenstein et al. 1995). Pine needle litter distribution allows fire to spread across a heterogeneous ground cover (Hiers et al. 2009; Loudermilk et al. 2014). If this matrix is disrupted, through timber removal or pine straw raking for example, fire spread can be halted, leaving patches of unburned vegetation (O'Brien et al. 2008; Mitchell, Hiers, et al. 2009; Jack et al. 2010). If these fire-free patches coincide with canopy gaps, suppressed hardwoods will be released and grow to a fire-resistant height (Mitchell et al. 2006; O'Brien et al. 2008). Needle litter has long provided a link between timber and fire management; this relationship is epitomized in the Stoddard–Neel system of ecological forestry (see Chapter 10), which promotes maintenance of stand ecological integrity among its goals (Mitchell et al. 2006). Less understood is the feedback mechanism between needle litter and other ground cover fuels, particularly bunchgrasses; this mechanism also creates significant variations in fuels and fire behavior at fine scales (Hiers et al. 2009).

Wildland Fuel Cell Concept

The wildland fuel cell concept was developed to connect variations in fuels to a relevant scale of variations in fire behavior by aggregating fuels with similar characteristics—such as type, quantity, and spatial arrangement. The outcome is a linkage between the observed variability in fire behavior and variation in fuels—a critical component of the ecology-of-fuels feedback loop—and confirmation that coupled fuel characteristics (structure, type, and biomass) are correlated to observed variation in fire behavior. Thus, defining the heterogeneity in fuels and fire and identifying appropriate scales (Figure 6.2) provides a gateway both for understanding fire effects and for identifying mechanisms that control patterns of plant diversity (Hiers et al. 2009).

The wildland fuel cell concept was originally developed for the longleaf pine habitats of the Coastal Plain, where the scale of fuel and fire heterogeneity varies at about the 0.25-m scale. Similar scales of fuel and fire behavior variation also characterize the less productive xeric sandhill habitats (Loudermilk et al. 2014). The scale of heterogeneity, which likely would become coarser in flatwoods and other shrub-dominated habitats, has yet to be defined across the full range of variation in longleaf pine ecosystems.

Fuel and Fuelbed Characteristics of Longleaf Pine Sites

In longleaf pine sites with herbaceous ground cover, fires generally can burn successfully through a stand every 18 months (Glitzenstein et al. 2003; Reid et al. 2012). Ground cover growth commences immediately after a fire and when combined with pine needle litter, promotes a quick recovery of biomass and available fuels. On a site with 10.8 m^2/ha basal area of mature longleaf pine, needle

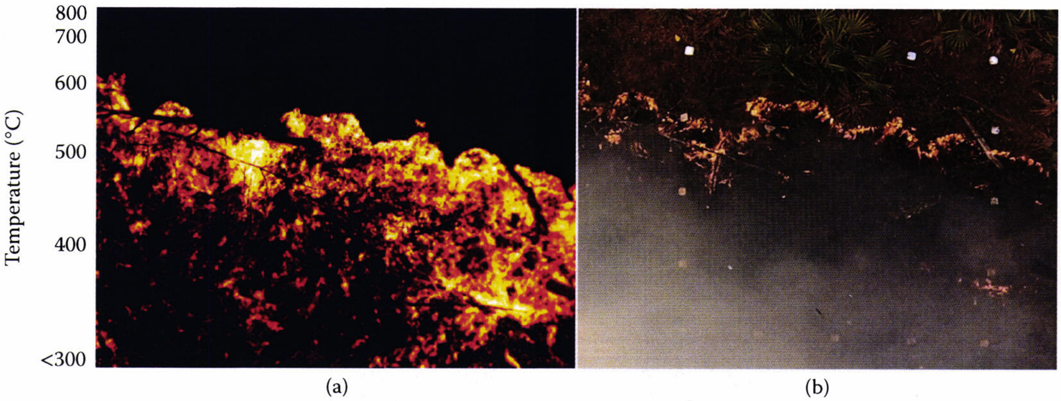


FIGURE 6.2 Depiction of a surface fire on a 4 × 4 m experimental plot captured by: (a) At-nadir forward looking infrared imagery, and (b) true-color photography showing the aluminum targets that were used for processing infrared imagery. Note the smoke penetration of the infrared image and the thermal signatures of flaming and smoldering combustion. (From O'Brien, J. J., E. L. Loudermilk, B. Hornsby, et al., *International Journal of Wildland Fire*, 25, 62–75, 2016.)

litter is produced at a rate of about 4884 kg/ha annually (Gresham 1982), providing about half of the fuel available to burn (Ferguson et al. 2002; Mitchell et al. 2006). Deciduous oaks (*Quercus* spp.) that are confined to the midstory by frequent fires can also contribute considerably to litter biomass, but their distribution and abundance can be quite variable (Wright 2013) and can be dramatically diminished by herbicide applications, mechanical tree removals, or other restoration efforts that affect oak abundance in a given longleaf pine area.

During burning, consumption of fine fuels ranges from about 50% to 70% (Goodrick et al. 2010), but can be as high as 92% (Ottmar, Hiers, et al. 2016). Coarse woody debris contributes about 10% of the fuel loading (Wright 2013). Small diameter (≤10-hour) woody fuels are relatively sparse because they are often completely consumed by frequent fires. Although large diameter (100- to 1000-hour) woody fuels are likely important in driving fire behavior and fire effects in small areas of a stand (Wiggers et al. 2013; Cannon et al. 2014; O'Brien, Loudermilk, Hiers, et al. 2016), they have little influence on stand-level fire behavior.

Fuel accumulation varies across longleaf pine sites depending on overstory basal area, habitat type, local climate, ground cover quality, and management regime. Larger basal area in the overstory results in more overstory-derived fuels (pine litter and woody fuels), but can also lead to smaller fuel loads that originated from ground cover (Mitchell et al. 1999; Gonzalez-Benecke et al. 2015). In general, wetter sites are more productive and therefore have larger postfire biomass accumulations, with differences across soil moisture gradients noticeable within a single year—for example, wiregrass (*Aristida stricta*) had twice the biomass in wet-mesic areas than in xeric areas at one site 1 year postfire (Kirkman et al. 2001). This suggests that maintaining frequent fire could be more important on mesic sites to prevent fuel accumulation and competition from species that grow faster in their more productive soils. Across the longleaf pine range, fuel biomass can change from a mix of herbaceous and woody fuels to predominantly woody fuels within just a few (3–4) years after a fire (Glitzenstein et al. 2003; Gonzalez-Benecke et al. 2015). In general, as the span of fire absence increases, fuel accumulation also increases, creating the potential for increased fire intensity (Ottmar et al. 2003). However, as the vegetation state changes from longleaf pine to a more oak-dominated forest—a phenomenon that can happen within just a few decades—grasses will be suppressed by litter accumulation, competition will degrade herbaceous vegetation, and pine recruitment will be inhibited (Hartnett and Krofta 1989; Reid et al. 2012). Also, for some oak species, the emerging oak canopy creates a denser fuelbed of oak litter that is less conducive to fire spread under typical prescribed fire conditions (Kane et al. 2008), creating a positive feedback in which the oaks are protected from fire damage and quickly grow to midstory height (Guerin 1993).

The interactions among fine fuels create a complex fuelbed matrix that contributes to fire spread and continuity (Hiers et al. 2009; Mitchell, Hiers, et al. 2009). Pine litter draped across shrubs, bunch-grasses, and other grasses in these communities creates a synergy among dry available fuels across the fuelbed (Fill et al. 2016) and an aerated medium that promotes continuous low-intensity fire spread.

Different individual fuel types create variations in burning characteristics within a fuelbed (Hiers et al. 2009). Longleaf pine needles are among the most flammable compared to other U.S. pine species (Fonda 2001), and their cones are among the longest smoldering (Fonda and Varner 2004)—making them an important fuel component for local fire behavior and fire effects (O'Brien, Loudermilk, Hiers, et al. 2016; Wiggers et al. 2013).

On longleaf pine sites, with consequent differences in flammability, oak variability can affect fire intensity and fire spread within and among those sites (Kane et al. 2008). In particular, turkey oak (*Q. laevis*) and post oak (*Q. stellata*) are pyrophytic, producing litter that is similar to longleaf pine litter in flammability, thus also facilitating fire spread. Other oaks such as live oak (*Q. virginiana*) and laurel oak (*Q. hemisphaerica*) have litter that burns poorly, impeding fire spread under their canopies. Many of the more pyrophytic oaks are critical components of longleaf pine systems, and their role in fire dynamics should be considered in restoration efforts (Hiers et al. 2014).

Flammability of vegetation can vary because different vegetative types have different fuel characteristics such as coarse woody debris, fine dead fuels, and height (Ottmar et al. 2007); different mixtures of species and guilds that affect the percentages of oak versus pine litter (Kane et al. 2008); different levels of fuel moisture content based on the amount of live versus dead moisture (Nelson and Hiers 2008); different leaf chemistry based on the amount of volatile content versus ash content (Gilliam 1988); or different physical traits that alter the arrangement and moisture of the fuel over time (Varner, Kane, et al. 2016). Historically, fire behavior modeling has often focused on fuel loading (the amount of fuel) and the relative size of fuel particles (Rothermel 1972; Andrews and Chase 1989); however, in the surface fire regime of longleaf pine ecosystems (Sandberg et al. 2007), fuel moisture dynamics (Reid et al. 2012), the interaction of flammability traits (Kane et al. 2008), and the heterogeneity that results could be more critical to fire behavior and fire effects. Suites of flammability traits have also been documented by species (Fonda 2001), and specifically for southeastern fuels (Reid and Robertson 2012), with categorization into litter syndromes that promote or facilitate high-intensity surface fires and those that dampen, diminish, or extinguish surface fires (Kane et al. 2008; Kreye et al. 2013; Mola et al. 2014). Such "suites of adapted traits" to survive and grow in longleaf pine landscapes result in increased diversity and forest structure, thereby perpetuating fire regimes through their influence on fire behavior—otherwise known as the ecology of fuels (Veldman et al. 2013; Hiers et al. 2014).

In the absence of fire, litter accumulates at a linear rate until a forest floor (organic horizon) develops and the process of decomposition and forest floor accumulation reaches an equilibrium (Olson 1963; Meentemeyer 1978). This equilibrium occurs after about 8–12 years postfire on longleaf pine sites (Olson 1963; Meentemeyer 1978) and perhaps longer on mixed pine sites (McNab et al. 1978). More importantly, the forest floor has a well-developed duff layer around adult pines, largely composed of decomposition-resistant pine bark litter (Varner et al. 2005). This duff layer can have considerable consequences for overstory mortality (particularly in larger trees) when fires are reintroduced in long-unburned sites. Fine roots that have grown into the duff layer are killed when the duff is consumed by fire, even in low-intensity prescribed fire conditions. This phenomenon is particularly prevalent in xeric sites, where water stress is heightened (Varner et al. 2007); for more detail see Chapter 7.

Fuel Moisture Characteristics

Fuel moisture content is a critically important factor governing fire behavior (Rothermel 1983). Both surface moisture and water in live and dead fuels alter fire behavior through several mechanisms: latent heat of evaporation, reduction in fire radiative power, and sensible heat flux. Nearly all models of fire behavior include fuel moisture content as an input variable (Matthews 2014).

Typically, fuel moisture is treated as a single characteristic, representing an average for 1-hour, 10-hour, and 100-hour dead fuel classes (Burgan and Rothermel 1984). Fuel moisture samples are often collected gravimetrically within a fuelbed. Expressed as the mass of water per unit mass of dry fuel, fuel moisture content can be >100%, particularly in live fuels. In the Southeast, researchers have collected fuel moisture content by four vegetative categories: herb, shrub, fine wood, and litter (Brenner 2002; Ferguson et al. 2002; Ottmar, Hudak, et al. 2016). Fine dead fuel moisture is less dynamic than live fuel moisture, which is quite variable (Heinsch et al. 2015) by species, season, and antecedent drought conditions. Although fire-behavior models typically homogenize the spatial variability of fuel moisture at the stand scale, such spatial variation can be important for fuel consumption and fire spread at certain scales (A. Smith et al. 2013).

Historically, the relationship between fuel moisture content and fire behavior has concentrated on moisture dampening curves at the stand scale, which terminate in the moisture of extinction for dead fuels, typically 25%–30% (Burgan and Rothermel 1984; A. Smith et al. 2013); the dead moisture of extinction is defined as "the characteristic moisture of dead fuels at which fire will not spread with a uniform front" (Burgan and Rothermel 1984). This definition implies that fire spreads heterogeneously and assumes that the moisture-of-extinction is nonuniform within the stand, but the role of spatial variability in altering fire spread is not understood (Viney 1991; Matthews 2014). The dynamics of live fuel moisture are also complex, interacting locally with fine dead fuel moisture within the fuelbed (Burgan and Rothermel 1984).

Spatial variability is probably responsible for the discrete patterns of fuel moisture within the fuel matrix that govern fire spread, both as fuels dry with exposure to sunlight and as they absorb moisture with increasing nighttime humidity. The observed patterns of moisture at various spatial scales are compatible with the tenets of the wildland fuel cell concept, with fuel moisture content within these cells undoubtedly contributing to observed differences in fire intensity that are documented at fine scales in longleaf pine (Hiers et al. 2009; Loudermilk et al. 2012).

At larger scales, fuel moisture represents a known source of error in estimating biomass consumption, but this issue can be overcome by using remote sensing to document spatial patterns of fuel moisture within forests. Chuvieco et al. (2002) analyzed multispectral satellite imagery and found that short-wave infrared bands are sensitive to water absorption. They also compared more traditional methods including the normalized difference vegetation index, which indirectly estimates fuel moisture via chlorophyll changes at a 30 × 30 m resolution. Another study (A. Smith et al. 2013) developed a spatial error correction for the effects of fuel moisture content on fire radiative power/energy. These landscape-scale approaches can be applied to wildland fuel cells at finer scales to understand the longleaf pine fuel moisture controls on fire behavior and energy release.

Ground fuels, such as duff or organic soils, are also critically responsive to soil moisture (Varner et al. 2005; Ferguson et al. 2002). For such fuels, fuel moisture conditions were found to significantly influence the patterns of fuel consumption that cause longleaf pine mortality after a smoldering fire (Varner et al. 2007; O'Brien et al. 2010). When compared to gravimetric destructive sampling, soil probes placed within organic fuels more closely mirrored the meteorological variables that caused trends in fuel moisture.

CHARACTERIZING SURFACE FUELS AND FIRE INTENSITY

Much of the focus of fire ecology has concentrated on investigating broad-scale patterns, at scales ranging from 10 m^2 to 10,000 ha (Hobbs and Atkins 1988; Turner et al. 1999; Finney 2001, 2003; Collins and Smith 2006). Usually the emphasis has been on understanding the mosaic of "green versus black" (burned versus unburned) areas across landscapes. Also, within-fire variations in intensity are usually not measured directly, but indirectly using coarse severity classes (Keeley 2009). Similarly, fuels classifications have focused on stand-level characterization (Ottmar et al. 2007; Ryan and Opperman 2013), even though variation of fuels within a stand can often exceed variation among stands (Brown and Bevins 1986). These kinds of classifications were developed to work with fire-prediction systems, which are based on semiempirical fire-spread models (Rothermel 1972; Burgan and Rothermel 1984) that assume fuel homogeneity. Furthermore, many of the techniques used to characterize fuels were developed to be effective in fuelbeds that are dominated by woody fuels (Brown 1974); fine fuels were usually collected in bulk and scaled up to the stand level.

In frequently burned ecosystems, low-intensity surface fires (Figure 6.2) often burn completely when fine fuels are continuous, leaving few unburned patches. Thus, understanding the variation in fire intensity within burned areas is especially critical to predicting fire effects (Hiers et al. 2009; Loudermilk et al. 2012). Furthermore, fine fuels are paramount in that they create the fuel continuity that carries fires across these landscapes. Capturing and understanding this fine-scale heterogeneity is important because this is where the most ecologically relevant fire effects occur (Rebertus et al. 1989; Mitchell et al. 2006; Thaxton and Platt 2006). Several researchers (Brewer et al. 1996; Thaxton and Platt 2006) acknowledged the potential importance of fine-scale variation in fuels, but the available tools for characterizing the combustion environment responsible for fire effects (including fine-scale patterns of fuels and fire behavior) remained inadequate to produce mechanistic connections. Before the early 2000s, attempts to measure fire were limited to indices of intensity derived from temperature-sensitive paints, evaporation of water, or thermocouples (Kennard et al. 2005). Similarly, fuels have been broadly and imperfectly categorized, with categories based on stand-level characterizations (Anderson 1982; Ottmar et al. 2003).

DeBano et al. (1998) showed that ignition properties, rates of spread, intensity, and other components of fire behavior are influenced by fuel loading and fuel depth (and thus density). Fuel properties, such as volume and loading, are drivers of models used to simulate fire behavior (Burgan and Rothermel 1984; Andrews and Queen 2001), and are important measurements for empirically understanding fire behavior and fire effects. Traditionally, measurements of surface fuelbed characteristics have been both direct and indirect. Common direct measurements are tallies of down woody fuels along planar transects (Brown 1974) coupled with destructive biomass sampling, also known as "clip plots" (Brown 1981). Indirect methods include visual cover estimates in plots or comparisons with photographs of known fuel loads or types (Ottmar et al. 2003; Keane and Dickinson 2007); although they provide estimates of characteristics—such as fuel load, bulk density, and packing ratios—that are useful for predicting fire behavior at the stand level (Burgan and Rothermel 1984; Reinhardt and Keane 1998; Andrews et al. 2004), such estimates are not suitable for calculating within-stand heterogeneity.

Furthermore, these methods have significant limitations. Direct sampling is labor intensive, often limiting sample size, particularly across large areas. Some techniques are not appropriate for all fuel types: for example, planar transects do not efficiently estimate grasses. Indirect measures can be subjective, resulting in biased estimates. Additionally, estimating volume for bulk density calculations relies on unrealistic simplifications; for example, shrub and grass volumes are calculated by assuming that the plants form simple geometric shapes, such as a spheroid or cylinder (Van Wagner 1968). Such traditional volume measurement techniques ignore complex plant architectural details that are important for characterizing leaf area and biomass (Loudermilk et al. 2009) and fire behavior (Loudermilk et al. 2012) at fine scales. These techniques were designed to estimate stand-level averages, which fail to capture the heterogeneity in fuels driving both fire behavior and fire effects in frequently burned ecosystems (Loudermilk et al. 2009; Mitchell, Hiers et al. 2009; Loudermilk et al. 2012; Wiggers et al. 2013, 2017; O'Brien, Loudermilk, Hiers et al. 2016).

Challenges of Surface Fuel and Fire Measurements

Johnson and Miyanishi (2001) observed that although "...the processes of combustion and heat transfer lie at the heart of fire ecology" very few studies actually quantify the energy released during a wildland fire—defined by the National Wildfire Coordinating Group (NWCG) (NWCG 2015) as any nonstructure fire (either prescribed burning or wildfire) that occurs in vegetation or natural fuels. As an example to illustrate measurement limitations, many studies have used pyrometers consisting of temperature-sensitive paints or waxes (Thaxton and Platt 2006; Davies et al. 2010; Brudvig et al. 2012) to characterize fire intensity. These point measurements are at best only qualitative approximations of fire temperature and are heavily influenced by their placement and construction (Iverson et al. 2004; Kennard et al. 2005). Thermocouples have also been extensively used to report fire temperatures, but these measurements are also limited by construction, placement, and probe energy balance (Yilmaz et al. 2008). They are primarily limited to measuring the convective energy fraction of fire at a single point, and their sensors have characteristics—such as convective cooling, thermal inertia, conduction along the sensor lead, and some radiant heating—that influence measurement accuracy.

The scale at which fuels vary in surface fire regimes makes measurements inherently difficult. Each fuel type found within the fuelbed matrix has a different set of properties such as fuel biomass, volume, bulk density, and surface-to-volume ratio (Fonda 2001; Ottmar et al. 2003; Fonda and Varner 2004; Kane et al. 2008) that influences fire behavior and fire effects (Loudermilk et al. 2012; O'Brien, Loudermilk, Hiers, et al. 2016) and that have consequences for longleaf pine restoration (Kirkman et al. 2013; Hiers et al. 2014). Many of these properties are related to fuel dimensions or structure.

Although biomass is the most difficult parameter to estimate using nondestructive means, considerable effort to derive biomass estimates for various fuel types in longleaf pine ecosystems has been made (Ottmar et al. 2003). The problem lies in connecting biomass, structure, and continuity across a fuelbed and throughout the forest matrix. For example, biomass estimates taken just outside plots that were measured for fire intensity or fire behavior did not necessarily represent the plots in question (Ottmar, Hudak, et al. 2016). This inconsistency was attributed to the spatial heterogeneity, random patchiness, and physical overlap of various fuel types—particularly low-growing shrubs and bunchgrasses—as well as heterogeneity in fuel consumption, wind gusts, and vegetative responses to fire.

With the possible exception of wiregrass growth patterns (Mulligan et al. 2002), longleaf pine litter and, to some degree, pine cone distribution, is likely the most predictable fuel type. Pine litter is produced regularly, with its abundance entirely dependent on site conditions and the size, density, and location of trees. The size and location of cone-producing trees can be used to predict cone distribution, but the timing of cone production is influenced by the highly variable and episodic masting events that are typical of longleaf pine (Boyer 1998). Time since last fire (needed to estimate fuel accumulation), site characteristics (such as land use and soil properties), and climate all contribute to the complexity of measuring and characterizing the fuelbed and should be considered in fuel measurement studies.

Characterizing wildland fuel cells or individual fuels across a fuelbed can provide insight into fuel-fire dynamics not apparent when focusing at the stand level. Because most ground cover plants are low growing, and with frequent fire coexist in small areas, fine-scale (<1 m) wildland fuel cells are quantifiable in longleaf pine systems (Hiers et al. 2009; Loudermilk et al. 2012; Bright et al. 2016). Connected across the fuelbed by ground cover plants mixed with leaf litter and coarse woody debris, wildland fuel cells can be categorized as bunchgrasses with perched pine litter, non-bunchgrasses, shrubs and perched pine litter, or pine cones and coarse woody debris (Hiers et al. 2009). Individual fuel types can be significant for influencing fire intensity and fire behavior, with pine litter serving as the main driver of fire spread in longleaf pine systems (O'Brien et al. 2008; Mitchell, Hiers, et al. 2009). Pine cones influence local fire intensity, potentially resulting in patches of plant mortality and affecting seed germination (Wiggers et al. 2013; O'Brien, Loudermilk, Hiers, et al. 2016). In addition, interactions between fuel patches and nonfuel patches create high-order nonlinear patterns of fire-atmosphere dynamics (Loudermilk et al. 2012) and produce "combustion legacies" within the burning environment. Combustion legacies are created when fuels that burn at one location alter the combustion environment for fuels either locally or at some distance. They can also result from patchy fuelbeds that contain areas of fuel and nonfuel. For example, sand mounds created by southeastern pocket gophers (*Geomys pinetis*) are common and can be numerous in many longleaf pine stands. These 30–50-cm circular mounds are devoid of vegetation and create fine-scale fuel-free patches that can dramatically alter the dynamics of fire as it spreads across the fuelbed (Figure 6.3). At low wind speeds (about 1.5–2 m/second), the mound can split a running head fire, and as the head fire passes the mound, it develops into two parallel flanking fires. Interactions between their convective plumes then pull the flanking fires together, resulting in a large patch of higher intensity fire immediately downwind of the mound. The head fire is then restored with the same geometry as the original head fire (O'Brien, unpublished data). Higher wind speeds would have a nonlinear impact on the fire-atmosphere and fuel dynamics (Figure 6.4): the fuel-free mound could have no influence on the head fire, as fire would flow over the mound and continue unimpeded (O'Brien, unpublished data).

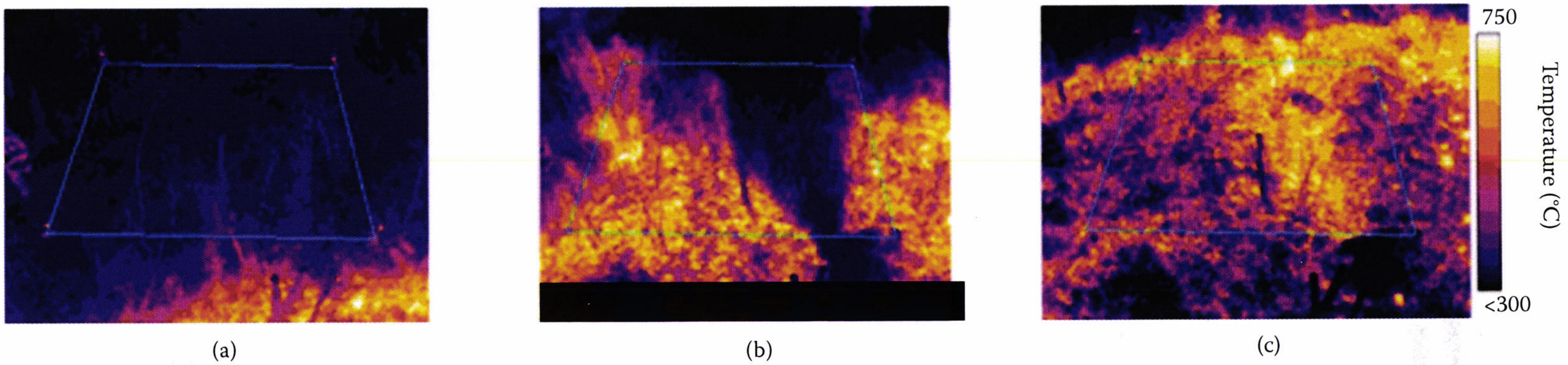


FIGURE 6.3 Three images, each collected every 30 seconds, of a head fire crossing a 4 × 4 m experimental plot in a longleaf pine stand, where wind speed was about 2 m/second: (a) Approaching fire in the lower-right corner, (b) mound of sand in lower-right corner breaking the head fire into two flanking fires, and (c) flanking fires recombining at a higher intensity and quickly reestablishing the head fire.

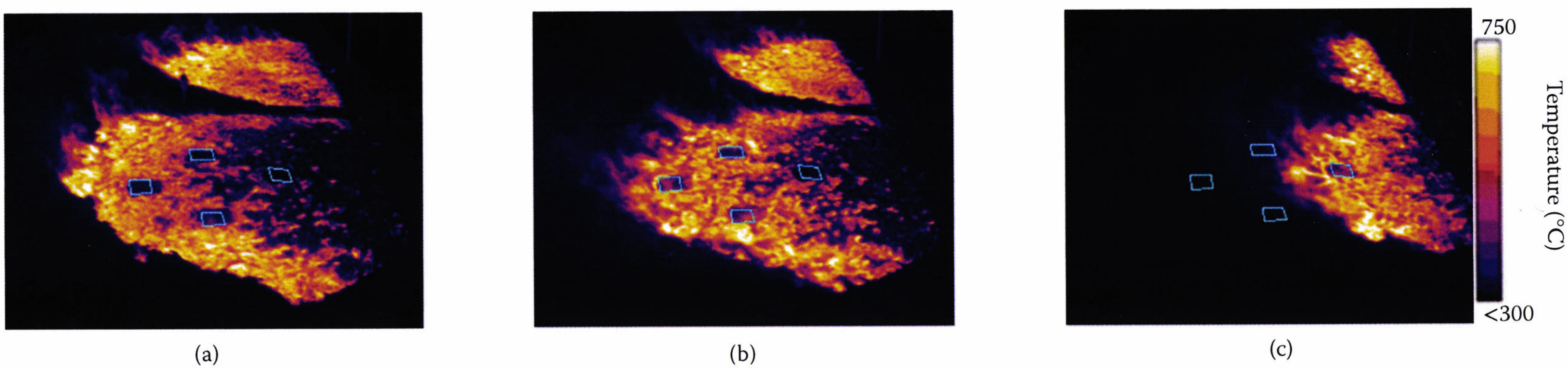
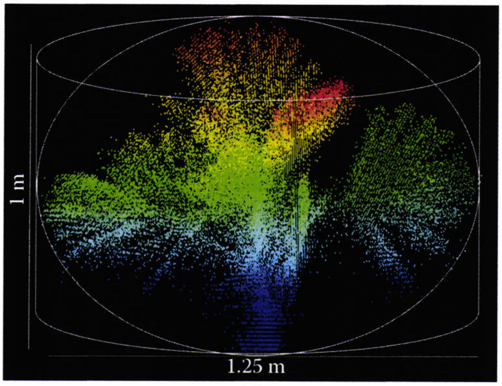
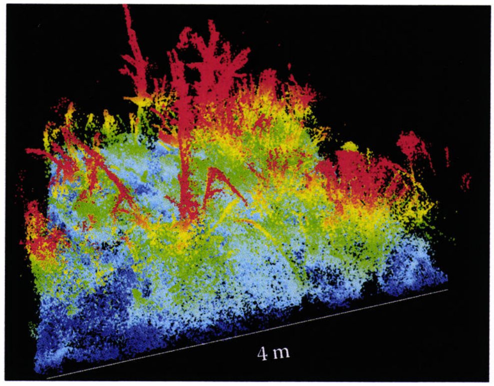


FIGURE 6.4 Images showing the progression of two 10 m lines of head fire that were ignited nearly simultaneously in longleaf pine fuels (upper fire line) and in four 1 m^2 plots that had been cleared of all fuel (lower fire line), with a 5 m/second wind coming from the right side of the images. Note that the wind speed was high enough to increase the intensity and rate of spread sufficiently to swamp any effect of fuel heterogeneity.



(a)



(b)

FIGURE 6.5 Output of three-dimensional point clouds from a terrestrial laser scanning for: (a) An individual saw palmetto shrub, and (b) a 4 × 4 m plot in a longleaf pine fuelbed, which has a maximum fuelbed height of 2 m. Note that fuel volume measurements of plants are usually based on a cylindrical or spheroid geometry. (From Loudermilk, E. L. et al., *International Journal of Wildland Fire*, 18, 676–685, 2009.)

Measuring and Characterizing Surface Fuels

Measuring fuels and fire at a scale necessary for meaningful interpretation requires nondestructive techniques, such as active remote sensing, that operate at high resolutions. Terrestrial laser scanning (TLS) is a remote sensing three-dimensional technique that has been used to capture structural heterogeneity of fuels in longleaf pine systems (Loudermilk et al. 2009, 2012; Rowell and Seielstad 2012; Rowell et al. 2015). TLS and other light detection and ranging (LiDAR) technologies provide a way to measure complex structures in the field with high accuracy and precision (Hopkinson et al. 2004). Unlike most LiDAR technologies, which are commonly used to quantify canopy structure across landscapes (Andersen et al. 2005; Hudak et al. 2009), TLS is positioned under the canopy to reduce the shadowing effects of overstory trees and can therefore provide fine-scale resolution (<1 m) data of the ground cover (Slatton et al. 2004). The high-density three-dimensional point data (>10,000 points/m^2) from TLS provide the precision needed to characterize the complex surface fuels within longleaf pine systems (Figure 6.5). Data extracted from TLS are in the form of fuel height distribution metrics (including average, maximum, variance, skewness, and kurtosis) and laser pulse intensity, which represents the combination of surface area and reflectance of individual fuel components. These values can be quantified in three-dimensional voxels or two-dimensional pixels (for example, 10 × 10-cm areas) across each measurement plot. This is useful for relating to other fuel characteristics, fire intensity measurements, or fire effects at similar scales.

TLS has also been useful for surface fuel characterization. Loudermilk et al. (2009) found that fine-scale volume estimates from TLS are strongly correlated to measurements of leaf area ($r^2 = 0.70$) and leaf biomass ($r^2 = 0.83$) for saw palmetto (*Serenoa repens*) and wax myrtle (*Myrica cerifera*)—two common shrub species in longleaf pine ecosystems. TLS measurements offered a significantly finer resolution and therefore were more precise than traditional methods of measuring volume (as a cylinder or spheroid), with discrepancies increasing as the size of plants increased. Results from other studies using TLS to estimate aboveground biomass and leaf area in colder and drier shrub-dominated systems (Olsoy et al. 2014; Greaves et al. 2015) can likely be applicable in longleaf pine areas.

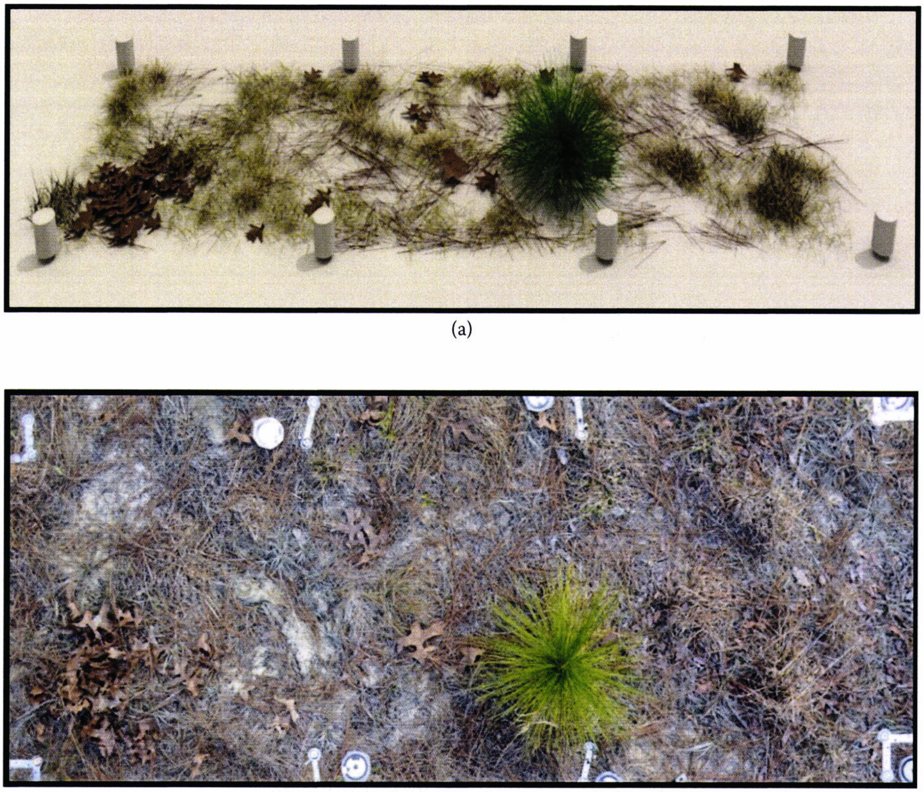
Rowell and Seielstad (2012) used pre- and postburn TLS data to distinguish fuel types in a longleaf pine fuelbed. Their goal was to distribute field-collected estimates of biomass across various fuel types to provide a continuous representation of fuels and biomass. In a follow-up study, Rowell et al. (2015) developed fuel-height models from TLS scans of treeless 2-ha sites that were dominated by mixed grasses and shrubs and located in an area adjacent to longleaf pine stands in northwestern Florida. These data are valuable for employing TLS technology to examine the accuracy and bias of fine fuels measurements across a relatively large area at a fine resolution (about 2 cm). The study results showed that the scaled up (<1-m^2 resolution) TLS heights were comparable to field measurements. However, the coarse sampling methodology produced height distributions of the original TLS data that differed from the field height distributions. Ultimately, TLS provided a continuous spatially explicit representation of fine-scale fuel heights at a scale and data richness level that outperformed typical field methods. Measurements using TLS to estimate the influence of fire on surface fuels and consumption are increasing (Wang and Glenn 2009; Gupta et al. 2015).

Airborne laser scanning is often unable to provide quality estimates of ground cover vegetation, partly because its horizontal resolution is limited to only a few decimeters and partly because of canopy-obstruction issues (Slatton et al. 2004). To overcome these obstacles, researchers have used airborne laser scanning to map shrub percentage cover over large landscapes in varying canopy densities of ponderosa pine (*P. ponderosa*) or mixed conifer forests (Martinuzzi et al. 2009; Wing et al. 2012) in two western forests. This work has promising applications for longleaf pine stands, as many of the ponderosa stands were of similar stand and fuelbed construct.

Although these technologies are powerful and can provide invaluable information, some limitations of using TLS or LiDAR should be considered. The expense of instrumentation and amount of time required for data acquisition and processing are both excessive, as is the expertise needed to handle data collection and analysis (Dassot et al. 2011). Estimating important fuel within the three-dimensional TLS point cloud types is difficult—and is especially so for pine needle litter, which drapes across other living and dead fuels and is virtually indistinguishable from the soil and other litter. Multiple scans are used to reduce shadowing effects, however, these effects still occur and are more pronounced in denser vegetation. Even though TLSs have large-range capabilities (for example, ≤1500 m for Optech's ILRIS-36D), the area that can be measured is limited by the density and size of tree boles, obstruction from other vegetation, overall vegetation density, and the differences in point-density that occur across larger areas (with spatial bias occurring toward the plot edges that tend to be closer to the TLS instrumentation) (Rowell et al. 2015).

An alternative to TLS for characterizing surface fuels is photogrammetry techniques. Since the 1930s, these techniques have used overlapping (aerial) photographs to create three-dimensional "stereophotos" for use in timber cruising, detecting land use and land cover changes, and estimating tree and stand characteristics (Spurr 1960; Slama et al. 1980; Miller et al. 2000; Naesset 2002; Zagalikis et al. 2005). When LiDAR was introduced in the 1980s, and soon afterward became more affordable and accessible, it quickly took the place of photogrammetry. Photogrammetry has, however, advanced over that time (Miller et al. 2000; Zagalikis et al. 2005), and digital imagery and photogrammetric software or workstations have replaced hard copy photographs and stereoscopes. Furthermore, photogrammetry has recently become competitive with light detection and ranging technology, producing high-quality three-dimensional renderings of urban and forest structures for a fraction of the cost (Dandois and Ellis 2013). In addition, Bright et al. (2016) have developed a method for using photogrammetry to measure three-dimensional ground cover vegetation and coarse woody debris in a xeric longleaf pine ecosystem. The resulting photogrammetric height metrics (similar to TLS) and color photo values (red, green, and blue) can be used to characterize centimeter-scale fuelbed height distributions similar to 10-cm scale point-intercept sampling, and to predict plant functional groups at this same scale. This work shows that three-dimensional photogrammetric points can provide fine-scale measurements of ground cover fuels and plants that are comparable to those derived from TLS.

New ways of creating virtual fuels and fuelbeds have been introduced to circumvent the need for physically measuring the ground cover fuelbed. Rowell et al. (2016) worked with the same photographs for photogrammetry as those used by Bright et al. (2016) to create models of individual fuel types (such as leaf litter, shrubs, grasses, and pine cones) and then constructed fuelbeds of mixed fuel types (Figure 6.6). With this approach, metrics of interest (such as bulk density, total volume, and height) can be extracted from the fuelbed without shadowing effects, variable point density distributions, limits on fuel type identification, and other issues associated with TLS. There is promise in constructing fuelbeds across larger areas (stands or management units) with simple guidance from photographs, measurements from field sampling and literature searches, and other known



(a)

(b)

FIGURE 6.6 Images of a fuelbed shown as (a) a three-dimensional synthetic model of fuelbed created from in-situ point-intercept fuel-type and height data, and (b) an at-nadir photograph. (From Rowell, E. and E. Loudermilk, unpublished data.)

variables such as time since last fire and fluctuations in cone production. In addition, this approach offers the potential to serve as a bridge connecting estimates of type and biomass from field sampling to the three-dimensional structural data from TLS. It can be used to produce continuous and consistent estimates of fuel types, biomass, and volume that would be valuable in efforts to estimate stand fuel loading and prepare spatial inputs to fire behavior models.

Measuring Fire

Capturing spatial fire behavior measurements is difficult and requires techniques beyond those that have been typically used in fire ecology studies. For many years, the available technology for measuring wildland fire intensity was limited to qualitative estimates, point measurements, and relative indices of intensity that do not lend themselves to comparisons across multiple studies (Kennard et al. 2005). These limitations hampered efforts to mechanistically link the energy released by fire to actual fire effects, especially for spatially disparate variables. Measurements of energy transfer (watts, joules), not just temperature, are essential for predicting and understanding both first- and second-order fire effects (Van Wagner 1971; Johnson and Miyanishi 2001; Dickinson and Ryan 2010).

Advances in infrared thermography have increased the possibilities of directly connecting fire behavior to fire effects (O'Brien, Loudermilk, Hiers, et al. 2016; O'Brien, Loudermilk, Hornsby et al. 2016). This well-established technique (Maldague 2001; Meléndez et al. 2010) is especially useful for measuring radiation emitted by surfaces that are heated by fire (Figure 6.7) and integrating the impact of

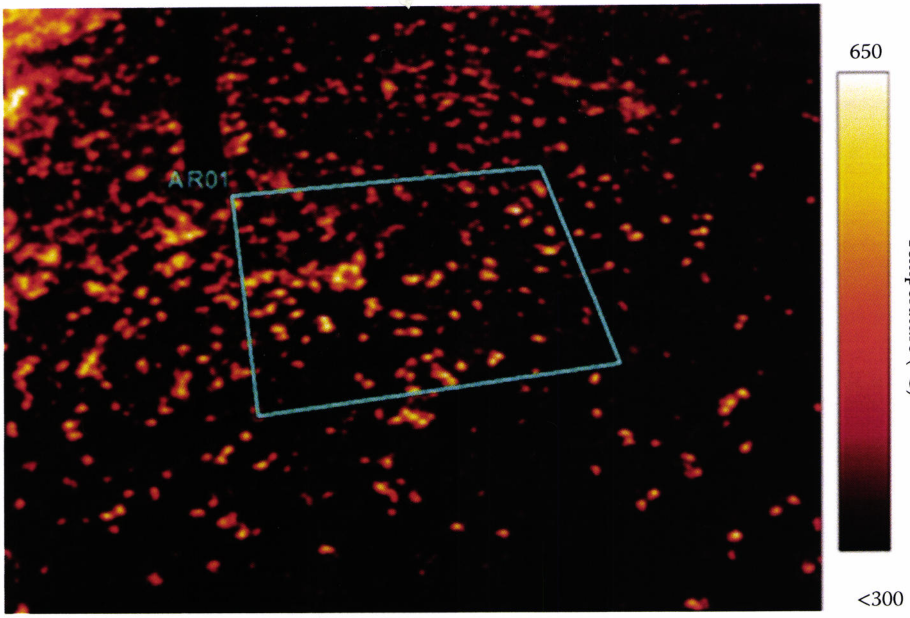


FIGURE 6.7 Infrared thermography capturing smoldering small coarse woody debris (pine cones and a few other 10-hour fuels) after the passing of a low-intensity fire through fuels under a longleaf pine (tree bole in upper left corner). The area is about 4 × 4 m, illustrating the fine-scale variability in fire intensity. (From Mitchell, R. J. et al., *Journal of Forestry*, 107, 391–397, 2009.)

radiative, convective, and conductive heating. Many available products offer high spatial and temporal resolutions (for example, 1 × 1-cm pixels collected at a frequency of 1 Hz), and some offer long-wave infrared radiation—a band especially useful for smoky environments (Rogalski and Chrzanowski 2002).

If exceptionally high-resolution information is not required, coarser-scale infrared instrument platforms are available to provide information on fire energy release and spread that can answer other relevant questions. For example, dual band radiometers (Kremens et al. 2012) can capture quantitative data on fire radiant heat release that can be used to examine the impact of forest structure on fire behavior and fire effects (Cannon et al. 2014). In addition, aerial and satellite platforms (Lentile et al. 2006; Dickinson et al. 2016; Hudak et al. 2016) can provide synoptic information on whole-fire heat release and fire spread.

Linking Fuels to Measurements of Fire

The advances in methods to measure multiscale fuels and fire described above provide a means to capture data on the mechanisms that control fire behavior in longleaf pine ecosystems. In addition, advances in statistical techniques facilitate the analysis of the resulting (potentially very large) data sets that have complex nonlinear, high-order relationships (Prasad et al. 2006; Seni and Elder 2010). In a southwestern Georgia longleaf pine woodland, Loudermilk et al. (2012) developed nonlinear correlations between fire behavior measurements recorded with infrared thermography and fine-scale fuels measured by TLS and field data. This work demonstrates the importance of coupling fuelbed height metrics, fuelbed continuity, and fuel types as driving influences on fire dynamics. They found that fire behavior is best predicted by characterizing fuelbed heterogeneity and continuity across multiple plots that have similar fire intensity, optimizing plot-to-plot variability in fuel characteristics and fire weather conditions; and their assessments of individual plots confirmed the significance of individual fuel types. These studies hint at the potential of such technologies and approaches to characterize fuels and fire in new ways, providing novel opportunities to advance fire-effects research in longleaf pine and associated ecosystems.

FUEL INFLUENCES ON FIRE EFFECTS DURING RESTORATION

Overstory Disturbance Impacts of Fuels

In the past two decades, efforts to restore longleaf pine communities have begun to move away from a simplistic focus of fire as a monolithic disturbance that primarily influences forest structure and toward a more holistic view of vegetation, fuels, and the variability of fire behavior—with fire in essence seen as many disturbances. This perspective has become a critical factor in the development of successful restoration projects, particularly on sites where fire regimes have been disrupted.

In many fire-excluded and poorly burned degraded stands, restoration has focused primarily on the removal of midstory stems of fire-intolerant hardwoods (Provencher, Herring, et al. 2001; Hiers et al. 2014). This strategy led to many unintended consequences for subsequent attempts to reintroduce fire, including overstory and old-growth mortality, escaped prescribed fire, and loss of species (Varner et al. 2005, 2007). Recognizing the necessity of first restoring an appropriate fuelbed has come slowly because doing so challenged the prevailing paradigm as to why ecosystems were degraded in the first place—that fire-exclusion creates an environment in which midstory plants encroach, blocking out light from the diverse ground cover flora of longleaf pine forests (Provencher, Herring, et al. 2001).

A more nuanced view resulted from a series of studies that quantified the role of duff consumption in prescribed fires that were applied during restoration projects (Varner et al. 2005, 2007; O'Brien et al. 2010). The researchers found that duff consumption not only compromises the integrity of the longleaf pine overstory through excessive mortality (Varner et al. 2005, 2007; O'Brien et al. 2010), but it also complicates future prescribed fires—in the short run by suddenly adding dead fuels (Varner et al. 2005), and in the long run by removing the overstory and thereby reducing needle cast (Mitchell et al. 2006; Mitchell, Hiers, et al. 2009). Just as critical, however, was the discovery that the accumulation of forest-floor matter plays a direct role in ground cover degradation and that it also inhibits ground cover recovery, at least in xeric sites (Hiers et al. 2007).

The prioritization of fuels management as a precursor to diversity recovery has become more widely accepted, but an overemphasis on forest structure—particularly on the presence of pyrophytic midstory hardwoods in xeric sites—continues to absorb resources while compromising restoration goals (Hiers et al. 2014). Taking a fuels-management approach to the restoration of fire regimes relegates forest structure to a secondary goal to be achieved by multiple burns over a longer time frame. Restoration objectives should be focused on the reduction of encroachments by semideciduous and evergreen hardwoods and shrubs to promote the reestablishment of fuelbeds that will propagate fire through stands (Hiers et al. 2007).

Plant diversity in longleaf pine communities is a direct product of frequent fire, both across and within stands. Any fuel disruption caused by overstory removal (hence, removal of pine needle sources), soil disturbances, or a combination of both, will affect plant recruitment patterns both directly and indirectly. Disturbances that disrupt soil profiles and alter soil structure and topography by compacting and churning mineral soils (such as entrenchments and vehicle tracks) can alter patterns of fire behavior, disrupt fire spread, and inevitably change plant recruitment patterns as well.

Incorporating Time into Fire-Based Restoration

Among the principles that guide ecological forestry is the need to incorporate time into strategies for recovering degraded ecosystems (Franklin et al. 1997, 2007). The fuels-driven strategy for ecosystem restoration is built on the old adage, "it took 50 years to degrade, it will take 50 years to restore." Despite the recent widespread trend of using herbicide and mechanical treatments, no surrogate is available to replace fire in ecosystem recovery (Menges and Gordon 2010; Outcalt and Brockway 2010). Often, the value of the "rush to restore with fire" approach is minimal because the recovery of fuels can take decades, particularly when considerable duff is present. An approach that incorporates time and patience is also likely to produce more lasting outcomes during periods of rapid ecological change, when variations of ecological conditions can drive restoration trajectories in unpredictable directions (Hiers et al. 2012; Loudermilk et al. 2016). Increasingly, understanding the role of time is also altering perceptions about appropriate restoration targets (Hiers et al. 2012; Kirkman et al. 2013). Longer term cycles can involve temporal dynamics that range from structural changes—such as those resulting from the massive 1996 longleaf pine seed crop—to compositional changes that are associated with recovery from long-term perturbations (Kirkman et al. 2013). Such long-term views on ecological variability will be critical in maintaining longleaf pine resiliency in a future of climate uncertainty (Loudermilk et al. 2016).

Fire Regime Effects

Long-term fire regime effects can dramatically alter fuelbed properties; these, in turn, mediate fire behavior through the compounded impacts of positive feedback loops that are associated with the ecology of fuels. Such effects can operate over several decades or more, and are particularly important for managed fire regimes because the edge effects from managed fire regimes can alter habitats within longleaf pine stands (Lashley et al. 2014). Fuelbeds in longleaf pine systems are dynamic in that their structure and continuity continuously change, both within a single fire cycle and over multiple fire events. Understanding these changes through time, in particular with changing fire-return intervals, is important for long-term restoration management. Applying fires as often as fuels will permit (often at 1–3-year intervals) maintains the highest levels of native plant diversity as well as maintains fuel levels, both of which experience significant changes at slightly longer (6–7-year) return intervals (Glitzenstein et al. 2003; Kirkman, Goebel, et al. 2004; Glitzenstein et al. 2012); for more details see Chapter 11. When fire-return intervals are regular over long periods, the effects can be seen directly in the relative proportion of fuel types—primarily grasses, forbs, and woody species (Glitzenstein et al. 2012). These changes are accompanied by alterations in fuel moisture, relative proportion of live and dead materials, and ultimately modifications of fire behavior. The changes in fire behavior, in turn, have a reinforcing effect on fire regimes over time (Glitzenstein et al., 2012).

IMPORTANT DIRECTIONS FOR FUTURE PROGRESS

The advancement in applications of fire ecology research to longleaf pine restoration requires the development of fire and ecosystem models that are increasingly mechanistic. Two examples of new mechanistic models are the ecosystem process models used to estimate carbon consequences of burn regimes (Martin et al. 2015), and the numerical models coupling fire-atmosphere dynamics (Linn et al. 2002) that examine the convective dynamics of wildland fires, including effects from aerial ignitions (Department of Defense Strategic Environmental Research and Development Program #RC-2643). At individual burn scales, model capacity to document convection-driven heat exchange is already challenging the conventional wisdom of a previous model-based management recommendation (NWCG 2015).

Also needed for understanding the complexities of fire behavior and effects is the ability to examine the impacts of fires on soil properties, plant diversity, longleaf pine recruitment, and interactions with other disturbances (such as the effects of drought on fire-soil interactions or the effects of hurricanes on canopy-fire feedbacks). The importance of understanding the variability of disturbances on ecological patterns and processes is gaining in recognition. Such variability not only drives ecological trajectories of longleaf pine community composition (Kirkman et al. 2013), but also can be critical for other processes affected by fire (Lashley et al. 2014; Hiers et al. 2014).

In a recent review of soil moisture research, Matthews (2014) summarized field research and modeling efforts since 1991, building on a review from Viney (1991), and outlined several areas of research needed to rectify important information gaps about fuel moisture and fire behavior:

- Although soil moisture research has concentrated on pine fuels, the diverse effects of hardwood litter are also important and deserve greater attention (Kane et al. 2008; Varner, Arthur, et al. 2016).

- An open question remains about the interaction of soil moisture with surface fuel moisture and drying rates in fuelbeds, particularly with respect to the role of capillary action. Microtopography and microclimate at the wildland fuel cell scale could dramatically improve predictions of low-intensity surface-fire regimes, but not the role of soil moisture at that scale.
- The temperature of fuel and its relationship to fuel moisture content has been assumed to be a geometrical model function, but field work has shown that solar radiation is confounded with or depends on vegetation structure or micrometeorology.
- Spatial data reflecting patterns of fuel moisture content are needed to test existing model limitations experimentally and improve understanding of model functioning (Matthews 2014). Spatial variability is likely to be critical to fire behavior in low-intensity surface-fire regimes, such as those used in longleaf pine ecosystems. Incorporating fuel moisture content explicitly into wildland fuels cells common to longleaf pine systems would improve the ability to predict fire behavior and to connect fire behavior to postburn fire effects.

For this emerging knowledge to be incorporated into management decisions by forest managers and owners, the wildland fuel cells concept, remotely sensed data, and three-dimensional fuel models need to be translated into useful products (such as those used to map fuels). To integrate wildland fuel cells into management, additional research must identify the relevant scale of fuel variation that drives fire behavior and fire effects for models. This would require further development of the wildland fuel cell concept within various types of longleaf pine communities. Information is available on the scale of wildland fuel cells, how to characterize them, and how they link to surface fire behavior in longleaf pine sandhills and other upland pine habitats; but shrub-dominated fuels, such as those found in longleaf pine flatwoods, remain an area of uncertainty.

More information is needed on how wildland fuel cells function (either with each other or when influenced by fire-atmosphere dynamics) to affect fire intensity and fire movement throughout a stand. Also needed is testing of the wildland fuel cell concept in other fire-driven ecosystems—focusing on the scale at which fuels and fire interact to produce fire effects. The use of TLS, airborne laser scanning, and photogrammetry to capture fuel heterogeneity more thoroughly is becoming widespread, and offers a tremendous opportunity to characterize variability relevant to fire behavior and ecosystem response, but linking fuels at multiple scales requires additional work. New fuel measurement techniques and the development of three-dimensional modeling techniques will provide valuable improvements in the quality of the fuel characterizations that are used for fire effects research and modeling fire behavior.

The challenge remaining for landscape-scale application of fire research is the tension between expanding the number of acres treated with prescribed fire and minimizing impacts on air quality and other societal values (see Chapter 13). To help navigate this increasingly narrow management space will require better tools for modeling smoke, seasonal fire effects, and ecosystem responses to less frequent fire regimes. Last, ecosystem process models—and the incorporation of realistic fire disturbances into their framework—would provide insights into longleaf pine and associated ecosystems and predictions of how these ecosystems might respond to changes in climate, climate-fire dynamics, and management in an era of continued constraints from urbanization. The value of such predictions will ultimately rely on robust monitoring of long-term ecosystem trends as well as understanding new and unexpected feedback loops within the ecology of longleaf pine fuels.

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