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Prescribed burning for hardwood control and fuel reduction in a 26-year-old loblolly pine plantation on gently sloping terrain on the Cumberland Plateau

Michael York

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To the Graduate Council:

I am submitting herewith a thesis written by Michael York entitled "Prescribed burning for hardwood control and fuel reduction in a 26-year-old loblolly pine plantation on gently sloping terrain on the Cumberland Plateau." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Forestry.

Edward R. Buckner, Major Professor

We have read this thesis and recommend its acceptance:

Ronald L. Hay, John C. Rennie

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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To the Graduate Council:

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PRESCRIBED BURNING FOR HARDWOOD CONTROL AND FUEL REDUCTION IN A 26-YEAR-OLD LOBLOLLY PINE PLANTATION ON GENTLY SLOPING TERRAIN ON THE CUMBERLAND PLATEAU

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Michael York
March 1988

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ABSTRACT

Four burns were conducted on each of three days: one day in the fall, spring, and summer. On each burn date, two burns were ignited on the north slope and two on the south slope of an east-west oriented ridge.

On the fall and spring burn dates, general windspeed was greater than 14 km/h which determined surface wind direction in the pine plantation. On the windward side of the ridge, upslope burns were headfires and downslope burns were backfires, whereas on the lee side upslope burns were backfires and downslope burns were headfires. On the summer burn date, general windspeed was lower than 11 km/h, and wind direction in the pine plantation was determined by topography. Wind direction was upslope on both slopes, making upslope burns headfires and downslope burns backfires.

Spring burns more effectively topkilled hardwoods (76 percent) than summer (54 percent) or fall burns (44 percent). Fuel loading was higher in the spring. There was little difference among the seasonal burns in percent of hardwoods totally killed (not sprouting): 21 percent in the summer, 19 percent in the fall, and 17 percent in the spring.

Spring burns consumed twice as much fuel (66 percent) as fall (34 percent) or summer burns (33 percent). Percent fuel reduction for the 12 burns was significantly correlated (P = .05) with fuel loading and fuel moisture.

On each of the three burn dates south slope burns were more effective than north slope burns in topkilling hardwoods and reducing fuels. Surface fuel on the south slope was mostly pine litter whereas a significant portion on the north slope was hardwood litter.

The burns were generally safe for pine crop trees. Basal area of the surviving pine crop trees was higher one year after burning than pre-burn basal area except following the headfire upslope in the spring. This fire burned in a heavy loading (38,700 kg/ha) of dry (26 percent moisture) pine litter.

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CHAPTER I

INTRODUCTION

Native forests of the Cumberland Plateau in East Tennessee were upland hardwoods with occasional yellow pines in mixture. Today these stands have low commercial value due to repeated high-grading, wildfire, and grazing.

In the 1950's pine-based forest industry moved onto the Plateau. Since large tracts of forest land were available at low cost, industry managers gambled that pines could be grown profitably on the shallow, dry soils of the Plateau. Many upland hardwood stands were converted to pine plantations.

In 1972 a U.S. Forest Service Forest Survey suggested that pines would be more productive than upland hardwoods on approximately 50 percent of the commercial forest land in Tennessee (Murphy 1972). Since then conversion of low-quality hardwood forests to pine plantations represents some of the most intensive forestry being practiced in Tennessee. Although not native to the Plateau, loblolly pine[1] has been the most widely planted species because it grows faster than the upland hardwoods and yellow pines native to this area.

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[1] Scientific names for species used in text are listed in Appendix A.

Statement of the Problem

Although chemical and mechanical methods have been used to control hardwoods, most pine plantations suffer from aggressive hardwood competition. Heavy fuel accumulation in older, well-stocked pine plantations and the Plateau's exposure to high winds make severe wildfires a continual threat. Safe and effective hardwood control and fuel reduction will enhance pine plantation management on the Cumberland Plateau. Although results from the Coastal Plain suggest that prescribed fire could be a useful silvicultural tool on the Plateau, prescribed fire on sloping terrain like that common in this region has not been adequately researched.

Study Objective

The objective of this study was to evaluate the effectiveness of prescribed burning for hardwood control and fuel reduction in loblolly pine plantations on gently sloping terrain on the Cumberland Plateau.

CHAPTER II

LITERATURE REVIEW

Prescribed fire has been widely used in pine stands on the Coastal Plain for more than 50 years. This experience is summarized in six USDA Forest Service reports that cover the effects of fire on flora, fauna, air, soil, water, and fuels (USDA Forest Service 1978; 1979a; 1979b; 1979c; 1979d; 1981). Crow (1982) compiled a bibliography with more than 1100 references which evaluated the potential benefits and harmful effects of prescribed fire in Southern pine forests. Most of this literature was concerned with the use of prescribed fire on flat terrain.

Effect of Fire on Hardwoods

Frequency of Burns

Although a single burn may kill a significant portion of the above ground hardwood biomass, repeat burns are necessary to kill enough rootstocks for effective sprout control (Waldrop and Buckner 1984; Mobley et al. 1978; Lotti et al. 1960). If uncontrolled, hardwood sprouts can reduce pine stocking and growth. A winter burn in a heavy rough topkilled 94 percent of the hardwoods smaller than 3.5 inches diameter at 6 inches above ground in a loblolly-shortleaf pine stand in Arkansas (Grano 1970). Thereafter, 11 annual burns killed 85 percent of the rootstocks. Lotti et al. (1960) found that, due to differences in sprouting vigor among species, two to four burns were needed to kill enough hardwood rootstocks for good natural regeneration of loblolly pine. Biennial burns were generally as effective as annual burns for sprout control (Grano 1970; Lotti 1962; Lotti et al. 1960). A primary advantage of using biennial burns was that more fuel was available to better sustain burns.

Firing Technique

Both headfires and backfires can effectively control hardwoods (Brown and Davis 1973; Neel 1965; Hodgkins 1958). Headfires expose stems to higher temperatures than backfires, whereas backfires expose stems to high temperatures for a longer time than headfires. Brender and Cooper (1968) reported that both headfires and backfires effectively topkilled hardwoods in a loblolly pine stand on sloping terrain on the Geoergia Piedmont. The disadvantage of using backfires, however, was their slow rate-of-spread (less than 1 chain per hour).

In a test of upslope and downslope headfires and backfires on sloping terrain in West Tennessee, de Bruyn (1981) found that downslope burns killed more hardwoods than upslope burns when the burns were moderately intense. There was danger of wildfire from upslope burns when relative humidity and fuel moisture were low (34 percent and 24 percent, respectively). He also found that when regional wind was weak, downslope fires behaved as backfires and upslope fires as headfires. This was due to an upslope surface wind, resulting from daytime heating of the slopes. The downslope backfires spread slowest as flames were above, and leaning away from, unburned fuel ahead of the fireline.

Season of Burn

Fires during the growing season controlled understory hardwoods more effectively than those during the dormant season (Brender and Cooper 1968; Ferguson 1961). Hodgkins (1958) claimed that sprouting was most effectively reduced when hardwoods were topkilled during the spring immediately after new leaves appeared because carbohydrate reserves in the root are lowest at this time. Summer fires kill the cambium more easily than winter fires due to higher air temperatures (Lotti et al. 1960; Riebold 1955). A series of biennial summer fires virtually eliminated the hardwood understory in a loblolly pine plantation (Lotti 1959). Chen et al. (1975), however, found that both summer and winter burns effectively killed hardwood rootstocks in a pine plantation on 5 to 35 percent slopes on the hilly Coastal Plain of Alabama.

Size of Stem

Prescribed burning is generally effective in controlling hardwoods smaller than 3 inches in diameter at the base of the stem (Ham 1980; Mobley et al. 1978). The smaller the hardwood stem, the more likely it will be topkilled by fire (Brown and Davis 1973). A summer headfire and a winter backfire topkilled an average of 80 percent, 45 percent, and 32 percent of the 1-, 2-, and 3-inch diameter hardwoods, respectively, in a pine stand in East Texas (Ferguson 1957).

Species

Tree species vary significantly in resistance to being topkilled by prescribed fires (Brown and Davis 1973). The most important measure of a species resistance to heat injury is bark thickness. Trees of all species generally become more fire resistant as they grow older because their outer bark usually thickens with age. Differences among species in the rate at which this occurs largely accounts for species variation in ability to withstand heat. Chen et al. (1975) reported that prescribed fire topkilled more sweetgum and winged elm than red oak and hickory on hilly terrain in the upper Coastal Plain in Alabama.

The resistance to topkill of individual trees is not indicative of a species ability to persist after repeated fires (Brown and Davis 1973). For example, Thor and Nichols (1974) found that sassafras regenerates abundantly after fires although individual trees are easily topkilled.

Effect of Fire on Surface Fuel Loading

Prescribed burning has been widely used to minimize the occurrence of devastating wildfires by reducing hazardous fuel accumulations and disrupting fuel continuity in pine plantations in the Coastal Plain (Mobley et al. 1978; Brown and Davis 1973). Pine needles, because they are highly decay resistant and are shed in fascicles, tend to form deep, well-aerated mats of litter that sustain intense surface fires. Prescribed burning every 3 to 5 years keeps fuels from reaching dangerous levels (Cooper 1975; Sackett 1975).

Three annual burns reduced the surface litter from 11,332 to 4,600 pounds per acre in a loblolly-shortleaf pine stand in Arkansas (Grano 1970).

Backfires are generally used to reduce heavy fuel accumulations because they are relatively easy to control and minimize scorch in the crowns of overstory pines (Cooper 1975; Brown and Davis 1973). Backfires usually consume more litter than headfires (Sackett 1975). Hodgkins and Whipple (1963) reported that backfires significantly reduced pine litter in a loblolly-shortleaf pine stand in the hilly Upper Coastal Plain of Alabama.

Cooper (1963) claimed that optimal fuel reduction occurs at about 40 percent relative humidity and 8 percent litter moisture. Generally, only small quantities of fuel are consumed when humidity is higher than 60 percent, whereas fires may be difficult to control when humidity is lower than 30 percent (Sackett 1975; Cooper 1975). Duff (partially decomposed organic material on the forest floor) moisture content should be no less than 20 percent so that the organic mat is not destroyed.

Effect of Fire on Pines

Southern yellow pines 4 inches diameter at breast height and larger have bark that is thick enough to insulate the cambium from the heat of well-planned prescribed burns (Ham 1980). Pine crop tree mortality following a fire is usually caused by crown scorch rather than damage to the cambium (Van Wagner 1970; Cooper and Altobellis 1969). Waldrop and Van Lear (1983) reported that after complete crown scorch of pole-size loblolly pine trees, 20 percent of the codominant trees died and 30 percent of the intermediate trees.

Crown scorch occurred when convection heat concentrated in crowns so that pine needles were exposed to a "killing temperature" (Lotti 1959). Pine needles die if exposed to 130°F for longer than 5 minutes, but die within a few seconds at 145°F (Mobley et al. 1978). The likelihood of crown scorch is increased where pine litter has accumulated in the lower branches of pines and in the tops of understory hardwoods, forming a "ladder" that carries fires vertically into the crowns (Sackett 1975).

In the South the low temperatures and steady northwesterly winds that are common in the winter enable burns that minimize the danger of crown scorch (Mobley et al. 1978; Cooper 1975). Midflame windspeed should be strong enough (about 1 to 5 m.p.h.) to dissipate heat throughout a pine stand so that the heat does not concentrate in the crowns. Lotti (1962) found winter burns to be safe for loblolly pines because thick scales protected the buds from heat damage. Winter burns for hazard reduction killed few dominant and codominant pines on the Coastal Plain in South Carolina (Sackett 1975). Pines were killed only where one or more of the following conditions existed.

1. Winds were insufficient to dissipate heat generated by the fire.
2. Headfires were driven by strong winds in heavy accumulations of dry fuels.

3. "Hot spots" formed at the junction of two fires.

Hodgkins and Whipple (1963) studied the effects of summer and winter backfires on loblolly and shortleaf pine on hilly terrain on the Coastal Plain in Alabama. Two burns--one on a moderate to steep slope and one on a gently rolling ridgetop--were conducted during each season. Each of the four burns was repeated after three years. They found:

1. The initial burns, which were conducted in 10-year fuel accumulations, damaged and killed a significantly greater number of pines (up to 6 inches d.b.h.) than the repeat burn.
2. Summer burns killed substantially more pines than winter burns in the 4 to 6 inch diameter class.
3. Burns on the slopes generally killed more pines than on the relatively flat ridgetops.

CHAPTER III

STUDY AREA

The study area is located approximately 8 km west of Spring City, Tennessee on an east-west oriented ridge on Walden Ridge (Figures 1 and 2). The land is owned by Hiwassee Land Company, a land management subsidiary of Bowaters Southern Paper Corporation. Walden Ridge is the name given to the southeastern part of the Cumberland Plateau east of the Sequatchie Valley (Luther 1977).

The Cumberland Plateau is a southern arm of the Appalachian Highland Region that extends approximately 210 km across East Tennessee in a north-south direction.[2] It is about 110 km wide at the Kentucky-Tennessee border but gradually narrows to about 80 km at the Tennessee-Alabama border (Phelps 1977). The Plateau occupies 12,950 km^2 in Tennessee, approximately 8 percent of the state.

Most of the Plateau is a gently rolling upland with an average elevation of approximately 610 m: the major exceptions are the Cumberland Mountains (peaks and ridges up to 1,070 m) in the northeast section of the Plateau and the Sequatchie Valley (average elevation of about 270 m) in the south-central section.

The Plateau stands 240 to 610 m higher than the Ridge and Valley Province on its eastern border and 240 to 300 m higher than the

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[2] Factors for converting Metric units to English units are given in Appendix B.

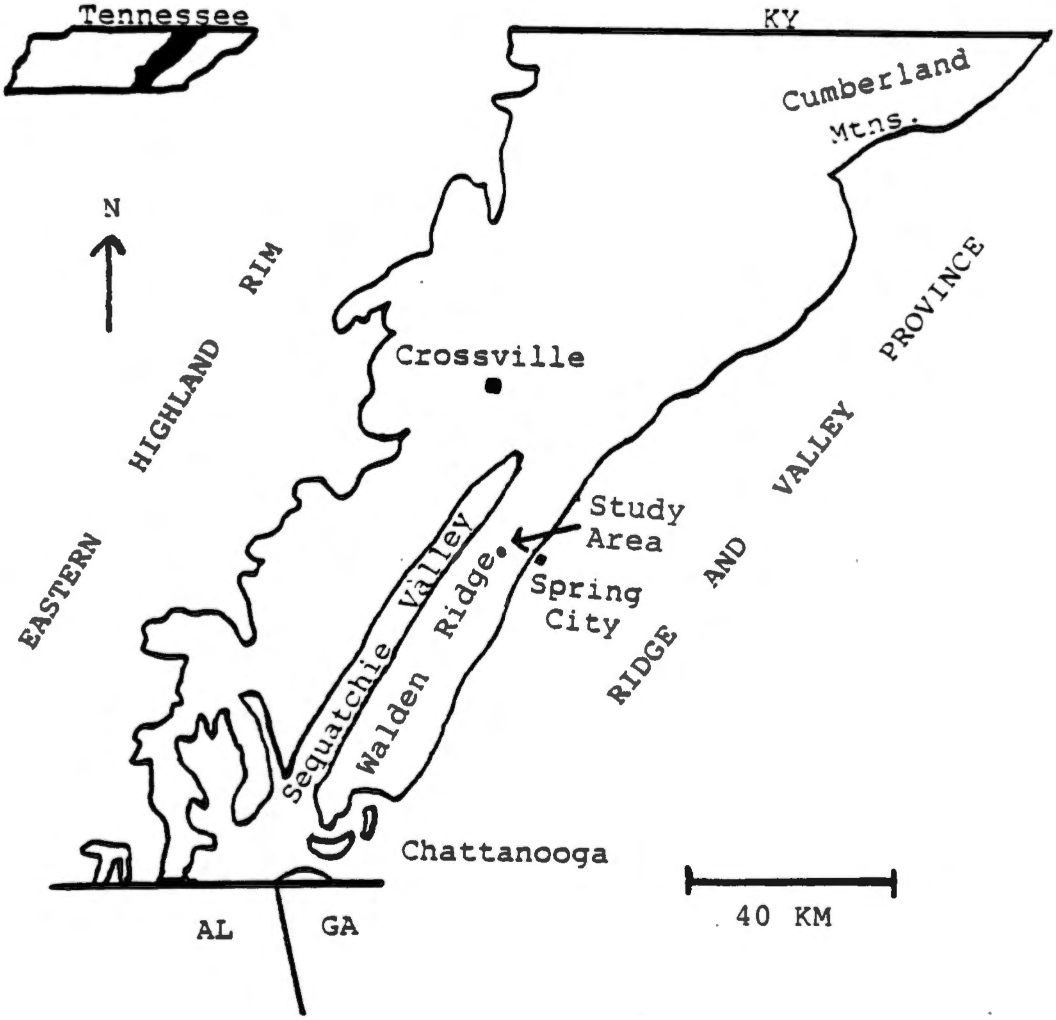

Figure 1. Map of Cumberland Plateau in East Tennessee.

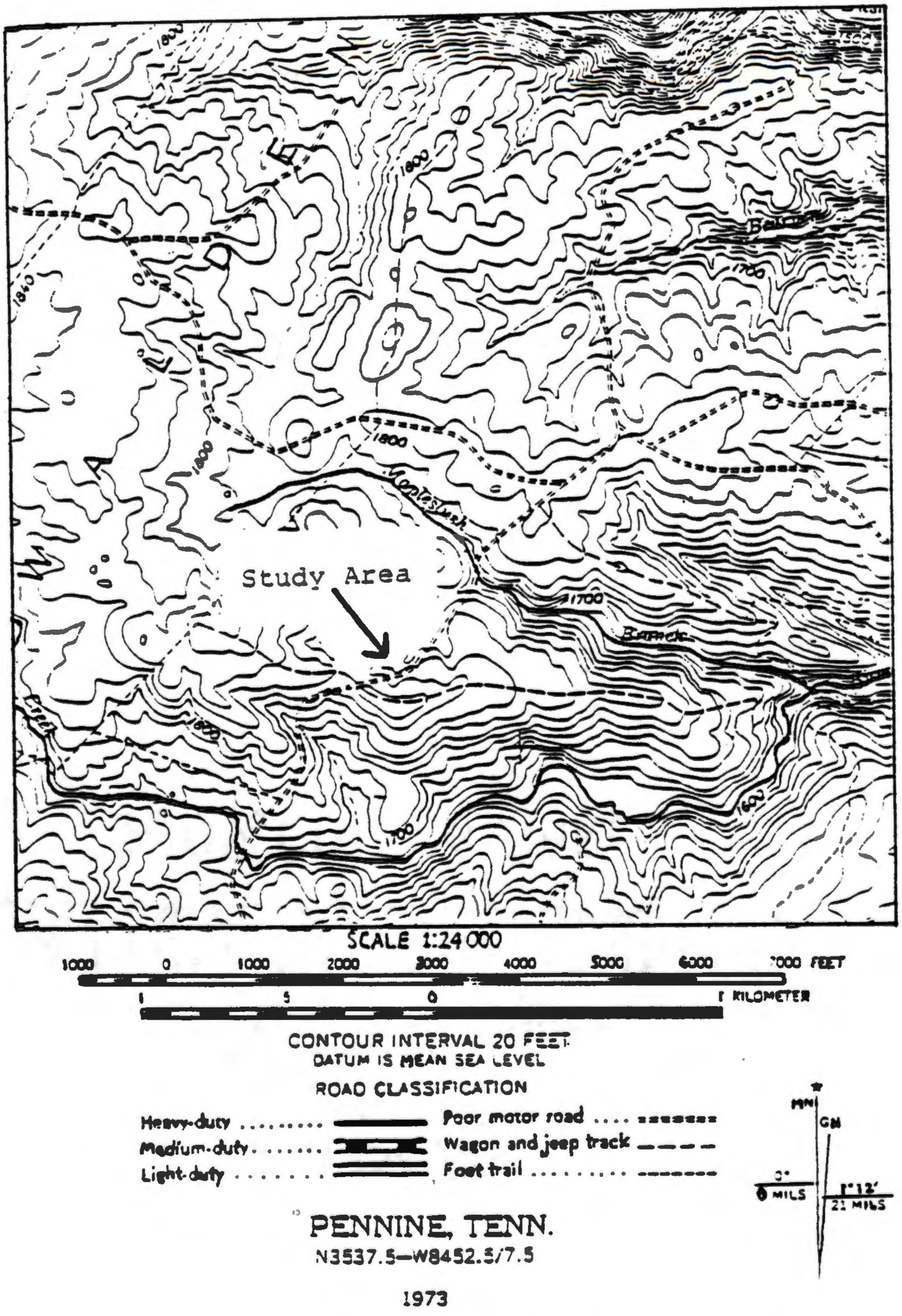

Figure 2. Topographic map showing the east-west oriented ridge where the study area is located.

Eastern Highland Rim on its western margin. It exists as an upland region because a massive, horizontally oriented sandstone "cap" protects softer underlying shales, siltstones, and clays from erosion.

Due to its height and exposure the Plateau has a cooler and wetter climate than adjacent regions to the east and west. Mean annual precipitation is 137 cm, but the shallow, sandy soils have low water-holding capacity and soil nutrients are readily lost to leaching (Hasty 1948). The Plateau is approximately 70 percent forested.

Vegetation

A 26-year-old loblolly pine plantation growing on both the north and south slope of the east-west oriented ridge provided the study area. The plantation was established after the commercial clearcutting of an upland hardwood stand. Site preparation consisted of chemical treatment to control hardwoods. Several years after plantation establishment herbicides were applied by helicopter to control hardwoods that were competing with the planted pines.

Because hardwood control was not highly effective, hardwoods were competing aggressively with the pine crop trees when the burns were conducted. There were 20,433 hardwood stems/ha on the north slope and 9,172 hardwood stems/ha on the south slope. Scattered red maple and various oaks remained in the overstory on the north slope. Pine crop tree basal area was 11.54 m^2/ha on the north slope and 23.08 m^2/ha on the south slope (see Chapter IV, METHODS).

Getting good pine stocking on north and east slopes on the Plateau has been difficult because hardwood competition is very aggressive on these cool, moist aspects.

The eight hardwoods listed in Table 1 comprised more than 99 percent of the hardwood stems growing on the study site. Sixty-six percent of these hardwoods were smaller than 0.5 cm in diameter.

Table 1. Distribution of hardwood stems on the study site by species and diameter class where diameter was measured at 15 cm above ground level.[a]

	Diameter Class (cm)								
Species	<0.5	0.5-2.4	2.5-4.4	4.5-6.4	6.5-8.4	8.5-10.4	>10.4	Total	Percent
				Number of Hardwood Stems/ha					
Red maple	3650	194	7	14	15	6	29	3519	26
Sassafras	2056	114	201	110	24	6	0	2511	17
Red oak	1525	254	99	182	136	97	204	2497	17
Blackgum	844	786	232	47	18	4	0	1931	13
Dogwood	1053	254	221	168	126	42	37	1901	13
Hickory	342	451	174	44	11	3	0	1025	7
White oak	237	82	50	62	53	21	51	556	4
Sourwood	85	54	62	83	67	53	61	465	3
Total	9792	2189	1046	710	450	232	382	14801	100
Percent	66	15	7	5	3	1.5	2.5		

[a] The number of hardwood stems/ha was derived from an inventory of hardwoods on the study site before the prescribed burns were conducted. See Chapter IV, METHODS, Establishment and Pre-Burn Inventory of Subplots.

CHAPTER IV

METHODS

Selection of the Study Area

Considerations that influenced selection of the study area included the following:

1. The gently sloping terrain was similar to much of the Plateau where loblolly pine has been planted.
2. The pine plantation was typical of many of the older plantations on the Plateau in that pine stocking was suffering from aggressive hardwood competition and there was a deep layer of surface fuel on the forest floor.

Establishment of Burn Plots

A wagon and jeep track along the ridgetop (Figure 3) provided access to the study area. The pine plantation occupied an area large enough to establish six burn plots on the south slope and six on the north slope with each of the 12 burn plots occupying approximately 0.70 ha. Slope length in each burn plot was approximately 80 m. The arrangement of the plots is shown in Figures 3 and 4.

Firelines were plowed along the four sides of each of the 12 burn plots. The only exception was the ridgetop side of the four

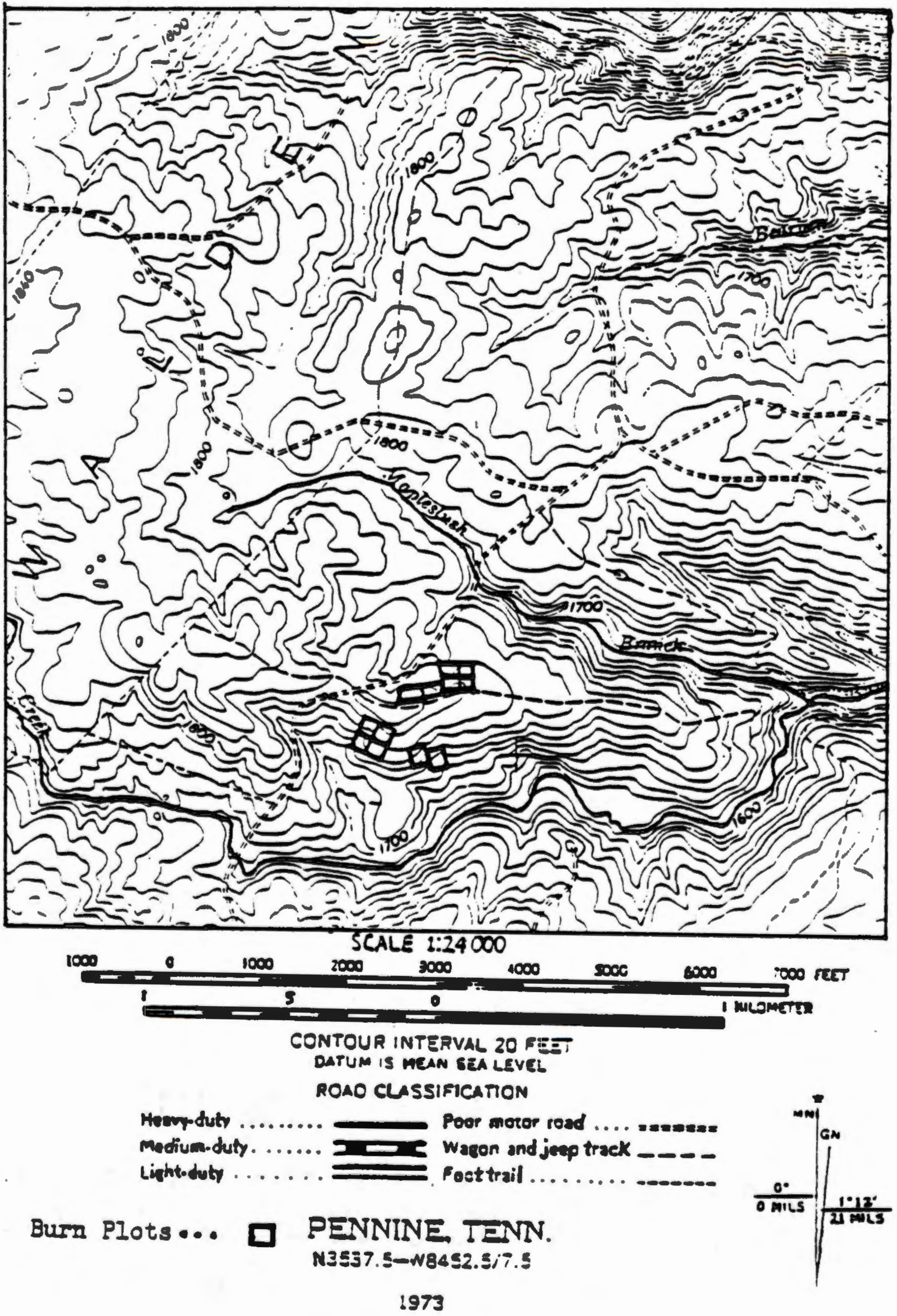

Figure 3. Topographic map showing the location of the 12 burn plots on the study area.

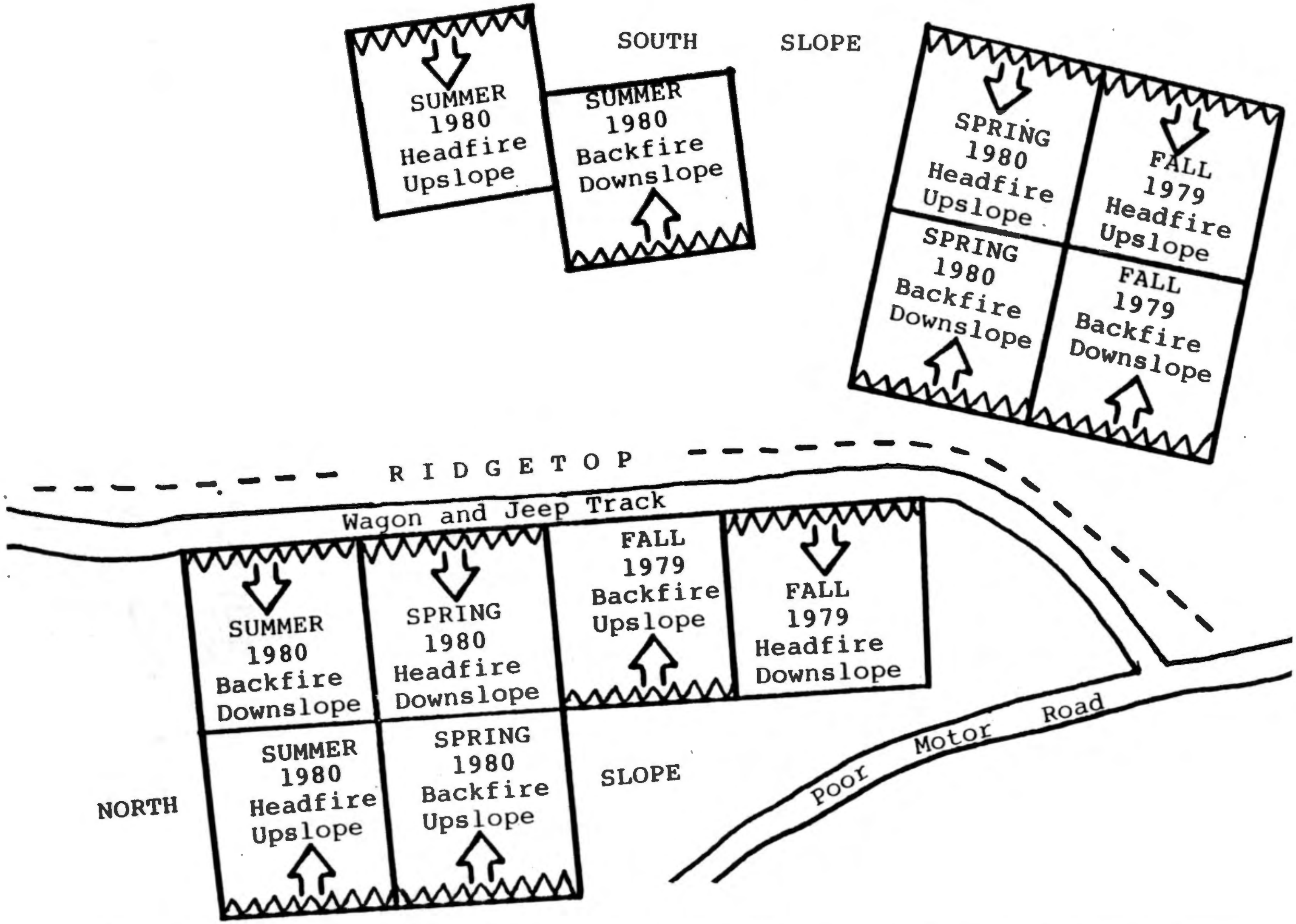

Figure 4. Diagram of the 12 burn plots showing the season when each plot was ignited and the type of fire that burned on each plot.

north slope plots where the wagon and jeep track provided a firebreak. A tractor/fireplow unit was provided by the Tennessee Division of Forestry.

Establishment and Pre-Burn Inventory of Subplots

Four subplots were established in each of the 12 burn plots (Figure 5) to determine the effect of each burn on vegetation. Each of the 48 subplots occupied 150 m^2, extending 3 m across the slope and 50 m parallel to the slope. The center line of each subplot was marked by six metal stakes at 10 m intervals along the slope. The subplots were also used to determine the rate-of-spread of each burn.

In each of the 48 subplots, the trees taller than 15 cm were mapped. The fall 1979 subplots were inventoried in May 1979; the spring 1980 subplots in October 1979; and the summer 1980 subplots in June 1980. Pine crop tree diameter was measured at 1.37 m above ground; basal area was determined for each burn plot. Species and diameter at 15 cm above ground were recorded for each hardwood stem.

Selection of Burn Dates

Three "biological seasons" were identified for this study to determine the effectiveness of prescribed burning in controlling hardwoods during different stages of biological activity. Seasons were: fall (September, October, and November); spring (March, April, and May); and summer (June, July, and August). Root carbohydrate

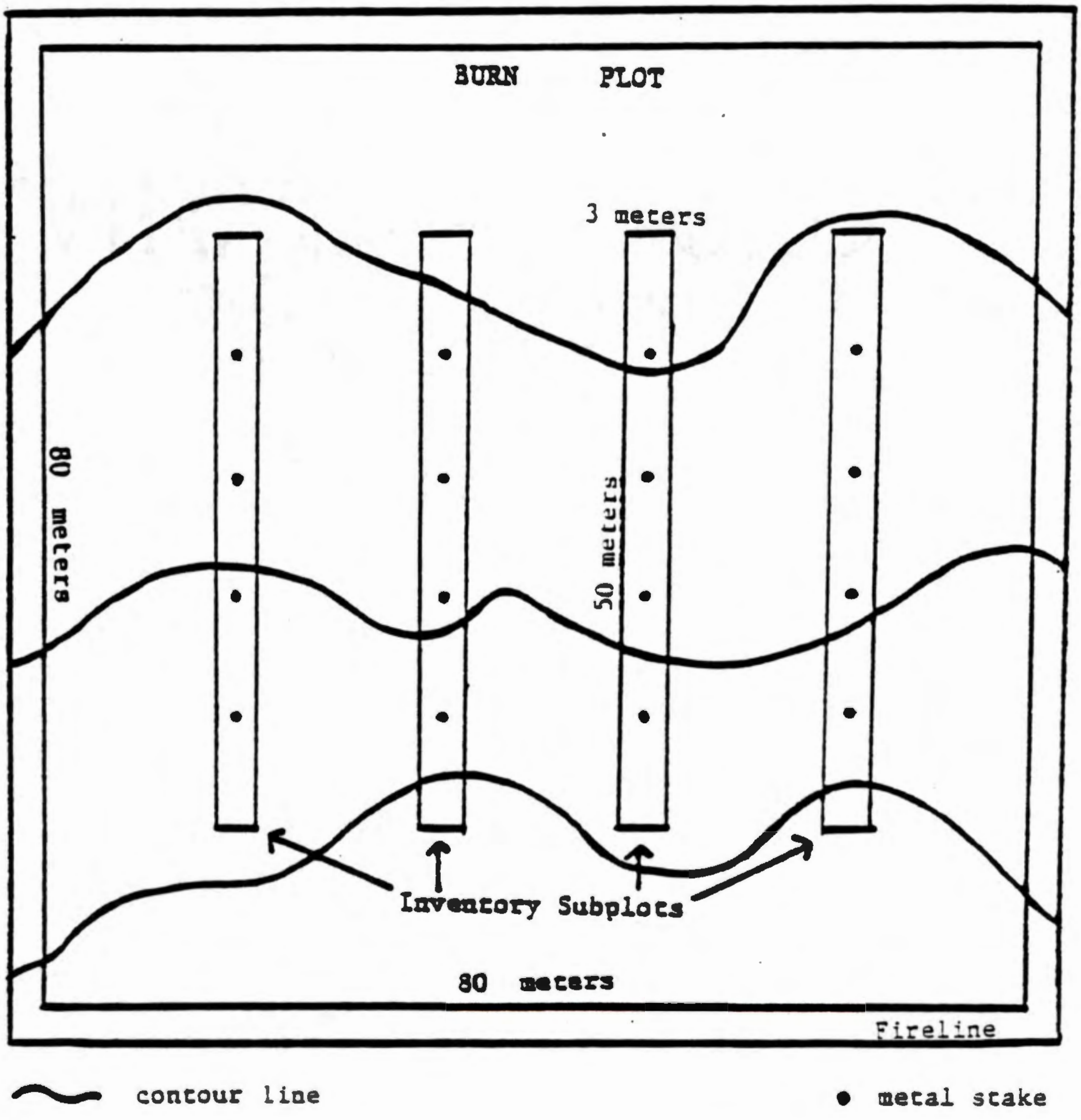

Figure 5. Diagram showing the four subplots extending along the slope length within a burn plot.

reserves are lowest in the spring after trees have leafed out. Active growth continues through August and by September the hardening off process is under way.

In each season an attempt was made to select a day for burning when the general wind (wind produced by pressure systems) was greater than 8 km/h but less than 29 km/h. At lower general windspeeds wind movement at the surface is generally not strong enough to prevent heat from rising vertically and scorching tree crowns; at higher general windspeeds there is danger of wildfire (Mobley et al. 1978). The fall burns were conducted on the afternoon of October 22, 1979; the spring burns on the afternoon of May 12, 1980; and the summer burns on the afternoon of August 27, 1980.

Pre-Burn Fuel Samples

Surface fuel samples were collected immediately before the burns were ignited. Three samples were collected at randomly selected locations in each burn plot: one sample was taken at the top of the slope, one at the middle, and one at the bottom. The samples were collected using a steel cylinder 25.4 cm in diameter (area = 0.0507 m^2). A sharp edge on one end of the cylinder was used to cut through the surface fuel (pine needles, hardwood leaves, cones, twigs) down to the mineral soil. The fuel inside the cylinder was placed in a plastic bag, which was then sealed to prevent fuel moisture changes.

The three fuel samples were pooled, weighed to the nearest 0.1 g, and oven dried at 70°C until there was no longer a weight loss. Percent fuel moisture and fuel loading were calculated for each burn plot.

Percent fuel moisture = [(wet wt. - dry wt.)/dry wt.)] x 100.

Fuel loading (kg/ha) = [dry wt. (g) x 10,000 (m^2/ha)/3 x 0.0507 (m^2)]/1000 (g/kg).

Firing Technique

Four plots were burned in each season, two on the north slope and two on the south slope, as shown in Figure 4. In each season, on both slopes, one plot was ignited at the top side so that the fure burned downslope and one plot was ignited at the base so that the fire burned upslope.

In each season the firing sequence for the burn plots was determined both by general wind direction and the direction (up or down slope) the burn was to spread. The general wind direction was from the South during the fall, spring, and summer burns. Surface wind movement in the pine plantation was upslope on the south (windward) slope. A backfire downslope on the south slope was always ignited first since it was expected to burn the slowest of the four burns. A headfire upslope on the south slope was ignited shortly afterwards. Due to a fast rate-of-spread, this fire was allowed to burn out before burns were ignited on the north slope. An upslope burn on the north slope was always ignited last since it was expected to burn fastest.

Measurements During the Burns

Weather conditions (windspeed in the pine plantation, air temperature, and relative humidity) were measured during the burns as often as time and manpower permitted. Windspeed in the pine plantation was measured by four anemometers--one located at the base and one at the top of both the north slope and the south slope. Also, the time that elapsed while a fire burned the length of the subplots (50 m) was recorded to determine rate of spread.

Post-Burn Data Collection

Three samples of the surface fuel were collected on each burn plot several days after the burns were conducted. The samples were collected in the same manner as the preburn fuel samples. After the post-burn fuel samples were oven dried, they were weighed to the nearest 0.1 g. Percent fuel reduction was calculated with the following equation.

Percent fuel reduction = [(preburn dry wt. - postburn dry wt.) /preburn dry wt.] x 100.

After one growing season the trees identified prior to burning were relocated using the subplot maps. Each hardwood stem was assigned to one of the following three categories: 1) alive; 2) topkilled but with sprouts; or 3) totally killed. Diameter of the loblolly pine crop trees was measured. Basal area of crop trees was calculated for each burn plot.

Statistical Analysis

Data were organized, displayed, and analyzed with SAS (Statistical Analysis System) procedures: CHART, CORR, FREQ, GLM, PLOT, PRINT, and TABULATE (SAS Institute, Inc. 1982). Correlation coefficients (r) were calculated among fuel conditions (fuel moisture and fuel loading), weather conditions (surface windspeed, temperature, and relative humidity), rate of spread, and effects [percent topkill, percent fuel reduction, and pine crop tree mortality (basal area decrease)]. These are presented in Appendix C. A probability level of 5 percent was used.

CHAPTER V

RESULTS AND DISCUSSION

Burn Type

On the fall and spring burn dates the general wind direction was from the South. Surface wind direction in the pine plantation was upslope on the south (windward) side of the ridge, making upslope burns headfires and downslope burns backfires. The general wind was strong enough to cause wind in the pine plantation to move downslope on the north (lee) side of the ridge so that downslope burns were headfires and upslope burns were backfires. The general windspeed during the fall burns ranged from 19 to 27 km/h with occasional gusts as high as 45 km/h; during the spring windspeed ranged from 14 to 24 km/h. The general windspeed was measured 6 m above ground approximately 30 km NW of the study area at the weather station at the F.A.A. airport in Crossville, Tennessee on the Cumberland Plateau.

On the day of the summer burns the general wind was too weak (8 to 11 km/h) to control wind movement in the pine plantation. Wind movement was upslope on both the north (lee) side of the ridge and the south (windward) side. Downslope burns on both slopes were backfires and upslope burns were headfires. When the general wind is weak, surface wind direction during the daytime is upslope (Brown and Davis 1973; Schroeder and Buck 1970). Upslope surface wind movement begins within minutes after a slope is heated by solar radiation. Air along the slope becomes warmer and lighter than air over an adjacent valley. The cooler, denser air over the valley moves horizontally toward the slope so that air along the slope flows upslope instead of rising vertically.

Burning Conditions

On each of the three burn dates windspeed in the pine plantation (Table 2) was much lower than the general windspeed. Windspeed in the pine plantation was very low (less than 1 km/h) in the summer when wind direction in the plantation was controlled by topography. The reason was probably that air over the shallow valleys adjacent to the ridge was only slightly cooler than air along the gentle slopes. The rise in elevation from the base of both slopes to the ridgetop was approximately 40 m. Slope winds generated by surface heating tend to be strong (6 to 16 km/h) only in mountainous terrain (steep slopes and deep valleys) where daytime temperature lapse rate is steep from valley floors to the elevation of adjacent ridgetops (Brown and Davis 1973).

Surface fuel on the south slope was primarily pine litter, whereas there was a significant hardwood litter component on the north slope. This was the case because: 1) pine stocking was higher on the south slope and 2) hardwoods were more numerous on the north slope.

Table 2. Weather conditions while the fall, spring, and summer burns were being conducted.

Season	Windspeed km/h	Time DST	Temperature °C	Relative Humidity %
Fall	11:43 A.M.-5:55 P.M.			
	South slope	1:15	22	74
	4.22	3:05	23	67
	North slope	5:10	21	71
	3.50			
Spring	12:36 P.M.-4:49 P.M.			
	South slope	12:40	27	58
	3.36	1:40	31	45
	North slope	3:00	29	54
	1.93	5:50	29	60
Summer	11:50 A.M.-5:25 P.M.			
	South slope	12:30	26	58
	0.86	1:30	30	52
	North slope	2:20	30	44
	0.76	3:25	31	40
		4:20	34	32
		5:25	32	43

Fuel moisture was generally lower in the spring than the fall and summer (Table 3). A major reason for the lower fuel moisture in the spring was that evaporation had exceeded precipitation for 14 days prior to the spring burns compared to 11 days before the fall burns and 7 days before the summer burns (NOAA 1985). Evaporation and precipitation were measured at the University of Tennessee Plateau Experiment Station, Crossville, located approximately 30 km from the study site. Higher relative humidity in the fall was also a reason why fuel moisture was higher in the fall than in the spring.

Fuel loading was higher in the spring than in the summer and fall (Table 4). The lowest fuel loading among the spring burn plots was 26,890 kg/ha and the highest was 43,570 kg/ha, whereas for the fall and summer plots the highest fuel loading was 20,420 kg/ha. The higher fuel loading in the spring was probably because less time had elapsed since leaffall than when the summer and fall burns were conducted.

Rate of Spread

In each season the headfire upslope (south slope) spread fastest and the backfire downslope (south slope) spread slowest (Table 5). The backfires downslope spread only 12 m/h. The flames of the headfires upslope were "bent" upslope toward fresh fuels that were lying in the path of the flames, maximizing the preheating of fuels so that they were ignited more rapidly. This is a major factor enabling the rapid spread of fires (National Wildfire Coordinating Group 1981). The flames of the backfires downslope were "bent" upslope,

Table 3. The 12 burns listed in order from lowest to highest percent fuel moisture.

Burn Type	Season	Aspect	% Fuel Moisture
Headfire Downslope	Spring	North	24
Headfire Upslope	Spring	South	26
Backfire Downslope	Spring	South	31
Backfire Downslope	Summer	North	35
Backfire Upslope	Spring	North	36
Headfire Upslope (Strip Fire)	Summer	North	36
Headfire Upslope	Summer	South	50
Backfire Downslope	Fall	South	55
Backfire Downslope	Summer	South	63
Headfire Upslope	Fall	South	66
Backfire Upslope	Fall	North	70
Headfire Downslope	Fall	North	82

Table 4. The 12 burns listed in order from highest to lowest fuel loading.

Burn Type	Season	Aspect	Fuel Loading kg/ha
Backfire Downslope	Spring	South	43,570
Headfire Upslope	Spring	South	38,700
Backfire Upslope	Spring	North	34,940
Headfire Downslope	Spring	North	26,890
Backfire Downslope	Summer	South	20,420
Headfire Downslope	Fall	North	20,420
Headfire Upslope	Fall	South	20,320
Backfire Upslope	Fall	North	19,310
Backfire Downslope	Summer	North	18,180
Backfire Downslope	Fall	South	17,320
Headfire Upslope	Summer	South	13,350
Headfire Upslope (Strip Fire)	Summer	North	12,590

Table 5. The 12 burns listed in order from fastest to slowest rate of spread.

Burn Type	Season	Aspect	Rate of Spread m/h
Headfire Upslope	Spring	South	176
Headfire Upslope	Fall	South	79
Headfire Upslope	Summer	South	49
Backfire Upslope	Spring	North	42
Headfire Downslope	Fall	North	28
Backfire Downslope	Summer	North	28
Headfire Downslope	Spring	North	20
Backfire Upslope	Fall	North	13
Backfire Downslope	Fall	South	12
Backfire Downslope	Spring	South	12
Backfire Downslope	Summer	South	12
Headfire Upslope (Strip Fire)	Summer	North	*

*Rate of spread was not determined because several strips of fire were ignited across the plot.

above and away from fresh fuels, minimizing the preheating of unburned fuels ahead of the fire.

The headfire upslope in the spring spread 176 m/h--this was approximately two times faster than the headfire upslope in the fall (79 m/h) and approximately three times faster than this fire type in the summer (49 m/h). The reason the headfire upslope in the spring spread faster was probably because fuel moisture was about one-half as high on the spring burn plot (26 percent) as on the fall (66 percent) and summer (50 percent) plot. Also, the "spring" headfire upslope was driven by a stronger wind (3.36 km/h) than the "summer" headfire upslope (0.86 km/h).

The backfire upslope (north slope) in the spring spread 42 m/h; this was approximately three times faster than its fall counterpart (13 m/h). Fuel moisture was lower on the spring burn plot (36 percent) than on the fall burn plot (70 percent).

The headfire downslope (north slope) in the fall spread faster (28 m/h) than the headfire downslope (north slope) in the spring (20 m/h). Windspeed in the pine plantation was higher in the fall (Table 2, page 27).

In the summer the backfire downslope on the north slope spread approximately two times faster than the backfire downslope on the south slope. The likely reasons were: 1) slope was gentler on the north slope plot (4 percent) than the south slope plot (16 percent); and 2) fuel moisture was lower on the north slope plot (35 percent) than on the south slope plot (63 percent).

The headfire upslope on the north slope was spreading so slowly that it would not have crossed the burn plot before being extinguished by high nighttime relative humidity and fuel moisture. Several strips of fire were ignited across the slope to finish burning the plot during the afternoon. The primary reason why this fire burned so poorly was that most of the surface fuel was hardwood litter that was largely decomposed. There was a small amount of pine litter because pine crop tree basal area was only 5.22 m^2/ha.

Hardwood Control

There was only a small difference in percent of hardwoods totally killed (not sprouting) among the seasonal burns: summer (21 percent), fall (19 percent), and spring (17 percent). Spring burns were no more effective than those in fall and summer probably because the hardwoods had replenished root carbohydrate reserves that were "spent" when the trees were growing new leaves. The spring burns were conducted on May 12; this was several weeks after the hardwoods had "leafed out."

In each season, the percent of hardwoods smaller than 0.5 cm diameter that were totally killed was high (50 percent or greater), but it decreased substantially for increasing diameter (Table 6). This was probably because the larger the stem, the more extensive its root system; thus, the greater its root carbohydrate reserves.

The spring burns generally topkilled more hardwoods than the fall and summer burns (Table 7). Higher fuel loading combined with

Table 6. Effect of the burns on the hardwood trees by season and diameter class where diameter was measured at 15 cm above ground.

Diameter Class (cm)	Post-Burn Status	Percent Burns Fall	Spring	Summer
<0.5	Alive	1	0	0
	Topkilled	32	50	36
	Totally killed	67	50	64
0.5-2.4	Alive	11	0	5
	Topkilled	60	73	58
	Totally killed	29	27	37
2.5-4.4	Alive	40	4	27
	Topkilled	47	88	58
	Totally killed	13	8	15
4.5-6.4	Alive	67	12	50
	Topkilled	22	78	39
	Totally killed	11	10	11
6.5-8.4	Alive	87	37	70
	Topkilled	6	54	24
	Totally killed	7	9	6
8.5-10.4	Alive	89	47	78
	Topkilled	6	46	10
	Totally killed	5	7	12
>10.5	Alive	100	68	94
	Topkilled	0	23	5
	Totally killed	0	9	1
Average	Alive	56	24	46
	Topkilled	25	59	33
	Totally killed	19	17	21

Table 7. The 12 burns listed in order from highest to lowest percent kill of hardwood trees.

Burn Type	Season	Aspect	Post-Burn Status: Alive	Post-Burn Status: Top-Killed	Post-Burn Status: Totally Killed	Total Percent Killed
			%	%	%	%
Headfire Upslope	Spring	South	3	82	15	97
Backfire Downslope	Spring	South	24	62	14	76
Backfire Downslope	Summer	South	28	56	16	72
Headfire Downslope	Spring	North	29	54	17	71
Backfire Upslope	Spring	North	40	38	22	60
Headfire Upslope	Summer	South	42	35	23	58
Backfire Downslope	Fall	South	46	35	19	54
Backfire Downslope	Summer	North	48	27	25	52
Headfire Upslope	Fall	South	52	31	17	48
Headfire Downslope	Fall	North	59	19	22	41
Backfire Upslope	Fall	North	68	15	17	32
Headfire Upslope (Strip Fire)	Summer	North	68	13	19	32

lower fuel moisture on the spring burn plots (Tables 3 and 4, pages 29 and 30, respectively) probably accounts for greater topkill by these burns. The correlation coefficient ($r = 0.74$) was statistically significant ($p = 0.05$) for fuel loading and percent topkill. The backfire upslope in the spring topkilled more hardwoods than both summer burns on the north slope even though fuel moisture was not lower on the backfire upslope plot (36 percent) than the summer plots (35 percent and 36 percent). Higher fuel loading in the spring was likely a seasonal effect. Heavy accumulations of hardwood leaves (especially oak and hickory) are a major reason why the "spring wildfire season" in Tennessee occurs from February 15 to May 31. Lower fuel moisture in the spring was not a seasonal effect; fuel moisture could have been just as low at any time of the year.

The three successful summer burns generally topkilled more hardwoods than the fall burns. The higher percent topkill for these summer burns was likely due to the combination of higher air temperature (Table 2, page 27) and lower fuel moisture (Table 3, page 29) in the summer. The higher the air temperature the less heat required to produce a "killing temperature" around tree stems (Mobley et al. 1978). Fuel moisture was lower on three of the summer plots than on the fall plots. The backfire downslope (south slope) plot in the summer had lower fuel moisture than three of the fall plots. The higher air temperature in the summer was a seasonal effect whereas the lower fuel moisture was not.

In each season both south slope burns topkilled more hardwoods than burns on the north slope (Table 7). The south slope burns were probably more intense because there was more pine litter on the south slope. Fires in pine litter are usually more intense than those in hardwood litter because: 1) pine litter forms deeper layers of fuel; and 2) pine litter is better aerated (Brown and Davis 1973; Brender and Cooper 1968). The southern yellow pines have 2-3 needles per fascicle so they tend to form cushioned layers of fuel when they are shed, whereas hardwood leaves are shed singly and tend to mat together so that there is little oxygen to support combustion. Hodgkins and Whipple (1963) found that backfires in mostly pine litter were more intense than backfires in mostly hardwood litter in pine plantations on hilly terrain in the Coastal Plain of Alabama.

On the south slope, in the spring, the headfire upslope topkilled more hardwoods (97 percent) than the backfire downslope (76 percent). In both fall and summer, however, the backfire downslope topkilled more hardwoods than the headfire upslope (Table 7). This indicates that when burning conditions are marginal (as in the fall and summer) slow-spreading backfires will likely provide the greater topkill.

Fuel Reduction

Burning was effective in reducing heavy fuel loadings in each season (Table 4, page 30; Table 8). Spring burns consumed more fuel than fall and summer burns (Table 8). The higher percent fuel

Table 8. The 12 burns listed in order from highest to lowest percent fuel reduction.

Burn Type	Season	Aspect	Fuel Reduction Percent	Post-Burn Fuel Loading kg/ha
Backfire Downslope	Spring	South	76	10,460
Headfire Upslope	Spring	South	68	12,380
Backfire Upslope	Spring	North	66	11,880
Headfire Downslope	Spring	North	54	12,370
Backfire Downslope	Summer	North	46	9,820
Headfire Downslope	Fall	North	38	12,660
Headfire Upslope	Fall	South	36	13,010
Backfire Downslope	Summer	South	36	13,070
Backfire Downslope	Fall	South	33	11,600
Backfire Upslope	Fall	North	30	13,520
Headfire Upslope (Strip Fire)	Summer	North	27	9,190
Headfire Upslope	Summer	South	22	10,410

reduction by the spring burns was due primarily to a combination of higher fuel loading and lower fuel moisture on the spring plots (Tables 3 and 4, pages 29 and 30, respectively). The correlation coefficients, $r = 0.96$ for percent fuel reduction and fuel loading and $r = -0.61$ for percent fuel reduction and fuel moisture, were statistically significant ($p = 0.05$, $n = 12$). For reasons discussed earlier, higher fuel loading in the spring was likely a seasonal effect.

Pine Crop Tree Mortality

Ten of the 12 burns killed so few pine crop trees that 1 year after burning basal area of the surviving pines was higher than pre-burn basal area (Table 9). Six burns reduced pine crop tree basal area less than 0.4 m^2/ha and four burns reduced basal area less than 1.0 m^2/ha.

Only one burn, the headfire upslope in the spring, reduced pine crop tree basal area so much (3.47 m^2/ha) that 1 year after burning basal area was substantially lower (2.97 m^2/ha) than pre-burn basal area. This fire killed more and larger pine trees (up to 18.3 cm diameter) than the other burns due to a combination of factors.

1. It burned in heavy fuel (38,700 kg/ha).
2. It burned in loosely compacted (well-aerated) pine litter.
3. Fuel moisture was low (26 percent).
4. It spread rapidly (176 m/h).

The faster a fire spreads, the more quickly heat is released; thus,

Table 9. The 12 burns listed in order from lowest to highest decrease in loblolly pine crop tree basal area after the burns.

			Basal Area			
			Pre-Burn	Post-Burn	Decrease	1-Year Post-Burn
Burn Type	Season	Aspect	m^2/ha			
Headfire Upslope (Strip Fire)	Summer	North	5.22	5.22	0.00	5.62
Headfire Upslope	Summer	South	20.80	20.59	0.21	21.55
Backfire Downslope	Summer	South	23.82	23.60	0.22	25.55
Backfire Upslope	Spring	North	5.20	4.98	0.22	5.62
Headfire Downslope	Spring	North	8.42	8.15	0.27	8.78
Backfire Upslope	Fall	North	19.17	18.80	0.37	20.38
Backfire Downslope	Spring	South	22.43	22.04	0.39	23.90
Backfire Downslope	Summer	North	12.27	11.60	0.67	12.15
Backfire Downslope	Fall	South	25.38	24.55	0.83	27.28
Headfire Upslope	Fall	South	26.80	25.89	0.91	27.72
Headfire Downslope	Fall	North	18.95	16.67	2.28	19.78
Headfire Upslope	Spring	South	19.22	15.75	3.47	16.25

the more likely that pine needles will be exposed to a "killing temperature" (Brown and Davis 1973).

Summary

When the general windspeed was greater than 14 km/h, the general wind controlled wind direction in the pine plantation. Upslope burns on the windward slope were headfires and downslope burns were backfires. On the lee slope upslope burns were backfires and downslope burns were headfires. When the general wind was less than 11 km/h topography controlled wind direction in the pine plantation. On both windward and lee slopes upslope burns were headfires and downslope burns were backfires.

In each season the headfire upslope spread the fastest and the backfire downslope the slowest. The headfire upslope in the spring spread faster than the headfires upslope in the fall and summer. Fuel moisture was much lower on the spring plot.

Burning was effective in killing hardwoods in fall, spring, and summer. Spring burns topkilled more hardwoods than fall burns and summer burns. This was probably a seasonal effect as fuel loading was approximately twice as high in the spring (36,030 kg/ha) as in the fall (19,340 kg/ha) and summer (16,140 kg/ha). Spring burns were not more effective in totally killing hardwoods. Hardwood root reserves were probably replenished when the spring burns were conducted (May 12) as hardwoods had been "in leaf" for longer than a month.

Burning was effective in reducing heavy fuel loadings in each season. Spring burns consumed more fuel than summer burns and fall burns. Fuel loading was much higher in the spring.

In each season south slope burns were more effective than north slope burns in killing hardwoods and reducing fuels. The only exception was in the fall when the headfire on the north slope consumed slightly more fuel than burns on the south slope. Surface fuel on the south slope was mostly pine litter whereas a substantial portion on the north slope was hardwood litter.

Only one of the 12 burns, the headfire upslope in the spring, reduced pine crop tree basal area so greatly (3.47 m^2/ha) that it was still lower one year after burning than before burning. This fire killed more pine crop trees than the other burns because: 1) it burned in deep, dry, well-aerated pine litter; and 2) it spread much faster than the other burns; thus, it likely raised air temperatures much higher.

Conclusions

Based on this research the following conclusions can be made.

1. Prescribed burning can effectively control hardwoods and reduce fuels in loblolly pine plantations on gently sloping terrain on the Cumberland Plateau.
2. Burning can be used without long-term (longer than 1 year) reductions in pine crop tree basal area. Caution should be exercised when using headfires upslope in heavy accumulations of dry pine litter.

3. Spring burns will generally topkill more hardwoods and consume more fuel than summer and fall burns conducted before leaffall.
4. Burning will be more effective on south slopes than on north slopes.
5. General wind direction will determine surface wind direction in pine plantations when general windspeed is greater than 14 km/hr, whereas topography will control surface wind direction when the general windspeed is lower.

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APPENDICES

APPENDIX A

COMMON AND SCIENTIFIC NAMES OF SPECIES IN TEXT

Table 10. List of common name and scientific name for each species in the text.

Common Name	Scientific Name
Blackgum	Nyssa sylvatica Marsh.
Dogwood	Cornus florida L.
Hickories	Carya spp.
Loblolly pine	Pinus taeda L.
Red maple	Acer rubrum L.
Red oaks	Quercus spp.
Sassafras	Sassafras albidum (Nutt.) Nees
Shortleaf pine	Pinus echinata Mill.
Sourwood	Oxydendron arboreum (L.) DC.
Sweetgum	Liquidambar styraciflua
White oaks	Quercus spp.
Winged elm	Ulmus alata

APPENDIX B

FACTORS FOR CONVERTING METRIC UNITS TO ENGLISH UNITS

Table 11. Factors for converting Metric units to English units.

	Metric Unit	Multiply By	English Unit
Length	cm	0.39	in
	m	3.28	ft
Speed	m/h	3.28	ft/h
	km/h	0.64	mi/h
Area	ha	2.47	a
	m^2	10.76	ft^2
	m^2/ha	4.36	ft^2/a
Weight	kg	2.20	lb
	kg/ha	0.89	lb/a
Temperature	°C	1.80 then add 32	°F

APPENDIX C

PEARSON CORRELATION COEFFICIENTS AND PROBABILITY > R FOR FUEL CONDITIONS, WEATHER CONDITIONS, RATE OF SPREAD, AND EFFECTS

Table 12. Pearson correlation coefficients (r) and probability > R (p) for fuel conditions, weather conditions, rate of spread, and effects.[a]

		Percent Topkill	Percent Fuel Reduction	Pine Mortality (Basal Area Decrease)
Fuel Moisture	r	-0.53	-0.61	0.06
%	p	0.07	0.03	0.86
Fuel Loading	r	0.74	0.96	0.33
kg/ha	p	0.01	0.0001	0.29
Windspeed	r	0.09	0.19	0.47
km/h	p	0.78	0.54	0.12
Air Temperature	r	0.43	0.33	-0.24
°C	p	0.17	0.30	0.46
Relative	r	-0.28	-0.12	0.30
Humidity %	p	0.38	0.70	0.34
Rate of Spread	r	0.52	0.30	0.77
m/h	p	0.10	0.36	0.0058

[a] n = 12 except for rate of spread where n = 11.

VITA

Michael York was born in Nashville, Tennessee on September 10, 1955. In 1973, he graduated from Glencliff High School where he majored in Biology and Math. Michael was then awarded a four-year Academic Scholarship to David Lipscomb College where he majored in History and minored in Biology. He received a Bachelor of Arts Degree in August, 1977. The following month, he began working as an assistant purchasing agent for McDowell Enterprises at the headquarters in Nashville, Tennessee. In the spring of 1978 he was promoted to the Accounts Payable Department. In September, 1979, Michael moved to Sevierville, Tennessee and began studying forestry at The University of Tennessee, Knoxville, where he was admitted to the Graduate School in the spring of 1980. He received the Master of Science Degree with a major in Forestry in March, 1988. The author has been a member of the Society of American Foresters for seven years.