DESCRIBING SINGLE-TREE SELECTION HARVESTS IN MISSOURI OZARK FORESTS

Greg F. Iffrig, Clinton E. Trammel, and Terry Cunningham[1]

Abstract—The European debate about uneven-aged forest management has been described as comparable to the religious wars of the Middle Ages. Likewise, here in the American Midwest, the forestry community has been largely unreceptive to the uneven-aged system of management, particularly the single-tree selection technique. Whereas a religious war may be more descriptive than accurate, disagreement is almost certain to continue in the literature as well as on the front lines within the forests. Despite that, we present evidence that use of the single-tree selection cutting technique for forests of the Lower Ozarks Region is an appropriate and successful management and restoration application. Drawing on more than a half-century of management experience and continuous forest inventory information, we trace the early development of single-tree selection harvesting, review its use as the harvesting technique on Pioneer Forest, and describe its implementation in detail.

EUROPEAN ORIGINS OF UNEVEN-AGED FOREST MANAGEMENT

The system of forest management, used on Pioneer Forest since the early 1950s, is a very old one, originating in the mountainous regions of Europe in the 1700s (Schutz 1997) in mixed beech-fir forests. As practiced at that time, the system represented an accumulation of knowledge among generations of private forest owners. Europeans viewed forests as an important economic asset that, through careful management, could yield income to be used for important and periodic family needs. Harvest revenues could be used for building construction or repairs, education, weddings, or emergency revenue. Through this experience, beginning nearly 300 years ago, European families passed along what developed into a recognized practice of periodically selecting trees from the forest for harvest.

In the late 1800s, a harvest technique known as single-tree selection was developed as a part of the more formal description of uneven-aged forest management by Henri Biolley (1901) in Switzerland and Adolph Gurnaud (1882, 1884) in France. From Gernaud came the idea of the sustainability of forests through the application of single-tree selection harvests whereas Biolley developed the technical rules for its use as a formal management tool.

Despite these advances, there has been a great deal of debate in European circles about the use of uneven-aged management. Schutz (1997) likened that debate as "comparable to the religious wars of the Middle Ages", with deeply held beliefs about even-aged forestry versus uneven-aged forestry, often to the point where dispassionate assessment of the respective methods on their own merits is difficult to find. But, the European experience is clear in one respect—that in certain forest types, when applied with a combination of scientific analysis and practical experience, uneven-aged management can be successfully implemented in the long term.

UNEVEN-AGED MANAGEMENT IN MISSOURI

In the central United States, the earliest literature describing either uneven-aged management or the practice of single-tree selection first appeared in the 1980s. Larsen (1980) developed a growth and yield model for mixed oak-pine forests using the Continuous Forest Inventory (CFI) information from Pioneer Forest as a database. Melick (1989) presented some of the earliest silvicultural prescriptions for the uneven-aged management of three specific forest stands on the Mark Twain National Forest. At this same time, Law and Lorimer (1989) prepared their own analysis for managing stands to achieve an uneven-aged character across the landscape.

In a series of research projects spanning the 1990s, a more specific analysis of uneven-aged forest management in oak-hickory forests was conducted on Pioneer Forest. Such a thorough analysis was possible primarily because of the long-term database from the CFI established on Pioneer Forest in 1952. Jenkins (1992) and Jenkins and Pallardy (1993) studied oak-hickory stands and suggested that the red oak group in uneven-aged stands on Pioneer Forest were less susceptible to mortality than similar stands under other management systems elsewhere. While not exclusive to Pioneer Forest, Johnson (1992) mentions the use of single-tree selection harvesting in his review of alternatives to clearcutting, although, at the time, only reluctantly recommending it as a prescription. Shortly after Johnson's review was completed, he and other researchers at the University of Missouri-Columbia continued to analyze the single-tree selection method and reported positive results. Loewenstein (1996) and Loewenstein and others (1995, 2000) investigated age/diameter relationships, as well as long-term changes in species composition and basal area (summary of the number and size of trees per acre). Results from this series of papers clearly demonstrated the success of the method over a 50-year period. Wang (1997) and Wang and others (1996) reported on the stability of diameter distributions, confirming that the diameter distributions for scarlet oak (*Quercus coccinea* Muenchh.), northern red oak (*Q. rubra* L.), and white oak (*Q. alba* L.) conformed to the expected negative exponential diameter distribution (described by Johnson and others 2002);

[1] **Greg F. Iffrig**, Chief of Recreation and Reserves, **Clinton E. Trammel**, Retired Forest Manager, and **Terry Cunningham**, Forest Manager, Pioneer Forest, Salem, MO 65560.

namely, with more trees in the small size, young age classes and fewer trees in the larger size, older age classes.

Two attempts in the recent past describe how the method applied on the ground. One was an initial work by Larsen and others (1997) where the authors, using regression models, projected height and density classes for regeneration based upon given residual basal area of the overstory. Then Larsen and others (1999) presented criteria for selecting the residual stand structure and density necessary to sustain a forest dominated by oaks. The basis for both of these treatments was a 40-year portion of the data-set from Pioneer Forest. More recently, Johnson and others (2002) thoroughly reviewed uneven-aged silvicultural methods, including an extensive discussion of the principles and some of the theory of the single-tree selection cutting technique. In this paper, we present in more detail the successful practice of marking and decision-making, which has been developed by a group of foresters who have applied the single-tree selection technique of uneven-aged management in Ozark forests since the 1950s.

BACKGROUND AND HISTORY OF THE LANDS OF PIONEER FOREST

Leo Drey began acquisition of the lands that are now Pioneer Forest in March 1951. Today these forests extend over 154,000 acres. He recognized that these forested landscapes could be productive while they were managed using a more conservative harvesting technique. Prior human-induced disturbance on much of these lands included fire, cutting, and grazing. Drey's goal was to establish a demonstration method of harvesting trees while retaining the structure and character of the forest across the landscape. The long-range objective for Pioneer Forest is to develop and manage native tree species of large diameter and high quality for wood products while also providing a host of recreational and ecosystem benefits.

There is significant information on the history of these forests prior to Drey's earliest acquisition. This history is not only interesting, but is also instructive in developing and then validating a successful prescription for single-tree selection harvesting.

Pioneer Forest is located in the oak, hickory, and pine region of the Ozark Highlands. Aside from scenic beauty, these forests provide recreation, water and soil conservation, watershed protection, timber products, fuel, and essential habitat for characteristic wildlife species. The topography was formed largely through a process of erosion with areas of greatest relief reaching a difference in elevation of 700 feet. This area of the Ozarks, and the lands of Pioneer Forest specifically, have many classic features of karst-influenced landscapes, including large springs, sinkholes, losing streams and numerous caves, plus bluffs, glades, fens, and clear streams.

We can only speculate as to the condition of these old and mature forests just prior to their first cutting, but we can learn a great deal from those who have examined, studied, and written about the condition of the Ozarks landscape at that time. Their observations, as well as what we know about the cutting during this early period are particularly helpful in understanding the subsequent results of the harvest method that has been researched and practiced on Pioneer Forest.

The earliest information we have comes from the study of tree ring chronologies. Guyette and others (2002) developed a method for constructing fire and disturbance models extending hundreds of years back in time through pre-European settlement. Study of disturbance regimes resulting from the long-term interactions between humans and their environment can provide specific information on forest succession and species abundances.

In the region of Pioneer Forest, evidence suggests that the highly dissected and heavily forested topography reduces the frequency of fire-related disturbance. Guyette and others (2002) noted that the interval between surface fires ranged from 9.8 to 17 years within the forested uplands immediately north of the Current River, compared to 16 to 29 years for the more mesic mixed-oak forests along the river during the period 1700 to 1850. Thus, the 15- to 30-year entry period that has evolved operationally for single-tree selection harvest parallels the earlier frequency of disturbance from fire in the region.

There also appear to be differences in the scale of disturbance locally versus regionally. Guyette and others (2002) noted that the Ozark Region is more than 80 percent forested, defined as having a percent canopy closure of more than 75 percent. However, they also noted that the locality of Pioneer Forest with its steep ridges and numerous streams and slopes that average 18 degrees, supported a pattern of small-scale rather than large-scale disturbance. The practice of removing individual trees that is typical of management on Pioneer Forest thus approximates the historic scale of smaller disturbances that were common in this vicinity.

Pine and deciduous forests made up most of the pre-settlement vegetation of the Ozarks, especially in areas of greatest topographic relief (Thom and Wilson 1980). From our own long-term work, as well as publications describing this particular area of the Ozarks, the majority of Pioneer Forest is located in what was and still is the most heavily forested region of Missouri. These landscapes are and have always been forests in the truest sense.

More information comes during the mid-20th century from an article about "Pioneer Forest," published by the Missouri Department of Conservation. Meyer (1949) describes these lands during the period from about 1920 to 1945. The following are a few of his observations:

> "The name Pioneer Forest is an ideal one, tying its past history to the cooperage company whose conservative use of the land made it possible for the forest now to be a going concern without a long period of building up the timber volume on the land.
>
> "The history of the forest begins about a quarter of a century ago [ed. note: about 1920] when 50,000 acres of virgin timberland was purchased by the cooperage

company from the old Current River Lumber Company. A lot of this land then supported ancient stands of shortleaf pine and of white oak..."

"And so the company had some land which had not been cut enough to even harvest the growth..."

These writings are clear in their description of forest, timber volume, and the dominant native species found in this region.

Around 1945, National Distillers purchased all of the lands owned by Pioneer Cooperage. By 1954, National Distillers had changed its forest management practices and began cutting all merchantable trees rather than using the more careful and selective approach initiated by Pioneer Cooperage. Cutting during this time removed many of the larger shortleaf pine (*Pinus echinata* Mill.) and white oak, as well as some black and red oaks. Farther away from the sawmills, larger trees were often left. Also, left within these forests were the pine and white oak trees generally smaller than 14 inches in diameter (Martin and Presley 1958). Misshapen or poorly formed trees were not cut. Also left were other abundant species of all sizes, including blackgum (*Nyssa sylvatica* Marsh. var. sylvatica), ash (*Fraxinus* spp.), hickory (*Carya* spp.), other oaks, walnut (*Juglans nigra* L.), basswood (*Tilia americana* L.), mulberry (*Morus rubra* L.), black cherry (*Prunus serotina* Ehrh.), elm (*Ulmus* spp.), and sycamore (*Platanus occidentalis* L.)—trees that we know are characteristic of the Ozark forests, but for which, at the time, there was no market.

Another source of information from the period immediately prior to Leo Drey's purchase of the forest provides a more detailed look at forest composition. H.H. Chapman, a well-known forestry professor from the Yale University School of Forestry, visited the National Distillers holdings in July 1951. The purpose of Chapman's visit was to produce a fairly detailed report (Chapman 1951) of the forest condition. During the period of July 5 to 15, Chapman traveled 1,500 miles, inspected 66,000 acres of land, and completed measurements from 106 of the 179 surveyed sections in which National Distillers owned land. This was during a time when many writers describe these Ozark forests as having been completely cutover. Included in Chapman's report was a 1949 calculation of the number of trees per acre from three diameter classes (4 to 10 inches, 12 to 14 inches, and trees greater than 16 inches in diameter). From his data, we know that there was an average of 38.4 trees per acre, including nearly eight saw log trees (individual trees greater than 12 inches in diameter) (table 1).

Whereas this average represents a relatively low stocking, it should be noted that at the time of his inventory in 1949, the only merchantable species were white oak, red oak, black oak, and shortleaf pine. We speculate that these data may have represented only the species that were merchantable at that time because only one species-specific class (the report lists white oak, the species of primary importance to the distillery company, as one class and then other species as another class) is mentioned in Chapman's report. If all species present had been measured, whether merchantable or not, then the forestwide number of trees per acre would have been higher. Our own data, compiled only 8 years later (table 1, 1957), show nearly double the total number of trees and nearly double the saw log trees when accounting for all species.

There is no question that early cutting (the peak period of which occurred between 1880 and the 1940s) substantially changed certain Ozark forests. Furthermore, there also is considerable evidence that while forests of the Ozarks were indeed cut, it is unlikely that the entire Ozark region would have been left barren.

In 1954, Drey concluded his purchase of all of the land holdings of National Distillers and, adding that to the forest acreage he had already purchased, he then renamed his long-range forest management effort Pioneer Forest. From its beginning, Pioneer Forest has used uneven-aged management, applying the single-tree selection harvest method on a truly landscape scale as an Ozark forest management project.

Table 1—Trees per acre by diameter at breast height (d.b.h.) and year of inventory from Pioneer Forest, Missouri[a]

D.b.h.	Chapman 1951	1957	1962	1967	1972	1977	1982	1987	1992	1997	2002
6		29.0	34.0	38.2	44.4	47.9	47.8	46.6	54.2	66.4	64.73
8	30.5[b]	18.0	19.0	22.8	24.2	27.3	30.7	32.5	34.2	36.2	33.09
10		11.2	12.5	14.6	16.4	17.0	18.1	20.0	21.8	24.3	22.9
12	5.8[c]	6.9	7.0	9.0	9.2	10.2	11.0	11.6	12.5	15.1	13.0
14		4.1	4.5	5.4	4.7	5.0	5.4	5.8	6.7	8.0	6.4
16	2.1[d]	1.6	2.0	2.7	2.3	2.3	2.5	2.3	2.8	3.6	3.0
18		0.6	0.8	1.0	1.0	0.7	0.8	1.0	1.2	1.7	1.2
20		0.3	0.3	0.4	0.4	0.4	0.3	0.3	0.5	0.6	0.7
22		0.1	0.1	0.1	0.2	0.2	0.2	0.1	0.2	0.2	0.1
24		0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.1	0.1	0.1
Total	38.4	71.9	80.3	94.3	102.8	111.0	116.7	120.1	134.2	156.2	145.2

[a] Data for 1951 from Chapman (1951), and for remaining years from the continuous forest inventory.
[b] Accumulated diameter class of all trees measured from 4 to 10 inches d.b.h.
[c] Accumulated diameter class of all trees measured from 12 to 14 inches d.b.h.
[d] Accumulated diameter class of all trees measured ≥16 inches d.b.h.

SINGLE-TREE SELECTION AS APPLIED IN PIONEER FOREST

The application of the single-tree selection harvest method lends itself more to a qualitative description, and somewhat less to being quantified. In many ways, this technique is at least as much art as it is science. From the very earliest days of Drey's ownership, the forest management philosophy was epitomized by the words of Russ Noah, former forester with Pioneer Forest: "if a tree would last for another 10 years (or until the next scheduled harvest), don't cut it." This philosophy is also expressed in a more recent and equally concise description of uneven-aged management by Guldin and Baker (1998), where markers are instructed to "cut the worst trees and leave the best within each diameter or product class." Although simple, both descriptions go a long way toward demystifying what many have been called impossible to describe.

First applied by foresters Ed Woods and Charlie Kirk on the properties of Pioneer Cooperage, the concept was to remove trees from the forest that might be lost before the next harvest. Infestations by insects, disease, or storm damage were all reasons to harvest a tree. Rather than removing all or a large portion of the trees from any given acre, only those trees that might be lost or were expected to significantly decline (in value or health or both) before the next harvest were considered for removal. The principal idea was to devise a harvesting technique that would allow selected trees to be removed periodically from the forest.

This removal was initially suggested to be every 10 years. Neither the expected period for this re-entry, nor the carrying capacity for these Ozark forests, were precisely known when foresters of the present-day Pioneer Forest began. Through practical experience and experimentation, the details of this technique have developed.

In many ways, the nature of the single-tree selection harvest technique is an accelerated version of the natural changes that might occur within the forest over much longer periods of time. Time, combined with risk factors such as mortality, make all the difference in understanding how this method of forest management works (fig. 1).

Overview

The prescription for field-marking, which we describe below does not attempt to quantify the many variables that are at play within the forest. Uneven-aged management, and especially the single-tree selection technique, is, by nature, a highly flexible forest management tool. Single-tree selection harvesting is more consistent with the dynamic conditions within the forest, combining the biological realities with various social objectives (Becker and Corse 1997), including income, recreation, and aesthetics. The biological realities such as drought, fire, ice, and wind, as well as the many human-inspired or human-inflicted changes that have affected these forests over long periods of time, are all constant and highly variable factors. Management and experience with an ecosystem at least several hundred years old continue to leave many details of their effects still unknown. These include the carrying capacity or standing volume, maximum diameter, and a strict Q-ratio—the factor used to calculate the number of trees within individual age/diameter classes (Johnson and others 2002). Therefore, as a purposeful precaution, our marking prescription aims for more broadly defined age and diameter classes within the forest and much less for the academic rendering of a numerical formula. This flexibility allows for specific targeted adjustments to be determined on-site, during each harvest, accounting for both natural and catastrophic change that may occur.

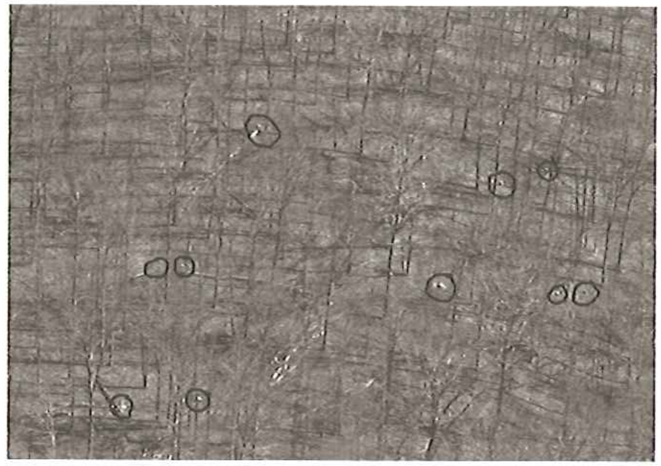

Figure 1—Aerial view of an oak-hickory stand on Pioneer Forest harvested using the single-tree selection method. Stumps of trees harvested during the harvest are circled. *(Pioneer Forest)*

The most basic requirement of uneven-aged management is that the resulting forest shall possess at least three distinct age classes. The age class or diameter distribution of the forest then follows what has become a classic reverse J-shaped curve (Johnson and others 2002). This curve portrays the forestwide array of diameter classes beginning with a greater number of younger aged, smaller diameter trees, and then progressively reducing the numbers of trees within each diameter class to reach fewer older aged, larger diameter trees. The difference between the real curve from actual forest data and the theoretical guiding curve provides the management target. Figure 2 portrays the results of our day-to-day interpretation of the qualitative prescription we describe here. The quantitative analysis of these results and the periodic fine-tuning over long periods of time determine successful management and demonstrate how well the technique works when applied across a large forested landscape.

Merchantability Standards

The merchantability of a given species depends on market conditions within a particular region. In the Pioneer Forest area, minimum merchantable hardwood saw log trees are 11 inches in diameter at breast height, with at least an 8-foot saw log containing a 10-inch diameter at the small end. Pine saw log trees must be at least 9 inches in diameter at breast height

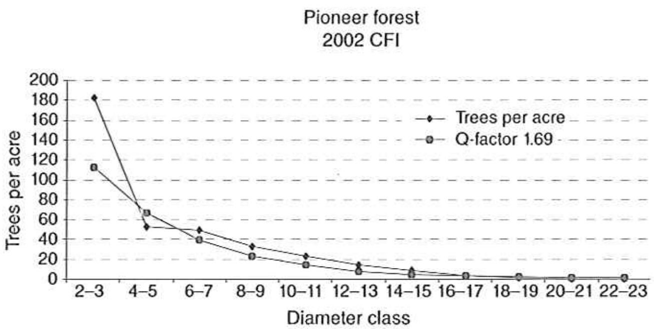

Figure 2—Distribution of stems > 2 inches in d.b.h. per acre from the 2002 Continuous Forest Inventory (CFI)—compared with a theoretical 1.69 Q-factor curve using an upper diameter of 23+ inches.

and have at least an 8-foot log length, with a minimum of 6 inches in diameter on the small end. Cordwood trees are those trees large enough to be a saw log but contain defects that will not allow merchantability as a saw log; or are less than the minimum saw log diameter at breast height, contain at least one stick of wood 4 feet in length, and are not less than 4 inches in diameter on the small end.

Harvest Cycle

Rotation describes the length of time between harvests or the maximum age a stand will be allowed to grow under an even-aged management system. The length of a rotation is the time between harvests. Using an uneven-aged management system, however, there is always a forest cover on the land and thus no recognizable beginning or end to the structure of the forest. Forest management through the application of single-tree selection becomes a series of separate entries, called cutting-cycle harvests, where each time a partial harvest occurs. These harvests can be thought to be analogous to the thinnings used in well-managed, even-aged stands, but unlike even-aged thinnings, mature, high-value trees are harvested during every uneven-aged cutting-cycle harvest. Success with single-tree selection management depends on the monitoring of canopy closure as well as a forest's structural characteristics. The ability to continually measure forest structure through time facilitates success and also quantifies and characterizes forest quality.

The timing between each entry has evolved from that used beginning in the early 1950s, of about every 10 years, to a slightly longer period used today of 15 to 30 years for individual stands. Past cutting history and the current condition of the stand are used to determine the timing of each harvest entry. Exact timing depends on the condition of any given area, primarily canopy closure for the forested area under consideration. The canopy cannot be allowed to fully close for any length of time without causing a loss of desirable seedlings, saplings, and poles, and significant components of stand structure. Other factors include physical condition of the trees, growth rate, and signs of mortality.

Marking Method

Marking for a single-tree selection harvest focuses on the condition and health of individual trees. When marking an area for harvest, every tree is examined and an assessment made as to the risk of that tree surviving through the next harvest cycle. Trees not marked are considered to be likely to survive, and, thus, are left to grow and gain in volume and value. The number and quality of retained, or "leave", trees found on every acre of the forested area are a distinguishing measure of single-tree selection harvesting. Leave trees are the dominant and most productive trees in each age and diameter class. As stand marking proceeds across the slope, the focus on any given area is to first determine which trees are to be left and only then to begin marking those trees that are to be cut. The best trees on each site are almost always left to be re-assessed during the next harvest. Specific considerations are age and species, physical condition, vigor, site quality, stand position and density, and cull or snag trees. A decision-tree was developed for marking a stand of timber to aid foresters in the conceptual understanding of the process (fig. 3).

The following marking guidelines have been developed to assist in the evaluation of trees during a particular harvest when using single-tree selection management. It should be remembered that when using this method, foresters mark and leave trees for the present harvest but also look ahead to one or more future harvests when assessing each tree's status.

Age (Size) and Species—The forester must observe characteristics of each tree to estimate its age and determine whether it is approaching biological maturity. For any given tree this requires a general understanding of the capability of any given species within this region. For example, a scarlet oak currently estimated to be 80 years old would be around 100 years of age at the next harvest entry used on Pioneer Forest. An age of 100 years would place a scarlet oak beyond the age considered to be its normal biological maturity, and, thus, would be at high risk of mortality. Such a tree would be marked for harvest. On the other hand, a white oak tree 150 years of age is well within the most productive growth period during its life cycle and could be retained for at least several more harvest entries.

Physical Condition—Each tree is examined for factors such as an unusual number of dead limbs, decay holes, percent crown spread, percent live crown, insects, and disease. For example, trees in poor physical condition or those infested with insects or diseases are considered at high risk of significant volume loss or of dying before the next entry and, thus, become candidates to be marked for removal during harvest. In addition, those trees infested with insects or disease will potentially become an infection site for the surrounding stand and should be removed. As marking moves across the slope or up the hill, each tree is observed from all sides. It is often the case that a tree observed from several sides, and initially thought to be a leave tree, will be reconsidered when a serious defect is observed from a side of the tree not yet seen. Oaks in otherwise good physical

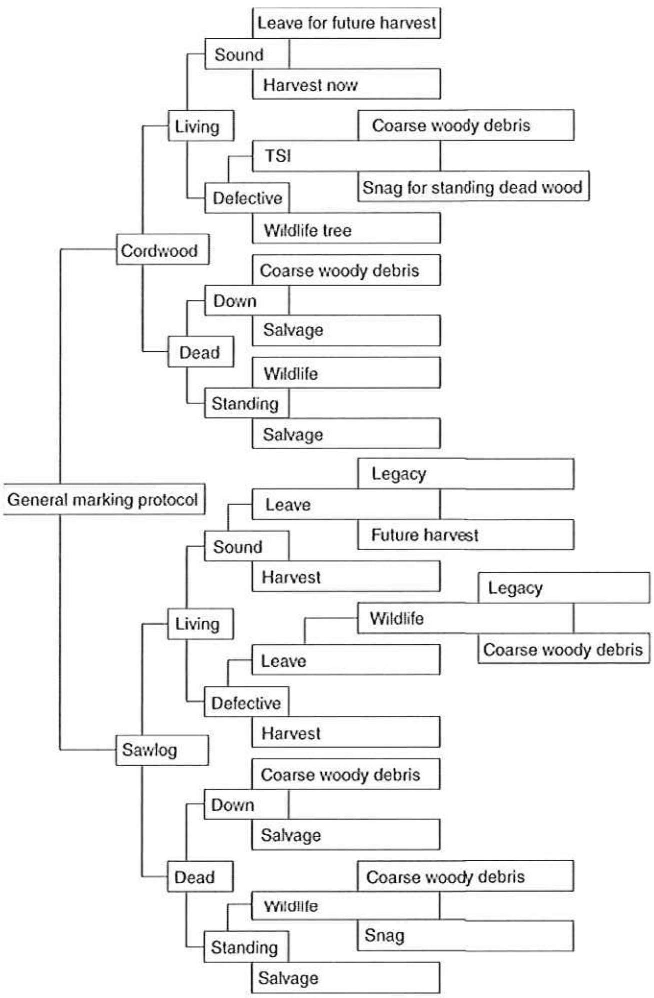

Figure 3—Key for determining cut or leave trees during a single-tree selection harvest. Definitions for terms used here are: cordwood—see definition earlier in this paper under merchantability standards; TSI—abbreviation for timber stand improvement, meaning the tree cut for TSI has no commercial value other than the value of removing it as a benefit to all of the surrounding trees; course woody debris—a cut tree left on the forest floor; wildlife tree—any tree presently or potentially used by any of a variety of wildlife species; legacy tree—any commercial tree left standing for various non-commercial reasons including its size, species, or form.

condition, but with a basal hole as opposed to a hole somewhere up on the trunk or bole, may be candidates for leave trees. The reason for this is that damage to the wood from this source always moves down in a tree, and, if the decay moves up, it does so very slowly. Such a tree could easily grow through another harvest cycle with considerable additional increase in volume but with much less increase in the measured defect.

Vigor—The overall health of each tree is considered. To be retained, a tree must be growing well. For example, red oaks must have a tight, relatively smooth bark with little difference between the bark ridges and valleys. This indicates a strong, healthy tree that is putting on good diameter growth. In this example, the bark indicates that the tree is healthy and growing rapidly. The tree should have a good, relatively thick, healthy-looking crown in relation to its size and position in the stand. A positive assessment indicates an ideal leave tree.

Site—The forester considers the conditions of the site on which the tree is growing, including slope position, aspect, soil type, and soil depth. During a day of marking, site conditions will change several times along and across a given hillside. These changes may be from a dry ridge top to a moist north cove to a warm west hillside. Marking is designed to encourage and leave those species best suited to each particular site condition. Therefore, marking for a single-tree selection harvest requires the continual assessment of site quality and species composition, with the goal of favoring those species that will survive adverse conditions between now and the next harvest cycle. Each harvest is directly related to growth rate as well as the standing volume. For example, a higher volume could be cut from the faster growing cove site than from the drier ridge top. Making these adjustments during marking compensates for varying growth rates and is consistent with the naturally higher stocking possible on better sites.

Stand Position and Density—Consider an individual tree's position in the stand when determining which trees to cut. Legitimate reasons exist to cut both poor and good trees, depending on localized stand conditions. There are two primary reasons why trees otherwise considered to be leave trees might be cut. Trees that have become suppressed for prolonged periods of time are often of poor quality, and do not respond well to release; as such, they are poor candidates to leave until the next harvest entry. On the other hand, a desirable tree may also be a candidate for removal via thinning in order to give other more desirable trees in close proximity room to grow.

Cull and Snag Trees—Cull trees are defined as living trees where more than 50 percent of the total volume is defective from a merchantability perspective. Snag trees are standing dead trees and have no commercial value. However, maintaining a component of defective, dying, and dead trees within the forest is considered a very important measurable benefit for wildlife. Thus, no attempt is made to remove all dead and dying trees from the forest. Individual merchantable trees showing signs of use for dens or nests by forest-dwelling mammals, birds, and reptiles are almost always left. Merchantable trees with no apparent wildlife use may be salvaged or left, depending on the density and distribution of culls and snags within the area. Trees of no merchantable value and no value for wildlife may be felled where they interfere with the growth of a desirable leave tree.

When Several Adjacent Trees Are Candidates for Removal or Leaving—When a small group of trees is under consideration for marking, and the criteria above do not make the choice clear, then choosing which trees to mark and which to leave becomes a matter of thinning. With all other factors appearing equal, this decision would prioritize the observed spacing within the group and, by removing one or more trees, would provide more opportunity for the leave trees.

Succession

From reviewing the literature on uneven-aged management at sites other than Pioneer Forest within the Central Hardwoods Region and elsewhere, the greatest error in application of single-tree selection seems to occur from overcompensating for succession. This happens when more attention is placed on managing for recruitment of seedlings on the forest floor than in managing the forest at hand. This perception has led others to favor group selection (Law and Lorimer 1989, Johnson 1992, Johnson and others 2002). Yet other researchers (e.g., Becker and Corse 1997) warn that using single-tree selection and group selection together could allocate more growing space than necessary for new regeneration in ponderosa pine forests.

Foresters have, for many years, assumed that oak forests here in the Missouri Ozarks would trend toward some combination of sugar and red maple (*Acer saccharum* Marsh. and *A. rubrum* L., respectively), along with other species such as basswood, blackgum, and dogwood (*Cornus florida* L.) (Law and Lorimer 1989) where these forests either were not managed or where management did not create large enough openings for sufficient light to provide for regeneration. Outside the Ozarks, where soils are deeper such as in the River Hills region of Missouri, there are forested canopies composed of a significant percentage of sugar maple. Shifley and others (1997) report three examples from north Missouri, two of which have sugar maple along with oak species as dominant and one with oak and other species dominant in the overstory. In one instance, one of the present authors measured an unmanaged forest canopy from north Missouri where sugar maple dominated. This was from a transect where sugar maple comprised 70 percent canopy coverage (Iffrig and Elder 1978). Data from another source indicated the canopy from this same north Missouri forest was 90 percent sugar maple (Weaver 1977).

Such evidence indicates that oak-hickory forests on higher quality sites, and perhaps on unmanaged forests, may show succession tendencies toward shade-tolerant nonoak canopies. However, if this were true for the Ozarks, then one would expect to see examples of nonoak canopies, particularly for the oldest aged canopies on the highest quality sites within the region. But this is not apparent on Pioneer Forest. For example, the canopy trees on the Current River Natural Area, located on Pioneer Forest, are oaks that range in age from 250 to 400 years, with the earliest ring width indicating they had regenerated under a full canopy, that is, in shade (Personal Communication. Richard P. Guyette, Associate Professor, University of Missouri, Columbia, MO 65211). This particular site is situated at the lower end of a north slope, and evidence indicates it has never been harvested.

Several anecdotal examples are instructive in further understanding the replacement dynamics within these oak-hickory-pine forests. Dogwood flourishes on the forest floor and frequently forms thick shrub canopies within the forest through which oak saplings grow to replace other oak as canopy dominants. Counts of seedlings on the forest floor have shown particularly high numbers of blackgum, elm, maple, sassafras (*Sassafras albidum* (Nutt.) Nees), and dogwood competing along with equally high numbers of canopy replacement species of black oak, white oak, and hickory (table 2). The data from table 2 suggest that oak, hickory, and even pine are highly competitive on these sites. Scarlet oak, even from relatively small stem counts, maintains its presence while growing into the larger diameter classes. Perhaps most interesting is that shortleaf pine seems to be able to compete into larger diameter classes under single-tree selection management. A particular species representation on the forest floor does not seem to be an accurate indicator of its future presence in the forest canopy. Following 50 years of data collection across thousands of acres of forest, we know of no evidence from the Missouri Ozarks where canopies, which have been dominated by oak, hickory, and pine for centuries, show measurable and significant change away from this historic composition.

Light

One requirement for successful regeneration is the presence of both direct and diffuse light. Harvest activities allow direct light to penetrate the forest canopy where a tree has been removed. Harvesting one or a few trees creates canopy gaps that vary in size but occur in an irregular pattern across the landscape. Light penetration continues for some time into the future until each canopy gap is eventually filled in. Diffuse light is also continuously present within the forest by being transmitted through smaller gaps in the canopy (such as dead limbs or spaces between adjacent trees), as well as by being reflected off of the leaves, trunks, and limbs of the trees within the forest.

Our experience with successful uneven-aged management at Pioneer Forest has shown that removing groups of trees from any given area is not necessary to promote the penetration of sunlight to the forest floor. Replacement of the canopy, primarily by oak and pine, has always been a result of the canopy gap dynamics occurring as a result of periodic harvest of one or more trees. Thus, the light environment promoted by removing individual trees appears to be sufficient to sustain regeneration in these forests.

Forests under single-tree selection cutting benefit from a continual provision of light as a built-in component of this method of forest management. Both direct and diffuse light reach the forest floor as trees are removed during each harvest entry. These sources of light continually shift in space and time. Whereas the actual source for light within the forest may vary (because of the heterogeneous nature of providing light energy through single-tree selection management), the provision of light is automatic. In this manner, light continuously influences the development and maintenance of the forest structure under this method of management.

Table 2—Stems/trees per acre for all species measured from the 2002 continuous forest inventory [a]

	Diameter class [b]														
Species	0	2	4	6	8	10	12	14	16	18	20	22	24	26+	Total
Black oak	224.4	3.9	1.8	4.0	4.7	3.7	2.7	1.5	0.7	0.3	0.1	0.0	0.0	0.0	247.9
Red oak	20.1	0.4	0.2	0.6	1.3	1.1	0.6	0.7	0.3	0.2	0.1	0.1	0.0	0.0	25.8
Scarlet oak	79.2	4.4	2.5	4.4	3.7	3.4	2.4	1.4	0.7	0.3	0.1	0.0	0.0	0.0	102.8
Blackjack oak	3.2	0.9	0.3	0.1	0.1	0.0	0.0	0.0	0.0	0.5	0.0	0.0	0.0	0.0	5.2
White oak	423.8	36.5	17.7	20.0	11.1	6.2	2.9	1.9	1.1	0.0	0.1	0.1	0.0	0.0	521.4
Chinquapin oak	15.3	4.4	1.7	0.4	0.4	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	22.6
Bur oak	0.0	0.6	0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2
Post oak	14.9	4.1	1.4	2.0	1.2	1.0	0.6	0.3	0.0	0.0	0.0	0.0	0.0	0.0	25.6
Shortleaf pine	16.1	1.5	1.2	3.2	3.6	4.0	3.0	1.7	0.7	0.2	0.0	0.0	0.0	0.0	35.2
Cedar	20.1	3.3	1.6	1.7	0.8	0.3	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	28.0
Hickory	296.3	12.5	2.3	6.2	3.7	2.3	0.9	0.5	0.1	0.0	0.0	0.0	0.0	0.0	324.8
Blackgum	239.8	24.7	4.3	1.1	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	270.3
Sycamore	4.0	8.4	1.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	13.8
Hackberry	0.7	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.2
Elm	351.8	2.4	0.8	1.0	0.4	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	356.6
Ash	19.2	3.9	0.6	0.3	0.2	0.2	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	24.4
Birch	0.1	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6
Cottonwood	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Boxelder	2.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.2
Basswood	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.7
Locust	0.0	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Maple	634.8	4.7	1.6	1.8	0.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	643.7
Black walnut	3.1	8.3	1.4	0.4	0.3	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	13.8
Butternut	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Sassafras	517.9	1.8	0.4	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	520.4
Dogwood	430.0	12.7	1.2	0.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	444.4
Redbud	44.9	6.4	0.4	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	51.8
Ironwood	56.3	15.2	1.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	72.7
Persimmon	0.9	1.3	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.5
Willow	0.8	1.5	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4
Mulberry	0.7	0.6	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.5
Buckeye	0.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.6
Blackhaw	19.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	19.3
Serviceberry	33.7	1.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	35.0
Black cherry	18.3	1.3	0.3	0.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	20.4
Sweetgum	1.0	1.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.1
KY Coffeetree	0.1	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.8
Plum	0.0	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.2
Hawthorn	2.2	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.4
Mimosa	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1
Buckthorn	2.7	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	2.8
Farkleberry	1.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	1.7
Hornbeam	0.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.4
Pawpaw	86.7	0.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	87.6
Totals	3,587.1	171.7	45.5	48.8	32.8	23.4	13.8	8.2	3.7	1.6	0.4	0.2	0.0	0.0	3,937.4
Q-factor 1.69	190.0	112.5	66.5	39.4	23.3	13.8	8.2	4.8	2.9	1.7	1.0	1.0			

[a] Diameter class n contains trees from n.0-(n+1).9, inclusive.

[b] The diameter for stems < 1.6 inches was measured at the root collar and for stems ≥ 1.6 inches was measured at breast height.

Other research on various oak species has suggested that shade tolerance may not be as fixed as often suggested (Johnson and others 2002). McGee (1976, 1988, 1997) has shown that oaks adjust to variation in light conditions by shifting the timing of their spring budbreak, based on their exposure to light during the previous year. Seedlings and saplings beneath a forest canopy begin growing earlier in the spring than open-grown oaks when light and moisture conditions are the most favorable. McGee (1997) found this same response in several oaks—namely, white, black, scarlet, post (*Q. stellata* Wangenh.), chestnut (*Q. prinus* L.), and northern red oaks. McGee (1986) also found this same response in hickories, red and sugar maple, and white ash (*F. americana* L.).

The highly irregular but constant provision of direct light through single-tree selection management may be the key to understanding the positive response of many species to this method of forest management in the Missouri Ozarks.

Regeneration

Single-tree selection on central hardwood sites, by its nature, is sustained by the accumulated regeneration of desirable species. The ability of oaks to accumulate in the understory has been well documented. As Johnson and others (2002) have pointed out, the early development of a large taproot and delayed shoot growth are characteristic of all oaks. Previous research has shown that oak seedlings sprout and grow, and then die back, repeating this response for many years while building a taproot (Johnson and others 2002). Dey and Guyette (2002) offer a brief review of oak regeneration ecology, pointing out that oaks are well adapted to repeatedly produce new sprouts from dormant buds located at the root collar. This root collar is often located beneath the soil surface and is naturally protected from such disturbances as low-intensity fire and some herbivores. With this adaptation, oak seedlings sprouted from acorns can develop beneath a forested canopy for decades, capable of rapid response to changes in light availability. Their response is to re-allocate energy from root into shoot development (Johnson and others 2002, Dey and Guyette 2002).

The cutting cycle used in single-tree selection harvests on Pioneer Forest is not long enough to allow the canopy to completely close, a condition that could, over long enough periods, result in a loss of oak regeneration and therefore a change in canopy species composition. Each cutting cycle reopens the canopy whereupon seedlings and stump sprouts, with well-developed taproots, are ready to capture the hole created in the canopy. Since the canopy gaps resulting from single-tree selection harvesting are small, the recruitment and regeneration present on the floor at any given time may number only a few saplings with perhaps a higher number of seedlings and sprouts. These numbers are small when compared to reproduction numbers using even-aged forest management. However, the young seedlings and saplings survive in sufficient numbers to replace the correspondingly smaller number of individual trees that are removed during each harvest.

Unlike even-aged management, where establishing regeneration is a one-time event, single-tree selection harvests provide for regeneration with each entry. This maintains the range of age classes characteristic of this technique of management.

Reducing Disturbance Effects and Harvest Damage to the Residual Stand

Under uneven-aged forest management, abiotic variables, such as percent canopy coverage, temperature, and humidity show measurably fewer changes among the trees than in forests under even-aged management (San Diego 2001). This reduced environmental variability provides for increasing stability to forest structure through time (when compared to the change created from even-aged management methods) and represents a unique opportunity to restore and then maintain a forest condition in the landscape. However, protecting leave trees during successive harvests and until maturity requires deliberate and careful application of specific cutting and removal techniques when compared to other methods of forest management. Table 3 describes such techniques for reducing damage from harvesting within the forest.

Age, Composition, and Resistance of the Canopy

Successful use of single-tree selection depends on the continual development of all of the age classes present within the forest. The oak-hickory-pine forests in the Ozarks represent one of the oldest natural communities within the region. The biological lifetimes of dominant canopy species range from scarlet oak and black oak at 80 to 100 years, and northern red oak at 90 to 130 years, to shortleaf pine at 200 to 300 years, to white oak exceeding 350 years (Personal communication. Richard P. Guyette, Associate Professor, University of Missouri, School of Natural Resources, Columbia, MO 65211). Runkle (1990) studied the spatial pattern of disturbance in old-growth forests and found the annual rate of canopy gap formation ranged from 0.4 to 0.2 percent for various temperate hardwood forests. Dey and Guyette (2002) estimated from these data that the turnover of the canopy in these forests studied by Runkle would occur in less than 250 years. Similarly, here in the Ozarks, LaVigne (2002), using a life history table, calculated the statistical range of age for the forest canopy on Pioneer Forest between 189 to 228 years. The range LaVigne describes is comparable to a 95-percent confidence interval with single-tree selection harvesting as the only source of mortality for trees that form the canopy. Rather than prescribing an arbitrary canopy rotation, single-tree selection harvesting allows individual species, as well as individual trees, to fully develop and mature within the forest over rather long periods of time, while providing managers the opportunity to utilize potential mortality.

Furthermore, these forests, which are managed using single-tree selection harvesting, seem to provide for a more natural composition of species, indicative of a particular site's capability. Our own sampling data from the Continuous Forest Inventory show that among various canopy species those most characteristic of pre-European settlement conditions are

Table 3—Techniques for reducing damage within the forest

1. Require that the felling and skidding operations work together, beginning at the bottom of a hill and proceeding to the top.
2. Mark each tree to be removed on both its uphill and downhill sides. Mark the uphill side at chest height and mark the backside at the base of the tree. Marking the backside of the tree allows the skidder driver to use marked trees as pivot points when a load needs to be turned, thereby reducing or eliminating damage to higher quality leave trees remaining in the forest.
3. Have sawyers trained in using directional felling. This is the ideal cutting technique for single-tree selection harvests, significantly reducing damage to the residual stand, as well as improving both production and safety. Directional felling reduces damage within the forest, as well as the potential danger from hanging up, as well as fiber pull, and splitting. An especially good overview of these ideas and the technique are found in Maine Employers' Mutual Insurance Company's Production Felling Through Safety (1994).
4. Reuse ridge roads and skid trails for removing logs and for equipment access. Require single lane for skid trails and keep improvements to a minimum.
5. Avoid late winter and early springtime operations while the sap is moving or when roads and skid trails are particularly subject to rutting and erosion. This simple technique will minimize rutting of roads and excessive bark damage on leave trees.

regaining a stronger presence in the canopy. Shortleaf pine and white oak, which were the focus of the earliest cutting in the Ozark Region, have shown a marked increase in the volume of saw log trees per acre (Iffrig and others 2004). White oak, perhaps the most impressive Ozark forest canopy species, has increased slowly, but over the past 25 years has more than doubled in its volume per acre (Iffrig and others 2004).

The nature of periodic entries used during single-tree selection cutting also seems to provide a more favorable environment where competition is substantially and regularly reduced. This is accomplished during each entry, which removes approximately 40 percent of the standing volume and 60 percent of the annual growth. Jenkins (1992), in studying oak decline on this and another forest, suggested that the factor of reduced competition might be advantageous, particularly in situations where mortality affects a particular age or species class. In other words, "at risk trees" are continuously removed from these forests and the variability, which is maintained through this method of management, thereby greatly reduces certain risk factors of catastrophic oak decline and mortality.

CONCLUSION

In addition to researching the many silvicultural aspects of single-tree selection management, there is also a body of other research demonstrating positive conservation, social, and economic influences that have resulted from its use. Over the past 50 years, uneven-aged management and the use of single-tree selection harvesting have proven to work, both as being ecologically and silviculturally appropriate, and as providing a strongly positive forest management application for the central hardwoods region.

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