Ecological Forestry in the Southeast: Understanding the Ecology of Fuels

Robert J. Mitchell, J. Kevin Hiers, Joseph O'Brien, and Gregory Starr

ABSTRACT

Fire is a dominant disturbance within many forested ecosystems worldwide. Understanding the complex feedbacks among vegetation as a fuel for fire, the effects of fuels on fire behavior, and the impact of fire behavior on future vegetation are critical for sustaining biodiversity in fire-dependent forests. Nonetheless, understanding in fire ecology has been limited in part by the difficulties in establishing the connections between fire behavior and vegetation response. To address this issue, we present the concept of the ecology of fuels, which emphasizes the critical role that fuels play in conceptually linking feedbacks between fire and vegetation. This article explores the ecology of the fuels concept for longleaf pine woodlands and illustrates its utility by evaluating the principles of ecological forestry (incorporating legacies of disturbances, understanding intermediate stand development processes, and allowing for recovery periods) in this chronically disturbed ecosystem. We review the research behind our understanding of these feedbacks in longleaf pine ecosystems of the southeastern United States and review the applications of these principles through the Stoddard-Neel method of ecological forestry. Understanding these feedbacks is critical for integrating fire ecology and ecological forestry in the Southeast and in other fire-dependent forest types.

Keywords: ecology of fuels, longleaf pine, ecological forestry, fire, tree selection

"Fire is the dominant fact of forest history" (Spurr and Barnes 1973, p. 347). In ecosystems with fire as a governing evolutionary influence, vegetation is adapted to reoccurring fires (e.g., fire return interval), and these adaptations result in fuel structure and properties that promote the continued burning patterns that cumulatively define the fire regime (Figure 1). Fire ecology as a discipline has begun to address many aspects of forest response to fire but has poorly connected fuel heterogeneity to fire behavior and fire behavior to fire effects (Johnson and Miyanishi 2001). This disconnect results, in part, from the lack of salient organizing concepts to describe complex responses of vegetation to fire behavior. We suggest that the tight coupling of vegetation as a fuel and fire as a major regulator of future vegetation (and thus future fuels) is best described as the ecology of fuels. This organizing concept emphasizes that fuels be viewed as a bridge between the combustion environment and the vegetation response, specifically that litter be incorporated into ecological feedbacks (Hiers et al. 2007), and that fire behavior and fuels be quantified at the appropriate scale (Hiers et al. 2009). In fire-frequented ecosystems, the concept of the ecology of fuels is critical for understanding the ecological dynamics that result from silvicultural practices, managed fires, and vegetation response. In this review, we use this concept to evaluate the application of ecological forestry principles to fire-frequented longleaf pine ecosystems of the southeastern United States.

Franklin et al. (2007) propose that ecological forestry silvicultural prescriptions should be based on three principles: (1) incorporation of legacies into silvicultural prescriptions, (2) inclusion of intermediate stand development process such as fire or variable density thinning, and (3) inclusion

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Figure 1. Frequent low-intensity prescribed burns sustain the high diversity characteristic of longleaf pine systems of the southeastern United States. (Photo provided by Richard T. Bryant.)

of appropriate recovery times. These principles have been described and investigated largely in catastrophic disturbance regimes where they are discreet in type and time (Franklin et al. 1997). However, legacies, fire, and recovery periods are all intertwined in both time and space in more chronically disturbed ecosystems. In frequently burned ecosystems, these principles can best be conceptually understood through linkages with fuel, fire, and fire effects feedbacks, i.e., the ecology of fuels.

In the southeastern United States, the intimate connection between frequent fire and the ecology of the vegetation has been long recognized (Harper 1913, Greene 1931, Stoddard 1931, Chapman 1932, Wahlenberg 1946). Pine savannas and woodlands of the region require frequent fire regimes (1–3 years) to maintain their diversity of plants (Glitzenstein et al. 2003, Kirkman et al. 2004a, b), which is among the most species rich in the Temperate Zone and is globally significant in rare and endemic plants (Hardin and White 1989). Declines in species richness (Glitzenstein et al. 2003, Kirkman et al. 2004b), as well as loss of rare species and endemics (Liu et al. 2005), have been recorded when return intervals exceed 3 years in southeastern pine woodlands.

Pines are a key functional guild in the region because they produce both the critical fuel that drives frequent fire (i.e., fallen needles; Ottmar et al. 2003) as well as the highly valued stumpage that determines the economic returns from timber management. Thus, silviculture not only influences the spatial and temporal distribution of pines, their age, and size distribution, but concomitantly governs the distribution of pine fuel. If management objectives include the conservation of biological diversity in concert with timber production—goals that are assumed if ecological forestry principles are in play—and diversity is fostered by fire return intervals of 1–3 years, then silvicultural prescriptions must sustain a frequent fire regime that is uninterrupted in time and space.

Because ecological forestry in the Southeastern Coastal Plain presumes that these dynamic feedbacks are incorporated into management strategies, the applications of ecological forestry principles (Franklin et al. 2007) to this chronically disturbed ecosystem can not be viewed as independent agents, but rather must be viewed as interwoven processes. The ecology of fuels concept is helpful in evaluating these principles and creates linkages among them that capture the dynamic nature of this ecosystem.

Legacies and Fuel Structure

Because frequent fire is a vital process regulating ecological dynamics of southeastern ecosystems, fuels are by extension a crucial legacy. The concept of biological legacies originally emerged from studies that found that natural disturbances rarely simplify and homogenize environments but rather create habitat variation and structural complexity (Franklin et al. 2007). The legacy concepts apply similarly to landscapes affected by large-scale, infrequent, catastrophic or mixed-severity fire regimes (Donato et al. 2006) as well as smaller-scale, frequent, low-severity surface fire regimes (Hiers et al. 2007, 2009). There is a tightly coupled feedback between fire and fuels because fire affects fuel properties and fuels in turn impact future fire. In the southeastern United States, the frequent fire regime is maintained by inputs of fine fuels. Fine fuels that sustain frequent fires are often characterized by their physical properties independent of the vegetation that produces them (Brown 1974, Anderson 1982). By taking the ecology of fuels perspective, ecological determinants of important characteristics such as chemical composition and spatial arrangement are emphasized. Recently, in grassland ecosystems in general, there has been an increasing appreciation for how spatial heterogeneity of vegetation, driven by other disturbances (grazing), contributes to future fire effects and plant community dynamics (Collins and Smith 2006, Kerby et al. 2006). Less well studied is how legacies of fine-scale heterogeneity in vegetation and fuels impact fire behavior and community dynamics (Thaxton and Platt 2006), but both fire and fuels vary at similar scales in longleaf pine woodlands (Figure 2; Hiers et al. 2009).

Silvicultural legacies can affect the ecology of fuels by altering the distribution, type, and amount of fuels (Mitchell et al. 2006). Longleaf pine needles provide ideal fine litter for frequent fire because of their high resin content (Fonda 2001) and structure (Hendricks et al. 2002). Bunchgrass crowns act as perches for fallen needles, creating a well-ventilated fuel bed that dries easily (Robbins and Myers 1992, Nelson and Hiers 2008). A synergy among fine fuels, i.e., grasses and needles, is the salient structural feature of this system that allows for the frequent fire regimes required to sustain the high levels of biodiversity characteristic of longleaf pine woodlands. Silviculture influences fine fuels by harvesting adult pines, by regulating the timing and distribution of regeneration, releasing trees and accelerating crown development, and by disturbance to the understory vegetation and fuels. The spatial distribution of fine fuels in these sys-

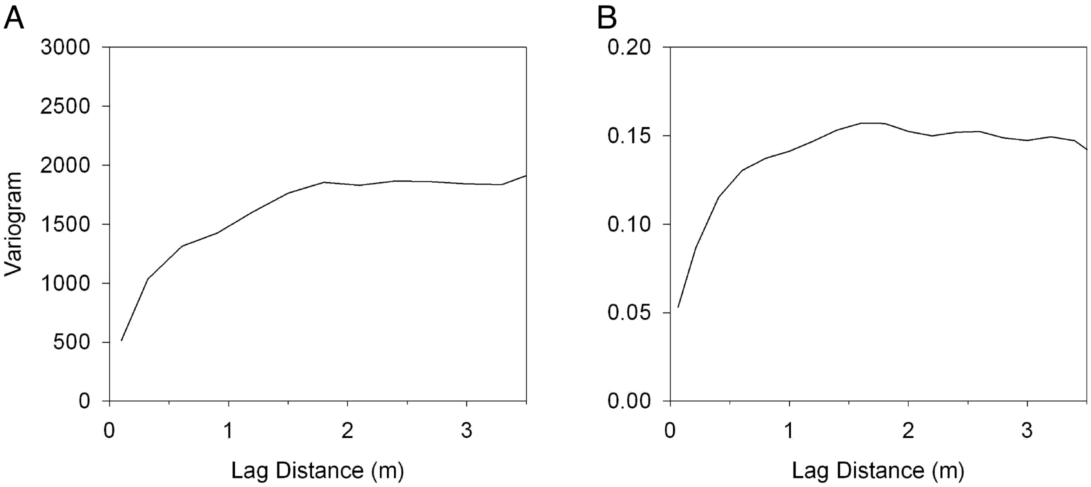

Figure 2. Semivariograms of plot data show that both fire temperatures (90th quantile of temperature readings, plot A) and fuel cell structure (LIDAR data, plot B) vary at submeter scales, because the sill is reached between 0.5 and 0.75 m in both cases. Small-scale variation in fuels and fire behavior may be critical to sustaining high diversity of plants at small scales (submeter to 10 m^2).

tems often mirrors the distribution of individual pine canopies.

The Ecology of Fuels and Longleaf Regeneration

Successful regeneration in longleaf pine woodlands is a product of the complex interaction among infrequent mast, fuel load, and frequent fires. Longleaf pine seeds require bare mineral soil for successful germination (Wahlenburg 1946). Fires before seed rain are necessary to remove the litter layer and competing vegetation (i.e., prepare the fuel bed). The timing of fire is also critical to natural regeneration. Fires set too far in advance of seed rain allow litter to accumulate, leaving insufficient bare mineral soil for successful establishment. Even if germination is successful, excessive fuels loads can also increase fire intensity resulting in mortality of germinants (O'Brien et al. 2008).

Fire not only manages fuel load and thus fire intensity, but fire affects the competitive environment around the new germinants. After successful germination, longleaf pine seedlings may spend 2–20 years without height initiation in a "grass stage," which confers significant protection from low-intensity surface fires (Wahlenberg 1946). Light availability limits the growth rate of "grass stage" longleaf seedlings (Pecot et al. 2005), and recently burned vegetation is shorter in stature, allowing more light to reach recent germinants (Pecot et al. 2005). Generally, the susceptibility of grass-stage longleaf pine seedlings to fire is measured by their root collar diameter (RCD; Grace and Platt 1995), with those seedlings growing more rapidly (>1.3-cm RCD) having a greater probability of surviving the first fire (Boyer 1974).

Further complicating regeneration in longleaf pine, however, is that as a mast seeding species (Silvertown 1980), it produces a regional seed crop only every 6–12 years, although some seed is often produced in a stand every 2 or 3 years by a few trees that are out of synchrony. Capturing regeneration from a mast year requires a break in the frequent return interval. This fire-free period required for seedlings to survive varies with site productivity from one to several years, and the variation in return interval may also be an important feature in sustaining other plant species (Robbins and Myers 1992, Hiers et al. 2000). Longleaf pine is a long-lived species (up to 500 years), and it produces more seedlings than are needed to replace those trees in the overstory. Advanced regeneration of longleaf seedlings plays a valuable role as insurance against catastrophic loss of overstory. In the absence of the large-scale canopy disturbances, however, this pool of seedlings experiences a high degree of turnover. Thus, a large percentage of regenerating pine is never released and will likely be lost to competition and fire. As such, it is not necessary for managers to attempt to protect all regeneration from fire, but rather sustain the overall health of the forest.

Stand Development, Competition, and Fire

In addition to the importance of the ecology of fuels on legacies and pine regeneration, stand developmental processes including competition, facilitation, and fire must be incorporated into silvicultural prescriptions. Overstory harvest increases light reaching the understory, alters the distribution of needle cast, and changes the competitive environment between species. Moreover, harvesting patterns can affect fire behavior through changes in microclimate. Cumulatively, these factors govern intermediate stand development processes through the interaction of competition and fire (Mitchell et al. 2006). In these open-canopy forests, light levels typically range from 30% of full sunlight to rarely >80–90% (Battaglia et al. 2003, Pecot et al. 2005). This variation in light is sufficient to sustain a vigorous and diverse understory (Kirkman et al. 2001), while the canopy is still capable of generating fine fuels to maintain frequent fire.

Pine needle cast represents the primary biomass responsible for fuel bed continuity and spread of fire (Williamson and Black et al. 1988, Ottmar et al. 2003, Hiers et al. 2009). Consequently, patterns of overstory retention may have dramatic impacts on fire effects through pine litter distribution (Mitchell et al. 2006). When pine fuels are absent, grass is often insufficient to carry fire across the fuel bed (O'Brien et al. 2008). Moreover, surface fuels disturbance by logging equipment, if concentrated, can eliminate grasses from the understory further limiting fire spread. If fuels are disrupted across space, particularly because of the concentrated harvesting through group selection resulting in large clearings, then oaks and other woody plants that were kept small in stature by competition and fire are often released (Pecot et al. 2005, Jack et al. 2006).

This release can result in less flammable litter that burns with lower intensity (Williamson and Black 1981). If gaps are cut so they create hard edges, wind eddies can form where surface winds move in the opposite direction of the canopy winds (Boldes et al. 2003, Gardiner et al. 2005). Such variation of within-stand wind speed and direction will affect fire behavior (Linn et al. 2005), and it can create unpredictability when applying prescribed fire to the stand. Fuel moisture and wind speeds may also differ between gaps and the forest matrix, making the selection of prescription parameters difficult to meet burn objectives in both stand conditions.

In longleaf pine stands the ecology of fuels captures the feedbacks between competition, fire behavior, and fire effects. Legacies of past fire suppression may have increased the density of fire-sensitive hardwoods and shrubs present in the stand. When fire line intensity is insufficient to top-kill advanced regeneration of shrub and hardwood competitors that are found in the surface fuel bed, dramatic shifts in vegetation are possible (McGuire et al. 2001, Mitchell et al. 2006). Maintaining continuity of forest structure both for the fuels they supply and for their competitive control on these fire-sensitive species is critical and often is overlooked. In the absence of fire or during longer fire-free intervals, hardwoods and shrubs grow to a fire-resistant size and outcompete grasses and forbs, causing quick decline in the diverse flora of longleaf pine ecosystems (Mitchell et al. 2006). The pine overstory is known to regulate oak growth through belowground competition (Pecot et al. 2007). Consequently, hardwoods grow more rapidly after harvest, and if the loss of fine fuels is sufficient to disrupt fire continuity, the result can be rapid colonization of the site by undesired shrubs and hardwoods (faster growing hardwoods are more difficult to control by fire alone). These changes can be rapid and difficult to reverse, resulting in an alternative ecological stable state (Beisner et al. 2003). Thus, regenerating pines in harvest regimes that do not take the ecology of fuels into account can lead to unintended consequences, requiring chemical or mechanical treatment to ensure pine recruitment and control stand development processes. The input of greater vegetation management may set ecological forestry goals back by causing ancillary damage to the understory floral diversity or by increasing the amount of timber that is harvested to pay for the increased need for site preparation.

Figure 3. Dead trees provide important legacies for cavity nesting birds when standing as snags, habitat for small mammals, herps, and reptiles when downed wood, and provide fuel legacies that open regeneration niches when consumed by fire.

The Ecology of Fuels Structure and Function

The feedback between fuels and fire exerts influences on ecosystem structure and function in longleaf pine woodlands. Perhaps, the best illustration of the structural influence of fire is its effect on the dynamics of dead trees. Fire not only creates snags if it is of sufficient intensity, it also regulates their persistence through consumption. Although the volume of coarse woody debris (CWD) is relatively low in longleaf pine forests compared with less frequently burned forests (Ottmar et al. 2003), the CWD that is present plays a critical ecological role (Harmon et al. 2004, Blanc and Walters 2008). Fire processes snags and downed woody debris of various species at different rates. In particular, the presence of heartwood in old longleaf pine significantly increases the longevity of snags and logs that can then alter fire behavior. When finally consumed, the legacies of logs are thought to be important microsites for understory species and pine recruitment (Figure 3; Brewer et al. 1996) and may regulate oak density in the understory vegetation (Thaxton and Platt 2006). Pine cones are an often overlooked component of CWD and are frequently not classified as a fuel type. When burned, longleaf cones can smolder for >30 minutes at 400°C (Fonda and Varner 2004). Smoldering at fine scales may at first appear insignificant, but after regional mast, individual trees may average >100 cones, which are all abscised the year after seed rain and concentrate underneath the canopy of adult pine (Figure 4).

Fire, Fuels, and Recovery Times

Allowing sufficient recovery time, the third principle of ecological forestry, is the least documented in the literature relative to silvicultural activity and impacts to fire regime. Harvesting timber not only removes pines and needles from an area, but repeated entries for harvest can disrupt grasses and fine fuels through vehicle impacts on soils and vegetation. Recovery times are related to type and extent of disturbance. If a disturbance, including harvesting or subsequent site preparation, results in substantive damage to the root systems of the perennial plants that dominant the fuel bed, floral diversity can decline (Hedman et al. 2000). Once lost, the diversity of this ecosystem may take considerable time to restore (Kirkman et al. 2004b, 2007). Thus, reducing damage caused by harvest is critical to sustaining biodiversity. Although the impacts

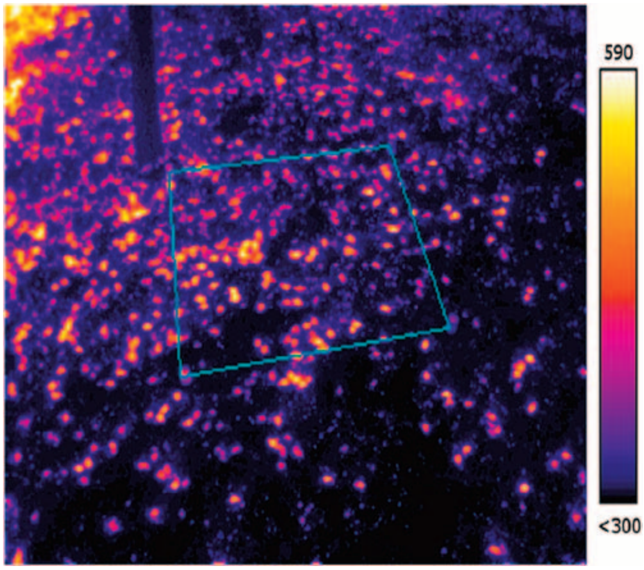

Figure 4. Pinecones present a long smoldering fuel source and may have large impacts in masting events where hundreds of cones concentrate underneath pine crowns (box represents a 4 × 4-m sampling plot).

of timber harvests on understory plant diversity and ecosystem recovery dynamics are poorly understood, many forests in this region have been harvested but maintain high levels of diversity (Drew et al. 1998).

Recovery should also be viewed with respect to the impact of natural disturbances, particularly hurricanes. Although all forests are vulnerable to class 4–5 hurricanes if near the point where the eye of the storm makes landfall (Myers and Van Lear 1998), longleaf pine stands that are outside the influence of the highest winds or are uninfluenced by the storm surge have been shown to be more resistant to damage than others pine species (Gresham et al. 1991). Multiaged stands with advance regeneration and cohorts in intermediate and suppressed crown classes often show considerable resilience to wind damage. Such advanced regeneration of pine seedlings can quickly colonize canopy openings after disturbance. However, managers are often reluctant to burn these fire-dependent ecosystems after hurricanes because of elevated fuel loads associated with storm damage. However, resumption of fire after storm damage is critical to both process the additional fine fuels from needle cast and broken crowns and control hardwood resprouting and preventing their release in newly created canopy openings. Furthermore, despite elevated fuel loadings, the early introduction of fire meters out the fuel available for consumption over several fires. Waiting even 2–3 years can increase fuel availability dramatically as small branches and stems decay and become more likely to burn, while fine fuels continue to accumulate (Ferguson et al. 2002, Ottmar et al. 2003). If smoke emissions are a major concern, salvage logging may be appropriate to eliminate smoke production in subsequent years as downed tree boles decay and become more likely to ignite. However if done, salvage logging should be carefully done to enhance the ecological goals, such as the ability to rapidly return fire frequently to the system, while not impinging on other ecological consideration, such as CWD, needed for sustaining structures that create diverse habitats.

Fire, Fuels, and C-Cycling

Ecological forestry has been often used when conservation of biodiversity is a major goal, but it is also relevant to maintaining or enhancing ecological services. The interaction among vegetation, fuels, and fire controls the dynamics of carbon cycling in ways that should inform ecological forestry. Fire plays varying roles in C-cycling as it pertains to the ecology of fuels and silvicultural practices. Fire suppression has been promoted as a means of augmenting ecosystem C sinks (Hurtt et al. 2002).

The suggestion that fire suppression might be an effective C-sequestration tactic ignores two salient features of fire-dependent ecosystems. First, carbon accumulation in fire prone systems occurs aboveground as flammable forest floor and increased fuel loading of live and dead vegetation. These fire labile pools are at greater risk to be revolatilized after a future and almost inevitable wildfire (Girod et al. 2007). Second, fire plays a critical role in driving the community dynamics of these systems, so that suites of fire specialist species disappear in the absence of fire (Bond et al. 2005), which has consequences for other ecosystem services. Although fire suppression might increase pools of fire labile carbon, frequent fire augments recalcitrant carbon pools, especially in soils (Czimczik and Masiello 2007, Deluca and Aplet 2008). In intensively managed pine ecosystems (plantations), the normal practice is to suppress fire. Under these conditions fuel loads build rapidly to dangerous levels and if a wildfire occurs, the results can be catastrophic. After high severity wildfires, stands are clearcut and replanted, which leads to the systems becoming a large carbon source for as many as 5 years after replanting (Clark et al. 1999, Binford et al. 2006). In contrast, natural longleaf pine systems that experience frequent fires tend to have low to moderate fuel loads that limit the potential for catastrophic wildfires and tend to have relatively stable net ecosystem exchange (Girod et al. 2007).

The Practice of Connecting Silviculture to Fire in the Southeast

The practice of prescribed fire and multiaged single tree selection harvesting were developed simultaneously in the 1920s in southwestern Georgia and northern Florida on private lands and has persisted for 80 years since. These practices fundamentally developed through keen observation and understanding of the connection between forest ecology, silviculture, and fuels. Controlled burning, or prescribed fire as it has come to be known, was a direct response to the declining game bird populations observed in the wake of widespread fire suppression, driven largely by early policies of the US Forest Service and other forest stewardship organizations. Realizing the essential role of fire in the ecology of southeastern forests, Herbert Stoddard coined the term “controlled burn” in his treatise on game management *The Bobwhite Quail: Its Habits, Preservation, and Increase* in 1931 (Stoddard 1931) and was the first to implement the principles of fire-based silviculture on conservation lands. Having fought for 10 years to ensure the right to burn (Stoddard 1969), Stoddard carefully developed a silvicultural approach that integrated the ability to use fire while meeting timber harvest goals. With multiple objectives including timber, wildlife management, aesthetics, and the conservation of biodiversity, Stoddard's system of controlled burning and ecological forestry led Aldo Leopold in 1939 to write, "I have just spent several days with Stoddard and came away with the conviction that he has been too modest about the conservation methods that he has worked out for the Southeast. They are commonly regarded as only applicable to game reserves, but in my opinion he has developed principles that are equally applicable to lumber company holdings, national forests, and other owners of Coastal Plain longleaf" (Way 2008). This system of harvest was further modified by Stoddard's protégé Leon Neel from 1955 to present and is now referred to as the Stoddard-Neel approach to single tree selection (see Mitchell et al. 2006).

The Stoddard–Neel approach was born out of a conservative strategy to harvesting that reflected an intuitive understanding of the connection between fire and silviculture. The ecology of fuels and the interaction of vegetation, fuels, and fire behavior were implicitly recognized as the principles that guided this fire-based silviculture. This approach continues to offer many lessons to be learned for both researchers and managers. It emphasizes that managers should consider vegetation and fuels when using individual tree selection or group selection approaches. Trees are selected for harvest based not only on their timber characteristics, but trees should be selected for retention within the stand to sustain fuel continuity and competitive dominance over the hardwood midstory. The longevity of its practice across a large landscape with diverse objectives illustrates flexibility for meeting the mandates of multiple use while providing sustained timber yield. The forested ecosystems conserved by this approach have offered opportunities to scientifically understand the complex feedbacks between fire, fuels, and plant community dynamics. This approach also provides a practical understanding of the ecology of fuels and offers a framework for applying the principles of ecological forestry to longleaf pine woodlands and other fire-dependent forested ecosystems.

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