Tree Density and Fire Scarring in Minnesota Oak Savanna: Implications for Restoration

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Abstract

Due to fire suppression subsequent to European settlement, Midwestern oak savanna has become one of the rarest ecosystems in North America, with only 0.02% of the original range surviving today. Because of the necessity of fire in perpetuating this ecosystem, restoration and management is difficult, especially because little is known about original conditions and fire dynamics of oak savanna. To address these uncertainties, fire scarring was studied at one of the longest-managed remnants of oak savanna at the Cedar Creek Natural History Area in Central Minnesota, which has been burned periodically since 1964. Fire scars lead to a lower life expectancy, therefore high levels of scarring can indicate the beginnings of a shift towards prairie or oak scrub. Both contact and non-contact scarring are prevalent in oak savanna at Cedar Creek, with scarring on as much as 80% of trees over 10 cm DBH. Contact scarring is more prevalent in areas with higher tree densities prior to the start of the burn program. Non-contact scarring is usually present only in smaller diameter classes, but with improper burning techniques, it may also affect larger trees. Both contact and non-contact scarring can be controlled by more careful management, leading to more successful restoration and preservation of oak savanna.

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Introduction

Definition of Savanna

Savanna generally means grassland with scattered trees (Dyksterhuis, 1957; Nuzzo, 1986; McPherson, 1997). In modern ecology, the term has been applied to North American vegetation especially when referring to the area of the Midwest that forms a transition zone between the eastern deciduous forests and the western prairie. This transition zone is dominated by oaks (*Quercus spp*.), and covers parts of Ohio, Missouri, Illinois, Indiana, Iowa, Michigan, Minnesota and Wisconsin (Dyksterhuis, 1957; Curtis, 1959; Nuzzo, 1986).

Most definitions of Midwestern oak savanna stress the dominance of grasses in the ecosystem, with prairie forbs and minimal amounts of shrubs mixed in (Curtis, 1959; Nuzzo, 1986; Botts, *et al.*, 1994). In contrast with forest, which can have many layers between forest floor and canopy, savanna generally consists of only two structural layers: the ground cover and the scattered trees (Botts *et al.*, 1994). These trees tend to be few and widely spaced, with spreading limbs (Pierce, 1954; Curtis, 1959; Leach and Ross, 1995).

Curtis (1959) categorized as savanna anything from one tree per acre to 50% canopy cover, though he stressed that this definition was arbitrary. Bray (1955) estimated that original Midwestern savanna had 2-6 trees per ha. These definitions are both very sparse, and current definitions have expanded to include areas with as much as 100% canopy cover in order to be more inclusive of degraded areas (Nuzzo, 1986; Botts *et al.*, 1994).

Within the context of Midwestern oak savanna, there are several subtypes (Figure 1). The oak barrens" and "oak openings" mentioned by early travelers and settlers are now taken to mean xeric sites with poor soils and mesic sites with higher quality soils respectively (Leach and Ross, 1995). In addition to park-like open savannas (Figure 1a) with widely spaced mature trees and no shrub layer or oak sprouts (Bray, 1955; Dyksterhuis, 1957; Curtis, 1959), early settlers also mentioned scrub savanna (Figure 1b) which consisted of oak sprouts and saplings and occasional small trees within a prairie matrix (Pierce, 1954; Grimm, 1984; Nuzzo, 1986).

Oaks tend to be early- to mid-succession species, thus an oak-dominated ecosystem will not persist without succession being arrested (Abrams, 1992). Since oaks are well adapted to survival on xeric sites or areas of poor soil (Abrams, 1992), oak ecosystems are sometimes maintained indefinitely in environments that are too harsh for other species to colonize. However, the primary reason for the persistence of oak ecosystems has been periodic disturbance in the form of grazing and especially fire (Abrams, 1992). Oaks are adapted to dealing with fire because of their thick bark, which acts as an insulator (Abrams, 1992; Sutherland and Smith, 2000) and their virtually unlimited ability to re-sprout if killed by a fire (Pierce, 1954; Curtis, 1959; Abrams, 1992).

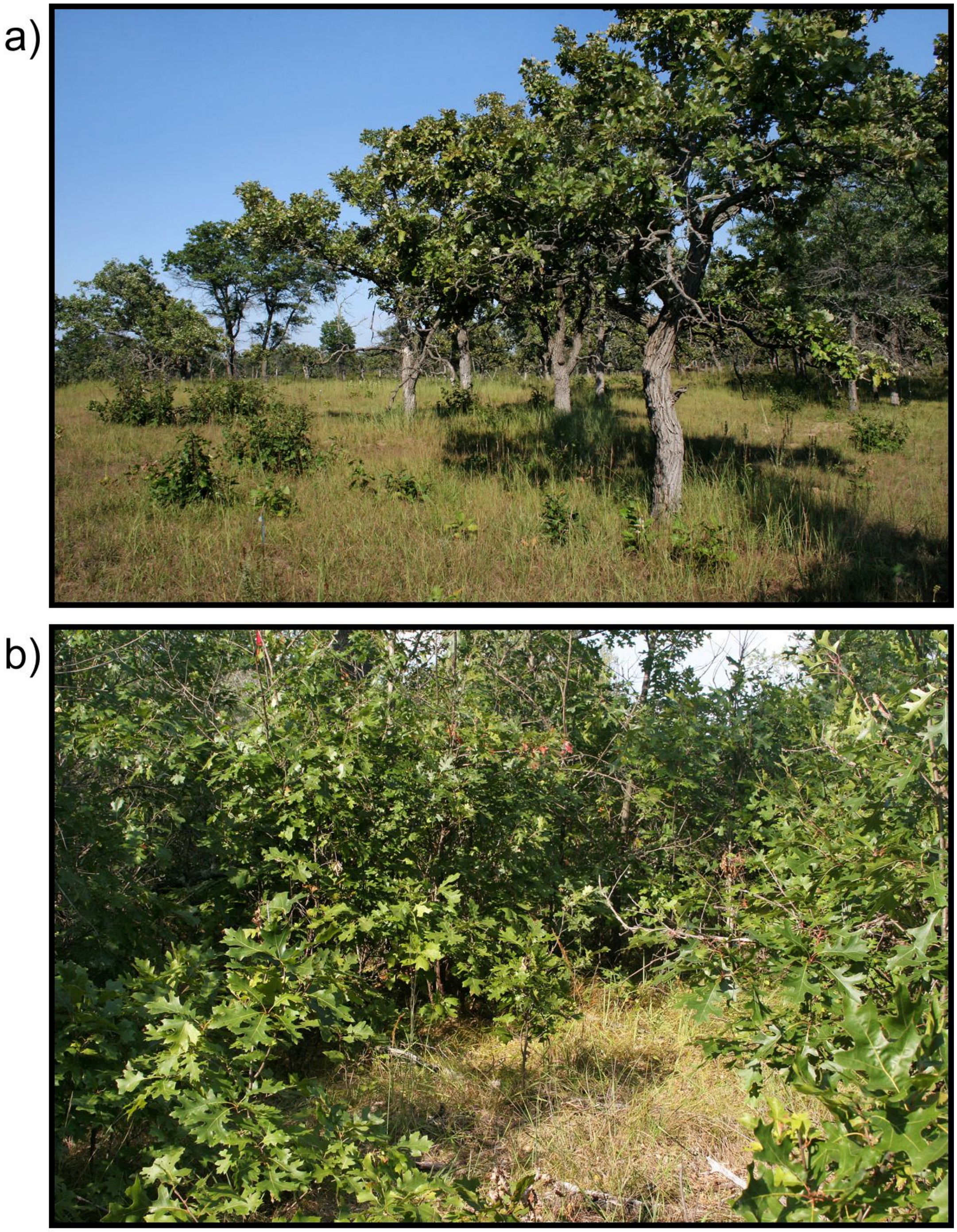

Figure 1. A comparison of open savanna (a) and scrub savanna (b) subtypes at Cedar Creek Natural History Area. The widely spaced trees in the open savanna are *Quercus macrocarpa* with grasses and forbs covering the ground and scattered oak sprouts. In the scrub savanna, thick undergrowth of *Quercus ellipsoidalis* is the predominant vegetation with small patches of grasses and forbs.

Historically, fires were common in the Midwest along the prairie-forest border (Curtis, 1959; Guyette and Cutter, 1991; Leach and Ross, 1995) and their frequency dictated whether an area would be prairie, savanna, or forest (Abrams, 1992). Areas that burned very often, especially multiple times per year, could not support trees and turned into prairie. Other areas that burned infrequently grew up in closed canopy forest. Savanna formed in areas of intermediate burn frequency, where only widely spaced oaks and fire-adapted prairie grasses and forbs could survive (Abrams, 1992).

These fires resulted from lightning, or were started by Native Americans either as a hunting tool, (Day, 1953; Stewart, 1956; Curtis, 1959; Pyne, 1983) or accidentally (Pyne, 1983). Because of the vast areas without firebreaks, one fire could burn a large area (Stewart, 1956). Pyne (1983) suggests that Native American fires could have been the origin of prairie and savanna in the Midwest. Stewart (1956) observed that reports of lightning-ignited fires in Midwestern literature were extremely uncommon, and that nearly all fires resulted from human activities.

Pre-Settlement Conditions

With the coming of European settlers, the fire-maintained savanna began to disappear quickly (Curtis, 1959; Nuzzo, 1986). Fire was actively fought and prevented by the Europeans. In addition, roads and agriculture created firebreaks, making the average areas burned much smaller (Nuzzo, 1986). Savannas on all but the poorest or driest of soils were converted to agricultural land (Nuzzo, 1986) and logging removed trees, converting some areas into prairie. The result of these changes was that savanna either lost trees, or grew into oak forest within a matter of 20 or 30 years (Curtis 1959).

At the time of European settlement, there were approximately 11 to 13 million hectares of oak savanna in the Midwest (Nuzzo, 1986). As of 1985, only 2,607 hectares of relatively high quality savanna remained, representing 0.02% of the original total and making it one of the rarest ecosystems in North America (Nuzzo, 1986). Approximately 17-22% of the original savanna persists in degraded condition sporting old, open-grown oaks (Klopatek *et.al.*, 1979); however, this can include anything from pastures to golf courses to forest. Currently there are no remaining high quality mesic or rich soil savannas; all the current remnants survived because their xeric nature slowed succession by other species, or their soil was too poor to farm (Nuzzo, 1986; Peterson and Reich, 2001).

Savanna Restoration

Because of the imminent loss of Midwestern savanna, managers are looking for ways to maintain areas of high quality savanna, and restore additional areas of degraded savanna (Botts *et al.*, 1994; Leach and Ross, 1995). Bray (1955) and Curtis (1959) found that there were few species endemic to oak savanna, however they conducted their studies years after settlement and fire suppression began, and some species may have already gone locally extinct (Packard, 1988). Even without many endemics, savanna is an important ecosystem. Its state of constant disturbance due to fire makes it a key habitat for the federally endangered Karner Blue butterfly (Shuey, 1994). Other species, especially birds, benefit from the open areas with protective islands of cover formed by the scattered trees that allow for good foraging grounds and protective nesting areas (Robinson, 1994; Sample and Mossman, 1994; Hartung and Brawn, 2005).

However, due to a lack of good reference information, the composition, structure, and interactions within an oak savanna ecosystem are not well known (Asbjornsen *et al.*, 2005; White, 1986) and current savanna remnants function with altered ecological processes (Botts *et al.,* 1994). There is also the question of what point in history is seen as the ideal state (Davis, 2000). Typically, "original vegetation" is taken to mean the status at the time of European settlement. However, the anthropogenic influence of Native Americans shaped the region for thousands of years before the settlers arrived (Pyne, 1983). Pollen studies show the presence of oak in the area during pre-historic times (Artist, 1939), but it is unclear whether these oaks grew in savanna or oak forest. Past savanna restoration efforts have been influenced by personal biases of what the system was like originally, or should be like now (Irving, 1970; Davis and Slobodkin, 2004).

Cedar Creek Natural History Area

Cedar Creek Natural History Area (2300 ha, University of Minnesota) lies in the transition zone between the tallgrass prairie biome to the west and the deciduous forest biome to the east (Tester, 1989). A large area of managed oak savanna lies in the southeastern part of the property. Adjacent to Cedar Creek to the south is Helen Allison Savanna, a 35-ha preserve managed by The Nature Conservancy. These savannas are dominated by Bur Oak (*Quercus macrocarpa*) and Northern Pin Oak (*Quercus ellipsoidalis*) (nomenclature follows Gleason and Cronquist, 1991).

Before the area was settled, early surveyors from the General Land Office recorded the dominant upland vegetation of the area in 1849 and 1854 as “bur oak” (*Q. macrocarpa*) and “black oak” (*Q. ellipsoidalis*) growing in oak openings and as scrub oak. Black oak was the most common tree used for bearings in land surveys followed by bur oak, and the average diameter at breast height (DBH) reported for both bur oak and black oak was 20-25cm, indicating relatively young stands. An occasional prairie was described, indicating areas of completely open prairie in the uplands (Pierce 1954). Pierce (1954) hypothesized that the presence of scrub oak was probably due to very frequent fires set by the Indians as a hunting tool.

Early settlers noted that fires frequently burned the area and evidence of natural fires was still common in 1954 when Pierce surveyed the area. There were still charred stumps and oak re-sprouting was common (Pierce, 1954). Settlement was not widespread until the 1860s, and early settlers burned the marshy areas to improve the haying, and these fires occasionally got out of control (Pierce, 1954). Pierce’s (1954) analysis of tree cores taken from pines shows evidence of grass fires from 1880-1910. Pines were often scarred by fires, but Pierce noted that ground fires did not damage the oaks, and that “catfacing or scarring is not a general feature of the oaks” (Pierce 1954). By 1954, the area was beginning to grow up in woodland, and Pierce mentioned large areas of *Q. ellipsoidalis* thickets.

In the fifteen years following Pierce’s survey, Cedar Creek Natural History Area underwent massive expansion with the University of Minnesota purchasing large tracts of land to the south, including the current savanna area. In 1962, The Nature Conservancy started burning at Helen Allison Savanna in an attempt to arrest the succession to forest

(Faber Langendoen and Davis, 1995) and in 1964; a similar program was started at Cedar Creek (Marshall, 1968). These programs were two of the earliest prescribed burning programs in the country. At Cedar Creek, 65 ha were subdivided into burn units separated by existing firebreaks, and units were randomly assigned different burn frequencies ranging from annual burns to one burn every 5-8 years (Irving, 1970). A permanent 50 m x 75 m plot comprising 3/8th of a hectare was set up in each burn unit in 1984, and all trees within the plot were tagged. Since 1984, research has concentrated on these permanent plots. Both Helen Allison Savanna and Cedar Creek still continue their respective burn programs and are two of the longest continuous studies on prescribed burning.

Land use history of the burn units before purchase included grazing, woodcutting, farming, and burning. Protection from these activities in the years prior to purchase by the University of Minnesota allowed shade-tolerant hardwoods and a heavy understory of American Hazel (*Corylus americana)* to develop. At the start of the burn program, *Q. ellipsoidalis* represented three times as much basal area as *Q. macrocarpa* (Irving, 1970).

Though Helen Allison Savanna is primarily focused on restoration, Cedar Creek focused on research from the very beginning. Some forty theses and papers have been done in the burn units since 1964 exploring a wide variety of topics. A list of the papers that focused on the effects of fire on woody stems is presented in Table I with a summary of their research.

Table I. Published research focusing on woody stems and fire characteristics conducted at Cedar Creek Natural History Area and Helen Allison Savanna since the start of the two burn programs. Papers are presented in chronological order with the author, year, and a brief summary on the focus of their research.

Author	Year	Focus of Research
Wick	1966	Fire characteristics and rate of spread measurements.
Sando	1967	Effects of burning, concentrating on mortality, fire injury, and *C. americana* status.
Irving	1970	Qualitative look at Cedar Creek burn units, initial conditions, and methodology used in burning.
Axelrod	1974	Resprout potential of *C. americana* over a variety of burn frequencies.
Axelrod & Irving	1978	Effects of prescribed fire on *C.americana* density and stem height.
Rimmel	1979	Fuel Composition, fuel load, rate of spread and fire intensity.
White	1981	Effects of soil type and topography on species composition.
White	1983	Tree diameter, density, and basal area in burned and unburned areas.
White	1986	Compared vegetation types in burned and unburned areas and proposed restoration plans.
Tester	1989	Litter, species richness, and tree density over a fire frequency gradient.
Faber-Langendoen & Tester	1993	Oak mortality in savannas following drought.
Faber-Langendoen & Davis	1995	Tree canopy cover in Helen Allison Savanna.
Peterson	1998	Fire effects on oak savanna and woodland vegetation.
Peterson and Reich	2001	Effects of fire frequency on stand structure, overstory density, and basal area.
Peterson *et al.*	2007	Response of plant functional groups to changes in fire frequency and canopy cover.

Though the literature is extensive, there have been few allusions to scarring at Cedar Creek. White (1986) mentions that large (> 10 cm DBH) stems are not harmed by low intensity fires with short residence times, and that these trees were only killed when high fuel loads in the form of downed trees were present nearby. Peterson and Reich (2001) note that trees at Cedar Creek may be scarred if fuel or weather conditions produce local conditions of unusually high temperatures, and that scarred trees are less resistant to future fires and more vulnerable to infection. Aside from these two studies, there has been no discussion of scarring in Cedar Creek literature.

However, scarring is common at Cedar Creek in all diameter classes. In 2003, Dr. Clarence Lehman noticed this and hypothesized that the scarring was due to contact with dead wood and that degraded savannas with high tree densities could trigger a positive feedback loop when burned, where a scarred tree eventually died, providing more fuel in the system to scar other trees. Since mortality was delayed a number of years after scarring, a savanna could potentially be on a trajectory towards prairie before fuel in the form of dead trees was exhausted. Dr. Lehman built a rudimentary computer model and found that high initial tree densities resulted in complete tree mortality (Clarence Lehman, personal communication). This prompted a pilot study in 2004 that measured scars and tree mortality in five plots with short fire intervals. Data from this pilot study showed that fraction of circumference scarred was significantly lower in live trees than in dead trees. This provided good evidence for a shorter lifespan for scarred trees. Scarring was common in the pilot study, with the percentage of scarred trees in a plot ranging from 20.7% to 54.3%. Scars also were directional, with the majority facing the southwest. This suggested non-contact scarring, however, since the pilot study had only recorded the general direction of the scar, further analysis was not possible.

Fire Scarring

Fire scarring is caused by an uneven distribution of temperature around the tree bole or trunk that concentrates the heat on a particular side causing partial cambial death on that side (Gill, 1974; Turnstall *et al.,* 1976). Within a few years, the bark falls off forming a fire scar (Smith and Sutherland, 1999). Lethal temperatures in the cambium depend on the thickness and insulating quality of the bark (Vines, 1968; Hengst and Dawson, 1994; Gutsell and Johnson, 1996), fire behavior, and initial conditions such as temperature and humidity (Turnstall *et al.*, 1976; Sutherland and Smith, 2000). The most important factor is bark thickness, and its ability to act as an insulator and slow the conduction of heat from the outside of the tree (Hare, 1965b; Vines, 1968; Guyette and Stambaugh, 2004). Thus larger trees with thicker bark are less susceptible to cambial wounding (Guyette and Stambaugh, 2004) unless exposed to a period of heating long enough to penetrate the bark (Vines, 1968; Sutherland and Smith, 2000).

Scarring leaves the tree open to infection by insects or fungi (Smith and Sutherland, 1999; Smith and Sutherland, 2006), and increases the chance of further damage by subsequent fires (McClaran, 1988; Peterson and Reich, 2001), or mechanical failure of the tree trunk (Gill, 1974). The scars heal slowly and larger scars can easily persist for the rest of the tree’s life (Gill, 1974). Thus, fire scarring lowers the tree’s fitness and life expectancy (Varner *et al.*, 2005).

Differential heating around the tree bole is always responsible for fire scarring; however, the reasons for differential heating vary (Gill, 1974). Local differences in fuel load can produce higher heat (Vines, 1968; Mcbride and Lewis, 1984; Smith and Sutherland, 2006) or a longer residence time (Rowe, 1967) for the fire on one side of the tree, causing a contact scar. Differential heating can also be produced by convection currents increasing the temperature on the leeward side of a tree in the presence of wind (Fahnestock and Hare, 1964; Gill, 1974; Gutsell and Johnson, 1996), which results in a non-contact scar.

Contact scars are formed because of increased fire temperatures and residence time caused by combustion of dead branches or trees in contact with, or near the scarred tree (Figure 2). Typical grass fires move quickly and thus fire temperatures remain low. However, a large piece of fuel can burn for half an hour or more, greatly increasing the localized residence time (Jacobs, 1955; Clarence Lehman, personal communication). Though actual contact of a burning log with a live tree is the most likely reason for this type of scar (Rowe, 1967; Vines, 1968), it may also be caused by be caused by intense heat from several meters away (Vines, 1968). Future contact scars can sometimes be identified by blackened bark (Figure 3), though often this is not the case. The fuel responsible for contact scarring usually burns up, and by the time the scar becomes evident a few years later, the remaining ashes have all but disappeared (Figure 3).

Figure 2. Photos of contact scars showing contact scarring taking place during a fire (left), and a tree that has been badly scarred by contact (right). Photo credits: Clarence Lehman.

Figure 3. The effects of contact scarring. The picture on the left (photo credit: Clarence Lehman) shows two trees freshly blackened by a log that burned between them in a 2002 fire. On the right (photo credit: James Mickley) are the same two trees five years later in 2007. Large scars have replaced the blackened areas, with rot already setting in.

Non-contact scars are caused by convection columns that form on the leeward side of the tree, holding heat in and increasing the temperature and residence time of the fire (Gutsell and Johnson, 1996). These scars have a directional bias due to their association with wind (Turnstall *et al*., 1976; Gutsell and Johnson, 1996). Since the original agent of scarring for contact scars is often not present, there is no direct way to differentiate between a contact and non-contact scar. However, the directional bias of non-contact scars may provide an indirect method of differentiation.

Objectives

Considering the findings of the 2004 pilot study and the model, we wanted to see if there was a relationship between initial tree density of the plots before burning commenced in 1964 and current levels of scarring. Because of the small scale of the pilot study, we also wanted to sample a wider range of fire frequencies and collect a larger dataset. We hypothesized that plots with higher initial densities would have more scarring due to higher fuel loads and fallen trees, increasing the prevalence of contact scarring. Finally, we wanted to examine the directionality of scars to determine if non-contact scarring was prevalent in oak savanna.

Materials and Methods

Study Sites

Olaf's Savanna, a small two hectare savanna, is located approximately 20 km east of Detroit Lakes in northwestern Minnesota at 46° 51' N, 95° 31' W. Dr. Clarence Lehman owns the property and personally oversees restoration, which he began in 1998. According to averaged climate data from the two closest weather stations (Detroit Lakes, MN, and Park Rapids, MN), the mean annual temperature is 4° C and mean daily temperature ranges from -30° C to 27° C. Average annual precipitation is 635 mm.

Aerial photos of the area show it under agricultural use in 1939 with only a few scattered trees. By 1965, the area was an abandoned field and the beginnings of the current trees could be seen. Dr. Clarence Lehman bought the property in 1982 and started restoring Olaf's Savanna in 1998. The area was bulldozed to remove invading quaking aspen (*Populus tremuloides)* and some of the staghorn sumac (*Rhus typhina),* and to level the numerous gopher mounds. In the spring of 1998, the herbicide Roundup was applied, and after the plants had died, the area was burned during the summer. After burning, the area was seeded with both local and non-local prairie mixes at a rate of 70 lb/acre, and seedlings were planted. The savanna was then burned in 2002 and 2006 in the spring using the strip headfire technique (Irving 1970, Kochsiek *et al.*, 2006) under moderate winds. Dead wood has been removed and *C. americana* has been burned a second time later in the summer during each subsequent growing season (Clarence Lehman, personal communication).

Cedar Creek Natural History Area is located on the Anoka Sand Plain in east-central Minnesota at 45° 35' N, 95° 10' W. Topography consists of gently rolling to flat glacial outwash ranging in elevation from 175-288 m (White, 1986; Tester, 1989). The soil is very sandy, well drained, and low in nutrients (Grigal *et al.,* 1974), making the uplands rather xeric. Mean annual temperature at Cedar Creek is 6° C and average daily temperatures range from -11° C in January to 22° C in July (Grigal *et al.*, 1974). Average annual precipitation is 790 mm with 64% of that falling from May to September (Peterson and Reich, 2001).

Aerial photos from 1938 show that the whole burn unit area was savanna, clearly showing less than 50% canopy cover, though there was considerable variation in the number of trees per hectare. Areas that showed up as closed canopy forest in 1960 were discernibly denser than their surroundings in 1938. Currently the area of open canopy cover is less than 10% of the original area, and is mostly confined within burn units with short fire intervals.

Burns at Cedar Creek are conducted using a strip headfire technique in the spring after snowmelt, but before trees have produced leaves (Irving, 1970; Kochsiek *et al.,* 2006). The preferred conditions are 25-40% humidity, 10-30° C, and a wind speed less than 20 mph (Irving, 1970). Aside from burning, no management work is done on the burn units.

Initial Density Estimates

Aerial photos from 1960 were scanned with an Epson Perfection 4490 photo scanner at 3200 dpi. Images were then rectified onto a base map of the study site using OmniGlyph PCB CAD and GIS software (Holophase Inc.). A simple rotation and scaling transformation of the images in OmniGlyph allowed the images to be accurately placed. Rectification was never perfect, but was usually accurate to within 5-10 m with this simple transformation.

Trees were counted by zooming in on each plot in the photo and attempting to determine what were trees. The direction of shadows in a photo was uniform and a black shadow could be used to point to where a tree should be. Trees were lighter and usually mottled, but not as light as bare ground. At least two counts of the same plot were obtained from separate photos and the average was taken. There was a wide range of image quality, so while the tree counts for most of the plots were extremely accurate, some plots were more of an estimate.

Scar Survey

Eight plots (Figure 4, Table II) were categorized according to fire interval (short, long, none) and initial density (high or low). The mean initial density for all plots in 1960 was 30.8 trees/plot, therefore 30 trees/plot was used as a cutoff between high and low initial density. Plots with a fire interval of over 3 years were considered to have a long fire interval, while those plots with an interval under 3 years were short. Plots were selected that best fit the six available combinations of fire interval and initial density—one in each category and two additional plots with a short fire interval. There were few unburned plots, or plots with long fire intervals, thus only one plot was surveyed in these categories.

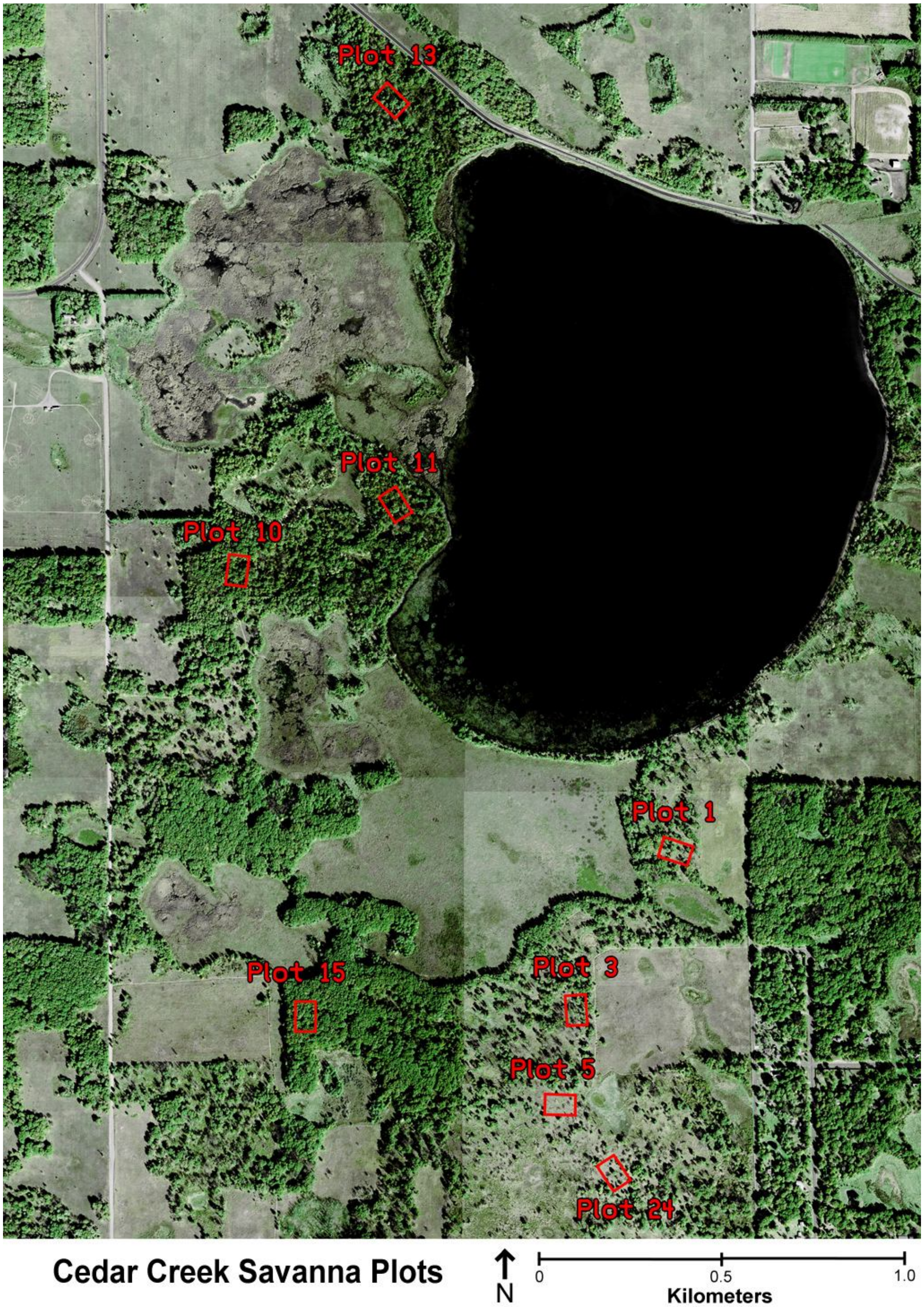

Figure 4. Composite aerial photo from 2000 showing the savanna plots surveyed at Cedar Creek. Frequently burned plots are in the lower right and are much less dense.

Table II. Demographics of the plots surveyed at Cedar Creek. Each plot was 50 x 75 m or 0.375 ha. The fire interval is the average number of years between burns. The 1960 density is from tree counts of the scanned aerial photos. Plots were classified into initial density and fire interval groups using 30 trees/plot for initial density and 3 years for fire interval as dividers.

Plot	Fire Interval (yr)	1960 Density (trees/plot)	Fire Interval	Initial Density
1	2.00	55	Short	High
3	1.26	81	Short	High
5	2.00	21	Short	Low
10	Unburned	21	Unburned	Low
11	8.80	28	Long	Low
13	8.80	36	Long	High
15	Unburned	51	Unburned	High
24	1.26	15	Short	Low

Trees were surveyed for scars in late August and early September of 2007. We measured DBH (diameter at breast height), survival status, and canopy health of all stems (separate trunks) larger than 5 cm at breast height in each plot, taking note of whether or not a stem was scarred. To standardize measurements, we always measured DBH in cm at 135 cm. If there was some abnormality in diameter of the tree at 135 cm such as a branch, we measured above or below it at the closest point where a representative diameter could be obtained.

We separated trees into three categories: alive, dead, or disappeared. Trees were counted as alive if they had green leaves on them, a measure which contained no ambiguity in August or September. If a tree recorded in previous surveys was not found, it was considered disappeared, and was not used in the analysis. If the tag on a fallen tree could be easily found, then we recorded it as dead, however we did not try to identify every tree on the ground. The canopy was defined as the branches of the tree that were not shaded by the tree’s other branches but included any branches that would be canopy in the absence of surrounding trees. Canopy health of the tree was estimated in 5% intervals as the percentage of original canopy that was still alive.

Scars were defined as a portion of the tree's circumference that was dead, and had not healed completely over. If a tree did not have evidence of healing, but had lost bark (especially with dead trees), then the wound was not considered a scar unless it was obvious that the wound had occurred during the current growing season and had not had time to show evidence of healing. We measured scars on all live trees and on dead trees where possible. If a scar on a tree was too badly burned to measure accurately or if the tree was on the ground in such a way as to restrict access to the scar, then only the variables that were measurable were measured. Scars that were out of reach were not measured; however, it was highly unlikely that these were fire scars. For each scar, we measured scar width, height to the bottom of the scar, height to the top of the scar, compass bearing, circumference at the scar, the cause of scarring, and the type of scar.

Distance from the ground to the bottom and top of the scar was measured in cm with a meter stick. The bottom of the scar was the lowest point at which the scar was unhealed while the top was the highest unhealed point. If the height to the top of the scar was more than 2 m, the height to top was estimated to the nearest cm. If the height was greater than 3 m, the height to top was estimated to the nearest meter. Scar width was measured from the insides of the live healing at the widest point of the scar, signifying the maximal width of the region of dead cambium. We molded a flexible ruler around the tree so that it held the original shape of the tree, and then measured the width from this position, instead of linearly at the inside of the scar. We used a DBH tape to measure the diameter of the tree at the widest point of the scar. This diameter was then converted to circumference to allow calculations of the fraction of circumference scarred. To measure directional bias in the scars we pointed a compass towards the center of the scar and then read the bearing to the nearest degree on the opposite side of the compass, which showed the direction the scar was facing.

Possible causes of contact scarring that were recorded were dead wood on the ground in the vicinity, a fork in the tree where fire had burned, a dead branch on the tree that had burned, or no obvious cause. We recorded the type of scar as fire, frost, deer, bulldozer or other. Deer scars were scars on small, smooth-barked trees that were obvious buck rubs and were characterized by ragged edges of the scar where bark had been worn off. Frost scars were evident as very narrow vertical cracks in the tree. Many were healed over, though some still had a narrow band of cambial death. Bulldozer scars were a special case used only on a few trees in Olaf's savanna that had been damaged during restoration. Fire scars tended to be much larger than other types and often were triangular in appearance and wider towards the bottom. In plots with no fire history, or when the type of scar was in question we counted scars as "other".

Statistical Methods

Chi-squared tests, t-tests, ANOVAs, and basic statistics were carried out with SPSS version 15.0. Figures and tables were made using Excel, Sigmaplot and a graphing extension for Tex called PicTex. All circular statistics were done using the circular statistics software package Oriana (Rockware Software Inc.).

For scarring direction distributions, mean vectors were calculated using Oriana. These mean vectors had a mean direction, and a length, which gave a magnitude of directionality. It was calculated by combining the individual vectors of all data points (Batschelet, 1981; Mardia and Jupp, 1999). To test for uniformity of a distribution or to determine if two distributions were significantly different, we used one and two variable Watson's U^2 tests. Watson's U^2 test calculated the mean square deviation of a specified distribution from a uniform distribution or second distribution and performed a goodness-of-fit test (Batschelet, 1981; Mardia and Jupp, 1999).

To account for different wind directions when each plot was burned, the compass directions of all the scars in the burned plots were normalized using the direction of the mean vector for each plot as north. The trees were then separated into three diameter size classes: 5-10 cm DBH, 10-30 cm DBH, and 30-80 cm DBH, and grouped by high or low initial density. The distribution of scar directions within each group was tested separately to determine if it was non-uniform with a significant directional bias. Additionally, high and low initial density groups within each size class were compared to see if their distributions differed significantly.

Means were calculated for measured fire scar variables in each size class to look for differences in fire scar properties between size classes. Height to the bottom of the scar, height to the top of the scar, overall height of the scar, canopy health, and fraction of circumference scarred (which was independent of tree diameter) were considered.

Results

Demographics

Within the eight plots at Cedar Creek, 1,418 stems were measured, of which 349 were scarred. Of these scars, 307 were fire scars, three were scars caused by buck rubs, two were frost scars, and the remaining 37 were of unknown cause and occurred in the control plots, which have not been burned since before the burn program was started. Only 16 scars were recognizably contact scarred: four were caused by a dead branch, seven by dead wood nearby, and five by a fork in the tree. The vast majority (95%) were not discernibly caused by contact. In frequently burned plots, there were only oak species, however in infrequently burned, or unburned plots, black cherry (*Prunus serotina*), shadbush (*Amelanchier sp.*), and red maple (*Acer rubrum*), were common.

In Olaf's Savanna, 38 stems were surveyed, ranging from 6.9 cm to 74.8 cm DBH. The smallest oak was 9.1 cm DBH. All were *Q. macrocarpa* except for one white ash (*Fraxinus americana*) and two *Q. ellipsoidalis*. Only four scars were found. One of these was on the *F. americana* which had a DBH of 6.9 cm. The other three were bulldozer scars caused when the area was cleared of aspen (Clarence Lehman, personal communication), and ragged edges or shapes unusual for fire scars were evident on these scars. One *Q. ellipsoidalis* had the beginnings of a scar where the bark had not peeled off enough to be measurable. There was little evidence of healed fire scars, though healed frost scars were common in this area. In this carefully managed savanna, fire scarring was extremely uncommon. However, in an adjacent area of open oak woodland that is also burned, scarring occurred (Figure 3), though this area was not surveyed.

Stem Density and Scarring Frequency

Frequent fires clearly reduced stem density (Figure 5). Though the burn program had been running for 43 years, burned plots with high initial densities still had higher densities in our study than low initial density plots with the same or similar fire intervals (Table III). There was no significant difference in density between the two unburned plots; therefore, in the absence of fire, current density was not dependent on initial density (Table III.). Olaf's Savanna had the lowest density at around 19 stems/ha. Of the Cedar Creek plots, plot 5 had a density of 37.3 stems/ha, and all other short fire interval plots surveyed at Cedar Creek had densities that were closer to 100 trees/ha.

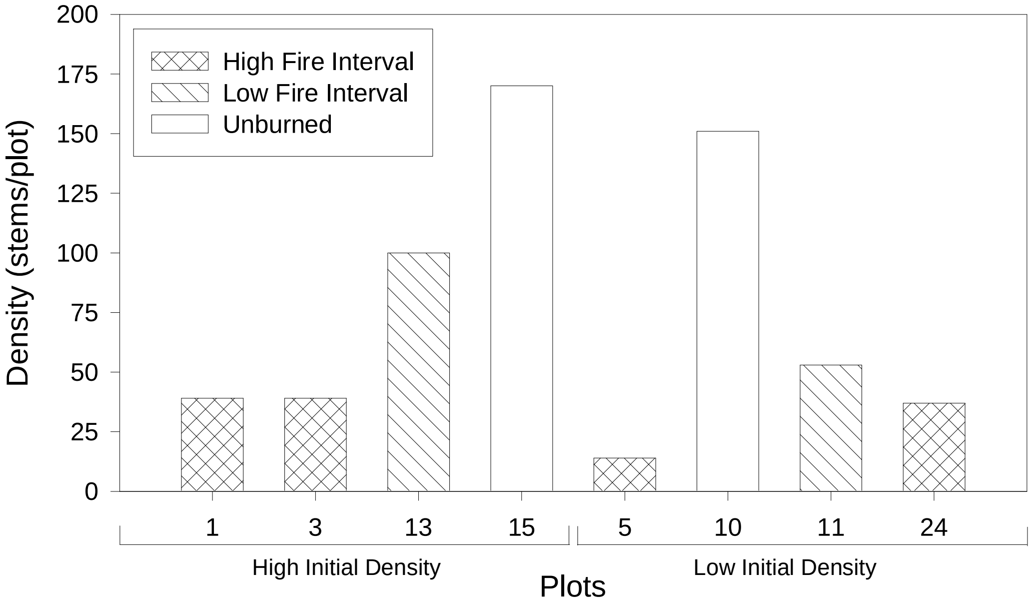

Figure 5. Density of stems over 10 cm DBH in each plot. Frequently burned plots had lower densities while unburned plots had the highest. High initial density burned plots had higher densities for their fire interval category than burned plots with low initial densities.

Table III. Summary of Chi-Squared tests comparing high and low initial density plots in each fire interval showing the number in each category, the test statistic, degrees of freedom and the significance.

	High Initial Density	Low Initial Density	χ2	Df	Significance
Short Fire Interval	78	51	5.651	1	p = 0.0174
Long Fire Interval	100	53	14.438	1	p = 0.0001
Unburned	170	151	1.125	1	p = 0.2889

Though the percentage of scarred stems in each plot varied considerably (Figure 6), there was no easily discernable pattern for this variance. Three of the four plots with short fire intervals had high levels of scarring; however, plot 24 did not. Unburned plots had very low levels of scarring (Figure 6) in keeping with their unburned status during the last 43 years. The percentage of scarred stems was not higher in high initial density plots, but rather the low initial density plots (5 and 11) were the highest in their fire interval categories. Olaf's Savanna had a lower fraction of scarred stems than any burned plot at Cedar Creek (Figure 6).

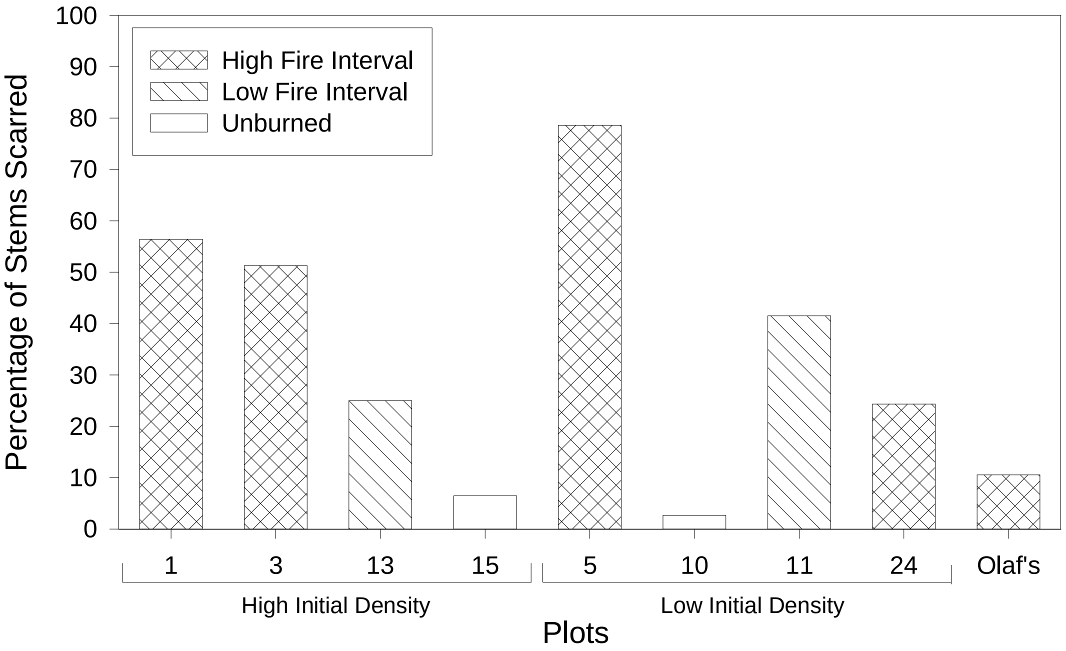

Figure 6. The percentage of stems over 10 cm DBH that were scarred in each plot. Frequently burned plots had more scarring, but there was no difference in scarring levels between high and low initial density plots. Olaf's Savanna had less scarring than any burned plot at Cedar Creek.

Directional Statistics

The directions of scars in the 5-10 cm size class were non-uniform in both high and low initial density plots (Table IV). That is to say, scars in both initial density groups were directionally biased. Both high and low initial density plots had mean vectors of similar magnitudes and the two distributions did not differ from each other significantly; there was a similar degree of directional bias (Table V). Because of their directionality, non-contact scarring was the primary cause of scarring.

Table IV. Summary of tests for uniformity of scar direction distributions in each density group and size class. Mean vector shows the magnitude of directionality while Watson's U^2 test shows the significance of directionality. Both distributions in the 5-10 cm size class were non-uniform to a similar degree. The 10-30 cm size class groups were also non-uniform, but the low initial density group had a higher degree of directionality. The largest size class (30-80 cm) was not directionally biased.

Size Class	Distribution Tested	mean vector	U^2	Significance	Directionality
5-10 cm	High Initial Density	0.41	0.50	$p < 0.005$	Directional
	Low Initial Density	0.45	0.78	$p < 0.005$	Directional
10-30 cm	High Initial Density	0.35	0.33	$p < 0.005$	Directional
	Low Initial Density	0.54	1.24	$p < 0.005$	Directional
30-80 cm	High Initial Density	0.26	0.16	$p > 0.05$	Random
	Low Initial Density	0.29	0.10	$p > 0.25$	Random

Table V. Summary of tests comparing the distributions of scar directions in high and low initial density plots for each size class using Watson's U^2 test. A significant test statistic indicated that distributions differed significantly. The largest and smallest size classes had similar distributions of scar directions for both high and low density plots; however, distributions for the 10-30 cm size class differed significantly, indicating an initial density effect.

Size Class	U^2	Significance	Initial Density Effects
5-10 cm size class	0.05	$p > 0.5$	Insignificant
10-30 cm size class	0.20	$p < 0.02$	Significant
30-80 cm size class	0.07	$p > 0.20$	Insignificant

Stems in the 10-30cm size class also had non-uniform scar direction distributions for both high and low initial density plots (Table IV). However, low initial density plots had a larger mean vector length and a higher degree of non-uniformity (Table IV). Furthermore, the distribution for low initial density plots differed significantly from that of high initial density plots (Table V). This indicated that scars in the 10-30 cm size class were more directionally biased in low initial density plots than in high initial density plots. Thus, high initial density plots were scarred more by contact.

The largest size class (30-80 cm DBH) was quite different from the two smaller size classes. Mean vectors for both initial density groups were much lower, and the distributions did not reject the null hypothesis of uniformity (Table IV). The two distributions also did not differ from each other significantly (Table V), indicating that in this size class, the effect of initial density on scarring was not statistically significant. Non-contact scarring was less prevalent because of the lack of directionality.

Because results in Table IV and Table V indicated that scars in the 5-10 cm size class were predominantly directional, and thus likely to be non-contact scars, we focused on all trees with a DBH greater than 10 cm to look for potential contact scarring. Figure 7 shows a comparison of normalized scar directions of trees larger than 10 cm DBH for high and low density plots. The distribution of scar directions was more uniform in high initial density plots while low initial density plots were decidedly directional (Figure 7). In addition, low initial density plots had significantly fewer scarred trees above 30 cm DBH (Figure 7; Chi-Squared test: $\chi 2 = 8.02$, df = 1, p = 0.005).

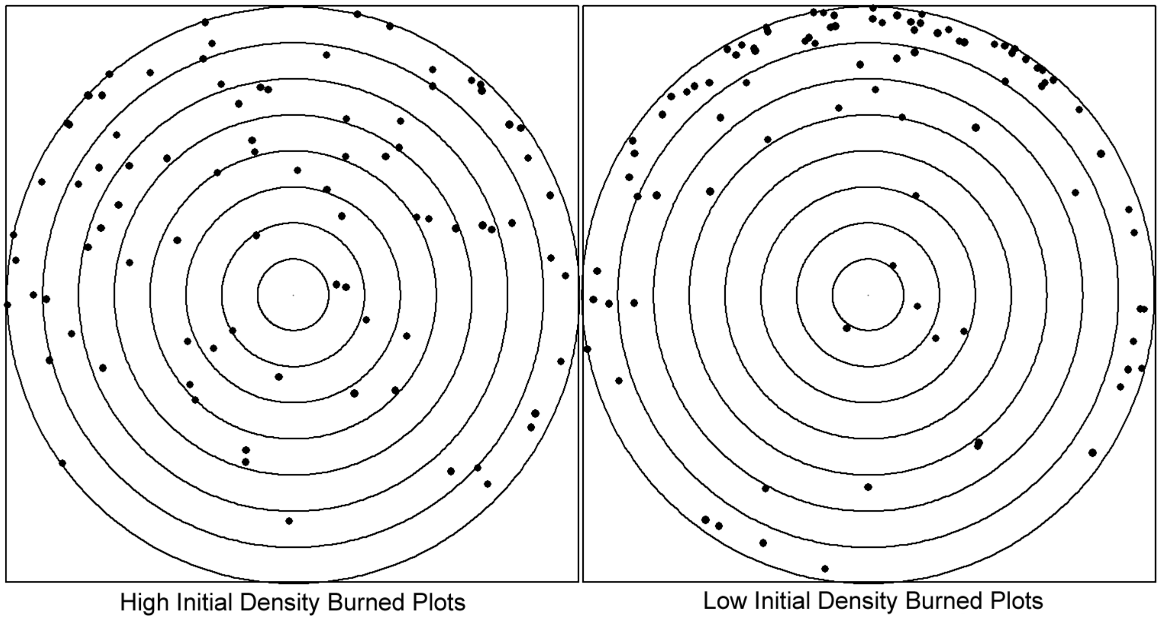

Figure 7. Normalized distributions of scar directions for scarred trees over 10 cm DBH. The concentric circles represent 10cm DBH intervals, with 10 cm as the outermost circle and 80 cm as the innermost circle. The distribution of scar directions is non-uniform in low initial density plots, especially in the 10-30 cm range. Low initial density plots have fewer scarred trees over 30 cm.

Measured Indicators of Scarring Type

Height to the bottom of the scar increased from the smallest size class to the largest (Table VI), however only the difference between the smallest and largest class was significant (Tukey's method, $p = 0.02$). Mean height to the top of the scar was similar in the two smaller size classes (Table VI) , but jumped significantly in the largest class (Tukey's method, $p < 0.001$) and overall height followed a similar trend (Tukey's method, $p < 0.001$). The fraction of circumference scarred decreased significantly as the size of the tree increased (Table VI; Tukey's method, $p < 0.03$). Canopy health of scarred trees also decreased as the size of the tree increased (Table VI), with a significant difference between the largest and smallest size classes (Tukey's method, $p = 0.004$).

Table VI. Summary of means and ANOVA results for fire scar variables across size classes. Height to bottom of the scar increased as trees got larger, while the fraction of circumference scarred and canopy health decreased. Height to top of the scar and overall height were much higher in the largest size class.

Variable	5-10 cm	10-30 cm	30-80 cm	F	df	Significance
Height to Bottom of Scar	7.6	15.9	19.2	5.1	2	p = 0.007
Height to Top of Scar	57.1	67.8	120.9	15.69	2	p < 0.001
Scar Height (Top-Bottom)	49.6	50	101.7	12.48	2	p < 0.001
Fraction of Circ. Scarred	0.275	0.222	0.158	8.27	2	p < 0.001
Canopy Health	81.7	77.5	66.2	5.32	2	p = 0.005

Discussion

Plot density was dependent on the initial density in 1960 in burned plots of all fire intervals. Contrary to our hypothesis, the percentage of all scarred stems in a plot was not related to initial density. However, results of circular statistical analysis showed that contact scarring was more common in high initial density plots and that low initial density plots had fewer large scarred trees, indicating that initial density influenced the amount of contact scarring. Non-contact scarring was very prevalent, especially in smaller size classes and was not dependent on initial density. Both of these types of scarring can be prevented by careful management techniques, as shown by data collected in Olaf's Savanna and theoretical equations for non-contact scarring.

Density Effects

Within plots with a short fire interval, none of the plots were within the upper limits of the density range set forth by Bray (1955) of 2-6 trees/ha. Coupled with the fact that initial density still played a role in current density, it seems that even 43 years was not long enough for natural processes to restore an acceptable savanna density with reintroduction of fire as the only management tool. This agreed with the findings of White (1983) who wrote “reversing the trend from oak savanna to oak woods may take > 13 yr using annual spring burns”, but on an even longer timescale. Unburned plots, however, seemed to stabilize rather quickly with the low initial density plot (10) nearly equaling the high initial density plot (15) in 43 years, showing how quickly an area can turn to oak woodland.

Since fire scarring leads to eventual mortality, fire scarring would be a key predictor for future mortality. Because mortality due to fire scarring is not immediate, there is a delay of potentially many years between the time the tree is mortally wounded and the time it dies. It is important that savanna restoration plans consider this;

otherwise, a savanna can be set on a trajectory towards prairie or oak scrub long before outward symptoms of this are present.

To better monitor and prevent scarring, a clear understanding of how and why trees are scarred in a savanna ecosystem is needed. Figure 6 indicates that while there tends to be more scarring in plots that are burned more frequently, this is not an absolute. When looking at Olaf's Savanna and plot 24, low levels of scarring in areas that are burned frequently show that with proper management it should be possible to control scarring, though the actual reasons for differences presented by these two plots remain unknown.

The hypothesis for contact scarring predicts that plots with a high initial density would have higher levels of scarring; however, two of the low initial density plots (5 and 11) had the highest levels of scarring at short and long fire intervals respectively (Figure 6). Therefore, this rejects the hypothesis of more scarring in high initial density plots. However, it does not eliminate the possibility of contact scarring occurring. If non-contact scarring were also occurring, this could confound the density-dependent effects of contact scarring.

Cause of Scarring

Very few scars had an identifiable cause such as dead wood nearby. This was not surprising though, as most agents of contact scarring are completely burned in a fire and signs of them disappear quickly in subsequent years. In addition, scarring is not immediately evident because bark may persist over the scar for several years following scarring, giving the agent of scarring further time to disappear. Even if contact scars were surveyed immediately after a fire, many would still be covered by bark. Therefore, there is usually no direct way of identifying a scar as a contact scar.

Since non-contact scarring only occurs on the leeward side of the tree, in theory this type of scarring should be directional with all scars oriented the same way. In practice, it is more complicated, because scars in each plot represent the results of multiple fires, each of which may have had a different wind direction. In addition, the wind direction can change during a burn. Normalizing the compass directions for each plot based on the mean vector for the plot eliminates some of this problem, but still does not account for fires from different years. Data from the 2004 pilot study suggested non-contact scarring because many of the scars seemed to be oriented between south and west, however because only the general direction of the scar was recorded instead of a measurement in degrees, detailed analysis was not possible. A larger sample size and more accurate direction measurements in this study allowed us to analyze the directional component of scars.

Distributions of scarring directions were non-uniform, especially in the 5-10 cm size class, which represented the most common of the three size classes, largely confined within the low fire interval plots. These plots were thick with young trees under 10 cm DBH, and the vast majority of them were fire-killed or scarred. In both high and low initial density plots, non-contact scarring was the primary reason for scarring in the 5-10 cm size class because both distributions were significantly directional. However, trees smaller than 10 cm DBH are not considered to be established, and in fact have been ignored in some studies (White, 1986; Faber-Langendoen and Tester, 1993). From a restoration standpoint, trees larger than 10 cm DBH, which should have acceptable fire resistance, are the ones for which risk of fire mortality due to scarring becomes an important factor.

In the 10-30 cm size class, distributions for high and low initial density plots were significantly different (Table V). The distribution of scar directions for low initial density plots had a higher mean vector (Table IV) implying a higher degree of directionality than in high initial density plots. This indicated that contact scarring was probably more prevalent in low initial density plots than in high. This is good evidence that both contact and non-contact scarring are occurring, and that the amount of contact scarring is in fact influenced by initial density.

In the largest size class (30-80 cm DBH), both distributions were uniform (Table IV), and not significantly different from each other (Table V). Uniform directionality is consistent with contact scarring because contact scarring is not directly related to wind direction and larger trees have thicker bark, which requires a much longer residence time for scarring to occur. Therefore, contact scarring was the primary type of scarring for these large trees. There were also fewer scarred trees over 30 cm DBH in low initial density plots than in high initial density plots. If it is assumed that contact scarring is the primary way these large trees can be scarred, then this is as expected because low initial density plots would have a much lower fuel load of dead, fallen trees. Trees in these plots would have a lower chance becoming scarred at all in a fire because of a reduced chance of contact scarring. These large trees are the focus of savanna restoration and management and therefore contact scarring is more of a management problem than non-contact scarring. Future restoration efforts in areas with high density at the beginning of restoration should proceed with caution to prevent the initiation of a contact scarring feedback loop.

Theoretical Considerations for Non-Contact Scarring

Non-contact scarring is usually a result of vortices or convection columns, which form on the leeward side of a tree during a fire (Gutsell and Johnson, 1996). Both laboratory (Hare, 1965a; Gill, 1974) and field studies (Fahnestock and Hare, 1964; Turnstall *et al.*, 1976; Gutsell and Johnson, 1996) of temperature distributions around a tree during a fire show higher temperatures on the leeward side.

The passage of air around a cylindrical object sets up these vortices, which increase the height of the flame (Gill, 1974), and increase the residence time of the fire (Gutsell and Johnson 1996). Gutsell and Johnson (1996) proposed a set of equations based on fluid dynamics to predict residence time and scarring as a function of fire and tree parameters. The residence time τ (s) of a free moving flame is related to the depth of the flame front w (m) and the fire's rate of spread R (m/s) (Equation 1).

$$\tau = \frac{w}{R} \qquad \text{Equation 1}$$

When a free-moving flame encounters a tree, the fire is drawn into the leeward vortices when the fire front reaches the tree bole. The leeward flames persist until the rear of the fire front moves out of the zone of leeward vortices which persist up to one diameter d (m) away from the tree bole (Figure 8). Thus, the tree increases the depth of the flame front by two diameters (Gutsell and Johnson, 1996). This leads to a second equation for the increased residence time (τ) on the leeward side of the tree (Equation 2).

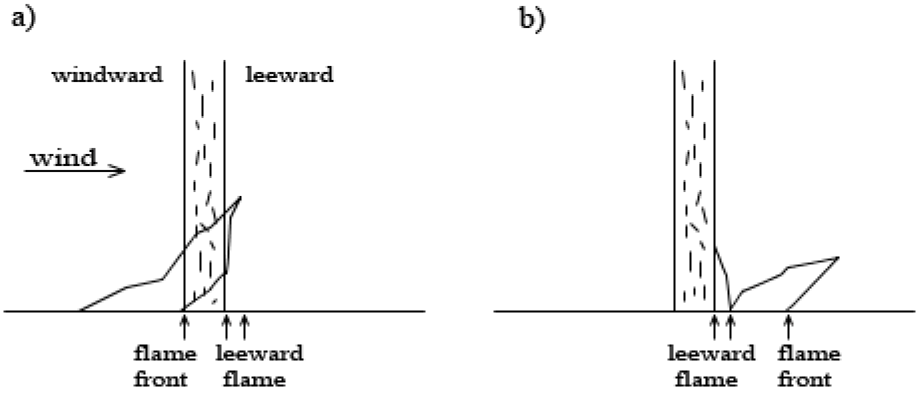

Figure 8. Diagram of a fire's behavior when it encounters a tree. As the flame front arrives at the windward side of a tree, the flame is drawn around the tree into the leeward vortices producing a leeward flame (a). As the flame front leaves the tree, the leeward flame persists until the rear of the flame leaves the area of leeward vortices (b).

$$\tau = \frac{w}{R} + \frac{2d}{R} \qquad \text{Equation 2}$$

Gutsell and Johnson (1996) and Peterson and Ryan (1986) further describe the relationship between residence time τ (s) and the initial temperature of the cambium *Tc* (°C), lethal cambium temperature *To* (°C), fire temperature *Tf* (°C), bark thickness *x* (m), and the thermal diffusivity constant for the bark being studied α (m^2/s) in Equation 3. In Equation 3, *erf*() refers to the Gaussian Error Function which describes the error associated with the excess temperature ratio on the left side of Equation 3.

$$\frac{Tc - Tf}{To - Tf} = erf\left(\frac{x}{2\sqrt{\alpha\tau}}\right) \qquad \text{Equation 3}$$

Equation 3 allows for predictions of scarring for a given tree and the time needed to scar or kill a tree. The relationship between bark thickness and tree diameter is approximately linear, and for *Q. macrocarpa*, bark thickness is roughly 5% of the diameter of the tree (Hengst and Dawson, 1994). A widely accepted value for the lethal temperature of cambium is 60° C (Hare, 1961; Peterson and Ryan, 1986; Jones *et al.,* 2006). Peterson and Ryan (1986) use 500° C as a value for flame temperature. Though the thermal diffusivity of bark may vary slightly between species (Hare, 1965b), most measured values are similar and range from 1.0 x 10^{-7} m^2/s to 1.5 x 10^{-7} m^2/s (Vines, 1968), with a conventional value of 1.35 x 10^{-7} m^2/s (Spalt and Reifsnyder, 1962; Gutsell and Johnson, 1996). If these conventional values for lethal cambium temperature, flame temperature, and thermal diffusivity of bark are accepted, then the variables needed for determining cambial death are initial cambium temperature, residence time, and tree diameter.

In Equation 3 from Peterson and Ryan (1986), and Gutsell and Johnson (1996) temperature is a minor contributor to predictions of scarring because of its position outside of the radical, making it a linear component. Therefore, the size of a tree scarred is not greatly influenced by initial cambium temperature or flame temperature. Since the thickness of the bark in Equation 3 can be described as a function of diameter, bark thickness does not influence the equation much either because an increase in residence time in the denominator from an increase in diameter is offset by thicker bark in the numerator. The thermal diffusivity constant and lethal cambium temperature are pseudo-constants, therefore the most important variables that influence Equation 3 and the size of a tree scarred are rate of spread and flame front depth, which are inside the radical as part of residence time. These two variables have the most effect on the size of the tree scarred.

Several conclusions can be made from these equations. First, burning on a cooler day (when initial cambium temperature is lower) or a cooler fire both make the residence time needed for a tree to experience cambial death longer, but not drastically so. Secondly, increasing the depth of the flame front increases residence time, and also lowers the relative difference between residence time on the leeward and windward sides of a tree, effectively decreasing the ratio of scarred:dead trees. Finally, as a fire's rate of spread decreases, the diameter of trees scarred or killed by the fire increases greatly. Figure 9 shows the relationship between rate of spread and diameter scarred using the conventional values reported in literature for lethal cambium temperature, flame temperature, and thermal diffusivity. The maximum diameter scarred begins to increase as rate of spread reaches 0.1 m/s, and drastically increases around 0.05 m/s, reaching 10 cm at 0.038 m/s (Figure 9).

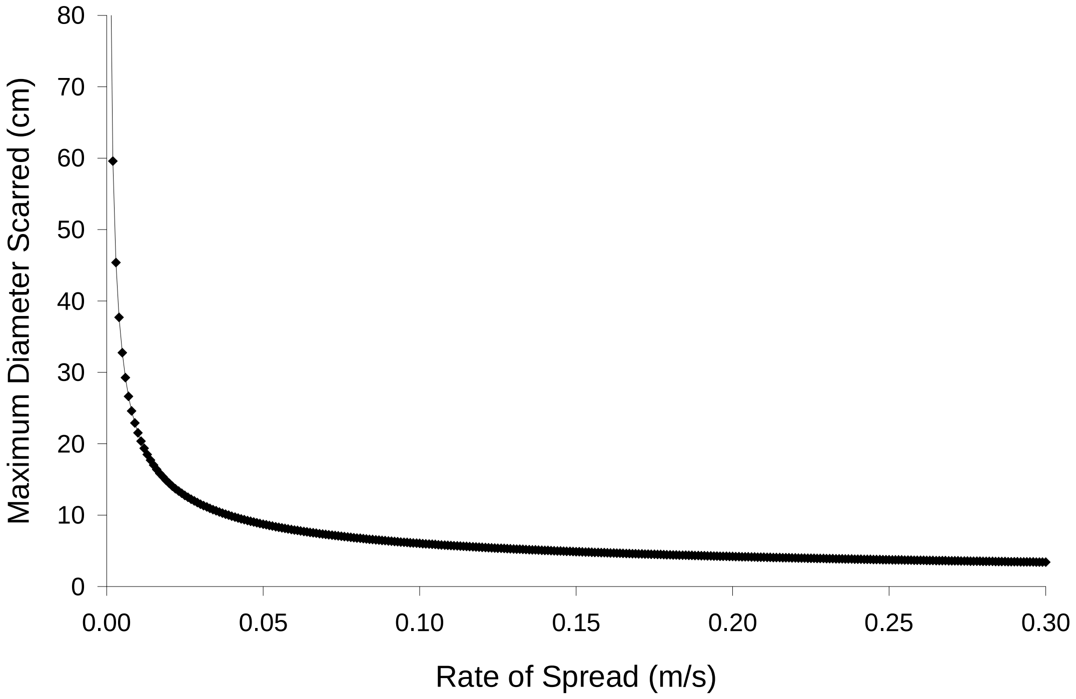

Figure 9. The maximum diameter scarred as a function of the rate of spread of a fire. As rate of spread approaches 0.1 m/s, the maximum diameter scarred begins to increase, reaching 10 cm DBH by 0.038 m/s and then quickly increasing.

Therefore, non-contact scarring could be controlled at least in larger size classes by only burning in conditions that do not result in a low rate of spread. This has wide implications beyond the context of Midwestern oak savanna. Land managers conducting prescribed burning in forested areas could control the size of tree killed or non-contact scarred by simply regulating the rate of spread and, to some degree, other fire parameters.

There have been several rate-of-spread measurements at Cedar Creek, though this has not been thoroughly studied over a range of weather and fuel conditions. Wick (1966) measured rates of spread between 0.043 m/s and 0.090 m/s. White (1981; 1983) recorded rates of spread from 0.13-0.28 m/s, while Rimmel (1979) claimed a range of 0.079 m/s to 0.11 m/s. Fires at Cedar Creek can burn as slowly as 0.01 m/s (personal communication, Troy Mielke) which would lead to a maximum diameter scarred of 21.5 cm using the parameters in Figure 9. With different parameters, the maximum diameter could be even higher. Thus, conditions of prescribed burns at Cedar Creek are well within the limits to allow non-contact scarring in trees as large as 20-30cm DBH

Indicators of Scar Type

To look for indicators of the type of scar (contact or non-contact) based on scar measurements these measurements were compared across size classes. Based on the above interpretations of the directionality of scarring, we assumed that the 5-10 cm size class represented non-contact scarring, the 30-80 cm size class represented contact scarring, and the 10-30 cm size class was a mix of the two scarring types. Scar measurements were compared for these three size classes. The height to the top of the scar was similar for the 5-10 cm and 10-30 cm size classes at around 60 cm. This is close to the average height for non-contact scars of 40 cm measured by Turnstall *et al.* (1976). The largest size class had scars much further from the ground, possibly because contact scarring has the potential to scar trees higher than non-contact scars, which rely on the height of the standing leeward flame.

The fraction of circumference scarred increased with each successive size class. Based on their fluid dynamic model, Gutsell and Johnson (1996) reported a theoretical angle of 110° from the center of the windward side to the edge of scarring for non-contact scars, and supported this with field data. This theoretical angle would lead to a fraction of circumference scarred of 0.389, which is higher than the fraction of circumference in the 5-10cm size class. However, the margins of the area under influence of the convection current might not heat as quickly, especially with thick bark such as that of the oaks; therefore, the actual fraction scarred may be slightly lower in this system. Relatively wider non-contact scars would be the reason for a decrease in fraction of the circumference scarred as scarring shifts from non-contact to contact scarring over the size classes, and might be a good measure of the relative amount of each type of scarring in a system.

The percent of original canopy still alive also decreased as the size class increased. Though percent canopy is somewhat of a subjective measure, this suggests that these larger trees may suffer more from scarring. Either contact fire scars are more severe, or older trees are influenced more by scarring. This highlights the importance of preventing contact scarring in large trees.

Future Research

Though there have been numerous studies on oak savanna at Cedar Creek, the majority have focused on the effects of fire, and few have discussed restoration techniques. Recently, Cedar Creek has begun shifting the focus of its burn program towards restoration, which is important because of the large amount of relatively high quality and degraded savanna present at Cedar Creek. Studies need to be done exploring alternative management techniques such as mechanical thinning, girdling, or herbicide application to decrease density quickly and reduce fuel loads, and therefore contact scarring. At short fire intervals, only the oaks will survive after 40 years of management, so there is a good argument for removing other species to reduce fuel loads and overstory density. This sort of structural manipulation approach has been shown to result in better savanna restoration than a process-only approach of letting natural processes work though the re-introduction of fire (Nielsen *et al.*, 2003).

Finally, more research is needed on scarring. Rate of spread measurements and surveying new scars after a fire with a known wind direction would be extremely helpful in determining the accuracy of Gutsell and Johnson's (1996) equations and the prevalence of non-contact scarring. Since contact scarring is not well studied, field and laboratory experiments to measure heat output, increased residence time, distance to fuel source, chimney dynamics and measureable characteristics of contact scars would be useful. Comparing fuel loads to rate of scarring might help to prove that contact scarring is a problem. Determining the difference in lifespan between scarred and unscarred trees is also important.

Conclusion

Conserving this rare ecosystem requires foresight because of the longevity and permanence of potential mistakes. Instead of simply burning and letting nature take its course, savanna restoration needs to be done with the knowledge that restoring and maintaining savanna must be handled differently. Maintaining savanna may be possible with prescribed burning alone, but restoring savanna requires an attempt to move the ecosystem towards the conditions it would have persisted in naturally. Since fires in savanna would have occurred during high winds and spread quickly, burning areas with low fuel loads, efforts should be concentrated on reducing fuel loads via thinning and removal of dead wood, and conducting prescribed burns in conditions more akin to natural burns. Fires during the growing season need to be utilized to prevent shrub ingrowth, and variable fire intervals could be used to allow occasional recruitment.

Savanna restoration itself creates an ethical problem. There is no indisputable record of how the ecosystem appeared or functioned before European settlement. Native American influence before settlement certainly was a large factor in shaping the region. Restoring an area to pre-settlement conditions does not remove the anthropogenic influence on the ecosystem, it merely changes it. The existence of Midwestern oak savanna as a non-anthropogenic ecosystem can be called into question.

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