EFFECTS OF LAND USE ON FUEL CHARACTERISTICS AND FIRE BEHAVIOR IN PINELANDS OF SOUTHWEST GEORGIA

Kevin M. Robertson[1] and Thomas E. Ostertag[2]
Tall Timbers Research Station, 13093 Henry Beadel Drive, Tallahassee, FL 32312, USA

ABSTRACT

Understanding the relationship between land-use history, fuels, and fire behavior is critical for land management planning in fire-dependent ecosystems. This study sought to examine fuel loads, fire behavior, and hardwood stem kill on southeastern U.S. pinelands managed for wildlife habitat using frequent fire and selective timber thinning. Fuel loads and fuel composition were compared between native (longleaf pine [*Pinus palustris*]–wiregrass [*Aristida stricta*]) and old-field (previously cultivated land currently dominated by shortleaf pine [*Pinus echinata*]–loblolly pine [*Pinus taeda*]) communities, 1 and 2 y since previous burn, and two ranges of tree basal area (1.9–8.6 m^2/ha and 8.7–19.1 m^2/ha) in Southwest Georgia. Native pinelands had higher total fine fuel loads resulting from greater grass dominance and greater needle cast by longleaf pine. Duff and pine needles accumulated between the first and second years following fire. Dead grass loads increased with time in native pinelands but decreased in old-field pinelands, attributable to more competition with understory hardwoods in old fields. Tree basal area had a significant positive effect on total fine fuel loads only in native pinelands but otherwise was neutral. Flame length, rate of spread, and intensity of fires generally corresponded to fine fuel loads, with largest values occurring in native stands with high basal area in the second year following fire. Hardwood stems were generally top-killed if burned, regardless of cover type, but burns were more patchy on old-field lands as opposed to native pinelands and in 1-y compared to 2-y roughs. The results suggest that prescribed burning in native pinelands can achieve effective hardwood understory top-kill under a wider range of fire intervals, fire behavior, and weather conditions than in old-field pinelands. Burning in old-field pinelands requires additional attention to the adequacy of burn conditions to achieve management objectives using fire.

keywords: Aristida stricta, Colinus virginianus, fire frequency, fuel loads, Georgia, hardwood resprouts, loblolly pine, longleaf pine, northern bobwhite, old fields, *Pinus echinata, Pinus palustris, Pinus taeda,* prescribed fire, shortleaf pine, southeastern pine forest, timber management, wildlife management, wiregrass.

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INTRODUCTION

In southeastern U.S. pinelands, management for native wildlife must include frequent fire to prevent hardwood encroachment and to maintain an herbaceous understory (Stoddard 1935). Thus, achieving fuel conditions that allow fires to effectively top-kill hardwood resprouts is a high priority. Fuel loads and associated fire behavior might be significantly influenced by such factors as history of soil disturbance (Hedman et al. 2000), time since previous fire (McNab and Edwards 1976), and timber volume (Harrington and Edwards 1999).

Southeastern pinelands managed for fire-dependent wildlife may be broadly categorized as either ''native'' (never plowed) or ''old-field'' (forests developed after abandonment of agriculture) communities. These community types generally differ in species composition and structure (Hedman et al. 2000; Smith et al. 2000; Kirkman et al. 2004; Ostertag and Robertson, *this volume*) in a manner that may influence fuel characteristics and fire behavior. The recommended fire interval for sustaining native wildlife species and maximizing plant biodiversity in southeastern native pinelands is 1–2 y (Moser and Palmer 1997, Conner et al. 2002, Glitzenstein et al. 2003). Land managers often alternate between burning at a 1- and 2-y rough (fire interval) on a given burn unit to balance the need for sufficient fuel accumulation with ability to kill young hardwood resprouts, as well as to provide a shifting mosaic of unburned areas for wildlife cover (Moser and Palmer 1997, Masters et al. 2003). Pine tree basal area (BA) also varies widely within the range considered to support the native herbaceous plant community and wildlife habitat in southeastern pinelands, from sparsely timbered savannas to approximately >20 m^2 BA/ha (90 ft^2/acre) (Platt et al. 1988, Moser and Palmer 1997).

The effects of these different community types, roughs, and BA ranges on fuel loads, fire behavior, and hardwood stem top-kill are not well documented, but some general observations have been made by land managers and a small number of published studies. Native pinelands usually burn within a wider range of fine fuel moistures and with greater intensity than old-field pinelands, attributable to greater abundance of bunchgrasses, especially wiregrass (*Aristida stricta*) in the eastern Coastal Plain (Lindeman et al. 1997) and abundant, pyrogenic needles of longleaf pine (*Pinus palustris*) (McNab and Edwards 1976, Platt et al. 1991, Harrington and Edwards 1999). Burning 1 y fol-

[1] Corresponding author (krobertson@ttrs.org).
[2] Current address: Florida Fish and Wildlife Conservation Commission, 620 S. Meridian Street, MS 2-A, Tallahassee, FL 32399, USA.

lowing fire, if previously treated with a 1- to 2-y fire return interval, may have the advantage of top-killing hardwood sprouts while they are small and more vulnerable and tends to promote grass dominance (White et al. 1991, Waldrop et al. 1992, Glitzenstein et al. 2003) if fuels are adequate to carry a fire. Burning 2 y following fire tends to provide a more continuous burn with greater intensity, attributable to further accumulation of fine dead fuels (McNab and Edwards 1976, Slocum et al. 2003).

With the BA range of such managed forests (up to about 20 m^2/ha [90 ft^2/acre]), relatively open stands provide more light, less root competition, and potentially greater productivity of herbs as fine fuels (Harrington and Edwards 1999, Dagley et al. 2002, Mulligan and Kirkman 2002). However, pine needle fuel increases with timber volume, potentially providing higher total 1-h fuel loads and higher fire intensities (McNab and Edwards 1976, Brockway and Outcalt 1998, Harrington and Edwards 1999). Denser stands may also result in higher fuel moisture due to shading.

The purpose of this study was to investigate the comparative effects of 1- versus 2-y roughs and varying levels of pine tree BA on fuel composition and loading, fire behavior, and hardwood stem top-kill in native versus old-field pinelands in southeastern U.S. uplands. Our approach was to compare plots representing these categories and their combinations. The investigation was limited to forests managed with 1- to 2-y fire intervals and thinning with single-tree selection during the previous few decades to maintain open stands for wildlife habitat.

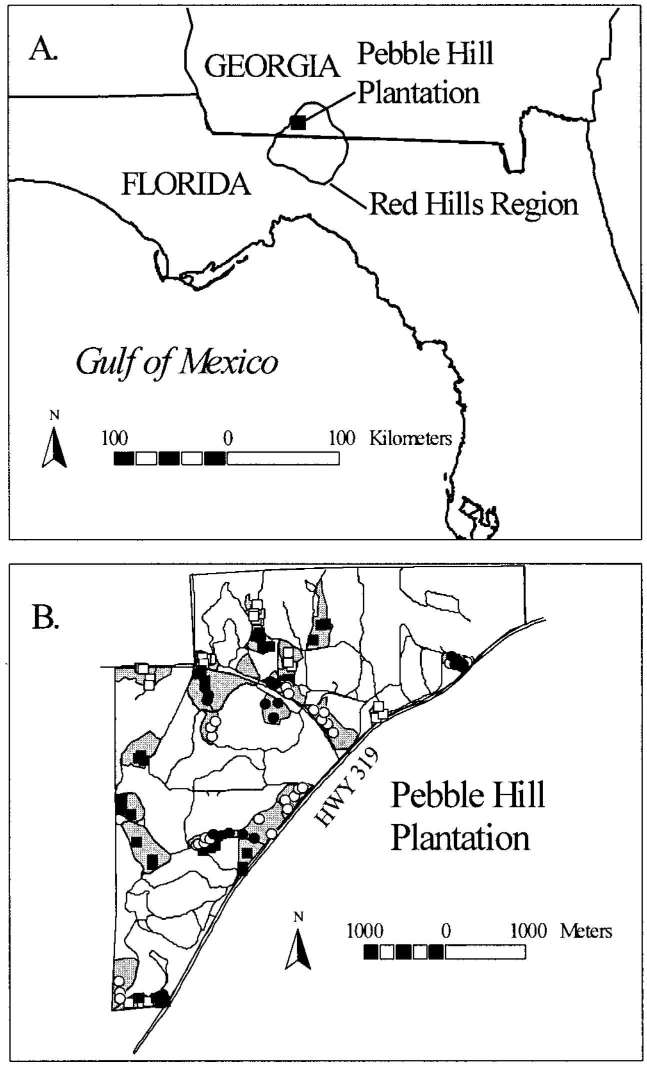

Fig. 1. (A) Red Hills region in southern Georgia and northern Florida and location of Pebble Hill Plantation (square). (B) Pebble Hill Plantation. Thin lines indicate roads, and studied burn blocks are shaded. Study plots are indicated as follows: circle = native; square = old-field; open symbol = 1 y post-burn, filled symbol = 2 y post-burn.

STUDY AREA

The study was conducted within the Red Hills region of southern Georgia and northern Florida on the 1,222-ha Pebble Hill Plantation (PHP) near Thomasville, Georgia (30°35′N, 84°20′W) (Figure 1). This region is characterized by Coastal Plain marine-deposited sediments with loamy sand and sandy loam soils characterized by argillic (clay accumulation) subhorizons (Calhoun 1979). Mean annual temperature is 19.6°C (11.0–27.4°C monthly means) and mean annual precipitation is 1,373 mm (Southeast Regional Climate Center 2004). The growing season for this region is from early March to November (Calhoun 1979; T.E. Ostertag and K.M. Robertson, Tall Timbers Research Station [TTRS], unpublished data).

TTRS has managed PHP since 1990. PHP began as a cotton plantation in the 1820s during the settlement period. However, much of its area remained natural and was probably burned annually or biannually, in accordance with regional land-use traditions adopted from Native Americans and mimicking frequent lightning-initiated fires (Komarek 1979). From 1896 to the present, it has been managed for hunting of northern bobwhite (*Colinus virginianus*). During that time, most agricultural fields were allowed to succeed to old-field pinelands, of which the youngest used in this study were abandoned around 1930, such that old-field pinelands studied were at least 70 y old. Northern bobwhite management has included burning of about 60–70% of both old-field and native pinelands each year (Brueckheimer 1979, Masters et al. 2003), with fires set 1 or 2 y following the previous burn. Unpaved roads traversing the property define burn units ranging in area from approximately 5 to 30 ha.

About one-third of the PHP pinelands are considered native, i.e., dominated by longleaf pine and an herbaceous layer of wiregrass, with a high diversity of other herbs and understory shrubs (Ambrose 2001; Ostertag and Robertson, *this volume*). Old-field pinelands are typically dominated by shortleaf pine (*Pinus echinata*) and/or loblolly pine (*Pinus taeda*), with an understory containing a higher proportion of forbs and woody species to grasses than native pinelands (Billings 1938; McQuilkin 1940; Oosting 1942; Hedman et al. 2000; Ostertag and Robertson, *this volume*). The overstory in both communities contains a minor component (<5% total

BA) of oaks (*Quercus* spp.), hickories (*Carya* spp.), and other hardwoods. Native pinelands on PHP are typically burned during April and May to promote flowering of wiregrass (Van Eerden 1988, Platt et al. 1991, Streng et al. 1993) and to maximize hardwood sprout top-kill (Waldrop et al. 1987, Platt et al. 1991, Glitzenstein et al. 1995), whereas old fields are burned in March when fine fuel moisture is sufficiently low to promote continuous burns. Hardwood resprouts from genetic individuals that were top-killed during the previous fire are common in both community types but usually have a higher frequency in old-field pinelands. Timber is managed to promote a multi-aged, naturally regenerating forest with BA of approximately 7–14 m^2/ha (30–60 ft^2/acre) at the burn-unit scale, although BA may vary widely at smaller scales.

METHODS

Field Sampling and Fire Measurements

In each of the two years of the study (2003 and 2004), the 80 upland pine burn units on PHP larger than approximately 2 ha were categorized as 1) old-field pineland with 1-y rough, 2) old-field pineland with 2-y rough, 3) native pineland with 1-y rough, and 4) native pineland with 2-y rough. Native areas had been identified in a previous study in which native forests were mapped based on the presence of wiregrass and other native indicator species (Ambrose 2001). Remaining pinelands were assumed to be old fields, based on the history of antebellum agriculture on the property and in the region (Paisley 1968, Brueckheimer 1979) and observations in the field to confirm the absence of native indicator species (Hedman et al. 2000, Kirkman et al. 2004) and dominance by shortleaf or loblolly pine.

In 2003, three burn units per community type and rough were randomly selected, and five study plot locations were randomly selected within each burn unit (60 plots total), using the Animal Movement Analysis extension (Hooge 2003) in ArcView 3.2 (Environmental Systems Research Institute 1999). In 2004, five additional burn units per community type and rough were randomly selected, and three study plot locations were randomly selected within each burn unit (60 plots total) for a total of 120 study plots, of which seven were later lost due to management accidents. Each plot was marked in the field using a piece of steel reinforcement bar. Plots were established in January and February in burn units scheduled to be burned in March or early April. Within a 2-m radius of the marker, two subplots were randomly located. At each subplot location, fuels were clipped and hand-collected to the mineral soil surface within a 0.1-m^2 area delineated by a square frame.

During collection, fuels were separated into duff (loose, partially decayed organic material that is difficult to differentiate), 1-h fuels (dead fuels ≤0.6-cm thickness), 10-h fuels (dead fuels 0.7- to 2.5-cm thickness), and live herbaceous fuels. The 1-h fuels were further separated into hardwood leaf litter, pine needle litter, dead grass, and dead forbs, vines, and hardwood seedlings combined (as these were difficult to distinguish in the field). Fuel samples were dried for 48 h at 90°C in a forced-air oven, which was found to be sufficient to achieve constant weight, and weighed to determine fuel load. Average fuel bed height was estimated at each plot. The fuel bed was considered to be the matrix of fine fuels sufficiently continuous to likely carry fire.

All trees ≥4 cm diameter at breast height (DBH) within a 20-m radius of the plot center were identified to species and measured for DBH to determine tree BA surrounding each study plot. After sampling, tree BA was used to further categorize study plots as low BA (<8.6 m^2/ha; 5.1 m^2/ha average) and high BA (≥8.6 m^2/ha; 15.0 m^2/ha average), corresponding to values below and above the median measurement for all plots.

To test for correlations among fuel loads, fire behavior, and hardwood resprout top-kill, hardwood stem BA was measured within 2 mo before and 1 mo following fire at each plot. All hardwood tree or shrub stems ≤2 cm DBH within a radius of 1–3 m from the plot center (varied to include at least 10 genets per plot) were measured for stem diameter (nearest millimeter) at 3 cm above the ground and noted for life status (live, top-killed by the fire). Species included trees and large shrubs and excluded very small-statured woody species, such as vines, running oak (*Quercus pumila*), and Darrow's blueberry (*Vaccinium darrowii*). Percent area burned within each plot was also estimated. A 2-m rod marked at 5-cm increments was laid at two random azimuths from the center of the plot, and percent area burned was estimated as the percentage of 5-cm segments intercepting burned areas.

In 2004, fire behavior variables were measured at each plot to interpret their responses to variation in fuel loads among the forest community types (native, old field), roughs (1, 2), and tree BA category (high, low). Burn prescriptions required a relative humidity (RH) of 20–40%, temperature (T) of 4–32°C, wind speed (WS) of 2–12 km/h, and 2–10 d since last rain. To assist in estimating flame length, reference markers made of metal conduit pipes marked at 0.5-m intervals were erected in a hexagonal pattern centered on each plot such that opposite pipes were 4 m apart. A strip fire was lit approximately 10 m upwind of the plot, while backing fires were at least 50 m away. Rate of spread (ROS) was measured between the first reference marker reached by the fire and the opposite pipe. Flaming combustion residence time (RT) was measured at both reference markers and averaged. Residence time was measured in seconds as the duration of flaming combustion at the base of each reference marker. Flame length (FL) was visually estimated in 25-cm increments as the flaming front passed each reference marker and estimates were averaged for each plot. During each run, wind speed was measured with a handheld weather meter (Kestrel 3000; Kestrel Design Group, Minneapolis, MN).

Analyses

Fuel loads were analyzed to determine if they differed significantly between community types, roughs, and tree BA ranges to test for interaction effects. A multivariate analysis of variance (MANOVA) was run using community type (native or old field), rough (1 y or 2 y), and BA range (high or low) as factors, each of the measured fuel categories as response variables, and fuel load averaged between the two subplots within each plot as units of replication ($n = 113$). Also, full factorial analyses of variance (ANOVAs), Type IV sums of squares (StatSoft 2004), were used to infer the response of each fuel type to community, rough, and BA range and their interactions. ANOVAs were similarly run to test for responses in hardwood sprout BA per hectare, tree BA per hectare, and fuel bed depth to treatment levels. Correlations between tree BA, hardwood stem BA, and fuel loads in each fuel category were tested (StatSoft 2004) to interpret possible effects of forest structure and competitive interactions on fuel loads.

Using data from the 2004 plots ($n = 54$), the effects of community, year, and tree BA on ROS, FL, RT, and estimated fireline intensity (FI) and reaction intensity (RI) were tested in separate analyses using full factorial ANOVAs, Type VI sums of squares (StatSoft 2004). A similar analysis was used to test for variation among treatments in T, RH, and WS measured during burns to determine whether or not fires occurred under relatively uniform conditions among treatments.

The percentages of hardwood stems burned at the base and the subset of those top-killed were compared between community types, roughs, and tree BA ranges. Comparisons were qualitative because of the large number of plots that had 100% top-kill.

RESULTS

Trees >4 cm DBH in native pineland plots were composed of 75% longleaf pine, 14% shortleaf pine, 3% loblolly pine, and 8% hardwoods by BA. In contrast, old-field pinelands comprised 14% longleaf, 44% shortleaf, 32% loblolly, and 10% hardwoods.

Fuels differed significantly in composition and loading among community types, roughs, and tree BA ranges in the studied forests. The MANOVA testing for the effects of these factors and their interactions on fuel loads showed each factor and two of the three interactions to be highly significant (Table 1). Univariate ANOVAs revealed that each fuel type, except 10-h fuels, had a significant response to community type, rough, and/or tree BA range (Figure 2).

Native pineland sites were characterized by significantly higher 1-h fuel loads, including higher needle loads and dead grass loads, as well as higher live herb loads compared to old-field sites (Figure 2). However, native sites also had lower duff loads. The 2-y-rough plots had significantly higher duff loads, needle loads, forb–woody 1-h fuel loads, and total 1-h fuels than 1-y-rough plots (Figure 2). Plots in the high tree BA range had higher needle loads and higher total 1-h fuels overall (Figure 2). Needle loads were significantly higher in native sites than in old-field sites (Figure 2).

Table 1. Main effects and two-way interaction effects (multivariate analysis of variance) of community type (native versus old-field pineland), rough (1- versus 2-y), and tree basal area (BA) (below versus above 8.6 m^2/ha) on fuel loads in multiple fuel categories in 2003 and 2004 on Pebble Hill Plantation, Georgia.

Factor	df	Pillai's trace	*F*	*P*
Community	1	0.697	45.1	<0.001
Rough	1	0.525	22.8	<0.001
Tree BA	1	0.298	8.7	<0.001
Community × Rough	1	0.218	5.7	<0.001
Community × Tree BA	1	0.232	6.2	<0.001
Rough × Tree BA	1	0.042	0.9	0.48
Residuals	107			

Tree BA was not significantly different between the two community types or between 1- and 2-y roughs (Figure 3), reflecting the timber management of these forests. In contrast, hardwood resprout BA was significantly higher in old-field pinelands and in 2-y roughs. In old-field plots, hardwood resprout BA was lower in the high tree BA category. Fuel bed height responded significantly only to community type, with highest levels in the native sites (Figure 3).

Correlations among fuel load types were found to be qualitatively the same between 1- and 2-y roughs, so results were presented separately for native and old-field pinelands and combined otherwise (Table 2). In native pinelands, tree BA was correlated with total 1-h fuel and needle litter loads, and hardwood stem BA was correlated with total 1-h fuel and hardwood leaf litter loads (Table 2). In old-field pinelands, similar relationships were evident between tree BA and needle loads and hardwood resprout BA and leaf litter loads, respectively, but we did not detect responses in total 1-h fuel loads (Table 2).

Weather variables (T, RH, WS) measured during the 2004 burns did not vary on average between community types, roughs, and tree BA ranges, with regard to main effects (Table 3). In contrast, fire behavior measurements had significant responses to certain factors (Figure 4). Fire behavior was generally more active (higher FL, ROS, FI, RI, heat per unit area) in native than in old-field plots, and more active in 2-y than in 1-y roughs in native pinelands (Figure 4). Residence times in old-field plots were approximately twice those of native plots in a given rough and tree BA range (Figure 4).

A total of 5,971 hardwood resprouts were censused in the plots (Table 4). The number of stems was lower in the 2-y-rough plots, while the average basal diameter of stems increased with time since fire (Table 4). Percentage of stems burned at the base was higher in the native than in the old-field plots and higher in the 2-y than in the 1-y rough, while differences between tree BA categories were not consistent (Table 4).

DISCUSSION

Fuel Loads

Fuel loads and corresponding fire behavior vary according to soil disturbance history, time since pre-

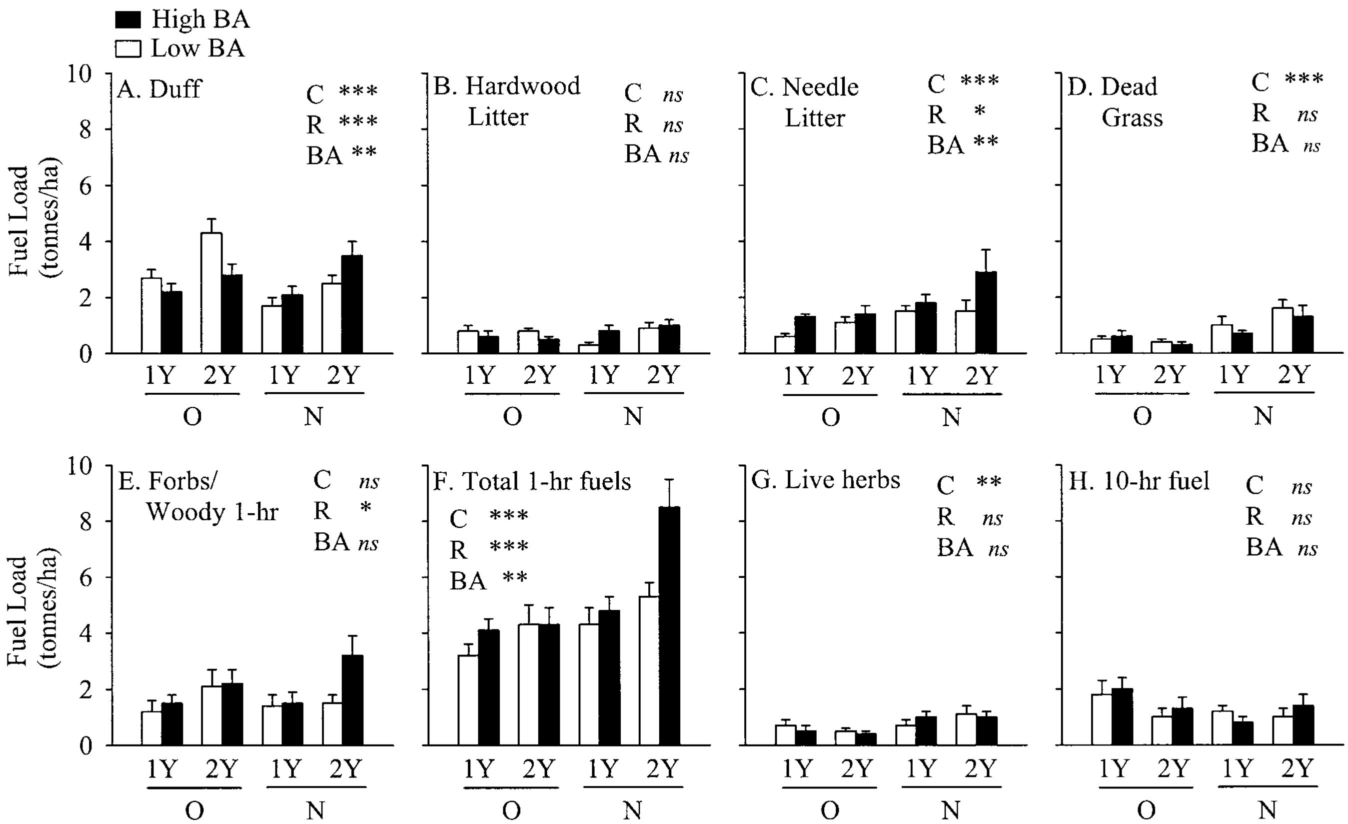

Fig. 2. Fuel loads for each fuel category in native versus old-field pineland communities on Pebble Hill Plantation, Georgia, 2003–2004, in each basal area (BA) range (low BA = 2–8.6 m^2/ha; high BA = 8.6–25 m^2/ha), rough (1 y post-burn [1Y] or 2 y post-burn [2Y]), and community type (N, native pineland, O, old-field pineland). Fuel categories include (A) duff, (B) hardwood litter, (C) needle litter, (D) dead grass, (E) forbs–woody 1-h fuels, (F) total 1-h fuels, (G) live herbs, and (H) 10-h fuels. Mean and standard error for plots are given (12–17 plots/bar, 113 plots total). Land cover main effects (C = community type, R = rough, BA) from ANOVAs are also given. *ns,* not significant. * P = 0.05–0.01, ** P = 0.01–0.001, *** $P < 0.001$.

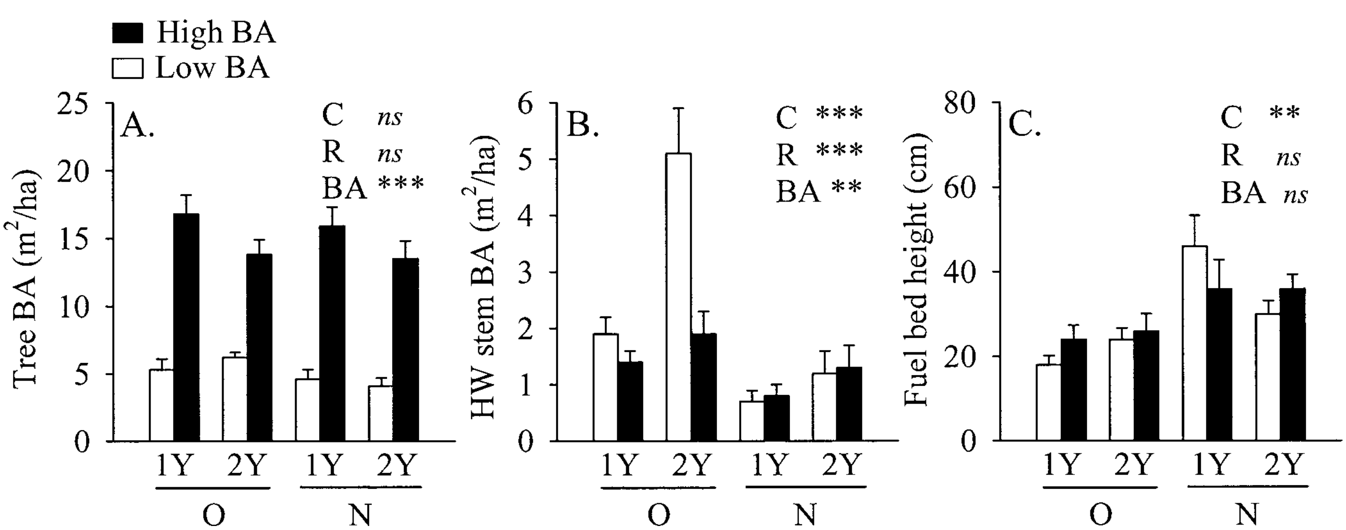

Fig. 3. Levels of (A) tree basal area (BA), (B) hardwood stem BA, and (C) fuel bed height in each BA range (low BA = 2–8.6 m^2/ha; high BA = 8.6–25 m^2/ha), rough (1 y post-burn [1Y] or 2 y post-burn [2Y]), and community type (N, native pineland; O, old-field pineland) in native versus old-field pineland communities on Pebble Hill Plantation, Georgia, 2003–2004. Mean and standard error of plots are given (see Table 3 for number of plots). Land cover main effects (C = community type, R = rough, BA) from ANOVAs are also given. *ns,* not significant. * P = 0.05–0.01, ** P = 0.01–0.001, *** $P < 0.001$.

Table 2. Correlations (α = 0.05) between pairs of variables measured at each plot in native versus old-field pineland communities on Pebble Hill Plantation, Georgia, 2003–2004.

Variable	Native plots (*n* = 60) Tree BA[a]	Native plots (*n* = 60) HW stem BA[b]	Old-field plots (*n* = 60) Tree BA	Old-field plots (*n* = 60) HW stem BA
HW stem BA	ns[c]		−0.38	
Duff	0.43	ns	−0.24	0.47
HW litter (1-hr)	ns	0.73	ns	0.32
Needle litter (1-hr)	0.32	ns	0.22	ns
Dead forb/woody (1-hr)	0.37	ns	ns	ns
Dead grass (1-hr)	ns	ns	ns	ns
Total 1-hr	0.44	0.33	ns	ns

[a] Basal area (BA) of trees >2 cm diameter at breast height (DBH) within 10-m radius of plot center.
[b] Basal area of hardwoods (HW) <2 cm DBH within the plot.
[c] ns, non-significant.

vious burn, and pine tree canopy cover in the studied pinelands. These variations may be attributed in part to species composition and competitive interactions between canopy, understory, and herbaceous plants, which vary among the land uses.

Native pinelands appear to have higher rates of herbaceous vegetation productivity, particularly with regard to grasses, contributing to higher total 1-h fuel loads in that community type. Correspondingly low understory hardwood density in native pinelands is consistent with the suggestion that dominance of bunchgrasses in longleaf pine–wiregrass forests limits hardwood dominance by burning intensely under a wide range of conditions (Noss 1989, Platt et al. 1991). In turn, competition between hardwoods and herbaceous plants is kept low, resulting in higher herb productivity (Brockway et al. 1998, Harrington and Edwards 1999). Greater abundance of grasses relative to forbs and leaf litter increases horizontal continuity of standing fine fuel and presumably results in lower fine fuel moisture. An increase in grass biomass in native pinelands between the first and second years following fire also suggests that grasses are not being suppressed by the hardwood understory, in contrast to old-field pinelands, where grass fuel loads decreased in the second year while hardwood dominance rapidly increased. Also, the most dominant forbs in the old fields, namely sand blackberry (*Rubus cuneifolius*), wrinkleleaf goldenrod (*Solidago rugosa*), and hyssopleaf thoroughwort (*Eupatorium hyssopifolium*) (Ostertag and Robertson, *this volume*), are large in stature and may compete with grasses in a manner similar to understory hardwoods. These stand in contrast to smaller-statured dominant forbs such as early blue violet (*Viola palmata*), pineland silkgrass (*Pityopsis aspera*), sensitive brier (*Mimosa quadrivalvis*), and oblongleaf snakeherb (*Dyschoriste oblongifolia*) in native pinelands (Kirkman et al. 2004; Ostertag and Robertson, *this volume*). The greater hardwood stem dominance in old fields likely relates to more successful establishment of hardwood tree and forb species relative to grasses following abandonment of plowed fields (Van Eerden 1988, Seamon et al. 1989, McGee 1996, Kirkman et al. 2004), creating an environment that is less flammable and more conducive to the survival of hardwoods.

Variation in pine needle litter in association with pine tree BA also contributed to differences in total 1-h fuel among land cover types. This positive association has been quantified in other studies (McNab and Edwards 1976, Harrington and Edwards 1999). Higher 1-h fuel loads in native versus old-field pinelands appear to result from differences in the dominant pine species, with longleaf pine producing significantly higher needle loads than loblolly and shortleaf pines at comparable levels of tree BA (Figure 2). Longleaf pine has longer needles than the other species and retains needles for only 2 y, compared to the 3-y needle retention time of loblolly and shortleaf pines (Mirov 1967, Landers 1991).

Within the relatively low range of tree BA studied (1.9–19.1 m^2/ha [8.3–83.2 ft^2/acre]), pine trees did not appear to have a negative competitive effect on grasses and forbs, judging from dead grass, forb, and live herbaceous fuel load responses to tree BA. Another study in longleaf pinelands with comparable ranges of tree BA and uneven-aged stands showed a limited response of herbaceous biomass to tree BA (Moser and Yu 1999). However, other studies of longleaf pine within this range of BA showed evidence for competitive effects of overstory trees on understory herbs (Wolters 1981, Mulligan and Kirkman 2002, Harrington et al. 2003), but those were conducted in young (<20 y), relatively densely stocked pine plantations where canopy cover may have been higher relative to BA.

The neutral effect of tree BA in old fields may relate to the negative relationship between tree BA and hardwood resprout BA found in this study, attributable to root competition or shading (Harrington and Ed-

Table 3. Means (± standard deviation) of weather variables during fire behavior measurements in native versus old-field pineland communities in 2004 on Pebble Hill Plantation, Georgia, 2003–2004.

Variable[a]	Old field 1-y rough Low BA[b]	Old field 1-y rough High BA	Old field 2-y rough Low BA	Old field 2-y rough High BA	Native 1-y rough Low BA	Native 1-y rough High BA	Native 2-y rough Low BA	Native 2-y rough High BA	All plots
No. of plots	8	6	9	5	5	6	10	5	54
T (°C)	74 (6)	75 (3)	69 (4)	75 (6)	80 (7)	76 (9)	71 (7)	74 (5)	74 (6)
RH (%)	34 (7)	30 (8)	32 (8)	30 (10)	26 (5)	34 (11)	35 (8)	29 (7)	31 (8)
WS (km/h)	2.5 (1.0)	4.8 (1.3)	3.6 (0.8)	3.2 (1.3)	3.4 (2.3)	3.6 (1.3)	3.2 (0.9)	2.9 (0.6)	3.4 (1.3)

[a] Abbreviations: RH, relative humidity; T, temperature; WS, wind speed.
[b] BA, basal area.

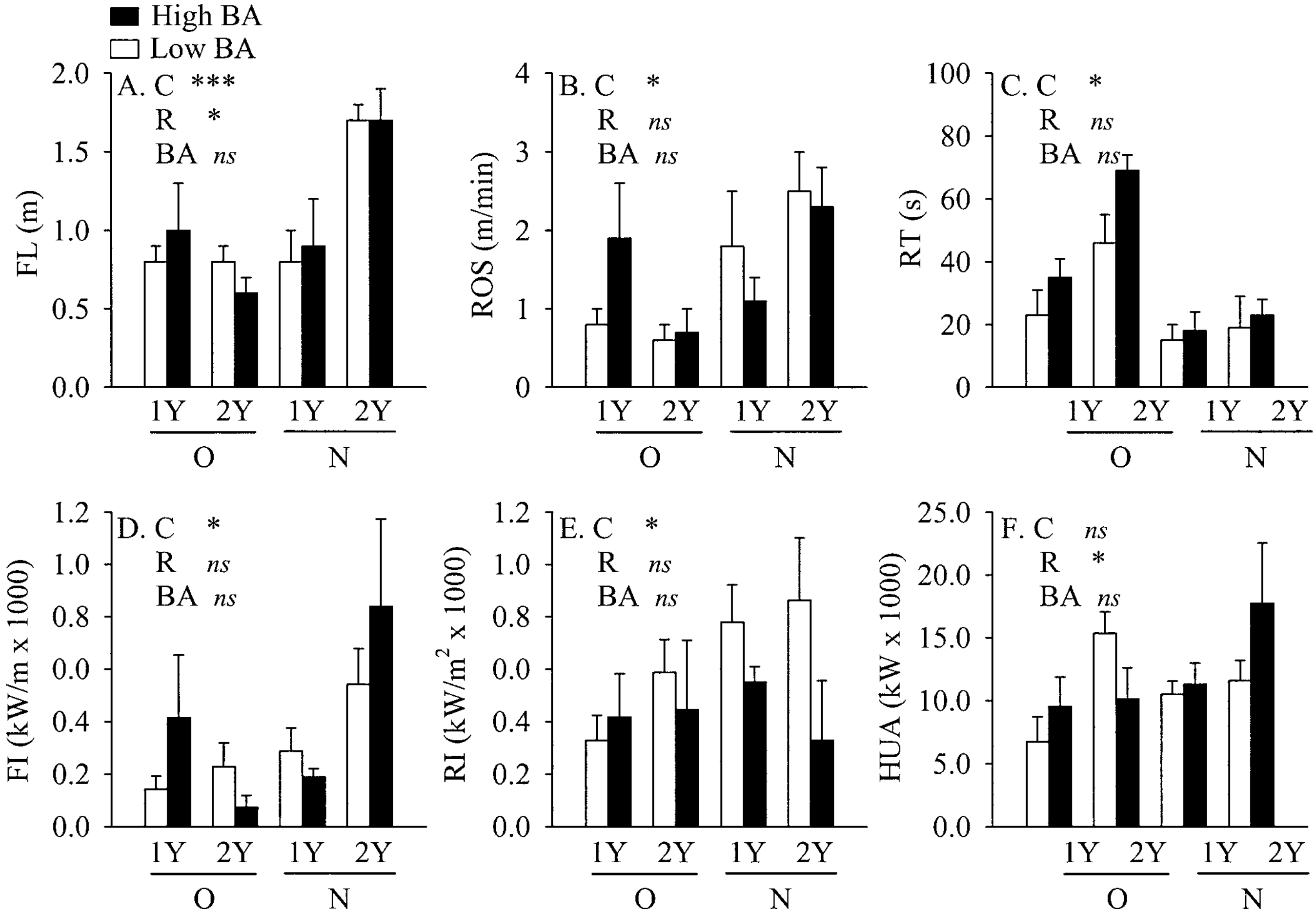

Fig. 4. Fire behavior measurements in native versus old-field pineland communities on Pebble Hill Plantation, Georgia, 2004, in each basal area (BA) range (low BA = 2–8.6 m^2/ha; high BA = 8.6–25 m^2/ha), year since previous fire (1 y post-burn [1Y] or 2 y post-burn [2Y]), and community type (N, native pineland; O, old-field pineland). Mean and standard error of plots are given (see Table 3 for number of plots). (A) Flame length (FL), (B) rate of spread (ROS), (C) reaction time (RT), (D) fireline intensity (FI), (E) reaction intensity (RI), (F) heat per unit area (HUA). Land cover main effects (C = community type, R = rough, BA) from ANOVAs are also given. *ns,* not significant. * P = 0.05–0.01, ** P = 0.01–0.001, *** $P < 0.001$.

wards 1999). The release of herbs from hardwood competition may compensate for competition between herbs and pines. This could explain the positive correlation between forb 1-h fuels and pine tree BA in native pinelands. Increases in tree BA beyond the range in this study are expected at some point to have a negative effect on herbaceous cover through shading, root competition, and litter fall (Brender et al. 1976, Masters et al. 1993, Harrington and Edwards 1999, Dagley et al. 2002, Harrington et al. 2003). Differences in crown structure suggest that longleaf pines allow a higher level of light penetration per basal area than do loblolly and shortleaf pines (Landers 1991), such that the suppression of herbs by pine canopy shading should occur at a higher level of BA in native pinelands. Correspondingly, 2005 timber cruise data on

Table 4. Mean hardwood stem (<2 cm diameter at breast height) responses to prescribed fire in native versus old-field pineland communities in June–July of 2003 and 2004 on Pebble Hill Plantation, Georgia.

	Old field				Native				
	1-y rough		2-y rough		1-y rough		2-y rough		
Hardwood stems	Low BA[a]	High BA	Low BA	High BA	Low BA	High BA	Low BA	High BA	All plots
No. plots	11	16	15	15	8	9	13	11	98
No. stems total	807	1,260	700	721	803	670	522	488	5,971
No. stems/plot	67	74	47	48	62	61	40	41	55
Stem base diameter (mm)	4.3	3.9	6.7	5.1	3.0	3.2	4.8	4.1	4.3
% burned	76.3	62.4	96.2	88.4	84.2	99.7	99.5	100.0	87.5
% top-killed	67.8	59.2	94.8	88.2	84.6	100.0	100.0	99.9	85.4
% top-killed of burned	92.6	99.3	96.5	99.2	100.0	100.0	100.0	99.9	98.0

[a] BA, basal area.

PHP showed that the regression slope of canopy cover (measured with a siting tube) over BA (measured with a prism) for longleaf pine was only 60% that of shortleaf and loblolly pines (TTRS, unpublished data).

The fuel load estimates in this study may be used as input for fire behavior models such as BEHAVE series (Andrews et al. 2003). The average native pineland fuel loads and bed depths found in this study correspond closely to fuel model 2 (Rothermel 1972), while some variation in fire behavior in response to time since previous fire and tree BA is expected to occur based on our results. Old-field pinelands are better represented by a hybrid of fuel models 2 and 8 (Rothermel 1972), given that 1-h, 10-h, and live herb loads and fuel bed height are intermediate between these two models. BehavePlus 2.0 has the option of combining the two fuel models, in which case a 50% coverage of fuel models 2 and 8 is recommended for old-field pinelands. The specific fuel loads provided by this study may also be used directly.

Fire Behavior and Hardwood Stem Top-kill

Overall, variation in fire behavior among the land cover types corresponded to patterns of 1-h fuel loading, with higher levels of ROS, FL, FI, and RI in the 2-y-rough plots of native pinelands. This pattern is attributable in part to the higher rate of accumulation of 1-h fuel loads in native pinelands, for which the difference between 1- and 2-y roughs was twice that of old-field pinelands. Differences in fuel structure between native and old-field pinelands also likely had an important effect. Native pineland fine fuels were less compact, having relatively higher proportions of standing dead fuels, higher fuel bed depths, abundant pine needles that drape in the grass, and lower duff loads, and thus were better aerated, prone to drying, and likely to promote higher fire intensities, rates of spread, and lower residence times (Noss 1989, Platt et al. 1991). Exploratory correlation analyses revealed that duff loads were significantly correlated with hardwood litter and forb fuels (data not shown), which may have higher decomposition rates and a more rapid transition from litter to duff fuels (Berg and Ekbohm 1991, Prescott et al. 2004), explaining in part the higher levels of duff in old-field pinelands. Also, lower fire intensity, patchier burns, and lower flammability of broadleaf litter fuels characteristic of the old fields may contribute to lower total combustion of 1-h fuels and greater duff accumulation.

The very close association between stems burned at the base and those top-killed suggests that completeness of area burned is an accurate predictor of stem kill within 2 y following the previous fire. The difference in percentage of total stems that were burned between the first and second years following fire in old fields (68% versus 92%) is attributable to lower fuel loads in the first year, resulting in patchier burns (Slocum et al. 2003). In native pinelands, the more modest change from 92% to nearly 100% stems burned in the first versus the second years is similarly attributable to fuel load accumulation and uniformity of the burn. However, in old fields, the higher survival rate of burned stems in the first year post-burn is attributable to lower fire intensity associated with lower fuel loads. Stems burned but not top-killed were limited to those with the largest diameters, presumably reflecting greater bark development and insulation of the vascular cambium (Hare 1965). Such survivors, which were overwhelmingly in old fields, effectively double their fire-free interval and have a higher chance of surviving subsequent burns. In turn, surviving stems increase shading, outcompete herbaceous vegetation, and shift the fuel structure to one that is more compact and less flammable.

The trend of increasing grass loads over time in native pinelands suggests that a 3- or 4-y fire-free interval may provide conditions for even more intense fires under a relatively wide range of weather conditions. However, at some length of fire-free interval the hardwoods would become less susceptible to even intense fires because of thickening of the bark (Hare 1965). In contrast, old-field pineland fine fuel loads are predicted to become increasingly dominated by duff, hardwood and pine tree litter, and dead forb fuels. Forb-dominated herbaceous layers are generally less flammable than those dominated by grasses (Brown 1981, Platt et al. 1991). Duff and litter fuels require drier, and thus more limiting, conditions for effective fire spread (Ferguson et al. 2002). Under very dry conditions, duff accumulated over 5 or more years can potentially endanger canopy trees because of high residence times (Chapman 1947, Varner et al. 2000, Hiers et al. 2003). These predictions are consistent with measurements of fuel loads and fire behavior in old-field pineland research plots burned at 1-, 2-, and 3-y intervals at TTRS since 1959 (R.E. Masters and K.M. Robertson, TTRS, unpublished data), and shed light on the ability of native pinelands to have persisted through the potentially widely varying fire intervals occurring on the presettlement landscape (Platt et al. 1991).

MANAGEMENT IMPLICATIONS

This study suggests that old-field (shortleaf–loblolly) pinelands require a narrower prescription window than native (longleaf–wiregrass) pinelands to achieve maximum hardwood stem kill, thus restricting management opportunities to fewer days per year. Under average early growing-season weather conditions, old-field pinelands appear to have the best fuel conditions for burning at a 2-y fire return interval, whereas native pinelands might be burned effectively at 1–3 y following the previous burn. Pine BA tends to correspond to fire intensity within the within the BA range studied (1.9–19.1 m^2/ha [8.3–83.2 ft^2/acre]) (Grace and Platt 1995). Conversely, the results suggest that thinning to lower levels may not have a marked positive effect on total 1-h fuels (Moser and Yu 1999), although this seems counterintuitive.

The effects of fuel loading on fire behavior can be altered by varying burn prescriptions. Prescriptions need to be balanced with other management goals, including burning at the time of year appropriate for certain wildlife species (e.g., Hermann et al. 1998, Bishop and Haas 2005) and allowing natural regeneration of pines (Lindeman et al. 1997). Managing old-field pinelands with fire for their many habitat values may require additional attention to fuel characteristics, time since burn, weather conditions, and competing management needs, in comparison to their native counterparts. Based on these results and our management experience, we recommend that old-field pineland prescriptions allow for 20–40% RH, 2 or more days since rain, and 7–10% fine fuel moisture, and that native pineland prescriptions allow 35–60% RH, 1 or more days since rain, and 10–15% fine fuel moisture.

The key variables ultimately distinguishing native from old-field pineland fuels in this study appear to be grass biomass, hardwood abundance, and pine species. Efforts to restore old-field pineland fuel structures to those found in native longleaf pine forests should focus on some combination of grass reestablishment, hardwood density control, and longleaf pine restoration (Harrington and Edwards 1999, Mulligan and Kirkman 2002). Many resources for such methods are available and have been reviewed elsewhere (Walker 1998, Kirkman and Mitchell 2002, Cox et al. 2004, Brockway et al. 2005). Restoration efforts to ameliorate fuel conditions may reduce long-term management expenses by resulting in more effective burns, reduced hardwood encroachment, and longer burn seasons. However, old-field pinelands are similar enough in fuel structure, fire behavior, and ecosystem function to provide habitat for a wide range of fire-dependent wildlife species that have become globally rare, demonstrating the feasibility of restoring valuable habitat using the relatively inexpensive tools of prescribed burning and timber thinning. In conclusion, this study provides insight into the tradeoffs between certain land-use decisions and the ability to meet management objectives using fire in southeastern U.S. pinelands.

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