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A comparison of fire intensity levels for stand replacement of table mountain pine (*Pinus* ***pungens*** Lamb.)

Thomas A. Waldrop[a,*], Patrick H. Brose[b]

[a] *USDA Forest Service, Southern Research Station, 239 Lehotsky Hall, Clemson, SC 29634.1003, USA*
[b] *Department of Forest Resources, Clemson University, 261 Lehotsky Hall, Clemson. SC 29634-1003, USA*

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Abstract

Stand-replacement prescribed fire has been recommended to regenerate stands of table mountain pine (*Pinus* ***pungens*** Lamb.) in the southern Appalachian mountains because the species has serotinous cones and is shade-intolerant. A 350 ha prescribed fire in northeast Georgia provided an opportunity to observe overstory mortality and regeneration of table mountain pine at various levels of fire intensity. Fire intensity for each of **60** study plots was classified by discriminant function analysis. Fires of low and medium-low intensity gave rise to abundant regeneration but may not have killed enough of the overstory to prevent shading. High-intensity fires killed almost all overstory trees but may have destroyed some of the seeds. Fires of medium-high intensity may have been the best choice; they killed overstory trees and allowed abundant regeneration. The forest floor remained thick after fires of all intensities, but roots of pine seedlings penetrated duff layers up to 7.5 cm thick to reach the mineral soil. In this study area, fire intensity levels did not have to reach extreme levels in order to successfully regenerate table mountain pine. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Lightning- and man-caused fires have played a significant role in the evolution of southern Appalachian plants and plant communities (Van Lear and Waldrop, 1989). Fire suppression policies in effect on public lands for 7-8 decades have probably reduced diversity in the southern Appalachians and may threaten the existence of some plants and communities. Federal fire management policies now call for the increased use of prescribed burning in the region to restore forests which were once dominated by fire-dependent species such as pitch pine (*Pinus rigida* Mill.) and table mountain pine (***P. pungens*** Lamb.) (Turrill, 1998). Stand replacement prescribed burning has been recommended for both species and was studied in pitch pine stands by Elliot et al. (in press), Vose et al. (in press), and Turrill (1998). Little research has been done in support of using prescribed burning to regenerate table mountain pine stands.

Table mountain pine occurs from central Pennsylvania to northeast Georgia and is endemic to the Appalachian mountains. It is found on thin, dry soils

*Corresponding author. Tel.: +1-864-656-5054; fax: +1-864-656-1407; e-mail: twldrp@clemson.edu

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with southern and western aspects at elevations of 300-I 200 m and is shade-intolerant (Zobel. 1969). Throughout the region. stands in which table mountain pine occurs are entering later seral stages where pines are beginning to be dominated by oaks (particularly chestnut oak, *Quercus prinus* L.) and hickories (*Carya* spp.) (Zobel. 1969; Turrill et al., 1997). This pattern indicates that the short-lived, shade-intolerant pines are being replaced by the longer-lived, tolerant hardwoods. Table mountain pine has serotinous cones and this suggests that fire may be needed to regenerate this species. Microsite conditions needed for seedling establishment are similar to those created by fire. Williams (1998) stated that table mountain pine stands are in decline as a result of fire suppression and inadequate understanding of the species' regeneration biology.

Research that addresses the use of fire to re-establish table mountain pine stands is limited and sometimes contradictory. Zobel's (1969) monograph on table mountain pine emphasizes the need for an intense fire. It was found that serotinous cones opened in lightly-burned areas but that seedlings survived only where fires killed overstory trees and erosion exposed mineral soil. Williams and Johnson (1992) found that seeds were abundant in lightly disturbed stands where no fire occurred. However, seedlings did not become established because suitable microhabitat was extremely limited. Seedlings were successful only on microsites that had thin litter layers (<4 cm) and were more open than the surrounding stand. The authors suggested that these microsites were similar to those that would be created by fire. Williams (1998) described successful regeneration of table mountain pine without fire in gaps created by ice storms.

Barden (1977) and Barden (1979) indicated that fire may not be necessary to maintain populations of table mountain pine. He found that historical fires helped to establish many stands on xeric sites, but that these stands have been regenerating without fire and have become uneven aged through gap-phase replacement. Even though Barden's studies provide valuable information about stand dynamics on xeric sites, they do not address the problem of restoring table mountain pine on the majority of sites where the species is found. Today most table mountain pine sites are progressing toward the later stages of succession and oaks and other hardwoods will shade any pine seedlings that may occur. Hardwood litter creates barriers to pine seedling establishment (Williams et al., 1990). Many stands with a significant component of table mountain pine also have a thick duff layer (the 0, and 0, horizons found below freshly fallen leaf litter and above the mineral soil). Because disturbance is often limited and because temperatures are cool, the duff can reach depths of 15–20 cm on southern Appalachian sites (Robichaud and Waldrop, 1994; Stone et al., 1995). Where this is the case, the duff layer may prevent the roots of pine seedlings from reaching the mineral soil.

Research on stand-replacement prescribed fire in table mountain pine stands is limited to a study by Turrill(1998). For that study, 10 fires were planned on federal lands throughout the southern Appalachian Region. Only four of the burns were successful and only one was in a table mountain pine stand, emphasizing the difficulty of using stand-replacement fire. The burning window is extremely limited, and safety of personnel and smoke management considerations are of primary concern. Prescriptions calling for intense crown fires effectively narrow the burning window and raise questions about worker safety and smoke management. If table mountain pine can be regenerated without crown fires, then some of these problems could be diminished or eliminated.

USDA Forest Service personnel attempted a stand-replacement prescribed fire on a 350 ha unit of the Tallulah Ranger District of the Chattahoochee National Forest, GA, on 4 April, 1997. This fire was large enough and fire intensity had enough variability to allow comparisons of regeneration success among areas burned at different intensities.

2. Methods

The study site is in the War Woman Wildlife Management Area of the Tallulah Ranger District in Rabun County, GA. Study plots were established in three separate stands located immediately south of Rabun Bald. All three stands were within the same 3.50 ha bum unit and had similar slope, aspect, and stocking of overstory hardwoods and table mountain pine. These areas were the only ones within the burn unit that had table mountain pine as a major component of the overstory. One stand occupies 18 ha and is located at an elevation of 1100 m. The remaining stands are both 12 ha in size; they are at elevations of 915 and 885 m. All study areas can be described as covering sharp ridgetops and steep slopes with northeastern or southwestern aspects.

Soils on the southwestern slopes belong to the Ashe Association, while those of the northeastern slopes belong to the Ashe-Porters Association (Carson and Green, 1981). The Ashe soil series (coarse-loamy, mixed, mesic, Typic Dystrochrepts) is predominant in both associations. Soils of these series are moderately deep, somewhat excessively drained soils that were formed in the residuum by the weathering of biotite gneiss interrupted by narrow dikes of schist. Solum thickness ranges from 41 to 74 cm. Depth to bedrock ranges from 66 to 117 cm. Coarse pebbles, cobbles, and stones account for .5-15% in the A and B horizons. The soil is very strongly acidic (pH 4.5-5.0) or strongly acid (pH 5.1 to 5.5) throughout.

Prior to burning, mean basal area in the study stands was 30.3 m^2 ha-‘. Hardwoods made up 21.3 m^2 of this total and pines the remaining 8.9 m^2. Chestnut oak (9.2 m^2) was the predominant hardwood and almost all of the-pines were table mountain pine. Few overstory trees were more than 41 cm dbh; only two were over 15 m tall. The shrub layer consisted almost entirely of mountain laurel (*Kalmia latifolia* L.), which ranged in density from very thick in some areas to completely absent from others.

All study stands were burned as one unit on 4 April, 1997. The fire covered the entire bum unit including the northeastern and southwestern slopes. Fire lines consisted primarily of existing roads and trails, but hand lines were required along portions of the western and northern sides of the bum unit. Backing fires were set by hand at upper elevations to secure fire lines, beginning at 09:00 hours. The interior portion of the bum unit was fired by helicopter using a plastic sphere dispenser beginning at 10:30 hours. Spheres were dropped at approximately midslope on the southwest and northeast side slopes. This firing pattern was intended to create a ring fire that would be most intense at the ridgetop, where table mountain pine predominated. Once the ring fire was secure, strips were set below the burned area (beginning at 13:00 hours), proceeding from upper to lower elevations, until the entire unit was burned. All burning was completed by 16:00 hours.

Relative humidity was 5 1% at the time the fire started, dropped to a low of 27% at 12:20 hours, and increased to 32% at 16:00 hours. Temperatures ranged from 15°C at 08:30 hours to 21°C at 13:45 hours. Eye-level wind speeds ranged from 3 to 13 km h^{-1} and were mainly from the south and southwest. Forest floor samples were collected at 10:30 hours; moisture content was found to be 8% for the duff and 6% for the litter layer. Rain totalling 1.93 cm fell 6 days prior to burning yielding a Keetch–Byram drought index value of 110 (Keetch and Byram, 1968).

Fire intensity was generally high, with crowning (flames reaching into tree crowns) in portions of the upper ridges and torching (flames taller than trees) occurring intermittently along the ridge. Other areas of the bum unit burned with high-intensity flames, but crowning was not observed. Although a high proportion of ground fuels was consumed throughout the bum, scorch heights were variable. The duff layer continued to smolder for approximately 36 h, after which rain totaling 4.4 cm began to fall.

Three months after burning, the entire bum unit was surveyed so that study areas exhibiting a range of fire intensity effects could be selected. Evidence of fire intensity included bark char height, mortality of overstory trees, portion of the crowns of living trees scorched, presence of scorched needles on the forest floor, soil exposure, insolation on the forest floor, presence of charred cones in the crowns of trees and on the forest floor, and size of branches on trees and shrubs that were left unconsumed by the fire. Sixty sample plots 10 x 20 m^2 in size (0.02 ha), were placed throughout the three table mountain pine stands and throughout areas burned at a range of intensity levels. Each sample plot was subjectively described by one of the four intensity levels (low, medium low, medium-high, or high) based on fire effects observed in the plot.

Within each 0.02 ha sample plot, the height, dbh, and species of each tree over 3 m tall were recorded. All standing trees were assumed to have been alive before burning unless they were in a late stage of decay. The height of bark char was recorded for all trees and each tree was characterized as alive, top-killed but sprouting, dying, or dead. Bark char height was measured as the lowest point on the bole of the tree above ground that was not blackened by the fire. The number of cones in the crown of each table mountain pine was estimated to the nearest five.

Cover of living and dead shrubs and hardwoods <3 m tall was measured in two 10x5 m^2 subplots which were located at each end of every 0.02 ha sample plot. Two measurements of crown spread were made for each shrub, one at the widest point of the crown and the other at a right angle to the first. These measurements were used to estimate the average radius to calculate the crown area.

Regeneration and microsite conditions in the burned areas were measured in each of the 28 subplots, 2x2 m^2 in size, spaced systematically throughout the 0.02 ha sample plots. Seven subplots were established along each of the four transects so that subplot centers would be at a 3 x 3 m^2 spacing. At each plot center, two 2 m long PVC pipes were placed at right angles to each other and crossing at their centers. With this placement, the pipes outlined four 1 x 1 m^2 quadrants. The number of pine seedlings, fire severity, and amount of insolation on the forest floor were recorded for all the four quadrants. Fire severity was described as one of the following categories:

1. unburned;
2. burned with partially consumed litter present;
3. no litter present and 100% of the area covered by duff;
4. soil exposure on 1–30% of the area;
5. soil exposure on 3 1–60% of the area, or;
6. soil exposure on 61-100% of the area.

Insolation was estimated between 10:00 hours and 14:00 hours on sunny days and was described as one of the following categories:

1. Full shade,
2. 1–30% of the area receiving direct sunlight,
3. 31-60% of the area receiving direct sunlight, or
4. 61-100% of the area receiving direct sunlight.

Seedlings and sprouts of hardwoods were counted and recorded by species in one randomly selected quadrant at each of the 28 subplots. For sprouts, number of sprouting rootstocks and the number of sprouts per rootstock were recorded. The number of pine cones present in this one quadrant was also recorded.

The total number of pine seedlings was counted, but seedlings were too young to identify their species. Seedling density was calculated from the total number of seedlings found in these subplots. The prescribed bum cannot be considered a success in regenerating a table mountain pine stand, however, if seedlings are clumped and not well distributed throughout the area. Therefore, stand stocking was used as a measure of seedling dispersal. The burned areas were considered to have 100% stocking if at least one seedling occurred in each of the 28 subplots. This stocking approximates a seedling spacing of 3 x 3 m^2 or 1100 seedlings ha^{-1}. Although this spacing is wider than that recommended for pine plantations, it has been shown to produce stands dominated by pine in the southern Appalachian mountains (Waldrop, 1997; Waldrop et al., 1989).

Pine seedlings were excavated along transects located approximately 7 m away from each of the 60, 0.02 ha-sample plots. These transects were 20 m long and parallel to the long axis of each sample plot. Ten pine seedlings and their root systems were excavated and measured at 2 m increments along each transect. Measurements included seedling height, duff depth, root length within the duff, and root length within the mineral soil. All measurements were completed at the end of the first growing season after burning (late August through early September 1997).

To minimize the judgement errors that might have occurred through our subjective assignment of plots to fire intensity categories, we employed discriminant function analyses to verify plot assignments. Eight variables representing measurable fire effects or conditions known to affect fire intensity were included in a stepwise discriminant function analysis. Input variables included plot means for severity category, insolation category, bark char height, bark char height as a percentage of total tree height, and percent cover of mountain laurel. Input variables for individual trees included: maximum dbh killed per plot, maximum height killed per plot, and maximum height of bark char on any one tree in the plot. Variables were considered to contribute significantly to the classification of fire intensity at α=0.15. Those variables selected by the stepwise procedure were then used to form discriminant functions. These functions were used as the basis for changing the subjective plot assignments. All analyses were conducted using the groupings defined by the discriminant functions.

Treatment means for fire intensity levels were compared by one-way analyses of variance (ANOVA) with mean separation by linear contrast (α=0.05). In analyses of pine seedling density and stocking, the total number of cones on the ground and in the crowns of trees in each plot was used as a covariate to adjust for differences in seed availability. Results of ANOVA tests are provided as descriptive statistics (Hurlbert, 1984) for this single prescribed fire. These results may not be applicable to other areas because no attempt could be made to experimentally manipulate and replicate large-scale fires at several levels of intensity. Regeneration responses are likely to be confounded with plot location, preburn fuel loading, or other variables.

3. Results

3.1. Classification of fire intensity by discriminant function analysis

Stepwise discriminant function analysis selected four variables that would significantly distinguish fire intensities among plots. Significant variables included (in the order that they were selected for inclusion into the model) mean bark char height, height of the tallest tree killed, bark char height as a percentage of total tree height, and percentage cover by mountain laurel. Use of the resulting discriminant functions caused us to re-classify 14 study plots. No plot was shifted by more than one category. After re-assignment, the number of sample plots in each fire intensity category was:

Intensity	*n*
Low	9
Medium-low	28
Medium-high	9
High	14

The mean value of each discriminating variable is given for each fire intensity category in Table 1. Mean bark char height ranged from 1.8 m for low-intensity fires to 12.2 m for high-intensity fires. As should be expected, bark char heights increased with increasing fire intensity. A similar pattern was seen with the mean percentage of tree height with char. Mean values of this variable ranged from 14 to 87%, with clear differences in values from category to category of fire intensity.

Values for the tallest tree killed per plot did not follow the predicted pattern. In low-intensity plots, the tallest tree killed averaged 10.1 m tall. All other fires killed trees up to about 15 m tall, which was approximately the height of the tallest trees throughout the bum unit. For classification of study plots, this variable likely identified low-intensity fires but was unable to distinguish among plots at all other fire intensities.

Inclusion of mountain laurel cover in the stepwise function provided a measure of prebum conditions rather than one of fire effects. Inclusion of this variable is logical because these shrubs serve as vertical fuels and greatly increase fire intensity. Values ranged from less than 30% for fires of low and medium-low intensity to 41 and 86%, respectively, for medium-high and high intensity fires.

3.2. Fire effects

3.2.1. Low-intensity fires

It was not possible to observe fire behavior in each plot or even for each fire intensity category. However, the values for discriminating variables should give an indication of the relative fire intensity at each level. Low-intensity fires occurred in areas with 26% cover by mountain laurel, killed trees up to 10 m tall, and

Table 1
Mean values of discriminating variables by fire-intensity category

Intensity	Mean bark char height(m)	Height of largest dead tree (m)	Bark char as a pct of tree ht	Percent cover of mountain laurel
Low	1.8	10.1	14.3	26.2
Medium-low	2.0	14.9	18.8	29.6
Medium- high	6.6	16.4	44.3	41.1
High	12.2	14.9	87.0	85.9

Fourteen of 60 plots were re-classified using the discriminant functions

Table 2
Basal area of overstory pines and hardwoods before and after burning by fire intensity category

Intensify	Pine basal area (m^2 ha^{-1})		Hardwood basal area (m^2 ha^{-1})	
	Before burning	After burning	Before burning	After burning
Low	6.2 a[a]	5.9 b	22.1 a	16.8 b
Medium-low	10.9 a	6.0 b	23.6 a	5.1 a
Medium-high	1.9 a	1.1 a	15.5 a	0.5 a
High	6.6 a	0.0 a	20.4 a	1.0 a

[a]Means followed by the same letter within a column are not significantly different at the 0.05 level.

charred the boles of trees up to a height of 1.8 m (Table 1). Mean dbh for the largest trees killed in the low-intensity fire plots was 18.2 cm.

Prior to burning, plots subsequently burned at low-intensity had 6.2 m^2 of pine basal area and 22.1 m^2 of hardwood basal area (Table 2). Low-intensity fires had little effect on pine basal area but decreased hardwood basal area to 16.8 m^2. Even though these fires killed 5 1% of all stems over 2.5 cm dbh, most of the mortality was among trees less than 15 cm dbh (Fig. 1). Low-intensity fires did not open the canopy sufficiently to allow sunlight to reach the forest floor. The mean insolation value after burning was 3.2, which indicated that the forest floor was receiving direct sunlight on no more than 60% of its area (Table 3). The mean fire severity category was 2.3, which indicated that the litter layer was removed but that the duff layer remained intact and little soil was exposed (Table 3). The shrub layer was effectively

Table 3
Mean fire severity and insolation categories by fire-intensity category

Intensity	Mean severity Category	Mean insolation Category
Low	2.3 a[a]	3.2 a
Medium-low	2.2 a	3.4 a
Medium-high	2.0 a	3.7 b
High	2.0 a	3.8 b

[a]Means followed by the same letter within a column are not significantly different at the 0.05 level.

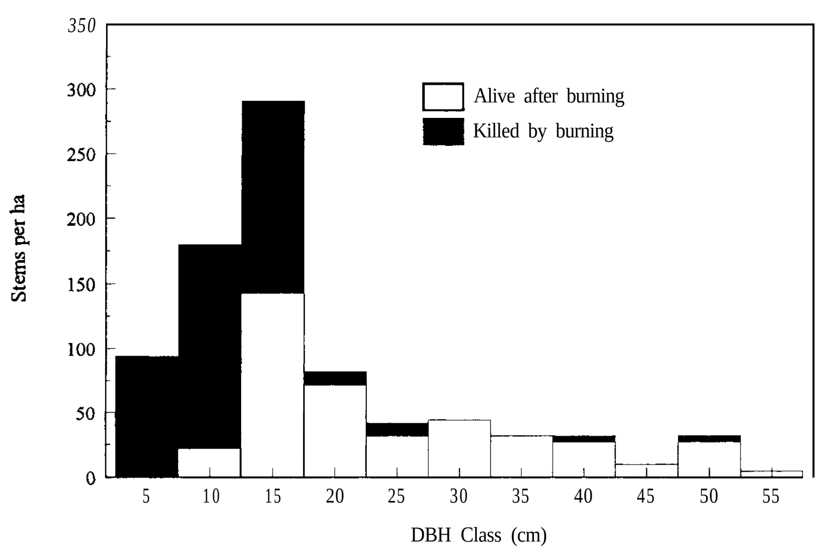

Fig. 1. Tree mortality by dbh class after fires of low-intensity.

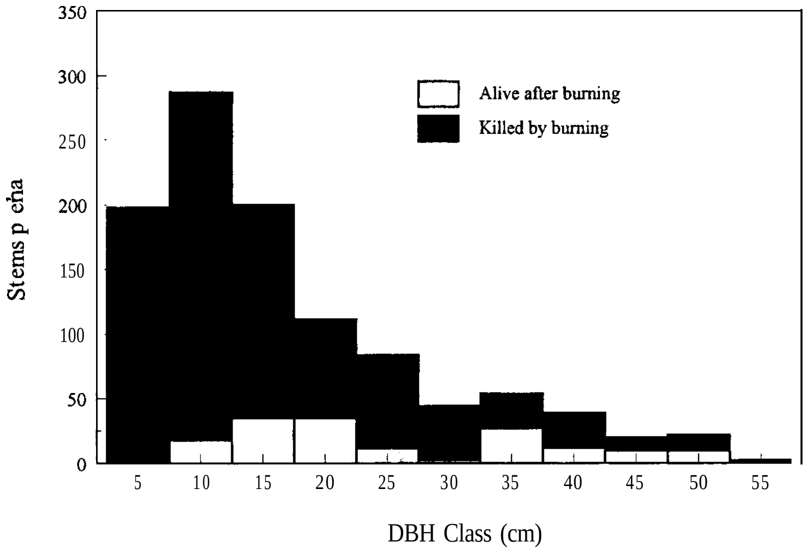

Fig. 2. Tree mortality by dbh class after fires of medium-low intensity.

removed by low-intensity burning and this may increase seed germination and seedling survival.

3.2.2. *Medium-low intensity fires*

Mountain laurel cover (29.6%), mean char height (2.0 m), and percent char (18.8) were slightly higher for medium-low-intensity burning than for low-intensity burning (Table 1). However, these fires were more effective than low-intensity fires in killing overstory trees. In medium-low intensity plots, means for the tallest tree killed and largest dbh killed were 14.9 m (Table 1) and 39.1 cm, respectively. These values generally describe the largest trees in the burn unit. Eightyfive% of all trees over 2.5 cm dbh were killed by medium-low intensity fires (Fig. 2). Mortality was greatest in the lower dbh classes, but some trees in all size classes were killed. The combination of a relatively low mean bark char height with mortality of large trees may indicate that hot spots occurred in many study plots.

Medium-low intensity fires reduced the basal area of both pines and hardwoods (Table 2). Pine basal area was reduced by 45% (from 10.9 to 6.0 m^2) while hardwood basal area was reduced by almost 80% (from 23.6 to 5.1 m’). Although fires of this intensity were much more effective than low-intensity fires in reducing overstory cover, they may not have killed enough of the overstory to allow adequate insolation for pine seedlings. Total stand basal area was 11.1 $m^2 ha^{-1}$ after medium-low intensity fires (Table 2) and the mean insolation category was not significantly different than that for low-intensity fires (Table 3). Mean fire severity category was 2.2, indicating that the duff remained intact and little soil was exposed. Prebum shrub cover was light and essentially all shrubs were killed by the fire.

3.2.3. *Medium-high intensity fires*

Tall flames that reached into the crowns of overstory trees were more widespread in plots burned at the medium-high intensity category than in plots burned at lower intensities. These flames may have been supported by mountain laurel, which covered a much higher proportion of each study plot (41%, Table 1). In addition, the mean bark char height (6.6 m) and the percentage of the total height of the tree with char (44.3%) were much higher than in plots burned at lower intensities. Height of the tallest tree killed (16.4 m) and dbh of the largest tree killed (39.1 cm) were similar to those for medium-low intensity plots and approximately equal to those of the largest trees in all plots.

Mortality of overstory trees was very high (96%) and was common in all dbh classes (Fig. 3). Medium-

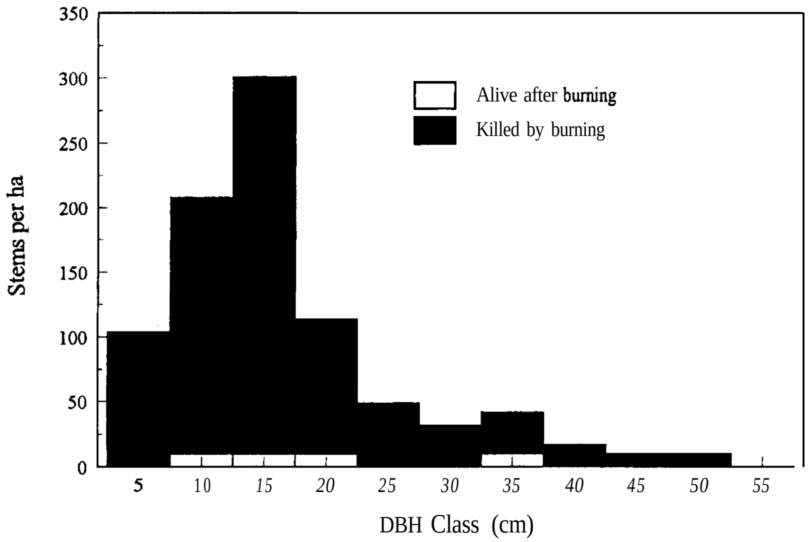

Fig. 3. Tree mortality by dbh class after fires of medium-high intensity.

high intensity fires reduced stand basal area from 7.9 to 1.1 m^2 for pines and from 15.5 to 0.5 m^2 for hardwoods. Insolation levels now reaching the forest floor (mean value 3.7) may be adequate for seedling survival. This insolation level is significantly higher than those for plots in the low and medium-low intensity categories (Table 3) and indicates that 60–100% of the forest floor area was receiving direct sunlight. As with all other intensity levels, the shrub layer was removed by burning. The boles of dead overstory trees cast most of the shade observed in plots burned at the medium-high-intensity.

An unexpected result was that fire severity was somewhat lesser in plots burned at medium-high intensity than in plots burned at lower intensities (Table 3). Mean severity for the medium-high intensity plots was 2.0, indicating that the litter layer was consumed but that the duff remained intact and mineral soil was not exposed.

3.2.4. *High-intensity fires*

Dense mountain laurel cover (86%) contributed to fire intensity in these plots. Flames were estimated to reach heights of 30 m (approximately twice the height of the tallest trees) at their maximum and were observed to carry between tree crowns. Mean bark char height was 12.2 m and most trees had evidence of char over their entire height (Table 1). Few trees survived this level of fire intensity (99% mortality) (Fig. 4), and stand basal area was reduced to only 1.0 $m^2 ha^{-1}$ (Table 2). Insolation reaching the forest floor was high but not significantly different from that for plots in the medium-high intensity category (Table 3). These plots had very high shrub cover prior to burning, but this layer was essentially removed. Most shade in these plots was cast by the boles of dead trees. As in medium-low intensity plots, fire severity was unexpectedly low (Table 3).

3.3. *Post-bum regeneration*

Post-bum counts of pine seedlings suggest that fires were of sufficient intensity to open serotinous cones throughout the bum unit including areas burned at low-intensity. Post-bum pine density ranged from 3448 stems ha-' to more than 22 000 stems ha^{-1} (Table 4). An unexpected result was that the lowest pine densities were in plots burned at the highest intensity levels. This pattern suggests that cones were consumed by fire or seeds killed by intense heat where flames reached into the crowns of trees.

Even though plots burned at high-intensity had fewer seedlings than other plots, the 3448 seedlings ha^{-1} that were present should create pine-dominated stands where seedlings are well dispersed. However, pine seedlings were found at only 5 1% of

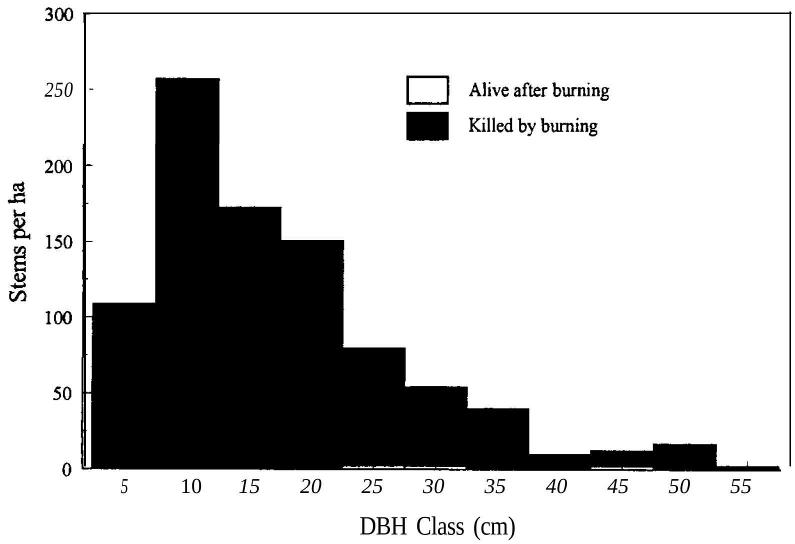

Fig. 4. Tree mortality by dbh class after fires of high-intensity.

Table 4
Density and stocking of pine regeneration one growing season after burning by fine intensity level

Intensity	Density (num ha-‘)	Stocking (percent)
Low	13 852 ab”	71.3 b
Medium-low	22551 a	93.8 a
Medium-high	9015 b	63.1 bc
High	3448 b	51.1 c

“Means followed by the same letter within a column are not significantly different at the 0.05 level.

the sampling points (Table 4). This indicates that portions of the burned areas had no pine regeneration and may be dominated by hardwoods. Plots burned at the medium-high intensity level also had low pine stocking (64%). Pine density and stocking levels for plots burned at low and medium-low intensities should be adequate to develop into pine-dominated stands if the seedlings receive adequate sunlight.

Competition from hardwoods and shrubs that sprouted after the fire may inhibit the development of a pine-dominated stand. The most common hardwoods were blackgum ***(Nyssa sylvatica*** Marsh.), oaks (especially chestnut oak), and sassafras ***(Sassafras albidum*** (Nutt.) Nees) (Table 5). There were no significant differences in the number of sprouts ha^{-1} by fire-intensity category for any species or for the total. This suggests that most hardwood rootstocks survived even high-intensity fires and resprouted. The total number of sprouts ha^{-1} was high at all intensity levels, ranging from 26 590 to 37 371. Stand development will be monitored for several years to determine the effect of hardwood competition on pine survival.

Table 5
Regeneration (sprouts ha^{-1}) of predominant hardwood species and species groups by fire intensity category

Intensity	Blackgum	Oaks[a]	Sassafras	Others Hardwoods	Total
Low	15 988	4678	474	2658	32 150
Medium-low	16 379	8588	9412	2932	37371
Medium-high	15 201	6118	1875	3396	26 590
High	11404	7815	4861	7457	31537

“Includes chestnut oak and scarlet oak.

Table 6
Height and rooting characteristics of pine seedlings by fire intensity category

Intensity	Postburn Forest floor depth (cm)	Seedling height (cm)	Total root length (cm)	Length of root in soil (cm)	Percentage of seedlings with roots in the soil
Low	5.3 ab[a]	6.9 a	9.4 a	4.6 a	71.1 a
Medium-low	3.8 a	8.6 b	10.4 a	6.4 b	94.6 b
Medium-high	7.6 b	7.1 a	10.2 a	3.6 a	63.0
High	6.6 b	7.4 a	9.7 a	4.3 a	56.1 a

[a]Means followed by the same letter within a column are not significantly different at the 0.05 level.

Pine survival may be limited if the roots of pine seedlings cannot penetrate the duff left after burning. Destructive sampling of pine seedlings showed little evidence of fire-intensity effects on root development (Table 6). Duff depth varied significantly among plots burned at various intensity levels but there was no clear relationship between duff depth and fire intensity. The thinnest duff layer did occur in plots in the low- and medium-low intensity categories. Thin duff layers might be associated with greater residence time for these lower-intensity fires, but prebum measurements of duff depth were not taken, so this is speculative.

The relationship of total root length, duff depth, and seedling height shows the importance of burning away much of the duff. In this study, total root length was unaffected by fire intensity or duff depth (Table 6). The roots of all seedlings sampled were approximately 10 cm long. Therefore, seedlings had a larger portion of their root penetrating into the mineral soil in areas where the duff was thin. In plots with the thinnest duff (medium-low-intensity), the proportion of seedlings with roots reaching the mineral soil, the length of root in mineral soil, and seedling height were significantly higher than in any other plots. Even though pine seedling growth was better with thinner duff layer, complete removal of the forest floor is not recommended. Stone et al. (1995) showed that severe bums on Appalachian sites create excessive erosion and reduce site productivity.

Root measurements from all areas were combined to show the relationship of duff depth to several pine seedling characteristics (Table 7). The number of seedlings sampled generally decrease with increasing duff depth. This pattern probably reflects a combination of increased mortality with increased duff depth and reduced sampling probability for the smaller area covered by the thicker duff layers. As we expected, the percentage of seedlings that had roots reaching the mineral soil decreased with increasing duff depth. A significant finding, however, is that the roots of over 80% of sampled seedlings were able to penetrate a duff as thick as 7.5 cm and almost all sampled seedlings had roots that penetrated a duff that was 5 cm thick. This finding makes it clear that the total consumption of the forest floor is not required for germination and survival of table mountain pine.

Seedling height was smaller as duff depth increased (Table 7). However, all of the seedlings present had survived the first growing season, and those on thicker duff layers may extend a larger portion of their roots to mineral soil in the next growing season.

Table 7
Seedling height and percentage of seedlings with roots penetrating the forest floor into mineral soil by forest floor depth

Duff depth (cm)	Seedlings sampled	Number with roots in the soil	Percent of total	Mean seedling height (cm)
2.5	170	162	95.3	8.9
5.0	223	209	93.7	8.1
7.5	103	83	80.6	7.4
10.0	70	28	40.0	6.6
12.5	47	9	19.1	6.4
15.0+	37	2	5.4	5.8

4. Conclusions

Even though it was impossible to measure fire intensity directly in this study, post-bum measurements of fire effects with intensity categories defined by discriminant function analysis may have been an acceptable substitute. Classification of fire intensity by discriminant functions appeared to provide a less biased approach in classifying fire intensity than ocular judgement. The method employed multiple variables and provides an overall indication of fire behavior for this reason. Based on the discriminating variables, fire behavior may be described as follows: low-intensity fires had flames that rarely reached into the crowns of trees and were relatively uniform across study plots. They top-killed all shrubs, but trees over 15 cm dbh survived. Medium-low intensity fires had flames that were slightly taller than those of low-intensity fires, but these fires had occasional hot spots that killed large trees. Medium-high intensity fires had much higher flames that typically reached into the crowns of overstory trees. Few trees survived these fires and insolation to forest floor was increased. High-intensity fires had flames that were as tall or taller than the tallest overstory trees and carried from crown to crown. Essentially no trees survived these fires and the forest floor received abundant sunlight.

Definitive recommendations about fire intensity needed to successfully regenerate table mountain pine stands cannot be made on the basis of a single prescribed bum or for stand development observed through one growing season. Because all study plots fell within one bum unit, it is impossible to determine if the differences reported here were due to fire intensity or other confounded variables. Also, pine numbers may increase with additional germination in the second growing season or decrease if that growing season is dry. However, the descriptive statistics shown here indicate that fire intensity levels did not have to reach extreme levels to successfully regenerate table mountain pine in this study area. Insolation levels to the forest floor increased by medium-high and high-intensity fires because of high mortality of trees and shrubs. Low- and medium-low intensity fires probably did not kill enough of the overstory trees to ensure seedling survival. In medium-high intensity plots, flames reached into the canopies of overstory trees but probably did not carry from crown to crown. In plots burned at this intensity level, overstory mortality was near 100%, insolation to the forest floor was abundant, and seedling density was adequate. Prescribed fires conducted at the medium-high intensity level are less dangerous and can be achieved during a larger burning window than high-intensity fires. Additional research is needed to determine if these cooler fires should be prescribed for all table mountain pine regeneration.

Previous research indicated that successful regeneration of table mountain pine required a thin forest floor (Williams and Johnson, 1992) and abundant insolation (Zobel, 1969). In this study, post-bum duff depth was not clearly associated with fire intensity and remained thicker in most areas than the 4 cm maximum recommended by Williams and Johnson (1992). However, large numbers of seedlings survived the first growing season on a duff layer that was nearly twice as thick as this maximum. This suggests that duff depth may not be as critical as once thought. Continued survival of these seedlings will show that prescribed fires can be conducted when the lower layers of the forest floor are moist, thus protecting steep slopes from erosion and loss of site productivity.

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