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Post-oak fire scars as a function of diameter, growth, and tree age

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Abstract

The biological and statistical characteristics of fire scarring will aid in predicting the effects of prescribed fire on trees and in the historical interpretation of past fire occurrences. We measured, tree-ring dated, and characterized 126 fire scars on post-oaks (*Quercus stellata*) from The Barrens complex of the Highland Rim, Tennessee, USA. We hypothesized that tree characteristics such as diameter, growth rate, and age would have an effect on the scarring of trees and found that the percent of circumference with cambial damage was a function of diameter, growth rate, and age. We quantified the probability of a tree being scarred using logistic regression that included tree diameter, growth rate, and age as significant independent variables. Post-oaks were more likely to be scarred and survive when they were from 9 to 22 cm in diameter and had a radial growth rate <2 mm per year. Predicting the effects of a prescribed fire on tree damage is particularly important where multiple resource objectives are integrated on a single site such as fire hazard reduction, high-quality timber production, wildlife habitat, and species diversity.

Keywords: *Quercus stellata*; Prescribed fire; Wildland fire; Oak; Fire scars; Probability; Tree-rings

1. Introduction

1.1. Fire scarring

The implementation of prescribed burning regimes and the reconstruction of fire history is enhanced by knowledge of the biological and statistical relationships among fires and tree scarring. Injury to trees in prescribed burning regimes is of concern to forest managers because of the effects of fire on stem death (Gutsell and Johnson, 1996; Hengst and Dawson, 1994; Lowery, 1968; Smith and Sutherland, 1999), the potential economic devaluation of timber, and the restoration of forest structure (Stambaugh et al., 2002) and biota (Jenkins et al., 1997; Grant et al., 2003; Guyette and Kabrick, 2002; Pyne, 2000). Records of the frequency and extent of historic fires rely on the accurate interpretation and homogeneous composition of fire scar records, which are often several centuries in length. We examined the response of post-oak (*Quercus stellata*), a species frequently used in fire history studies (Dey et al., 2004; Guyette and Cutter, 1991; Guyette et al., 2002, 2003), to injury by historic and prescribed fires in the Barrens of the southeastern Highland Rim in middle Tennessee, USA. Dated and measured fire scars were used to determine how scarring is related to tree characteristics. Specifically, we hypothesized that: (1) fire scars are statistically different from other types of scars, (2) fire scar features can be anatomically differentiated from non-fire scars, and (3) fire scar frequency and size are a function of tree diameter, growth rate, and age.

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Fire scars on trees provide unique temporal, spatial, and ecological information about historic fires. Fire scars, commonly located at the base of the tree, are the result of partial cambial death of the tree bole (Gutsell and Johnson, 1996; Smith and Sutherland, 1999). Tree-ring dating of fire scars provides temporal information about the effect of an injury on a single tree's subsequent growth or the forest wide growth response following fire disturbance. Collating tree-ring data from many trees from the same site can increase the length of the fire history record (because some trees will be longer lived than others) and increase the probability that less severe and intense fires are identified. The locations of fire scars in a particular year are useful spatial information about the location of historic fires and the number of trees scarred in a given spatial extent can be used to estimate fire size and severity (e.g., percent of trees scarred). This spatial historic fire information is scale-dependent; where at large scales (e.g., 1000 km^2) the locations of fire scarred trees can be used to understand fire size and at small scales (e.g., 1 km^2, a fire history site) the location of fire scarred trees can be used to understand fire severity or intensity. At present, combining the spatial and temporal information of fire scars is one of the best techniques for understanding the ecological significance of historic fire events. Other data important for understanding and describing historic fire events are the diameter of trees when scarred (Guyette et al., 2003), the distribution of the ages (cohorts) of trees (Heinselman, 1973), the diameter and location of unscarred trees during a known fire year, and the aspect of the fire scar on the tree bole (fire direction) (Beaty and Taylor, 2001).

2. Methods

The study site is an oak-dominated upland hardwood forest community (ACS Conservation, 2003) located on Arnold Air Force Base (Coffee Co.) in middle Tennessee, USA (86°4′50″W, 35°23′28″N). The site lies within The Barrens of the southeastern Highland Rim, a southeastern portion of the Interior Plateau Physiographic Province (Fenneman, 1938). The term "barrens" was used by early land surveyors and others to describe areas of land that was grassland with forbs and interspersed with sparse tree cover (Bourne, 1820; Engelmann, 1863; Sauer, 1927; Braun, 1950; Baskin et al., 1994). The term "barrens" was used loosely to describe a variety of forest types (e.g., Pine Barrens of New Jersey and northern Lake States, oak barrens of the Midwest) that occurred on a wide range of soils, geology and with variable climate (Tyndall, 1994). Recently an ecosystem management plan (Call, 2002) developed for Arnold Air Force Base addressed the unique habitats of barrens communities and allowed for their biological assessment (Clebsch and Pyne, 1995; Grant et al., 2003; Guyette and Stambaugh, 2003; The Nature Conservancy, 1998). Being the largest public land unit in The Barrens region (Pyne, 2000), the AAFB provides an important opportunity to document the historic fire regime and implement barrens restoration across a large physiographic region.

The study site was selected because baseline data (e.g., fire date, percent of area burned) relevant to the effects of fire on tree scarring had been collected for three prescribed fires. The study site has very little slope (<2%) or relief (<3 m) and is primarily composed of scarlet (*Quercus coccinea*) and post-oak tree species. The basal area of all live stems at the study site before prescribed burning began in 1997 was about 21 m^2 per ha (Fitch, 2004). This is a higher basal area than was found at similar sites (about 12 m^2 per ha) that had been burned for 27 years at the nearby Highland Rim Forest Station (DeSelm et al., 1990). Oak stems at the study site, mostly in small diameter classes, decreased from 736 to 478 per ha between 1997 and 2001. However, the total stem relative abundance of oak species increased between 1997 and 2001 from 26 to 31%. We sampled 26 post-oaks within a 3 ha area at a prescribed burn site on Arnold Air Force Base for the purpose of describing statistical, anatomical, and temporal frequency of fire scars and relating the occurrence of fire scars to the diameter, growth, and age of post-oak. Trees selected for sampling were of various diameters and heights all of which had charcoal present on their bark exterior. Cross-sections were cut with a chain saw from trees that ranged in size from 10 to 70 cm in diameter at a height of between 5 and 15 cm above the soil surface. Orientation of each cross-section was recorded in the field.

We cross dated all tree-ring series of all cross-sections and identified the calendar dates of all fire scars. Dormant season fire scar dates represent scarring from fires that burned sometime during an 8-month period (September–April) and prior to the beginning of cambial expansion in April. For example, the first evidence of a fire that killed cambial cells in the fall of 1997 occurs with cambial growth in April of 1998. We measured the tangential extent of the cambial death (i.e., fire scars), the diameter (inside bark) of the tree at the time of scarring, the aspect of the scar on the tree bole, and the pith date of each tree. Bole circumference at age was calculated using the measured radius (mm) and the equation for the circumference of a circle. The age of each tree at the time of scarring was calculated by subtracting the pith date from the scar date.

Fire scar data were plotted and statistically described (e.g., percent trees scarred, mean fire interval) using FHX2 software (Grissino-Mayer, 2001). We used SAS (SAS/STAT, 2002) logistic regression to examine the probability of a tree being scarred given its diameter, historic growth rate, and age at the time of burning. Non-linear regression techniques were used to document the relationship between the percent of tree circumference killed and tree diameter.

3. Results

3.1. Quantitative and qualitative fire scar identity in post-oaks

The most important aspect of this study is to verify that heat and not other agents of scarring such as lighting, skidding damage during logging operations, mammals, or insects cause scars identified on post-oaks as fire scars (Fig. 1). We use a multi-dimensional approach that includes anatomical features and statistical validation. Using anatomical features, we exclude scars with features characteristic of lightning (e.g., longitudinally long, narrow width, without closure, often with a strip of bark in the center), insects (e.g., tunnels and cambial mining), and mammals (e.g., teeth marks on cambial tissue). With few exceptions this leaves scars caused by logging

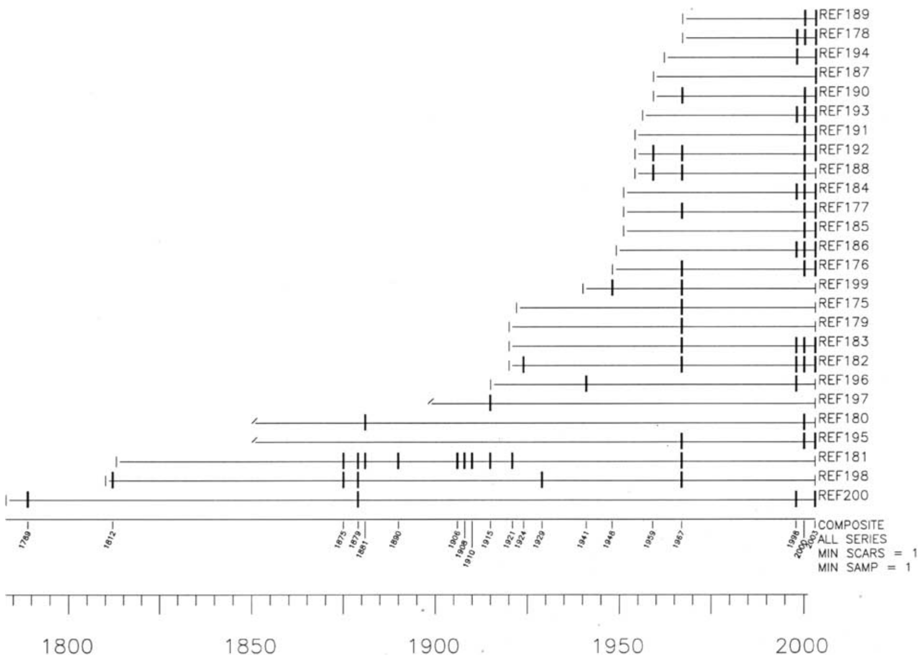

Fig. 1. The Barrens study site fire history chronology showing fire dates on individual trees. The short vertical bars are fire scar years. The horizontal lines represent the tree-ring record of each tree. The composite fire scar chronology with all fire dates is shown at the bottom of the figure. The fire scar record is poorly replicated prior to 1850, a period when fires may be under-represented.

Table 1
Comparison of stem scars from logging damage (Bruhn et al., 2002) and fires

Injury type	Fire scars	Logging scars
Mean width of scar (mm)	48	139
Scar width as percent of tree circumference	12	24
Frequency (percent of trees scarred)	57	17

operations as the most difficult type of scar to distinguish from fire scars during the more recent centuries of most fire chronologies. Scars from logging operations are basal and tend to occur in a single year, thus mimicking fire scars in the location on the tree and temporal coincidence in the historical record provided by trees.

Our results show that both statistical comparisons of fire scarring and scar anatomical features allow for differentiation between logging scars and fire scars. These are: (1) the mean width of fire scars is less than those caused by logging, (2) the percent of the circumference injured by fire is less than that caused by logging, (3) basal scarring is more frequent in fires than in selective tree logging (Table 1), and (4) the identity of some fire scars is confirmed by the *bark fissure pattern* of scarring (Fig. 2). Basal scarring from fire tends to be more frequent (i.e., scars per ha) because fires disturb more site surface area than select logging operations that impact primarily trees along skid trails or transportation routes (Bruhn et al., 2002). Distinctive scarring patterns are caused by the differential heating of the cambium due to the variable bark thickness. The expansion of the xylem over the period

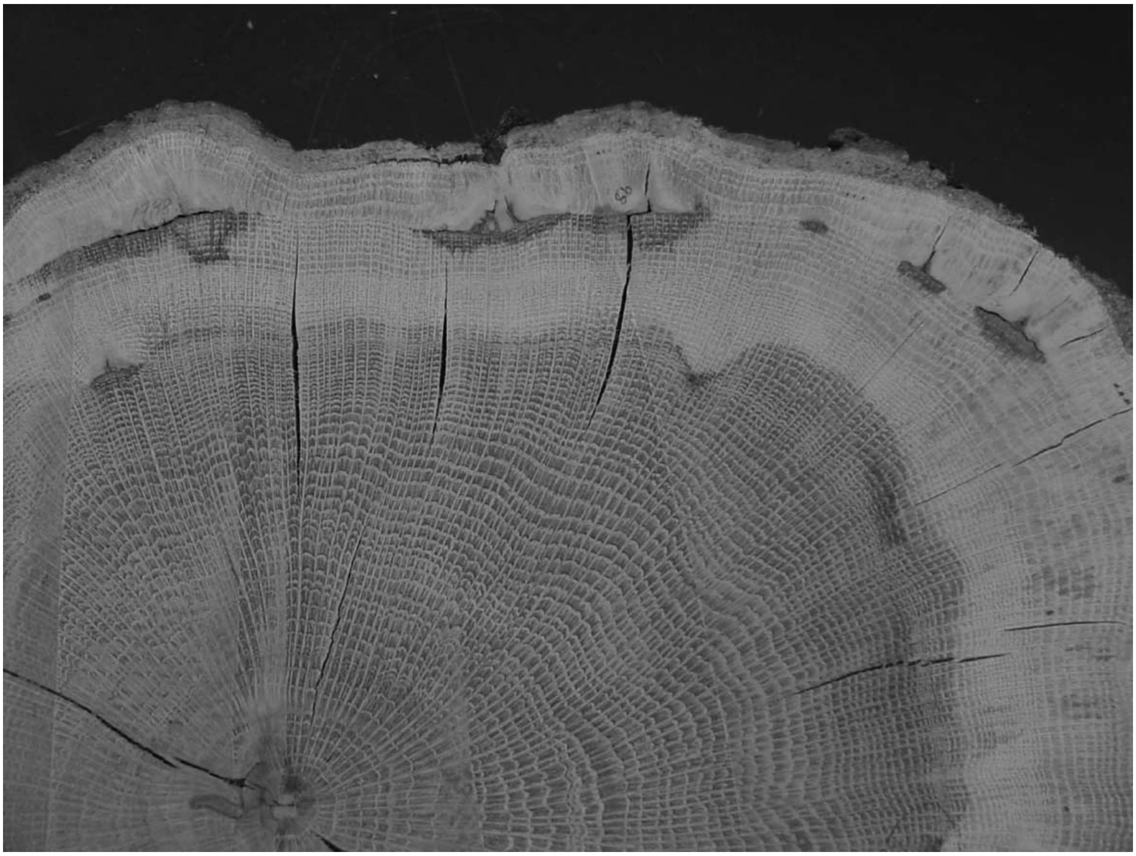

Fig. 2. The photograph illustrates *bark fissure pattern* scarring in the 1998 radial growth increment (i.e., tree-ring) of a sample post-oak caused by a prescribed fire in the fall of 1997. Multiple small scars distinguish heat killed cambium from the larger basal scars caused by log skidding.

Table 2
Frequency of fire scars by tree per fire and non-fire years

	N	Trees per year with scars	Trees per year without scars	Percent of trees scarred
Fire years	4	71	44	57
Non-fire years	33	0	856	0

Data are for the period 1967–2003.

of years results in deep fissures in the bark of trees such as post-oak that have very inelastic bark. This type of bark results in *bark fissure pattern* scarring, a distinctive feature of thermally induced cambial death (Fig. 2).

The temporal distribution and co-occurrence of fire scars (Fig. 1) over the last 37 years of tree-ring record indicates that: (1) basal scars on post-oaks are excellent recorders of fire events, and (2) there are few other scarring agents that might confound the fire scar record (Table 2). On average more than half of the trees were scarred during prescribed fires (Table 3). This indicates that scars on post-oaks are reliable proxies for fire events. Equally important are the 856 annual observations (i.e., tree-rings) on the 26 trees that showed no scars that could be confused with fire scarring. Thus, by differentiating scars by anatomical features, statistical comparisons, and close interpretation of the temporal distribution of the fire scar record, the potential for non-fire basal scars to be misinterpreted as fire scars is extremely reduced if not eliminated.

3.2. Statistical description of post-oak fire scars

Statistical descriptions of scars known to be caused by fire help in understanding and describing the variance in scarring between fire events (Table 3). Multiple scars were common both within trees (during different years) and within annual rings. Mean scar width (approximately 48 mm) was consistent among the four fire events but still highly variable within fire scar years (see scar width range, Table 3). Scar width, as the percent of tree bole circumference scarred, varied from very small scars (equivalent to <1% of the circumference) to much larger percentages for small trees (>75%). The percent of circumference scarred may not be comparable among fire years because of the possible mortality of injured trees. Greater variation existed in the percent of trees scarred (35–65%) than in the percent circumference scarred.

3.3. Prescribed and wildfire scar dates

Fire scar dates are plotted for each tree in Fig. 1. A composite fire scar chronology (bottom of Fig. 1) of all fire years shows that post-oaks recorded historic wildfires fires as well as recent prescribed fires (1998, 2000, and 2003). Although reconstructing the historic fire regime was not a study objective, there is evidence for five fires in the last 53 years, of which at least three were prescribed fires. Between 1850 and 1950 there were 13 fires with a mean fire interval of 7.7 years and between 1850 and 1795 three trees recorded two fires.

3.4. Scar frequency and size versus tree characteristics

The percent of cambium killed (PCK) was significantly correlated with bark width, tree diameter, growth rate, and tree age (Table 4). Faster growing trees showed a higher potential for reduced cambial death as result of heating by fire (Fig. 3). The relative size of a fire scar (i.e., PCK) was a

Table 3
Calendar year fire dates, seasonal fire scar dates, and associated scar characteristics for 101 fire scars formed during four fires

Fire date	Tree-ring fire date	Fire type	Area burned (%)	Scar width mean and range (mm)	Circumf. scarred (%)	Percent trees scarred	Number scars
NA	Dormant season, 1967	Unknown	NA	47 (10–118)	18 (1–52)	54	19
Fall 1997	Dormant season, 1998	Prescribed	NA	49 (2–305)	10 (1–80)	35	26
March 2000	Dormant season, 2000	Prescribed	72	49 (5–265)	12 (1–92)	62	30
March 2003	Dormant season, 2003	Prescribed	93	48 (10–204)	8 (1–30)	65	26

Prescribed fire data are from Arnold Air Force Base (unpublished data). Percent of fire prescription area that was burned is given in column four.

Table 4
Correlation coefficients among the PCK and tree characteristics given by recent prescribed fire years

Tree characteristics	Fire 2003	Fire 2000	Fire 1997	All years
Bark width	−0.04	-0.57^{**}	-0.52^{**}	-0.42^{**}
ln(diameter)	−0.17	-0.59^{**}	-0.59^{**}	-0.60^{**}
Diameter	−0.22	-0.36^{*}	-0.41^{*}	-0.43^{**}
Radial growth rate	0.09	-0.42^{*}	−0.31	-0.30^{**}
Age	−0.24	−0.23	−0.15	-0.29^{*}

'All years' is the pooled data from 2003, 2000, and1997. Statistical significance levels are given by single ($P < 0.05$) and double ($P < 0.01$) asterisks.

negative exponential function of tree diameter (Fig. 4) and is described by the equation:

$$\mathrm{PCK} = 100\,\mathrm{e}^{-0.0095d} \tag{1}$$

where PCK is the percent of tree circumference killed, e the exponential constant (2.718), and d the diameter of the tree cross-section (mm). This equation demonstrates that larger post-oak trees have a lower percent of their circumference killed or have a higher resistance to fire scarring than smaller trees. Although the percent of stem circumference killed and tree diameter are not statistically independent the relationship has biological relevance and important application for prescribed burning management.

3.5. Modeling the probability of scarring in fire years with multiple tree characteristics

The scarring of trees was negatively related to the tree's diameter, radial growth rate, and age. We combined these predictor variables in a logistic regression with a binary response variable (scar or no scar) for the purpose of predicting the probability of a tree being scarred. The logistic regression for the probability of a fire scarring a tree during a fire year is

$$\mathrm{scar} = -3.05 + (1.33\,\mathrm{ldiam}) - (0.965\,\mathrm{rgrate}) - (0.0279\,\mathrm{age}) \tag{2}$$

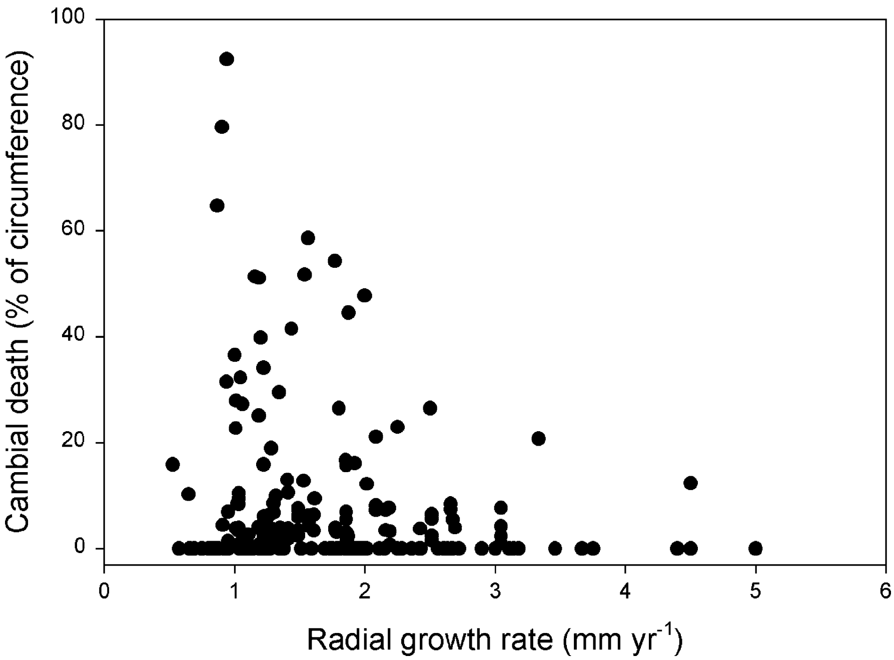

Fig. 3. Scatter plot illustrating the relationship of radial growth rate to the percent of post-oak stem circumference killed by heat.

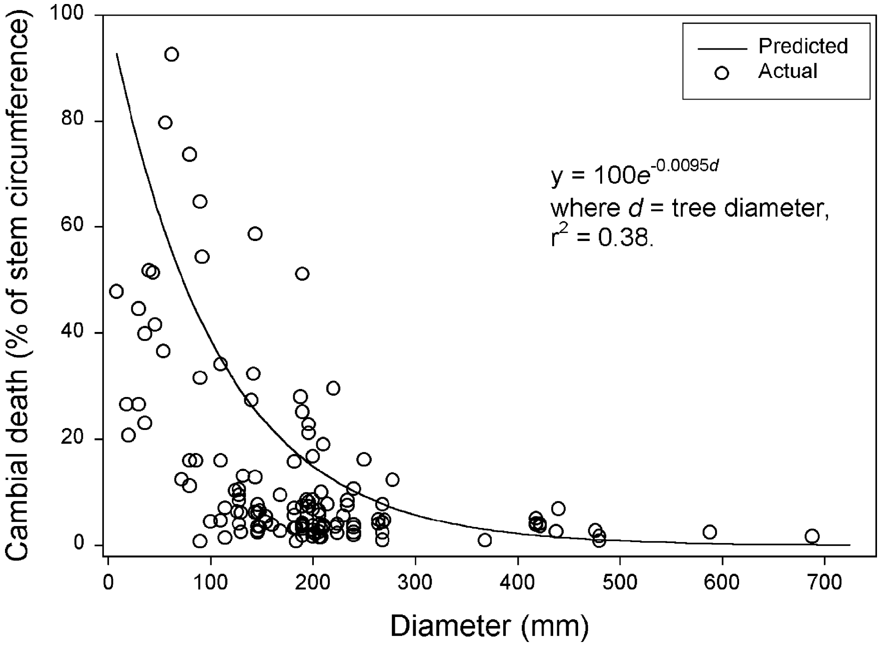

Fig. 4. Illustration of a non-linear function that predicts the percent of oak stem circumference killed by fires (both wild and prescribed) with post-oak basal diameter.

where scar = (tree scarred (0) or not (1), binary variable), ldiam = ln(diameter) in mm, rgrate = radial growth rate (mm per year), and age = age of tree at time of scarring. All variables and the intercept were significant at the 0.01 level. The AIC of for the intercept and covariates is 289. The predicted probabilities and the observed response were 74.7 concordant and 24.5% discordant. The predicted odds for a large diameter tree being not be scarred in a fire year were about four times (378%) greater than for a small diameter tree. Probability of a tree being scarred is given by the equation:

$$\mathrm{Pr} = [1 + \mathrm{e}^{-bx_i}]^{-1} \qquad (3)$$

where bx_i is the scar (from Eq. (2)), e the exponential constant (2.718).

Tree diameter, growth rate, and age were all significant variables in the logistic regression. The probability of a tree being scarred and surviving was highest when tree diameter was between approximately 9 and 22 cm (Fig. 5). Trees smaller than about 9 cm in basal diameter were more likely to be killed and would not have lived through previous fires or be included in our data set. Trees with radial growth rates greater than about 1–2 mm per year were most likely to be scarred (Fig. 6).

3.6. Bark thickness and scarring

Bark thickness is an obvious and important factor that insulates and protects the living cambium during fires. We related bark thickness to diameter, radial growth rate, and age using linear regression. Only bark thickness data from 2003 was used because bark thickness of the current year likely does not reflect the bark thickness of a tree in the past. Bark thickness is a function of radial growth rate, tree age, and diameter defined by the equation:

$$\text{Bark thickness} = 2.82 - 0.285\,\text{dia} + 6.23\,\text{rgrate} + 0.101\,\text{age}$$

where dia = diameter (mm), rgrate = radial growth rate (mm per year), age (years), model $r^2 = 0.36$, partial $r^2 = 0.12$ for diameter, for growth rate = 0.09, and for age = 0.15. All variables are significant ($P < 0.05$).

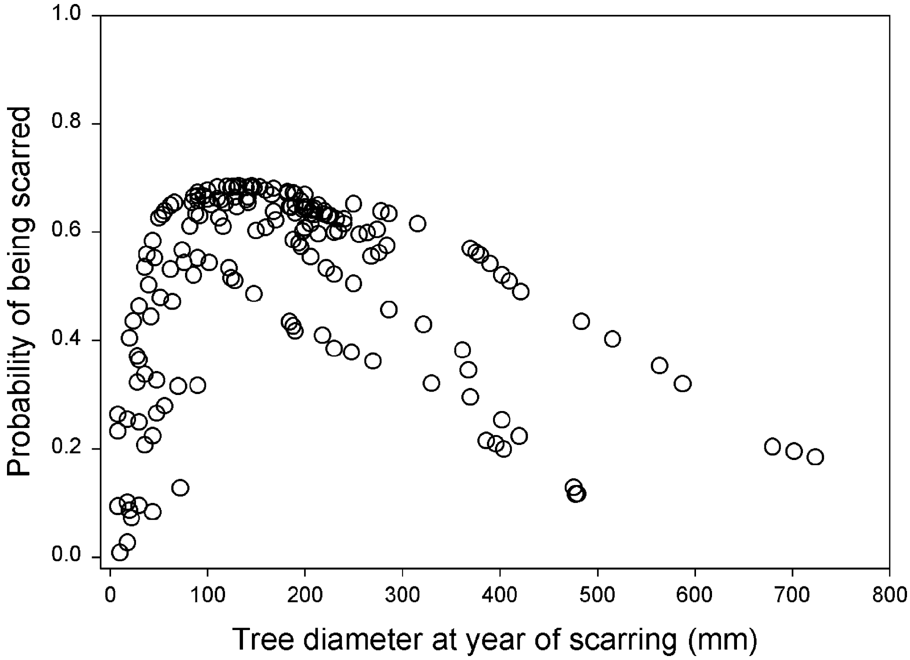

Fig. 5. Logistic model (Eqs. (2) and (3), see text) predictions of the probability of a tree being scarred given its diameter. Probability estimates are based on empirically developed non-linear models that include diameter, growth rate, and age as predictors. Model predictions for very small trees (<50 mm basal diameter) are biased by mortality and thus were excluded from the data set and invalidate the model for small diameter trees.

4. Discussion

One challenge in reconstructing fire histories from fire scars, particularly without the direct association of charcoal present in the scar, is that wounding events such as those caused by skidding logs can mimic wounds caused by fire. The misrepresentation of a fire scar date can have important implications for describing the characteristics of the historic fire regime (e.g., fire frequency, percentage of trees scarred). Scar misidentification is restricted to scars without charcoal (most hardwood scars are of this type) and forests that have been logged which, in the region, is limited to the last two centuries. The results of our study indicate that *bark fissure pattern* scarring, caused by variable degrees of bark insulation against heat damage, is a useful anatomical feature for differentiating between fire and logging scars. Smith and Sutherland (1999, 2001) also observed *bark fissure patterning* on other oak species as result of prescribed burning.

There are several implications for improving the experimental design and construction of fire scar chronologies that result from this analysis. One, even with only two trees there is a probability of 0.67 that a fire will be recorded by at least one tree. Thus, although sampling as many trees in as small an area as possible is the best method for recording fires, when the rate of scarring is about 57% then there is a probability of about 0.94 of a fire being recorded with only five trees in the record ($P = 1-0.57^5$). Second, smaller and younger trees should be included in the temporal sample space to avoid missing fires that may have occurred recently and have a lower probability of scarring large trees. Ideally, there would always be three to five trees in the 10–20 cm diameter class represented at any part of the fire history record as these are the size classes more likely to be scarred and not killed. Third, the presence of *bark fissure pattern* scarring within a group of scar dates that occur in the same year is definitive evidence of a fire in that year.

Throughout the past decade prescribed burning practices have become more widely used for restoration and management activities. Increased use of prescribed fire has resulted in an increase in demand for information that can be used to guide prescribed

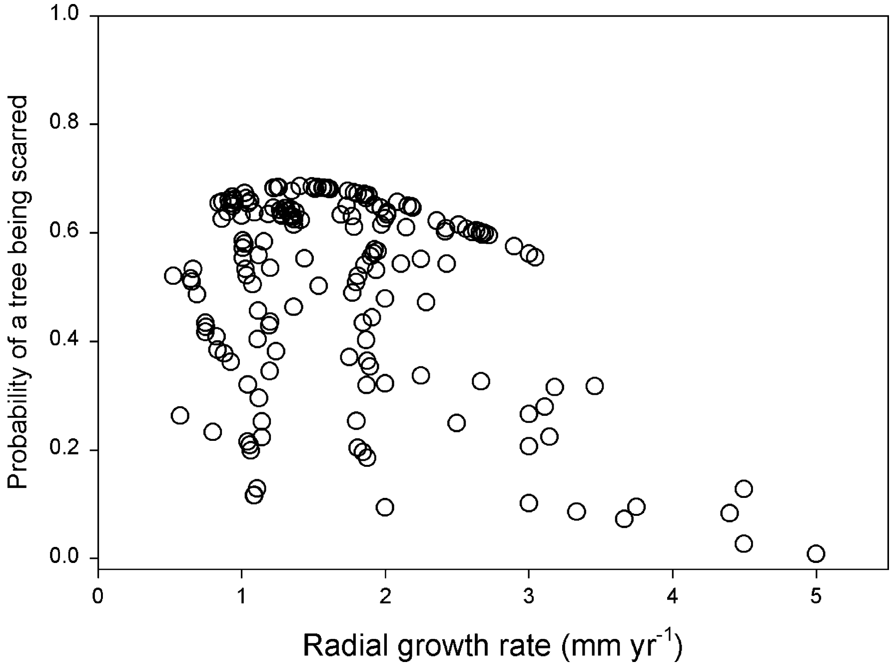

Fig. 6. Logistic model (Eqs. (2) and (3), see text) predictions of the probability of a tree being scarred given its radial growth rate. Probability estimates are based on empirically developed non-linear models that include diameter, growth rate, and age as predictors. Growth rates based on ring width are not independent of tree diameter, thus the similar probabilities were compared to Fig. 5.

burning management and planning. The relationship between scarring and tree diameter, growth rate, and age provides an important tool for managers for assessing the prescribed fire conditions needed to accomplish the desired effects on tree survival, species composition, and forest structure. Managers can use the above equations to modify the intensity (i.e., seasonality, burning technique) of the prescribed fire so to better predict and regulate tree damage and mortality. The predictability of the effects of a prescribed fire on tree damage is particularly important where multiple resource objectives are integrated on a single site such as fuel hazard reduction, high-quality timber production, wildlife habitat, and species diversity.

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