Site preparation burning to improve southern Appalachian pine-hardwood stands: fire characteristics and soil erosion, moisture, and temperature’

LLOYD W. SWIFT, JR.,* AND KATHERINE J. ELLIOTT
Southeastern Forest Experiment Station, Coweeta Hydrologic Laboratory,
999 Coweeta Lab Road, Otto, NC 28763, U.S.A.

AND

ROGER D. OTTMAR AND ROBERT E. VIHNANEK
Pacific Northwest Research Station, Fire and Environmental Research Applications Group,
Global Environmental Protection Program, 4043 Roosevelt Way NE, Seattle, WA 98105, U.S.A.

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Three southern Appalachian stands with sparse and unproductive pine-hardwood overstories and dense *Kalmia latifolia* L. understories were treated to restore productivity and diversity on steep slopes. An adaptation of the fell and burn practice was applied in summer and fall 1990. About one-half of the woody fuels were consumed at each site. A range of fire intensities was observed. Flame temperatures approached 800°C, but the heat pulse into the forest floor only reached 60°C at 5 cm. Humus and charred leaf litter remained on most of the surface after burning. Evidence of soil erosion was spotty and related to points of local soil disturbance. No soil left the sites. At the end of the first growing season, 23% of the burned surfaces were covered by growing plants and 62% by residual forest floor and woody debris. Felling and burning reduced evapotranspiration so that soil in the treated areas remained moister than under adjacent uncut stands. Opening the sites increased soil temperatures 2 to 5°C at IO cm during the first 16 months after treatment.

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Trois peuplements du sud des Appalaches presentant un couvert épars improductif de pin et de feuillus avec un sous-étage dense de *Kalmia latifolia* L. ont été traités pour restaurer la productivité et la diversite sur des pentes abruptes. Une adaptation de la pratique impliquant l’abattage des tiges et leur brûlage a été appliquée à l’été et à I’automne de 1990. Environ la moitié des combustibles ligneux ont été consumes sur chaque station. Un éventail d’intensités de feu a été constate. La temperature de la flamme a approché 800°C mais le flux de chaleur dans le parterre forestier n’a atteint que 60°C à 5 cm. L’humus et la litière carbonisée restaient en place sur la majeure partie de la surface après le brfilage. L’évidence d’érosion du sol Ctait ponctuelle et reliée à des perturbations locales du sol. Aucune exportation de sol n’a été constatée. À la fin de la premiere saison de croissance, 23% des superficies brûlées Ctaient recouvertes par des plantes en croissance et 62% par des résidus de parterre forestier ou de debris ligneux. La coupe et le brûlage ont réduit l’évapotranspiration de sorte que le sol dans les secteurs traités est demeuré plus humide que sous les peuplements ajacents non coupes. L’ouverture des stations a provoqué une augmentation de la temperature du sol de 2 à 5°C à 10 cm durant les 16 premiers mois après l’application du traitement.

[Traduit par la redaction]

Introduction

Forests in the southern Appalachian Mountains have been shaped by disturbance. Precolonial forests were disturbed by windstorms, floods and landslides, insect and disease epidemics, and Native American and lightning-caused tire (Komarek 1974; Van Lear and Waldrop 1989). These disturbances often were large, but led to regeneration of the forests and so determined their natural structure and composition (DeVivo 1991). However, colonial through present-day forest utilization has selectively removed the higher value trees from the upper, less productive slopes. Insect, disease, and maturity decimate the remaining forest, while protection from catastrophic fire may have prevented a natural means of forest ecosystem regeneration. The net result is a significant area of dense stands of mountain laurel (*Kalmia latifolia* L.) on upper, drier slopes, which competes with and substantially limits reproduction and growth of both woody and herbaceous vegetation (Van Lear and Johnson 1983).

Fell and bum is now being prescribed as a silvicultural treatment to reduce shrub competition and restore mixed hardwood forest on low-diversity, low-productivity xeric mountain sites. Previous studies used understory burns to temporarily reduce dense ericaceous shrub competition in a moist-site southern Appalachian hardwood forest (Hooper 1969) or to encourage oak regeneration (Teuke and Van Lear 1982; Van Lear 1991) and improve wildlife habitat (Van Lear and Johnson 1983). Fire with cutting was used in low-quality mixed-hardwood stands to suppress hardwood competition and favor planted pine (Danielovich et al. 1987). The fell and bum treatment, as proposed by Abercrombie and Sims (1986) and Phillips and Abercrombie (1987) for southern Appalachian pinelands, consists of removing merchantable timber and cutting the remaining woody stems in the spring after leaf out. As the cut vegetation dries, new shoots sprout from cut stumps and from roots. A midsummer bum consumes the slash that impedes planting of pine seedlings and reduces the vigor of the sprouts that compete with pine.

The fell and bum treatment reported here differs from previous fell and bum studies because the goal was to encourage

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‘Author to whom all correspondence should be addressed.

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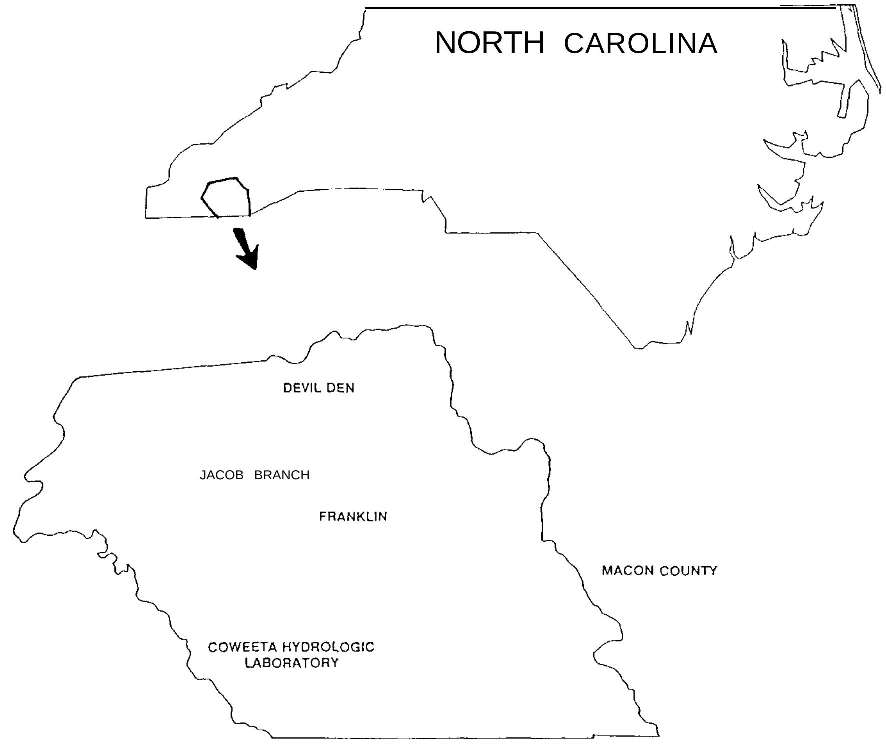

FIG. 1. Location of fell and burn study sites: Devil Den and the two sites at Jacob Branch.

hardwood regeneration, not to emphasize pine. Also, time of cutting and burning is later because the growing season begins later on the upper mountain slopes. Anecdotal experience in the mountains holds that cutting alone, without fire, results in essentially the same type of stand, still dominated by *K. latifolia*. Growing-season fires are preferred because they reduce *K. latifolia* sprout vigor and encourage tree species such as oak to sprout from below ground and thereby produce stronger reproduction (Roth and Sleeth 1939; Sanders and Van Lear 1987). Growing-season fire is easy to control in the moist southern Appalachians because a ground fire will die when it reaches the shade of the adjacent uncut forest and the soil disturbance and expense of constructing firelines can be avoided. Where natural regeneration lacks full species distribution, seedlings may be planted.

Increasing use of the fell and burn treatment has refined the methodology for land managers and produced some desirable results, but detailed questions remain. How does the treatment impact the nutrient status of the site? What is the vegetation response? Are diversity and productivity improved? Is erosion increased? Are soil surface characteristics changed by fire and how does this influence soil moisture and temperature, nutrient cycling, and plant regeneration? A study was initiated by Coweeta Hydrologic Laboratory and cooperators to answer these ecologically related questions for the southern Appalachian Mountains. Treatments imposed and sites selected are typical of those used by public and private land managers in this region. This was the most intensive detailed study done to date of on-site and off-site impacts of prescribed fire in eastern United States mountain hardwood forests.

This paper describes the treatment and burn characteristics, evaluates erosion, and quantifies changes in soil moisture and temperature.

Materials and methods

Experimental sites

Three sites, at least 5.25 ha each, were chosen from areas previously selected and approved for prescribed burning under the Land Management Plan for the Wayah Ranger District of the National Forests in North Carolina. All sites were north of Franklin, Macon County, in the Nantahala Mountains of western North Carolina (Fig. 1). Selection criteria were (i) vegetation typical of *K. latifolia* dominated forest stands; *(ii)* similar soil depth and texture across sites; *(iii)* perennial streams for measuring off-site impacts; and (iv) access to facilitate instrumentation and repeated measurements. Typical sites tend to be on upper slopes so only one of the selected three sites had stream sampling.

The three sites were designated as Jacob Branch East (JE), Jacob Branch West (JW), and Devil Den (DD). Each site extended from a ridgeline down a west- to southwest-facing slope. Midelevations were about 765 m for 200 m long slopes at JE and JW and 1040 m for the 96 m long slope at DD. Steepness ranged from 35% on JW to 45% on JE. Soils were in the Cowee-Evard complex and were fine loamy, mixed, mesic Typic Hapludults with infrequent rock outcrop and having a sandy clay loam layer approximately between 30 to 60 cm depth. The overstory vegetation was mainly scattered *Pinus rigida* Mill., *Quercus coccinea* Muenchh., and *Quercusprinus* L. with basal areas from 9 to 19 m^2/ha. The shrub understory of *K. Zatifolia* had basal areas of 18 to 3.5 m^2/ha. A total of 65 species of herbs and grasses were identified, with the greatest variety at the DD site. Vose and Swank (1993) described stand structure and biomass in detail.

Even though the stands were lightly stocked with stems greater than 10 cm diameter, the annual diameter growth of individual trees was poor. Rings measured on disks cut from eight dominant Q. *prims* stems on JE showed that these trees ranged from 72 to 168 years old. The largest one was only 38.4 cm in diameter, and the oldest was 22.6 cm. Rapid growth ended 35 years earlier. Thereafter, diameter growth averaged 55% of previous rates. Many P. *rigida* stems were dead or dying from an extant southern pine beetle *(Dendroctonus frontalis* Zimm.) epidemic. The density of stems >10 cm diameter

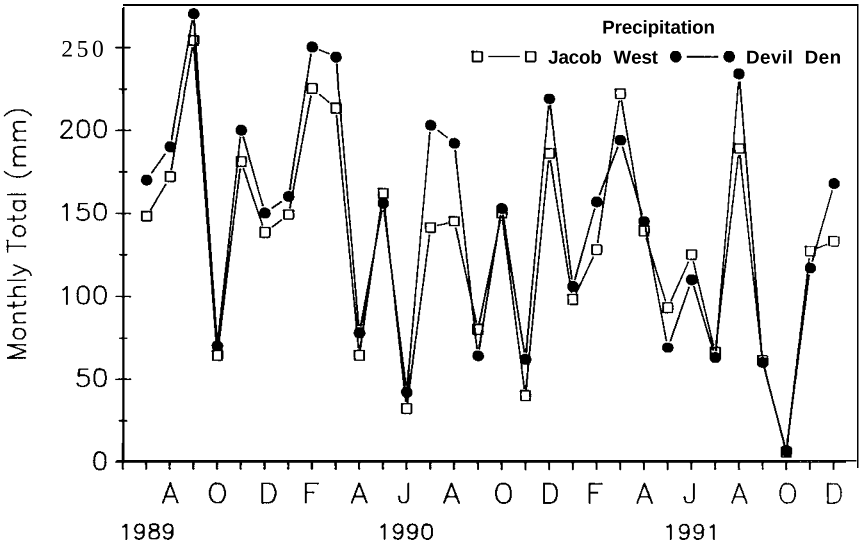

FIG. 2. Precipitation at fell and bum sites during the study period. For the two Jacob Branch sites, data from Jacob Branch West were used.

was about 450 to 470 stems/ha across all three sites. The density of shrubs on DD was 25 454 stems/ha, about twice that on either JE or JW. All sites had signs of previous logging and may have been grazed. The JE and JW sites were partially logged in 1972, and disturbed soil profiles in JW suggest a cultivation history, probably 60 or more years ago.

Each site was divided into a control area and a 4-ha treatment area. In summer 1989, 0.05-ha plots (15 x 33.3 m) were established with their long axes parallel to the contour. Plot locations were chosen to sample across both the width and elevation of each site. There were 4 plots in each control and 5 in each treatment area, for a total of 27 plots. All vegetation sampling, surface cover, and soil moisture, temperature, and chemistry measurements were concentrated in these plots. Erosion, fuel load and consumption, and smoke chemistry were measured adjacent to the permanent plots.

All vegetation was cut by chainsaw in summer 1990. A low stand value on such sites eliminates logging and associated risk of soil disturbance. JE was cut first, between June 20 and July 24. JW was completed by August 7 and DD by August 29. Before the cutting treatment, all vegetation (including herbaceous) was measured by species on each plot. Total woody biomass and nutrient pools were estimated (Vose and Swank 1993). Immediately before the September burns, fuel loading was measured (Ottmar and Vihnanek 1991). Biomass and nutrient concentration of foliage, herbaceous vegetation, and litter and humus layers were determined from samples taken before and after burning (Vose and Swank 1993).

On February 6, 1991, ***Pinus strobus*** L. seedlings were hand planted at 5 x 5 m spacing on JE and JW. Survival, growth, and physiological response of seedlings to competition are reported by Elliott and Vose (1993). Clinton et al. (1993) report the structure and composition of nearby stands resulting from similar fell and burn treatments made 13 years earlier.

Climate, erosion, and soil measurements

Monitoring of climate and precipitation stations was started on JW and DD in June 1989. Climate stations had sensors in the control and treatment areas that were adjusted during the study to 1.5 m above current vegetation. Solar radiation, wind speed, air temperature, soil temperature, and relative humidity were sampled each minute and summarized hourly by electronic data loggers. Weekly precipitation amounts and storm intensities were measured by pairs of 8-in (1 in. = 25.4 mm) standard and recording (dual-traverse chart) gages. Precipitation chemistry samples were collected with polyethylene funnels and bottles (Swank and Henderson 1976) at the gaging sites.

Precipitation recorded at the study sites (Fig. 2) was correlated with that measured at Coweeta Hydrologic Laboratory to obtain long-term estimates of mean annual precipitation, equalling 1355 mm at JE and JW and 1480 mm at the higher elevation DD site. Except for above-average precipitation in the early pretreatment months, on-site totals fluctuated around estimated long-term monthly means throughout the study. Similarly, mean annual temperatures for the two locations were calculated to be 12.9 and 11.8°C. Most mean monthly air temperatures during the study (Fig. 3) were up to 4°C above the estimated long-term means.

To estimate erosion, fabric sediment traps (Dissmeyer 1982) were installed across ephemeral channels near the lower edge of each site. Four were placed directly below the felling boundary in October 1989 before cutting, and four were added inside the treated areas before any sediment movement was observed after the bum. Silt-fence material was supported by posts 0.8 m high with its lower edge embedded in the soil. Traps ranged from 4 to 12 m wide. Depth and area of accumulation were checked weekly, and depth was measured at 6 to 10 markers distributed within the first meter up slope of each fence line. Samples of accumulation were collected in August 1991 and analyzed for percent mineral versus organic content by weight using a Perkin-Elmer 2400 CHN Analyzer and by volume using flotation and settling in a water column. Surface infiltration rates were determined before and after the fell and burn treatment using a 10 cm diameter double-ring intiltrometer.

In June and September 1991, postburn surface cover was determined from a pair of 33.3 m long transects across each burned plot. The intercept lengths of bare soil, rock, intact forest floor, wood in contact with the surface, and live plant were measured and summed across each transect to determine percentage of surface for each cover type. Sampling coincided with the beginning and ending of the first full growing season after burning. Coefficient of variation of cover percentages between transects ranged from 20% for intact forest floor to 50% for live plant.

Soil moisture measurements started in August 1989 at JE and JW and in November 1989 at DD. Weekly determinations of percentage by volume soil moisture were made on each plot at O-30 and 30-60 cm depths using the time domain reflectometry method (Topp et al. 1980). These depths were selected to define the moisture content in the sandy-loam surface horizon and in the sandy clay loam horizon below.

As part of the larger study, porous cup lysimeters were installed at the same two depths on each plot to collect weekly soil water samples for nutrient analysis (Knoepp and Swank 1993). Weekly precipitation

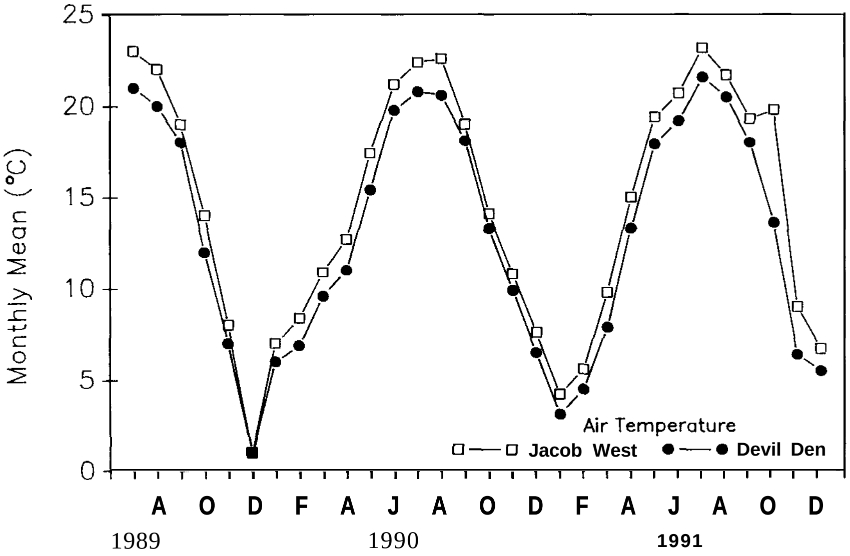

FIG. 3. Air temperature at fell and burn sites during study period. For the two Jacob Branch sites, data from Jacob Branch West were used.

collected at the two climatic stations and stream water samples collected below control and treatment areas at JE were analyzed for the same ions as soil-water samples. Standing pools of soil nutrients were measured in the upper two soil horizons in all plots before and after burning and rates of nitrogen mineralization and nitrification were determined (Knoepp and Swank 1993).

Soil temperatures were measured weekly at depths of 10, 30, and 60 cm below the top of consolidated forest floor (Oe layer) on each plot using a digital meter and thermistor probe. The 1 O-cm measurements began 5 months prior to the burn, while the measurements at the deeper layers started immediately after the burn.

Prescribed burn

The Fire and Environmental Research Applications Group of the Pacific Northwest Research Station, USDA Forest Service, characterized the fuel loading, fuel consumption, and heat pulse into the soil during the bums (Ottmar and Vihnanek 1991). They established 18 sample points in the treated portion of each site near the permanent plots. Fuel load was described by fuel moisture time-lag classes (Deeming et al. 1977). The l-h class was dead herbs and grasses and wood up to 6 mm diameter. Larger classes and diameters were as follows: 10 h, 6 to 25 mm; 100 h, 25 to 75 mm; and 1000 h, 75+ mm. The 100- and 1000-h time-lag fuels were measured on eighty 15-m transects radiating out from the sample points. The l- and 10-h time-lag fuels were measured over 1- and 2-m radii. Forest floor, litter, branch, and wood samples were analyzed for moisture content and wood density. Eleven steel pins and 5 ceramic tiles coated with heat-sensitive paint were inserted into the forest floor around each sample point to mark the top of the duff layer (the organic material below the loose litter, i.e., the Oe and Oa layers). The paints melt at 45 and 60°C, a range that brackets the thermal lethal point for most plants (Hare 1961). The duff pins provided two pieces of information (Ottmar and Vihnanek 1991): *(i)* the distance between the top of the pin and the charred forest floor was converted to a volume measure of consumption of humus; *(ii)* the distance down to the change in thermal paint was a measure of penetration of lethal temperature. The depth of loose litter (Oi) was not included in this measurement, but change in weight of forest floor components was determined by Vose and Swank (1993). Data loggers buried in the treated area recorded soil and flame temperatures during each fire.

The Fire Chemistry Project, Intermountain Research Station, USDA Forest Service, sampled smoke emissions during the JW and DD fires (Ward et al. 1991). Two temporary 14-m towers on each site held sampling units that collected particulate and gas samples for 40 min and measured temperature, selected gases, and vertical smoke velocity, for a total of 100 min. Sample collection began as the fire reached each tower and continued for 10 min during each of the flaming and intermediate stages and for 20 min during the smoldering stage (see Ward et al. (1991) for sampling and analysis protocol). On JW, the instruments were below plots 3 and 4, sampling along an elevational gradient. At DD, the instruments were at about the same elevation on the slope near plots 2 and 4.

Wayah Ranger District managed the burns as well as the vegetation cutting that preceded. Standards and guidelines specified in forest management planning for National Forests in North Carolina were followed (USDA Forest Service 1987; Southern Forest Fire Laboratory Staff 1976). Guidelines were as follows: to schedule burns when moisture in 1000-h fuels was >25%, l-h fuels were dry but forest floor under the litter was moist (>50% by weight; Brown et al. 1985); and 10-h fuels had 10–12% moisture, while similar-sized materials outside the cut area were above 14%. These fuel moisture guidelines are often met 30 to 60 days after cutting and 3 days after a soaking rain (Abercrombie and Sims 1986).

Because the three sites were cut in midsummer, the burns were later than those described in other published reports of the fell and burn technique on lower elevation sites. The three sites were burned on separate days from September 18 to 21, 1990, beginning 3 days after a 48-h precipitation period that totaled 38 mm and ending 1 day before a 31 mm rain. About 80% of the 134 storms in an average year are smaller than 30 mm (Swift et al. 1988). Site-specific fire weather forecasts were received each morning from the National Weather Service. Ignition began with a test fire at the highest point in the cut to verify smoke production and wind dispersal predictions. After a backfire along the ridgeline and down both flanks established a protective zone, slash across the lower cutting boundary was ignited and a head fire moved rapidly upslope.

Statistical analysis of soil moisture and temperature

Soil moisture content was averaged over pretreatment months to obtain an initial moisture condition for each plot to use as a treatment versus control covariate in subsequent analyses. Moisture varied consistently between plots within a site. Soil moisture tended to be lower in the upper slope plots and higher in plots that were near the heads of ephemeral channels. These differences are assumed to be largely unaffected by treatment. An analysis of covariance was conducted at the whole-plot level to determine the significance of any difference in treated and control moisture levels in the pretreatment period. Separate analyses were conducted for each depth. In all cases, the

TABLE 1. Fuel loading and consumption (means with standard errors in parentheses) for Jacob Branch East (JE), Jacob Branch West (JW), and Devil Den (DD)

(A) Fuel loading

Fuel	JE (Mg/ha)	JW (Mg/ha)	DD (Mg/ha)
Duff	35.0 (2.56)	23.2 (1.60)	39.2 (2.32)
O-6 mm diam.	13.0	9.9	12.6
6-25 mm diam.	21.6 (3.02)	16.4 (2.85)	21.1 (2.17)
25-75 mm diam.	38.1 (1.29)	23.1 (1.17)	22.6 (0.81)
>75 mm diam.	93.0 (5.59)	65.5 (5.20)	40.6 (6.03)
Total woody	165.7	114.9	96.9
Total fuels	200.7	138.1	136.1

(B) Fuel consumption

	JE		JW		DD	
Fuel	Mg/ha	%	Mg/ha	%	Mg/ha	%
Duff	23.3 (1.63)	66.6	10.8 (0.59)	46.6	11.9 (0.86)	30.4
O-25 mm diam.	34.6	100.0	26.3	100.0	33.7	100.0
25-75 mm diam.	37.4 (6.41)	98.2	20.6 (2.12)	89.2	19.1 (2.14)	84.5
>75 mm diam.	29.4 (5.17)	31.6	9.6 (1.07)	14.7	5.8 (0.63)	14.3
Total woody	101.4	61.2	56.5	49.2	58.6	60.5
Total fuels	124.7	62.1	67.3	48.7	70.5	51.8

NOTE: Duff is all forest floor above mineral soil except loose, unconsolidated litter (Oi layer). The 0–6 mm diameter loading was modeled from 6–25 mm measured loading, and the combined O-25 mm diameter fuel classes were presumed to be totally consumed.

covariate was highly significant ($p < 0.005$) and was included in the split-plot analysis of variance models.

Although time is a repeated measure factor (multivariate analysis of variance), under appropriate conditions it can be treated in a univariate manner in a split-plot analysis of variance. Thus, a split-plot analysis of variance was used to test for month and treatment by month interactions for each site (JE, JW, and DD) at O-30 and 30-60 cm soil depths. The whole-plot factor was treatment applied to plots and the split-plot factor was time identified by month. The whole-plot error was obtained from the average pretreatment soil moisture content for each plot nested within treatment, the plot(treatment) term in the analysis of variance tables.

Split-plot factors were tested. A contrast was tested for the difference between control and treated during the post-treatment growing season months, April through September 1991. This contrast should be considered somewhat liberal, because we used only the split-plot error term rather than a combined or weighted average of both whole-plot and split-plot error. A significant difference ($p < 0.05$) in the "linear slope difference" indicates that the burned and control areas had different drying patterns during the post-treatment growing season.

For soil temperature, an analysis of covariance was conducted at the whole-plot level to determine the significance of the pretreatment soil temperature at 10 cm soil depth. In all cases, the covariate (pretreatment soil temperature) was not significant; thus it was not included in the analysis of variance models. A split-plot analysis of variance was used to test the difference between control and treatment soil temperature at both 10 and 30 cm soil depths, similar to the procedures for the soil moisture analyses. The whole-plot error term was plot nested within treatment, the plot(treatment) term in the analysis of variance tables. Contrasts were excluded from the soil temperature analyses because soil temperature was consistently higher on treated than control plots from April through October at all sites. Thus, the test of treatment at the whole-plot level sufficiently addresses the question of treatment effect on soil temperature.

Results

Burn characterization

Observed mean daily air temperatures averaged 20 to 21 °C during the preburn drying period. Cut vegetation cured for 55 to 89 days on JE and an average of 50 days on JW before burning. DD fuels cured for less than 44 days and leaves in the underside of brush piles were still uncured at the time of burning. In addition to having drier fuels, the total fuel load was 45% greater on JE than on either JW or DD (Table 1). Ignition at all three sites was delayed until midday because of morning fog.

JE was burned on September 18, 1990, after 33 mm of rain fell between 05:45 on September 13 and 03:00 on the 15th. On September 11, soil moisture in the top 30 cm averaged 22% by volume, and the day before ignition duff moisture was 77%. At time of ignition, air temperature was 22°C, relative humidity was 50%, and wind was peaking at 4.5 m/s from the south. Fuel moisture sticks held 11% moisture in the burn site and 17% in the adjacent forest. The fire ran rapidly up slope, producing flame heights in excess of 10 m and a large cloud of white smoke. Flame duration was short; temperature peaks in the slash lasted 2 min or less, and the flaming phase for the whole slope was essentially over in about 20 min. The heat pulse into the soil lasted 10 min at about the soil-humus interface. The flame temperature, and thus the rate of burn, were higher ($p < 0.10$) at this site than at the other two (Table 2). Duff and woody fuel moistures, heat pulse, and flame temperatures were measured by Ottmar and Vihnanek (1991).

JW was burned the next day. Air temperature and relative humidity, 24°C and 55%, respectively, were slightly higher than for the JE burn, and wind peaked at only 1.6 m/s. Fuel moisture sticks were also wetter (14% in the-open and 19% in the forest), but duff moisture was only 59%. Again, the burn was rapid and hot, with flame temperatures peaking at 694°C in the slash (Table 2) and 280°C at 10 m above the surface (Ward et al. 1991). The fire died quickly, as shown by reductions in both particulate and CO_2 release rates across the flaming, intermediate, and smoldering stages. Most of the gaseous carbon was released as CO_2, an indication of high fuel consumption rates (Ward et al. 1991).

DD was burned 2 days later on September 21, 1990. Air temperature was 25°C and relative humidity was 74%, considerably higher than during the other two burns. Wind was about 1 m/s. Soil moisture in the top 30 cm averaged 26%, and duff moisture was 99%. Fuel moistures for woody material <75 mm and duff were greater than at either of the other two burns (Table 2). This third fire had the lowest flame temperatures (not significantly different from JW), but the 60°C heat pulse penetrated about as deep as the more intense burn on JE (Table 2). The burning front seemed to move more slowly up the comparatively short DD slope. Vertical wind speed, CO_2 and particulate releases, and temperature of the smoke during the flaming stage were all less than during the JW burn (Ward et al. 1991).

Fine fuels (<25 mm diameter) were completely consumed by all three burns (Table 1) except on the edges of cut areas, which had been partly shaded (Ottmar and Vihnanek 1991). Essentially all the 25-75 mm diameter fuels were consumed

TABLE 2. Preburn fuel moisture of woody slash and forest floor with temperatures during burn (means with standard errors in parentheses) for Jacob Branch East (JE), Jacob Branch West (JW), and Devil Den (DD)

Burn site	Fuel moisture by diameter class (%)				Heat penetration (mm)		Mean peak flame temp. (°C)
	6-25 mm	25–75 mm	>75 mm	Duff	45°C	60°C	
JE	23	30	47	77	58	45	812
	(1.96)	(2.00)	(1.10)	(9.27)	(5.38)	(2.39)	(46)
JW	16	23	44	59	43	37	694
	(2.12)	(2.83)	(1.30)	(13.17)	(2.63)	(1.67)	(33)
DD	28	38	46	99		44	630
	(0.57)	(0.71)	(1.10)	(15.80)		(2.11)	(78)

NOTE: The 45°C heat penetration data are not available for DD burn.

by the JE burn, while 89 and 84% were consumed on JW and DD. Another measure of the difference in fire intensity was a 32% consumption of >75 mm diameter large woody material on JE, while only 14% of this size class was burned at the other two sites. Mean diameter reduction of logs on JE was 29.2 mm. Table 1 lists the fuel loading and consumption by size class.

Simard (1991) stated that fire severity is best measured by impacts on the ecosystem. Wells et al. (1979) described severity in terms of changes in forest floor (humus and soil). Overall, the severity of these burns would be classed as light because the forest floor remained essentially intact over most of all sites and components such as acorns were singed but easily recognizable. Having burns of light severity is the present operational goal of managers for this fell and burn treatment. However, severity was moderate on portions of each burn where topography increased the fire intensity, causing greater consumption of forest floor in patches of about 0.50 ha or less. Effects were severe in a few spots where ribbons of soil were exposed after partly decomposed logs in contact with the forest floor ignited and smoldered until consumed. The mean reduction of duff thickness in the forest floor ranged from 67% on JE to 30% on DD (Ottmar and Vihnanek 1991). The mean thickness of remaining duff was 11 mm on JE and JW but 26 mm on DD. Duff reduction estimates exclude consumption of the overlying loose litter above the duff, which is reported by Vose and Swank (1993), who found that the Oi (litter) layer was equal in biomass to 50% of duff weight. Thus one-third of the forest floor weight reduction occurred at the Oi layer of all sites.

Erosion

No soil movement to the sediment traps was observed before felling and burning. Although the 18 mm of precipitation that fell on the second day after the JW burn included peak intensities of over 30 mm/h, only minor and very localized movements of burned plant fragments and soil were observed throughout all sites. About 25% of the storms recorded at Coweeta Hydrologic Laboratory included intensity periods over 30 mm/h (Swift et al. 1988). The fibrous humus layer was charred on the surface but one-third or more remained unburned and the forest felt spongy when walked upon. Even where elevated large woody material was consumed, the forest floor below remained intact. The potential erosion sources of bare soil exposed by smoldering logs have not produced any sediment movement off site. Sediment did move from patches of exposed soil at pre-existing wind-thrown root mats, animal burrows, and disturbances created by research activities, but the material was trapped within a short distance by residual forest floor and wood debris. Dry ravel and mass failure were never observed on any of the three sites.

Herbs, tree seedlings, stump sprouts, and grasses appeared as early as 19 days after the burns, and a diverse mixture of wild flowers, woody sprouts, and open-field weeds grew in spring 1991. In June 1991, live plants covered an average of 16% of the sites. By October, the mean plant coverage for the three sites had grown ($p < 0.001$) to 23%. As vegetation spreads, it provides a second cover for the residual forest floor. Surface rock was a small component, being less than 2%, and wood in contact with the forest floor covered a consistent 7 to 8% of all sites. Early in the post-treatment period, intact forest floor ranged from 55% on JW to 73% on DD, but after 11% reduction ($p < 0.001$) was still the major component (55%) of surface cover in September 1991. Some breakdown of the forest floor increased soil exposure ($p < 0.001$) from 9 to 14% between June and September. Before cutting, virtually all of the surface was covered both by intact forest floor and by vegetation canopy.

Of the eight sediment traps on the three sites, only two collected transported material, in each case less than 1 m^3. Potential source area above these two traps exceeded 400 m^2 each. In fall 1991, the observed maximum bare soil exposure of 31% was on JW plot 2. However, no soil or charcoal reached the sediment trap in the uncut forest immediately below this plot. Carbon represents 7 to 14% by weight of the material trapped by the two fences, but the volume of carbon exceeded 40%. Initially, much of the trapped material was light charcoal particles. Later, fibrous fragments of forest floor moved down slope.

On JE, the first measurable amount of deposition, 0.41 m^3, occurred during the week of April 23-30, 1991, when three storms totaled 52 mm. One, a 12-mm afternoon thundershower, had an intensity of about 50 mm/h. About 10% of storms contain that intense rainfall rate (Swift et al. 1988), and only two other storms with high intensities occurred at JE and JW during this study. Two days after the burn, 8 mm fell at the rate of 50 mm/h. No soil was collected in traps, but waves of carbon were observed on the slope surface akin to step formation of debris described by Dissmeyer and Foster (1980). The other intense storm on August 9, 1991, raised the accumulation at the one JE trap to 0.64 m^3 when 50 mm rain fell in 14 h. Almost half of the amount of this storm came in two intensity periods of over 50 mm/h. The only erosion event at DD occurred on June 16, 1991. It deposited 0.49 m^3 of soil and charcoal in a storm of 37 mm which contained a maximum intensity period of 77 mm/h. Even though these sites

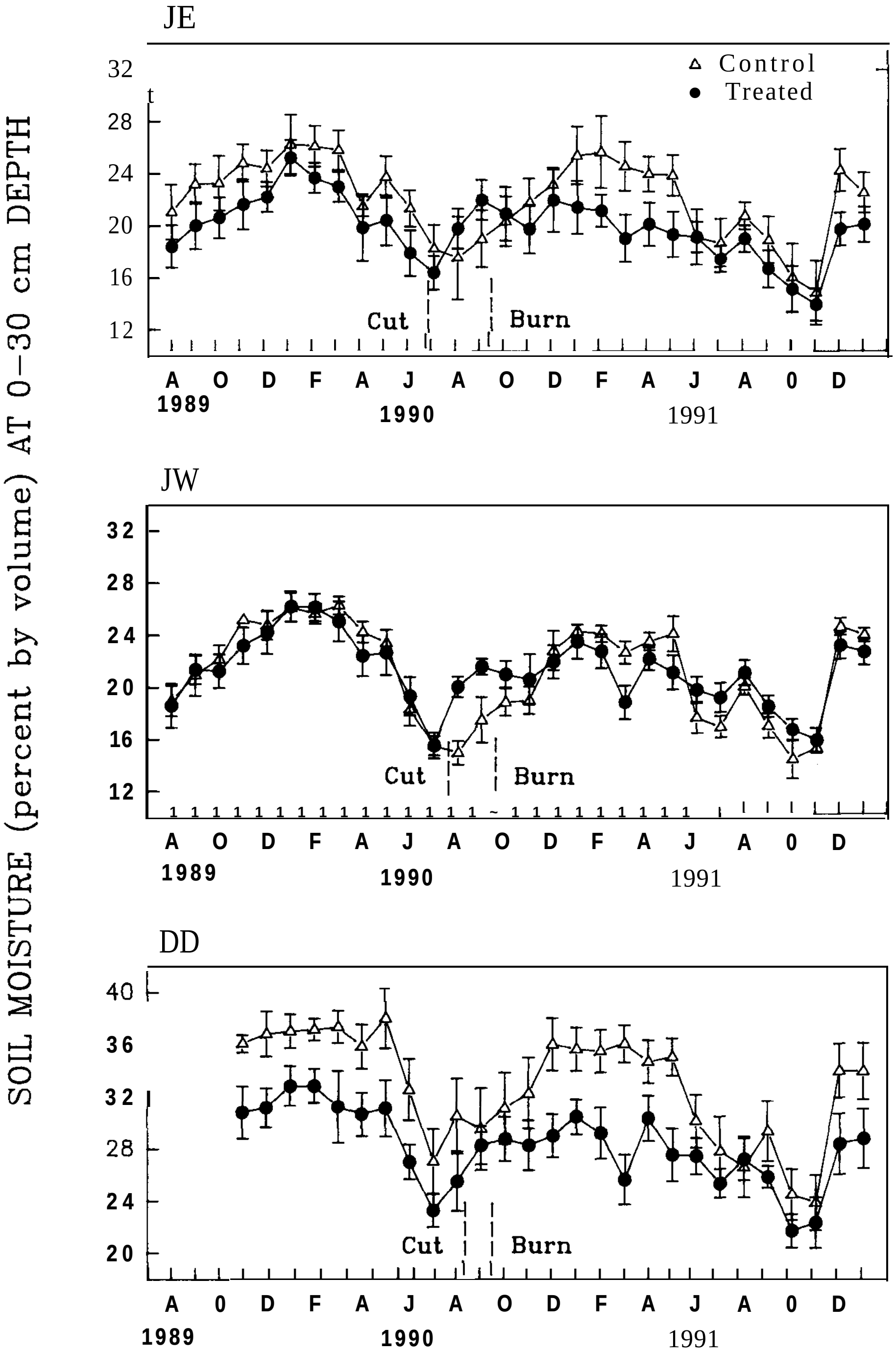

FIG. **4. Monthly means** of weekly percent soil moisture, by volume, over the 0 to 30 cm layer averaged across five plots in the fell and burn treatment and four plots in the uncut control for three sites: Jacob Branch East (JE), Jacob Branch West (JW), and Devil Den (DD).

received 10 other storms totalling 30 to 70 mm each, storms with intensities less than 50 mm/h did not move measurable amounts of charcoal or soil. In each case where sediment was moved, antecedent soil moisture in the plot nearest the sediment trap was 20 to 25% by volume.

Soil moisture and soil temperature

Soil moisture was 8% higher on DD than on JE and JW, and there was an obvious difference between treated and control plots at JE and DD in the 11-month pretreatment period (Fig. 4). Before cutting, JE and JW soil moisture ranged from a high of 26% in January to 16% in July at the O-30 cm level. For the treated plots, 30-60 cm layer was 2 to 4% wetter than the O-30 cm layer on JE and JW, but moisture contents were similar for the two depths on DD (Fig. 5).

From immediately after cutting until October, when the major evapotranspiration season ended, soil moisture increased at all treated sites and at both depths relative to the pretreatment relationship (Figs. 4 and 5). At DD, the soil moisture increase occurred later in response to the later cutting treatment. By midwinter, soil moisture had returned to pretreatment relationships, and by early spring soil moisture in the O-30 cm

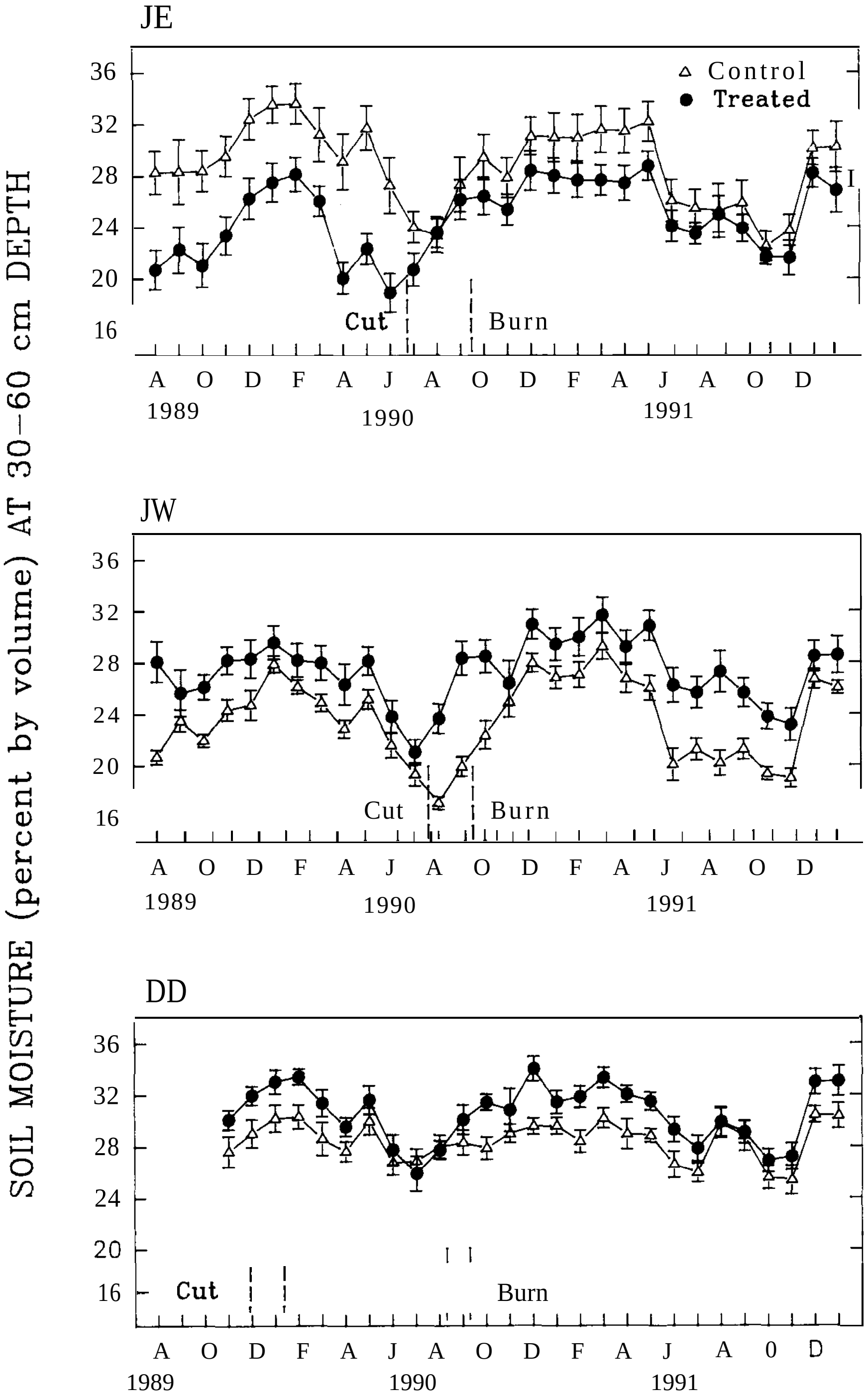

FIG. 5. Monthly means of weekly percent soil moisture, by volume, over the 30 to 60 cm layer averaged across plots as in Fig. 4.

layer was drier in the treated areas relative to the control (Fig. 6). Growing-season soil moisture differences developed again after May 1991, but adjusted differences between treated and control areas were only half those found immediately after cutting. The growing season response extended into October and November. There was a significantly different drying pattern during the April-September growing season at JW and DD, but there was not a significant difference in growing-season moisture level at JE (Table 3).

In the 30-60 cm zone, soil moisture response to treatment in the first full growing season was inconsistent across sites (Fig. 5). In JE and JW, increases in the treated plots were similar in magnitude to the period immediately after cutting and twice the increases in the upper soil layers. Soil moisture increases at 30-60 cm were not apparent for DD. The contrast test shows that there was a significant increase in soil moisture on JE and JW treated plots relative to controls during the growing season but no differences at the DD site (Table 3). Increased soil moisture contents in the treated sites were mirrored in larger soil water volumes collected by lysimeters.

Immediately after felling, weekly 10-cm depth soil temperatures rose 0.5 to 2°C above those in the controls and averaged

TABLE 3. Split-plot analysis of covariance with contrast to examine the difference in treatment soil moisture content during the growing season (April-September 1991) at O-30 and 30-60 cm depth for Jacob Branch East (JE), Jacob Branch West (JW), and Devil Den (DD)

		Significance ($p > F$)					
		O-30 cm depth			30-60 cm depth		
Source	df	JE	JW	DD	JE	JW	DD
Whole-plot factors							
Treatment	1	0.6012	0.1686	0.2449	0.2803	0.1198	0.2178
Covariate	1	0.0035	0.0011	0.0001	0.0036	0.0001	0.0004
Error plot(treatment)	7						
Split-plot factors							
Month	17	0.0001	0.0001	0.0001	0.000 1	0.000 1	0.0001
Treatment x month	17	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Error	119						
Contrast							
Linear slope difference	1	0.1035	0.0029	0.0043	0.0053	0.0002	0.5625

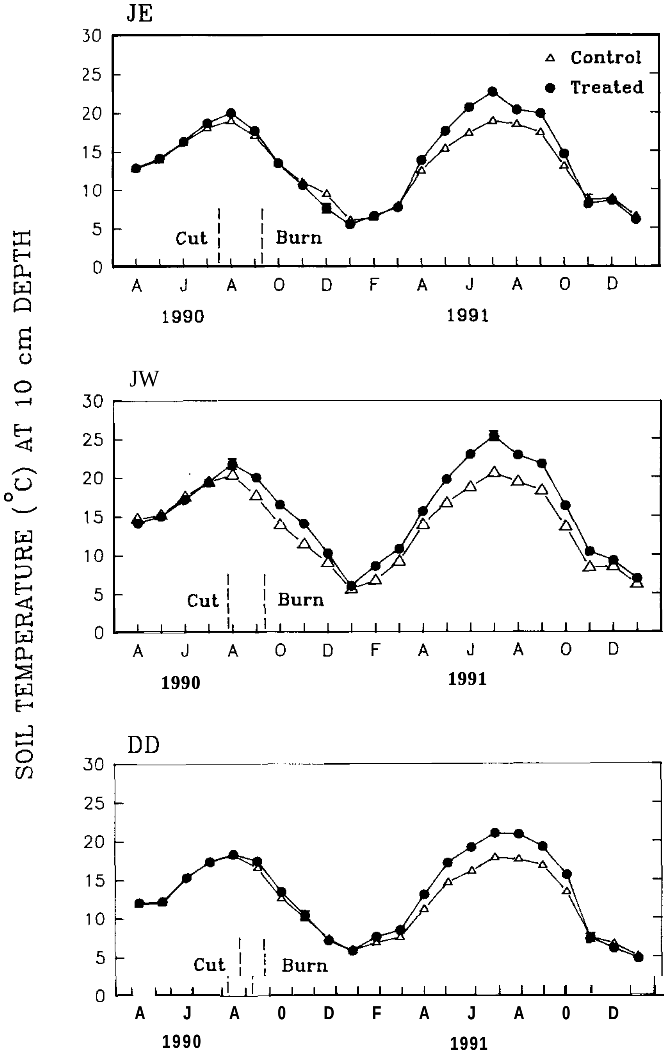

FIG. 6. Monthly means of weekly soil temperatures at IO-cm depth averaged across plots as in Fig. 4.

3°C higher on JW after the burn. Monthly mean near-surface temperatures (Fig. *6)* show a smaller effect because measurements for overcast and sunny days are averaged. Differences were small in both winters and greatly expanded in the summer of 1991, the means being 5°C warmer for JW burn plots in July. This resulted in a significant treatment by month interaction for all sites (Table 4). The standard error bars for most points in Fig. 6 are smaller than the plotting symbol.

Soil temperatures at 30 cm depth were 4 to 5°C higher in treated than in control plots from April through October 1991 at all three sites (Fig. 7). Differences were smaller from November through March. Only on JW did soil temperatures at 30 cm show a treatment effect in the first fall after felling and burning. The soil temperature analyses of variance for 10 and 30 cm led to equivalent conclusions.

Discussion

As is true for most fell and burn treatments in the southern Appalachian Mountains, those in our study were done later in the year than were studies previously cited for the southern Appalachian foothills and upper Piedmont. As a result of the shorter drying period, the light fuels on DD were incompletely dried before that burn. The range in burn conditions across these three sites resulted in a variety of responses reported in this and associated papers. An advantage that might be achieved by burning in August rather than late September would be that rapid-sprouting vegetation has an opportunity to provide some immediate ground cover before winter. Logs were not removed as part of our treatments. Few merchantable stems were available, and our intent was to study the effects of the treatment without other causes of soil disturbances. The results were higher fuel loads in the largest size class and more debris to trap sediment. The land slope was steeper, mean annual precipitation greater, and the forest floor better developed than for many previously cited studies of fell and burn in the southern Appalachians.

Fire characteristics

Site configurations, fuel loading, and moisture levels led to different fire characteristics on the three sites. DD was on a long ridge with a relatively short slope length. JE had the steepest and longest slope, which accelerated the development of the head fire. JE also had 47% more fuel than JW or DD and a substantially larger loading in the >75 mm size class (Table 1). The humidity was lower and the wind speed greater for the JE burn, and 3 I % of the log component was consumed

TABLE 4. Split-plot analysis of variance for soil temperature at 10 cm soil depth at Jacob Branch East (JE), Jacob Branch West (JW), and Devil Den (DD)

Source	df	Significance (p >*F*)		
		JE	JW	DD
Treatment	1	0.1005	0.0001	0.0102
Error plot(treatment)	7			
Month	1.5	0.0001	0.0001	0.0001
Treatment x month	1.5	0.0001	0.0001	0.0001
Error	105			

compared with only 14% at the other two sites. The diameter of large woody material was reduced an average of 29 mm (see Hall (1991) for a discussion of the physics of limited consumption of larger fuels in high-intensity fires). The notably higher flame temperature (Table 2) and greater fuel consumption (Table 1) marked the JE fire as the most intense of the three. Total fuel loading was the same on JW and DD, but size distributions were different. JW had a greater component of large stems and less duff, while DD had twice the number of shrub stems as either JW or JE. However, the most important difference between the JW and DD bums was the high fuel and soil moisture on DD. The drying periods for JW was just under the guideline of 60 days, but above-average air temperatures probably contributed to low fuel moistures. DD vegetation had less than 44 days to cure and because of its higher elevation, received more rain in July and August (Fig. 2) and recorded about 1°C lower air temperatures. Smoke measurements of particulates and CO_2 release (Ward et al. 1991) confirmed that the DD bum was the least intense.

The depth of duff in the forest floor at JE was reduced from 33 to 11 mm. Temperature in the slash reached 800°C, but the 60°C heat pulse only reached 45 mm into the forest floor or 12 mm into the mineral soil. At the other extreme, slash temperatures on DD peaked at 630°C and heat penetrated only 7 mm into soil. With the slower moving fire on DD, the duration of soil heating was greater, but the high duff moisture of 99% on DD (Table 2) reduced consumption of this component to half that on JE. The lighter load of small-diameter woody fuels on JW may have reduced heating and heat penetration into the soil. The management goal was to complete the burns without deep penetration of heat into the organic forest floor and soil. We did not want to kill seeds, roots, or soil organisms. Except in spots where the forest floor was consumed, lethal temperatures penetrated less than 50 mm into the Oe and Oa layers. DeBano et al. (1979) noted that heat penetration depends upon duration of heating and soil moisture. Thus, the moist soils after rains and rapid progress of these growing-season burns acted to protect the soil ecosystem. The early revegetation was evidence that seeds and roots survived the bums. The density and ubiquity of open-field weed plants suggested that seeds were dormant in the forest floor and soil before the cutting and survived the fires. Higher mortality of ***P. strobus*** seedlings on DD may have been due to the thicker duff (26 mm) remaining on DD compared with both JE and JW.

Soil erosion

Forest land management plan standards and guidelines were followed to consume small woody debris without destroying the forest floor. The residual forest floor proved to be resistant to erosion over the range of bum intensities experienced. Hydrophobic conditions (Debano 1971) in the soil or residual forest floor were not apparent and did not function to create overland flow. First-season vegetation covered 23% of the surface. Intact forest floor and woody debris covered an additional 62% at the end of the first growing season. Douglass and Goodwin (1980) found that soil erosion was greatly reduced on gently sloping Piedmont lands when a cover of rocks, wood, and plants exceeded 60%. Soil erosion on these burned sites has been small in volume and localized in patches, and eroded material has remained on site.

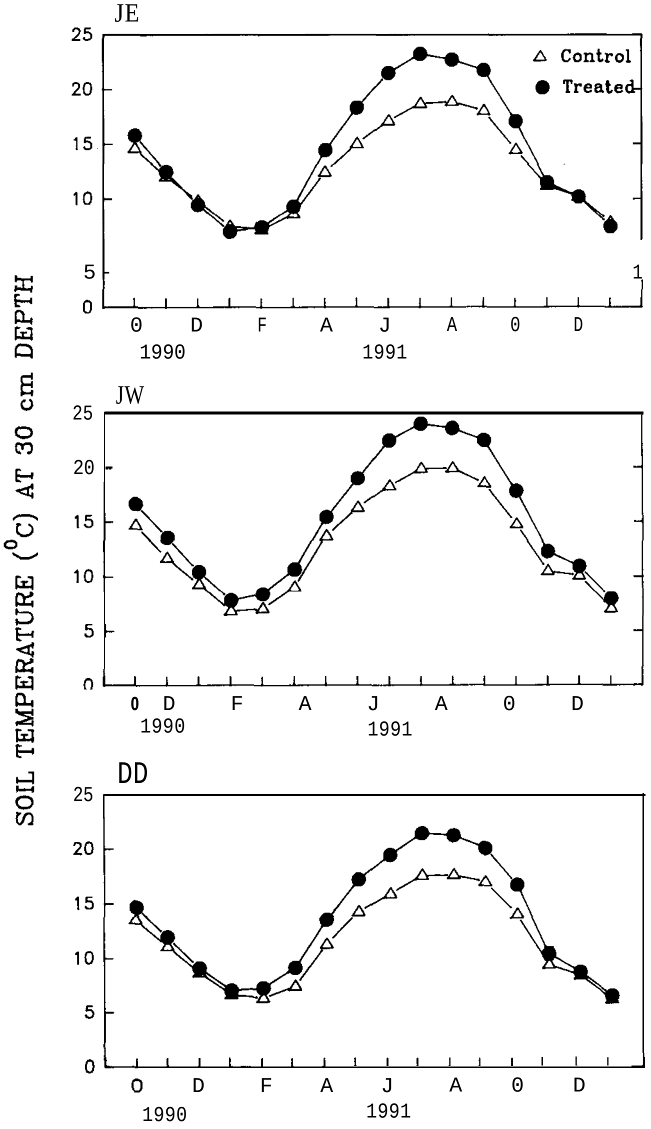

FIG. 7. Monthly means of weekly soil temperatures at 30-cm depth averaged across plots as in Fig. 4.

Tiedemann et al. (1979) cite reports of increased soil erosion following fire, but many of these studies were conducted in the western United States. Goebel et al. (1967), Neary and Currier (1982), Van Lear and Waldrop (1986), Van Lear and Danielovich (1988), and Shahlee et al. (1991) report little or no erosion after light to moderate intensity fires in the southeastern United States. However, bums in forests with a previous soil disturbance history can increase erosion (Ursic

1970; Van Lear et al. 1985; Van Lear and Kapeluck 1989). Soil disturbance caused by skidding of logs during the felling treatment will increase the probability of soil erosion after burning. The sample plot on DD that regularly registered the least soil moisture is in the zone that released sediment into a trap, suggesting that consumption of the forest floor was greater on this dry site. The small amount of sediment released and transported within our bum sites was produced by storms with rainfall intensities of 50 mm/h lasting for at least 15 min. The principal material moved during rains was light-weight charcoal particles. Infiltration rates averaged 5000 mm/h on these porous mountain soils, and all tests on the bum plots infiltrated in excess of 600 mm/h. Frost heaving in winter may accelerate the breakdown of the residual forest floor. Sediment was prevented from leaving the burned sites by unburned brush and undisturbed forest floor at the lower margins of the treatment areas. This result suggests that a best management practice might be to fell vegetation at the lower margin of the clearing, parallel with the contour and in contact with the forest floor, thus providing natural sediment traps.

Soil moisture and temperature

The microclimate of the new vegetation in the burned areas was warmer and the soil moisture higher than in the adjacent uncut areas. Soil moisture was greater at all depths in the late summer after cutting and increased even more after the bum. Klock and Helvey (1976) and Adams et al. (1991) found soil moisture increases of 6 to 10% after wild and prescribed fires. Like Adams et al. (1991), we found soil moisture increases in summer and fall, but soil moisture levels were similar between treated and control plots in the winter owing to precipitation and dormant vegetation. Reasons are unclear why burned plots indicated less soil moisture than controls in early spring, particularly in March 1991 at the O-30 cm level. Adams et al. (1991) found springtime reductions in soil moisture after cutting and burning, which they attributed to increased vegetation use in the open site. In our case, leafless vegetation could not be making heavy transpiration use of soil water in March. The difference in moisture near the surface was less in summer 1991, but soils at 30 to 60 cm were again moist in the JE and JW treated areas. This phenomenon may be caused by differences between water use and depth of rooting of *K. latifolia* on the control and of open-field vegetation on the treated plots. The latter may not access the heavier soil in the lower zone. Elevated soil moisture levels in late summer and fall, when moisture otherwise tends to reach the annual minimum, should extend the growth period for regenerating vegetation and accelerate microbial and decomposition processes dependent upon soil moisture.

Because soil moisture responses to withdrawal and recharge lag the start and end of the period of peak transpiration losses (Fig. 4), an analysis of soil moisture from June through November might be more pertinent to describe the effects of the growing season. It might rectify the apparent discrepancy between Fig. 4 and Table 3 of significance of treatment effect for JE. Covariance analysis was suggested because the means of the treated and control plots were obviously and consistently different for JE and DD sites during the pretreatment period. Soil moisture plots near ridges tend to be drier than most, and plots near the heads of ephemeral channels are wetter. At DD, three of the four control plots regularly had higher soil moisture in the O-30 cm layer than the median of all nine plots. These DD control plots are near the head of the valley, and their slope distance to the ephemeral channel was less than all but the wettest plot in the treatment area. To a lesser extent, control plots on JE are also in topographically moisture locations, while an even balance was achieved between wet and dry sites when the JW site was established. Forest cutting on watersheds at Coweeta Hydrologic Laboratory near these bum sites has resulted in measurable increases of streamflow (Swank et al. 1988). While streamflow changes were not measured in this study, felling and burning will decrease evapotranspiration and presumably lead to flow increases.

In the pretreatment period, there was closer agreement between treated and control 10-cm soil temperature than for soil moisture. Under the dense *K. latifolia* canopy and duff accumulation, large spatial variation in soil temperature would not be expected. At 10 cm, soil temperatures after treatment were 5°C warmer, reaching an observed maximum of 27°C in August 1991, well below the thermal damage level for plants (Hare 1961). JW showed the greatest temperature changes in both years (Fig. 6) and best represents the midafternoon maximum temperature difference of the three sites because field measurements always were scheduled for this site in the afternoon and thus had the full impact of solar heating. The treatment effect tested least significant on JE ($p < 0.1005$, Table 4), where treatment plots were always measured first in the cool morning, while shaded control-plot temperatures were measured in midmorning. This reduced the potential for showing a treatment effect. The DD soil temperature treatment effect is more significant because DD treatment plots were measured in midmorning after some warming had occurred in the burned area. Soil warming in the fell and bum areas reached 30 cm depth.

Because soil temperature and moisture regulate many processes (including microbial activity, organic matter decomposition, and herbaceous and woody plant growth), these responses to burning will tend to accelerate rates of microbial transformations and decomposition of residual forest floor and extend the active growth season for some sprouts and seedlings. Although expected, accelerated decomposition of the soil humus layer followed by surface disturbance through winter frost heaving was not observed as a major process, and no further erosion events were recorded in the second winter and spring after treatment.

Acknowledgements

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