Anthropogenic fire history and red oak forests in south-central Ontario

by Daniel C. Dey[1] and Richard P. Guyette[2]

The regeneration and dominance of northern red oak (*Quercus rubra* L.) has been associated with fire throughout eastern North America. Red oak in central Ontario grows near the northern edge of its distribution in mixed hardwood-coniferous forests under mesic conditions where it competes with more shade-tolerant species. We hypothesized that the abundance of red oak in these stands was largely the result of anthropogenic burning and natural fires, which would favor the regeneration and recruitment of northern red oak over such shade-tolerant species as sugar maple (*Acer saccharum* Marsh.). Fire histories dating from the mid-1600s were constructed by dendrochronological methods from fire scars on stumps, trees, and natural remnants of red pine (*Pinus resinosa* Ait.), white pine (*Pinus strobus* L.), and red oak at six sites in south-central Ontario. Fire histories of the sites are characterized by abrupt changes in fire interval. As much or more variance in fire interval is found within sites as is found among sites. Differences in the mean fire interval among sites are related to the density and migration of historic aboriginal and European populations. The mean fire interval varied from more than 70 years to six years depending on site location and historic period. The occurrence and abundance of red oak is linked to anthropogenic fire regimes.

Key words: northern red oak, white pine, fire history, ecology, anthropogenic, fire regime, dendrochronology

La régénération et la dominance du chêne rouge (*Quercus rubra* L.) ont été associées au feu dans tout l'est de l'Amérique du Nord. Le chêne rouge du centre de l'Ontario croît à proximité de la limite nordique de sa distribution dans des forêts mixtes de feuillus et de conifères sous des conditions mésiques où il entre en compétition avec des espèces plus ombrophiles. Nous avons poser l'hypothèse que l'abondance du chêne rouge dans ces peuplements était en grande partie le résultat de feux de forêt anthropogéniques et naturels, qui favoriseraient la régénération et la croissance du chêne rouge nordique par rapport aux espèces ombrophiles comme l'érable à sucre (*Acer saccharum* Marsh.). L'historique des feux datant du milieu du XVIIe siècle a été établi par des méthodes dendrochronologiques à partir des brûlures sur les souches, les arbres et sur les rémanents naturels de pin rouge (*Pinus resinosa* Ait.), de pin blanc (*Pinus strobus* L.) et de chêne rouge dans six stations du centre-sud de l'Ontario. L'historique des feux sur ces stations est caractérisé par d'abruptes changement dans les intervalles entre le feux. Une variance semblable et encore plus prononcée dans l'intervalle entre les feux est retrouvé tant dans les stations qu'entre elles. Les différences dans l'intervalle moyen entre deux feux entre les sites sont reliées à la densité des populations historiques et des migrations d'Autochtones et d'Européens. L'intervalle moyen entre deux feux variait de plus de 70 ans à six ans selon la localisation de la station et de la période historique. La présence et l'abondance du chêne rouge est lié aux régimes de feux anthropogéniques.

Mots-clés: chêne rouge nordique, pin blanc, historique des feux, écologie, anthropogénique, régime des feux, dendrochronologie

Introduction

Aboriginal peoples in North America purposefully manipulated their environment to favour those plants and animals they needed for food, shelter, clothing, and the other necessities of life (Williams 1989, Kay 1995). The main management tool they used to alter the vegetation was fire (Pyne 1982, Williams 1989, Davies 1994, Kay 1995, Anderson 1996, Cowdrey 1996, Olson 1996, Barden 1997). While the pre-European landscape of eastern North America has been portrayed as one dominated by primeval forest shaped by and in balance with the forces of nature, in actuality it was a "natural" artifact, shaped by the interactions of humans and nature over thousands of years. The burning of large portions of North America over the millennia affected the distribution of plant species, the extent of grasslands and the character of forests. That it was a land "untouched" by humans is an idea now challenged by the concepts that ecosystems are constantly in a state of flux, or non-equilibrium, and that humans are an important disturbance agent in the natural system (Williams 1989, Botkin 1990, Anderson 1996).

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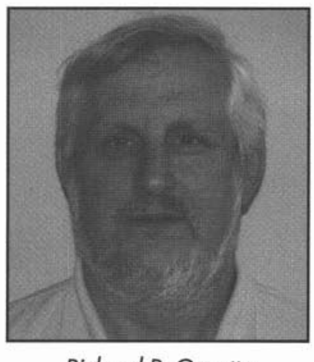

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Aborigines burned areas of one to over 1000 ha to clear them for the growing of maize and other agricultural crops (Black Hawk 1833, Williams 1989). In south-central Ontario, the Hurons and other tribes developed an agricultural based economy on a large scale. They produced a surplus of corn, which was used in trade with the Nipissings, Cree and other tribes (Trigger 1994, Trigger and Day 1994).

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Table 1. Site names and characteristics. (Mr = red maple, Pw = white pine, Mh = sugar maple, By = yellow birch, Pr = red pine, Bw = white birch, At = aspen).

Site name	Location	Oak abundance (%)	Other overstory dominants	Site type
Bracebridge	45°48′ N 77°47′ W	45	Mr, Pw, Mh	Aboriginal and European settlement
Jocko River	46°36′ N 79°13′ W	10	Mh, By	Major travel corridor
Papineau Lake	45°21′ N 77°48′ W	39	Mh	European settlement
Seguin Falls	45°24′ N 77°46′ W	10	Pw, Mh	Minor travel corridor
Basin Lake	45°75′ N 77°46′ W	45	Mh, Pr, Pw	Algonkin hunting and gathering
Opeongo Lookout	45°37′ N 78°20′ W	0	Pr, Pw, Bw, At	Aboriginal and minor travel corridor

Throughout North America, the extent and abundance of the tall grass prairies, oak and pine savannas, barrens, and other such ecosystems so often noted by early European immigrants were largely the result of aboriginal burning practices (Williams 1989, Pyne 1982, Whitney 1993, Barden 1997). Periodic fires of low to moderate intensity were ignited in the spring or fall to promote the production of grasses and forbs that provided habitat and forage for large game and fowl (Williams 1989, Davies 1994, Kay 1995, Anderson 1996, Olson 1996, Barden 1997).

Woodlands were burned to increase the production of browse for wild game, and the yield of berries, fruits and nuts that not only provided a substantial part of the aboriginal diet, but also provided food for deer, bear, turkey and other wild game. In the northeastern U.S., aborigines used fire to culture nut trees such as oaks, hickories and chestnuts (Davies 1994). California aborigines practised a form of horticulture by using fire to create and maintain oak savannas for the production of acorns (Martin 1996). Wherever oaks grew in North America, acorns were a part of the aboriginal diet (Black 1980, Walker 1991, Martin 1996).

During the initial period of European settlement, pioneers adopted aboriginal fire practices (Pyne 1982, Whitney 1993, Martin 1996). Their objectives in burning were very similar to those of the aborigines. Fire was instrumental in clearing the forest for agricultural development. Woodlands were burned to improve grazing conditions for livestock that were raised on open range. Forests were also burned to enhance berry and nut production, to increase browse for wild game, to facilitate hunting, and to control insects, disease and other vermin.

Fires burned over millions of hectares in the Lake States and south-central Ontario around the turn of the century, fuelled by the slash left by the pine loggers (MacKay 1978, Pyne 1982, Whitney 1993). Howe and White (1913) recorded how Europeans affected the forests in south-central Ontario during the settlement period. Logging, agricultural development and frequent fires (every five years) that burned over the land drastically altered the character and extent of the forests. Beginning in the 1920s, suppression of wildfires in Ontario has established a new disturbance regime that is promoting the replacement of oak-pine forests with more shade-tolerant species. The history of fire in south-central Ontario is intricately linked with human populations and the history of land use.

Anthropogenic fire, both Native and European, has shaped the nature of our modern day forests, specifically the present day abundance of oak forests throughout North America (Abrams 1992, Johnson 1993, Whitney 1993, Anderson 1996, Martin 1996). Knowledge of the characteristics of wildland fire regimes and their effects on forest vegetation is a prerequisite for understanding the present abundance of red oak in south-central Ontario. The objectives of this study are to examine fire histories, and to relate changes in fire disturbances to anthropogenic factors and the presence of red oak (*Quercus rubra* L.).

Methods

Site Locations and Characteristics

Over much of the range of red oak in south-central Ontario, partially decayed white pine (*Pinus strobus* L.) and red pine (*Pinus resinosa* Ait.) stumps and natural remnants remain from the earliest pine logging operations. Pine stumps, remnants and live red oaks were used to construct fire histories for six study sites. District foresters of the Ontario Ministry of Natural Resources were queried as to the locations of red oak stands with old pine stumps and remnants. The presence of preserved pine remnants in the stand was necessary for dendrochronological analysis of fire scars. Study site locations and stand information are given in Table 1. The study sites ranged in size from 50 ha to 100 ha. Sites ranged in elevation from 274 m to 502 m. Sites varied in topographic roughness from level to gently sloping to steep with frequent changes in aspect. Fuels were mainly leaf litter from hardwoods and softwoods. The Bracebridge and Jocko River sites were completely forested whereas the Seguin Falls, Papineau Lake, Opeongo Lookout, and Basin Lake had small patches of open woodlands without complete canopy cover. All of the sites had mature red oak in the overstorey with the exception of the site at Opeongo Lookout. The Opeongo site was included because it bordered an extensive hardwood ridgetop, and because it had an abundance of old fire-scarred red pines that pre-dated European settlement in this area.

Sample Collection

Cross-sections of red pine natural remnants and stumps were cut with a chain saw. In the case of white pine, the sound wood of the stumps was dug out from under decayed wood and organic debris to ground level. White pine stumps were preserved by anaerobic conditions, the resin content of wood, water saturation, low soil pH, and low soil temperature. Cross-sections of white pine remnants were cut with a chain saw (Stihl 66 with a 76.2 cm bar) between ground level and 20 cm. Felling wedges were used to prevent the weight of the stump from pinching the saw bar and chain. The remnants were selected for sampling by their soundness, degree of entirety, and the presence or possibility of fire scars.

Fire Scars

All pine remnants sampled had charcoal associated with the remnant in the soil and organic debris. Charcoal was present on all of the red pine samples but was only rarely found on the white pine cross-sections. Charred woody remains of the stumps were often found mixed in the organic debris around the white pine stumps. Fire scars are defined as the death of a cambial section occurring near ground level on the tree bole.They were identified by callus tissue, local cambial growth disruption and traumatic resin canals, and sometimes were associated with an overall growth response. Many injuries were not counted as fire scars. Scars with evidence of mechanical damage (wood indentations, etc.) or small point injuries were noted but not as fire scars. Injuries that may have been fire scars were not included if callus tissue was not present. Fire scars ranged from large open injuries to smaller injuries at ground level on buttress sides and ends. The anatomical details of fire scar formation in white pine were verified using cross-sections cut from live trees at ground level in stands with recent and known histories of prescribed burning at both the Petawawa Research Forest and near North Bay, Ontario (Guyette *et al.* 1995). Cross-sections were cut from a site suspected of having few fires along the Opeongo River in Algonquin Park, Ontario as a control for fire scar verification, stump condition, and age. Records for that Opeongo site indicated that logging took place along the river in the 1860s.

Cross-dating

The detailed observations of annual rings necessary for cross-dating required that cross-sections be surfaced to reveal the structure of the rings. Cross-sections were surfaced with an electric hand planer with a sharp carbide blade. Where rings were narrow or indistinct, the ring structure and cellular detail were revealed by sanding (220 to 600 grit) the sample.

Visual cross-dating was used to identify years (signature years) in which climate limited the growth of all trees (Stokes and Smiley 1968, Guyette and Cutter 1991). Ring-width plots with anatomical notes on ring structure (e.g., false rings and latewood characteristics) were used for visual cross-dating and comparison. Computer programs (Holmes *et al.* 1986, Grissno-Mayer 1996) were used to insure the accuracy of relative dating among the samples, absolute dating of the samples, and to graph fire scars. From one to three ring-width series from each sample were measured either from pie-wedges of the cross-section or from traced acetate overlays of ring-width radii. The traced acetate overlays were necessary because the diameters (0.75 to 1.4 m) of the cross-sections were much too large for the measuring equipment, and intact cross-sections were needed for fire scar analysis. The radius of measurement was taken from the most undisturbed ring-width series on the cross-section in order to maximize climate related ring-width variation. The normally wide rings (some more than a centimetre) of the white pine cross-sections permitted the use of the acetate overlay technique with very little loss of accuracy.

A floating chronology (undated in absolute time) was established from all samples at each site. The mean between tree correlation of ring widths was 0.48. Absolute dating of the pine remnants was accomplished by ring-width comparisons with a white pine ring-width chronology from Dividing Lake, Algonquin Provincial Park (Guyette and Dey 1995a), and another white pine chronology from Hobbs Lake, Hobbs Township, North Bay District (Guyette 1996). Both of these chronologies overlapped all of the sample ring-width series from the study sites by at least 100 years.

Population Estimates

We calculated average human population density at the study sites for the period of the fire scar record from estimates and trends of 17th and early 19th centuries populations in central Ontario (Heidenreich 1971, Gentilcore 1987, Harris 1987, Thornton 1987, Hessel 1993). These population estimates were averaged for comparison with the fire scar record from 1650 to 1850. The 20th century Papineau Lake fire-scar chronology was compared with late 19th and early 20th century records (Gentilcore 1987) of Euro-Canadian populations. Population density for each site was calculated by summing density estimates of Nipissing, Huron, Temiscimi, Algonkin, and Northern Algonkin groups in central Ontario. The density of each group at each site was calculated by dividing their population by the area of a circle whose radius was the distance between the population centre and a study site. This method provides a relative estimate or index of population density among the study sites because it does not account for the great variation in population density within an area or the actual territory of the population. These population density estimates are, however, close to the range of population densities (0.07 to six humans per km^2) given for the Great Lakes region and eastern North America (Kroeber 1934, Dobyns 1983, Ramenofsky 1987, Thornton 1987). The relative pattern of population densities calculated in this paper are similar to present day demographics because of the dependence of agriculture and commerce on factors such as climate, soil fertility, and topography.

Results and Discussion

Fire Interval

Fire intervals, the number of years between two successive fires in a given area (Agee 1993), at the study sites (Table 2) were more variable but within the range of fire intervals found by others in oak forests in Ohio (Sutherland 1997), Missouri (Guyette and McGinnes 1982, Guyette and Cutter 1991, Cutter and Guyette 1994, Guyette and Cutter 1997), and Arkansas (Jenkins *et al.* 1997). Cwynar (1977) found evidence for 16 fires between 1696 and 1920 in Barron Township (18 600 ha in Algonquin Park). He calculated a mean fire interval of about 70 years. The mean fire interval is the arithmetic

Table 2. Fire intervals at various sites in south-central Ontario. The mean fire interval and range of individual fire intervals are given in years. The sum of the number of annual rings in all cross-sections for a period is the "years of record." (* = the site mean fire interval).

Site	Period	Mean fire interval	Range in individual fire free intervals	Years of record	Number of fire scars
Bracebridge	1852–1811	>42		260	1
	1810–1741	5		873	19
	1740–1664	>76		583	1
	1850–1700*	10	2 to 39		
Papineau Lake	1840–1643*	29	10 to 60	2535	15
Papineau Lake 2	1994–1875*	6	2 to 18	2432	17
Seguin Falls	1861–1780	>70		582	1
	1779–1656	15 (3–17)		1281	13
	1850–1650*	21	3 to 70		
Basin Lake	1856–1781	>44		730	1
	1780–1733	12		1212	25
	1732–1665	>20		1218	2
	1840–1670*	21	5 to 44		
Jocko River	1920–1721*	12	5 to 29	3584	24
Opeongo Lookout	1940–1780	17		1520	33
	1779–1636	>117		1324	1
	1850–1660*	27	10 to 45		

average of all fire intervals in a given area over a given time period (Agee 1993). In this study, the mean fire interval is about 69 years for historic periods (Table 2) of less frequent fire averaged across the sites, which is consistent with Cwynar's estimate. However, many of our site-mean fire intervals for other periods of the chronology (1636 to 1994) are much shorter than 70 years. Cwynar's mean fire interval may be higher because he selected trees along lake shores (i.e., fire breaks), and he sampled little of the upland areas in Barron Township. Thus, the 70-year mean fire interval may be an underestimate of the actual occurrence of fire in this region. Differences may also be attributable to variations in demographics and thus anthropogenic ignitions between the study sites. Loope (1991) estimated a mean fire interval of 21.8 years in a mixed white pine-hardwood forest in Michigan before the late 19th century. This estimate is very close to the overall mean fire interval (20 years) for the period before 1850 among the sites in this study. A study of a single tree near Sault Ste. Marie, Ontario (Alexander *et al.* 1979) yielded a mean fire interval of about 29 years.

Natural Versus Anthropogenic Fire

Natural fires generally refer to those that result from ignition sources other than human. Lightning is the primary ignition source of natural fires. Based on weather and fire records from the past century, lightning causes six to 10 fires per 400 000 ha annually in a zone extending from about Parry Sound, Ontario northeast into Quebec (Schroeder and Buck 1970). In this same area, fire managers with the Ontario Ministry of Natural Resources have observed that lightning has ignited five fires per 400 000 ha per year in Algonquin Provincial Park, Ontario during the past 60 years (Strickland 1990). In the last 30 years, the upper limit of lightning fires in pine forests in the upper Great Lakes region has varied from two to eight fires per year per 400 000 ha (Loope and Anderton 1998). In contrast, lightning started less than one fire per 400 000 ha every year in southern Ontario south of a line drawn between Midland and Belleville. Elsewhere in south-central Ontario, lightning causes from one to five fires per 400 000 ha per year.

If we assume that the mean fire intervals observed at our study sites, which were each about 1 km^2 in area, were representative of the surrounding country, then about 58 wildfires per year burned in an area of 400 000 ha during periods of relatively low fire activity over the past 300 years. This was calculated using an overall mean fire interval of 69 years. During periods of higher fire activity in the study area (i.e., when the mean fire interval was 20 years), as many as 200 fires per year may have burned throughout a 400 000 ha area. These levels of fire occurrence are substantially greater than the rate of natural fires caused by lightning. The difference in our estimates of wildfires and the observed number of lightning fires in the study area is probably due to anthropogenic ignitions, unless the level of lightning activity has changed that much over the past 300 years, and we have no reason to believe that is has. Loope and Anderton (1998) observed that 100 fires per year per 400 000 ha burned in coastal pine forests of the Great Lakes in northern Michigan and Wisconsin during the period 1750 to 1910. They attributed this significant increase in the rate of wildfire above the background level due to lightning to burning by Native Americans. The widespread use of fire by Native Americans and early European settlers is well documented (refer to introduction). In the absence of humans, natural fire would have shaped the development of vegetation in the study area and provided opportunities for red oak to persist. However, the current abundance of oak and other genera such as the *Pinus* in south-central Ontario would not exist if it were not for anthropogenic fire.

Lighting is responsible for about 35% of the annual fires in Ontario, whereas humans have caused 60% or more of the fires over the past 30 years based on Canadian fire statistics compiled by the Petawawa National Forestry Institute (Ramsey and Higgins 1991, Higgins and Ramsey 1992). The percentage of human-caused fires in south-central Ontario is probably higher than reported provincially because the incidence of lightning and severity of fire climate decreases from west to east in Ontario, lightning generally occurs with precipitation during the summer months, vegetation has high moisture content during most summers, and the density of human population is greater than in the boreal region (Heinselman 1981). In more densely populated regions of eastern North America, humans are responsible for most of the fires in modern times (Westin 1992, Garner 1999). In Arkansas and Missouri, lightning caused < 2% of all fires during the last 30 years.

Regional Population Density and Fire

Historical aboriginal population densities are an important factor influencing the frequency of ignitions and wildland fires (Guyette and Cutter 1997). For example, the occupation of southern Ontario (Crawford Lake area) by the Iroquois from 1360 to 1650 caused substantial increases in fire as evidenced in the amount of charcoal in lake sediments (Clark and Robinson 1993, Clark and Royall 1995). They used fire to develop their corn-based agricultural economy and in the process caused the decline of beech and sugar maple forests and promoted the dominance of oak and pine. Population densities in south-central Ontario varied greatly over the past 400 years. Decreases in the mean fire intervals of the seven study sites were inversely related to average population densities for the period 1650 to 1850. This relationship is described by the equation and graph in Fig. 2. A log transformation of the population density estimates enables the use of a linear regression to describe the non-linear relationship between the site-specific mean fire intervals and population density. The non-linear relationship between population and the mean fire interval in time series data has been found in a previous study (Guyette and Dey 1997).

Regional Temporal Interpretations

Unfortunately, the spatial and temporal influence of humans at each of the study sites is difficult to quantify. General anthropological principles and historical details regarding the activities of humans near the study sites can be used to interpret temporal variations. Some important processes affecting human populations and subsequent fire regimes were disease, migration, resource exploitation, and conflict. Here, we relate temporal trends in fire history to population at the regional, and when possible, at the site level.

Regionally, the de-population of aboriginal peoples caused by European-borne diseases may have reduced anthropogenic ignitions and increased the length of fire intervals in the early part (before 1730) of the fire scar record (Fig. 2). The effects of disease on early Aboriginal populations is well documented (Dobyns 1983, Ramenofsky 1987). Heidenreich (1971) described an abrupt decline of the major population concentration in south-central Ontario, that of the Hurons, in the mid-1600s.

Another factor related to the shift in fire interval in the mid-1700s is the increase in the number of French fur traders travelling by canoe through the study region in the spring, fall, and summer. The number of traders under contract leaving Montreal with legal permits increased from less than 40 before 1715 to more than more than 400 in the early 1740s (Harris 1987). Francis *et al.* (1992) estimated that the number of actual traders was five to six times that of those with legal permits. Thus, by the 1740s there may have been as many as several thousand traders moving into and through the study region. The trade in beaver brought anthropogenic ignitions into more isolated areas that were visited less often by humans in the past.

Historic Populations and Site Level Interpretations

Bracebridge

The mean fire interval for the entire chronology averaged 15 years at this site but varied by historic period from more than 76 years (1664–1740) to as few as five years (1741–1810). This change in fire intervals illustrates the great temporal variability in anthropogenic fire regimes. The abrupt decrease in the length of fire intervals in the 1740s is attributed to increases in human population near the study site, which is located on the north branch of the Muskoka River, a major travel route (Guyette *et al.* 1995). Aboriginal occupation within a few kilometres of the site has been documented (Murray 1963). The abundance of red oak in this forest and the documented use of acorns by Algonkin groups (Black 1980) may have contributed to visitation and ignitions at the site. The Bracebridge site was the closest of the sites to the fertile soils and large populations of southern Ontario. Upwards of 40 000 Hurons and Iroquois lived within 200 km of this site at the time of European contact (Harris 1987, Thornton 1987). Huronia, with a population of over 20 000 Hurons, was about 120 km southwest of the Bracebridge site (Heidenreich 1971). Disease and Iroquois conquest reduced and scattered this Huron population in the mid-1600s (Trigger 1994).

Seguin Falls

The Seguin River may have been a travel corridor that would have contributed to the frequency of anthropogenic ignitions around the study site (Dey and Guyette 1996a). A large population of Iroquois and Huron occupied an area 100 to 250 km south of the Seguin River (Harris 1987). Northern Algonkin groups lived in villages along Georgian Bay near the present day Parry Sound area, just 30 km from Seguin Falls. The period of most frequent burning at the Seguin Falls site, which begins in 1741, parallels that at the Bracebridge site 50 km to the southeast. Fires occurred at both sites in 1741, 1744, and 1761. Topography may have influenced the frequency of fires near Seguin Falls. Although the site is somewhat insulated from the spread of fire by the several small lakes less than 3 km to the west and northeast of the site, there are large areas of nearly level land to the north and south. Fires could spread rapidly through the fine fuels of these level areas.

Jocko River

Many of the fires at the Jocko site between 1721 and 1937 are hypothesized to have resulted from anthropogenic ignitions associated with travel corridors and local aboriginal populations (Dey and Guyette 1996b). Perhaps most important, the Jocko site is near the confluence of two major travel routes, the Ottawa and Mattawa Rivers, that served as passageways for aboriginal commerce and provided access to the western interior during the fur trade era. Both French and indigenous peoples travelled to and from Montreal by river. Fire could have easily spread to the Jocko site from the Ottawa, Jocko, and Mattawa Rivers or from the vicinity of Lake Nipissing. As an illustration, in 1922, a fire burned just north and east of the Jocko site (< 3 km away) a distance of 20 to 25 km to the Ottawa River (Donnelly and Harrington 1978). Because the Jocko River site is adjacent to travel routes, the changes in human population density and anthropogenic ignitions may have been more stable than at sites near transient villages and hunting camps.

The Jocko River site is within travel corridors used by the Huron, Nipissing, Cree, Kipawa, Iroquois, French, and English for trade, seasonal hunting, and warfare for hundreds of years (Harris 1987). A population of Kipawa lived about 30 km to the northeast of the Jocko site. These people practised some agricultural burning as well as burning to promote the growth and fruiting of blueberries (Moore 1982). In 1755, 120 packs of fur were shipped from near Lake Temiscaming, about 50 km northeast of the Jocko site. About 500 to 1000 Nipissing people lived 50 km to the southeast of the Jocko site at the time of European contact. Although non-agricultural (Harris 1987), they were highly mobile. The Nipissing crossed the Jocko River when traveling between Lake Nipissing and Lake Temiscaming where they traded at the French fort.

Basin Lake

The upland location of the Basin Lake site, along the northeast side of the Bonnechere River, increased its exposure to anthropogenic ignitions. Algonkins lived, hunted, and fished along the Bonnechere River for hundreds of years (Hessel 1993). The frequency of anthropogenic ignitions probably changed with the plagues of war and disease. The Iroquois Wars resulted in the genocide of many Algonkin tribes and families. As a result, Algonkin peoples fled into remote locations, perhaps through or into areas near the study site. Introduced diseases decimated the Algonkins during the 1600s and this may have caused a reduction in anthropogenic fires and may account for much of the variability in the fire scar record at this site (Guyette and Dey 1995b).

Opeongo Lookout

The fire scar chronology from Opeongo Lookout (Guyette and Dey 1995c) perhaps best illustrates how the fire interval can change abruptly with the introduction of anthropogenic fire. Fire intervals decreased by more than an order of magnitude beginning in 1780 as Aboriginal peoples were pushed into more remote areas by Euro-American settlers. This site lies close to the Opeongo Road in Algonquin Park where fires have been suppressed since the 1930s.

Papineau Lake

Topographic and cultural factors most likely affected the length of fire intervals near Papineau Lake during the 17th and 18th centuries (Dey and Guyette 1996c). The close proximity of surrounding lakes and the steep, hilly topography of the area may have limited the spread of fire to the site and thus increased the length of fire intervals by reducing fire size and spread rate. The study site is 1 km northeast of Papineau Lake, 7 km southwest of Kamaniskeg Lake, and 8 km south of Bark Lake. The average slope surrounding the study site is 9 degrees. The study site was isolated from known 17th and 18th century travel routes and villages (Harris 1987) that might have contributed to an anthropogenic fire regime.

Papineau Lake 2

Fire intervals decreased in length during the late 19th and early 20th centuries, at a site bordering the Papineau Lake site mentioned above, to a mean fire interval of six years (Guyette and Dey 1995d). This decrease in fire interval was coincident with limited agricultural development and settlement in the area. Increases in fire disturbances may have favoured the regeneration of red oak and its present dominance in this mixed hardwood forest. The 19th century logging of all white pine at the site followed by frequent fires may have contributed to the drastic reduction in white pine at the present day study site. Before European settlement, white pine regeneration, as indicated by germination dates (circa 1640), occurred in this mixed hardwood-coniferous forest in response to a stand replacement event such as severe fire or windthrow.

Oak Regeneration and Fire

Periods of short fire intervals observed in most of these fire histories are hypothesized to have advanced the regeneration and dominance of red oak over sugar maple and contributed to the presence of red oak within these forests, especially on the more mesic sites. Red oak is intermediate in its ability to tolerate shade, and it is unable to replace itself in the overstorey by development of regeneration in understoreys characterized by low light levels (Crow 1992, Dey and Parker 1996). The environment in the open park-like, pre-European forests provided enough light at the forest floor for the growth of red oak seedlings. Frequent fires maintained the open nature of these forests by inhibiting the more shade-tolerant species such as sugar maple, beech and ironwood, and the more intolerant species such as aspen and white birch. Oaks are better adapted to surviving surface fires than their competitors because of (1) the abundance of dormant buds about the root collar, which is often buried in moist mineral soil, insulated from the heat of surface fires, (2) their ability to sprout prolifically following death of the shoot by drought, grazing or fire, and (3) their ability to develop thick bark that protects the cambium from fire.

Oak seedlings exhibit slow shoot growth during the early years following germination. It is at this stage that they are most susceptible to suppression by larger reproduction of shade-tolerant species (e.g., sugar maple) or faster growing intolerant species (e.g., white birch). Oak seedling sprouts that survive repeated fires are able to develop a large root system and the carbohydrate reserves needed for accelerated shoot growth. Under a disturbance regime with fire intervals from five to 10 years, oaks remain in a "grub" or seedling-sprout stage, continuing to accumulate root biomass. Early explorers have described oak barrens and scrub oak-pine forests throughout North America where fires occurred frequently (Whitney 1993). In these forests, oaks were kept in the grub stage by fire. Given a sufficiently long fire interval, larger oak grubs, or seedling sprouts, are capable of growing rapidly enough to have a good chance of surviving another fire, and then of growing into the overstorey.

Over the past 300 years, the length of the fire interval was highly variable at almost all of our study sites (Table 2, Fig. 1). Periods of short fire intervals would have favoured oak regeneration by controlling competition and allowing oak seedling sprouts to develop. During longer fire intervals, which we observed may have been as long as 40 to 70 years since the mid-1600s, the oaks would have been able to grow into the over-

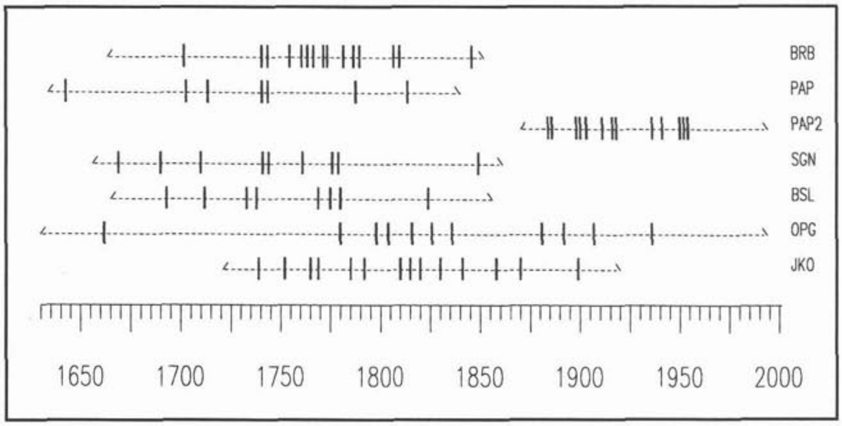

Fig. 1. Fire years and period of record at the study sites. Trends in the number of fires is given by the composite index given at the bottom of the figure. Sites and site codes for the study areas are Bracebridge (BRB), Papineau Lake early (PAP), Papineau Lake modern (PAP2), Seguin Falls (SGN), Basin Lake (BSL), Opeongo (OPG), and Jocko River (JKO).

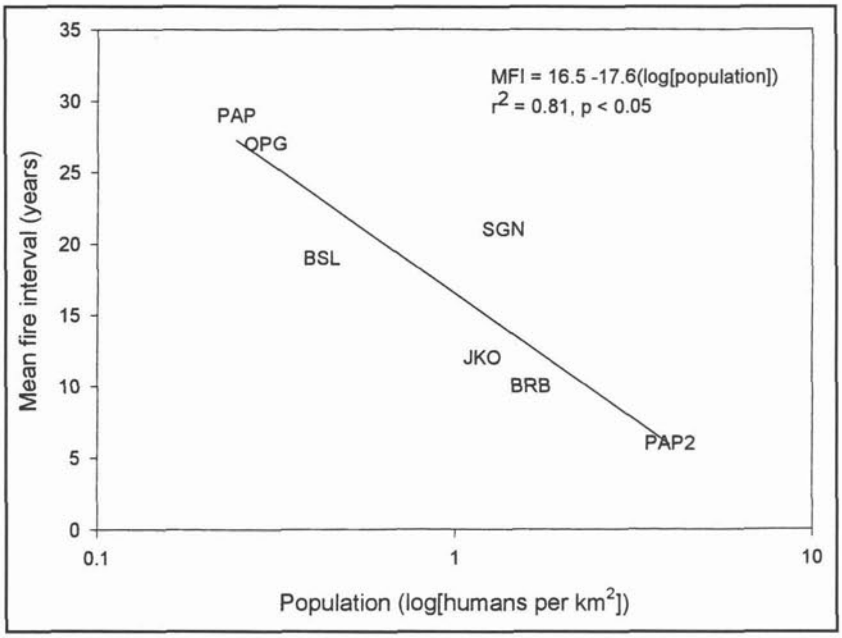

Fig. 2. Scatter plot illustrating the relationship between mean fire interval and reconstructed population density. Site codes (see Fig. 1) are used to plot the various study sites. The regression line is plotted for the regression equation given. Population density is plotted as the base 10 log.

storey. These cycles of short and long fire intervals may have contributed to the development of multi-aged oak forests in Ontario (Guyette and Dey 1995d). Analyses of pith dates of overstorey oaks indicates that there are pulses of regeneration that account for many of the codominant and dominant oaks. A small number of seedlings survive to grow into the overstorey between the major regeneration events, thus creating a multi-aged stand of oaks. The age structure of oaks is probably also affected by the occurrence of more extensive, higher intensity fires that coincide with years of severe regional drought (Cwynar 1977).

Frequent disturbances, first by aboriginal and then by European-set fires, and later by European logging and settlement, favoured the regeneration of red oak in south-central Ontario. Europeans increased the occurrence and extent of fire and other human disturbances at the turn of the 20th century (Guyette and Dey 1995d). Then, fire was suddenly and effectively eliminated as a significant disturbance factor with the adoption of fire suppression programs by the provincial government and industry. For the past 40 to 70 years, forests have been protected from fire in south-central Ontario (Lynham 1985). Initially, in the absence of fire, oaks were able to gain dominance in the overstorey, especially on upland sites. But with the continued suppression of fire, new disturbance regimes are transforming the forests by gap dynamics processes that favour shade-tolerant species over the oaks (Runkle 1985, Crow 1988, Pallardy *et al.* 1988, Lorimer 1993). Now, managers are increasingly interested in restoring the historical and ecological role of fire through prescribed burning to ensure oak regeneration because traditional forest management practices have failed to stop the loss of oak throughout North America (Nyland *et al.* 1982, Van Lear and Waldrop 1988, Lorimer 1993, Schlesinger *et al.* 1993, Lorimer *et al.* 1994, Schuler and Miller 1995, Brose and Van Lear 1997).

Conclusions

1. Fire intervals varied greatly among the study sites and through time at a given site. Mean fire intervals ranged from six to 29 years among sites and from five years to more than 76 years between historic periods at some sites.
2. Fire intervals at the sites were positively related to regional human population density, indicating that the fires were largely of anthropogenic origin.
3. Abrupt changes in fire interval were common during the period of early Euro-aboriginal contact. Changes in anthropogenic ignition frequency and fire resulted from population shifts and migrations caused by subsistence economics,

diseases introduced by Europeans, and conflict among aboriginal and European groups.

4. The regeneration of oak forests was facilitated by periods of frequent fire followed by periods with few fires.

5. Oak forests flourished under anthropogenic disturbance regimes dominated by fire.

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