FIRE AND THINNING IN AN OHIO OAK FOREST: GRID-BASED ANALYSES OF FIRE BEHAVIOR, ENVIRONMENTAL CONDITIONS, AND TREE REGENERATION ACROSS A TOPOGRAPHIC MOISTURE GRADIENT

Louis R. Iverson, Anantha M. Prasad, Todd F. Hutchinson, Joanne Rebbeck, and Daniel A. Yaussy[1]

Abstract—Prescribed fire alone and in combination with thinning were accomplished in late 2000 to spring 2001 at Zaleski State Forest in southern Ohio. Sites were monitored before and after the treatments were applied. Light was assessed via hemispherical photographs taken in July 2000 and 2001. Oak and hickory seedlings and saplings were sampled during those same time periods. Soil moisture was monitored eight times in 2001 via time-domain-reflectometry (TDR). Air temperature was recorded every 2 seconds during the fires, and soil temperature was recorded hourly in the months following the fires. These data allow us to evaluate, in concert with the landscape moisture patterns: (1) aspects of fire behavior, and (2) effects of the thinning and burning on soil moisture and temperature, light, and vegetation. The thin-and-burn treatment, relative to the control, generally resulted in more light, higher soil moisture, higher seasonal soil temperatures, but no short-term effects on oak-hickory regeneration. The integrated moisture index (IMI), a GIS-derived index categorizing landscape into three moisture regimes, was related to many of the measured variables: sites modeled as topographically wetter had more soil moisture, lower fire and seasonal soil temperatures, less light penetration, and less oak and hickory regeneration.

INTRODUCTION

Ohio is undergoing a conversion from its oak-hickory (*Quercus* and *Carya*) forests to primarily maple (*Acer* L.) and tulip poplar (*Liriodendron tulipifera* L.) forests. This change is typical among many midwest and eastern states. Data from the USDA Forest Service forest inventories between 1968 and 1991 (Kingsley and Mayer 1970, Dennis and Birch 1981, Griffith and others 1993) indicate that the proportion of total volume in oak and hickory declined substantially relative to maple, tulip poplar, and black cherry (*Prunus serotina* Ehrh.). The relative importance of several oak and hickory species in Ohio declined by at least 22 percent during this same period while maples and tulip poplars increased by at least 38 percent in total volume. This trend corroborates regional patterns in Illinois (Iverson and others 1989, Iverson 1994), Pennsylvania (Nowacki and Abrams 1992), and several other eastern states (Powell and others 1993). This trend has prompted a large scientific effort to assess the problem and search for management solutions (e.g., Loftis and McGee 1993, Abrams 1996, Brose and others 1999, Elliot and others 1999, Huddle and Pallardy 1999, Tybirk and Strandberg 1999, Johnson and others 2002).

Several factors contribute to the decline of oaks in eastern forests. Oaks do not regenerate well under closed canopies and thus are declining while more shade-tolerant species are thriving (Hilt 1985, Loftis and McGee 1993). In addition, when light and moisture are not limiting (e.g., after a clearcut), tulip poplar and some other species can out-compete the oak (Beck 1990, Marquis 1990). The success of oak regeneration after a canopy-changing disturbance seems to follow a moisture gradient, that is, regeneration of oak is adequate only under xeric conditions in situations where it can successfully compete with more mesic species (Iverson and others 1997).

Historically, fire has been a component of oak forests in southern Ohio. Dendroecological studies have shown that fires were frequent from the time of Euro-American settlement ca. 1800 to ca. 1930 (Sutherland 1997; Hutchinson and others 2002). However, after ca. 1930, fires usually were suppressed, resulting in a dramatic increase in recruitment of maples and other non-oak species.

Preliminary findings of an earlier study in southern Ohio indicated that several burns did not sufficiently increase light to the forest floor for satisfactory oak regeneration to occur. Therefore, a new study was initiated in 2000 to assess the effectiveness of thinning, in addition to prescribed fire, for its potential to improve oak regeneration. As part of the national Fire and Fire Surrogates Study (FFS), our group is studying these treatments as possible means of reducing maple abundance and fostering oak recruitment in the Oak Hills study region.

Microclimatic effects have been found to be critical in forest ecosystems. Topographic characteristics and surface cover can greatly influence several microclimatic factors, including air temperature, soil temperature, and moisture (Kang and others 2000). Human-controlled factors such as silvicultural cutting and fragmentation, also can have profound influences on microclimatic factors (Chen and others 1999, Zheng and others 2000). Thus, our study stratified sites by moisture class to allow this feature to be evaluated with the applied treatments.

[1] Landscape Ecologist, Ecologist, Forest Ecologist, Forest Physiologist, and Forester, USDA Forest Service, Northeastern Research Station, Delaware, OH 43015, respectively.

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The objectives of the FFS project are to measure the effects of both fire and thinning on oak regeneration and on components of biodiversity within the ecosystem. In this paper, we present a preliminary analysis, of one site, of how the following characteristics vary among moisture classes and treatments: (1) fire behavior; (2) seasonal soil temperature and moisture following treatment; (3) canopy light penetration before and after treatment; and (4) oak and hickory seedlings and saplings before and the first season after treatment.

METHODS

Site Description and Study Design

The results reported here are from the Zaleski State Forest, located in Vinton County about 80 km southeast of Columbus, OH (82° 25' W, 39° 18' N). This is one of three southeast Ohio sites that are part of the FFS study. The area is part of the unglaciated Allegheny Plateau and is characterized by dissected topography and less than 100 m of total relief. The overstory is dominated by oak, especially in the more xeric positions on the landscape. Oak establishment occurred from ca. 1840-1925, under conditions of frequent fire (Hutchinson and others 2002). Common species include chestnut oak (*Quercus prinus* L.), white oak (*Q. alba* L.), red oak (*Q. rubra* L.), scarlet oak (*Q. coccinea* Muenchh.), black oak (*Q. velutina* Lam.), pignut hickory (*Carya glabra* (Miller) Sweet), mockernut hickory (*C. tomentosa* (Poiret) Nuttall), and bitternut hickory (*C. cordiformis* (Wangenheim) K. Koch). Other common overstory species include red maple, tulip poplar, and American beech (*Fagus grandifolia* Ehrhart), which are more abundant on mesic positions of the landscape.

Oaks are much less abundant in the midstory and understory layers, and species composition in these layers is more strongly related to topographic influences. Oak and hickory regeneration is present only on a few highly xeric and open ridge-top positions. Red maple and a few other species tend to dominate the lower strata and will likely dominate the next forest.

The Integrated Moisture Index (IMI) was used to capture the influence of varying topography and soils across the landscape (Iverson and others 1997). The IMI is a GIS model (0-100 scale) of long-term moisture availability based on solar radiation, position on the slope, curvature of the landscape, and water-holding capacity of the soils. IMI has been used to predict forest site productivity and composition, understory composition and richness, soil nitrogen, aluminum, pH, and bird distributions (Iverson and others 1996, Hutchinson and others 1999, Dettmers and Bart 1999, Boerner and others 2000, Dyer 2001). In this study, plots were categorized into three IMI classes: xeric (score 11-34.5), intermediate (34.5-46), and mesic (46-78.5).

A sampling grid (311 points) was overlaid on the Zaleksi site by establishing a point every 50 m, using a global positioning device (fig. 1). The site was divided into four (26 to 31 ha) treatment units: control (C), burn only (B), thin only (T) and thin+burn (TB). Only C, B, and TB were evaluated for this paper.

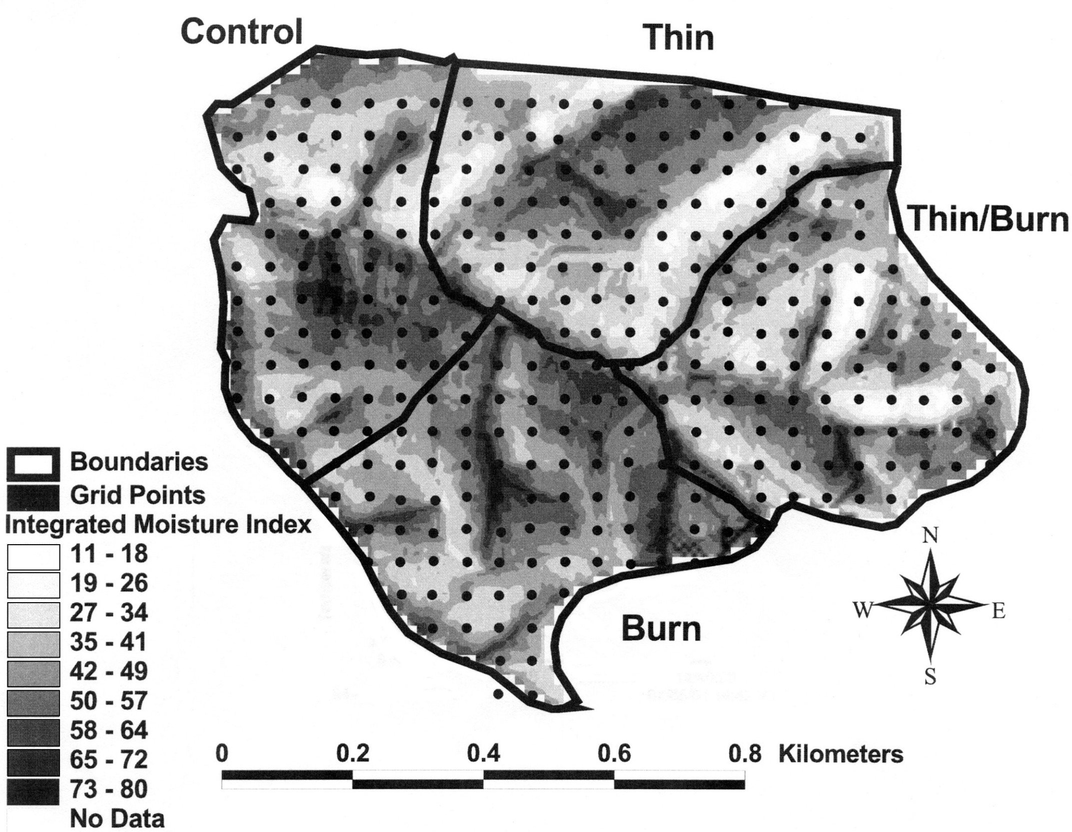

Figure 1—Map of treatment units, grid points, and IMI classes in the Zaleski State Forest.

Thinning occurred during the fall of 2000. For the TB site, basal area was reduced 27 percent, from 25.5 m²/ha to 18.5 m²/ha. The density of canopy trees (dominant/codominant) was reduced 26 percent, from 192 to 142 stems/ha, and midstory density was reduced 41 percent, from 255 to 150 stems/ha.

The fire was conducted on 4 April 2001 between 1300 and 1553 EST. Three firing teams ignited across the north line, across the south line, and down the middle. Each firing team used two or three drip torches, allowing them to set several lines of fire parallel to the control lines. During the fires, air temperature ranged from 15 to 18 °C, relative humidity from 23 to 35 percent, and windspeed from 5 to 6 km/hr. The area received a dusting of snow on April 1 and about 0.3 cm of rain on the morning of April 3, so the coarser fuels were not dry at the time of the burn. However, warm and dry air on April 3 dried fine fuels rapidly.

Fire Temperatures and Analysis

Prior to the burn, stainless steel temperature probes (Type K thermocouple) were installed at 60 grid points in the B unit and 63 points in the TB unit (fig. 1). The thermocouples were placed 25 cm above the soil surface. Hobo® data loggers (Onset Computer Corporation) were buried 2 m away in closed PVC containers and connected to the probes via a buried cable. Extreme care was used to limit disturbance of the litter layer during the burial of the cable; a hatchet was used to cut a small slit in the ground to lay the cable and the litter layer was reconstructed over the closed slit.

The data loggers were programmed to capture air temperature every 2 seconds on the day of the burn. From these data, we calculated the following: (1) maximum temperature; (2) duration of temperature above 30 °C; (3) a heat index, defined as the summed temperatures above 30 °C (an integral under the temperature curve); and (4) time of maximum temperature. An example output from the Hobo data logger software is shown in figure 2.

An animation of the burning fire was created using the data from maximum temperature, duration of elevated temperatures, and time of the maximum temperature. For each of 123 grid points from which the data were successfully collected, spreadsheet functions were built, for each of 248 30-second time periods, to linearly raise the temperatures for each grid point to the maximum and down from the maximum. The duration was used to calculate the beginning and ending times of the elevated temperatures. The 248 time-slice temperatures for each grid point were then linked to 248 maps via ArcView 3.2a (Environmental Systems Research Institute 1996) and interpolated via an inverse-weighted distance function, then merged into a movie.

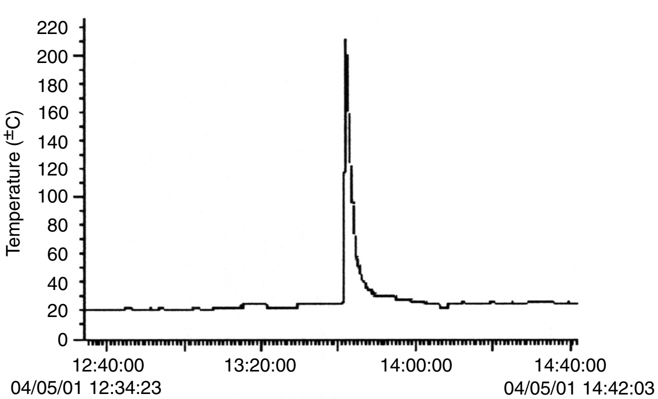

Figure 2—Example output of the air temperature data recorder on the day of the fire.

Environmental Monitoring

Light, soil moisture, and soil temperature were monitored following the burns to assess differences among treatments. Light also was measured before the treatments. Monitoring for all three variables was conducted at each grid point that was not within a 50 m buffer of a treatment boundary, on just the C (45 points) and TB (60 points) units. The two extremes were selected for evaluation because evaluating all four treatments was cost-prohibitive. (Ten 0.1 ha-plots in each treatment unit are used to assess the environmental variables at a less extensive scale. The data are not reported here.)

To estimate understory light levels, hemispherical photographs were taken at each grid point with a digital camera in July 2000 and July 2001. The images were analyzed for percentage open sky and percentage transmittance with the Gap Light Analyzer (GLA) program (Frazer and others 1999).

Soil moisture was recorded eight times during the 2001 growing season: 3 May, 17 May, 7 June, 14 June, 6 August, 20 August, 4 September, and 12 September. The large time gap between June and August was due to equipment failure. Moisture was sampled with a TRIME (Time Domain Reflectometry with Intelligent MicroElements) – TDR (Time-Domain-Reflectometry) sensor. PVC tubes, sealed at the bottom and with a removable cap at the top, were buried in the weeks following the burn to a depth of 50 cm or bedrock. A power auger was used to drill a hole sized equally to the outside diameter (~5 cm) of the tube and the tube was inserted carefully to ensure close contact between the soil and the tube throughout its depth. The sensor measures the volumetric soil water via electromagnetic field measurement of the dielectric constant of the soil.

The temperature probes used to monitor fire behavior also were used to monitor soil temperature following the fires. On the TB grid points, the probes were turned from a vertical to horizontal position into the soil at a depth of 2 cm. On the C grid points, the probes were positioned in a similar fashion. The Hobo data loggers were programmed to acquire soil temperature hourly from setup in April to October 31, 2001.

Oak and Hickory Regeneration

At each grid point, the number of oak and hickory seedlings (<50 cm height) was recorded in a 12.6 m² circular plot (2 m radius) centered on the grid point. Oak and hickory saplings [>50 cm height to 10 cm diameter at breast height (d.b.h.)] were recorded in a 78.5 m² circular plot (5 m radius) also centered on the grid point. Vegetation data, also recorded at the grid points but not reported here, include the abundance of seedlings and saplings of all tree species, species and basal area of overstory trees (recorded with a 10 basal area factor prism), and the cover of forbs, graminoids, shrubs, woody vines, and tree seedlings on the forest floor.

Statistical Analysis

Analyses and graphic outputs were produced in Splus (Mathsoft 1996). Analysis of variance was used to detect trends due to treatment (B vs. TB for the response variables for fire behavior; C vs. TB for response variables light, moisture, soil temperature, and oak and hickory seedlings and saplings) or moisture class (xeric, intermediate, or mesic). For oak and hickory regeneration, the year (2000 vs. 2001) was also compared with an analysis of variance. Interactions among treatments were also evaluated in each analysis. Where appropriate on the three IMI classes, multiple means were tested with Tukey's multi-comparison test. To test significant differences in oak and hickory seedling or sapling densities between 2000 and 2001, a pairwise t-test was used with 100 paired samples.

RESULTS AND DISCUSSION

Fire behavior

The B unit had an average maximum temperature of 174 °C, while the TB unit averaged 138 °C (fig. 3). The B unit burned later in the day when there was higher air temperature and lower humidity. However, on the TB unit, temperatures exceeding 30 °C lasted an average of about 11 minutes, compared to 9.5 minutes on the B unit; likely the result of fuel moisture differences. The average heat index, which takes into account both temperature and duration, was 10,556 for the B unit and 9,177, or about 13 percent less, on the TB unit (fig. 4).

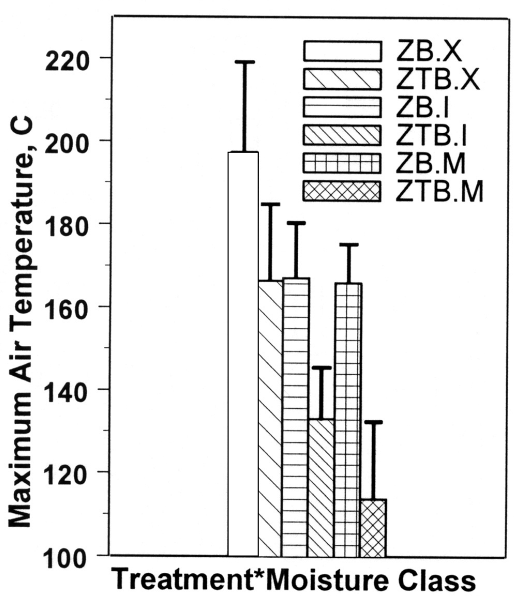

Figure 3—Maximum air temperatures (+ standard error of mean) recorded during the day of the fire, by treatment and moisture class. Legend: (1) site - Z=Zaleksi; (2) treatment – B=Burn, TB=Thin and Burn; (3) moisture class - X=xeric, I=intermediate, and M=mesic.

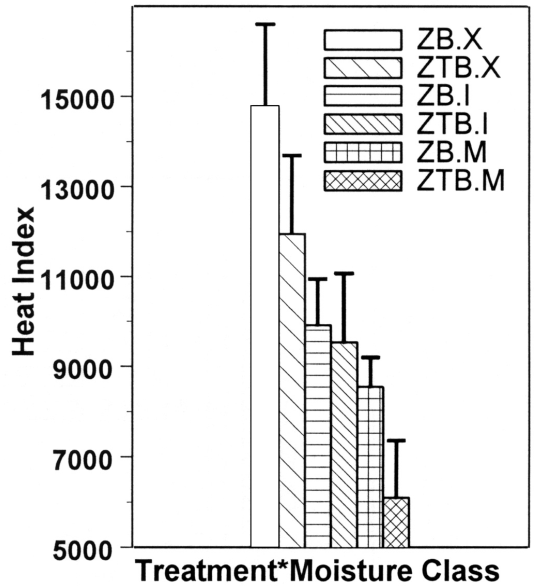

Figure 4—Cumulative heat index, calculated from maximum temperatures and duration, by treatment and moisture class. Legend: (1) site - Z=Zaleksi; (2) treatment – B=Burn, TB=Thin and Burn; (3) moisture class - X=xeric, I=intermediate, and M=mesic.

There was a significant trend with moisture class for average heat index (ANOVA, P = 0.02): 12,734 for xeric, 9,729 for intermediate, and 7,639 for mesic sites (fig. 4). This trend is reflective of conditions where the fuels remained moister in the mesic areas from the rain and snow dusting the previous few days. Maximum temperature was not statistically different among moisture classes, although xeric sites had higher temperatures (175 °C) than the intermediate (150 °C) or mesic sites (147 °C) (fig. 3).

Animation of fire

The recorded information from the sensors located each 50m throughout the study area allowed us to evaluate and visualize some aspects of the fire behavior. Although the animation cannot be shown in this paper, the reader is encouraged to view it at the web site at: http://www.fs.fed.us/ne/delaware/4153/ffs/zaleski_burn.html.

This animation shows the fire being set from the east, along both north and south fire lines, as well as some internal firing. The simulation also shows a slower rate of spread in the valleys, with hotter, faster fires on the more xeric locations.

Light

A total of 112 hemispherical photographs were analyzed with the GLA software: 43 in 2000 (pre-thinning and burning) and 69 in 2001 (post treatments). There was a large increase in percentage open sky after thinning and burning, from 7.1 percent to 11.9 percent, on average (fig. 5). The percentage open sky varied by moisture regime, with the more mesic locations having a slightly more closed canopy

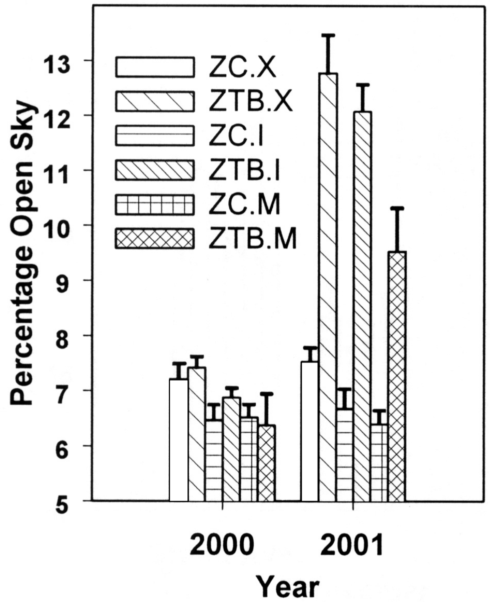

Figure 5—Percent open sky, 2000-2001 for Zaleski, as analyzed from hemispherical photographs and the GLA software. Legend: (1) site - Z=Zaleksi; (2) treatment - C=control, TB=Thin and Burn; (3) moisture class - X=xeric, I=intermediate, and M=mesic.

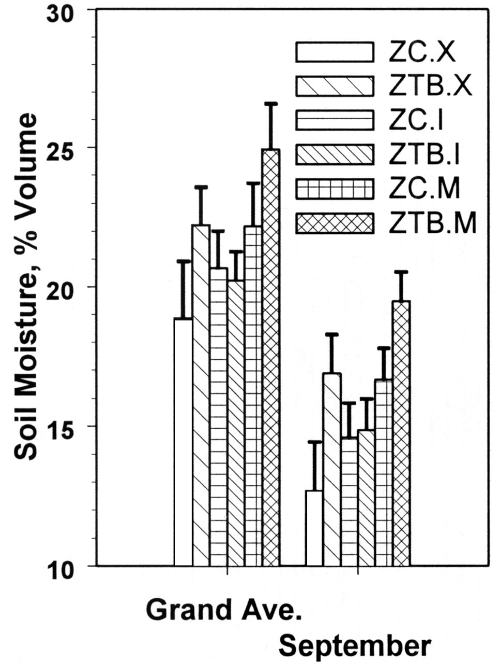

Figure 6—Percent soil moisture, by volume, for the Zaleski site during the 2001 growing season. Shown are the overall average values (eight sampling dates and three depths) and the last sampling date, from September 12-17, 2001. Legend: (1) site - Z=Zaleksi; (2) treatment - C=control, TB=Thin and Burn; (3) moisture class - X=xeric, I=intermediate, and M=mesic.

than xeric or intermediate. Even after thinning, the mesic locations had only 9.5 percent open sky as compared to over 12.1 percent for the other two treatments (fig. 5). The mesic sites, in addition to receiving less solar radiation, were more difficult to harvest because of longer skid distances and often steep topography.

Moisture

In general, the moisture levels decreased as the season progressed (fig. 6). The September 2001 data showed much drier conditions than the average values. Soil moisture variability was fairly high as expected from the field data. Many factors contribute to the detected moisture levels at a given location, including the amount of litter, green material, proximity to large tree roots, macro- and micro-topographic influences, drainage, microfissures in the soil, nearby animal activity, and errors associated with the technology.

Though not statistically significant, mean moisture levels were usually higher on the TB unit compared to C (fig. 6). We suggest that the removal of trees during thinning may have reduced substantially the amount of soil moisture transpired. The smaller plants, more abundant on the TB sites, transpire only a fraction of what larger trees do, so removal of overstory trees will substantially remove total leaf area and reduce transpiration. Transpiration per unit of land area has been shown to generally increase with greater leaf area index unless the canopy boundary layer resistance is so high that energy input controls evaporation (Landsberg 1986). In addition, the TB unit tended to have more green coverage at the herbaceous level, possibly providing a 'living mulch', which reduces solar radiation at the surface, perhaps to a level even lower than that on the C unit.

Moisture levels tended to increase from xeric to mesic IMI classes, though differences were not statistically significant.

The higher moisture readings observed on the xeric TB unit can be traced to several outlier points which exist in complicated topographic settings not captured adequately in GIS using 30 m digital elevation model pixels. One would expect that it is more likely to find pockets of mesic conditions within an area classified as xeric (e.g., small drainages not detectable in 30 m grid cells), than vice versa.

Soil Temperature

Soil temperatures were recorded hourly from 13 April to 31 October, 2001, for each of the 105 points. There was a substantial treatment effect, with the TB unit having significantly higher ($P < 0.001$) soil temperatures than the C unit throughout most of the season (fig. 7). The greatest differential was in April, when the soil surface was blackened following the spring fires. At this time, the daily maximum temperature differentials were as much as 4 °C. In an earlier study, we found similar trends, with soil temperatures as much as 6.2 °C higher on burned vs. control sites in May (Iverson and Hutchinson 2002).

There were also significant ($P < 0.03$) temperature differences among moisture classes in all months except August ($P = 0.06$) and October ($P = 0.37$). In general, daily maximum temperatures were greatest on xeric and least on mesic areas (fig. 7). This pattern can be explained by increasing soil moisture content and associated thermodynamics (fig. 6), as well as decreasing solar radiation exposure (fig. 5) from the xeric to mesic moisture regimes.

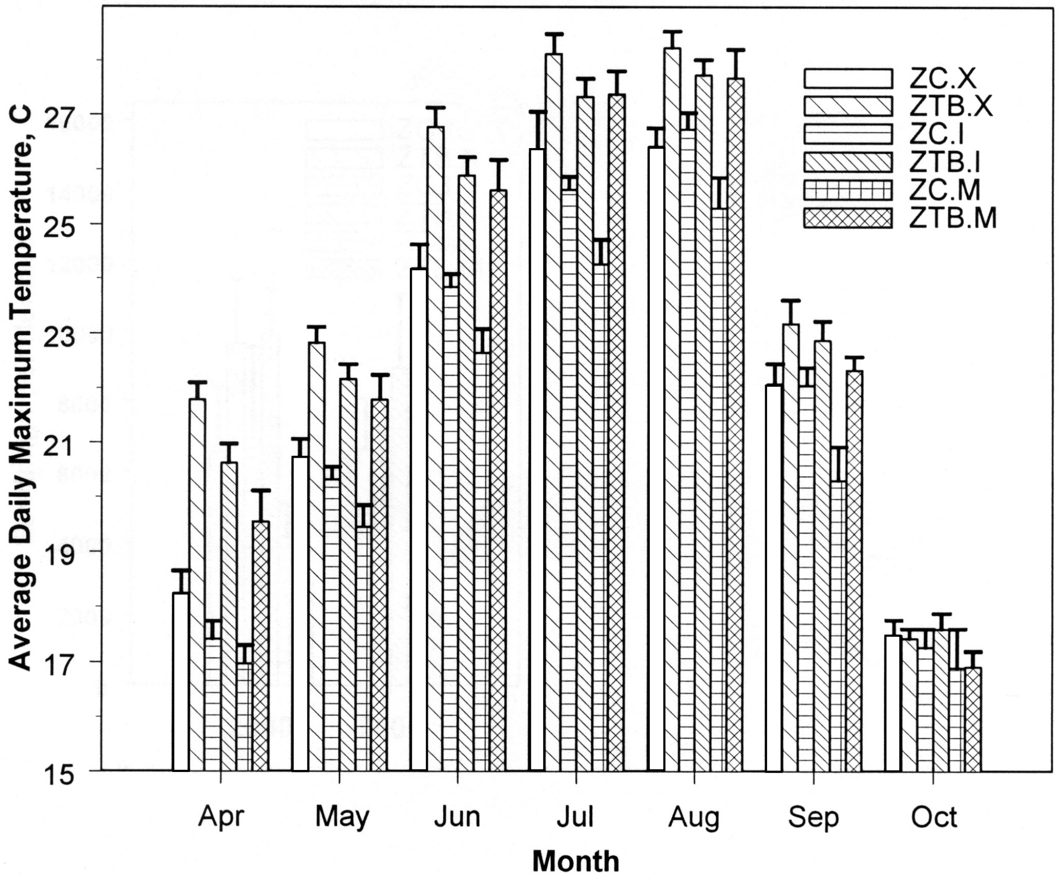

Figure 7—Daily maximum soil temperatures, averaged by month, for the Zaleski site during the 2001 growing season. Data were extracted from hourly data collect from 105 sensors. Legend: (1) site - Z=Zaleksi; (2) treatment - C=control, TB=Thin and Burn; (3) moisture class - X=xeric, I=intermediate, and M=mesic.

Oak and Hickory Regeneration

There was an average of 8,060 oak or hickory seedlings/ha in 2000 and 6,390 seedlings/ha in 2001. There were very few oak or hickory saplings (>50 cm to 10 cm d.b.h.): 40 per ha in 2000 and 48 per ha in 2001. There were no significant differences in oak and hickory seedling or sapling densities between years using a pairwise t-test (N = 100 paired samples).

Oak and hickory seedling densities were significantly different among moisture classes (ANOVA, P=0.02), while treatment effect was nearly significant at the 5 percent level (P = 0.06), and year was not significant (fig. 8). No interaction effect was present. Fire and thinning treatments did not alter the number of oak or hickory seedlings in the first growing season following the spring fires: similar patterns existed before (2000) and after (2001) treatment. In both years, the TB unit had slightly more oak and hickory seedlings on the xeric and intermediate moisture classes, and slightly less on the mesic sites. Over both years and both treatments, the mesic sites had significantly fewer oak and hickory seedlings as compared to the other moisture classes. There were no significant differences in sapling densities among moisture classes, treatments, or years.

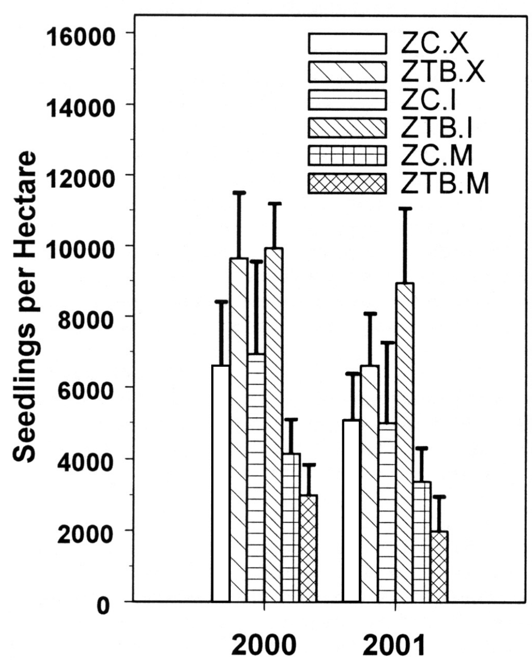

Figure 8—Oak and hickory seedling numbers per quadrat (2 m radius circle=12.87 m2) for Zaleski, 2000-2001. Legend: (1) site - Z=Zaleksi; (2) treatment - C=control, TB=Thin and Burn; (3) moisture class - X=xeric, I=intermediate, and M=mesic.

CONCLUSIONS

We have demonstrated a method to capture some aspects of fire behavior during prescribed surface fires in eastern forests. Thermocouples and data recorders buried prior to the fires successfully logged temperatures every 2 seconds, which allowed analysis of maximum fire temperatures, duration, and heat index. With a spatial analysis of the data, a movie animation of the fire was created.

This study also provides a preliminary analysis of two primary factors related to landscape-level microclimate and vegetation: a human-controlled silvicultural regime of thinning and burning, and a topographically controlled moisture index. The thin-and-burn treatment, as compared to the control, resulted in higher seasonal soil temperatures. The blackened surface and the open canopy facilitated more absorption of solar radiation. The TB unit also increased soil moisture levels near the soil surface apparently because of reduced evapotranspiration. An evaluation of the thin-only and burn-only treatments (pending analysis of plot-level data) is needed to better assess these cumulative effects. In this first season after treatment, we did not detect a difference in oak and hickory regeneration between TB and C units.

The integrated moisture index also was related to the measured variables. The wetter sites had higher soil moisture, though there was a lot of variability associated with fine-scale features on the landscape. The IMI was based on a 30 m digital elevation model (DEM). If a finer-resolution DEM were available, perhaps the small ravines (less than 30 m wide) would be captured more accurately by the moisture index. Wetter sites also had lower fire temperatures and seasonal soil temperatures due to less incoming solar radiation. We also found lower light availability on the wetter zones. These sites tend to be the most difficult to harvest with poor accessibility. Finally, the wetter zones had significantly fewer oak and hickory seedlings and saplings. In fact, it was difficult to find a sapling on any site, but especially in the wetter zones. These data provide further evidence that these species regenerate poorly under closed-canopy, mesic conditions.

Though oak and hickory regeneration densities were unaffected by treatments, personal observation indicates that at least some of the resprouted oaks and hickories exhibit increased growth given adequate light and reduced competition from fire-sensitive species such as red maple. We are hopeful that over time, adequate oak and hickory advance reproduction will develop on the treated sites, thus improving the sustainability of forests that have been long dominated by oaks and hickories.

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