CONSUMPTION AND REACCUMULATION OF FOREST FUELS IN OAK SHELTERWOOD STANDS MANAGED WITH PRESCRIBED FIRE

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Abstract—In the shelterwood-burn technique, a moderate- to high-intensity growing-season prescribed fire is essential to achieve desired oak regeneration goals. These levels of fire intensity are dependent on the increased fuel loadings created by the preceding first removal cut. However, the loadings of forest fuels and their fluctuation during implementation of the shelterwood-burn technique have not been studied. From 1994 to 1997, three mature uncut oak stands, three oak shelterwoods, and three burned oak shelterwoods in central Virginia were examined to determine fuel loadings before, during, and after implementation of the shelterwood-burn technique. Prior to the first removal cut, total fuel loadings averaged 10.5 tons/acre and this was evenly divided between small and large fuels. The harvest increased total fuel loadings to between 20 and 25 tons/acre with nearly all this increase occurring in medium and large fuels. The prescribed burns consumed virtually all the small fuels and about half the medium/large fuels, but loadings for all size classes were 80 percent of pre-treatment levels within 3 years after the fires. It appears that forest fuel loadings in oak shelterwoods return to their initial levels within 5 years post-fire.

INTRODUCTION

Throughout the eastern United States, resource managers are increasingly using prescribed fire to regenerate, restore, or sustain upland oak (*Quercus* spp.) forests (Dickinson 2006, Hutchinson 2009, Yaussy 2000). A popular regeneration method to use when a sufficient density of oak seedlings exists is to proceed with stand renewal via the shelterwood-burn technique (Brose and others 1999a, b). This technique entails integrating a moderate to high intensity prescribed fire between the first and final removal cuts of a two-step shelterwood sequence. Because of the harvest – burn – harvest order of this method, an understanding of the forest fuels that will carry the fire and help give it the required intensity is necessary to safely and successfully implement this technique. However, information on the consumption and re-accumulation of forest fuels in upland oak stands is limited, especially those partially harvested or prescribe burned.

Much of the early oak forest fuel research was conducted in Missouri. Loomis and Crosby (1968, 1970) reported that a mixed oak – shortleaf pine (*Pinus echinata*) stand contained 5.0 to 6.5 ton/acre of fuel on its forest floor at age 21. Control of hardwoods via aerial herbicide application increased the fuel loading to approximately 10.4 tons/acre five years after the spraying. The increase was almost entirely in forest fuels that were less than 3 inches in diameter. Crosby and Loomis (1974) and Loomis (1975) followed the annual accumulation and decomposition of leaf litter in a 40-year-old oak stand. They showed that (1) litter fall added approximately 2 tons/acre/year to the fuel loading; (2) leaf litter loadings were largest in November (6.2 tons/acre); and (3) smallest in September (4.2 tons/acre). They also showed that the decay rate was uneven; the freshly fallen leaves of November did not substantially decompose until the following summer, then they decayed quite rapidly.

More recently, research into oak forest fuels has involved the eastern replicates of the National Fire and Fire Surrogate (NFFS) project. In North and South Carolina, several studies reported that forest fuel loadings in mature, undisturbed oak forests averaged approximately 6.0 tons/acre and fluctuated little over time (Phillips and Waldrop 2013, Waldrop and others 2004, 2007). Thinning decreased the leaf litter loading via mechanical disturbance and increased loading of small woody fuels, i.e., less than 1 inch diameter. Loading of large woody fuels, i.e., more than 3 inch diameter, was not affected because the treatment was a pre-commercial thinning. Prescribed fire alone and as a follow-up treatment to the thinning decreased leaf litter and small woody fuel loadings, but had no effect on large woody fuel loading. At the southern Ohio site of the NFFS study, Graham and McCarthy (2006) reported that a commercial thinning increased loading of all forest fuel categories and the subsequent burning reduced just the leaf litter and small woody fuel loadings. However, those reductions were no longer evident by 3 years post-fire. In a Missouri study

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closely related to the NFFS project, Kolaks and others (2004) found that thinning decreased leaf litter and small woody fuel loadings, increased large woody fuel loading, and resulted in an overall increase in total fuel loadings from 8.0 to 25.0 tons/acre. A subsequent prescribed fire in the thinned oak stands reduced total fuel loading to approximately 18.0 tons/acre. Nearly all the reduction occurred in the leaf litter and small woody fuel.

Also in the southern Appalachian Mountains, the Coweeta Hydrologic Laboratory in North Carolina has examined numerous understory burns for a myriad of ecological effects including reductions of forest fuels. Clinton and others (1998) reported a 50-percent reduction in leaf litter and small woody fuel loadings following such a fire in a mixed oak – pine stand. Understory burning in mixed oak – pine stands on dry and mesic upland sites resulted in reductions of leaf litter and small woody fuel loadings of 28 and 14 percent, respectively (Clinton and Vose 2007). Another understory burning study found 82 to 91 percent of the Oi layer and 26 to 46 percent of the Oe + Oa layers consumed by dormant-season prescribed fires (Knoepp and others 2009).

This paper addresses four forest fuel questions important to resource managers interested in using the shelterwood-burn technique to regenerate upland oak forests. Those questions are:

1. What are the fuel loadings in upland oak stands that are ready to begin the shelterwood – burn regeneration process?
2. How much fuel does the first removal cut create?
3. How much fuel does the prescribed fire consume?
4. How quickly do fuel loadings re-accumulate postfire?

The answers to these four questions will help forest managers make better use of the shelterwood-burn technique to regenerate upland oak forests.

METHODS

Study Sites

This study was conducted at the Horsepen Wildlife Management Area in the Piedmont of central Virginia. This area consists of broad gently-rolling hills on sandy loam soils (Reber 1988). Climate is warm continental with 50 inches of precipitation distributed evenly throughout the year and an average growing season of 190 days. The area is presently owned and managed by the Virginia Department of Game and Inland Fisheries (VDGIF).

At each of three sites (Dunnavant, Lake Road, and Ward Farm), two adjacent mixed-oak stands (one undisturbed and one shelterwood) were selected in 1994 for the study. Each of the six stands was 20 to 50 acres in size and was on productive upland soils; oak site index$_{50}$ ranged from 70 to 80 feet. The undisturbed stands were mature (~100-year-old), fully stocked (basal areas ranged from 110 to 130 ft^2/acre), and dominated (67 percent of the basal area) by four upland oak species [black (*Quercus velutina*), northern red (*Q. rubra*), scarlet (*Q. coccinea*), and white (*Q. alba*)]. Other hardwoods present in these stands included American beech (*Fagus grandifolia*), blackgum (*Nyssa sylvatica*), flowering dogwood (*Cornus florida*), hickory (*Carya* spp.), red maple (*Acer rubrum*), and yellow-poplar (*Liriodendron tulipifera*). According to VDGIF records, the three uncut stands suffered some light ice storm damage in 1989; otherwise they had been undisturbed for at least 30 years. The three shelterwoods had been partly harvested between 1990 and 1992 as a result of moderate levels of ice storm damage. The harvests removed the poor-quality oaks and the low-value species resulting in average residual basal areas of 50 ft^2/acre in each shelterwood. Slash was left in place following the harvesting.

Sampling Procedures

Each of the shelterwood stands was divided into two units with one unit being burned while the other remained unburned. These two shelterwood units in conjunction with the adjacent undisturbed stand formed a chronosequence of the treatments (uncut, shelterwood, and burned shelterwood) that constitute the shelterwood-burn technique.

In each treatment, 15 to 45 fuel inventory transects were systematically installed to uniformly sample the area. Each transect was 50 feet in length and was inventoried for woody fuels using the planar-intersect method (Brown 1974). Sound woody fuels (those not in an advanced state of decay) were tallied by the time-lag size classes of Fosberg (1970). One-hour (1-hr) fuels were less than 0.25 inch diameter while ten-hour (10-hr) fuels were 0.25 to 1.0 inch diameter. These two size classes were tallied along the proximal 6-foot section of each transect. Hundred-hour (100-hr) fuels were 1.0 to 3.0 inch diameter and were tallied along the distal 12-foot section of each transect. Thousand-hour (1000-hr) fuels were 3.0 to 8.0 inch diameter and were tallied along the entire length of each transect. Rotten woody fuels in all size classes and fuels larger than 8 inch diameter were ignored because it was felt that these would not appreciably contribute to fire spread and fire intensity. For each transect, the woody fuel counts in each time-lag class were converted to tons/acre using established fuel equations (Brown 1974) and hardwood specific gravities (Anderson 1978). For each treatment, a mean fuel loading for each time lag class was calculated by summing the appropriate loading of each transect and dividing by the number of transects. Similarly, a mean total fuel loading for each treatment was calculated by summing all the time-lag fuel loadings of each transect and dividing by the number of transects.

Leaf litter loading was measured by collecting two 1.36-ft^2 samples per transect of the Oi and Oe horizons. Samples were collected near the midpoint and distal end of each transect. The samples included the litter and the woody material smaller than 1.0 inch diameter found among the leaves. Samples were dried at 122° F for 72 hours then weighed on an electronic scale to the nearest 0.1 ounce. The masses of the two leaf litter samples from each transect were averaged and the average was converted to tons/acre.

Each transect was inventoried for leaf litter and woody fuels during winter 1994. Following that initial inventory, the portion of the each shelterwood designated for burning was burned by VDGIF personnel in accordance to department policy and state law. The prescribed fires were not all conducted at the same time because they were part of an oak regeneration study (Brose and Van Lear 1998). Rather, they were conducted in different seasons during 1995 (table 1). All prescribed fires were lit using drip torches in a strip headfire ignition pattern commencing at the downwind side of the burn block. Generally, burning conditions were good to excellent with clear skies, dry fuels, low humidity, steady winds, and typical seasonal temperatures (table 1). Fire behavior was most active in the spring burn treatment with headfire flame lengths ranging from 3 to 6 feet and rates-of-spread averaging 4 feet/minute. The summer and winter fires were quite similar; headfire flame lengths ranged from 1 to 3 feet and rates-of-spread averaged 1.5 feet/minute. Subsequent fuel inventories occurred in September 1995 and September 1997.

Statistical Analysis

The fuels data were grouped into three classes (small, medium, and large) based on their sizes and how they affect fire behavior. Small fuel included leaf litter, 1-hr, and 10-hr woody fuels as these primarily affect the rate-of-spread of a fire. Large fuel was the 1000-hr woody fuels as these principally affect fire intensity. Medium fuel was the 100-hr woody fuel as these contribute to both fire intensity and rate-of-spread. For the rest of this paper, the forest fuels will be referred to by these three classes.

The data were analyzed as a randomized complete block using repeated measures analysis of variance (ANOVA). Each site served as a block and each block contained three treatments (uncut, shelterwood, and burned shelterwood). Additionally, there were three years of data, 1994 (preburn), 1995, and 1997, for each treatment in each block. In the ANOVA model, treatment and year were the fixed effects and block was the random effect. Dependent variables were the loadings (tons/acre) of the small, medium, and large forest fuels. The Student-Newman-Kuels (SNK) means separation test was used to determine if significant differences existed among the nine treatment-year combinations for each of the dependent variables. An alpha of 0.05 was used for all tests and residuals were checked to ensure compliance with the statistical assumptions of an repeated measures analysis of variance.

RESULTS

Initial analysis of the 1994 fuel loadings found only minor differences among the three blocks for the three treatments. Furthermore, changes in fuel loadings through time for the three treatments were consistent, regardless of block. Therefore, data were pooled across blocks to ease reporting.

At the beginning of the study (1994), total fuel loading in the uncut treatment averaged 10.5 tons/acre (table 2). This loading was concentrated in the small (4.1 tons/acre) and large fuels (4.9 tons/acre) with the remaining 1.5 tons/acre being in the medium size class. In the shelterwood and burned shelterwood treatments in 1994, the average total fuel loading ranged from 22.6 to 24.4 tons/acre with no differences detected between the two treatments for any of the fuel classes. However, this total loading was more than double that of the uncut control due to a 5-fold increase in 100-hr loading and a 1.25x increase in 1000-hr loading. Small fuel loading did not differ among the three treatments; it averaged 4.5 tons/acre.

After the prescribed fires in 1995, several significant differences in fuel loadings were detected among the three treatments (table 2). Total fuel loadings were greatest in the shelterwood (24.4 tons/acre) while total fuel loadings in the uncut and the burned shelterwood were comparable (10.7 and 9.0 tons/acre, respectively). For the large fuels, the shelterwood had more loading (12.2 tons/acre) than the burned shelterwood (6.1 tons/acre) and the uncut control (4.9 tons/acre). The same pattern of distribution among treatments was found for the medium fuels; the shelterwood had the most loading (7.9 tons/acre) followed by burned shelterwood (2.1 tons/acre) and the uncut control (1.5 tons/acre). Small fuel loadings were equal between the uncut control and the shelterwood, each was 4.3 tons/acre, and this was larger than the small fuel loading of the burned shelterwood treatment (0.8 tons/acre). Relative to the previous year, the total fuel loading and its distribution among the fuel classes were unchanged in the uncut control and the shelterwood treatments. However, the fuel loading in the burned shelterwood treatment had decreased from 23.0 to 9.0 tons/acre. The decrease occurred in all fuel size classes; large fuel loading dropped 45 percent, from 11.1 to 6.1 tons/acre, medium fuel loading declined 69 percent, from 6.8 to 2.1 tons/acre, and the small fuel loading was reduced from 5.1 to 0.8 tons/acre, an 84 percent loss.

Table 1—Dates, times, and environmental conditions of the Winter, spring and summer prescribed fires in the oak shelterwood stands at the Dunnavant, Lake Road, and Ward Farm study sites

Season/Condition	Dunnavant	Lake Road	Ward Farm
Winter Prescribed Fire			
Burn Date	25Feb1995	27Feb1995	27Feb1995
Time of Burn	1300	1100	1430
Air Temperature (°F)	46	43	48
Relative Humidity (%)	26	62	54
Wind Direction tab	NW	E	E
Wind Speed (mph)	4	1	2
Cloud Cover (%)	0	100	100
1-HR Fuel Moisture (%)	6	12	12
10-HR Fuel Moisture	10	15	15
100-HR Fuel Moisture	18	20	20
Slope (%)	10	5	5
Aspect	NE	E	E
Spring Prescribed Fire			
Burn Date	26Apr1995	26Apr1995	26Apr1995
Time of Burn	2000	1630	1830
Air Temperature (°F)	68	73	70
Relative Humidity (%)	28	20	20
Wind Direction	SW	SW	SW
Wind Speed (mph)	1	5	3
Cloud Cover (%)	0	0	0
1-HR Fuel Moisture (%)	9	5	7
10-HR Fuel Moisture	10	10	10
100-HR Fuel Moisture	12	12	12
Slope (%)	7	5	10
Aspect	E	SW	E
Summer Prescribed Fire			
Burn Date	24Aug1995	24Aug1995	24Aug1995
Time of Burn	1630	1430	1230
Air Temperature (°F)	92	95	95
Relative Humidity (%)	56	44	46
Wind Direction	SW	SW	SW
Wind Speed (mph)	0	5	8
Cloud Cover (%)	0	0	0
1-HR Fuel Moisture (%)	11	9	9
10-HR Fuel Moisture	10	15	15
100-HR Fuel Moisture	14	14	14
Slope (%)	3	10	5
Aspect	NE	W	NW

Table 2—Mean loadings (tons/acre ± 1 standard error) of small, medium, large, and total fuels by treatment and year. Means followed by different uppercase letters are different within that row while means followed by different lowercase letters are different within that column. N = 45 for each cell

Fuels	Treatment	1994	1995	1997
Small[1]	Uncut	4.1 ± 0.3Ad	4.3 ± 0.3Af	4.3 ± 0.3Af
Small	Shelterwood	4.3 ± 0.2Ad	4.3 ± 0.3Af	4.3 ± 0.2Af
Small	Burned Shwd	5.1 ± 0.4Ad	0.8 ± 0.1Ci	3.2 ± 0.3Bg
Medium[2]	Uncut	1.5 ± 0.2Ae	1.5 ± 0.2Ah	1.4 ± 0.2Ah
Medium	Shelterwood	7.5 ± 0.4Ac	7.9 ± 0.3Ad	7.8 ± 0.5Ad
Medium	Burned Shwd	6.8 ± 0.4Ac	2.1 ± 0.2Cg	6.3 ± 0.4Be
Large[3]	Uncut	4.9 ± 1.5Ad	4.9 ± 1.4Af	4.9 ± 1.5Af
Large	Shelterwood	10.8 ± 1.4Ab	12.2 ± 1.4Ab	12.1 ± 1.5Ac
Large	Burned Shwd	11.1 ± 0.8Ab	6.1 ± 0.9Be	10.2 ± 0.7Ac
Total	Uncut	10.5 ± 0.5Ab	10.7 ± 0.6Abc	10.6 ± 0.6Ac
Total	Shelterwood	22.6 ± 2.1Aa	24.4 ± 2.0Aa	24.2 ± 2.3Aa
Total	Burned Shwd	23.0 ± 2.1Aa	9.0 ± 1.1Cc	19.7 ± 1.7Bb

[1]Small fuels are leaf litter and woody material less than 1.0 inch diameter.
[2]Medium fuels are woody material between 1.0 and 3.0 inch diameter.
[3]Large fuels are woody material greater than 3.0 inch diameter.

In fall 1997, 2 to 2.5 years after the fires, fewer differences in fuel loadings among the three treatments were detected (table 2). The shelterwood had a total fuel loading of 24.2 tons/acre. This amount differed from that of the burned shelterwood (19.7 tons/acre), but both were more than the total fuel loading found in the uncut control (10.6 tons/acre). The two shelterwood treatments had equivalent loadings of large fuels (12.1 and 10.2 tons/acre) and equivalent loadings of medium fuels (7.8 and 6.3 tons/acre). All of these amounts were greater than the corresponding loadings of the uncut control (4.9 tons/acre for large fuels and 1.4 tons/acre for medium fuels). However, the uncut control and the unburned shelterwood treatments had greater leaf litter loadings (4.3 tons/acre for each) than the shelterwood + fire treatment (3.2 tons/acre). Relative to 1995, fuel loadings had not changed in the uncut and the shelterwood treatments. However, in the burned shelterwood treatment, loadings for all fuel classes had substantially increased from 1995 to 1997. Small fuel loading rose 300 percent, from 0.8 to 3.2 tons/acre. Medium fuel loading climbed 200 percent, from 2.1 to 6.3 tons/acre. Large fuel loading increased 67 percent, from 6.1 to 10.2 tons/acre. These increases made the large and medium loadings in 1997 equivalent or nearly so to what they had been in 1994, but the leaf litter loading (3.2 tons/acre) was only 60 percent of what it had been prior to the prescribed fires.

DISCUSSION

In this study, the uncut control treatment represents upland oak stands at the beginning of the shelterwood-burn technique. Small fuel loading was approximately 4 tons/acre. This amount of small fuel is consistent with the findings of numerous researchers studying forest fuels in mature, fully-stocked upland oak stands in Georgia (Clinton and others 1998), Iowa (Kucera 1952), Missouri (Loomis 1975), Ohio (Graham and McCarthy 2006), South Carolina (Metz 1954), and Tennessee (Blow 1955). The combined loading of medium and large fuels, 6.4 tons/acre, is slightly less than the range of 7.5 to 9.5 tons/acre reported for upland oak stands of comparable ages and site conditions (Lang and Forman 1978, MacMillan 1981, McCarthy and Bailey 1994) indicating that medium and large fuels will likely continue accumulating in the uncut stands as time passes. Apparently, the uncut oak stands used in this study are quite similar to that of other undisturbed upland oak forests throughout the eastern United States when it comes to total fuel loadings and how those loadings are distributed among the fuel size classes.

In the shelterwood-burn technique, the purpose of the first removal cut is to promote the development of the existing oak reproduction and increase the fuel loadings so the subsequent prescribed fire has the intensity to control the competing mesophytic hardwoods (Brose and others 1999a, b). In this study, the first removal cuts created shelterwood stands by removing intermediate trees from the midstory strata and weak co-dominant stems from the main canopy. On average, the residual basal area and canopy closure of each shelterwood stand were 50 feet^2/acre and 50 percent, respectively. Because these first removal cuts occurred 2 to 4 years before the start of the study, it is unknown what the fuel loadings were immediately after the harvesting. However, after 2 to 4 years, these oak shelterwoods had total fuel loadings that were more than double those of the undisturbed oak stands (~23 tons/acre versus ~10 tons/acre). This drastic change was concentrated in the large and medium fuels due to the logging slash being left on site. Small fuel loading was probably initially diminished by the harvesting operation (Graham and McCarthy 2006, Kolaks and others 2004), but subsequent leaf fall replaced this loss resulting in no net change in small fuel loading 2 to 4 years later. In the shelterwood-burn technique, the recommended time interval between the first harvest and the prescribed fire is 4 to 7 years (Brose and others 1999b). Forest managers wanting to implement this regeneration method can expect candidate oak shelterwood stands to have 20 to 25 tons/acre of leaf litter and woody fuels when they are 4 to 7 years old.

The desired prescribed fire in the shelterwood-burn technique is a medium- to high-intensity fire (2- to 4-foot flame lengths) in mid spring when the leaves of the mesophytic hardwood seedlings are at least 50 percent expanded (Brose and others 1999a, b). With total fuel loadings ranging from 20 to 25 tons/acre and a ubiquitous leaf layer, achieving the desired fire behavior is rather easy provided the weather conditions are conducive for prescribed burning. Based on the results of this study, the fire will incinerate between half and two-thirds of the total fuel loading. Nearly all of the small fuels, especially the leaf litter, and more than 50 percent of the medium fuels will be consumed. Decreases in large fuel loading will be centered where there are concentrations of logging slash that increase fire intensity and residence time.

After the prescribed fire, the oak and mesophytic hardwood reproduction must be evaluated to determine if the burn objective was met. Generally, this is done in the second growing season postfire (Brose and others 1999a, b). If the mesophytic hardwood reproduction has not been adequately controlled, a second burn may be necessary. The timing of this second burn is dependent on the re-accumulation of the small fuels, especially the leaf litter, so that the fire can easily move through the stand. In mature, fully-stocked oak stands, leaf litter production is about 2 tons/acre/year with a total leaf litter loading of 4 to 6 tons/acre once equilibrium between foliage production and litter decomposition is reached (Loomis 1975). Consequently, repeat understory burns in mature stands can occur on a 2- to 4-year interval to allow for adequate re-accumulation of the leaf litter to carry the fire. In oak shelterwoods, leaf litter production will be considerably less due to the removal of half or more of the basal area via the first removal cut. In this study, small fuel loading had risen from 0.8 tons/acre shortly after the fires to 3.2 tons/acre by the end of the third growing season. The 3.2 tons/acre loading was only 60 percent of the pre-burn small fuel loading (5.1 tons/acre). Obviously, more time is needed for the leaf litter to re-accumulate to pre-burn levels, probably an additional 2 to 4 years. In oak shelterwoods, a second prescribed fire should be feasible 4 to 7 years after the first one, depending on site quality.

The re-accumulation of the large fuel loadings to pre-burn levels was somewhat surprisingly, but not totally unexpected. The prescribed fires had injured or killed a few of the overstory trees, especially ones with slash piles near their boles. By the third year after the fire, some of the branches from these injured or killed trees had fallen to the ground and were inventoried as large fuels.

In conclusion, the shelterwood-burn technique is an oak regeneration method that takes 8 to 14 years. Most of that time occurs in two separate intervals of 4- to 7-years each. Both intervals are absolutely necessary and are based, to some degree, on the dynamics of the forest fuels. The first interval comes between the first removal cut and the prescribed fire. It allows the leaf litter to re-accumulate following the logging disturbance so the prescribed fire can easily burn through the stand. It also permits the woody fuels to dry so that the desired fire intensity can be readily attained. The second 4- to 7-year wait occurs after the prescribed fire. During this interval, leaf litter re-accumulates so if a second fire is needed, it can be easily conducted.

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