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RESEARCH NOTE

Fire History Reconstruction in the Black Oak (*Quercus velutina*) Savanna of High Park, Toronto

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ABSTRACT: We employed tree-ring analysis to reconstruct the fire history of High Park, Toronto, Canada, in one of the largest remnants of black oak (*Quercus velutina*) savanna in Ontario. This heavily urbanized area has a long history of fire suppression, which has degraded the native savanna. Efforts to reintroduce fire would benefit from a fire history record. Ring width patterns were quantified for 38 black oak chronologies on 14 cross-sections and 10 cores using dendrochronology software that employs scanned (digital) ring sequences. Scar and sealing patterns and rapid growth responses following scarring were dated to indicate the timing of fire events. These dates were compared with the timing of regeneration pulses and the establishment of multistemmed individuals that would have sprouted in response to fire disturbance. Our records suggest that most of the mature black oak stems established synchronously, around 1865, following an apparently extensive fire event or set of events. We have evidence of four other fires in the century that followed. Dendrochronology in black oak savanna presents challenges due to this tree species' thick bark, and the low intensity savanna fires that do not breach all individuals in a stand. Further, the present black oak population has succumbed to disease and old age, leading to decay of the central stem and the loss of the oldest rings that were more likely to be scarred as they formed during the tree's youth. This is likely to be a limitation in other savanna communities in long-settled regions of North America. We suggest inclusion of corroborative evidence, such as that employed in the present study, including the use of multistemmed individuals as indicators of stem recruitment following fire, and demographic data for the population.

Index terms: dendrochronology, fire history, fire suppression, oak savanna, *Quercus velutina*, restoration ecology

INTRODUCTION

Savanna ecosystems are transitional between grassland and forest, characterized by the codominance of scattered trees within a matrix of herbaceous vegetation (Scholes and Archer 1997). The patchy savanna structure is maintained by a cycle of disturbance and regeneration (Dorney and Dorney 1989; Arabas 2000; DeSantis et al. 2010) associated with periodic understory fires (Tester 1989; Scholes and Archer 1997). The absence of fire results in canopy closure and shading out of fire adapted tree species' seedlings, grasses, and forbs (White et al. 2011), causing a transition to closed forest (Abrams 1992; Peterson and Reich 2001).

Savanna species have physiological and morphological adaptations to periodic disturbances that facilitate their dominance on landscapes with frequent disturbance (Dorney and Dorney 1989; Peterson and Reich 2001). Oaks resist fire damage through thick bark, deep taproots, and compartmentalization or "sealing" of wounds (Guyette and Stambaugh 2004), thus giving them a competitive advantage over fire-sensitive species (Henderson 1983).

Oak savanna has developed with frequent fire (Henderson and Long 1984), probably maintained by Native Americans who used fire for hunting, clearing riparian areas, and tree felling (McClain et al. 2010). With European settlement came active fire suppression (Guyette and Spetich 2003), altering the composition and dynamics of the savannas (Abrams 1992; Wolf 2004). Oak savannas have, thus, become one of North America's most threatened ecosystems, occupying only 0.02% of their historical range (Nuzzo 1986). Less than three percent of the presettlement savanna remains in southern Ontario, in the form of small fragments (Rodger 1998; Tagliavia 2002; Etwell 2004). Oak savanna is present in only four areas, the largest of which is the black oak (*Quercus velutina* Lam., Fagaceae) savanna in High Park, within the densely populated City of Toronto (Kidd et al. 2008) (Figure 1). In 1989, the Park was designated as an Area of Natural and Scientific Interest (ANSI), a classification given to important landscapes for natural heritage, scientific study, or appreciation (Kidd et al. 2008). However, competition with nonnative species, prolonged drought and disease, as well as a history of fire suppression, have eroded the black oak population and understory grass and forb community (Kidd et al. 2008; K. Sharratt, unpubl. report). The reintroduction of fire by park staff has promoted tree and understory species regeneration (City of Toronto 2002), but these efforts are hindered by the lack of historical information on fire frequency, intensity, and spatial extent. Studies of other black oak savannas give

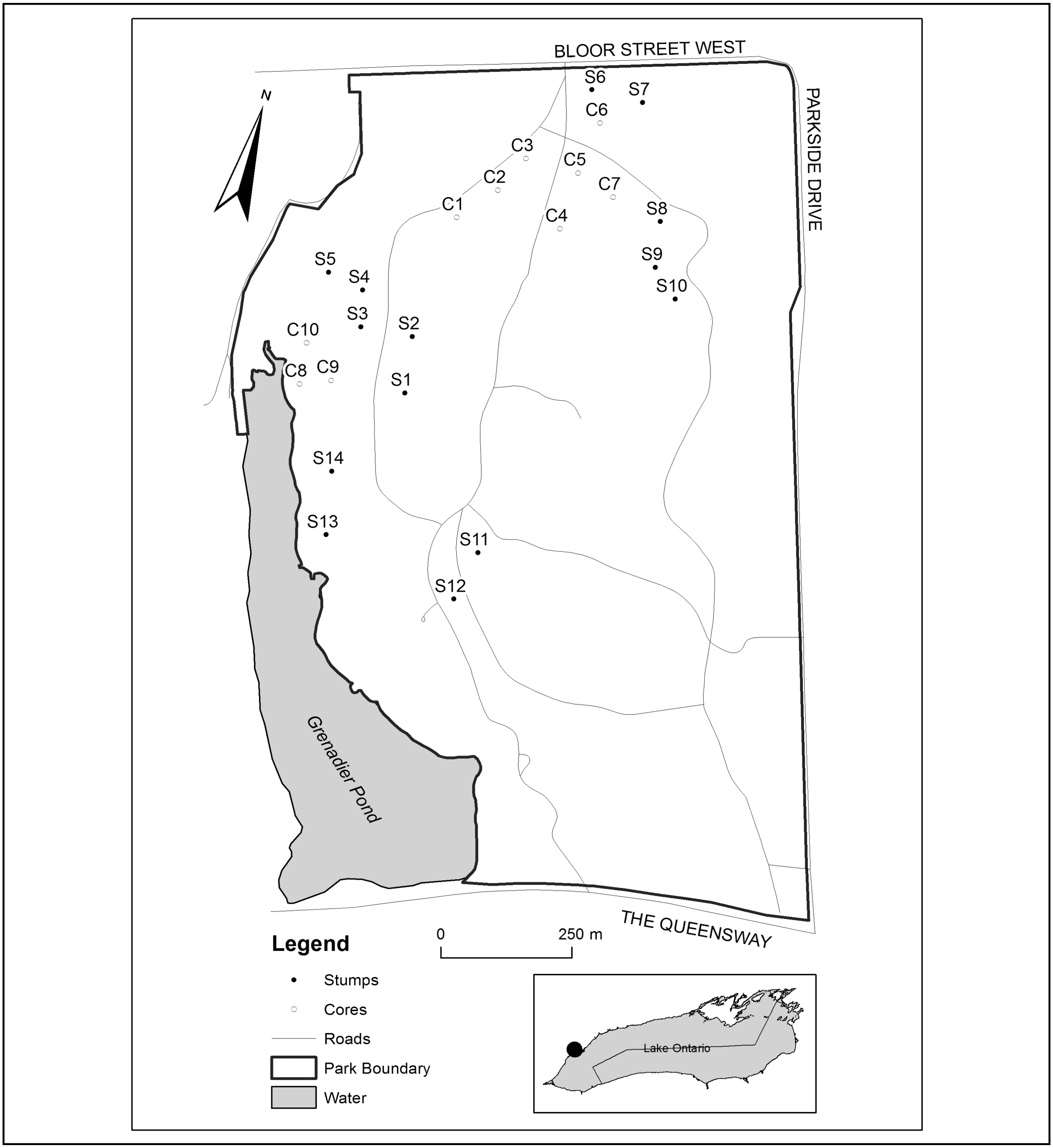

Figure 1. Map of High Park, Toronto, Ontario, and sample locations. The map includes public sector datasets made available under the City of Toronto Open Data License v2.0. Stumps (S; collected in 2009), and cores (C; collected in 2011), are marked along with their number. For example, the three samples at the top of the map are Stump #6 and Stump #7 and Core #6.

mean fire intervals of 5–11 years in Indiana (Henderson and Long 1984), 1.5–2.4 years in Illinois (mean; Considine et al. 2013), and 17 years in Pinery Provincial Park, Canada (using fire scars on pine instead of oak) (Bravo 2004). A Wisconsin bur (*Q. macrocarpa* Michx.) and white oak (*Q. alba* L.) savanna had a 4.6 year interval (Wolf 2004), and Missouri post oak (*Q.*

stellata Wangenh.) savannas had 4.3 and 5.2 year mean fire intervals (Guyette and Cutter 1991).

Our objective is to reconstruct the fire history of High Park in Toronto, Canada, to before and after presettlement time, with minimal damage and disturbance to the community. We also evaluate the use of black oak in savanna fire history reconstructions.

METHODS

Study Site

High Park is a 161-ha city park on the north shore of Lake Ontario in Toronto, Ontario, Canada (43°39'05.39" N; 79°27'58.03" W, Figure 1), and is one of the major green spaces in the city (K. Sharratt, unpubl. report). The Park occurs within the basin of former glacial Lake Iroquois. The sandy, low nutrient, parent material of the glacial lakebed promoted the occurrence of frequent surface fires and the development of savanna on upland sites (Nuzzo 1986; Ryu et al. 2010). Black oak is the dominant tree species in the savanna communities (Kidd et al. 2008). Red oak (*Q. rubra* L.), white oak, and bur oak are also present, along with a species-rich herbaceous understory (Calabrese et al. 2010).

The study area was settled in the mid-1800s by a private landowner, who later deeded it to the city for public enjoyment (Kidd et al. 2008). Fire suppression during this period led to encroachment of closed forest into the savanna. There is no clear historical record of when fire suppression began and to what extent it controlled fires (J. Gibb, Natural Resource Specialist for the City of Toronto, pers. comm.), but a suppression policy, formal or informal, was likely to have been in place in High Park longer than in other regional oak savannas (e.g., Considine et al. 2013), which are situated in less heavily built-up areas. The remnant savanna in High Park has been progressively fragmented by walking trails, and the aging oak population is affected by drought conditions, infestations of fall cankerworm and fungal pathogens, and the introduction of nonnative invasive species such as European Buckthorn (*Rhamnus cathartica* L.) (K. Sharratt, unpubl. report). Since 2000, Park managers began conducting prescribed burns and transplanting seedlings to restore the oak savanna in designated management units (City of Toronto 2002).

Field and Dendrochronological Methods

Basal cross-sections were collected from the stumps of 14 large (>50 cm diameter at breast height, dbh) dead individuals that were cut down by Park staff (Figure 1). Fire studies in other oak communities have similarly relied on small, opportunistically obtained samples due to the low population densities of oaks and the need to prevent destructive sampling (e.g., Wolf (2004) had 16 samples). Cores are inadequate for oak savanna fire reconstruction as the typically low intensity surface fires leave small scars, often on multiple sides of the trunk, which seal over and become hidden as the tree matures (McBride 1983; Nowacki and Abrams 1997). Complete cross-sections also facilitate accurate dating by revealing sections of the trunk with ring abnormalities, such as false or missing rings (Nowacki and Abrams 1997; Carrer and Urbanti 2004; McEwan et al. 2007). Using a chainsaw, the top weathered layer of the stump was removed and cross-sections were cut within 5 cm of the ground surface since scars in oak savanna occur at, or close to, ground level (Anderson and Brown 1986). Latitude and longitude were recorded. The majority of these samples were from the northern section of the Park (Figure 1). To facilitate dating of ring series, we obtained 10 cores using a Haglof increment borer from living black oaks in the areas where stem cross-sections were taken. All samples were air dried and the surfaces prepared for analysis following Stokes and Smiley's (1968) classic method involving sanding with successively finer grades of sand paper. We used Rinntech's Lignovision (Version 1.37) to assign ring-boundaries visible in image files using scanned digital photographs. Within each image, planes (or "trace lines") with clear ring boundaries were chosen. Oak wood is ring porous (Speer 2010), making ring boundaries easily distinguishable (Rozas 2003; Speer 2010). Ring series were measured in micrometers (µm) on 2–3 radii per cross-section and on all tree cores. In total, 38 ring series from cross-sections and tree cores were measured.

Ring series from cross-sections were visually cross-dated with cores using graphed ring width series. While cross-sections were harvested from stumps in 2009, the trees had been cut in 2005 and Park staff reported that several of these were already dead by 2001 (J. Gibb, Natural Resource Specialist for the City of Toronto, pers. comm.). Cross-dating, therefore, proceeded on the assumption that the last growth ring on all cross-sections was 2005 or earlier. Fire scars were identified on the complete cross-sections and assigned to the corresponding ring in the chronology (see "Fire Event Detection," below). Chronologies were subsequently synchronized by shifting scar dates on trees at the same location that were within a few years (≲5) of each other, assuming these represented a single fire event (Arno and Sneck 1977). A master composite fire chronology was produced. While this may yield some error in calendar dating, results should be within a couple of years of the actual date. Identification of climatic events from climate data using ring patterns was unsuccessful, perhaps due to complacency of these oak populations and/or their sensitivity to local microclimate in this topographically varied parkland. There are no dendrochronological records for nearby oak populations, so cross-dating with a regional chronology was not possible. An unpublished study from Pinery Provincial Park on Lake Huron (Bravo 2004) is climatically different.

Five cross-sections were missing rings in central portions due to decay; two were missing rings along a portion of the center. We employed an empirical *Internal Growth Rate* (IGR) model to estimate the number of missing rings (Rozas 2003). This involved calculating the average number of rings per unit length of the central portion of complete cross-sections (n = 12 ring width series across seven cross-sections) to approximate the number of rings missing along the radial length of rotted cross-sections. Since age related growth varies minimally within oak species (Stephenson and Demetry 1995), the results of this method are likely robust. The missing distances to the pith measured in heart-rotted cross-sections ranged from 1 to 11 cm. The IRG model provided a reasonable estimate of the number of rings missing (R^2 = 0.42).

Fire Event Detection

We used scar and sealing characteristics to detect fire events, including destruction of annual rings by fire and distortion of later rings as cambium grew over and sealed the wound (Speer 2010) (Figure 2). Ring scars had been sealed over for more than 100 years on many cross-sections, were relatively small, and had little visible carbon, limiting the use of charcoal as an indicator. We also used ring width responses to fire. Fire scars are often accompanied by ring width increases after an event because of release from resource competition, particularly light, with surrounding vegetation (McBride 1983; McEwan et al. 2007). Ring width response was determined by comparing the average ring width in the five years before and after an event. A difference of greater than one mm was identified as a widening or narrowing event. The low intensity of savanna fires combined with oak adaptations for fire resistance in the form of thick protective bark (Peterson and Reich 2001; McEwan et al. 2007; Stephens et al. 2010) means that fires would not necessarily mark all individuals in a burn. We therefore used the following corroborative fire event indicators: (1) the timing of establishment of multistemmed individuals (three of the 14 cross-sectioned individuals), which, among oaks, indicates basal resprouting in response to having been top-killed as a sapling, typically by fire or other disturbance (Keeley 1992; Del Tredici 2001), and (2) the presence of even-age cohorts in the pre-settlement period, which is suggestive of a fire-induced recruitment period (Abrams 1992; Peterson and Reich 2001). Our sample of cross-sections was also used to determine establishment dates (n = 14). With respect to multistemmed individuals, resprouting following fire disturbance occurs simultaneously across all

Figure 2. Example of fire scarring within a black oak cross-section (S7 in Figure 1), collected in 2009, High Park, Toronto. Subsequent ring growth exhibited sealing over the scar and an episode of increased ring width.

stem sprouts, so ages were determined (as above) for one stem per multistem. Other stems of the multistemmed individuals were of similar diameter (and thus, age) to the measured stem.

RESULTS

Cores collected in the same general area had similar annual growth patterns, suggesting that individuals were responding to local site conditions. Stems from these co-occurring individuals were more readily cross-datable to each other and to local cross-sections. Tree age ranged from 50 to 200 years. Only two samples represented the period before 1865 (Figure 3). Ten of the cross-sectioned individuals (n = 14) established between approximately 1864 and 1878, in what can be considered a regeneration pulse for the sampled oaks. Core samples were missing piths due to decay or sampling effects and were not included in these establishment estimates, but given the size of the cored oaks and the approximate length to the pith (N. Hewitt, pers. obs.), several of these established in the same period.

We found evidence for five distinct fire events (Table 1, Figure 3). Three of these were recorded among individuals located in the northeast section of the park. We found no fire scars on any specimens over 62 years of age (Figure 3), even from known fires (e.g., prescribed burns), likely due to the increasing bark thickness and protection as black oak matures (McBride 1983). The three cross-sectioned oaks with multiple stems were recruited in the year of, or following, two of the fire events (Table 1), presumably due to resprouting following fire destruction of the original "leader" stem. Increased ring width occurred in three of five fire-scarred individuals. All three were in their immature phase when they would be most sensitive to increased light associated with fire disturbance.

The earliest recorded fire event, in 1865, appears to have been widespread, affecting individuals in both the southern and northern portions of the Park (Table 1). This date coincides with recruitment of many of the cross-sectioned oaks (Figure 3), suggesting that this, or another fire event(s) occurring around this time, was associated with a regeneration pulse.

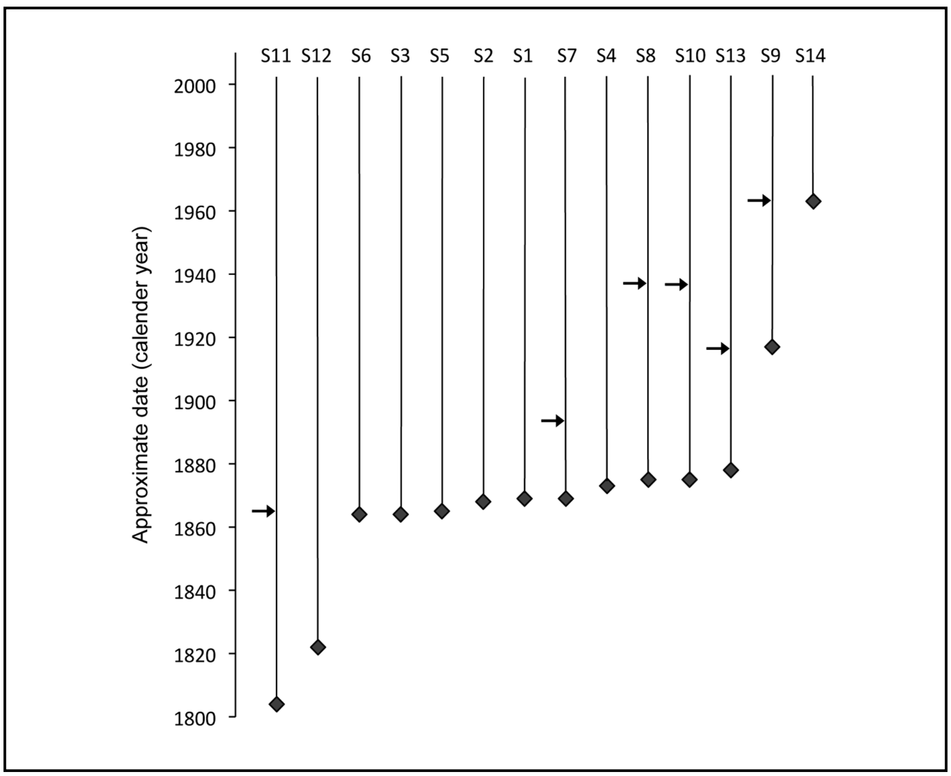

Figure 3. Timing of establishment and fire scarring among black oak individuals cross-sectioned in 2009 in High Park, Toronto. The vertical axis represents calendar year. Each vertical line represents a cross-section. The diamonds are recruitment years of each stem and arrows indicate the approximate dates of fire scars on those individuals. Labels at the tops of bars are stump samples corresponding to Figure 1.

DISCUSSION

Fire Interval

This study provides the first data for High Park's fire history. We identified five fires that occurred since the beginning of the chronology in 1804 (establishment date of the oldest specimen). The best evidence of fire was the 1865 event (Table 1, Figure 3), which occurred in both the southern and northern portions of the Park. This circa 1865 fire event, or events, triggered the stand-wide establishment episode responsible for much of the present-day black oak canopy, which is currently comprised of a large, aging cohort, with few younger individuals and little regeneration (see also Varga 1989; Kidd et al. 2008).

The widespread 1865 event suggests that effective fire suppression was not immediately practiced by the landowners upon settling the Park area around 1836 (City of Toronto 2002). No other fires were recorded in our sample between 1836 and 1865. It is also possible that suppression of any smaller fires in that interval promoted a buildup of fuel leading to this large fire. At any rate, this 1865 event stands as an important disturbance event associated with the regeneration of oaks in the Park. The four subsequent burns in our record appear to have been relatively localized. These may represent the often low intensity, patchy fires characteristic of savanna ecosystems (Peterson and Reich 2001), or may be fire events curtailed by early control efforts. Fire suppression policy and control efforts were formally put in place sometime after the park was deeded to the City in the mid-1870s (City of Toronto 2002), and appear to have been effective by the late 1930s, after which time we detected only one apparently small burn in 1962.

Table 1. Approximate fire dates and lines of evidence for fire events.

Date	# Fire scarred individuals	# Multiple stem recruits within 1–2 years of fire date	Location of scarred and / or multistemmed individual(s) in Park	Ring width response >1 mm following fire date
1865	1	2	SW, NE, NW	N
1892	1	-	NE	Y
1918	1	-	NW	N
1937	2	-	NE	Y
1962	1	1	NE, NW	Y

Our data suggest fires were relatively infrequent or were otherwise of too low intensity to breach black oak bark. We measured less than one fire per 30 years across the sampled population if a fire is assumed to have occurred around 1804 when the first individual in the sample recruited, to 1936, the date of the second most recent fire recorded. Given the small available sample size and possible role of fire suppression over part of this period, the presettlement burn frequency is likely an underestimate. Further, not all trees burn in a fire and not all fires leave scars (Farris et al. 2010; Stephens et al. 2010). Thus, a lack of fire scars is not evidence of absence of fire (Smith and Sutherland 1998), and fire-return intervals are always considered minimum estimates (Arno and Sneck 1977). Oak's thick protective bark for fire resistance (Peterson and Reich 2001) may further lead to under-representation of fire events in oak communities. The patchy nature of savanna fires will not scar all trees on a site (Guyette and Muzika 2002; McEwan et al. 2007; Brose and Waldrop 2010; Speer 2010). Nevertheless, southern Ontario is a humid region that supports edaphically and topographically (rather than climatically) derived savanna ecosystems. The upland sandy soils of the Park not only produce xeric well-drained soils, but also create lower nutrient conditions that are associated with slower growth rates, which in themselves are conducive to perpetuation of herbaceous cover and fire propensity, and thus, savanna maintenance (Kellman 1984; Bond 2010). Fire intervals may be expected to be lower here than in the Midwestern (USA) savannas documented in the North American literature (Henderson and Long 1984; Guyette and Cutter 1991; Wolf 2004; McEwan et al. 2007). Indeed, the fire record from Pinery Provincial Park in southern Ontario that includes areas of black oak savanna had a relatively long fire-free interval of 17 years using *Pinus* records rather than oak (Bravo 2004). Additional data are needed to extend this estimate further into the presettlement period and to evaluate the possibility that this savanna was maintained with relatively low fire frequencies. Tree-ring data may be augmented over time as additional individuals become available, or with cross-sections from other individuals (e.g., other oak species) within the savanna mix.

Recommendations for Dendrochronological Assessments of Fire History in Black Oak Savanna

Tree-ring based fire history reconstruction is a challenge in oak savanna communities by virtue of their sparse cover and fires that are low intensity and often do not leave scars. Only 12% of white oak samples were scarred in fires (McEwan et al. 2007), and white oak has thinner bark and is more susceptible to fire damage than the black oak available for use in the current study (Henderson 1983). Since bark protection increases as oaks age (McBride 1983), a sampling strategy would ideally include individuals across a wide age range, with young specimens that scar more easily, present throughout the measurement period. However, as is probably the case in most oak savanna with long fire histories, the oak population in this study was a relatively even-aged, older cohort. Further, the central stem of older trees is critical to fire reconstruction as it houses the oldest portion of the record and the youngest growth rings that would have been most likely to scar and record an event. This portion is vulnerable to decay in many modern oak populations, including in our study area. Thus, the oldest, most valuable ring records are often lost. Finally, complete cross-sections are the most reliable and accurate sampling method for reconstructing fire histories (Wolf 2004), but this approach relies on availability of dead or downed individuals to avoid destructive sampling, which may be more problematic where tree population densities are already sparse.

To compensate for these common limitations in fire-suppressed North American oak savannas, particularly those that are black oak dominated, we recommend using the following four lines of evidence to supplement dendrochronological methods of fire reconstruction:

1. Young black oak trees, unlike the often-used conifers in fire reconstruction, will resprout if the main leader is killed (e.g., Henderson 1983). This provides evidence of a disturbance such as fire when the stems sprouted. Thus, if a multistem pith dates to a year when fire scars occurred among other, established, trees, or if the establishment date is repeated across multistemmed individuals, or marks a regeneration pulse within the local stand, it lends corroborat-

ing evidence (Henderson 1983).

2. Multistemmed individuals are more susceptible to fire than single-stemmed saplings because leaves and other litter get trapped, increasing fire intensity (Henderson 1983), and may, themselves, be targeted for tree-ring analysis if they become available for cross-sectioning.

3. The density of black oak stems generally increases after fire (Ikauniece et al. 2012), with establishment occurring within 2–3 years of a burn (Etwell 2004). Thus, tree-age reconstruction to establish cohort years that coincide with other fire indicators is a good way to evaluate the spatial distribution and extent of historical fire events.

4. Additional fire history records, such as those obtained from soil charcoal analysis, can be combined with dendrochronological information. Soil charcoal has been used to augment the fire history record in woodlands lacking *Pinus* or other easily scarred species (Hart et al. 2008). While soil charcoal may have less fine-scale temporal resolution than dendrochronological records, it provides excellent spatial fire evidence and will extend the fire record further back in time.

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Theresa Dinh holds a B.Sc. in Environmental Science from York University and is currently a M.Sc. student in Physical Geography at the tree-ring (CEDaR) lab at the University of Guelph, ON. Her interests and training are in biogeography, wildfire ecology, and dendrochronological methods. She was an undergraduate researcher at the time of this study.

Nina Hewitt is a biogeographer and earned her Ph.D. from York University in 1999. She teaches courses on vegetation, soil science, and biogeography in the Geography departments of York University and the University of Toronto. Her research examines processes of colonization, invasion, and stand dynamics in forests and savanna of Ontario, the Midwest, and the Karakoram-Himalaya.

Taly D. Drezner is an Associate Professor at York University (Toronto), and earned her Ph.D. from Arizona State University in 2001. She works on a protected keystone cactus, including developing an age-height model to estimate age, which she uses to reconstruct its demographics and the factors that affect its regeneration over time and space. She has also done work on disturbance and succession in both rural areas and in urban green spaces.

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