Spatiotemporal Complexity of Fire in an Island-Lake Landscape, Border Lakes Region, Minnesota, USA

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Dedication

For Pheebs

Abstract

My dissertation focuses on the strength of synchrony (coincident events in space and time) in the history of fire occurrence as a function of various casual agents between points of interest in the Border Lakes region of northern Minnesota. I specifically investigate how spatial and temporal patterns of fire arise from mechanisms such as climate, landscape characteristics, and human land use. My research is aimed at identifying the mechanisms responsible for variations in fire occurrence, such as those that lead to large (synchronous) fire events versus small (asynchronous) fire events.

My research incorporates various methodological approaches to address research questions including spatial analysis using GIS, R, and statistical testing. Data used in this research was developed from 541 fire-scarred red pine (*Pinus resinosa*) trees collected from the Boundary Waters Canoe Area Wilderness and Voyageurs National Park (1489–2016). Trees were grouped into 14 regions using complete linkage clustering and similarity matrices were used to test the relationship in shared fire events between regions and distance. From this, the degree of similarity, or fire synchrony, between regions in the Border Lakes region was determined.

The relationship between fire synchrony and asynchrony across regions was then tested in relationship to driving mechanisms including, climate, site elevation, slope, aspect, and spatial isolation. The strength of the relationships was then tested using several measures of spatial and temporal variability including chi-squared analysis and principal component analysis.

Finally, the Border Lakes region is naturally fragmented by lakes and streams producing a setting to evaluate island biogeographic tenets relation to fire disturbance. To address how area and isolation influences fire activity I investigated the past fire regime on 65 islands and 59 mainland sites between 1489 and 2016. The similarity between fire occurrence on mainland sites and island sites was also tested to help understand fire spread and locations of high versus low fire activity.

I have been able to demonstrate that climate, specifically periods of extended drought, are responsible for larger, synchronous fire events while smaller, asynchronous fire events were not related to the variability landscape characteristics and may be related to human land use. In addition, fires were frequent on both islands and mainland sites and the fire event dates between these sites are similar across the landscape. Significant temporal variability in fire events occurred on islands and mainland sites between 1780 and the late 1800s, with fire events accumulating more on islands prior to 1830 and mainland sites accumulating more fire events after 1860. I speculate that fires in the Border Lakes region accumulated more rapidly on islands between 1780 and 1830 due to intense use of the landscape by humans, corresponding to the fur trade era.

This result has significant weight regarding management considerations where historically, research has suggested that Indigenous communities have contributed relatively little to the frequency of ignitions. My research argues for the greater integration of traditional practices in natural resource management, specifically regarding prescribed burning where Indigenous communities likely had a significant effect in these forests.

This research also has important implications regarding forest resiliency in the face of climate change. Paleoecological studies such as this provide a framework for understanding past patterns of disturbance and the agents of change. For instance, the result that a fire event has a greater chance of becoming large/synchronous during periods of drought has important implications when developing mitigation plans that addresses impacts from climate change and for predicting how disturbances may behave in the future.

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CHAPTER 1: Introduction and Background

Border Lakes Region

The study area for this research lies within the Border Lakes Subsection of Minnesota and is located in the north-northeastern portion of the state along the Canadian border. The Border Lakes Subsection includes the Boundary Waters Canoe Area Wilderness (BWCAW), Superior National Forest (SNF), and Voyageurs National Park (VOYA; Figure 1.1) and is approximately 1,121,570 hectares (2.8 million acres). This research specifically addresses temporal and spatial patterns of fire in the BWCAW and VOYA with the study area hereafter referred to as the Border Lakes region (BLR) and equals about 417,900 ha. Water is prominent in the BLR, consisting of over 1,200 lakes making up approximately 110,900 ha (~26.5% of the area; Coffman et al. 1980; Heinselman 1996; MDNR 2006).

Geologic Structure

This BLR landscape is within the Laurentian Upland physiographic province and is the result of erosion from continental glaciers of the Pleistocene era with the last advance occurring during the late Wisconsin glaciation occurring about 16,000 years ago (MDNR 2006). Advancing ice ground down and plucked away weathered and fracturing rocks, deepened already existing valleys and lowlands and rounding off ridges. As a result, over 1,200 interconnected lakes and streams were formed in the region. Soils were formed from glacial till and consist of a heterogenous mix of sand, and silt (Heinselman 1973 and 1996).

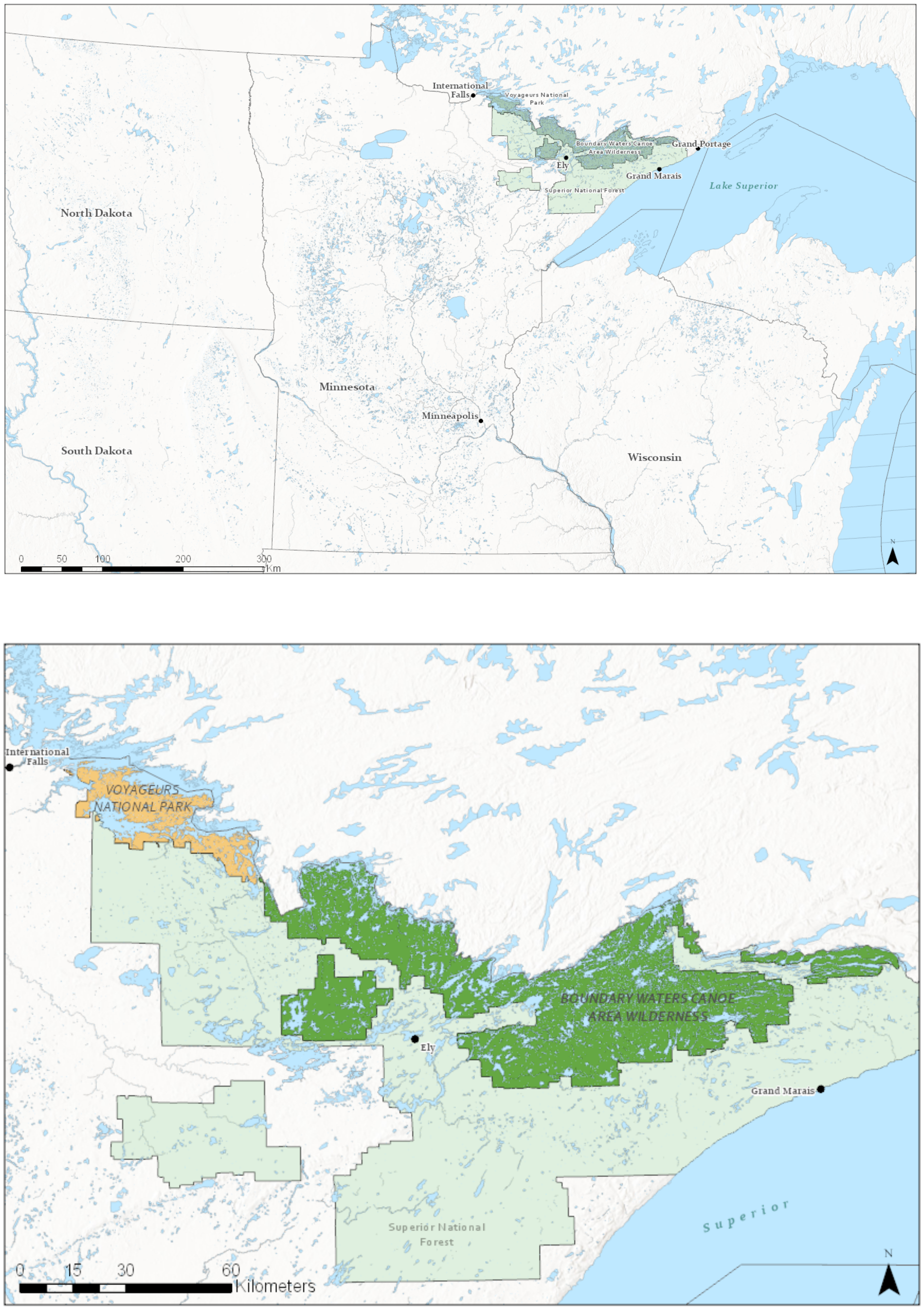

Figure 1.1. Top: Location of the Border Lakes Subsection and study area within Minnesota. The study area is shaded in dark green, while the larger Border Lakes Subsection, which includes Superior National Forest, is shaded in light green. Bottom: Close up of the Border Lakes Subsection, with the study areas: Boundary Waters Canoe Area Wilderness shaded in dark green and Voyageurs National Park shaded in orange.

Terrain

Generally, topography is dominantly rolling with irregular slopes and many outcrops of bedrock. Topography influences the spatial variability of vegetation (type, amount, moisture content) such as the productivity and the biophysical conditions of the site by influencing energy and water balances that control microclimate conditions (e.g. temperature, precipitation, direct solar radiation, and wind exposure; MDNR 2006). Generally, north-facing slopes are more mesic while southwest facing slopes are typically more xeric. Thus, habitats can be dramatically different depending on aspect direction. The presence of lakes in the Border Lakes creates an island mosaic producing variation in landscape structure across short distances. For example, islands in relatively close proximity vary in size and topography resulting in complex patterns of aspect, elevation, and slopes, creating variation in vegetation structure within and between islands (Figure 1.2).

Climate

The region has a cool continental climate, with an average annual precipitation of around 63 cm that primarily falls as rain between the months of May through September (Arguez 2010; MDNR 2006). Snow accumulation begins in early November and typically lasts into May, with 145 mean number of snow days. Average July maximum temperature ranges from 26.6°C in the western portion of the region to 21.3°C in the eastern portion and minimum January temperatures range from -24.2°C to -15.6°C (Arguez 2010; Figure 1.3).

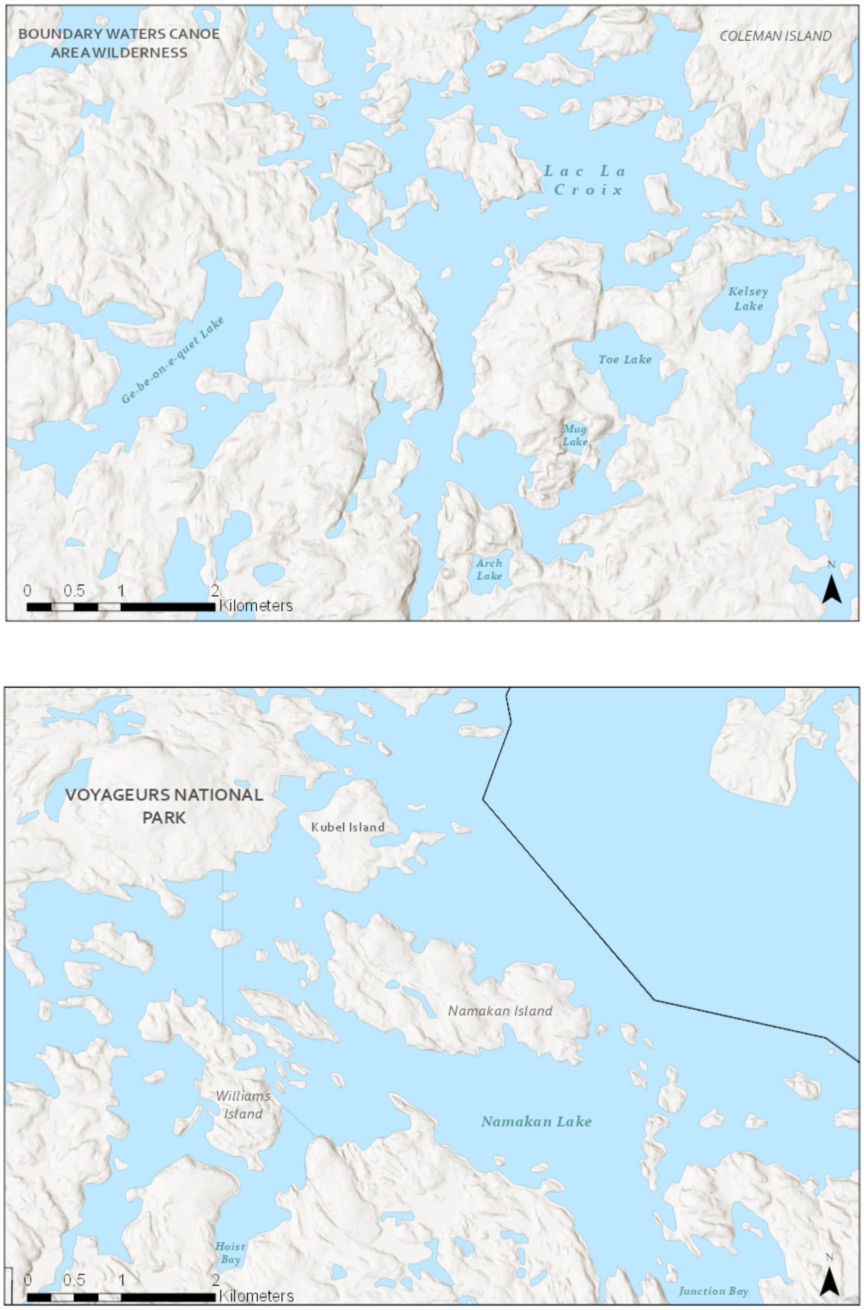

Figure 1.2. Top: Portion of the Lac La Croix region located in the Boundary Waters Canoe Area Wilderness. Bottom: Portion of the Namakan Lake region located in Voyageurs National Park. Both maps show the variability in the landscape, such as island size and degree of isolation.

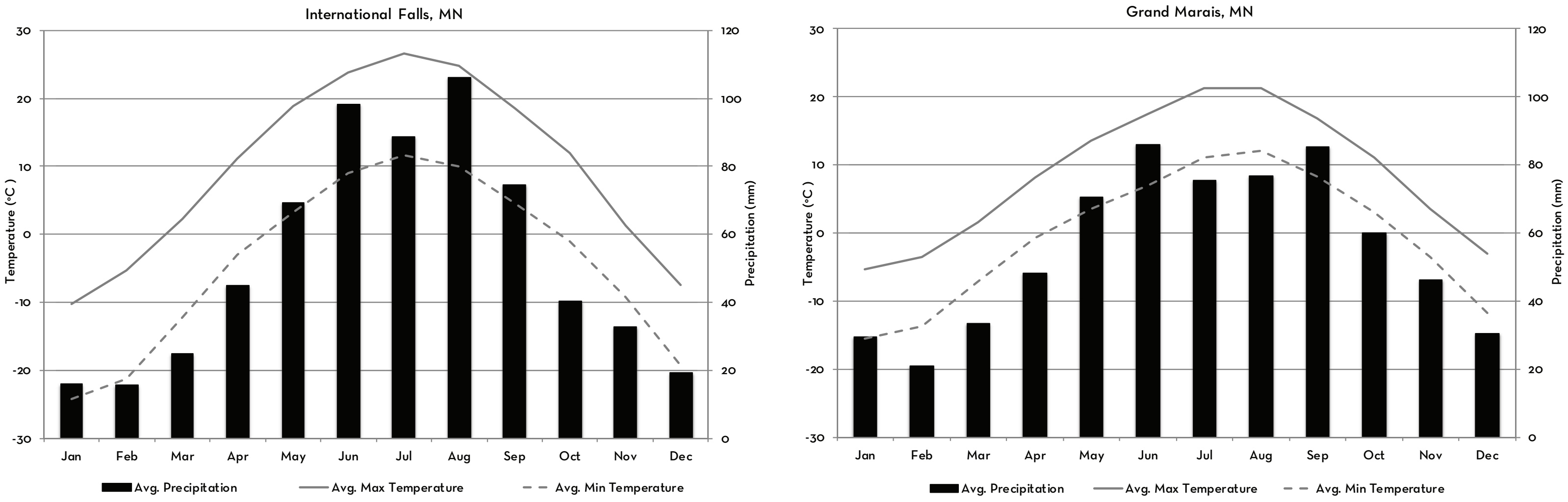

Figure 1.3. Climographs for the northeastern portion of the study area (left, International Falls, MN, Figure 1.1;) and the southwestern portion (right, Grand Marais, MN, Figure 1.1; data compiled from World Climate, 2019).

History of Land Use

The Border Lakes region has a rich history of land use with evidence dating back into the Pleistocene era. Migration of people into the Border Lakes region dates to 12,000–8,000 years ago and is characterized by nomadic Clovis hunters. Around 8,000–2,800 years ago, with the onset of warm-dry conditions humans began using waterways as travel arteries. The Woodland Tradition is defined as the time period between 2,800 and 300 years ago with the development of pottery, and hunter-gather lifestyle. Beginning about 1690 AD to 1865 marks the Voyageurs era with the first Europeans arriving and exploring the region. The Great Lakes fur trade began in the 1730s and extended into the 1860s with European voyageurs and indigenous groups using the Border Route, which extended between Lake Superior and Rainy Lake to trade goods, repair canoes, and extract resources (Heinselman 1996).

Present Vegetation

Vegetation in the study area is classified as near boreal forest situated within the ecotonal transition zones of the boreal forest and temperate forest (Heinselman 1973; Kurmis 1986, Heinselman 1981; Heinselman 1996; Frelich 2002). Boreal species exist on the southern edge of their range interspersed with non-boreal temperate species located at the northern edge of their range (Heinselman 1981; Frelich 2002). Boreal species in this ecosystem include jack pine (*Pinus banksiana* Lamb), black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.), quaking aspen (*Populus tremuloides* Michx), balsam fir (*Abies balsamea* (L.) Mill.)), northern white cedar (*Thuja occidentalis* L.), and paper birch (*Betula papyrifera* Marshall). Species in this ecosystem include white pine (*Pinus* *strobus* L.), red pine (*Pinus resinosa* Aiton), red maple (*Acer rubrum* L.), and black ash (*Fraxinus nigra* Marshall) (Heinselman 1996; Frelich 2002; Frelich 2014). Today, major forest communities include jack pine forests, white pine-red pine forest, and hardwood-conifer forests consisting of balsam fir, white spruce, paper birch, and trembling aspen (MDNR 2006).

Disturbance

Northern Minnesota ecosystems are disturbance dependent (Frelich 1998), influenced by fire, insects, winds, among others (e.g. disease, human land use) and the following section is a synthesis of each and their influence on various species within the region.

Insects

There are many species of insects present in the forests of the Border Lakes region and are variable in their timing, severity, and impact. Spruce budworm (*Christomeura fumiferana*) is a native insect and outbreaks have periodically defoliated forests for hundreds of years. Larvae eat the needles of balsam fir and white spruce causing defoliation, top kill, and mortality and tend to occur when there are extensive and continuous areas of mature and over-mature balsam fir. Jack pine budworm (*Christoneura pinus pinus*) larvae eat the needles of jack pine causing defoliation, top kill and mortality tend to occur in poorly stocked stands, over stocked stands, over mature stands or stands with low-vigor trees. Forest tent caterpillar (*Malacosoma disstria*) outbreaks result in the defoliation of most hardwood tree species, especially aspen, birch, basswood and oaks. There are several species of bark beetle (e.g. pine engraver beetle – *Ips pini*) that exist in Minnesota, with the pine engraver being common and sometimes abundant. These beetles reproduce in moist cambium of freshly cut, recently killed, or blown down red pine, jack pine and occasionally white pine. Typically bark beetle populations increase after a blowdown. Other types of insects that are present in the region include the gypsy moth (*Lymantria dispar*), white pine weevil (*Pissodes strobe*), larch sawfly (*Pristiphora erichsonii*), and poplar borer (*Saperda calcarata*; MDNR 2006).

Wind

Wind disturbance plays an active role in the Border Lakes forests with three major storm types, straight-line thunderstorm winds, tornadoes, and cyclonic winds. Straight-line winds can occur in the form of downbursts or microbursts and occur during severe thunderstorms. Derechos are a downburst wind pattern that can result from a thunderstorm and have been known to occur within the region. For example, a derecho occurred in Minnesota in May 1998, traveling over 2000km, beginning in Minnesota and ending at the Atlantic Ocean. This storm caused significant canopy blowdown across the study area, leveling forests in its path. Tornadoes may also occur in northern Minnesota, however, are rarer with a rotation period of about 6,000 years. Finally, cyclonic winds (i.e. gales) are general winds that occur around low pressure cells with intensity less than straight-line winds and tornadoes (Frelich 2002).

Fire

Fire is an important determinant of ecosystem change and is widely recognized as a natural process responsible for modifying community composition. Fire acts in much the same way as a keystone predator by reducing the abundance of strong competitors resulting in altered forest types, composition, structure, and biological processes. Fire is often necessary for the maintenance of health and regeneration of species by increasing soil nutrients, clearing dead wood, removing competition, and thus promoting seed germination. Fire also provides habitat for nesting birds by creating standing dead and cavity trees for animals and controls insects and pests by killing older diseased trees, leaving younger healthier ones. Frequent fires reduce fuel build up, thereby lowering the likelihood of a potentially large wildland fire. In many ecosystems fire is necessary to maintain biodiversity, ecological processes, and protect vegetation communities.

The forest patch mosaic of the Border Lakes region has been shaped by the interaction between individual species traits and disturbances such as fire and wind that occur at a variety of severities and frequencies. The location, timing, and severity of disturbances influence the complexity of species composition and the overall structure of the near boreal forest. The native plant communities in this forest system are dominated by species that are adapted to frequent fire with severities ranging from low to high. Fire suppression efforts started about 1910 (Heinselman 1996) and have altered forest vegetation by affecting natural processes including forest succession. Most pine logging occurred from 1895–1930 with a majority of the forest outside of the BWCAW was logged by 1936. About half of the BWCAW’s pine forests were removed and subsequently burned. Conversion of pine stands to aspen and birch forests most often occurred where large areas were effectively clearcut of all mature pines followed by intense slash fires. The resulting forests contain more early successional stands of aspen, birch, and balsam fir that are now abundant on the landscape and in relatively advanced stages of succession.

Mitchell and Conzet (1927) described the fire season as bimodal generally spanning between the months of April to October (Figure 1.4). Between 1916 and 1925 they observed a peak of fire occurring in May after snow melt and before major green-up, and a second, lesser peak occurring around late September to early October after summer storms and when trees were entering dormancy. A small peak of fire may occur in the mid-summer months, however fires during this period are generally related to periods of extended drought and high temperatures. Since Mitchell's early work, the bimodal fire season generally holds with peaks of fire in the spring and then again in the fall months (Heinselman 1996).

Understory species that are adapted to fire and indicators of fire dominated ecosystems include bush honeysuckle, lowbush blueberry, understory white pine, velvet-leaf bilberry, spreading dogbane, wintergreen, running clubmoss, and cow-wheat (MDNR 2006).

Vegetation Types, Composition, and Structure and Relation to Disturbance

Four of the most common forest types in this region include jack pine and upland spruce, aspen-fir, red and white pine, and bog and rich swamp forests. These forest types can occur as general mixtures or transitioning between types in relatively short distances resulting in a complex mixture of species, age, and structure. Below are descriptions of

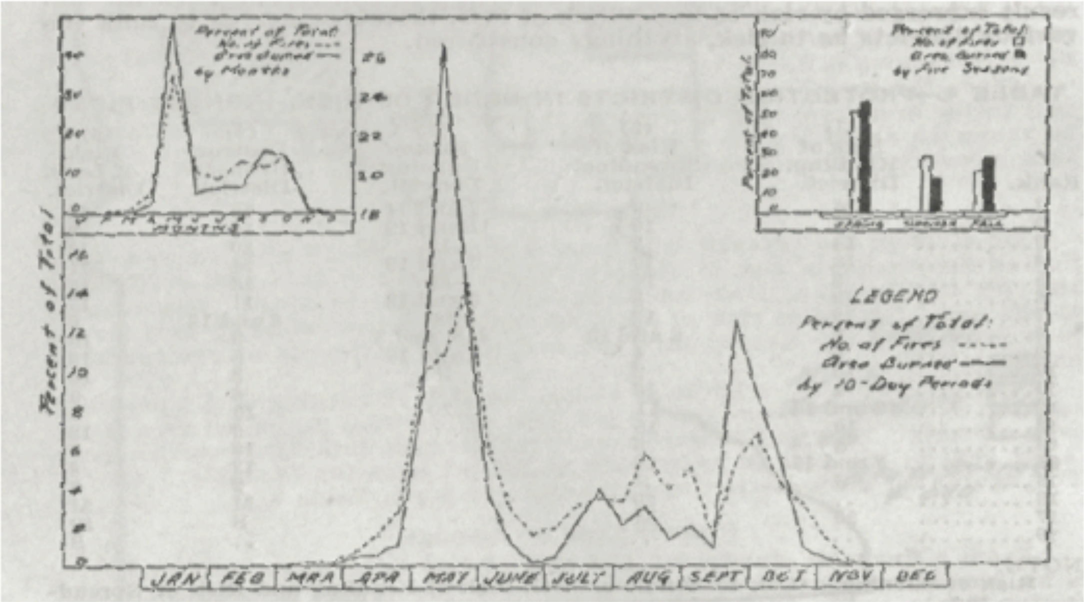

Figure 1.4. Bimodal chart of fire occurrence between 1916 and 1925 (chart taken from Mitchel and Conzet 1927).

the four main forest types found in the region, with defining species characteristics and adaptations to both wind and fire disturbance.

Jack Pine and Upland Black Spruce Forests

The jack pine-upland spruce forest type is primarily found on convex landforms and upland slopes with thin, poorly drained shallow soils (Ohmann and Ream 1971; Frelich and Reich 1999; FEIS 2017). Jack pine stands are relatively even aged with black spruce interspersed throughout the canopy and understory. These species may occur as pure stands or with aspen, birch, fir, and red pine at various stages of growth (Ohmann and Ream 1971; Heinselman 1996).

The relative abundance of jack pine and spruce depends on both site factors (e.g. slope position, soil moisture) and the frequency of fire. Both jack pine and black spruce are shade intolerant, evergreen conifers with the fire adaptation of serotinous cones. Jack pinecones are sealed with resin, typically requiring high temperatures reached during a fire event to open and release seeds (FEIS 2017). Black spruce cones are semi-serotinous and tend to gradually open over time in the absence of fire, but in the case of extreme heat cones open and disperse seeds rapidly (Frelich and Reich 1995; Heinselman 1996). The adaptation of serotinous cones in these two species demonstrates that these forests establish and regenerate the stand after fire. The fire regime for this community type is moderate to severe, stand-replacing fires that typically occur every 40 to 150 years and in some cases a fire return interval as low as 20 years (Table 1.1, Figure 1.5; Heinselman 1981; Frelich and Reich 1992; Heinselman 1996). Both trees are highly flammable with thin bark, low hanging branches, and low foliar moisture. Fire likely results in high

Table 1.1. Border Lakes fire regime characteristics, forest communities, and landscape characteristics (Data derived from Ohmann and Ream 1971; Heinselman 1973; Frelich 2002).

Dominant Fire Severity	**Fire Interval**	**General Forest Community**	**General Landscape Characteristics**
High Severity	200 +	Black Spruce Bog Mixed Conifer Swamp	Very Wet; Lowland and Bogs; Deep Soil Layer; High Soil Moisture
	50–200	Aspen-Birch-Conifer	Moist; Valley to Upper Slopes; Relatively Deep Glacial Clays; Wet, Fertile Soils
Mixed Severity	20–150	Aspen-Birch	Lower slopes and valleys; All Positions; Deep soils; Higher Soil Moisture
	20–150	Jack Pine-Spruce	Upper and Lower Slopes; South-Southwest facing; Coarse Shallow Soil
Low – Moderate Severity	150–200	Red and White Pine-Birch-Aspen	Common on lakeshores; All Slope Positions; Low-Moderate Soil Moisture
	5–50	Red and White Pine	Upland-Ridgetops; South-Southwest Facing Slopes; Shallow Soil Layer; Lower Soil Moisture

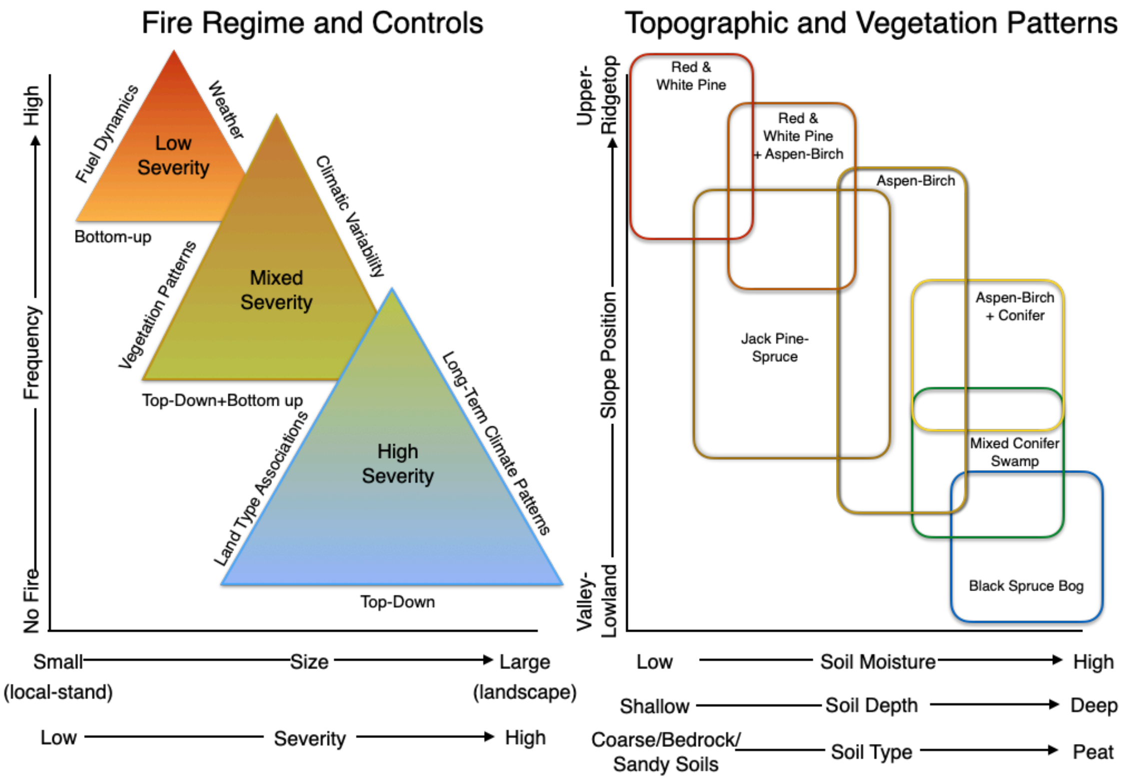

Figure 1.5. Conceptual diagram depicting variation in the fire regime and the controls at various spatial and temporal scales (left), and vegetation composition related to soil characteristics and slope position (right). The width of the box corresponds to soil characteristics while the height corresponds to dominant position on slopes. Vegetation communities (right) and fire triangles (left) are colored relative to the range in moisture content with red being the driest and blue representing wet conditions. The location of the various fire regimes on the left corresponds to the vegetation communities on the right (diagram on the left is derived from Parisien and Moritz (2009) with modifications made to match the Border Lakes Ecosystem) Note that on the left hand axis, fire frequency ranges from no fire present at the bottom to reflect dynamics in black spruce bogs to high frequency fires towards the top.

mortality rates, removing most or all trees and thus allowing for regeneration of the stand, by way of seeds that were released from their cones during the fire event. In the absence of fire, jack pine-black spruce stands transition in dominance to later successional species such as aspen, birch, fir, and cedar (Figure 1.6).

Both jack pine and black spruce have light, wind-blown seeds that can disperse anywhere from 70 to 130 feet (FEIS 2017) and can germinate rapidly (within 10 years) after a fire. Both seed types establish well on mineral rich soil after fire and under open stand conditions (Ohmann and Ream 1971). Jack pine and black spruce can produce viable seeds around the age of 15–30 years (Heinselman 1996; FEIS 2017). Once trees reach maturity it is easier for the stand to regenerate back to jack pine and black spruce in the case of a fire event. Jack pine can have a lifespan of 150–200 years without fire, reaching an average height of 120 feet. Black spruce has a lifespan ranging from 180–220 years and is generally smaller than jack pine with an average height of 40 feet (FEIS 2017).

Aspen-Birch-Fir Forests

The aspen-birch-fir forest community type is most common on concave landforms with moderately moist soils. Both aspen and birch are small to medium sized trees reaching heights ranging from 45 to 80 feet (birch tend to be slightly larger in size) and reach an average age of 120 years given the absence of fire (FEIS 2017). Balsam fir is generally smaller in size and grows as an understory species, however canopy gaps can allow for balsam fir to move into the canopy layer.

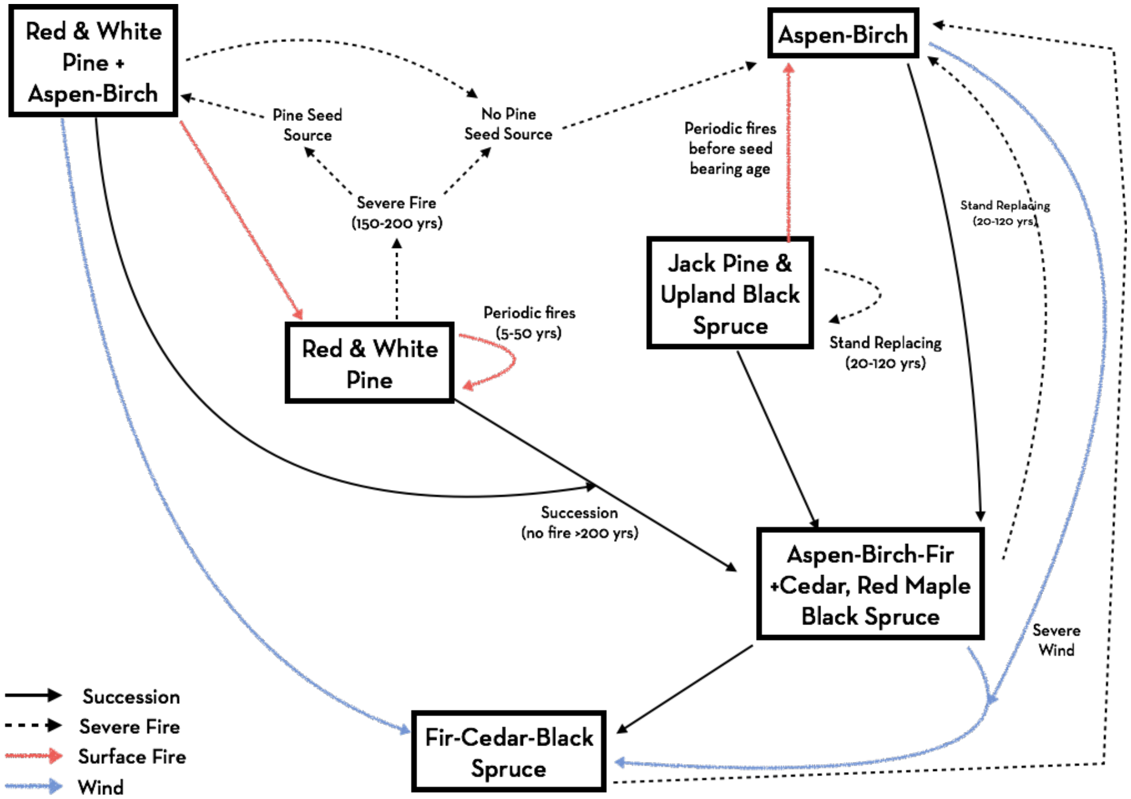

Figure 1.6. Succession and disturbance pathways of the forest community types of the Border Lakes Ecosystem. Common forest communities are represented in the black boxes with primary successional pathways (black line), however a variety of species mixtures are likely to occur. Disturbances are depicted as a dashed line, and red and blue lines (severe fires, low severity fires, and wind, respectively). Adapted from Frelich 2002; Snyder 2005; Frelich 2014 to include the forest communities, disturbances, and interactions covered in this chapter.

Balsam fir has very flammable foliage, often acting as a ladder that carries fire from the surface into the crowns of the aspen and birch trees, which have a higher foliar moisture content (Ohmann and Ream 1971). Paper birch has thin, highly flammable bark, allowing for it to be killed by fire. Once paper birch is ignited fire can spread throughout the stand. Aspen-birch-fir forests have a fire return interval ranging from 50–200 years with an average interval of 70–110 years (Table 1.1; Figure 1.5; Frelich 2002). In some cases, fires may occur in relatively short intervals (<20 years), which generally occur in aspen-birch dominated stands that are present on drier, south facing slopes. In this case aspen tends to first dominate after fire because of easily dispersed seeds and ability to vegetate reproductively after a fire.

Species such as spruce and cedar are also common components in these stands occurring as understory elements early after disturbance and increase in abundance as time since last fire increases (Ohmann and Ream 1971; Frelich 2002). Red maple can also occur in mature aspen and birch stands, and in the aspen-birch-fir stands both in the canopy and in the understory. Red maple may survive low severity fire, given its mature age and thick bark, however red maple generally grows on sites that have been absent of fire for long periods. Red maple is moderately shade tolerant producing seeds when it’s fairly young (10 years of age) and can sprout from a stump or root, growing relatively fast (Ohmann and Ream 1971; Heinselman 1996; FEIS 2017).

Aspen, birch, and balsam fir begin to produce viable seeds once they reach 25 years of age and are prolific seed producers. Aspen and birch produce light winged seeds that can easily be blown far distances, while balsam fir produces more heavy winged seeds typically landing within the stand (FEIS 2017). Aspen can regenerate by root suckering, establishing within 10 years after a fire (Ahlgren 1960; Heinselman 1996). Birch can resprout from the root collar of fire-killed birches and as a result birch often occurs as multi-stemmed trunks. Balsam fir is a late successional species (shade tolerant species), establishing a number of years after a fire. It is common for aspen-birch-fir stands to have a mixture of cedar, jack pine, red maple, and in some cases white pine and red pine at various stages if fire has not occurred in the site for many years.

White and Red Pine Forests

Red and white pine often occur on well-drained soils located on dry slopes and ridge tops (Ohmann and Ream 1971; Grigal and Ohmann 1975; Ahlgren 1976). Red pine is more abundantly found on south to southwest facing slopes close to water or on island sites. White pine can be found in forests at all successional stages, can grow on wetter soils (compared to red pine), and can be found on varying slope aspects, however, the species primarily occurs on south facing slopes (Ohmann and Ream 1971). Both species are large evergreen coniferous trees reaching heights upwards of 75–120 feet (white pine tends to be taller; FEIS 2017). White and red pines have thick bark and long trunks free of branches, and red pine has fairly resinous wood.

Red and white pine needles facilitate the ignition and spread of fire, reaching depths of 8 inches in some locations (Ahlgren 1976; FEIS 2017). Adaptations to fire, including thick bark, resinous wood, and self-pruning branches make these species tolerant to fires of lower severity resulting in individuals scarred by fire but not killed. Stands of pure red pine typically experience low severity surface fires of intervals of 5 to 50 years. Higher severity fires that result in the mortality of older trees range from 150 to

250 years in occurrence (Figure 1.5). Due to the prevalence of growth on moister sites pure white pine stands experience less frequent fire return intervals (anywhere from 25–200 years) and high intensity fires every 200–300 years (Heinselman 1996; Frelich 2002).

Red and white pine have wind-dispersed seeds promoting seedling establishment after a fire of higher severity. Establishment is facilitated by the rich mineral soil that is exposed after a fire and the removal of late successional competing species (Ahlgren 1976). The frequent nature of fire in these drier, warmer stands encourages the maintenance and regeneration of both species. Given frequent, low to moderate severity fires red pines have an average lifespan of 300 years, while white pine has an average lifespan of 300–350 years (older white pines generally occur on wetter sites with less fire; Ahlgren 1976). Species such as jack pine, northern white cedar, black spruce, and balsam fir can frequently occur in the understory of these stands. Given canopy gaps any of these species can move into the canopy layer, increasing the competition with red and white pine. Fire typically eliminates any competition, removing these late successional species.

Bog and Rich Swamp Forests

Black spruce is common in wet lowlands and on cooler north facing slopes (FEIS 2017). Black spruce, northern white cedar, and black ash are all common in these lower acidic bog sites. Typically jack pine and spruce forest types occur just upland of these bog sites. Because of the adjacency of these stands, fire can travel from the upland site to the lowland bog if conditions are dry enough. Due to the high moisture content of the bog sites, fire return intervals are typically longer than the adjacent upland sites, requiring more prolonged drought in order to burn. The crown fire interval ranges from 100–150 years first producing even aged black spruce stands, then infiltrated with black ash and white cedar in later years (Heinselman 1981; Frelich 2002). White cedar is very susceptible to mortality from fire yet can reach old age (500+ years) in fire-protected sites (Heinselman 1996).

Black spruce regeneration typically occurs first in these stands due to serotinous cones with adjacent stands providing an important seed source for lowland stands. Black ash seeds are dispersed by wind and are moderately shade tolerant, regenerating on stumps and root crowns in recently disturbed sites (Ahlgren 1960; Heinselman 1996; FEIS 2017). White cedar can occur in these bogs, which require wetter soil moisture for germination while establishment occurs sometime after a fire (Frelich and Reich 2003). Even though white cedar occurs as a swamp species it can also be found on more upland, well-drained sites (given moist soils) with older aged cedars occurring on rock outcrops along lakeshores.

Successional Changes

Early successional and shade intolerant species such as quaking aspen, jack pine, and red pine have a high susceptibility to wind disturbance and mortality (Rich et al. 2007). Species that have a lower susceptibility to wind disturbance are late successional species such as cedar, red maple, and paper birch, while balsam fir has a low susceptibility when it is young and bole size is small but increases with age and size (Frelich and Reich 1995; Rich et al. 2007).

In aspen and jack pine dominant stands (e.g. jack pine-upland spruce and aspen-fir-birch communities) a severe wind event has a greater chance of removing the shade intolerant species (e.g. jack pine and aspen; Rich et al. 2007). As a result, these forests increase in late successional species such as balsam fir, cedar, and black spruce that take advantage of canopy gaps (Frelich and Reich 1999; Anoszko et al. 2017). In the case of stands with paper birch, wind can increase their dominance taking advantage of canopy openings. Red and white pine stands are susceptible to mortality from wind events particularly when individuals are older and larger in size. Overall, wind disturbance can shift forest communities away from a post-fire successional state (aspen, jack pine, and red pine) and result in a greater presence of late successional species (Figure 1.6; Rich et al. 2007).

Role of Multiple Fire Disturbance

In the instance of multiple fire events within a short time frame, the hardwood-conifer forest complex (jack pine-upland spruce and aspen-fir-birch mixtures) is generally replaced by even-aged aspen stands (Figure 1.6; Ohmann and Ream 1981). Dominance of aspen can occur if jack pine and other species have not reached viable seed production age before the next fire event. Aspen tends to establish on recently disturbed areas first due to the ability to disperse seeds at long distances and they regenerate quickly by root sprouting. In red and white pine dominated stands, the occurrence of multiple low severity fires in short succession further promotes the growth of these species by eliminating competition in the understory and by increasing the mineral layer of the soil facilitating regeneration. In the occurrence of multiple higher severity fires at relatively short intervals the red and white pine forest community may convert to aspen and birch but is dependent on the availability of seeds for this to occur (Frelich and Reich 1999).

Role of Wind in Manipulating Forest Structure

Wind has varying effects on species and forest types, with susceptibility related to bole size of the tree and landscape characteristics. Generally larger trees are more susceptible to wind disturbance due to less flexibility in the trunk, a higher position within the canopy, and the greater chance of decay (Frelich 2002). Smaller trees tend to be more flexible in the chance of high winds, allowing the tree to bend protecting it from wind damage. Forest communities located from mid-slope to ridge tops are at higher susceptibility to wind disturbance due to exposure to prevailing winds (Rich et al. 2007). Heinselman (1996) has also suggested that islands are more prone to fire disturbance due to the openness and vulnerability of stands as opposed to stand more inland and thus more protected. Wind disturbances can remove individual large trees creating canopy gaps and also remove entire stands. Trees can either be damaged by upper canopy breakage or by the tree entirely uprooting (Heinselman 1973). Species growing on clay soil are more likely to uproot as opposed to species growing on deep sandy soils (depending on the species and size).

Stand-leveling wind has an estimated rotation period of 1000+ years primarily occurring in the summer months due to severe thunderstorms and associated downbursts (Frelich and Reich 1995; Frelich 2002). Severe wind events generally occur through downbursts sometimes occurring as large scale, straight lined winds (e.g. in 1998 a derecho hit an area totaling 100–200 km in length; Frelich 2002). During these occurrences, wind speeds can reach up to 250 km/h resulting in stand-leveling events. Cyclonic winds are another form of wind disturbance, generating from extra-tropical low-pressure centers with severity ranging from individual tree to entire stands.

The variation in disturbance type and variability in frequency and severity has resulted in a complex patch mosaic of community types. Fire is a prevalent process in the near boreal forest, with forests in the ecosystem considered to be fire dependent. This means that vegetation composition, age structure, and range of successional stages can be attributed to the frequency of fire. Wind is also pervasive disturbance often interacting with fire, maintaining the diversity, productivity, and stability of the entire Border Lakes Ecosystem.

Interactions Between Fire and Wind Disturbance

Fire and wind disturbance have important interactions, influencing both the susceptibility of a location to disturbance and the intensity of either disturbance at a particular place and time. Heavily wind damaged areas tend to have greater fuel loads positively enforcing high severity fires. A fire event that follows a wind event can burn with greater intensity as opposed to fires occurring in areas without prior windstorm damage. While both data on wind disturbance and wind history plus fire disturbance history is generally lacking, efforts are being made to understand the implications from their interactions by evaluating more recent disturbances and community outcomes (Anoszko 2017). Overall, multiple disturbances cause a decrease in conifer species as a whole by reducing their seed source (have longer time to sexual maturity), while deciduous species generally increase. This is because deciduous species are capable of dispersing their seeds long distances and most are capable of vegetative reproduction following disturbance.

Overall, stands that experience a wind disturbance followed by a fire event will result in an increase in quaking aspen and paper birch species (Frelich and Reich 1999, Frelich et al. 2014). Due to aspen's ability to live on a variety of soil types, slope aspects, ability to disperse long distances, and fast establishment time this species benefits from the removal of overstory vegetation and competing species. Red maple also does well after multiple disturbances taking advantage of canopy gaps. The reduction in regeneration of previously dominant species may be because many species fail to reach seed producing age within a short disturbance window subsequently being replaced by aspen and birch. For example, jack pine is susceptible to blowdown from wind events and in the case of a fire occurring after a wind disturbance, the downed jack pine can increase the intensity of the fire due to the increase available fuel loads. Depending on time between disturbances, jack pine may fail to produce viable seeds, limiting regeneration of stands. Further limiting regeneration of jack pine, greater intensity fires can result in higher mortality rates for the serotinous cones and seeds that may be located within the seedbank.

Red and white pine stands are very susceptible to wind caused mortality due to their large size. In the case of a fire event that occurs after a wind event, red and white pine stands may diminish in dominance. This is due to mature individuals being killed from wind, increasing fuel loads and thus fire intensity. Regeneration of these pines can be limited due to the high severity fires and resulting in the reduction of seed sources

(Ahlgren 1976). Black spruce and balsam fir increase after wind disturbances due to the removal of aspen and jack pine but can decrease significantly if a fire event occurs. White cedar is fairly tolerant to wind yet decreases significantly in the present of fire.

Mechanisms of Fire

Top Down and Bottom Up Controls

Wildfires shape and are shaped by the ecosystems in which they burn. Patterns of fire are driven by a multitude of factors including, climate, weather, topographical features, and human interactions (Whitlock et al. 2010; Bowman et al. 2009; Flannigan et al. 2009) with causes and impact varying greatly across spatial and temporal scales. Fire behavior and effects typically reflect the relative strengths of multiple drivers that interact at variable scales in space and time. At fine scales, fire spread and intensity are determined by properties of fuel (availability, spatial arrangement), ignition (type, frequency, spatial distribution), and ambient weather (air temperature, wind speed, humidity; Figure 1.7). These controls have strong influences at smaller scales, such as tree, or the stand level (bottom-up mechanism), affecting fire spread at large spatial scales (Table 1.2). At the broader scale of landscapes and regions other factors begin to gain importance, such as broad topographic variation (landscape configuration) and climate. The co-occurrence of fire across multiple sites is often associated with broad-scale climate mechanisms, such as regional drought (top-down mechanism). Bottom-up and top-down controls may shift in importance depending on the relative strength of forcing factors. For example, fine-scale topographic influences may be stronger in years with mild climate drivers, but severe fire weather can override local factors and result in widespread co-occurrence of fire (Falk et al. 2007; Yocom et al. 2014).

Fire Synchrony

Fire synchrony refers to the co-occurrence of events, related to coincident changes in ecological characteristics. Patterns in synchrony are related to the dominant controls within and across a landscape for a particular time. In certain years, strong top-down controls can be evident by synchronous fires occurring at widely separated sites (Figure 1.8). Asynchronous fire occurrence is generally evident of more bottom-up controls, exerting local scale influences on the fire regime. Asynchrony thus refers to events that are isolated to a particular place and/or time. An important note is that the synchrony of fire is highly dependent on scale. As scale increases, such as when more time or larger space is evaluated, the likelihood of synchrony such that a greater area or time period will capture more events.

Human Land Use

Four historical periods are recognized in the last millennium in regard to the BLR based on demographic or cultural factors, each with a distinct fire regime (Dickmann and Cleland 2002). These periods include the pre-Columbian period (AD 1000–1500), immediate post-Columbian (AD 1500–1800), the European colonization-exploitation period (AD 1800–1920), and the fire exclusion period (AD 1920–present). During the pre-Columbian period, fire frequencies were high with both lightning-caused fires and recurrent ignitions by indigenous people. European explorers and associated diseases devastated indigenous populations and during the centuries following Columbian contact

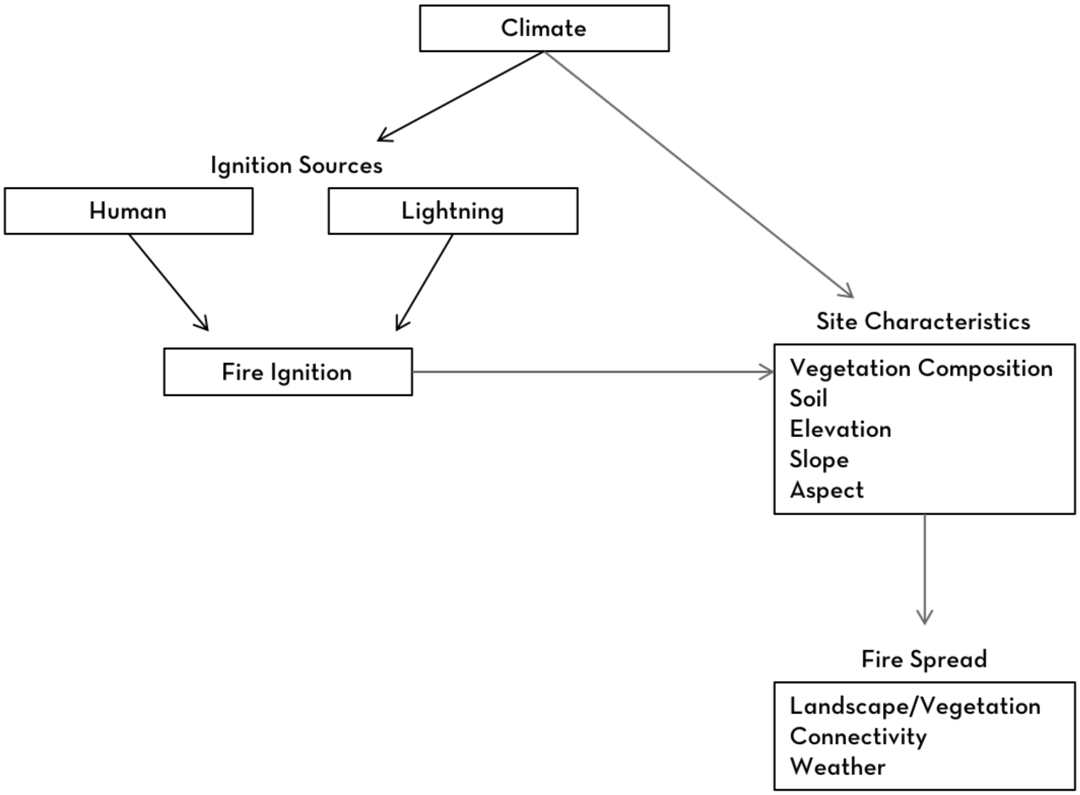

Figure 1.7. Connection between climate variability, ignition sources, site characteristics, and fire.

Table 1.2. Controls of Fire Regime Variability

Regime Properties	Regional (Top-down)	Local (Bottom-Up)
Temporal Distribution		
Frequency:	Ignition availability	Vegetation type, fuel abundance
Duration:	Climate dynamics	Fuel connectivity
Seasonality:	Length of fire season	Fuel type, moisture
Spatial Distribution		
Extent/Pattern:	Spatial ignition occurrence	Connectivity, vegetation, type, topographic controls
Severity/Intensity:	Local weather	Vegetation configuration, topographic controls

Modified from McKenzie et al. 2011 and Falk et al. 2007

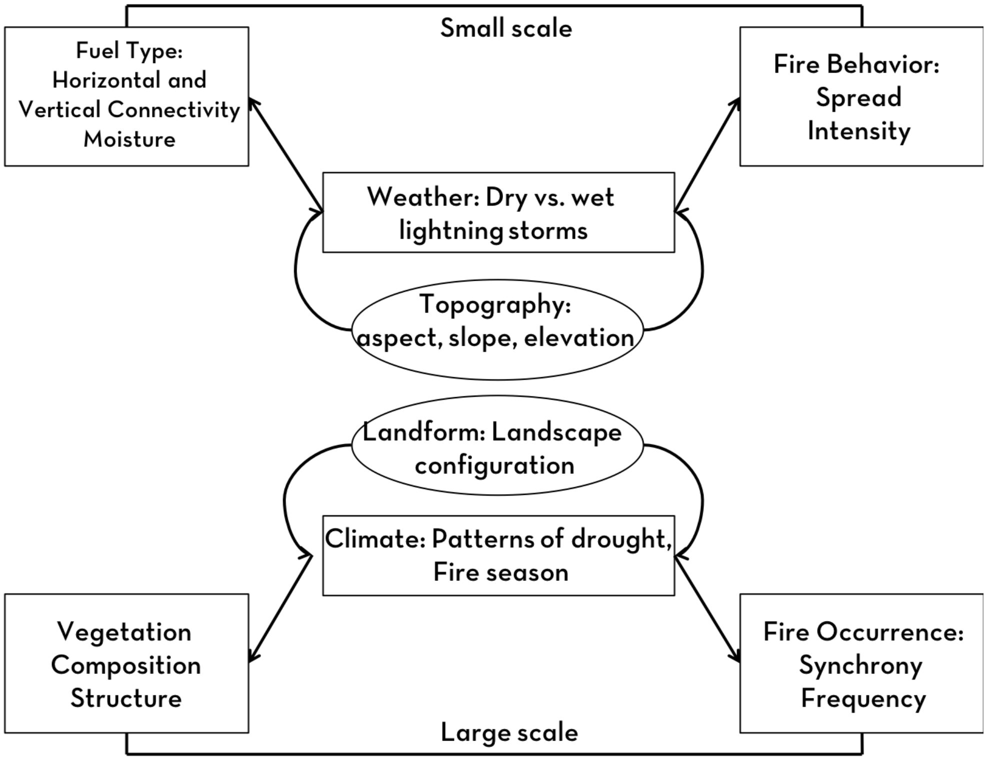

Figure 1.8. Conceptual diagram depicting the interactions between small scale and large-scale controls on fire regimes. Modified from Falk et al. 2007.

indigenous ignitions and fire frequencies declined. During the European colonization period fire frequencies and intensities were higher and were primarily set by humans for the purposes of land clearing and logging. Finally, the fire exclusion period is marked by a general decrease in fire frequency and a build-up of fuels and an increase in extent of flammable, early and late seral communities.

Fire History Research in the Border Lakes

The integral role of fire in the Border Lakes has been well known for decades with several studies documenting the history of fire and its influence on ecological characteristics. For example, in 1973 three papers were published in a special issue of *Quaternary Research* with a focus on the northern forests of Minnesota (Heinselman 1973; Swain 1973; Frissell 1973). Swain (1973) was able to show through lake sediment data that fire has been an integral factor in the Border Lakes forest. The frequency of fire in the past 1000 years ranged from 60 to 70 years and charcoal levels and corresponding pollen evidence of fire adapted species were relatively consistent in the sediment core over the last 10,000 years. Frissell (1973) presented a similar paleoecological study on the importance of fire from Itasca State Park, slightly southwest of the Border Lakes region. Through a dendrochronological approach Frissell was able to show that between 1650 and 1922, 32 fires occurred within the roughly 13,000 ha park and a mean fire interval of 8.8 years at the landscape scale for all fires and 10.3 years for larger fires and an MFI of 22 years at the point scale. Finally, the formative work of Heinselman (1973) and his later works in 1981 and 1996 provided a baseline for fire ecology in the Border Lakes region. Heinselman used a mix of fire scar data, aerial photographs, and age structure data to assess the history of fire and impacts of fire suppression on the forested communities. Primarily, Heinselman documented the history of landscape-scale stand-replacing fires, reporting a 3.5-year fire interval between 1727 and 1910.

Later research corroborated these shorter intervals adding to the argument of frequent fire in the region. For example, Clark (1990) reported a 26 year in Itasca State Park, Loope and Anderton (1998) reported a 19 year interval for the southern shores of Lake Superior, Drobyshev et al. (2008) reported a 25–35 year interval for red pine stands in the Seney National Wildlife Refuge in the Upper Peninsula of Michigan, and Johnson and Kipfmueller (2016) observed a 34 year fire interval for the Lac La Croix region of the BWCAW (data used in this research).

Current Research

This dissertation builds on prior fire history research by using recently developed tree-ring based fire history reconstructions for both Voyageurs National Park (Kipfmueller et al. 2017) and the Boundary Waters Canoe Area Wilderness (Johnson and Kipfmueller 2016; Kipfmueller et al. forthcoming). These reconstructions were developed in part to understand the history of fire in the region, document the complexity in the surface fire regime, and to evaluate the influence that humans had on the disturbance regime. Samples from all three studies and for both landscapes were combined for this research to represent fire in the broader Border Lakes region. In total, fire-scar samples from 565 red pine trees were collected from remnant stumps, logs, and snags and 541 were dated, with 128 from VOYA and 413 from the BWCAW. All trees were processed and analyzed using standard dendrochronological methods with fires dated to the exact calendar year of formation. This data set represents a surface fire history reconstruction for the red pine forests of the Border Lakes region.

The BLR fire history extends from 1489 to 2016, with 217 unique fire years. The first recorded fire year was in 1546 and the last recorded in 1972. The mean fire interval (MFI) at the individual sample level is 34.1 years (Weibull Median 28.6 years) and the landscape MFI is 1.9 years (Figure 1.9) and the fire frequency for all samples is 0.0164 (Figure 1.10). The 1700 to 1900 period has the most recorded fire events with a total of 165 fire years (71 events between 1700 and 1800 and 94 between 1800 and 1900; Figure 1.11). Fire events became less frequent after the 1900s corresponding to the fire suppression era. Fire was also less frequent prior to 1700 and is likely the combined result of lower sample depth in the early portion of the record and less human land use (Figure 1.12).

Sample collection for each of these research projects used a targeted sampling approach with a focus on red pine dominated stands. Because of this, there may be some inherent bias in the number of samples collected for particular areas and thus the depth of the fire record. For example, the Lac La Croix region has close to 200 trees while other similar sized regions, such as Saganaga Lake, has 84 whereas Cummings Lake has 46 trees. Various ways of clustering samples are performed in the following chapters to minimize the effects from sample bias; however, some may still exist.

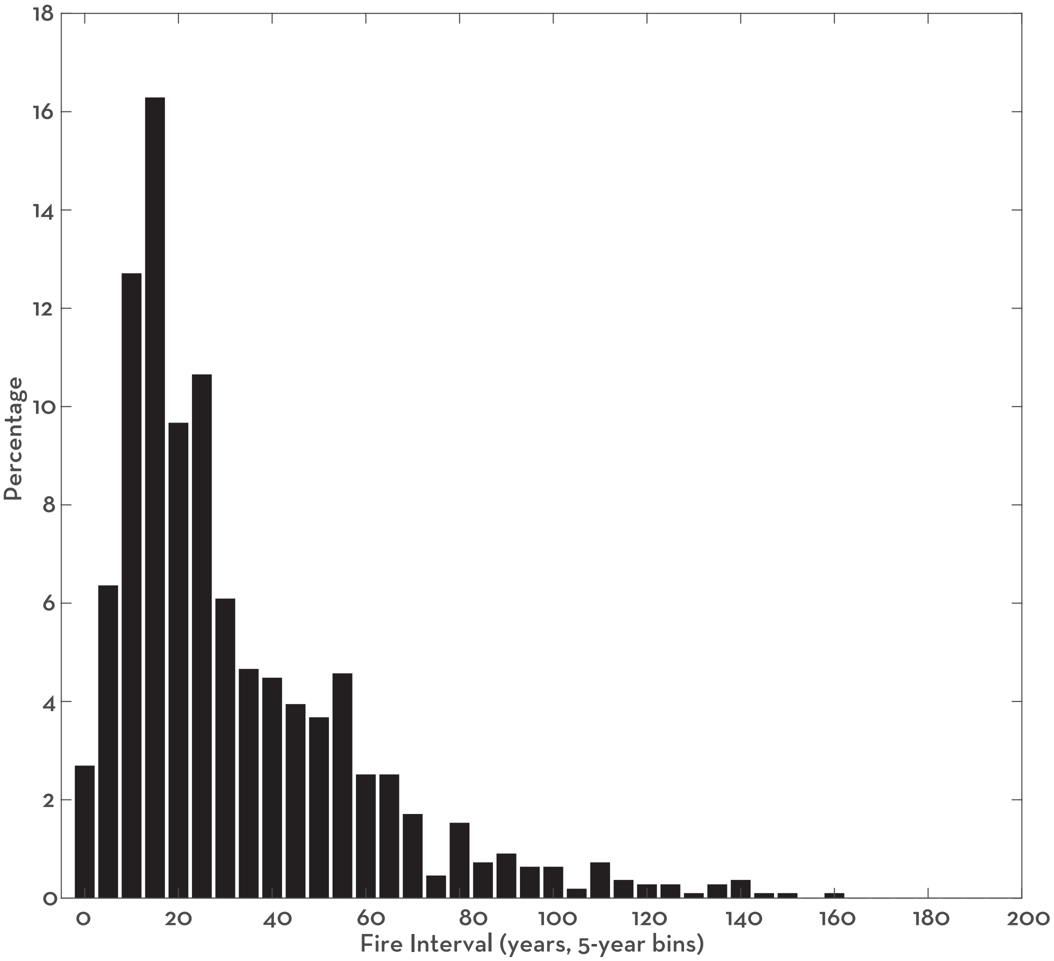

Figure 1.9. Point fire interval distribution for the Border Lakes region.

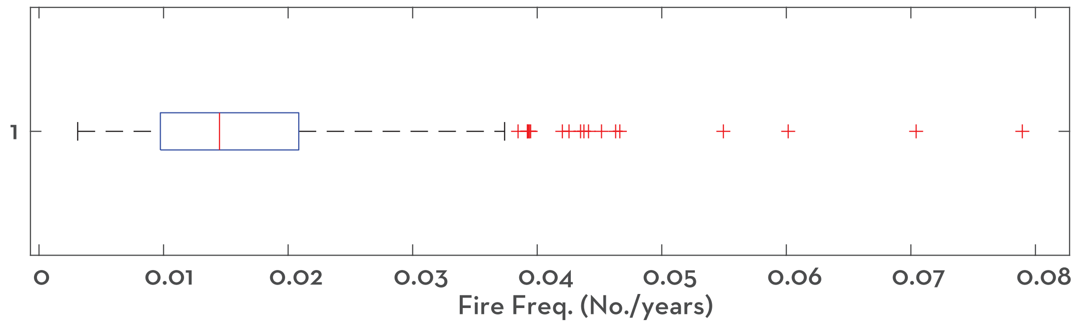

Figure 1.10. Fire frequency distribution for all 541 samples.

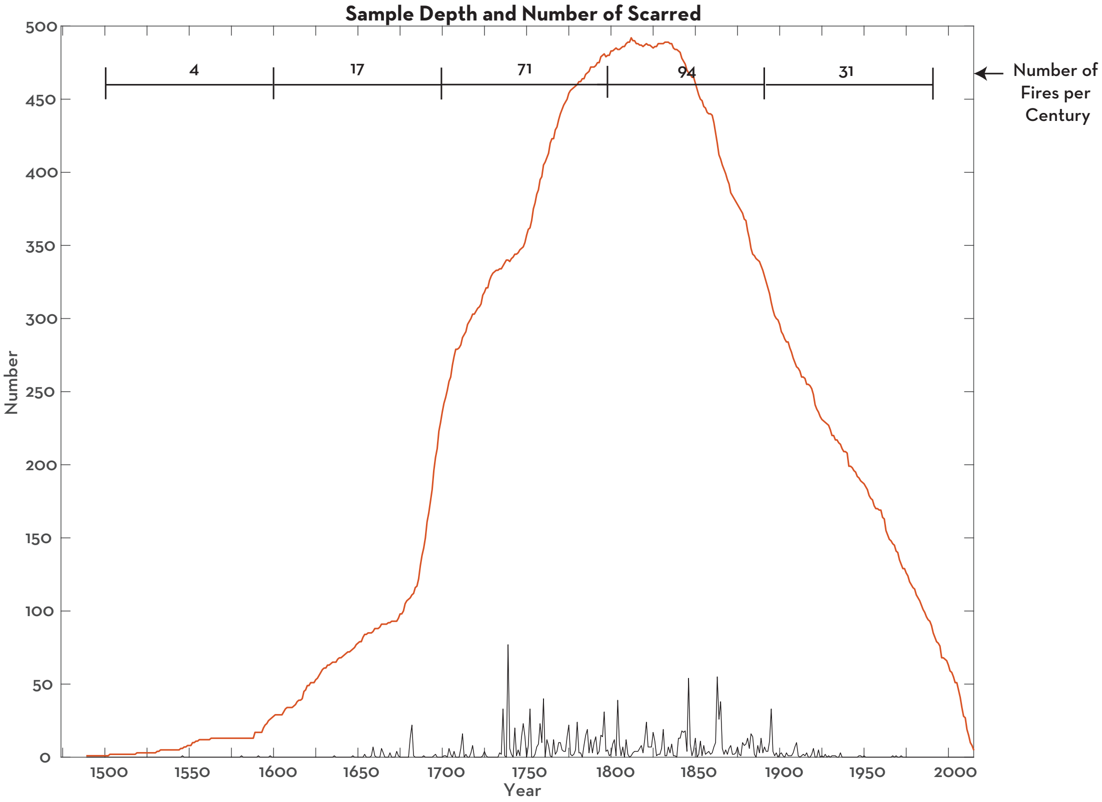

Figure 1.11. Number of samples scarred, sample depth (red line), and number of fires per century.

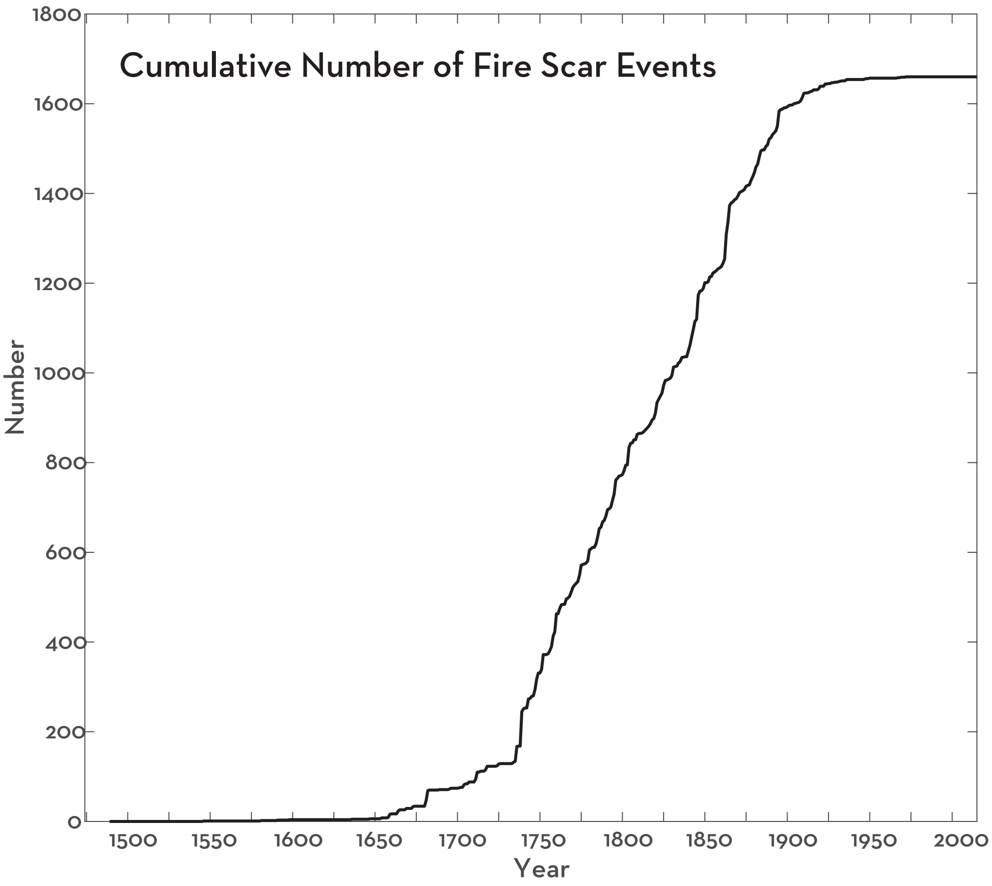

Figure 1.12. Cumulative fire scars recorded between 1489 and 2016 for the BLR region.

Current Role of Fire and Research Needs

The complexity in the landscape, climate, history of land use, and role of disturbance makes the Border Lakes a unique region to evaluate the historical dynamics of fire events and the mechanisms driving variability in ecological processes. The fragmented landscape and resulting variability in topography may impart important controls on where fire occurs and how fire behaves. For example, locations that are more isolated may experience greater fire asynchrony compared to locations that are in closer proximity to other landmasses or are more connected. Topographic complexity, such as elevation, degree of the slope, or aspect may also result in variable fire conditions making an area more or less prone to ignition and spread. The climate of the region can also influence fire, producing predictable patterns. Finally, human land use, especially Indigenous practices can have profound direct and indirect effects on the ecosystem altering the frequency and timing of fire events.

This dissertation research evaluates the patterns of fire synchrony and asynchrony and specifically links patterns to bottom-up and top-down controls of fire building on prior studies that emphasized the important role of fire in shaping forested communities in the Border Lakes region, specifically those that occurred in red pine dominated forests. This research is becoming more important as the effects from land use associated with Euro-American colonization has limited fire as a key disturbance process. The alteration in the fire regime has influenced stand structures and the resiliency of the forested vegetation (Heinselman 1973; Frelich and Reich 2009; Paulson et al. 2016).

While fire managers have long recognized the importance of fire on the landscape and note the significant impact the lack of fire is having on the structure and composition of ecological communities, several barriers exist that limit fire management strategies. For example, the lack of money allotted for fire management, the public's perception of fire such that fire is seen as dangerous and as a negative impact on the environment, optimal weather conditions conducive to burn, and a lack of understanding on how fire influenced the landscape in the past, such as frequency, timing, and severity. The following chapters attempt to address the gaps in the understanding of the Border Lakes fire regime by evaluating the variability in spatial and temporal patterns of fire in red pine dominated forests, specifically the mechanism that influence small versus large fire events in the red pine dominated forests.

Dissertation Outline

Chapter 2: Spatial Patterns of Fire Occurrence in the Border Lakes Region of Minnesota

This chapter addresses the degree of shared fire occurrence in relation to distance separating locations of fire history. The purpose of this chapter is to determine the overall synchrony and asynchrony in fire events within this region.

> Research Questions: (1) How spatially synchronous are fire events in the Border Lakes region of Minnesota? (2) What is the relationship between fire synchrony and the distance separating sites?

Chapter 3: Mechanistic Controls of Fire Synchrony

This chapter evaluates the spatiotemporal variability of fire synchrony and the potential mechanisms responsible for observable patterns. The evaluation of underlying patterns in the fire regime can further understanding of the complexity in fire occurrence and how fire events occur from one place to another. For example, what locations in the study area may have more or less synchrony in fire through time and how is that variation driven by various agents?

> Research Questions: (1) What are the temporal patterns in the fire regime, particularly during times of high fire synchrony? (2) What are the spatiotemporal patterns of fire synchrony? (3) What are the mechanisms influencing spatiotemporal variability in fire synchrony?

Chapter 4: Spatial Complexity of Fire in an Island-Lake Landscape

This chapter evaluates the distribution of fire events through a combination of techniques involving the theory of island biogeography and fire event similarity.

> Research Questions: (1) How do the fire frequencies on mainland sites compare to island sites? (2) What is the degree of fire similarity between islands, between islands and mainland sites, and between mainland sites? (3) Do the primary components of island biogeography, specifically area and isolation, help explain patterns in fire regimes of islands?

Table 1.3. Definition of common terms used within this dissertation (terms are adapted and expanded from Hargrove et al. 2000; Forman 1995).

Term	Definition
Configuration	Arrangement of spatial elements, often associated with spatial structure or patch structure
Connectivity	Spatial continuity of a habitat or cover type across a landscape
Fragmentation	Breaking up of a habitat or cover type into smaller, disconnected patches
Heterogeneity	Dissimilar elements. For example, mixed habitats or cover types
Synchrony	Coincident changes in the ecological characteristics at spatially or temporally separated populations that influence the co-occurrence of events (Defined in this dissertation as fire events occurring in multiple defined regions in the same calendar year)
Asynchrony	Isolate events that are not shared between spatially or temporally disjunct locations
Disturbance Regime	The cumulative effects of multiple disturbance events over space and time
Fire Occurrence	Number of fires per unit time in a specified area
Fire Frequency	How often the disturbance occurs or its return time
Fire Intensity	The magnitude of the fire disturbance
Fire Severity	The impact of the fire on the environment
Bottom-up Controls	Controls that have strong influences at smaller scales, such as tree, or the stand level. These can include fuel type, arrangement, and amount, weather, and topographic features
Top-Down Controls	Controls that have strong influences at larger scales, such as multi-stand and landscape level. These can include structure of the terrain (landscape configuration) and climate patterns
Fire Event	Evidence of a fire in a particular place
Fire Year	Year with a recorded fire event

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CHAPTER 2: Spatial Synchrony of Fire Occurrence in the Border Lakes Region of Minnesota

Synopsis

Generally, more complex landscapes, such as those with greater heterogeneity or greater fragmentation, have more variable patterns in disturbance. For example, the amount, size, and location of water bodies, rugged topography, or heterogenous vegetation structures can alter the occurrence, spread, and severity of fire disturbance. The Border Lakes region of Minnesota is naturally fragmented by a complex combination of over 1,200 lakes ranging in size from 4 to 4,000 hectares. The history of fire is well-documented in this region providing a unique opportunity to evaluate the amount of shared fire (i.e. fire synchrony) across a naturally fragmented landscape. The objective of this research was to evaluate the spatial occurrence of fire events among spatially disjunct regions to examine synchrony in the historical fire regime of the Border Lakes Region. Data used in this research were developed from 541 fire-scarred red pine (*Pinus resinosa*) trees collected from the Boundary Waters Canoe Area Wilderness and Voyageurs National Park (1489–2016) in northern Minnesota. A complete linkage clustering analysis grouped sampled trees into 14 distinct regions. Similarity matrices of fire occurrence were used to test the relationship between shared fire across the 14 regions and compared to the distance between regions.

Historically, fire occurrence was synchronous with 63% of fires occurring in two or more regions, 49% in three or more regions, and 29% four or more regions. The number of shared fire events between regions did not show a clear relationship with distance. These results suggest that fire event occurrence in the Border Lakes region of

Minnesota were spatially synchronous across the 418,000-hectare region and landscape connectivity did not have a strong influence on the co-occurrence of fires at spatially disjunct regions. This pattern likely exists due to strong casual mechanisms that override the landscape barriers to shared fire occurrence leading to autocorrelation in ecological factors at spatially disjunct regions. Projected changes in climate will likely accentuate the spatial connectivity of fire events in the Border Lakes region resulting in larger, more spatially extensive events. This research adds to the growing number of studies conducted in the area that demonstrate the significance of fire as an ecological process and serves as a useful baseline for considering the spatial patterns and mechanistic controls of the fire regime.

Introduction

Synchrony refers to coincident changes in ecological phenomena at spatially or temporally separated units that influence the co-occurrence of events (Bjornstad et al. 1999; Hudson and Cattadori 1999; Koenig 1999; Buonaccorsi et al. 2001). Both spatial and temporal synchrony have been observed in many ecological phenomena, including predator-prey relations (Stenseth et al. 2004), growth of mammals (Huitu et al. 2003), masting events in plants (Koenig and Knops 2013), insect outbreaks (Williams and Liebhold 2000), and disease epidemics (Viboud et al. 2006). Studies such as these have highlighted how multiple populations in different locations fluctuate in the same way (i.e. spatial covariance), likely reflective of underlying causal mechanisms operating at large scales. For example, three species of oaks in central coastal California, USA show synchrony in annual acorn production, closely tied to patterns in regional spring temperature and rainfall (Koenig 1999; Koenig and Knops 2013). Ecological disturbances such as fire have also been shown to be synchronous over geographically separated units. The timing of fire events has been shown to covary and is often related to the synchronizing effects of mechanistic controls such as climate (Heyerdahl et al. 2001; Liebhold et al. 2004; Kitzberger et al. 2007).

The synchrony of events is a function of environmental correlation and dispersal such that variables at nearby locations are not strictly independent from one another (Legendre and Legendre 1998). For instance, two populations that are in close proximity may experience similar environmental variations and as a result will fluctuate in similar ways (Liebhold et al. 2004). The strength of that synchrony then diminishes as distance between populations increases (Ranta et al. 1995; Sutcliffe et al. 1996; Bjørnstad et al. 1999; Liebhold et al. 2004). The degree of synchrony observed between populations can reveal information concerning the strength and relationship to shared mechanistic controls. For example, Liebhold et al. (2004) evaluated synchrony in species dynamics and suggested that fluctuations in populations may arise from controlling mechanisms such as dispersal among populations, exogenous factors such as climate, and trophic interactions. Generally, the more synchronous dynamics are among populations, the greater the strength of mechanistic controls. The variability that can occur within mechanistic controls generally increases with distance, leading to the distance decay pattern commonly observed (see Figure A.1; Moran 1953; Ranta et al. 1995; Paradis et al. 1999; Haynes et al. 2013). An analysis of synchrony can reveal how variation in controlling mechanisms alter the timing, behavior, and strength of particular events. More specifically, the synchrony of ecological phenomenon and relationship to distance is important to study as it can provide necessary information regarding the dynamics of an ecosystem. Understanding the mechanisms behind spatial synchrony could provide critical information for understanding and managing disturbances, species conservation, insect outbreaks, and disease epidemiology.

The spatial configuration of a landscape can also be an important factor to consider when analyzing patterns of synchrony. The propagation of fire disturbance across a landscape is a function of spatial heterogeneity (Romme 1982; Turner 1989; Turner et al. 1989; Swetnam and Lynch 1993). Generally, more complex landscapes will have a greater likelihood of barriers to dispersal and spread (Bergeron 1991; Larsen 1997; Niklasson and Granström 2000; Heyerdahl et al. 2001; Hellberg et al. 2004). For example, the presence of lakes and streams, changes in slope, aspect, and rock outcrops can impact the spread of disturbance relative to flat, connected landscapes. An element of a landscape's physiography that is particularly important as it relates to fire is the amount and location of water bodies, since water can act as a barrier to fire spread (Nielson et al. 2016). Lakes specifically can act as important firebreaks, limiting the potential spread of wildfires resulting in distinct patterns in the forest mosaic (Nielson et al. 2016). Thus, fragmented landscapes (e.g. greater proportion of lakes) do not burn as uniformly as those with highly continuous fuels. In addition, the proportion of natural firebreaks is often identified as a key variable explaining broad-scale wildfire patterns (Nielson et al. 2016).

Typically, well-connected landscapes will have more spatially synchronous events, compared to landscapes that are more fragmented, assuming that top-down, region-wide mechanisms exert an important control (Opdam and Wascher 2004;

Cushman 2006). This pattern likely exists because locations that are close together experience similar endogenous and exogenous factors (Bjørnstad et al. 1999; Liebhold et al. 2004). Landscape structure and fragmentation can add complexity to this relationship by modifying the distance-decay relationship. Because synchrony is likely influenced by a multitude of factors within or between locations, the more fragmentation or barriers present in a landscape, the fewer shared events (i.e., fire synchrony) should occur between locations.

Disturbance events such as fire can become synchronized, such that the co-occurrence of fires have been observed at spatially disjunct locations. Fire events may become synchronized by factors such as landscape and fuel connectivity, weather conditions, climate mechanisms, interactions with other disturbances, and fuel type, amount, and moisture content (Brown et al. 2001; Liebhold et al. 2004; Kellogg et al. 2008; Yocom et al. 2014; Bigio et al. 2016). These factors can influence the intensity, severity, extent, and timing of fire (Falk et al. 2007). The extent to which fire becomes synchronized at disjunct locations, reflects the relative roles of shared environmental characteristics, the influence of those factors, and the interaction between various mechanisms (Kitzberger et al. 2007; Gill and Taylor 2009). Identifying patterns of fire can reveal important spatial aspects inherent in the fire regime and potential factors that contribute to variations in fire disturbance.

Research Objectives

This research attempts to quantify spatial patterns in the historical fire regime in the Border Lakes region of Minnesota and the degree of shared fire events between spatially separated locations. This landscape provides a setting to investigate the spatial synchrony of fire events owing to the unique topography, vegetation patterns, and well-documented fire history. The landscape is naturally fragmented, with forest patches interspersed with lakes, streams, and wetlands. Fragmentation of the terrain creates an island-lake landscape potentially resulting in greater variability in fire events from one location to another, despite relatively close proximities. Because the landscape is fragmented with many lakes, it likely has a strong impact on the behavior of disturbances that occur within the landscape. Prior research has shown that island-lake landscapes generally have greater variability in fire regimes compared to sites on the mainland or more continuous environments (Bergeron 1991; Arabas et al. 2006; Niklasson et al. 2010; Nielson et al. 2016).

This research addresses how locations with shared fire dates are spatially structured across the study area by evaluating the relationship between shared fire events (fire synchrony) and the distance separating regions. Evaluating spatial patterns in the historical fire regime, using a simplified distance-synchrony approach, can help us to understand the prevalence of shared fire events across the landscape and the possible connection between the natural fragmentation of the landscape and fire. This research uses a fire history reconstruction developed from fire-scarred red pine (*Pinus resinosa* Sol. ex Aiton) trees collected across the Border Lakes region of Minnesota. Specifically, this chapter addresses:

(i) the degree to which fire events are spatially synchronous and

(ii) the relationship between fire synchrony and distance separating regions within the Border Lakes landscape.

Addressing these questions will help us understand how landscape structure, using distance as a proxy, may play a key role in driving the degree of shared fire events between spatially separated locations. In addition, evaluating the spatial aspect of the fire regime can reveal important variations in the dynamics of the ecosystem, particularly patterns of historically synchronous fire events.

Methods

Site Description

The fire history data used in this research are derived from tree-ring samples collected across Voyageurs National Park (VOYA; Kipfmueller et al. 2017) and the Boundary Waters Canoe Area Wilderness (BWCAW; Figure 2.1; Johnson and Kipfmueller 2016; Kipfmueller et al. forthcoming). The study area encompasses about 417,900 ha of land with over 110,900 ha of lakes (~26.5% of the area; Coffman 1980; Heinselman 1996). These two regions are part of a larger forested complex (over 1,000,000 ha) that encompasses Quetico Provincial Park and Superior National Forest. Forested land in the area is comprised of near boreal species with a complex mixture of sub boreal species and northern hardwood forests (Heinselman 1973; Coffman et al. 1980). Common species in this region include, *Pinus strobus* L. (white pine), red pine*,* *Pinus banksiana* Lambert (jack pine), *Populus tremuloides* Michx. *P. grandidentata* Michx. (trembling and bigtooth aspen, respectively), *Betula paperifera* Marshall (paper birch), *Picea glauca* Moench Voss. (white spruce), *Thuja occidentalis* L. (northern white cedar), *Abies balsamea* L. Mill (balsam fir), and *Acer rubrum* L. (red maple) (Heinselman 1973; Grigal and Ohmann 1975; Weyenberg and Pavlovic 2014).

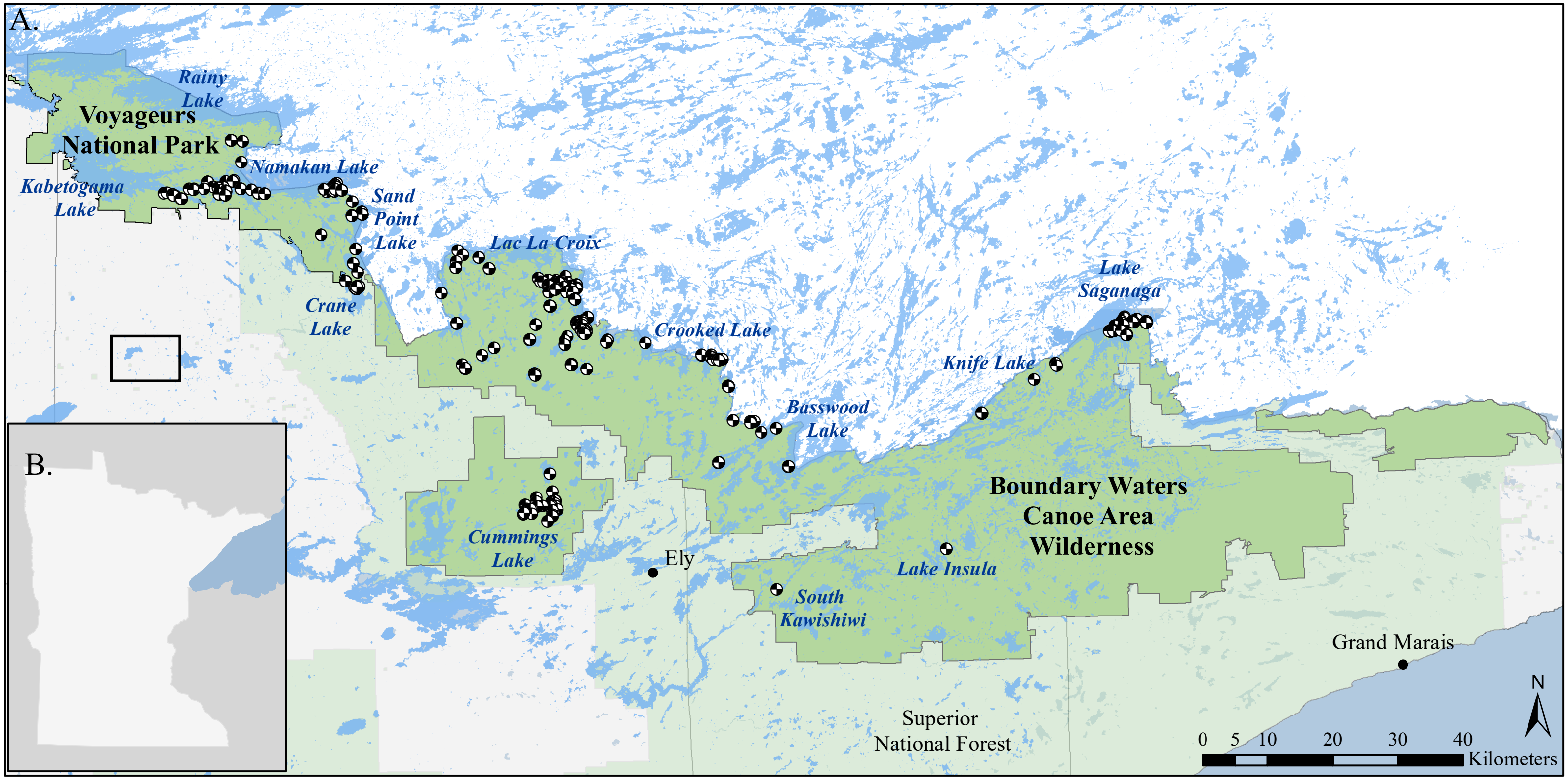

Figure 2.1. (A) Study area map depicting the point locations of fire-scarred trees collected for reconstructing the fire regime. The boundary of the study area is outlined and shaded in green. (B) Location of the study area within Minnesota.

The climate of the region is considered northern continental with an average annual precipitation of around 63 cm that primarily falls as rain between the months of May through September (Arguez 2010). Snow accumulation begins in early November and typically lasts into May, with 145 mean number of snow days. Average July maximum temperature ranges from 26.6°C in the western portion of the region to 21.3°C in the eastern portion and minimum January temperatures range from -24.2°C to -15.6°C (Arguez 2010).

Fire was historically an integral disturbance in the Border Lakes region of Minnesota. Prior research has indicated a mixed fire regime with frequent low severity fires punctuated by less frequent, large stand-initiating fires (Heinselman 1973; Johnson and Kipfmueller 2016; Kipfmueller et al. 2017). However, the effects from land use associated with Euro-American colonization has limited this key disturbance process over the last century influencing stand structures and forested vegetation (Heinselman 1973; Frelich and Reich 2009; Margruder et al. 2013; Paulson et al. 2016). During the early and mid-twentieth century fire-management plans in the Border Lakes region emphasized fire suppression and exclusion methods as an important forest management tool (Coffman 1980; Alexander and Dubé 1983). These management practices have since led to fuel accumulation and altered stand composition (Paulson et al. 2016). Over the past several decades, the importance of management through fire practices has been emphasized (Coffman 1980; Heinselman 1996; Weyenberg and Pavlovic 2014), however, fire management activities remain largely focused on fire exclusion and suppression due to sociopolitical factors and limited funding to implement fires as a management tool.

The impacts from fire suppression and exclusion in the Border Lakes are mirrored in landscapes across the western United States and Canada. Research has revealed a strong relation between fire suppression practices and the increase in fuel loads in many forested landscapes (e.g., Backer et al. 2004; Flannigan et al. 2009; Pechony and Shindell 2010). This change has led to an increased threat of large, catastrophic wildfires across the United States owing to the increased build-up of flammable materials (Parks et al. 2016; Davis et al. 2017; Schoennagel et al. 2017). Additionally, as temperatures continue to rise due to anthropogenic climate change, the amplitude and duration of extreme fire weather is likely to increase, compounding the impact of increased fuel loads (Abatzoglou and Williams 2016). The relative impacts of suppression and climatic change in the Border Lakes region is less known in relation to changes in fire frequency and intensity, yet management targeted to reduce the threat has been echoed in prior research (Heinselman 1996 Frelich and Reich 2009).

A site-based, annually resolved fire history reconstruction is used for this research, collected from VOYA (Kipfmueller et al. 2017) and BWCAW (Johnson and Kipfmueller 2016; Kipfmueller et al. forthcoming). This dataset consists of 541 georeferenced fire-scarred red pine trees collected between 2012–2017, including 128 trees from VOYA, and 413 trees from BWCAW (Figure 2.1). All samples and individual fire scar events were dated to an annual year using standard dendrochronological methods (Stokes and Smiley 1968; Dieterich and Swetnam 1984). Data used in this study was collected as part of ongoing research efforts to reconstruct the historical fire regime of red pine systems in the Border Lakes region and investigate mechanisms influencing fire occurrence (Johnson and Kipfmueller 2016; Kipfmueller et al. 2017; Kipfmueller et al. forthcoming).

Cluster Analysis

To evaluate the fire history of the BLR fire scar data were grouped into regional designations based on location of the sample. Grouping samples allows for more effective analysis of the fire history as the fire event data for each location can be filtered and/or assessed for patterns in small versus large fires. For this research, all fire-scarred trees were grouped into regions of relatively equal area and similarity in the number of samples collected. To achieve this, complete linkage clustering was used, a method of hierarchical clustering where trees are combined first at the shortest pairwise distance and then further grouped together by increasing distance (Legendre and Legendre 1998; Camiz and Pillar 2007). Complete linkage clustering generates compact clusters of trees that are approximately equal in diameter, thus producing regions that are of equal size ideal for this comparative analysis. Complete linkage cluster analysis was performed using the *vegan* package (Oksanen et al. 2013) in R. Trees were grouped into regional designations by Euclidean distance at a threshold of 15 km to balance the number of trees included in each regional cluster while maintaining a sufficient number of distinct regions to permit a robust analysis (Wilks 2011). While other thresholds were evaluated (1km, 5km, 10km, 20km, and 25km), a distance of 15km was chosen for this research because it produced regional clusters with an approximately equal number of trees. Larger cluster designations (e.g. larger than 15km) resulted in trees being grouped into too few regions with significant variation in the number of trees included (e.g. 1 to 185). Whereas smaller cluster size designations produced too many regions where a majority of them included only one or two trees, resulting in the removal of over half of the defined regions due to low sample depth.

Synchrony Analysis

In order to evaluate synchrony, most analyses involve measurements overlapping in time and taken at multiple locations over a geographical area (Koenig 1999). These analyses attempt to discern patterns in spatiotemporal variation of ecological variables over large geographical areas, revealing the spatial autocorrelation (synchrony) of ecological phenomena. A common approach for determining synchronous fire events is by filtering the fire history by including only fire dates that occur on greater than a determined percentage. Ten percent and 25% filtered fire histories are typically used to represent the fires that are likely to be progressively more widespread with a study site. For example, fire events are considered synchronous when 25% of the samples/trees/sites are scarred in a given year (Swetnam and Baisan 1996). By applying these filters, smaller/spot fires which may have only impacted a few trees are eliminated from the analysis with emphasis on those fires that are more widespread across a landscape. The main objective for applying these filters is to better understand the Mean Fire Interval and Fire Frequency of the study area (Swetnam and Baisan 1996). In the early stage of data analysis I did use the 10% and 25% filters on the fire event data, however while doing so I was noticing that (1) because there are so many fire event years, the 10% and 25% were too small of filters to use at a given region; (2) I was noticing that because there are varied sample depths at a given site, the filters widely ranged from one to another (25% in one site varied a lot from 25% in another site which increased disparity between sites).

In addition, the main focus of using these filters is to produce fire metrics, MFI and fire frequency, that are more representative of widespread fire events (eliminating small/isolated fire events). For my research, I am less concerned with the fire metrics (MFI and fire frequency) and more interested in the spatial and temporal pattern of shared fire events. In the initial stages of analysis, I found that the common fire scar filters were not representing the spatial and temporal patterns inherent in the dataset of the BLR's fragmented landscape. Instead, I choose to test shared fire and patterns of asynchrony versus synchrony using the number of shared fire events between regional designations. By testing the number of shared fire events between regional designations I was able to test more effectively pure number of shared fire events in relationship to distance. This also reduced the problems I was encountering when I was comparing regions that varied significantly in sample size.

For this research, the degree of shared fire events across the landscape were evaluated using two matrices: (1) linear distance between all pairs of fire history locations, and (2) a similarity matrix that measures the similarity in fire history (i.e. shared fire event dates) between those locations. The similarity matrix can then be plotted against the derived geographic distance to visualize how similarity in shared fire events changes as a function of increasing distance.

For each regional designation produced in the cluster analysis, a centroid was defined and the distance between all region centroids was calculated using the *vegan* package in R (Oksanen et al. 2013) and converted into a matrix. The fire event years for each region were then identified and converted into a presence-absence matrix (0 indicating no fire, 1 indicating fire). Three measures of similarity were calculated between the regions to evaluate synchrony including: the percentage of unique fire events occurring in each region, the number of shared fire events between each region, and the Jaccard similarity. The percentage of unique events represents those fires that only occur within one of the defined regions and in this study was considered an asynchronous fire event. The number of shared fire events between regions was calculated and evaluated for fire events shared between two or more regions, three or more regions, and four or more regions (fire events of increasing spatial synchrony). Finally, the Jaccard similarity index (Sj) was calculated as:

$$Sj = \frac{a}{a+b+c}$$

where a is the total number of fire events present in the two regions being compared, b is the number of fire events only present in the first region, and c is the number of fire events only present in the second region. All similarity metrics were calculated in R using the *simba* package (Jurasinski and Retzer 2012). A correlation plot representing Jaccard similarity and number of shared fire events for each pairwise region was created to evaluate similarity relationships between each region. The measures of similarity were then plotted against distance to identify patterns between synchrony in fire events and the distance separating them. A locally weighted regression was fit to each scatter to assess the similarity-distance relationship producing a LOESS curve. The locally weighted regression fits a line through a scatter diagram, minimizing variance or prediction error and makes no *a priori* assumptions about the form of the relationship (Cleveland et al. 1992).

Similarity in fire events between regions was calculated for both the full fire history record (1489 to 2016) and for the truncated period of 1750–1900. To account for low sample depth in the early portion of the record (lack of preserved samples due to decay and subsequent fire events) and low sample depth in the latter part of the record (fire suppression period and the inability to sample living trees), I calculated the percentage of fires recorded by one region, two or more regions, three or more regions, and four or more regions for the 1750–1900 period. The 1750–1900 time period more accurately reflects the part of the fire regime that is reconstructed with the highest level of confidence.

Results

The fire history reconstruction for the study area extends from 1489 to 2016, with 217 unique fire events and a mean fire interval of 34.1 years based on the individual trees. For detailed fire history methods and additional results that are not reported here see: Johnson and Kipfmueller 2016; Kipfmueller et al. 2017; and Kipfmueller et al. forthcoming. The cluster analysis resulted in 16 distinct regions (Figures 2.2 and 2.3). Two of the 16 defined regions, South Kawishiwi and Lake Insula, were removed from the analysis due to low sample depth (one tree and two trees, respectively). Similarity analysis was then performed on 14 of the defined regions. The fire history for each region was compiled into a presence-absence matrix and resulted in the number of fires recorded in each region ranging from nine to 92 (Knife Lake and Central Lac La Croix, respectively; Table 2.1).

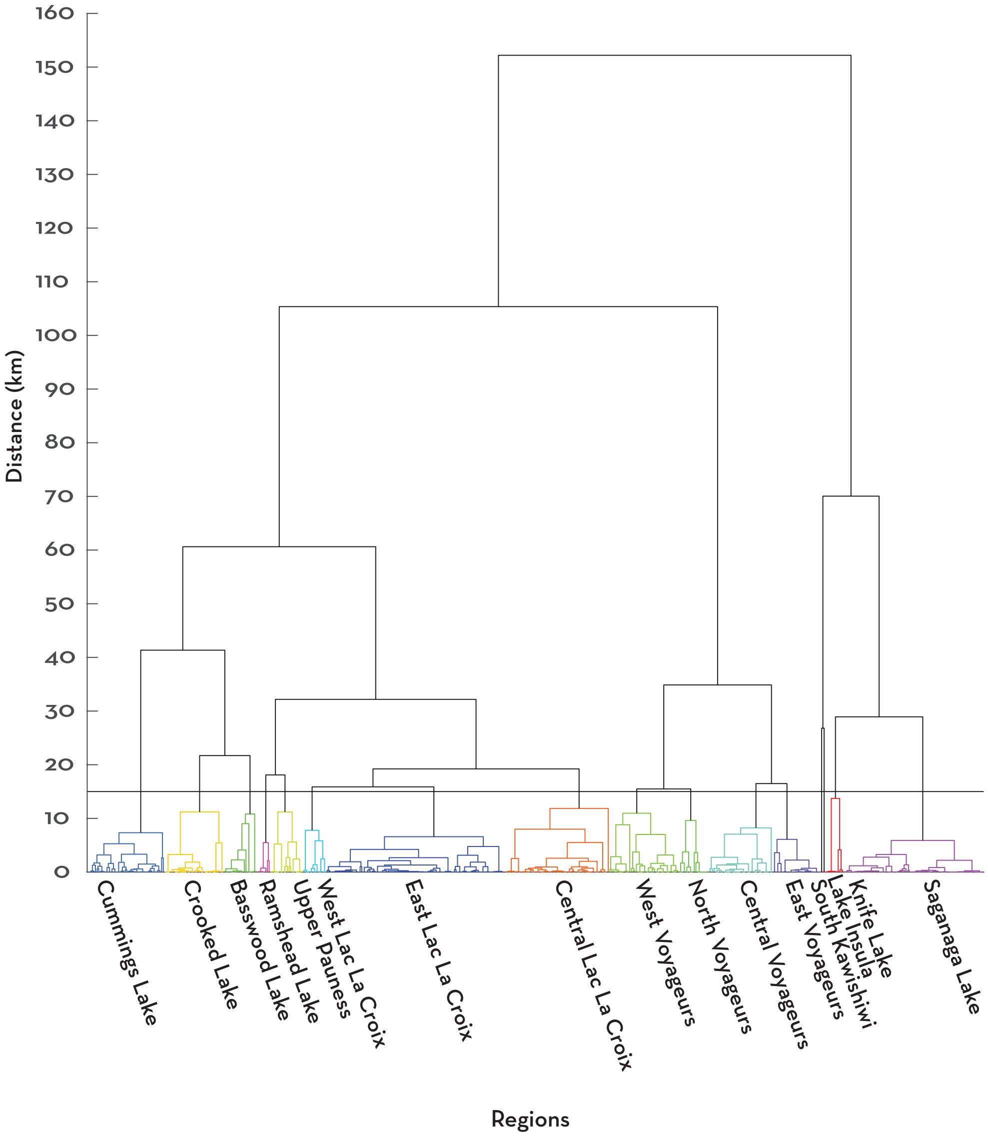

Figure 2.2. Results of a complete linkage cluster analysis based on sample locations. Sixteen regions (labeled) are defined at the 15km threshold (horizontal line).

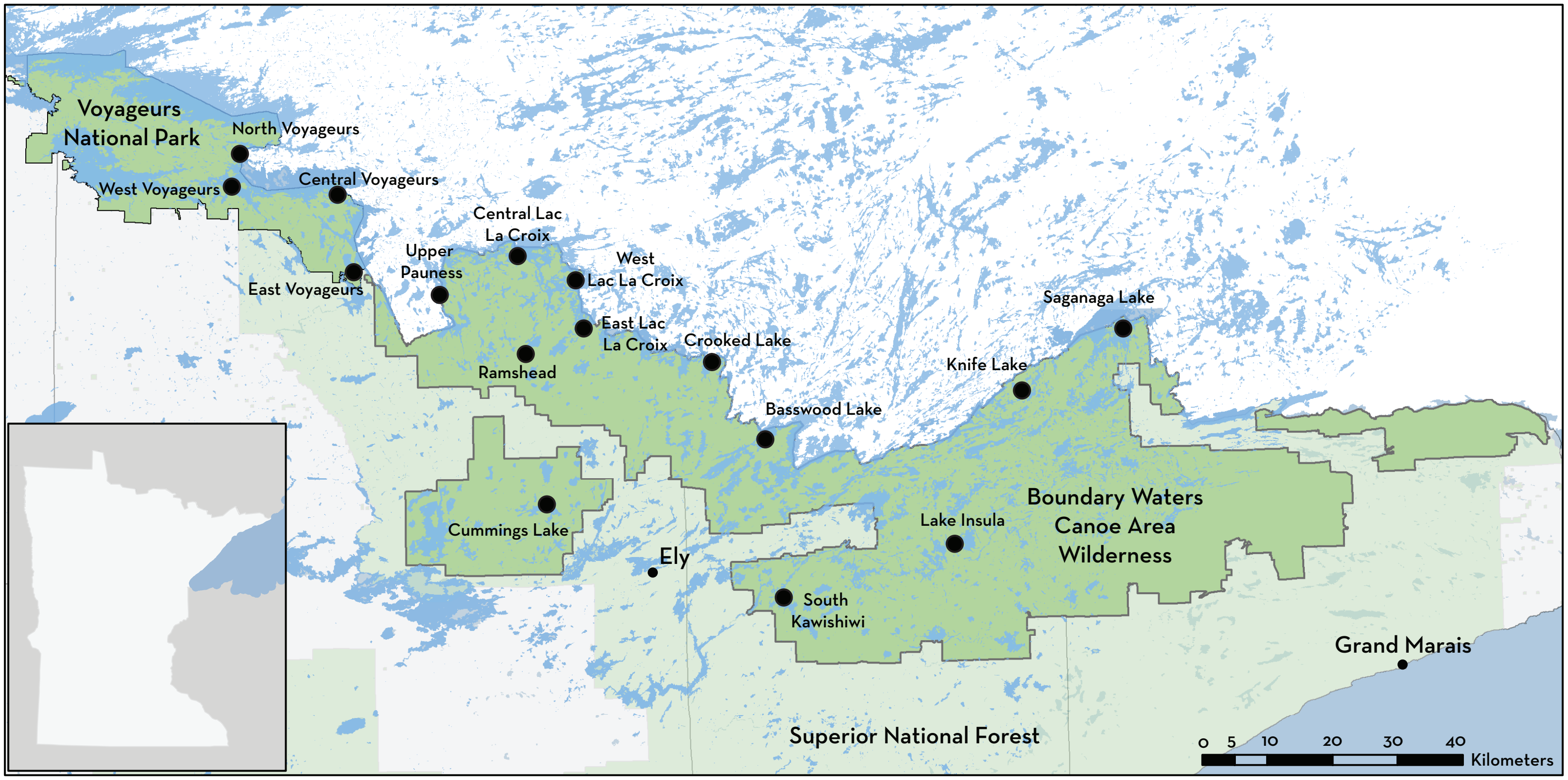

Figure 2.3. Regional centroids defined by the complete linkage cluster analysis.

Table 2.1. Characteristics of regional cluster groupings and percent of shared fire with other regions.

Cluster Name	**# of Samples**	**Total # of Fires**	**% of Unique Fires** [†]	**% Fires 2+ Regions**	**% Fires 3+ Regions**	**% Fires 4+ Regions**
Cummings Lake	46	26	0.12	0.88	0.69	0.54
Upper Pauness	14	11	0.09	0.91	0.64	0.46
Ramshead Lake	8	13	0	1	0.69	0.54
East Lac La Croix	108	48	0.12	0.88	0.71	0.4
West Lac La Croix	20	23	0.13	0.87	0.61	0.43
Central Lac La Croix	63	92	0.22	0.78	0.53	0.37
Crooked Lake	36	41	0.1	0.9	0.66	0.44
Basswood Lake	20	30	0.03	0.97	0.63	0.53
South Kawishiwi*	1	4	0	1	1	0.75
Lake Insula*	2	2	0	1	1	1
Knife Lake	11	8	0	1	0.88	0.88
Saganaga Lake	84	67	0.22	0.78	0.58	0.37
West Voyageurs	41	46	0.15	0.85	0.7	0.46
North Voyageurs	19	25	0.04	0.96	0.72	0.56
Central Voyageurs	39	60	0.17	0.83	0.68	0.48
East Voyageurs	29	43	0.16	0.84	0.53	0.47

* Removed from the regional analysis due to low sample depth

[†] Unique fire events are those that are only recorded in one region.

Synchrony of Fire Events

Thirty-six percent of the recorded fire events (79 events) occurred in only one region, while 64% were shared between two or more regions (Figure 2.4). Individual regions varied in the number of unique fire events, ranging from 3% to 22% (Basswood Lake and Saganaga Lake, respectively; Table 2.1). For the 1750–1900 period, the percentage of unique fire events was 21.1%, while the percentage of fire events that occur in two or more regions (i.e. synchronous fires) for the same time period is 78.9% (Table 2.2). Nearly half of the fire events burned in three or more regions and about 29% of the fire events were present in four or more regions (Table 2.2). Examples of synchronous fire event years include: 1804 (71%, 10 of the 14 regions), 1863 (57%, 8 regions), and 1864 (64%, 9 regions). Fire event years recorded in 50% of the regions were 1682, 1736, 1739, and 1895 (Figures 2.5 and 2.6 and 2.7).

Table 2.2. Degree of fire synchrony by analysis period.

Time Period	# Fire Events	% Unique Fires	% of Fires in 2 + Regions	% of Fires in 3 + Regions	% of Fires in 4 + Regions
Full Period	217	35.9%	64.1%	36.4%	21.7%
1750–1900	138	21.1%	78.9%	49.2%	28.9%

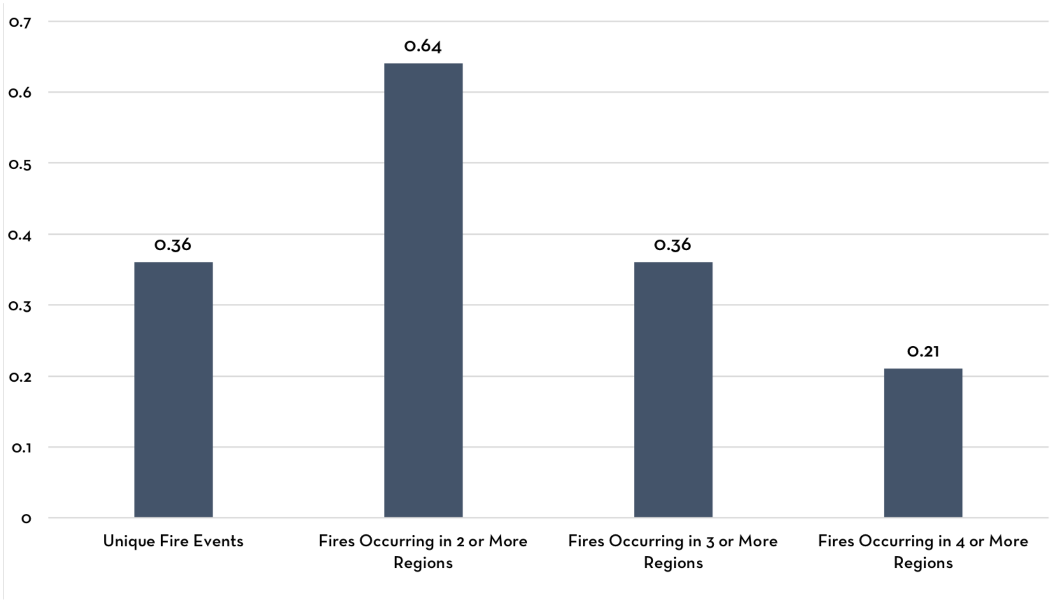

Figure 2.4. Proportion of fires shared within a certain number of regions considered.

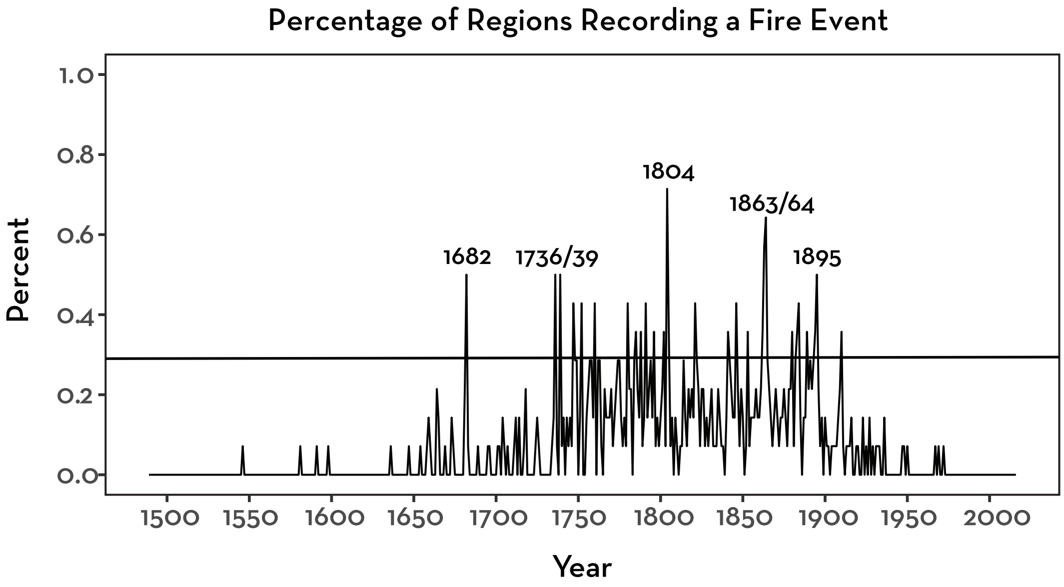

Figure 2.5. Percentage of the 14 regions recording the same fire event (1489–2016). Fires that are recorded in 50% or more of the regions (seven or more regions) are labeled and the black horizontal line marks where four or more of the regions (28.6%) are recording a fire event.

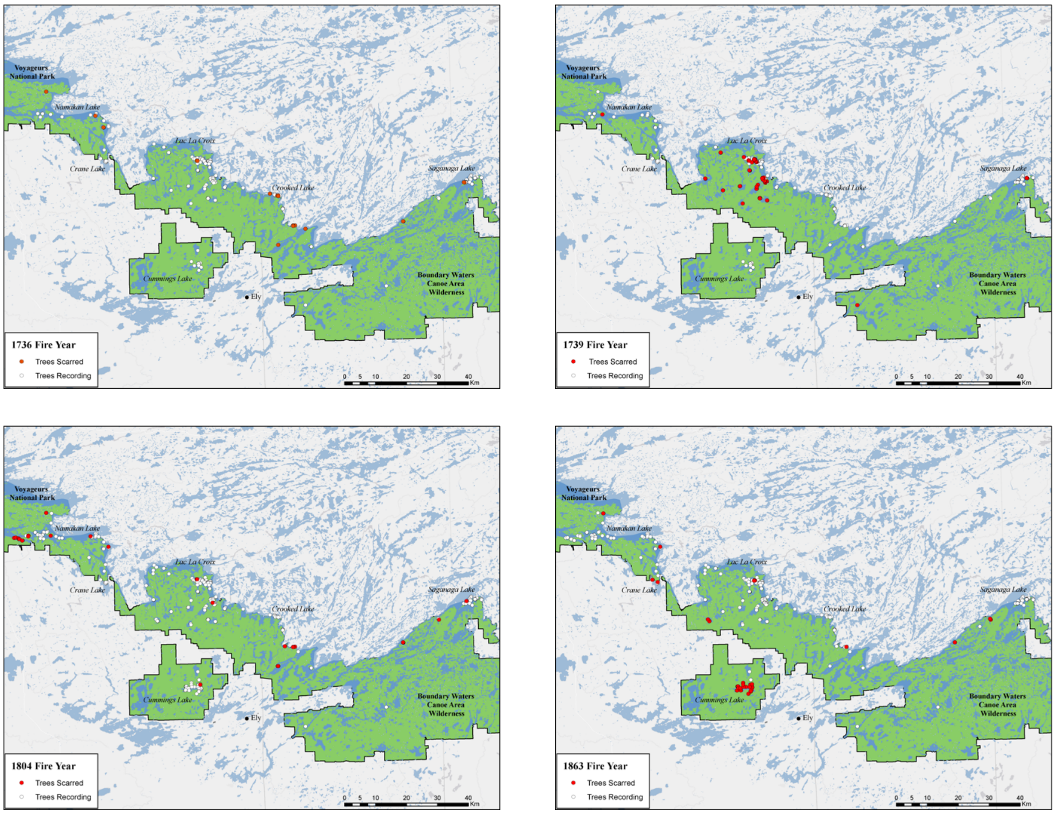

Figure 2.6. Samples recording fire (red dots) in four regional fire years: 1736 (number of samples = 33; number of regions = 7), 1739 (number of samples = 77; number of regions = 8), 1804 (number of samples = 39; number of regions = 10), and 1863 (number of samples = 55; number of regions = 8).

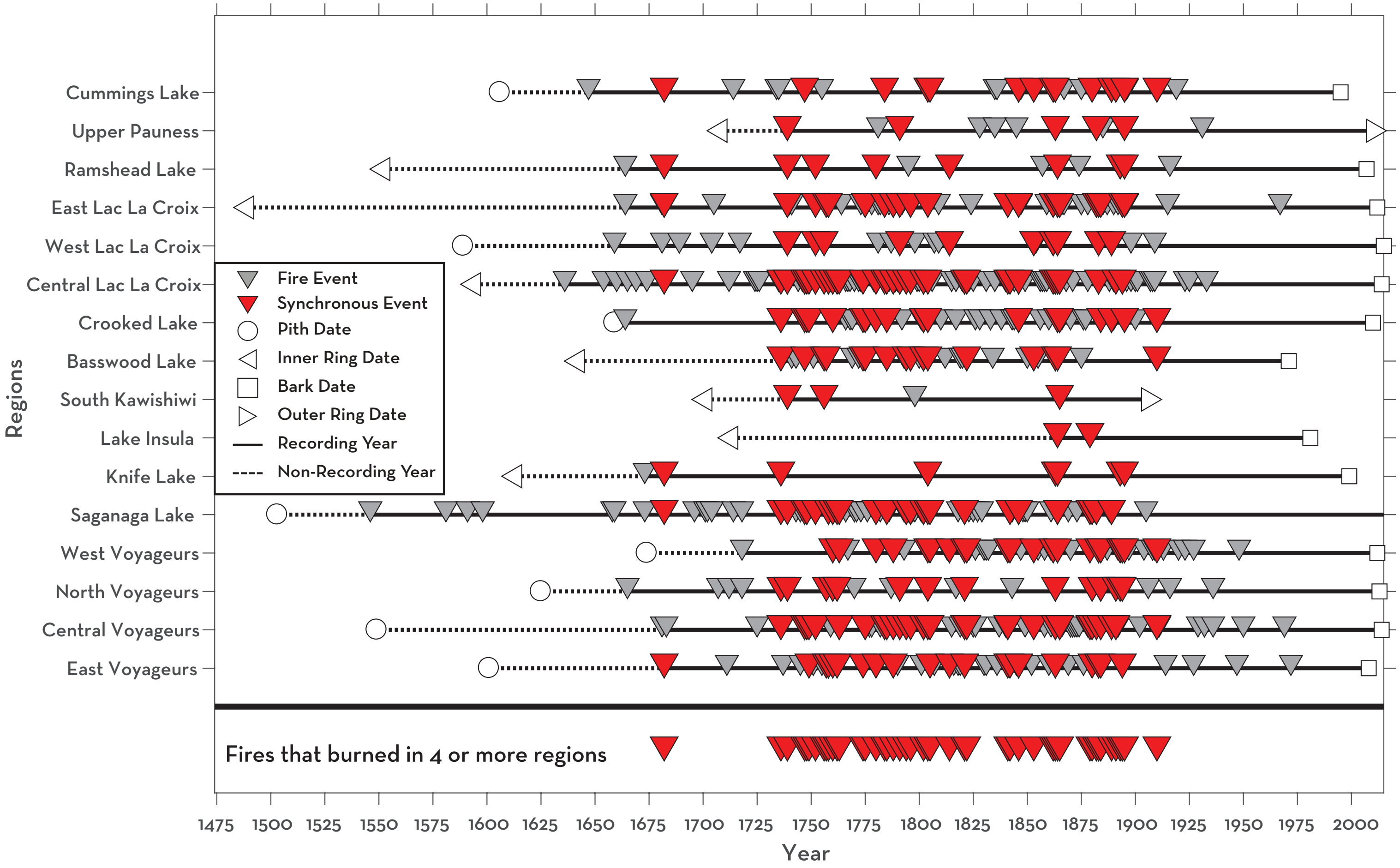

Figure 2.7. Regional fire chart depicting all fire events (grey triangles) and fires that are recorded in four or more regions (red triangles).

Similarity and Distance

Pairwise relationships between regions reveal that some regions are more similar than others (Figure 2.8). For example, Saganaga Lake and Central Lac La Croix have a relatively high degree of similarity, as well as East Lac La Croix and Central Voyageurs. However, there does not appear to be a clear relationship when comparing all possible pairwise combinations of regions (Figure 2.9). In general, regions that are closer in proximity are more similar, however this tends to vary and be mostly driven by a few geographically close regions sharing few fire events (e.g. Basswood Lake and Ramshead). On the other hand, several regions that are far apart are similar. For example, Central Voyageurs and Saganaga Lake are 122 km apart and have 21 fire events in common (Jaccard similarity of 0.198; Figures 2.8 and 2.10). Some regions have low similarity with all other regions, such as Upper Pauness (Figure 2.8), which shares between one to six fires with other regions (West Voyageurs and East Lac La Croix, respectively) and has Jaccard similarity values ranging from 0.017 to 0.117 (West Voyageurs and Knife Lake respectively; Figure 2.8).

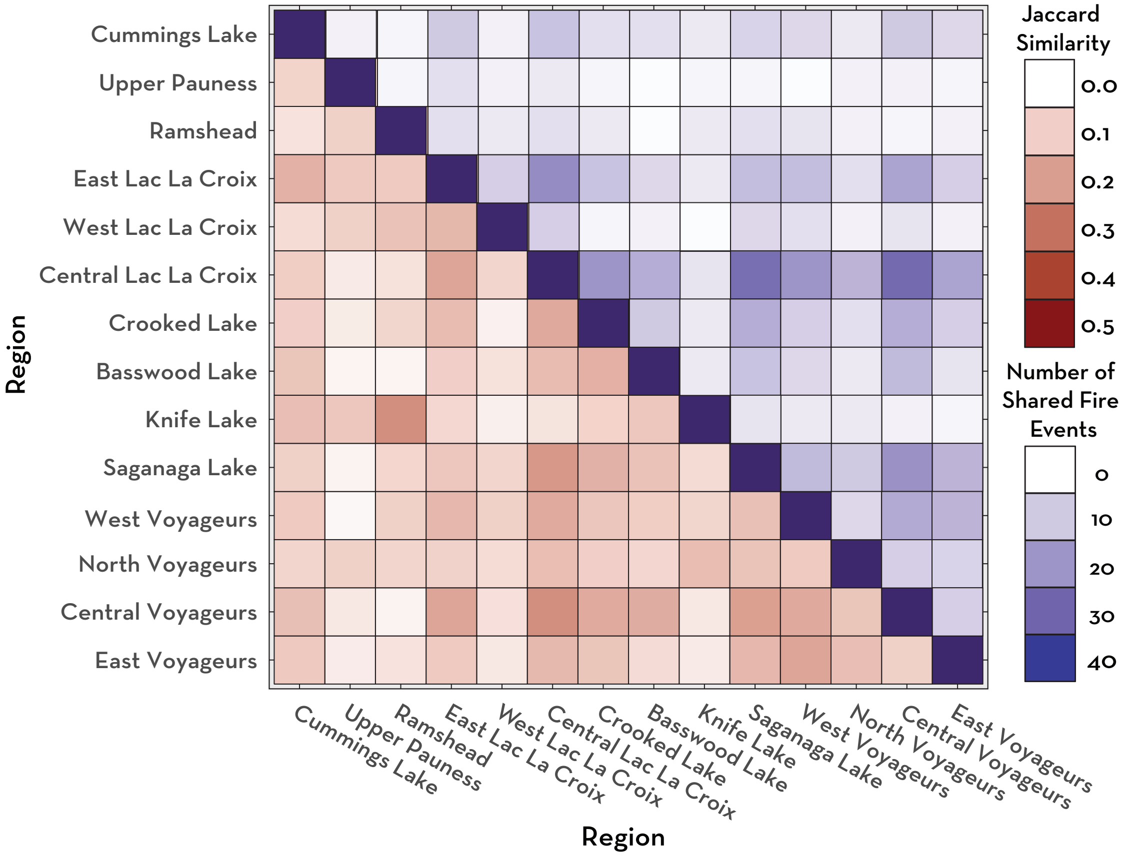

Figure 2.8. Lower plot (red values) represents Jaccard similarity in shared fire events between regions. Upper plot (purple values) represents number of shared fire events between regions.

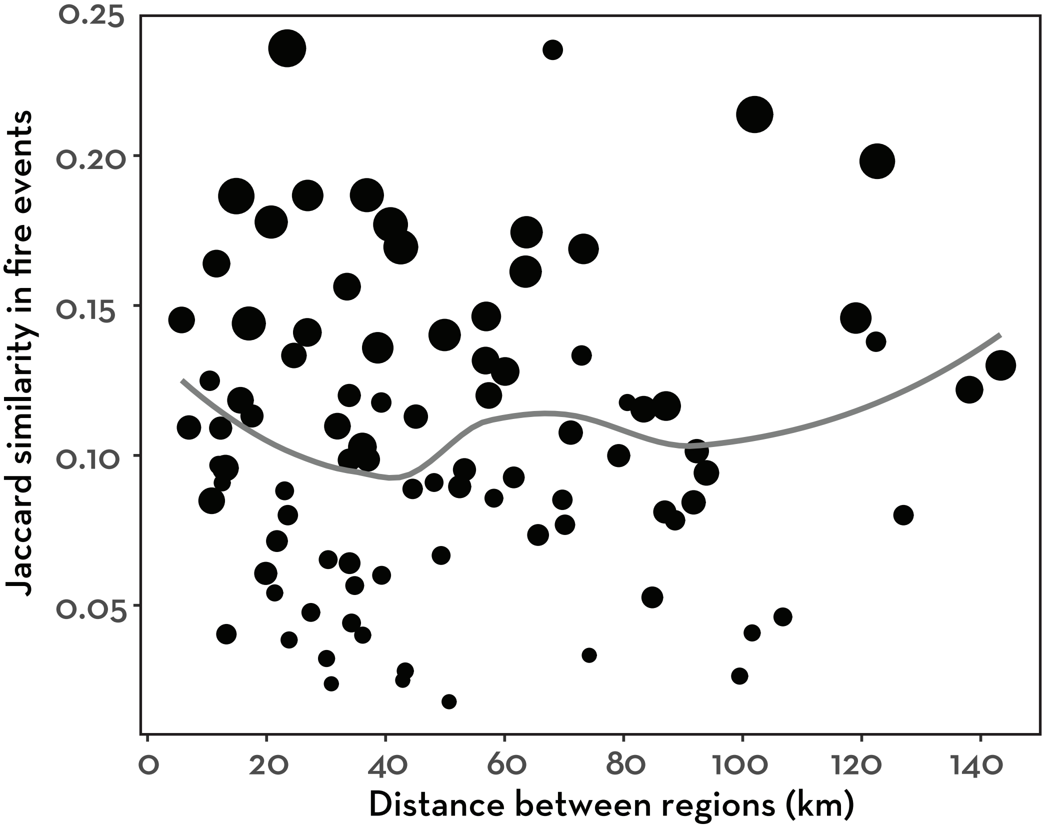

Figure 2.9. Jaccard similarity in fire events between regions and distance separating them. The size of the circle reflects number of shared fire events between the regions with larger circles representing greater shared fire events. Grey line represents the loess smoothed relationship.

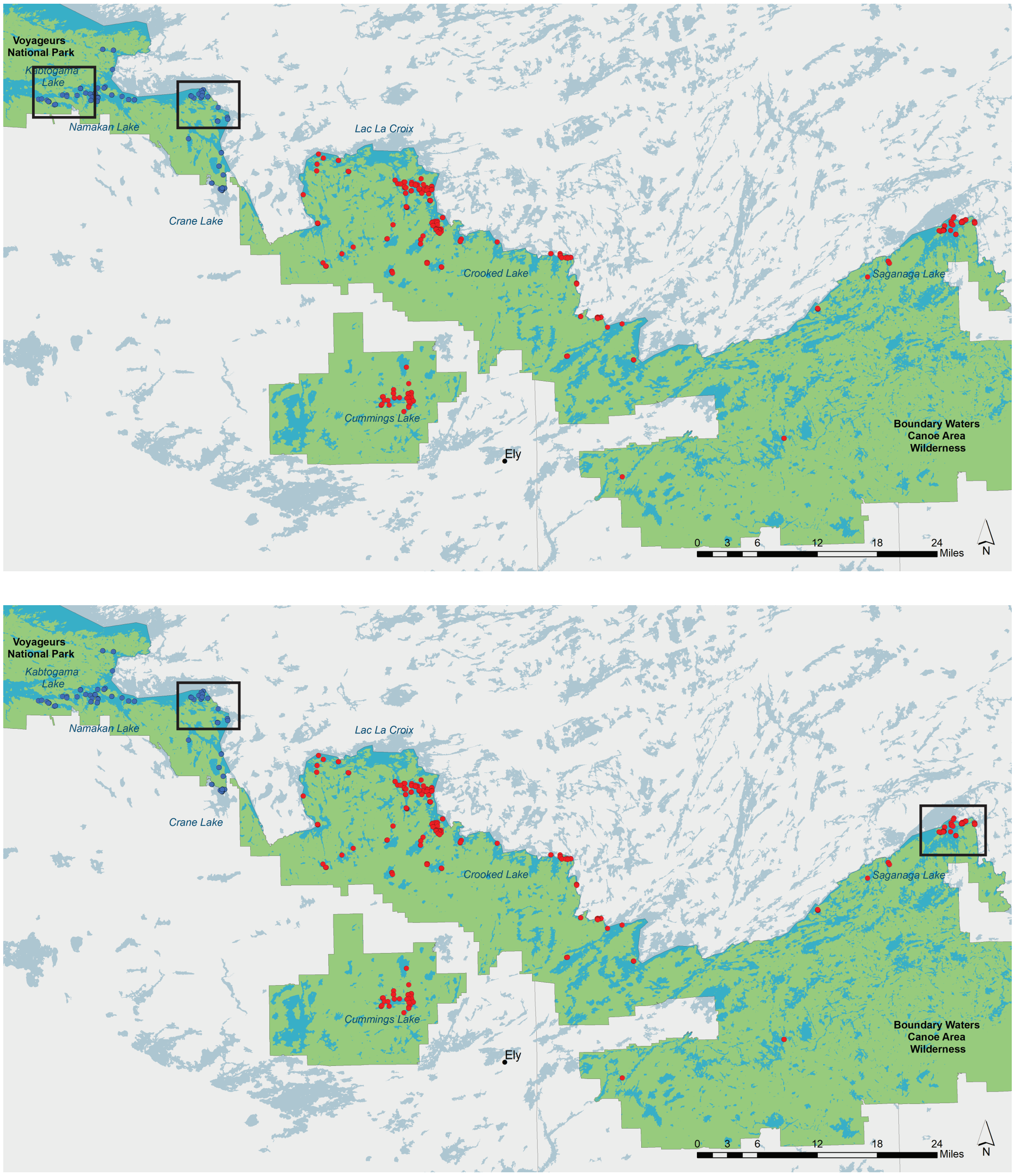

Figure 2.10. Top panel: Central Voyageurs and West Voyageurs, 16 common fire years, 21 km apart, and a Jaccard similarity of 0.178. Bottom panel: Central Voyageurs and Lake Saganaga, 21 common fire years, 122.6 km apart, and a Jaccard similarity of 0.198.

Discussion

The frequency of fire occurrence and the degree to which fire events are shared between disjunct regions in the Border Lakes is evidence for the significant role of fire in this landscape. Considering the distance between the defined regions, fire synchrony results are greater than might be expected when these results are compared with similar studies (Bergeron 1991; Niklasson et al. 2010; Stambaugh et al. 2018). The analysis on the distance between regions and shared fire events did not reveal a clear linear relationship (Figure 2.9). In addition, Jaccard similarity between highly separated regions is often similar to those closer together (Figure 2.8). For example, Central Voyageurs and West Voyageurs are approximately 21 km apart, share 16 fire event years (out of a total of 99 unique fires recorded between the two regions), and have a Jaccard similarity index of 0.17. In contrast, Central Voyageurs and Saganaga are 123 km apart, share 21 fire event years in common (out of 108 fire events recorded between the two regions), and a Jaccard similarity index of 0.198. It is likely that this pattern exists due to strong top-down mechanisms that override local barriers to fire spread or shared fire occurrence leading to autocorrelation in ecological factors at spatially disjunct regions (evaluated in Chapter 3 of this dissertation). For example, extreme climate events, such as consecutive drought years can synchronize endogenous and exogenous factors within the forested landscape, thus leading to shared fire events (Heyerdahl et al. 2001; Kitzberger et al. 2007; Gill and Taylor 2009).

The research presented here evaluates the relationship between distance and patterns in the fire regime. Typically, as distance between two objects increases the similarities between them decreases, reflected as a negative exponential relationship

(Koenig 1999; Liebhold et al. 2004; Stambaugh et al. 2018). This pattern is related to the ecological processes that influence the ecosystem that become more variable as distance increases. Decreasing similarity with distance is well replicated in ecology and fire history research. For example, a recent study by Stambaugh et al. (2018) evaluated the fire history across pine forests in central Pennsylvania. For the 12 sites that were evaluated, Jaccard similarity in fire events decreased with distance and the greatest distance separating sites was around 200 km (compared to 140 km for the Border Lakes). It would be expected that shared fire events between nearby locations should be less common in the Border Lakes, considering the landscape consists of over 1,200 lakes ranging in size from 4 to 4,000 ha and make up over 25% of the landscape. Despite the many barriers to fire spread present in the BRL, there is no clear relationship between shared fire events and distance.

Niklasson et al. (2010) evaluated the fire regime in a mainland-island landscape located in south-east Sweden. They hypothesized that the spread of fire from mainland sites to islands or between islands should be rare. To evaluate this, they collected data from 36 mainland sites and 18 island sites spanning 1536–1999. Fire spread was minimal from the mainland to the islands and between islands as well. Bergeron (1991) studied a similar island-mainland landscape located in northwestern Quebec, encompassing an area of about 200,000 ha. A total of 41 island sites and 114 lakeshore sites were sampled. From 1593–1988, 82 fire event years were recorded with 37 fire event years recorded on the lakeshore sites and 56 on islands. Shared fire events between islands and lakeshore sites (eight fire events) only occurred on islands that were within 1 km of the lakeshore. Fire events were also not shared between islands, showing asynchrony of fire in this study area. Comparing results from the Border Lakes landscape to those in the Niklasson et al. (2010) and Bergeron (1991) studies, the number of fire events recorded, and number of fire event years shared between regional designations is higher. The Border Lakes fire history reconstruction revealed 217 fire years spanning from 1489 to 1972 (first and last fire event year; with 94 fire events between 1800 and 1899), while results from Niklasson et al. (2010) showed 100 fire events from 1536–1999, and Bergeron (1991) had 82 fire event years from 1593–1988. Both of the fire history results from Sweden and Quebec revealed that fires occurred in about 20% of the years recorded, while 50% of years in the Border Lakes recorded a fire event. Shared fires are also more numerous between disjunct regions, with over 64% of the fire events being shared between regional designations.

All regions have greater synchrony of fire events (fire events shared with two or more regions) compared to asynchronous fire events (unique to that region). However, there does appear to be regional differences in the amount of fire synchrony and asynchrony. For example, Saganaga Lake and Central Lac La Croix regions have the greatest percentage of unique fire events (asynchronous events) at 22% (Figure 2.11). It is important to note that both of these regions also have the greatest number of total fires recorded. Generally, the greater the number of fires recorded in a region, the greater the percentage of asynchronous fire events. While total number of fires recorded in a region is related to the degree of unique events, the relationship between the number of samples present in a region and number of synchronous events is less clear. For instance, the East Lac La Croix region has the greatest number of samples present in the 15km cluster (n = 108), however only has 48 fire events recorded, with 12% of those unique to that region.

In comparison, the Central Voyageurs region, has 39 samples, and has 60 fire events recorded, with 17% of those unique to that region and 48% of the 60 fires shared with four or more regions.

Overall, historical fire events in the Border Lakes region of Minnesota were numerous with a number of events being shared across the larger landscape. Results indicate that even though the landscape is generally fragmented with numerous lakes there is a high degree synchrony between disjunct regions. Numerous analyses, ranging from population dynamics to fire history research, has shown that geographic synchrony in environmental factors decline with increasing distances (Ranta 1995; Koenig 1999). This pattern, however, is not evident in the number of shared fire events in the Border Lakes region.

This research does not consider the change in synchrony between regions over time, or whether certain regions are more or less synchronous over specific time periods. Results from this research also do not quantitatively address whether the synchrony of fires in the Border Lakes landscape is statistically unexpected given results from other studies done in landscapes with more or less fragmentation. Instead this research attempts to quantify the spatial patterns in the historical fire regime and the degree of shared fire events between spatially disjunct regions. While the synchrony of fire events indicates that multiple regions recorded a fire event in the same year this research does not address or imply causal ignition agents (see chapter 3 of dissertation). In addition, when two disjunct regions record a fire event in the same year, it is unknown whether the fire

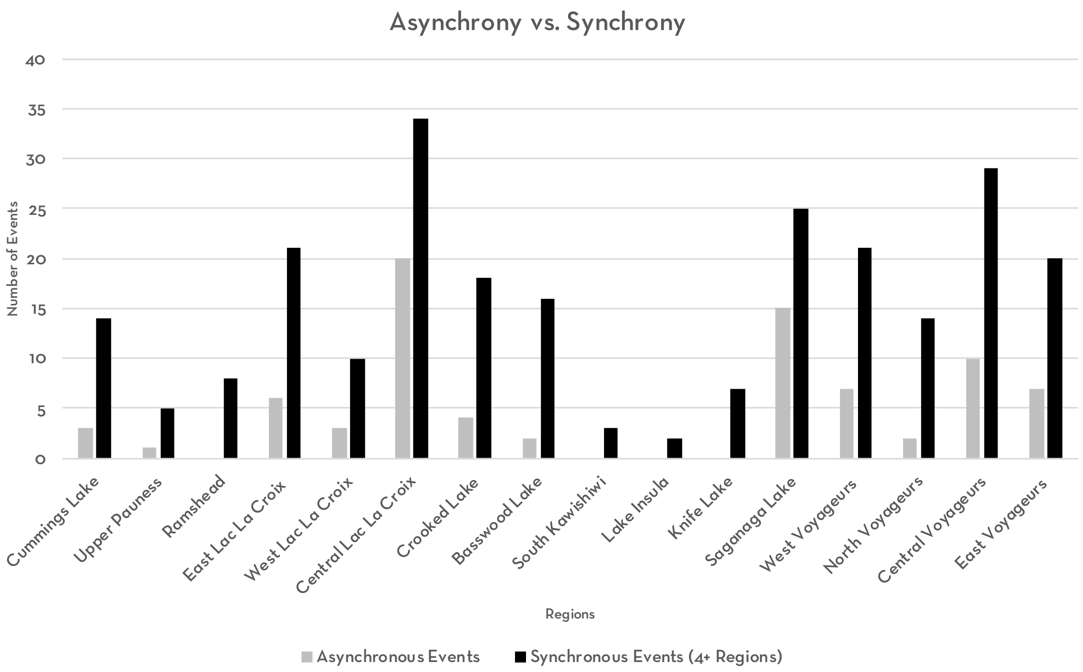

Figure 2.11. The number of asynchronous fire events (unique to that region, grey bars) vs synchronous fire events (fire events that are shared between 4 or more regions, black bars).

started from one single ignition and spread, fire spotted into stands, or if those fire events are the result of separate ignitions. Ignition data (point of ignition) cannot be reconstructed, therefore, samples recording a fire in the same year may be the result of spread, spotting, multiple ignitions, or a combination of both. In this research, shared fire events between multiple regions is an indication of shared fire occurrence and the synchrony of events yet it does not imply fire spread between regions.

In recent years there has been evidence that in the Border Lakes larger wildfire events do occur from both a complex of multiple ignitions and from a single ignition (both natural and human caused) that results in fire spread/fire spotting. For example, the Famine and Red Eye fires in 2006 were part of a complex of lightning fires started in September. In total eight fires were detected on the Gunflint and Tofte Ranger Districts with most fires the result of lightning. The Cavity Lake fire, which was part of this wildfire complex had lots of spotting to nearby islands in the Seagull Lake area. The Ham Lake fire of 2007, which began from an unattended campfire in May also had a lot of fire spotting to islands, fueled by a dry spring and strong winds.

Fire occurrence is spatially synchronous across the 418,000-ha region indicating shared mechanisms influencing disturbance at geographically separated locations. Such mechanisms may include climate, vegetation, time since disturbance, and topographical features. While the mechanisms of the fire regime are not studied in this chapter, prior research has demonstrated the significance of drought leading to large (extensive) fire years (Kipfmueller et al. 2017; Johnson and Kipfmueller 2016). Drought events likely synchronize fire events by influencing fuel moisture loads at regional scales, increasing the likelihood of ignition and/or spread.

Conclusions

The number of synchronous of fire events in the Border Lakes region of Minnesota is higher than asynchronous events (64% of fire events occurring in two or more regions) and is interesting considering that more than 25% of the landscape is water. Developing a context by which fire events occurred among disjunct regions is critical for understanding the spatial extent that fire can have in this landscape. This research is becoming increasingly necessary as fire regimes across North America are expected to change over the next several decades due to anthropogenic climate change (Dale et al. 2001; Parks et al. 2016). Broadly climate change is expected to increase the length of drought events and increase the amount of area burned (Flannigan et al. 2009; Littell et al. 2010; Cansler and McKenzie 2014). More specifically, winter temperatures in Minnesota are increasing and larger, more frequent extreme precipitation events are expected to occur. While overall precipitation amounts in Minnesota are expected to increase, precipitation is likely to occur through heavier downpours with the potential for longer dry spells. Thus, synchronous fire events are likely to increase due to the overall history in the synchrony of wildfire, expected changes in climate, and impacts from prior land use. More importantly, the lack of fire over the 20th century has likely led to a landscape with more fuel and might lead to larger, more severe fires, with greater spatial extent. Because fires were historically synchronous in the Border Lakes region, projected changes in climate will likely accentuate the spatial connectivity of fire events resulting in larger, more spatially extensive events. Results from this research can help us to understand the extent to which fires historically impacted the landscape and guide future research regarding potential mechanisms. This research also provides a useful context to understanding the potential extent to which fires have and can occur.

Appendix A – Distance Decay Relationship

Expected relationship between distance and the number of shared fire events (i.e. synchrony).

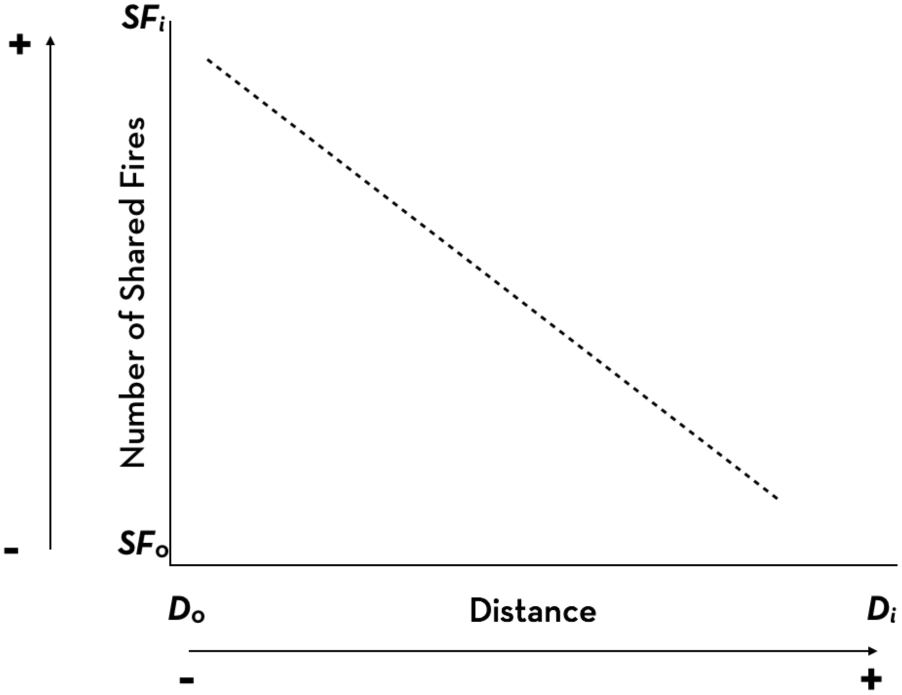

Figure A.1. Theoretical model showing the relationship between distance and number of shared fires. As distance increases, number of shared fires should decrease.

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CHAPTER 3: Mechanisms of Fire Synchrony in the Border Lakes Region of Minnesota

Synopsis

The propagation of fire disturbance across a landscape is a result of dynamic interactions between the terrain, climate, topographic features, and human land use. Generally, more complex landscapes such as those with greater fragmentation or fuel variability, present barriers to the spread of disturbances resulting in variable fire patterns. The Border Lakes region in northern Minnesota has a rich history of fire disturbance, is naturally fragmented by a complex of over 1,200 lakes, variable terrain within short distances, a history of human modification to the landscape, and variable climate dynamics. Understanding temporal and spatial patterns in the Border Lakes fire regime and the drivers of fire is important for both vegetation and fire management and for increasing the understanding of how landscape patterns and climate influence fire.

A fire reconstruction for the Border Lakes was evaluated for spatial and temporal variability in synchrony and mechanistic controls of fire patterns were tested. Quantitative understanding of the interactions between landscape patterns, climate, human land use, and disturbances is necessary for managing landscapes with an ecosystem perspective. Evaluating spatiotemporal patterns of fire synchrony is critical for 1) predicting the fire effects under changing climate, 2) understanding departures from pre-20th century fire regimes, 3) planning restoration of fire as an ecosystem process, and 4) mitigating potentially hazardous fire conditions at broad (landscape) scales. From a fire management perspective, the evidence for regionally synchronous fire activity during drought emphasizes the importance of identifying the potential for regional fires to occur.

Understanding of the potential and probability for regional fires are improved by further climate analyses associated with these years. It is also critical to understand the variation in drivers of asynchronous fire events versus synchronous fire events because the potential for an asynchronous event to become synchronous is partly dependent on the strength and interactions between drivers.

Results from this chapter indicate that in the Border Lakes, drought was a significant influence on synchronous fire events. While this result is important and furthers the understanding on the dynamics of larger, widespread fire events, the occurrence of asynchronous fire events in cool, wet years is an important finding. Asynchronous fire events in wetter conditions may be the result of several factors. First, wetter conditions may mean more convective producing storms and conditions that limit fire spread (due to relatively high fuel moisture), yet smaller fires may ignite and burn. Second, asynchronous fire events could be the result of human ignitions either on purpose or accidental. Determining the relative roles of climate and humans in fire regimes can be difficult, however the occurrence of asynchronous fire events in cool, wet years and the lack of evidence relating site-based controls suggests a fire regime that has a human component. Results further suggest human modification of the fire regime by regional variation in synchrony. For instance, both the Saganaga Lake and Central Lac La Croix region, have evidence of human occupation between 1750 and 1900 and are both statistically different from all other regions in the occurrence of asynchronous fire events. While human influence on the fire regime is not evaluated in this research, prior studies have noted their significant role in manipulating the landscape and resulting disturbance regime and results here add to the growing list of a human modified fire regime.

Introduction

The historical fire regime of the Border Lakes region of Minnesota is characterized by synchronous fire, with events co-occurring across spatially disjunct locations. Between 1750 and 1900 only 12 years did not have a recorded fire event. In comparison, there are 31 years with no recorded fire between 1900 and 2000. The role of fire across the landscape and the spatial variability in fire occurrence is notable as the landscape is naturally fragmented, consisting of over 1,200 lakes making up over 25% of the landscape (Chapter 2 of this dissertation). Generally, historical fire events were synchronous, that is, fire events were more likely to co-occur at spatially disjunct locations than events that occurred in spatially disjunct locations (asynchronous events). Within the landscape, locations of fire history did not show a relationship to distance, such that locations that were spatially distant were as similar to locations that were spatially near. The degree to which historical fire events were frequent and spatially synchronous demonstrates a possible relationship to controlling mechanisms in this landscape.

Fire is a spatial and temporal process influenced by variables that operate across a range of scales. Generally, mechanisms that operate at larger spatial extents, such as climate, are likely to control region-wide or landscape scale occurrence, frequency, spread, and severity of fire events (synchronous fire events). Whereas site-based characteristics are more likely to control fire events at smaller scales (asynchronous events) by either inhibiting or promoting the co-occurrence of fire at larger scales. Variability in the fire regime (e.g. year to year) such as seasonality, frequency, extent, and severity are reflective of varying local and regional controls and the relative strength of those controls (Gill and Taylor 2009; Ireland et al. 2012; Bigio et al. 2016).

At fine scales, fire spread and severity are determined by properties of fuel condition (availability, spatial arrangement), ignition (type, frequency, spatial distribution), and ambient weather (air temperature, wind speed, humidity; Falk et al. 2007; Iniguez et al. 2008; Ireland et al. 2012; Yocom et al. 2014). For a fire to spread, there needs to be fuels that are dry enough to ignite. However, if those fuels are not arranged continuously across the land surface then the fire cannot spread uniformly. Fuel continuity is a necessary component of the environment of wildland fire and affects a fire's ability to sustain combustion and spread (Cochrane et al. 2015). Variations in topography can cause dramatic changes in available fuel and resulting fire behavior. These smaller scale factors typically have a strong control at the tree or stand level (i.e. bottom-up mechanism) and can reduce the co-occurrence of fire at larger scales by limiting fuel continuity, effectively reducing fire spread.

Examples of fine scale factors include variations in slope, elevation, aspect, and vegetation. Elevation influences general climate thereby affecting fuel availability. Different amounts of precipitation received, snow melt, and green-up are all fairly dependent on elevation. Temperature and relative humidity vary with aspect, with northeast facing slopes characterized as cool and moist, and southwest facing slopes characterized by dry, warm conditions. Moisture levels also vary based on slope position, such as valley bottoms (wet) and upper slopes/ridgetops (dry). The local distribution of flammable fuels and topography determine when and where a fire occurs, and subsequently the rate and direction of spread. Fine-scale influences, for instance, may be stronger in years with mild climate forcings, but severe fire weather can override local factors and result in widespread occurrence of fire (Brown et al. 2001; Falk et al. 2007; Yocom et al. 2014). Variability in these factors may determine if an area burns, fire severity, regeneration patterns, and time to next disturbance by modifying moisture levels and vegetation types. Fire regimes that are strongly controlled by bottom-up mechanisms tend to have smaller, more asynchronous fire events (i.e. more isolated and less likely to spread).

At larger scales, broad landscape patterns (e.g. patterns in terrain), presence of large water bodies (lakes, streams, and wetlands), and climatic variability (i.e. top-down mechanisms) have region-wide effects on the fire regime. Variation in climate, specifically drought events, and the overall structure of the landscape have a significant impact on the timing and severity of fire. Climatic events alter the moisture balance of a location resulting in fuel susceptibility to burning at both broad spatial scales and at various time scales. Synchronous fires are more likely to occur in years of extreme climate (prolonged drought), such as when fire activity can overcome the barriers to fire spread that operated in more moderate conditions (Flannigan and Harrington 1988; Drobyshev et al. 2010; Liu et al. 2013). Broad dynamics in landscape terrain impart a control in the structure of landscape characteristics (topographic) and overall vegetation type, composition, and structure. For example, landscapes that have complex topography or diverse vegetation may result in a smaller potential for fires to spread between stands (Turner 1989; Turner et al. 1994) effectively limiting the potential for fire to occur over wide areas. In comparison, less spatially complex landscapes or those that are more connected, have a greater probability of larger, more spatially extensive fire events.

Regional variations in climate and terrain may indicate years and locations that are more prone to a fire occurring and spreading from one place to another. Generally, a fire regime that is strongly controlled by top-down mechanisms are more likely to have synchronous fire events (larger, or more co-occurrence).

Identifying spatial and temporal variability in the fire regime is key to understanding when and where fires occurred. Once variability within the fire regime is identified casual mechanisms can be evaluated and related. Understanding the drivers of spatial and temporal variation in fire is key to ecosystem management and restoration because fire modifies forest development, structure, and composition in many landscapes. In the Border Lakes, fires have been excluded from the forests for more than a century by land use changes that include logging, changes in human occupation, and fire suppression. As a result, the density of shade tolerant, small-diameter trees that are fire intolerant have increased. Thus, managers are taking various approaches to restoring fire to forests but are in need of information on the patterns in historical fire and the factors driving variations in the regime.

Research Questions

This chapter further evaluates the spatiotemporal variability in the fire regime of the Border Lakes region and the potential mechanisms responsible for observable patterns. The evaluation of underlying patterns in the fire regime can advance the understanding on the complexity in fire occurrence and how fire events occur from one place to another. For example, spatial and temporal patterns in fire synchrony and asynchrony can be elucidated as well as how patterns are driven by mechanistic controls.

To address this, temporal and spatial patterns in the fire regime were addressed and then evaluated in the context of possible mechanisms (both bottom-up and top-down drivers). Bottom-up factors evaluated for this research are defined by topographic variation (slope, aspect, elevation, and percentage of water present in a region), and climate is considered top-down component influencing fire. Overall, this chapter attempts to answer three questions regarding the spatiotemporal patterns in the fire regime and the mechanisms of historically synchronous and asynchronous fire events:

(1) *What are the temporal patterns in the fire regime, particularly times of increased fire synchrony?*

(2) *What are the spatiotemporal patterns of fire synchrony?*

(3) *What are the mechanisms influencing spatiotemporal variability in fire synchrony?*

Geographic patterns of historical fire disturbance exhibit both systematic properties and high variability. Local topography, vegetation type, weather, climate patterns, human land use, and prior disturbances produce patterns in the frequency and timing of fire events. Variations in the system and effects on fire disturbance over time can be measured, furthering the understanding on the dynamics of ecosystem processes. Results from this research will provide context into this complex, dynamic ecosystem for which fire was once an important process.

Site Description

The Border Lakes region is located in the northern portion of Minnesota and runs along the state's northeast border with Canada. The study area consists of both

Voyageurs National Park (VOYA) and the Boundary Waters Canoe Area Wilderness (BWCAW) and represents a way to investigate the prevalence of fire owing to the unique topography, vegetation patterns, climate, and cultural history. The landscape is naturally fragmented, with forest patches interspersed with lakes, streams, and wetlands providing natural firebreaks that limit the spread of fire. The region is about 417,900 ha with over 110,900 ha of lakes (~26.5% of the area; Coffman 1980; Heinselman 1996). The fragmentation of the terrain creates a mainland and island habitat configuration which can create variability from one location to another (see Chapter 2 results). Islands may vary in topographic features such as slope, elevation, and aspect influencing the type, composition, and structure of forested stands. As a result, forested stands range from early successional to late successional species and near-boreal to temperate type species, transitioning between types in relatively short distances. The variation in the landscape allows for the testing of several complex variables that fluctuate over short distances.

Methods

Data

Fire event data for this research was developed by Kipfmueller et al. (2017; VOYA) and Kipfmueller et al. (forthcoming; BWCAW) for the purposes of reconstructing fire and evaluating mechanisms of fire in the region and is part of a larger regional analysis of fire in the Border Lakes. The fire regime data used here consists of 541 with 1,660 annually dated fire scar events spanning from 1546 to 1972 (record spans: 1489–2016) and represents 217 individual fire years. Fire scar samples were grouped into 14 distinct regions by geographic location (see Chapter 2 for methods and justification for choosing 14 regions) for the purposes of evaluating variation in the fire regime across the landscape. The aggregation of samples at this scale reduces noise that is present at smaller spatial scales and eliminates some of the bias in sample size discrepancy among the regions. By addressing spatiotemporal variability between regional based clusters, locations in the study area can be characterized by their synchrony and evaluated for changes over time. Synchronous fire events here are defined as events that are recorded in two or more regions, three or more regions, and four or more regions, while asynchronous fire events are those events that only occur in one region (unique events; see chapter 2 for methods). Fire events that are recorded in greater number of regions (e.g. four and five plus regions) are considered to be more synchronous events as they have a greater spatial extent. As such, the common climate signal for these fire event years may reflect strong climatic controls (e.g. drought) that lead to more spatially extensive fire events (Falk et al. 2007).

Landscape characteristic data were derived from USGS DEM data (SRTM 1-arcsec DEM tiles from USGS EarthExplorer data). Topographic variables calculated for this research include slope, aspect, elevation, and percentage of water using raster data, generating an elevation dataset for the region. Climate data used for this research are a tree-ring reconstruction of summer (June–August) Palmer Drought Severity Index (PDSI; Palmer 1965). PDSI is an estimate of the departure of soil moisture relative to average conditions and incorporates temperature, precipitation, evapotranspiration, and soil characteristics (Palmer 1965; Alley 1984). Values range from negative 6 (drought) to positive 6 (moist conditions; Figure 3.1). The PDSI record was obtained from the North American Drought Atlas (Cook and Krusic 2004) from the nearest grid point (197).

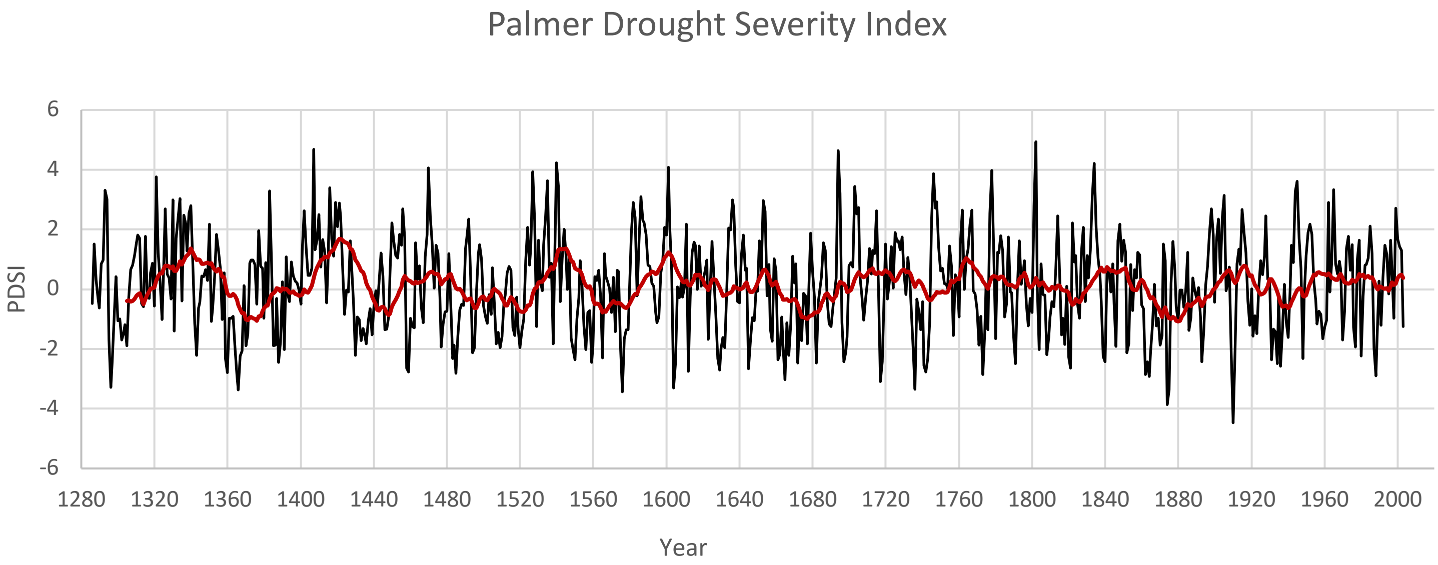

Figure 3.1. Reconstruction of the Palmer Drought Severity Index for grid point 197 used in this research. The reconstruction extends from 1286 to 2003 (black line). The red line represents a 20-year smoothed average of the reconstruction.

Spatiotemporal Analysis of the Fire Regime

In order to understand what regions are more or less synchronous throughout the analysis period I tested differences in the number of asynchronous and synchronous fire events by time and by region. For the temporal analysis, the fire regime was divided into 50-year periods starting in 1700 and ending in 1949. Next, each 50-year time period was tested for differences in the number of asynchronous versus synchronous events against the total number of fire events occurring using a chi-square test of independence.

Null hypothesis: There is no difference in the number of synchronous fire events and asynchronous fire events over time.

A chi-square test was used as it is appropriate for testing independence in nominal data for smaller datasets, allowing for the comparison in observed values. Chi-square results will indicate whether values are expected based on observations or are occurring by chance. The spatiotemporal variability in asynchronous and synchronous events for each individual region was further evaluated for independence by testing the significance of events occurring in each region by 50-year time steps.

Null hypothesis: There is no difference in the number of asynchronous and synchronous fire events occurring in each region (all regions have similar synchrony and asynchrony).

Mechanisms Influencing Synchronous Events

To evaluate the influence climate has on the occurrence of fire events a superposed epoch analysis (SEA) was used to test the common climate signal (represented by PDSI) in specified years using MatLab. SEA is a compositing technique widely applied in fire-climate analyses that computes the mean value of a climate parameter of interest for key event years (Baisan and Swetnam 1990; Brown and Schoettle 2008). This assists in the identification of antecedent climate conditions that may be related to fire occurrence by determining the mean climate value in the years prior to fire occurrence as well as determination of the conditions during fire years. Confidence intervals are determined by a Monte Carlo simulation by drawing random fire event years, equal in number to the observed number of events, and generating confidence limits around departures of the actual values minus simulated values. This randomization procedure selects sets of fire years equal to the number of observed fires (e.g., fire years where two or more of the regions recorded a fire), calculates a mean value for the climate parameter for the windows of these events, and subtracts the observed values from the simulated values. This procedure was completed 1000 times and the average of the 1000 departures with associated confidence limits are determined.

A window of five years was used in the SEA analysis, with three years prior to the fire event year, the fire year, and one year after. This window was chosen to identify any patterns in the observed relationships. SEA was performed on (1) years when no fire events were recorded, (2) fire years that are unique to just one region (i.e. asynchronous fire years), and four designations to test changes with increasing fire synchrony. The SEA was also stratified to test for (3) fire events shared between two or more regions, (4) three or more regions, (5) four or more regions, and (6) fires shared between five or more regions.

Mechanisms Influencing Asynchronous Events

Local topographic data used in this research includes elevation, aspect, slope and percent water. Slope (percent), aspect (degrees), and elevation surfaces were derived from a 1-meter digital elevation model (DEM), while percent water was derived from a shapefile of water boundaries (MNDNR data). Local topography was calculated for each fire scar location in the dataset. The topographic data for each region were summarized with the minimum, maximum, median, and the upper and lower quantiles calculated (Figures B.1–B.5 depicts boxplots of regional variability in each site characteristic). To avoid the issue of circular data and be able to use values in regression, aspect values which are measured in degrees (0–360) were transformed. To achieve this, aspect was transformed using cosine with resulting values scaled between 0 (warmer, drier, southwest facing slopes) and 2 (cooler, moister, northeast facing slopes; Beers et al. 1996; McCune and Keon 2002). Percent of water for each region was calculated based on amount water present in each region. Boxplots of regional variability in each of the topographic variables were then plotted to visually assess variation by region (see Appendix B).

A Principal Component Analysis (PCA) was used as a tool to test the mechanisms that may have an influence on the variability in asynchronous fire events. PCA is an ordination technique that reduces dimensionality of multivariate data and was chosen because variables used in the PCA are measured on different scales (Gotelli and Ellison 2004). Variables used in the PCA analysis were slope, elevation, aspect (transformed), and percent water. PCA calculation is done by a singular value decomposition of the data matrix using the *prcomp* function (R Core Team 2015). Characteristic variables defined for each of the 14 regions were used in the PCA analysis to evaluate the relative strength of site-based characteristics influencing fire events. The number of asynchronous fire events for each region was mapped to the resulting PCA to reveal any patterns. Lastly, a stepwise linear regression was used to predict the influence of the topographically derived PCs on fire synchrony to determine if the generated PC loadings (predictor variable) are related to the occurrence of asynchronous fire events (dependent variable).

Results

Temporal Variability

Between 1800 and 1899 there are 94 fire events recorded within the study area (1800–1849: 47 events, 1850–1899: 47 events). In comparison, the 1700–1799 period had 71 recorded fire events (1700–1749: 27 events, 1750–1799: 44 events) and from 1900 to 1999 there were 31 fire events recorded (see Figure 1.12). The 1750–1799 period has the greatest number of synchronous fire events recorded with 16 events, and the 1850–1899 period has 15 synchronous fire events recorded (Table 3.1), while the 1700–1749 and the 1800–1849 periods have a greater number of asynchronous events than synchronous events (Table 3.1).

A chi-square test of independence revealed, overall, there is a difference in the number of synchronous fire events and asynchronous fire events occurring by time period (chi-square: 26.096, *p-value* < 0.01). Each time period was then tested independently to see if there is a difference in the number of asynchronous versus synchronous fire events (individual p-values for each timer period are indicated in Table 3.1). The chi-square test revealed that during the 1750–1799, 1850–1899, and 1900–1949 there is statistical difference in the number of synchronous fire events and asynchronous fire events occurring than what would be expected by chance alone (Table 3.1). The difference between asynchronous fire events and synchronous fire events between the 1800–1849 and 1700–1749 periods were not statistically significant from the other time periods (Table 3.1).

Spatiotemporal Variability

The number of synchronous fire events varies by region, however, each of the regions have a greater number of synchronous fire events than asynchronous (Figure 3.2). The Central Lac La Croix region (CLLC, n = 34) has the greatest number of synchronous fire events recorded as well as the greatest number of asynchronous events, followed by Central Voyageurs (CVOYA, n = 29), and Saganaga Lake (SAG, n = 25). Regions with the fewest number of synchronous events include Upper Pauness (UPN, n = 5) and Knife Lake (KNI, n = 7). Both the CLLC and SAG regions were statistically different in the number of asynchronous events when compared to all other regions ($p = 0.023$ and $p = 0.048$, respectively, Table 3.2).

Regions have temporal variability in fire synchrony (Table 3.3). For example, the CCLC, BAS, SAG, and EVOYA regions are different in the number of asynchronous and synchronous events that are occurring in the 1750–1799 and the 1850–1899 (Figure 3.3). In addition, the 1850–1899 period the CMG, WVOYA, NVOYA, and WLLC regions are

Table 3.1. Results of Chi-Square Test of Independence on Temporal Variability in the Fire Regime

Time Period	**# of Asynchronous Events***	**# of Synchronous Events†**	**Total**	***P-value***
1700–1749	13	5	18	0.153
1750–1799	7	16	23	**0.0037**
1800–1849	15	9	24	0.537
1850–1899	7	15	22	**0.0074**
1900–1949	19	1	20	**0.0001**
Total	61	46	107	**0.00003**

*Asynchrony is calculated based on fire events only occurring in one region.
†Synchrony is calculated based on fire events recorded in four or more regions
Bold numbers indicate significance at the 95% confidence interval.

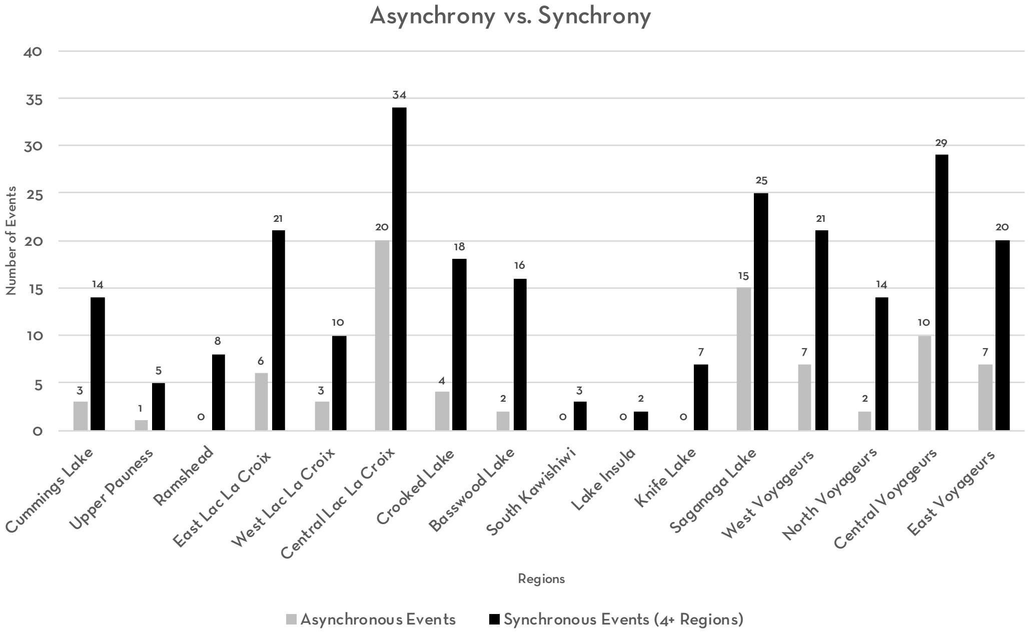

Figure 3.2. Number of asynchronous (unique fire events) versus synchronous fire events (four plus regions shared fire) recorded in each region.

Table 3.2. Chi-square results on the significance of regional synchrony

Region	**# of Asynchronous Events**	**# of Synchronous Events**	**Total**	***P-value***
Cummings Lake	3	14	17	0.48
Upper Pauness	1	5	6	0.64
Ramshead	0	8	8	0.1
East Lac La Croix	6	21	27	0.742
West Lac La Croix	3	10	13	0.88
Central Lac La Croix	**20**	34	54	**0.023**
Crooked Lake	4	18	22	0.454
Basswood Lake	2	16	18	0.165
Knife Lake	0	7	7	0.124
Saganaga Lake	**15**	25	40	**0.048**
West Voyageurs	7	21	28	0.984
North Voyageurs	2	14	16	0.241
Central Voyageurs	10	29	39	0.902
East Voyageurs	7	20	27	0.892
Total	74	47	121	0.191

Bold values indicate significance at the 95% confidence interval.

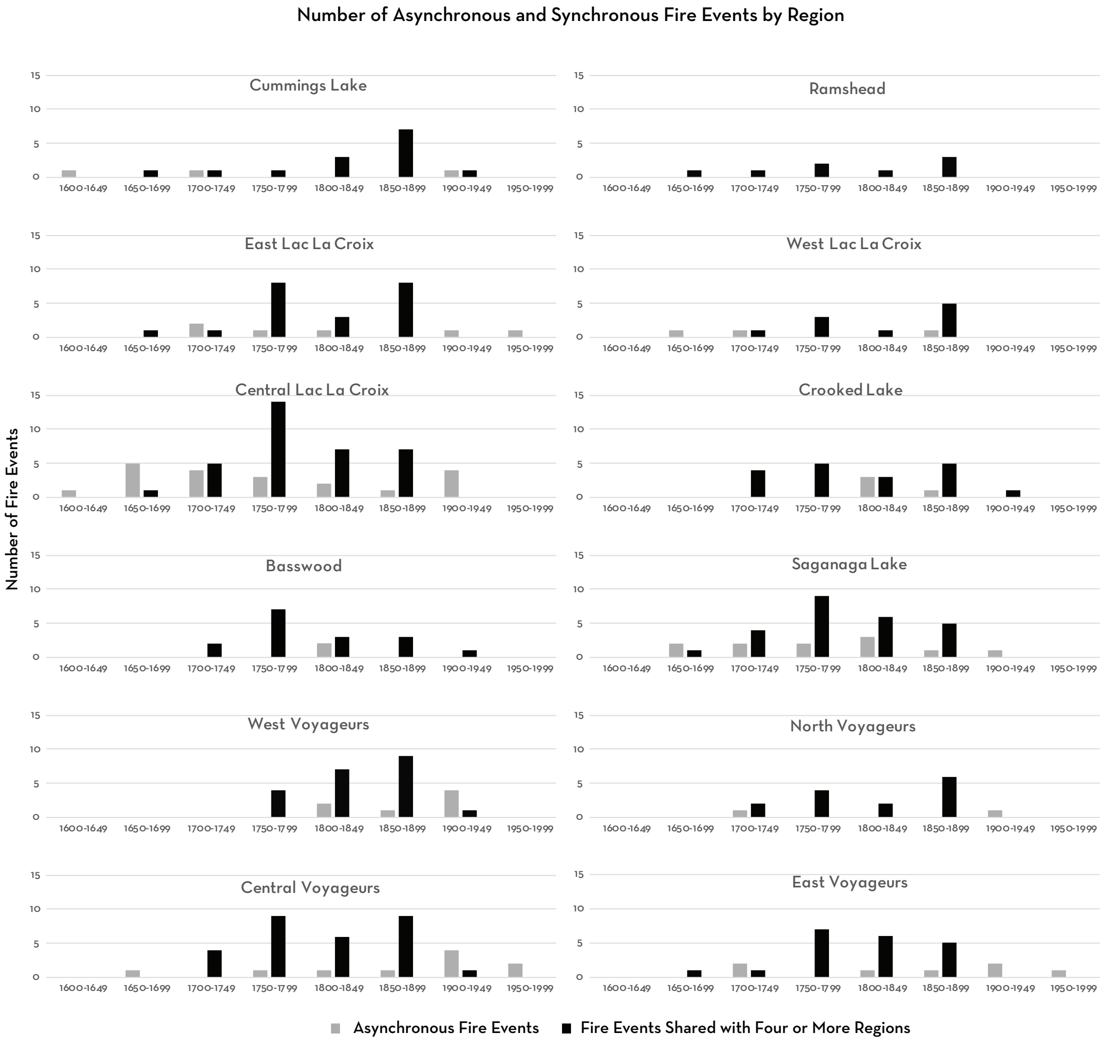

Figure 3.3. Temporal asynchrony and synchrony for each region (*Upper Pauness and Knife Lake are excluded from this figure due to low representation of both synchronous and asynchronous fire events).

Table 3.3. Spatiotemporal difference in the occurrence of synchronous fire events and asynchronous fire events.

Region	1750–1799	1800–1849	1850–1899	1900–1949
Study Area	*		*	*
Cummings Lake		*	*	*
Upper Pauness				
Ramshead				
East Lac La Croix			*	
West Lac La Croix				
Central Lac La Croix	*	*		
Crooked Lake				*
Basswood	*			*
Knife Lake				
Saganaga		*		
West Voyageurs		*	*	
North Voyageurs			*	
Central Voyageurs		*	*	
East Voyageurs	*	*		

*significant (95% confidence interval) difference between synchronous and asynchronous fire events different in their occurrence in synchronous and asynchronous fire events compared to other regions. Regional synchrony does fluctuate through time, with some regions experiencing periods of greater synchrony or asynchrony (Figure 3.3). For example, the CLLC region has a higher number of synchronous fire events occurring between 1750 and 1899 and more asynchronous fire events in the 1900-1950 time period. This pattern can also be seen in all four of the defined VOYA regional designations (Figure 3.3).

Mechanisms Influencing Synchronous Fire Events

No statistical association was detected between years with no fire and PDSI. However, years of asynchronous fire occurred during years that were significantly wet during both the fire year and the year prior to occurrence (Figure 3.4). Synchronous fire events are related to warm-dry conditions. For example, years that recorded fire in five or more regions (considered to be synchronous) occurred in years of significant low moisture availability both in the years of fire and in the years prior to fire occurrence (Figure 3.4F). In comparison, in years when a fire event was not as synchronous (e.g. fire events recorded in just two regions; Figure 3.4B) there was no statistical association found with PDSI.

Mechanisms Influencing Asynchronous Fire Events

Site based characteristics varied by region (Table 3.4). Median elevation between regions ranges between 168 m (Basswood Lake) and 242 m (Crooked Lake). Percent of water in each region ranges from 19% (Crooked Lake) and 82% (Saganaga Lake). While most regions were sampled on southwest facing slopes, aspect does range between all

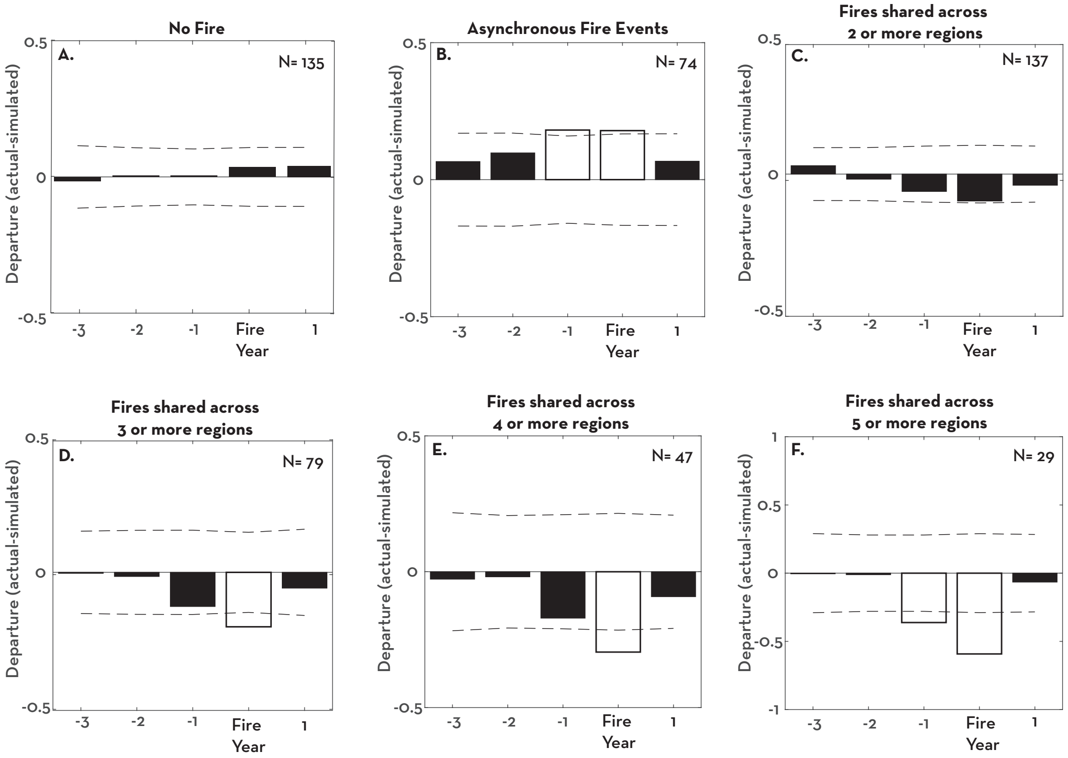

Figure 3.4. Superposed epoch analysis results representing the relationship between the Palmer Drought Severity Index and conditions during and before fire event years. (A.) All years in which no fire events are recorded. (B.) Fire event years that burned in just one of the defined regions (asynchronous fire events). (C – F) Fire events that are recorded in two, three, four, and five or more regions. Note that the y-axis on graph F has a different scale compared to all others.

exposures. There is less variation in slope degrees with the median values ranging between 1.4 degrees (Central Voyageurs) and 4.4 degrees (Knife Lake).

The first principal component accounts for 42.5% of the variation, PC2 accounts for 32.5%, PC3 accounts for 20%, and PC4 accounts for 5% of the variation (Table 3.5). Two PCs were retained based on the Kaiser Guttman criterion (Kaiser 1960), of considering only PCs with eigenvalues >1 (Table 3.5). Based on PC loadings, PC1 has a large positive association with aspect (0.655) and a negative association with elevation (-0.597), this suggests that there is an inverse relationship with elevation meaning that PC1 is low with higher elevation and higher with lower elevation (Table 3.6). PC2 has a positive association with slope (0.832) suggesting that PC2 is lower with flatter terrain and higher with steeper terrain (Table 3.6 & Figure 3.5). PC3 has a large positive association with the percentage of water (0.8579) suggesting that PC3 is high with the greater amount of water present in a region. The stepwise linear regression resulted in a final model which included PC1, PC2, and PC3, however the test did not indicate a significant relationship of measures to the number of asynchronous fire events (Table 3.7).

Table 3.4. Characteristics of each region

Region	# of Samples	Total # of Fires	Median Elevation	Median Slope	Median Aspect	Transformed Aspect	% Water
Cummings Lake	46	26	448	2.6	210	0.49	0.25
Upper Pauness	14	11	226	2.3	226	1.73	0.24
Ramshead Lake	8	13	382	2.3	228	1.31	0.4
East Lac La Croix	108	48	366	2.2	238	1.25	0.29
West Lac La Croix	20	23	365	2.4	240	1.77	0.29
Central Lac La Croix	63	92	368	2.0	175	1.09	0.43
Crooked Lake	36	41	389	2.4	242	0.10	0.19
Basswood Lake	20	30	397	1.7	168	0.41	0.35
Knife Lake	11	8	438	4.4	232	1.51	0.26
Saganaga Lake	84	67	441	2.4	229	0.37	0.82
West Voyageurs	41	46	352	1.6	191	0.63	0.52
North Voyageurs	19	25	352	3.3	190	1.58	0.48
Central Voyageurs	39	60	337	1.4	228	1.31	0.39
East Voyageurs	29	43	345	2.3	169	1.36	0.3

Elevation, Slope, and Aspect are calculated using all samples within that region

Table 3.5. Results of PCA analysis

Importance of Components	**PC1**	**PC2**	**PC3**	**PC4**
Eigenvalues	1.305	1.139	0.8954	0.4436
Proportion of Variance*	0.4255	0.3249	0.2004	0.0492
Cumulative Proportion	0.4255	0.7504	0.9508	1

*Variance explained by the varimax rotated principal components

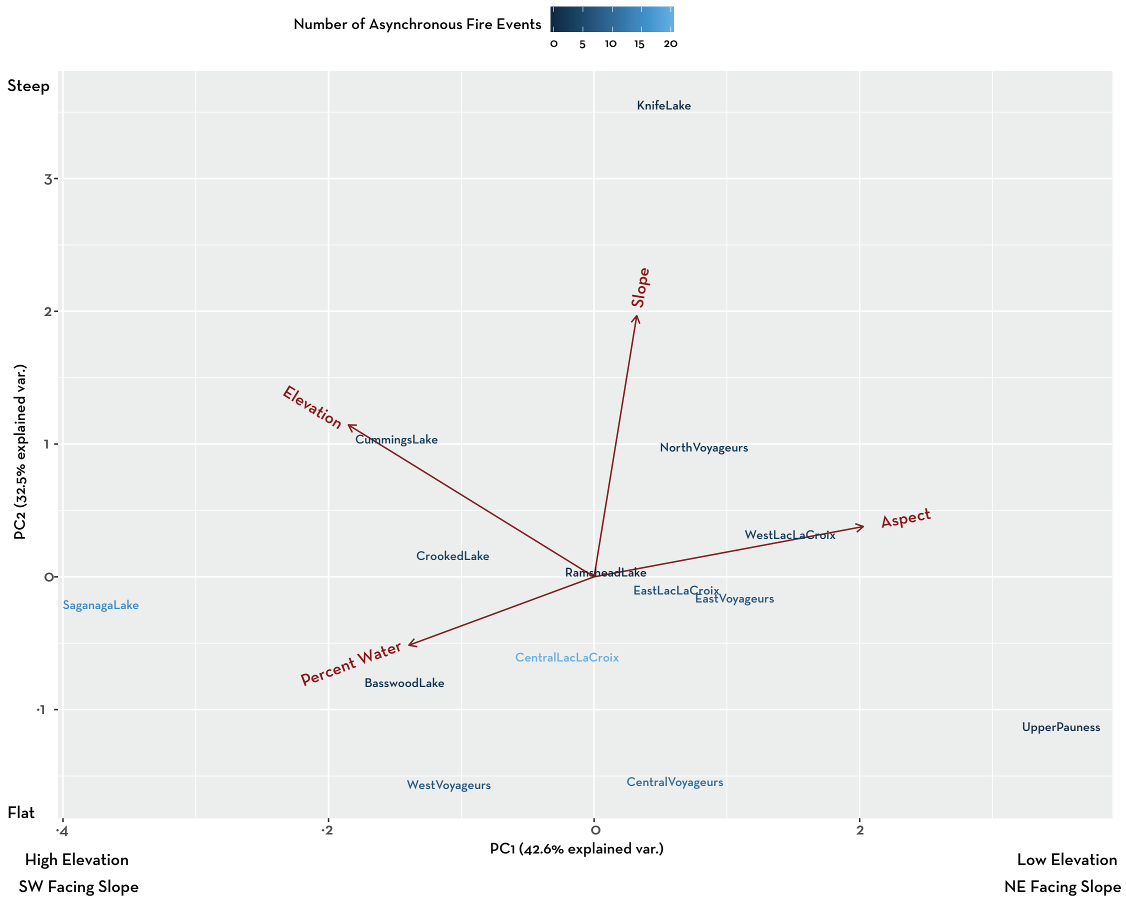

Figure 3.5. Principal component analysis representing the first two PCs (75% variance explained). PC1 (42.6% explained variance) is associated negatively with elevation and positively with aspect and PC2 (32.5% explained variance) is associated with slope. Each region is colored by number of asynchronous fire events. Note that the scales are different for the x and y axes.

Table 3.6. Rotated principal component loadings

Characteristic	PC1	PC2	PC3	PC4
Elevation	**-0.5978**	0.4841	-0.1057	**0.6301**
Slope	0.1037	**0.8321**	0.1971	-0.5078
Aspect	**0.6548**	0.1602	0.4626	0.5758
Percent Water	-0.4506	-0.2179	**0.8579**	-0.1163

Table 3.7. Results of stepwise regression on PC Loadings

Number of Asynchronous fire events ~ PC1 + PC2 + PC3

Coefficients	**Estimate**	**Std. Error**	**t value**	**P**
Intercept	5.714	1.377	4.149	0.001
PC1	-1.754	1.096	-1.601	0.140
PC2	-2.038	1.254	-1.625	0.135
PC3	1.983	1.596	1.243	0.242

Multiple R-square: 0.403

Adjusted R-square: 0.2238

AIC: 50.83

Discussion

Overall, these results demonstrate that climate, specifically periods of extended drought, are associated with larger, synchronous fire events while smaller, asynchronous fire events did not have a clear connection with topographic variables. In addition, years in which asynchronous fire events occurred were more closely associated with wetter than average conditions in the year of and the year before the fire event (Figure 3.4).

Temporal analysis indicates that fire fluctuates between periods of asynchrony and synchrony from 1700 to 1950 and varies by regional designation. For example, both the Central Lac La Croix region and the Saganaga Lake region are statistically different from all other regions in the occurrence of asynchronous fire events. While variation between regions and time periods exists, there are no distinguishable patterns in regional synchrony. For example, it would be expected that regions that are close spatially would fluctuate similarly in their synchrony and asynchrony, however patterns are not apparent (see chapter 2 for further discussion regarding distance relationships between regions). Instead, regions fluctuate in synchrony through time, independent of geographic distance.

Most regions experienced greater asynchrony than what is expected by chance alone in the 1900–1949 period. During this time there are 19 asynchronous fire events in the fire record compared to one synchronous event (ca. 1910). This period coincides with the beginning of fire suppression and exclusion with changes to land use and management practices. In comparison, while there are numerous fire events recorded prior to 1700, sample depth is lower compared to the latter portion of the fire record, most likely due to sample decay. As a result, the variation in synchronous and asynchronous fire events prior to 1700 cannot be evaluated with a high degree of certainty. The decrease in fire occurrence after 1900 is echoed in many forested ecosystems across the United States (Swetnam and Dieterich 1985; Swetnam and Betancourt 1990; Donnegan et al. 2001; Hessl et al. 2004; Taylor and Scholl 2012; Drobyshev et al. 2015), with fire suppression and exclusion efforts geared towards limiting flammable fuels and the potential for severe, widespread events.

Results from this research indicate that more synchronous fire events are associated with drier than average conditions. For instance, historical fire events that were recorded in three or more regions occurred in anomalously dry years while events of greater synchrony, such as those recorded in five or more regions, occurred in years of anomalously dry years and were also preceded by significant dry conditions (Figure 3.4). Dry conditions in the years before and in the year of a fire event have been observed in the region in the last 100 years. For example, major fires during this time period that coincide with drought conditions include: 1910, 1929, 1936, 1948, and 1972 (Wolff 1958; Johnson and Kipfmueller 2016).

While drought appears to be modifier of synchronous fire events in the Border Lakes and furthers the understanding on the mechanisms influencing larger and more spatially extensive fire events, the occurrence of asynchronous fire events in cool, wet years is an important result. Smaller fire years occurring in anomalously wetter than average may be the result of several factors. First, wetter conditions may mean more convective producing storms. Although conditions may not promote fire spread in that year due to relatively high fuel moisture, smaller fires may ignite, burn, and not spread to nearby stands. Second, asynchronous fire events could be the result of human ignitions, either on purpose or accidental. Separating historical climate and human influences on fire is confounded by the inability to distinguish ignition sources discriminating between human and lightning causes of fire. While determining the relative roles of climate and humans in fire regimes is difficult, the occurrence of asynchronous fire events in cool, wet years and the lack of evidence relating site-based controls suggests a fire regime with a human component.

Multiple studies have noted the significance of humans as a fire factor with human activity in the region extending for millennia with generations of Indigenous communities, explorers, fur traders, trappers, prospectors, and loggers (Day 1953; Denevan 1992; Loope and Anderton 1998; Anderton 1999; Nute 2004; Nelson 2009; Johnson and Kipfmueller 2017; Kipfmueller et al. 2016). The most prominent group occupying the area were various bands of Border Lakes Anishinaabeg (the cultural groups also referred to as Ojibwe or Chippewa, but who refer to themselves as Anishinaabe (s) or Anishinaabeg (pl)). Traditional knowledge suggests that fire was a tool used by the Anishinaabeg, used to clear encampments, increase resource productivity, and maintain trails and portages (Anderton 1999; Lewis and Ferguson 1988; Johnson and Kipfmueller 2016). For instance, Berkes and Davidson-Hunt (2006) interviewed elders of First Nation at Shoal Lake on traditional fire practices. They found that fire was used to maintain early stages of plant succession, clearing brush, thin stands, and maintain berry patches. Several other studies have suggested the importance of Indigenous communities manipulating the fire regime (e.g. Day 1953; Denevan 1992; and Anderton 1999). For example, changing fuel types, modifying fuel structure and continuity, and igniting fires (intentional or unintentional) in different seasons and under various weather conditions (Bowman et al. 2011). Motivations for manipulating fire regimes range from arson, warfare, skillful management of natural resources, and protection of infrastructure (Bowman et al. 2011). While motives are less well understood and documented it is suggested that fire was used to alter vegetation mosaic to reduce impacts of catastrophic lightning caused fires along with traditional subsistence strategies.

These results suggest, that humans likely had a role in the Border Lakes historical fire regime, contributing to the frequency, timing, and location of fire events, specifically, the occurrence of fire events in prolonged periods of wet conditions. While lightning ignitions commonly co-occur with coherent weather controls, anthropogenic ignitions can result from diverse activities and potentially be forced to overcome otherwise limiting weather and environmental controls (Stambaugh et al. 2018). Due to the high usage of the land by humans (Indigenous communities, explorers, fur traders, trappers, prospectors, and loggers) it is likely that they were a source of ignitions, contributing to both the occurrence of synchronous and asynchronous events.

Prior research has argued that the impact of human caused fires is small relative to background rates of natural ignitions (Allen 2002; Bowman et al. 2011; Fulé et al. 2011). For instance, in environments saturated by lightning ignitions, humans would have contributed relatively little to the frequency of ignitions and their effects would instead be in altering the seasonal timing or location of ignitions and/or altering fuels. The majority of the forests on which this sentiment is based, are in the American Southwest where there is a dominant climate mode with distinct dry season and plentiful lightning activity. In the Border Lakes, however there is not a strong seasonal climate-fire pattern similar to that in the Southwest. While lightning storms are frequent, the probability of a dry convective storm occurring is less likely with convective storms often coinciding with heavy rainfall.

Anthropogenic ignitions and modifications to the landscape likely intensified the natural regime in the Border Lakes, increasing the frequency of fire events. For forests in the American Southwest, Allen (2002) argues that it is appropriate to dismiss anthropogenic fire use as an important influence on fire regimes as the high levels of lightning ignited fires observed today are sufficient to generate the frequent return interval in the historical fire scar record. In comparison, while modern lightning records in the Border Lakes region could explain infrequent, large fires they cannot account for historical fire frequencies, with a sharp decrease in fire occurring in the late 1800s coinciding with changes in land use, such as the decrease in Indigenous populations in the area. Thus, I argue that human land use, specifically Indigenous fire practices, likely had an influence on the historical fire regime of the Border Lakes, contributing to the frequency of ignitions.

Separating past climate and human influences on the fire regime is difficult with historical data because no tools or techniques are available to discriminate between human and lightning causes of fire. Prior research conducted in various ecosystems has attempted to quantify the human component of historical fire regimes using several forms of analysis and lines of evidence to associate humans to fire regimes. For instance, Muzika et al. (2015) suggested fire events occurring in wet years are primarily the result from human ignitions either accidental or on purpose by calculating an Anthro Fire Index (AFI) for the Huron Mountains Reserve in the Upper Peninsula of Michigan. They proposed that the absence of fires in drought years (PDSI <0) was due to lack of ignitions (human or lightning) and that the occurrence of fires in wet years (PDSI >0) resulted from humans, likely lit during short dry periods with ignition aided by humans. While the Anthro Fire Index used in Muzika et al. (2015) provides an estimate for the human component of the fire regime, I am hesitant to associate all fires in wetter than average years solely to anthropogenic causes. Instead, I suggest a relation between humans and fires occurring in wet years versus providing an index. Similarly, I am also hesitant to use the AFI because human ignitions likely contributed to fire events in dry conditions, not just in wet periods.

In research performed in the American Southwest, fire history data has been compared to human occupation dates. For example, Swetnam et al. (2016) related human occupation to the fire regime in the Jemez Mountains of New Mexico by applying a comparative analysis between fire reconstruction data and a human occupation chronology. Human chronologies were then compared to innermost ring date of trees and fire scars near village and agricultural areas of varying degrees of human population density. Human occupation dates were determined by LiDAR surveys, ceramic-based chronologies, tree-ring dating of structures, and documentary evidence. They determined that fire event synchrony across the study site fluctuated with pulses in human occupation. Generally, larger fire events were related to interannual climate variability while Indigenous communities likely influenced fire at finer spatiotemporal scales (time and place specific). Both the Muzika et al. (2015) and Swetnam et al. (2016) studies have demonstrated the complexity and uncertainty that comes with the scale and quality of data when evaluating historical human occupation of an area and the relationship to fire.

The ability to assess the human influence on the fire regime is strongly tied to the type, quality, and availability of data.

Lastly, results from this research further suggest human modification of the fire regime by spatiotemporal variability in synchrony. For instance, both the Saganaga Lake and Central Lac La Croix regions are statically different from all other regions in the occurrence of asynchronous fire events and have evidence of human occupation between the 1730s and the late 1800s (Johnson et al. 2018). Both regions are located along the historical "Border Route" a travel route between Lake Superior and Rainy Lake. Fur trade in this region began in the 1730s and extended into the 1860s with European voyageurs and indigenous groups using this route to trade goods, repair canoes, and resource extraction. Through archaeological evidence, several sites have been established in the Saganaga Falls Portage area (BWCAW), Lac La Croix (BWCAW), and Sand Point Lake (VOYA). In addition, evidence in dendrochronological dating of culturally modified trees (i.e. modified by Indigenous people and utilized for traditional purposes) have corroborated the use of the Saganaga Lake sites by Anishinaabeg during this time period (Johnson et al. 2018). Both the Saganaga Lake and Central Lac La Croix regions have statistically significant number of asynchronous fire events than what would be expected by chance alone, likely reflecting the presence of humans in these areas contributing to the occurrence of smaller fire events. It is likely that humans actively set fires during these cooler, wet periods either with the knowledge that fires were unlikely to spread during these wet periods, using these conditions to control fire spread. Or, it is possible that human ignitions were so frequent/often (contributing to both asynchronous and synchronous events) regardless of weather conditions. In all likelihood both scenarios are possible with multiple factors influencing the fire regime.

Conclusions

These results emphasize the overall importance and frequency in the history of fire events in the Border Lakes regions. The spatial and temporal patterns in fire synchrony are related to climate patterns such that periods of extended dry conditions are related to more synchronous fire events. Drought appears to be a significant influence on the occurrence of synchronous fire events. In comparison, smaller asynchronous fire events were tested in relationship to site-based landscape characteristics and no relationship was found. Asynchronous fire events may be related to human land use or could represent those areas that were dry enough to burn in a wetter than average year. The evidence for regionally synchronous fire activity during drought emphasizes the importance for fire management practices that addresses potential locations where fires could become large/synchronous during periods of drought.

Appendix B – Regional Characteristics

Boxplots of regional characteristics were generated to visually assess the variation between islands. Fire frequency, elevation, slope, aspect, and profile was plotted for the 14 regions used in Chapter 3 analysis.

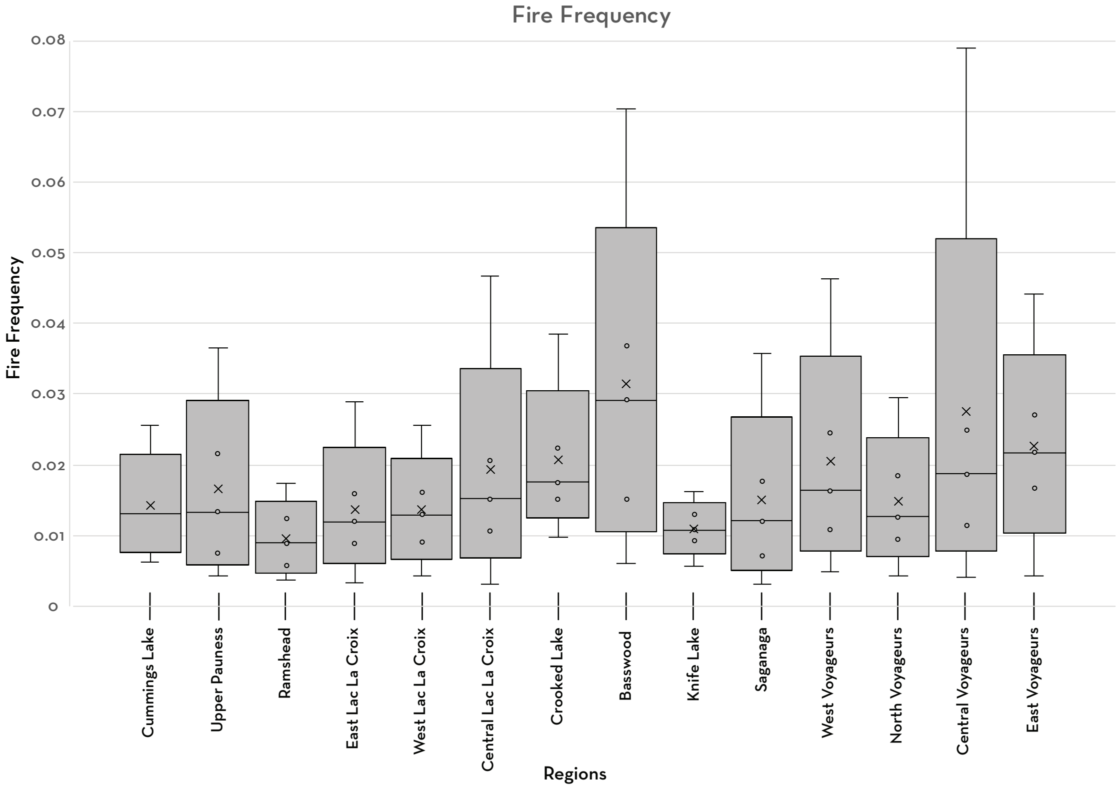

Figure B.1. Variability in fire frequency recorded in each region.

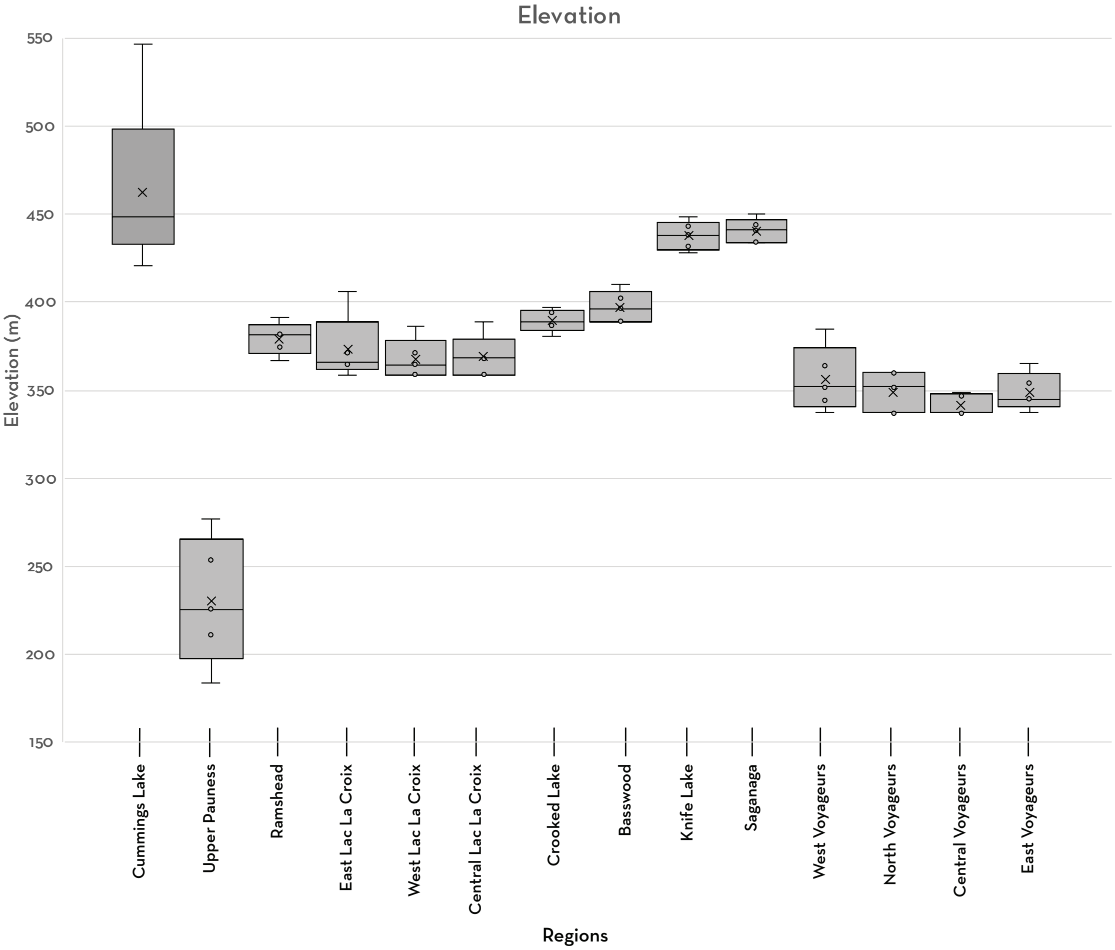

Figure B.2. Variability in regional elevation.

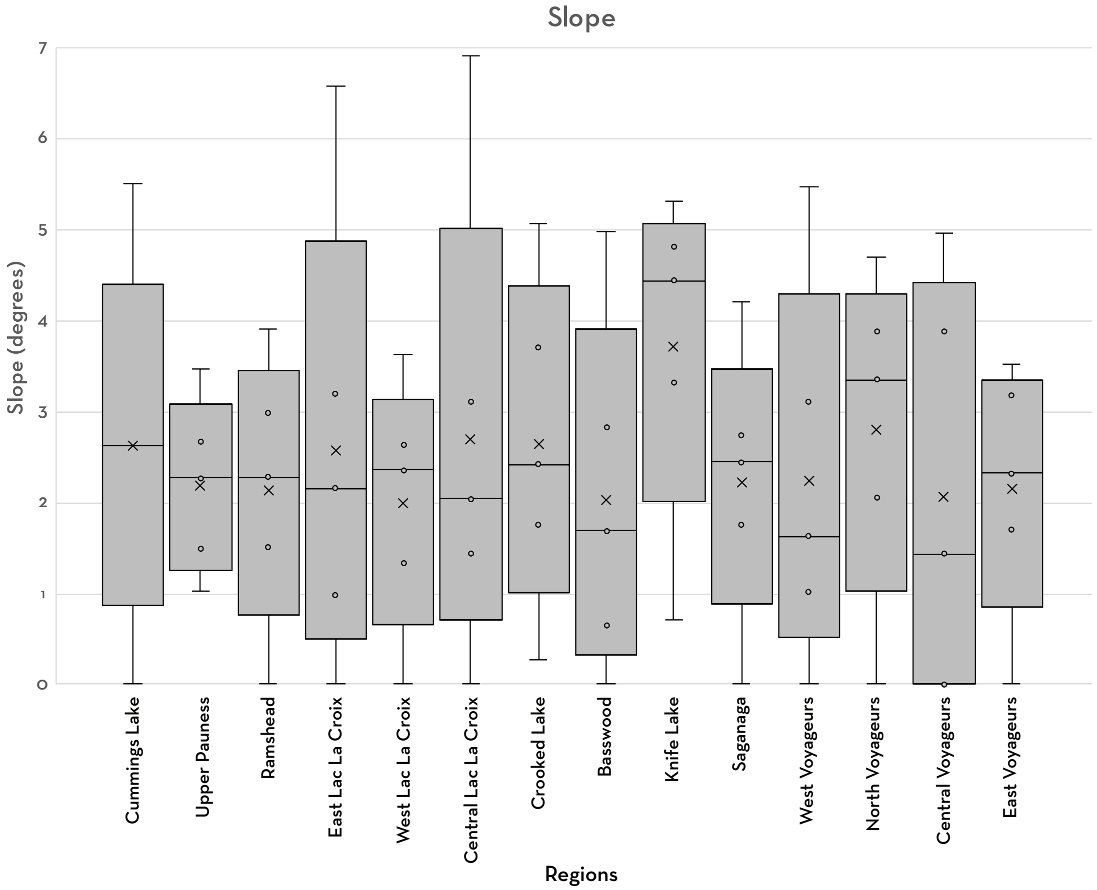

Figure B.3. Variability in regional slope.

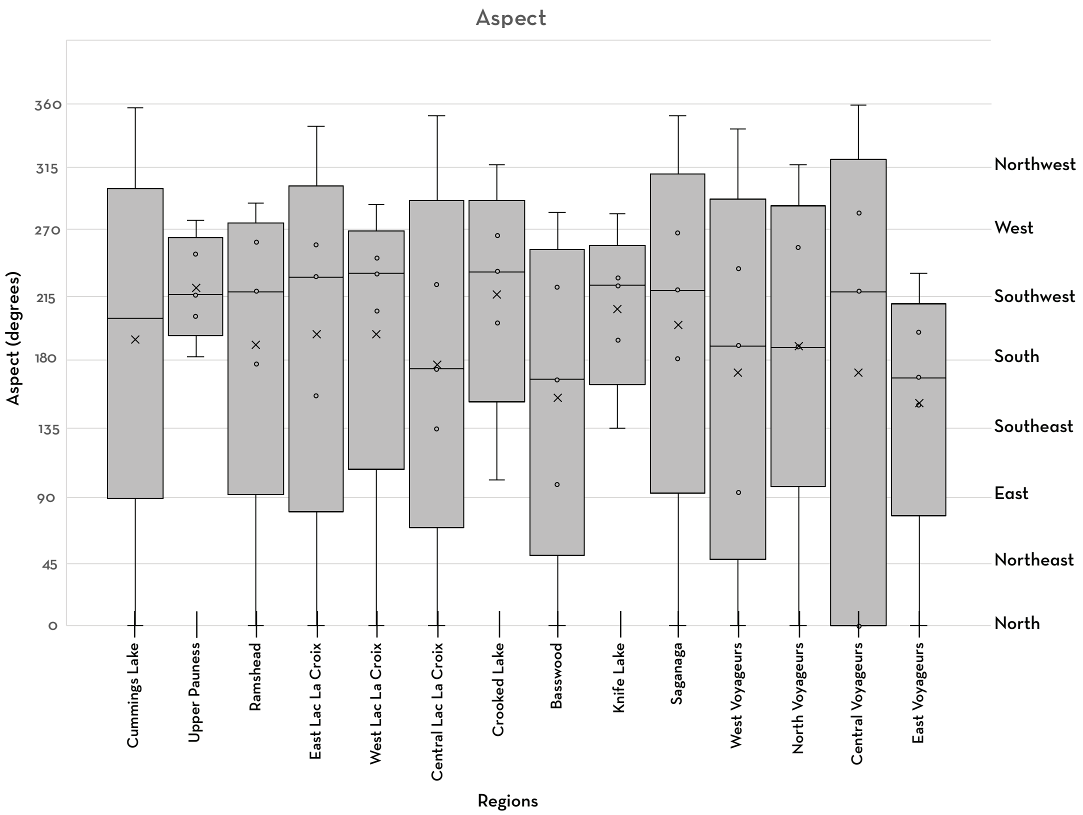

Figure B.4. Variability in regional aspect.

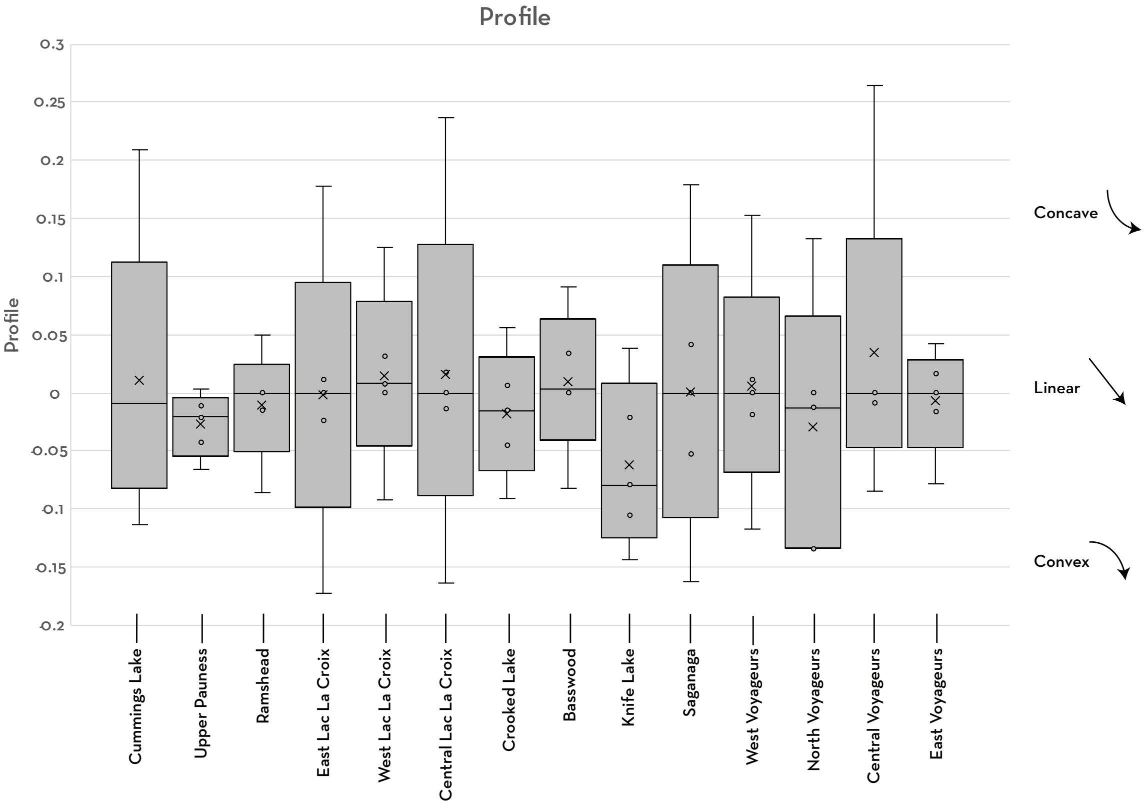

Figure B.5. Variability in regional curvature of the landscape. Zero values indicate a more linear slope, negative values indicate more convex surfaces, while positive values indicate a more concave slope. Common raster values for a hilly area (moderate relief) vary from -0.5 to 0.5.

PDSI variation in synchronous and asynchronous fire events

PDSI values were plotted to determine if a certain time period is dominating the climate trend found in the SEA. While there are no distinctive differences, PDSI in synchronous fire years occurring between 1850 and 1899 have less variation than previous time periods.

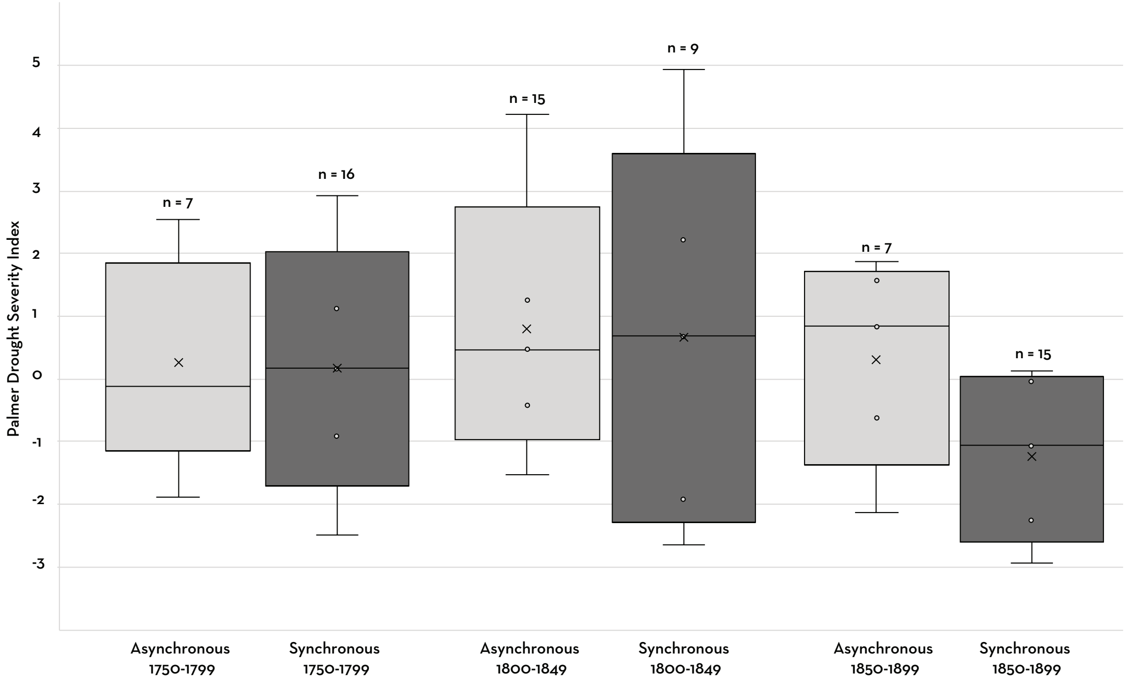

Figure B.6. Variation in PDSI values by 50-year time periods in asynchronous fire events and synchronous fire events (events recorded in four or more regions).

Information on fire years occurring in four or more regions (Table B.1) and non-fire years (Table B.2)

Table B.1. Fire years that are recorded in four or more regions (n = 47)

Fire Year	Number of Regions Burned	Number of Samples Scarred	PDSI
1682	7	22	-2.473
1736	7	33	-3.349
1739	7	77	-1.349
1747	6	14	2.705
1748	4	23	2.929
1749	4	14	1.409
1752	6	33	0.185
1756	4	7	0.788
1757	4	9	-1.541
1758	4	23	0.486
1760	6	40	-0.92
1762	4	12	2.656
1763	4	8	-0.015
1774	4	14	-1.466
1775	4	22	0.112
1780	6	24	-1.663
1784	4	8	1.277
1785	5	15	-0.919
1788	5	12	-0.086
1791	6	14	-2.487
1794	4	15	0.167
1796	5	31	0.964
1802	5	12	4.94
1804	10	39	-2.025
1805	5	9	0.845
1814	4	4	2.45
1821	6	24	-2.64
1822	4	7	2.228
1841	5	13	0.614
1842	4	18	0.676
1846	6	54	-1.921
1853	5	11	-1.822
1862	5	10	-2.848

1863	8	55	-2.427
1864	8	26	-2.932
1865	5	16	-2.1
1879	4	8	-0.576
1880	5	9	-1.058
1882	4	6	-0.022
1883	5	33	-0.599
1884	6	14	-0.035
1889	5	13	-0.053
1891	4	7	0.063
1893	4	4	-2.429
1894	5	11	-1.451
1895	7	33	0.129
1910	5	10	-4.473

Table B.2. Non-fire years between 1700 and 1900

Non-Fire Years	PDSI	Non-Fire Years	PDSI
1700	0.788	1731	-0.184
1703	3.453	1732	1.057
1706	0.46	1733	0.357
1708	-1.033	1738	-0.731
1709	-0.306	1742	-2.763
1710	0.293	1750	0.606
1713	1.308	1753	0.173
1715	2.627	1754	0.033
1716	0.079	1761	1.535
1719	-0.068	1765	1.335
1720	1.524	1783	1.785
1721	-0.332	1808	-2.194
1722	0.219	1811	-0.413
1723	1.42	1839	-2.268
1727	1.621	1851	1.245
1728	1.324	1886	-1.373
1729	1.748	1899	1.814
1730	0.502		

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CHAPTER 4: Spatial Complexity of Fire Dynamics in an Island-Lake Landscape

Synopsis

Island biogeographic theory offers a powerful conceptual framework for understanding insular diversity and ecological disturbances (MacArthur and Wilson 1963). The observation that islands usually contain fewer species than comparable areas on the mainland has spawned scientific research that touches many fields of theoretical and applied ecology. The theory has potential for applications that extend beyond the study of species diversity, particularly considering ecological disturbance such as fire within the framework of island biogeography principles. The research presented here evaluates how fire disturbance occurs in insular areas by specifically testing how island area and isolation influences variability in fire events. The Border Lakes region is naturally fragmented by lakes and streams producing a setting to evaluate the relationship between fire disturbance and island biogeographic tenets. My approach to evaluating the occurrence of historical fire events uses concepts derived from island biogeographic theory with comparisons made between fire on islands and fire on the mainland. To address this, I investigated past fire regime on islands and mainland sites using a red pine fire history reconstruction for 65 islands and 59 mainland sites that spanned the years 1489 to 2016 in the Border Lakes ecosystem of northern Minnesota. Island area and isolation were tested in relationship to fire regime metrics. Historically, fires were frequent on both islands and mainland sites and the fire event dates between sites are similar across the landscape. Significant temporal variability in fire events occurred on islands and mainland sites between 1780 and the late 1800s, with fire events accumulating more on islands prior to 1830 and mainland sites accumulating more fire events after 1860.

I speculate that fires in the Border Lakes region accumulated more often on islands between 1780 and 1830 due to intense use of the landscape by humans, corresponding to the fur trade era. After 1860, fire events occurred more rapidly on mainland sites likely related to the end of the fur trade. The core tenets of the theory of island biogeography, area and isolation, were evaluated as potential factors in influencing fire regimes on islands. I found that the area of islands are positively correlated ($p \leq 0.01$) with fire regime metrics including fire frequency, total number of fire events, and number of shared events between islands. In comparison, the isolation of islands was not significant ($p \leq 0.05$) in influencing fire regime metrics. Understanding fire disturbance within landscapes and the impacts of these fires, is increasingly important for natural resource management. Unfortunately, historical patterns in shared fire between locations and the potential spread of fire can be unpredictable. The goal of this chapter is to gain a better understanding of how landscape characteristics contribute to variability in fire disturbance and help to identify contemporary locations that differ from historical patterns, are potentially in need of ecological restoration, and that may require changes in disturbance for restoration. For instance, some ecosystems may require more frequent fire for effective restoration, while others may require less fire or altered fire-severity patterns.

Introduction

Biogeography is the study of temporal and spatial distributions of plants and animals and commonly considers issues such as migration, extinction, dispersal, disturbance, habitat change, and speciation (Hubbell 1997). Islands provide a unique case to study processes of biogeography because they are simpler than a continent or an ocean with discrete boundaries and communities, enabling questions to be addressed about ecosystems over ecologically meaningful spatial scales. By studying clusters of islands, the complexity of continental or ocean biogeography is reduced. Islands provide a model for studying factors that shape biodiversity or human related species loss, particularly issues related to fragmentation. Islands also have an advantage because of their multiplicity, variation in shape, size, and degree of isolation providing variation and necessary replication by which hypotheses can be tested (MacArthur and Wilson 1967).

The theory of island biogeography (TIB; MacArthur and Wilson 1963 and 1967), was used to examine phenomena on islands at the species level to identify the factors that determine biodiversity, such as the rates of extinction and colonization (MacArthur and Wilson 1967, Simberloff and Wilson 1969). The TIB has two main features to help explain biodiversity patterns observed on islands: (1) distance or isolation, in that more distant areas tend to be more dissimilar, and (2) area, such that larger area tends to equate to greater diversity in species. The theory postulates that species-area relations of island archipelagoes are driven by colonization and extinction rates of species with island area and isolation playing pivotal roles in the determination of island diversity (Walter 2004). Concepts of island biogeography have since been applied to terrestrial habitats, increasing the understanding of factors that shape biodiversity. Most importantly, the TIB has been applied to conservation practices such as determining the size of nature preserves (May 1975; Balser et al. 1981; Higgs 1981; Boecklen 1997), preservation of endangered species (Temple 1981; Kadmon and Allouche 2007; Stortini 2018), and evaluating the impacts from fragmentation (Hilty et al. 2006).

Several studies have suggested the unreliability and simplicity of the species-area concept and the TIB when applied to real and/or more complex data and conservation situations (Simberloff and Abele 1976; Zimmerman and Bierregaard 1986). For instance, the model does not consider specific species that may be immigrating or going extinction and thus applying the predictions to conservation practices leaves out important species factors and traits. In addition, criticism has been raised over the simplification of ecological situations and problems, such that these do not generalize well, and systems may simply not operate in the way envisioned by the theory (Doak and Mills 1994). While these limitations and criticisms exist it has been suggested that to effectively apply the theory, nuanced quantitative data are needed, modelers should use the simplest models necessary to capture relevant details in their system (Ludwig 1989; Schemske et al. 1994), and limitations should be acknowledged (Doak and Mills 1994).

Island biogeographic theory can offer a powerful conceptual framework for understanding insular diversity and ecological disturbances. The observation that islands usually contain fewer species than comparable areas on the mainland has spawned scientific research that touches many fields of theoretical and applied ecology (Villa et al. 1992). While the theory, specifically the two main tenets of area and isolation, has potential for applications that extend beyond the study of species diversity, few studies have applied the theory to other ecological questions (Villa et al. 1992). For example, evaluating ecological processes such as disturbance in terms of the TIB can provide a greater understanding regarding the complexity of nature and patterns that span a range of spatial and temporal ecological scales (Lomolino 2002).

Island biogeographic theory may help to explain the complex patterns of fire disturbance in fragmented landscapes. Larger area increases space availability for higher abundance of populations, more resources, more habitats, and more microclimates. (Walter 2004). Equating this to disturbance, larger areas have the potential for more fire events, greater area for more potential ignitions, and more variable fire regimes (Wardle 1997). In comparison, smaller areas generally lack diversity and the potential for a fire to become large. For example, in areas with less fuels, it will be harder for fires to spread between stands. Isolation on the other hand may influence fire spread or fire spotting, such that greater isolation or distance between locations will result in fewer shared fire events across the landscape (Bergeron 1991). Islands that are more isolated should thus have fewer fire events in common with the mainland or with other nearby islands due to the greater distance for a fire to travel (assuming fire event spread versus multiple ignitions). Several studies note the importance of area and isolation in influencing the patterns of fire (Bergeron 1991; Wardle 1997; Arabas et al. 2006; Drobyshev et al. 2011; Niklasson et al. 2010), yet few directly apply the TIB concepts or recognize their importance in potentially driving fire activity.

Prior research has shown that a feature of islands' fire regime is the very low probability of fire spread into the island from the surrounding landscape (Bergeron 1991; Arabas et al. 2006; Drobyshev et al. 2011; Niklasson et al. 2010). Water acts as a fire break and can only be crossed by the transport of hot particles (fire spotting) under extreme fire hazard conditions (Drobyshev et al. 2011). Dendrochronological reconstructions show that fires occurring on a mainland and on islands rarely coincide, suggesting fire spotting is possibly an infrequent occurrence (Bergeron 1991; Danereau and Bergeron 1993; Drobyshev et al. 2011). In many landscapes where lightning is the only source of fire ignition, there is a high degree of spatial independence in island fire regimes and mainland fire regimes, such that multiple ignitions are generally rare (Drobyshev et al. 2011). Other research has shown that fire occurrence is generally higher on islands than on the surrounding mainland for two reasons. First, islands act as a lightning attractor due to their topography, such that islands are generally dome shaped which can attract more lightning strikes than flatter surfaces (Bergeron 1991). Second, fuels dry out faster on islands due to smaller size, wind effects, and highly variable topography, thus making it easier for a fire to ignite (Bergeron 1991; Wardle 1997). Island size is also a factor, such that larger islands typically have a higher fire frequency than smaller islands (Wardle 1997). The TIB has also been applied to forest isolates (kipukas) created by lava flows in the Pacific Northwest (Arabas et al. 2006) showing similar area and isolation effects on the fire regime. For instance, fire occurred more frequently on forest isolates, were asynchronous with events occurring in the surrounding forest, and fires were predominately lightning initiated.

The aim of this chapter is to enhance the current understanding of the pattern of historical fire reconstructed for red pine dominated stands in a naturally fragmented landscape through the use of fire event data and the application of island biogeographic concepts. By using a historical perspective, the influence of landscape structure in creating past, current, and future patterns of fire across a range of scales can be highlighted. While the previous chapters indicated that landscape structure (elevation, aspect, and slope) were not significant drivers of asynchronous fire events (see Chapter 3 results), the landscape may influence how fire disturbance behaves. For example, it may be that fire events on the mainland occur more or less frequently than fire events on insular habitats. In addition, the area and/or isolation of habitats may lead to differences in fire events. The evaluation of fire disturbance in the context of island biogeographic theory can provide an important understanding of how area and isolation impact the variability of fire disturbance in red pine dominated forests and help us to understand how particular areas (connected versus insular) historically experienced fire. This can provide a framework to understanding changes from the past to contemporary conditions and provide insight into the conservation of patchy, island landscapes.

Research Questions

This chapter evaluates the spatial and temporal distribution of fire events in the Border Lakes region (BLR) through a combination of techniques involving the theory of island biogeography and fire event similarity. The general assumption as put forth by prior research (Bergeron 1991; Danereau and Bergeron 1993; Arabas et al. 2006; Drobyshev et al. 2011; Niklasson et al. 2010) and TIB tenets, is that islands should have a low probability of shared fire between them and with mainland counterparts because water acts a fire break both limiting the spread and transport of fire. Islands should also have a higher occurrence of fire events with larger islands being more variable whereas sites located on the mainland should be more similar in their fire history (Wardle 1997). The area and isolation of islands should also influence fire resulting in fewer shared fires on more isolated islands and a greater variability in fire events on larger islands compared to smaller ones. This dissertation chapter addresses three research questions to gain a more nuanced understanding into the dynamics of the fire regime in the BLR and how the tenets of island biogeography help explain the complexity in spatial and temporal patterns of fire.

1. How do the fire frequencies on mainland sites compare to island sites?

Null hypothesis: There is no difference in fire frequencies on island sites and mainland sites.

Assumption: Islands have a higher rate of fire because (1) islands act as a lightning attractor due to their topography (typically dome shape) and (2) fuels dry out faster on islands due to smaller size, wind effects, and highly variable topography, thus it is easier for a fire to ignite.

2. What is the degree of fire similarity between islands, between islands and mainland sites, and between mainland sites?

Null hypothesis: Fire regimes do not differ between islands, between islands and mainland sites, and between mainland sites, such that the number of shared fire events are equal.

Assumption: There is low probability of shared fire events between islands and between islands and mainland sites because water acts as a fire break. Whereas mainland sites should have a greater number of shared fire events due to stand connectivity.

3. How do the primary components of island biogeography, specifically area and isolation, help explain the complexity in the fire regime on islands?

Null hypothesis: Area and isolation have no influence on island fire regimes.

Assumption: First, islands that are more isolated (i.e. greater distance from the source - to another island and/or mainland) will have fewer number of shared fire events than islands that are closer in proximity to other islands and/or the mainland. Second, larger islands should have greater complexity in their fire regime (e.g. higher fire frequency, greater number of fire events, and a greater chance of shared fire events compared to smaller islands).

Methods

This research uses both fire event data and spatially defined landscape characteristics to better understand fire patterns. Fire data used are derived from a fire-scarred red pine reconstruction developed for both Voyageurs National Park (Kipfmueller et al. 2017) and the Boundary Waters Canoe Area Wilderness (Johnson and Kipfmueller 2016, Kipfmueller et al. forthcoming). Fire scar samples (n = 541) are geo-referenced and fires are dated to the exact calendar year. The landscape was defined in a GIS with islands and mainland sites defined. Each island was characterized by area, perimeter, distance to the nearest mainland point, distance to the nearest ten islands, and distance to the nearest island with fire history. The ten nearest islands were chosen due to both computational time and a post-hoc understanding of the landscape structure, whereas the ten nearest islands threshold generally captured variability in near small and large islands. Fire scars on the mainland were grouped into 1 km clusters. A 1 km cluster was chosen because the average size of sites on islands is 1.1 km. Fire regime characteristics were then summarized for each island and mainland site including recording years (inner and outer ring dates), number of fire events, fire frequency, mean fire interval, and number of unique fire events.

Fire Frequency Comparison

Fire frequencies for both islands and mainland sites were tested for normality and then the distributions were tested for statistical difference using a Student's t-test. A Student's t-test was chosen for fire frequency comparisons as it determines if the two groups originate from populations with similar distributions (Sokal and Rohlf 1995; Legendre and Legendre 1998). The temporal stability of fire events occurring on both islands and mainland sites was also compared using the cumulative number of fire events and the two distributions were tested to determine if fires occurring on islands and mainland sites are statistically different from one another using a Kolmogorov-Smirnov (KS) test (Legendre and Legendre 1998). The KS test was used as it appropriate for continuous distributions such as the cumulative number of fire events through time (Gotelli and Ellison 2004).

Fire Event Similarity

Presence-absence matrices of fire occurrence were generated by year for both island sites and mainland sites (fire = 1, no fire = 0) and the matrices were tested for similarity in fire year occurrence using the *simba* and *vegan* packages in R (Jurasinski and Retzer 2012; Oksanen et al. 2017). Comparisons between fire matrices were made and compared both the number of shared fire events between all pairwise combinations of sites and the Jaccard similarity index was also evaluated. Fire event similarities were made between three groups: between islands (island-island), between mainland sites (mainland-mainland), and between island and mainland sites (island-mainland). The Jaccard similarities between the three groups were then plotted to help visualize overall comparisons between sites. The three distributions were then tested for statistical difference using an ANOVA, as it is appropriate for testing the difference in means between three or more groups.

TIB and Island Fire Metric Analysis

Finally, the primary components of island biogeography, area and isolation, were evaluated as potential factors in influencing fire regimes on islands. To evaluate isolation as a factor influencing fire, a total isolation variable (TIV) was calculated for each island:

$$TI_{i1} = D(IS_{i1} + IS_{i2} + \cdots IS_{in}) + M$$

where, D is the distance between the island and the ten nearest islands, $IS_{i1}, IS_{i2} \ldots IS_{in}$, and M is the distance to the nearest mainland point. Spearman's rank correlation coefficients were calculated to discover the strength between variables and was chosen because it does not assume measurements are distributed normally or have a linear relationship (e.g. correlations are less restrictive than that of a linear relationship) with correlations representing the strength and direction of association between variables. Spearman's rank correlations were calculated between the fire regime metrics: number of unique fire events (events occurring in just one region; see Chapter 2 methods), fire frequency, total number of fire events, and number of shared fire events, and the metrics: area of the island, perimeter, distance to nearest island, distance to nearest mainland, distance to nearest fire island, and TIV.

Results

Fire Frequency Comparison

In total, 65 islands were defined with fire history and 59 mainland sites (Figure 4.1). Between 1503 and 2016 there were 347 fire events observed on islands, representing 168 individual fire years. In comparison, 362 fire events were observed on the mainland between 1489 and 2015, representing 150 individual fire years (Table 4.1). Of the 168 fire years occurring on islands, 33 of those were unique to island sites, whereas 19 of the 150 fire years on the mainland were unique to the mainland sites. Mean fire intervals varied slightly between islands and the mainland with MFI on islands 32.14 years and 31.6 years on the mainland (Table 4.1). Fire frequencies were somewhat higher on mainland sites then on islands (0.022 and 0.019, respectively; Figure 4.2). Fire frequencies were not normally distributed and were log transformed. A Student's t-test on the log transformed variables indicated that the differences in fire frequencies are not statistically significant (p-value 0.105; Table 4.2).

Over time the cumulative number of fire events varied slightly between islands and mainland sites with islands accumulating more events between 1780 to 1830 (71 events occurring on mainland sites and 91 events on islands) and mainland sites accumulating more events between 1860 and 1900 (99 events occurring on mainland sites and 79 on island sites; Figure 4.3). A two-sample KS test indicates that overall the two distributions are statistically different from one another (D=0.209, p-value ≤ 0.000).

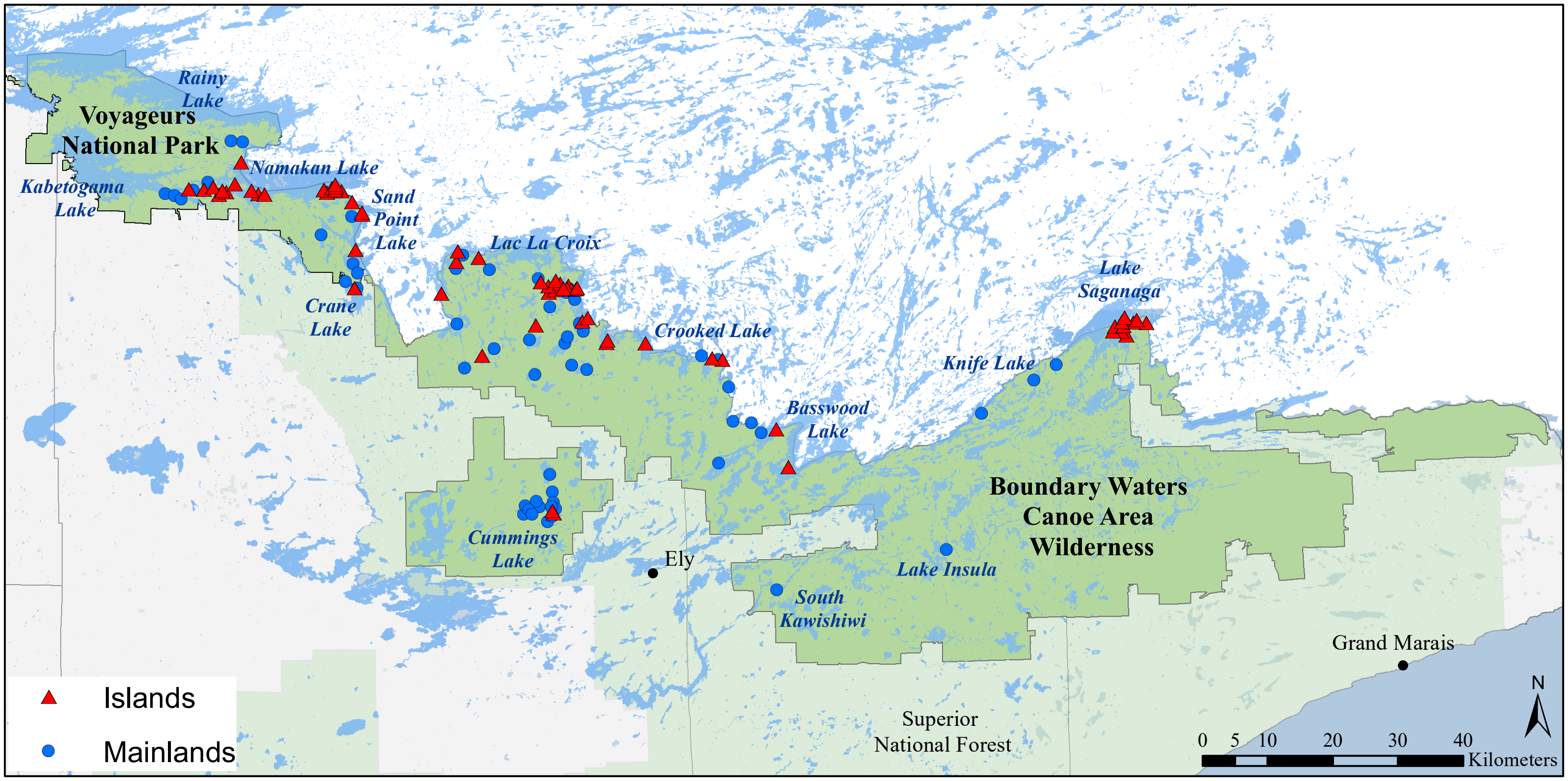

Figure 4.1. Study area map showing mainland sites (blue dots, n = 59) and island sites (red triangles, n = 65) in the Border Lakes region.

Table 4.1. Fire Regime Characteristics on Island and Mainland Sites

	Island	**Mainland**
Length of Fire Record	1503–2016	1489–2015
First Fire Recorded	1546	1647
Last Fire Recorded	1936	1972
Number Sites	65	59
# Fire Events	347	362
# Fire Years	168	150
# Unique Fire Events	64	46
# Unique Fire Years	33	19
MFI (years)	32.14	31.6
Fire Frequency	0.019	0.022

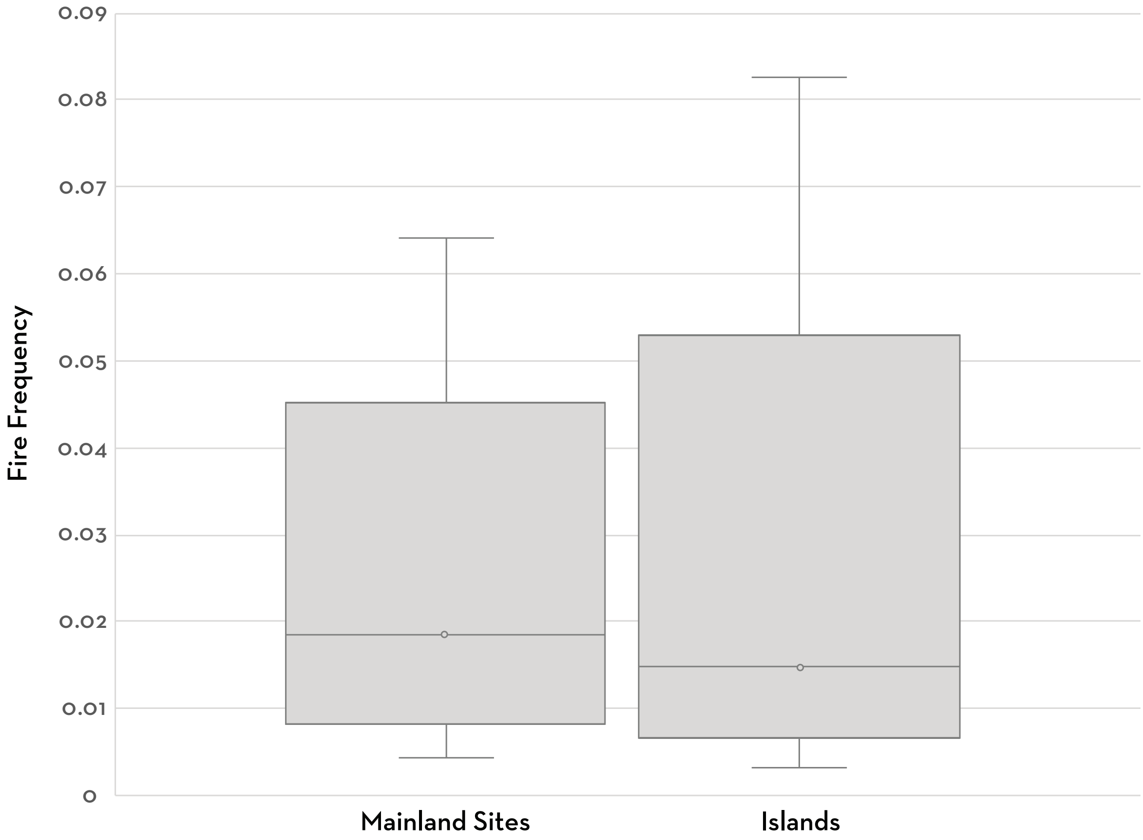

Figure 4.2. Distribution of fire frequencies reconstructed for mainland sites and islands.

Table 4.2. Results of a Student's t-test on log transformed fire frequencies

	Mainland Sites	Islands
Mean of fire frequencies	0.022	0.019
Mean of log fire frequencies	-4.015	-4.209
Hypothesized Mean Difference	0	
t Stat	1.636	
Degrees of freedom	122	
p-value	0.105	
t Critical two-tail	1.979	

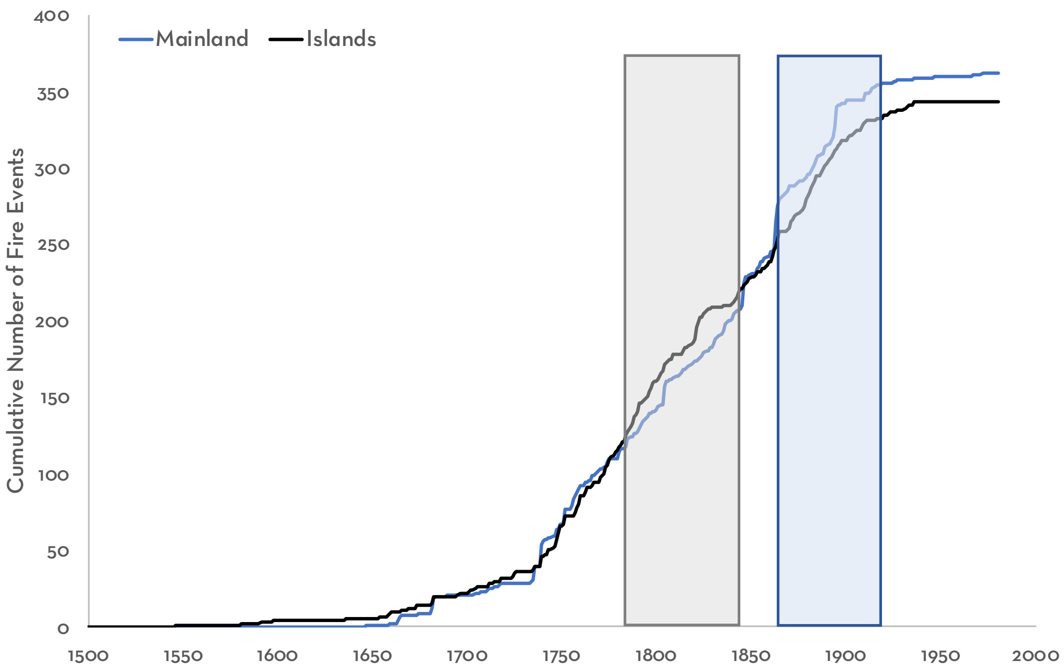

Figure 4.3. Cumulative number of fire events for islands and mainland sites. Grey shaded region indicates the period when islands are accumulating more fire events (1780 to 1830), and the blue shaded region indicates the period when the mainland is accumulating more fire events (1860 to 1900).

Fire Event Similarity

Overall 168 fire years are recorded on island sites with the first fire year in 1546 and the last in 1936 and 33 of those fire years are unique to just one island (Table 4.1). In comparison, a total of 150 fire years are recorded on mainland sites with the first fire recorded in 1647 and the last in 1972 and 19 of those fire years only occur at one mainland site. Jaccard similarity plots, [*why are we giving trophies to mediocre white men for doing stuff they should already be doing*] which evaluated the similarity in fire years between all island and mainland sites comparisons visually indicates that mainland sites have more similarity than those between islands or those between island and mainland sites (Figure 4.4). However, ANOVA results indicate that the number of shared fire events in the three grouping are not statistically different from one another (p-value = 0.76).

TIB and Island Fire Metrics

Spearman’s rank correlations between the island biogeographic metrics and landscape variables and the fire regime metrics suggest that area and perimeter have a significant influence on the fire regime. This suggests that the larger the island and greater amount of core area the higher the fire frequency, greater number of fire events, and greater number of shared fire events between islands (Table 4.3). While distance to nearest fire island and TIV are negatively correlated to the fire regime metrics (as isolation increases the number of fire events and fire frequency decreases), these values are not significant.

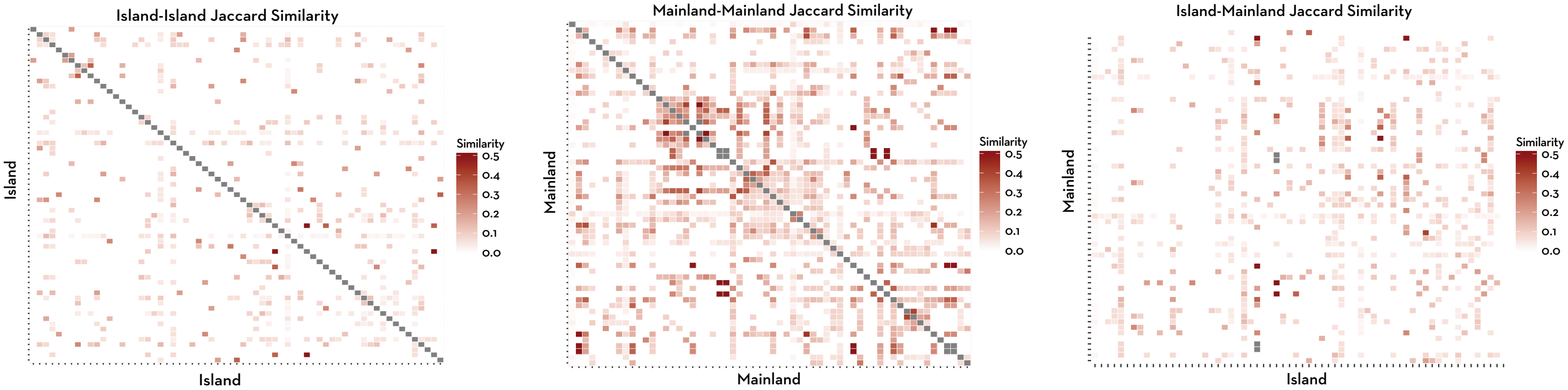

Figure 4.4. Jaccard similarity between all pairwise combinations of islands (left), pairwise combinations of mainland sites (middle), and pairwise combinations of islands and mainland sites (right). Similarities were plotted to help visualize overall comparisons between sites.

Table 4.3. Spearman Rank Correlations Between Fire Regime Metrics and Island Biogeography Variables

	Area	**Perimeter**	**Dist. To Nearest Island**	**Dist. To Nearest Mainland**	**Dist. To Nearest Fire Island**	**TIV**
Number Unique Fire Events	0.237	0.224	0.025	-0.007	-0.126	-0.126
Fire Frequency	0.384*	0.357*	0.047	0.099	-0.207	-0.207
Number of Fire Events	0.435*	0.42*	0.071	0.155	-0.233	-0.233
Number of Shared Fire Events	0.453*	0.439*	0.062	0.138	-0.225	-0.225

* $p \leq 0.05$

Discussion

This research is concerned with how fire disturbance occurs in insular areas by comparing fire occurrence on mainland and islands sites and specifically relates island area and isolation to the variability in fire activity. Results indicate that island and mainland sites are fairly similar in their fire regimes. This is reflected in both their fire frequencies, which are not statistically different (Figure 4.3 and Table 4.2), and in their fire event similarity. While mainland sites share more fire events between them, which would be expected due to connectivity of sites, the number of shared fire events is not statistically different from those occurring between islands or between islands and mainland sites (Table 4.3). A significant difference was found in the temporality of fire events accumulating on islands and mainland sites (Figure 4.3). Early in the fire history reconstruction, beginning around the 1650s, the number of fire events occurring on both islands and mainland sites are similar with both slowly accumulating fire events. Around 1780, islands begin to accumulate more fire events until 1830. In 1861, this switches with mainland sites accumulating more fire events than islands. After 1900, both islands and mainland sites stop accumulating fire events with the onset of fire management practices. The importance of island size is reflected in correlation analysis results which revealed that the area of the island is a significant influence on the number of unique fire events while isolation and distance to another site is not a significant factor (Table 4.3).

These results contradict prior research which shows that islands will generally have a higher fire frequency than their mainland counterparts. It might be expected that fire frequency will be higher on islands because they tend to be drier and warmer and fuel may ignite easier than on mainland sites which tend to be moister (Bergeron 1991, Drobyshev et al. 2011). The moisture content of fuels typically determines how quickly a fire can spread and how intense or hot a fire may become. High moisture content will slow the burning process, because heat from the fire must first eliminate moisture. Lower moisture content is generally expected on islands given their greater exposure to wind and sun whereas a higher moisture content is expected on mainland sites which are more protected with a greater amount of core area. The result that islands and mainland site fire frequencies do not differ may be because most mainland sites are near the shoreline with the average distance between the lakeshore and a mainland site being under 1 km. As a result, mainland sites may effectively receive the same wind and sun effects as islands.

Theoretically, islands should have a more variable (independent), asynchronous fire regime whereas mainland sites should have a more synchronous fire regime. On islands, stands are limited to the space, resulting in a lack of connected stands and fuel. Fuel continuity is an important factor in the behavior of fire because it indicates how quickly and why a fire may spread. When fuels are patchy, scattered, or separated by natural barriers such as water, fire events will be irregular and spread more slowly. Because of this, it would be expected that fire events would be more similar between mainland sites due to an increase chance of connectivity between stands and thus fire spread compared to the fires occurring on islands. However, these results indicate that there is no statistical difference in the number of shared fire events occurring between mainland sites, between islands, and between islands and mainland sites (Figure 4.4).

These results contradict prior dendrochronological reconstructions that show fire years on the mainland and on the islands rarely coincide (Bergeron 1991; Dansereau and Bergeron 1993; Drobyshev et al. 2011). The lack of statistical difference between fire frequencies on islands and mainland sites and in fire event similarity in the Border Lakes may also be a result of the location of many of the mainland sites as well as the overall high rate of fire occurrence in the region. For instance, fire occurrence may be so frequent within red pine dominated forests that the difference between islands and mainland sites would be small.

Fire events accumulate more rapidly on islands between 1780 and 1830 with a notable peak in fire occurrence between 1818 and 1832. This then switches with mainland sites accumulating more fire events then islands after 1860 with two notable peaks occurring from 1861 to 1873 and another from 1883 to 1900. Niklasson et al. (2010) observed a similar pattern of fire occurrence on mainland sites and islands in an island archipelago in south-east Sweden. They found that fires before 1750 were less frequent on islands than on the mainland (58 vs. 25 years), while between 1750 and 1860 fire intervals were shorter on islands (15 vs. 29 years). They suggest that this difference is due to more intense use of the islands by the local population during the same time, resulting in an increase in the number of intentional and unintentional ignitions with fire likely used to improve pastures on islands.

I speculate that fires in the Border Lakes region accumulate more rapidly on islands between 1780 and 1830 due to intense use of the landscape by people. This period corresponds to the peak of the fur trade era which occurred between the 1730s and the 1860s with European voyageurs and indigenous groups using the Border Route to trade goods, repair canoes, and resource extraction (Johnson and Kipfmueller 2016; Larson et al. 2019). Regions including the Saganaga Falls portage, Lac La Croix, and Sand Point Lake were all well-established sites, are along the Border Route, have a disproportionate number of island sites, and have a higher occurrence of asynchronous fire events (see Chapter 3 results). It is possible that the greater number of fire events accumulating on islands corresponds to the use of fire by people as well as unintentional burning along the Border Route. After 1860, fire events occurred more rapidly on mainland sites (particularly LLC and VOYA – no islands in SAG), corresponding to the end of the fur trade. A notable shift in land use also occurred in the late 1800s with an increase in logging, primarily occurring on the mainland.

Human use of the landscape may also contribute to the lack of statistical difference in fire frequencies and the similar number of shared fire events between islands and mainland sites. For instance, intentional and unintentional fires may be so frequent that differences in island and mainland fire regimes may be indistinguishable.

Area and Isolation Influence on the Fire Regime

The species-area curve is one of the best documented patterns in ecology and central to the theory of island biogeography. The theory assumes species richness increases with island area and connectivity. In this study, fire occurrence and fire synchrony were used as descriptors in place of species richness to evaluate how landscape structure may influence the historical fire regime in the Border Lakes region. I was able to demonstrate that fire occurrence was positively related to area and not associated with isolation of an island. Moreover, I found that while fire frequencies on island and mainland sites were not statistically different from one another, fire event accumulation varied on islands and mainland sites over time.

In consistence with TIB predictions, the total number of fire events, fire frequency, and the number of synchronous fire occurrence increased with island area. The habitat heterogeneity hypothesis of the TIB assumes that large areas tend to contain a greater diversity of environmental conditions (Connor and McCoy 1979; Zhao and Zhou 2018), and in the case of this research a greater diversity in fire occurrence. In the case of larger islands, the greater diversity in both vegetation and the landscape, there is possibly greater potential for a fire to ignite. For instance, the possibility for a greater number of microsite conditions may be present with larger areas. A caveat to this relationship is the sampling hypothesis that assumes the more species found in large areas is caused by greater sampling efforts in these areas (Rosenweig 1995; Zhao and Zhou 2018). This pattern is apparent in the BLR dataset, where larger areas have more fire-scarred samples present. While this pattern exists, it is hard to know if it is the result of over sampling, greater potential for fire activity due to larger area, or other possible factors (e.g. islands may attract lightning ignitions. Because these factors were not tested, I encourage further investigation on the effects of sampling on the reported fire occurrence (see further discussion on future work in Chapter 5). Regardless, the fire occurrence-area relationship found in this research provides important detail into the past patterns in fire occurrence and the relationship to landscape structure.

The theory of island biogeography also predicts that species richness decreases with increasing isolation by decreasing the number of potential colonists into the island (MacArthur and Wilson 1967; Rosenweig 1995). In the study presented here, a total isolation variable (TIV) was calculated for each island and evaluated in relationship to fire metrics (i.e. total number of fire events, fire frequency, and the number of asynchronous and synchronous fire events). Fire activity and isolation was also evaluated in regard to distance to nearest island, distance to nearest mainland, and distance to the nearest island with fire history. No relationship was found between the fire metrics and isolation measures. The lack of relationship fond could be because variables not included in this analysis may not be important explanations. For example, habitat type, shape of the island, and the relationship to lake size. Human land use may also be an important factor influencing fire occurrence in this area and I encourage a more comprehensive study to incorporate these factors into studying fire occurrence patterns in the BLR (see Larson et al. 2019 and Kipfmueller et al. forthcoming).

Conclusions

Fire occurrence on 65 islands was positively related with island area and not related to isolation. Temporal variability in the fire occurrence on islands and mainland sites did exist, with more fire events occurring on islands between 1780 and 1830 and switching to more fire events occurring on mainland sites after the 1850s. The evaluation fire occurrence and can help us to understand the patterns in the history of fire and the relationship between points of interest. The results of this chapter point to the important role of fire in red pine ecosystems, its variability across the landscape, the variability in where fires occur over time, and the relationship between island size and the occurrence of fire.

Appendix C – Island and Mainland Variation

Distance between island and mainland sites.

The distance between all pairwise combinations of sites was plotted to visually assess if there is a difference in the distance between island sites and between mainland sites. The assumption is that island sites would be further apart due to landscape structure and connectivity. However, the boxplots show that, while the distance between mainland sites has more variability, the median difference between island sites and the distance between mainland sites are similar.

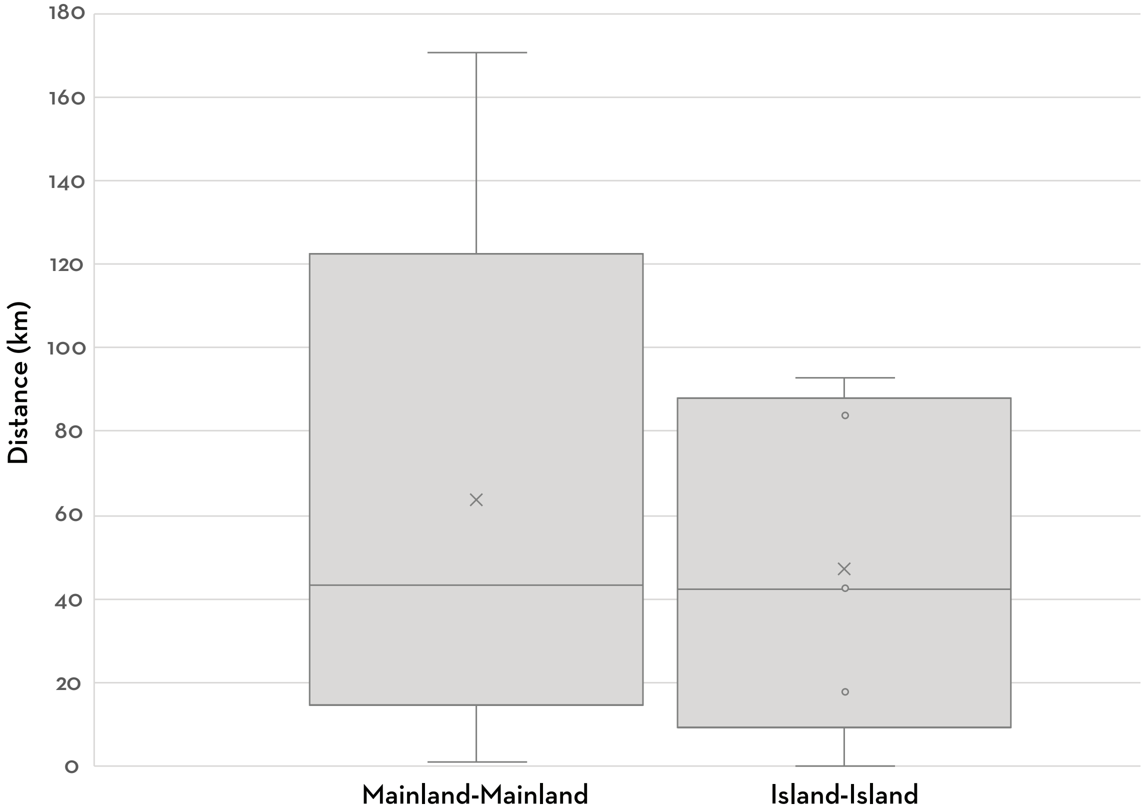

Figure C.1. Distance between pairwise combination of sites.

Comparison in the number of cumulative fire events

The cumulative number of fire events were determined for both island and mainland sites occurring in generally defined regional designations. Five general regions were determined based on the coordinates of each sample. For each region, the number of fire events over the analysis period was plotted. The purpose of this graphic is to evaluate the temporal variability of fire events occurring on islands and mainland sites by geographic region.

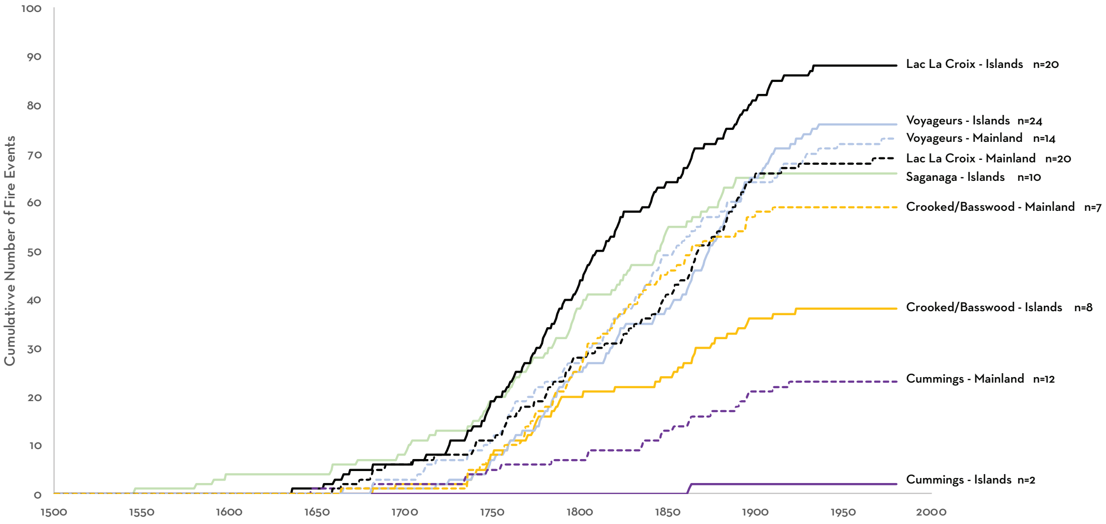

Figure C.2. The number of cumulative fire events occurring in each region (5 regions broadly defined). Solid lines represent number of fire events occurring on islands and dashed lines represent number of fire events occurring on mainland sites. The number of sites is labeled. Note that Saganaga has no mainland sites. These were plotted to see if there is a particular area that is driving the mainland/island difference in number of fire events occurring.

Relationship Between Island Area and Fire Regime Metric

Log transformations were performed on island area and the fire regime metrics evaluated in Chapter 4. The plots that follow illustrate the relationship between island area, total number of fire events, number of shared fire events, and fire frequency.

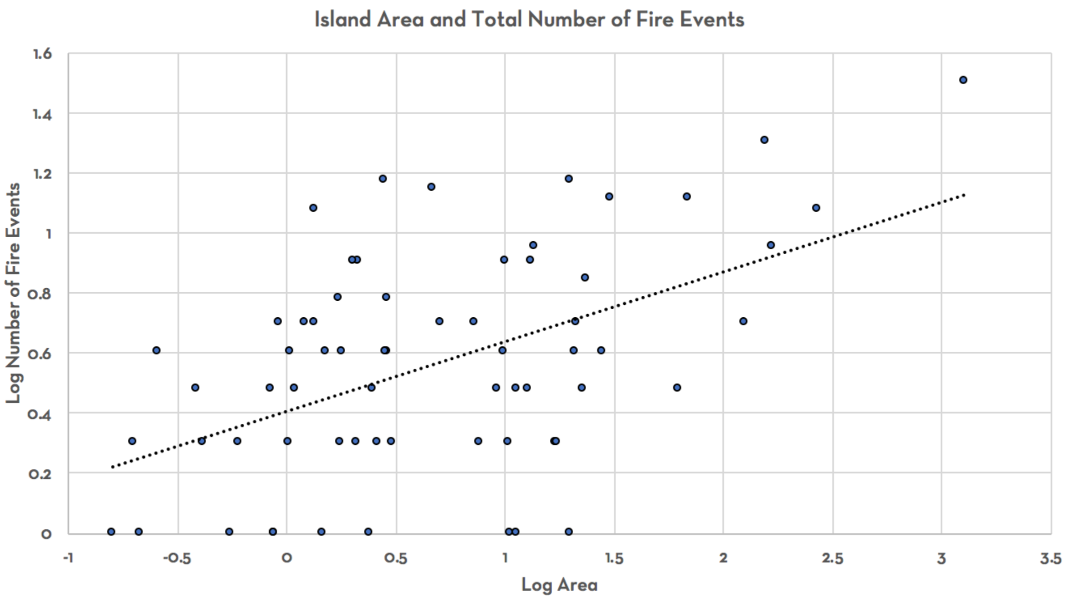

Figure C.3. Log relationship between the total number of fire events occurring on each island and island size.

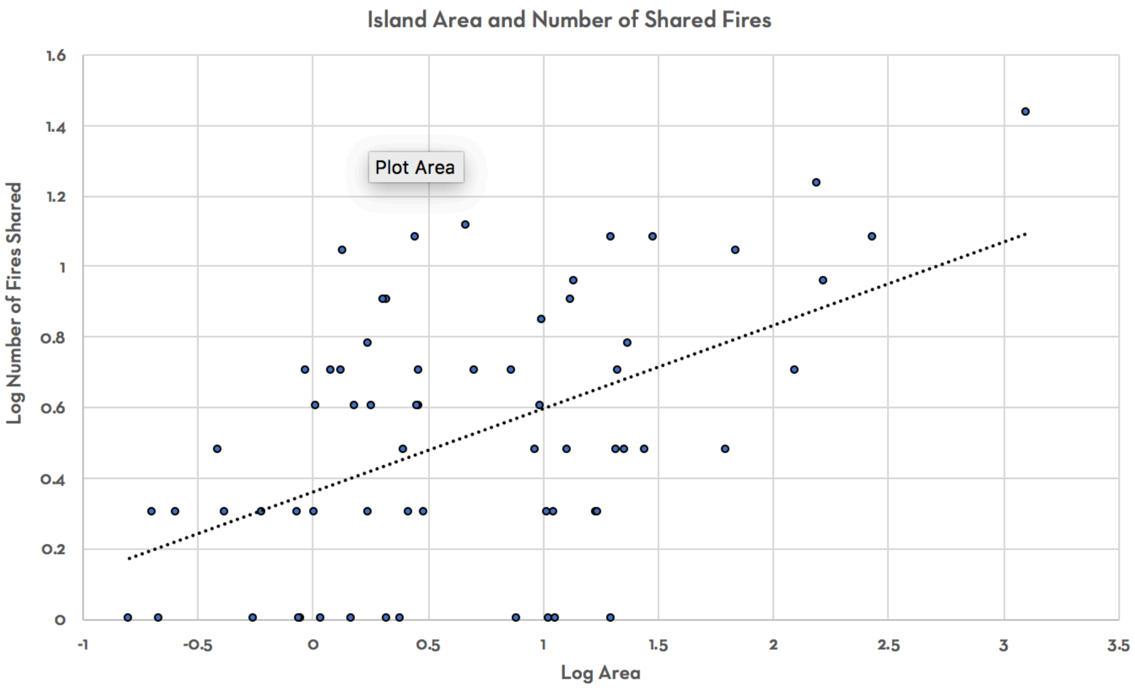

Figure C.4. Log relationship between the number of shared fire events occurring on each island and island size.

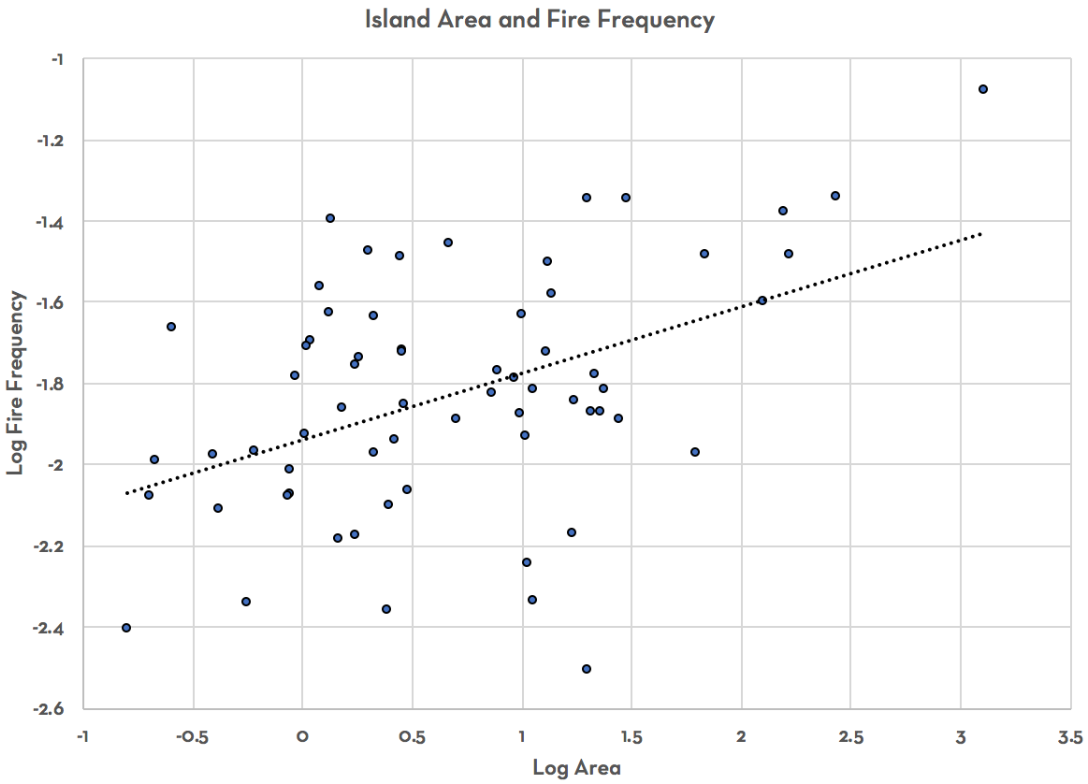

Figure C.5. Log relationship between the fire frequency of each island and island size.

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CHAPTER 5: Conclusions and Synthesis of Research

Fire Synchrony

Results from this dissertation emphasize the overall importance of fire in the Border Lakes region. Generally, fire events occurring between 1546 and 1972 (first and last fire recorded) tended to be more synchronous than asynchronous. For example, of the 217 fire events recorded, 138 fire events were shared between two or more of the defined 14 regions. Synchrony did vary over time, for instance, between 1800 and 1899 there were 94 fire events recorded with 72 of those being synchronous (76% occurred in two or more regions). In comparison, the 1700–1800 period had 71 fire events, with 51 of those being synchronous (72%) and the 1900–2000 period had 31 fire events recorded and just one of those was recorded as synchronous. The shift to fewer fire events and fewer synchronous events may be the result of land use changes occurring in the late 1800s and early 1900s. Synchronous fire years include: 1804 (71%, 10 of the 14 regions), 1863 (57%, 8 regions), and 1864 (64%, 9 regions). Fire event years recorded in 50% of the regions were 1682, 1736, 1739, and 1895 (see Figures 2.5 and 2.6 and 2.7).

Patterns also varied spatially, with certain regions have a greater number of synchronous or asynchronous fires than others. For example, both the Central Lac La Croix region and the Saganaga Lake region are statistically different from all other regions in the occurrence of asynchronous fire events. The Central Lac La Croix region (CLLC, n = 34) has the greatest number of synchronous fire events recorded as well as the greatest number of asynchronous events, followed by Central Voyageurs (CVOYA, n = 29), and Saganaga Lake (SAG, n = 25). Regions with the fewest number of synchronous events include Upper Pauness (UPN, n = 5) and Knife Lake (KNI, n = 7).

Regions have temporal variability in fire synchrony (see Table 3.3). For example, the CCLC, BAS, SAG, and EVOYA regions are different in the number of asynchronous and synchronous events that are occurring in the 1750–1799 and the 1850–1899. In addition, the 1850–1899 period the CMG, WVOYA, NVOYA, and WLLC regions are different in their occurrence in synchronous and asynchronous fire events compared to other regions. While this variation between regions and time periods exists, there are no distinguishable patterns in regional synchrony. For example, fire event similarity was not related to the amount of distance separating regions. In Chapter 4, which evaluated how fire activity varies between islands and mainland sites, results indicate that between 1780 and the late 1800s, fire events accumulated more on islands prior to 1830 and mainland sites accumulating more fire events after 1860.

Drivers of Fire Synchrony

This research demonstrates that between 1546 and 1972 there was a greater number of synchronous fire events occurring than asynchronous events and that climate, specifically periods of extended drought, are responsible for larger, synchronous fire events while smaller, asynchronous fire events were likely driven directly and indirectly by Indigenous activities. In addition, fires were frequent on both islands and mainland sites and the area of an island is related to the number of fire events and fire frequency, whereas the isolation of an island is not a significant factor influencing fire activity.

Fire History Comparison

This research adds to the growing number of studies conducted in the area that demonstrate the significance of fire (Mitchell and Conzet 1927; Ahlgren and Ahlgren 1960; Heinselman 1973; Heinselman 1981; Weyenberg and Pavlovic 2014; Johnson and Kipfmueller 2016; Kipfmueller et al. 2017; Kipfmueller et al. forthcoming) and serves as a useful baseline for considering the spatial patterns in the fire regime. Most notably, is the foundational work of Heinselman (1973) who reconstructed the fire regime for the Boundary Waters Canoe Area Wilderness. Heinselman (1973) used a combination of fire scar dates, age structure data, and aerial photographs to determine the historical pattern of fire in the BWCAW. He identified 70 individual fire years occurring between 1542 and 1972 on 178 trees and 11 major fire events defined by events that burned 100 or more square miles (Table 5.1). In comparison, the fire history used in this research (BLR) identified 217 individual fire years between 1489 and 2016 on 541 trees (data includes Voyageurs which was not a focus of Heinselman 1973) and 137 major fire years (defined as events that burned two or more regions, see Chapter 2 methods). A total of 54 fire years are shared between the two datasets including nine major fire years shared, with 1692 and 1727 recorded as a major fire year in Heinselman's record and not the BLR record.

The most significant fire events occurring in the Border Lakes region as defined above, include 1682, 1736, 1739, 1804, 1863, 1864, and 1895 (Figure 2.5), which are those that recorded in seven or more of the 14 defined regions. There is disparity between Heinselman (1973) and the BLR major fire events, with several fires occurring within

Table 5.1. Fire interval comparisons between Heinselman (1973) and BLR data

Data	Record	No. Samples	No. Fire Years	MFI All Fires 1542–1972	MFI Settlement Period 1868–1910	MFI Presettlement Period 1727–1868	MFI Major Fires 1727–1910
Heinselman	1542–1972	178	70	6.1	2.1	4.3	26[a]
BLR	1489–2016	541	217	1.8	1.1	1.1	3.6[b]

[a] Heinselman: Major fire years are defined as those with burns over 100 square miles.

[b] BLR: Major fire years are defined as those that are recorded in four or more regions

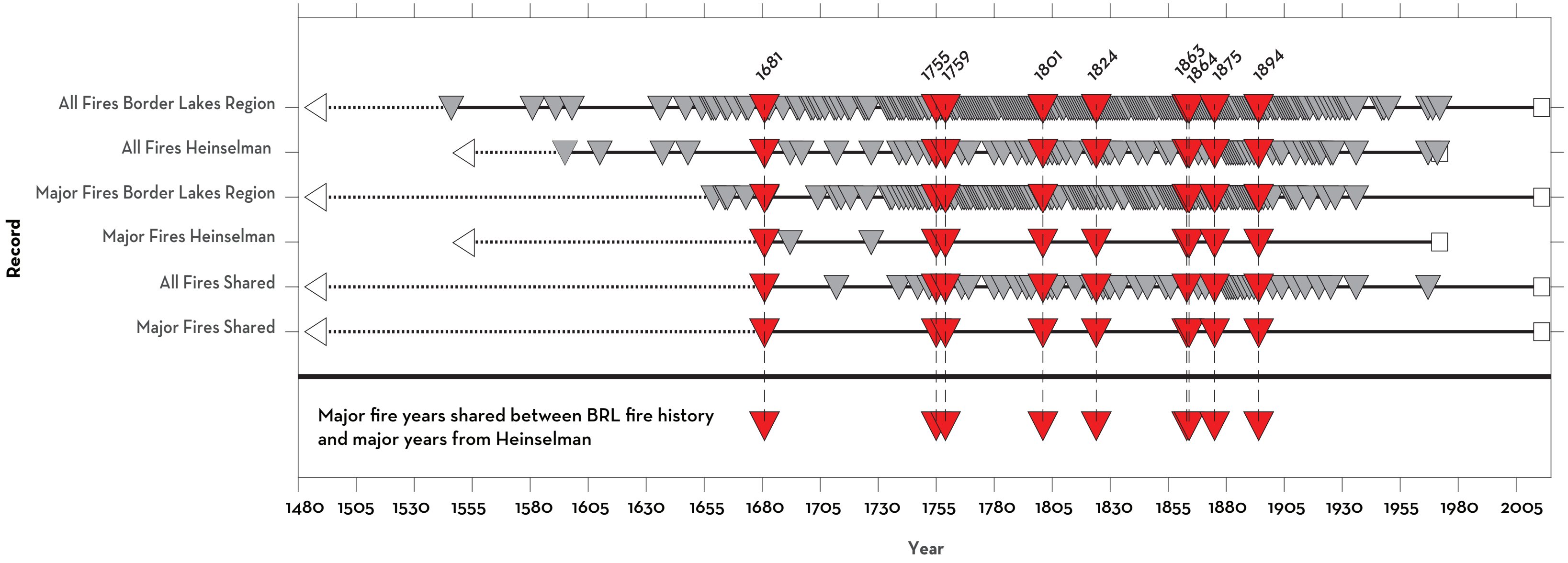

Figure 5.1. Fire history comparison between the fire history used in this research (Border Lakes Region) and fire years reported in by Heinselman 1973. Major fires years in the BRL are defined by years that are recorded in two or more regions (regions defined above), whereas Heinselman 1973 has defined major fire years as those fires that burning more than 100 square miles. The major fire years that are shared between the two records are shown in red.

one year of each other (Figure 5.1). For example, Heinselman records a major fire event in 1681, while this is also a synchronous event in the BLR data (found in two regions) the BLR data records the 1682 event as more synchronous, occurring in seven regions. Similarly, there is evidence that the 1895 fire event occurs in seven regions, whereas Heinselman records 1894 as a large fire event (also recorded as a synchronous fire event in the BLR, occurring in four regions). While these differences do exist, it is hard to make direct comparisons between the two studies because they differ in the study area and methods used. Heinselman's approach to fire history analysis relied deriving fire dates from not just fire scars but also stand-age dates and aerial photographs. As a result, the scale of Heinselman's work is larger and the results here offer nuance to his findings.

Significance

Paleoecological studies such as this provide a framework for understanding past patterns of disturbance and the agents of change and can have important implications regarding forest change and forest resiliency. For instance, the result that a fire event has a greater chance of becoming large/synchronous during periods of drought has important implications when developing mitigation plans that addresses impacts from climate change and for predicting how disturbances may occur in the future. The relationship between drought and larger fire events likely exists due to strong casual mechanisms that override the barriers to shared fire occurrence leading to autocorrelation in ecological factors at spatially disjunct regions. Projected changes in climate will likely accentuate the spatial connectivity of fire events in the Border Lakes region resulting in larger, more spatially extensive events. In addition, considering the management of fire on islands, larger islands could be targeted for active management as they tend to have a greater number of total fire events as well as shared fire events.

This research adds to the growing number of studies conducted in the area that demonstrate the significance of fire and serves as a useful baseline for considering the spatial patterns and mechanistic controls of the fire regime. Research studies such as this are becoming increasingly necessary as fire regimes across North America are expected to change over the next several decades due to anthropogenic climate change (Dale et al. 2001; Parks et al. 2016). Broadly climate change is expected to increase the length of drought events and increase the amount of area burned (Flannigan et al. 2009; Littell et al. 2010; Cansler and McKenzie 2014). More importantly, the lack of fire over the 20th century has likely led to a landscape with more fuel and might lead to larger, more severe fires, with greater spatial extent. Because fires were historically synchronous in the Border Lakes region, projected changes in climate will likely accentuate the spatial connectivity of fire events resulting in larger, more spatially extensive events.

Limitations

The data and the analyses performed in this dissertation do have their limitations. For instance, the data were collected as part of two separate research projects with goals of each project differing slightly. The data used from Voyageurs National Park was collected for the purposes of reconstructing the history of fire in the Park to help guide management strategies, with specific locations in the park targeted over others. As a result, some areas of the park may be sampled with greater intensity over others. Likewise, the data from the Boundary Waters Canoe Area Wilderness was collected to evaluate the history of fire with a focus on determining the relationship between fire and people. Data collection efforts for this research targeted sites along the historical Border Route and sites further away. Sample depth does vary between regions, for instance the South Kawishiwi region had just one sample, whereas the East Lac La Croix region has 108 samples. Clustering methods performed in Chapter 2 tried to lessen the bias in the sampling depth between regions, however some likely still exists. For example, the number of samples is related to the number of fire events recorded. To eliminate regional bias in the number of samples collected future research could divide the landscape into grids and perform a random selection of samples and then evaluate patterns in synchrony. While this dissertation recognizes the bias and the limitations in regard to the sampling design, these data and statistical analyses were used due to availability and time limitations.

Future work

Future work is needed in regard to comparing the fire history presented in this dissertation and the fire history reported by Heinselman (1973 and 1996). A more detailed comparison would provide greater clarification in the variability of fire years reported by each study. This research would also improve with a comparative analysis. By comparing results from this research to other landscapes we could have a greater understanding if the degree of synchrony is higher/lower to other regions. For example, a number of studies have been done on the synchrony of fire in the Southwestern United States, with fire synchrony being tied to the monsoon climate and interannual and variations in climate.

Appendix D – Additional Figures

Fire History

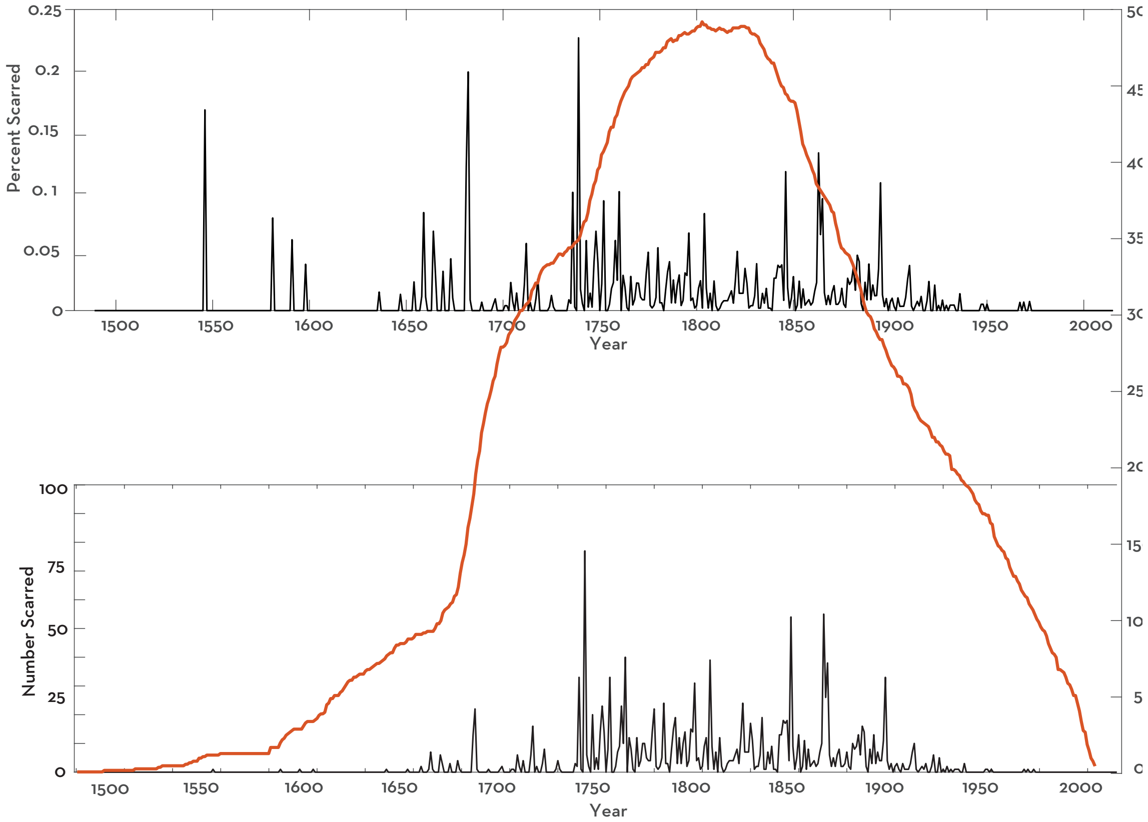

Figure D.1. Top: Percent of samples scarred from 1489 to 2016. Bottom: Number of samples scarred. Red line represents sample depth.

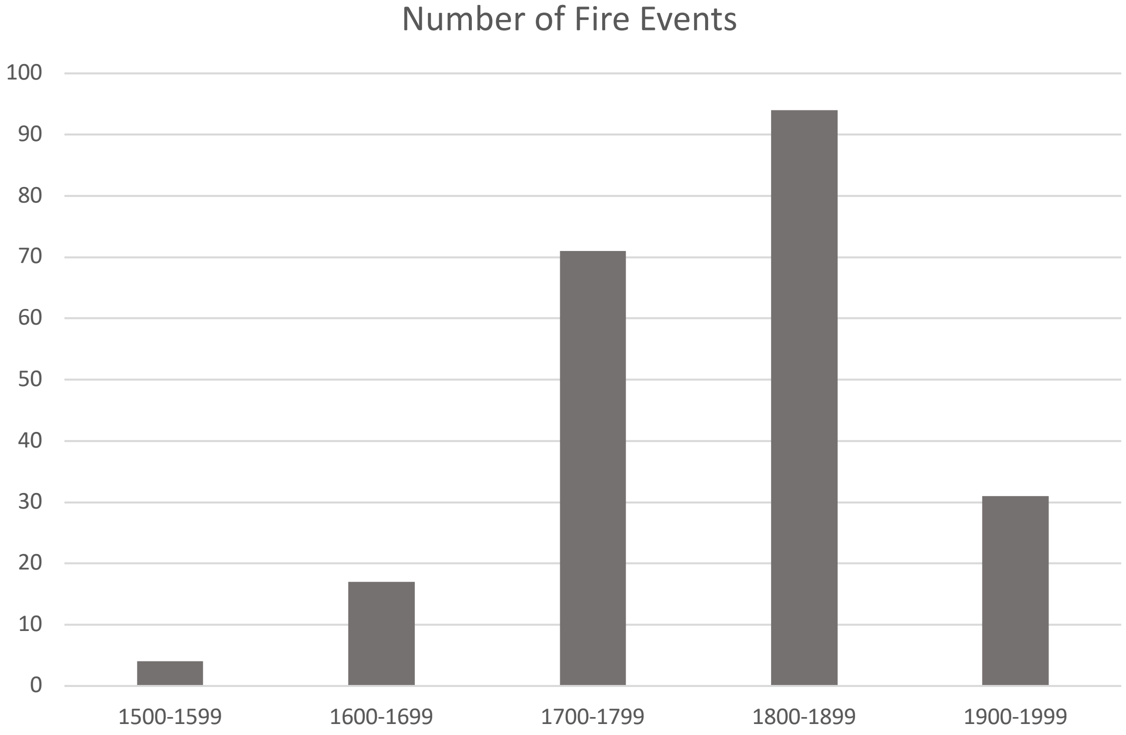

Figure D.2. Number of fire events by century

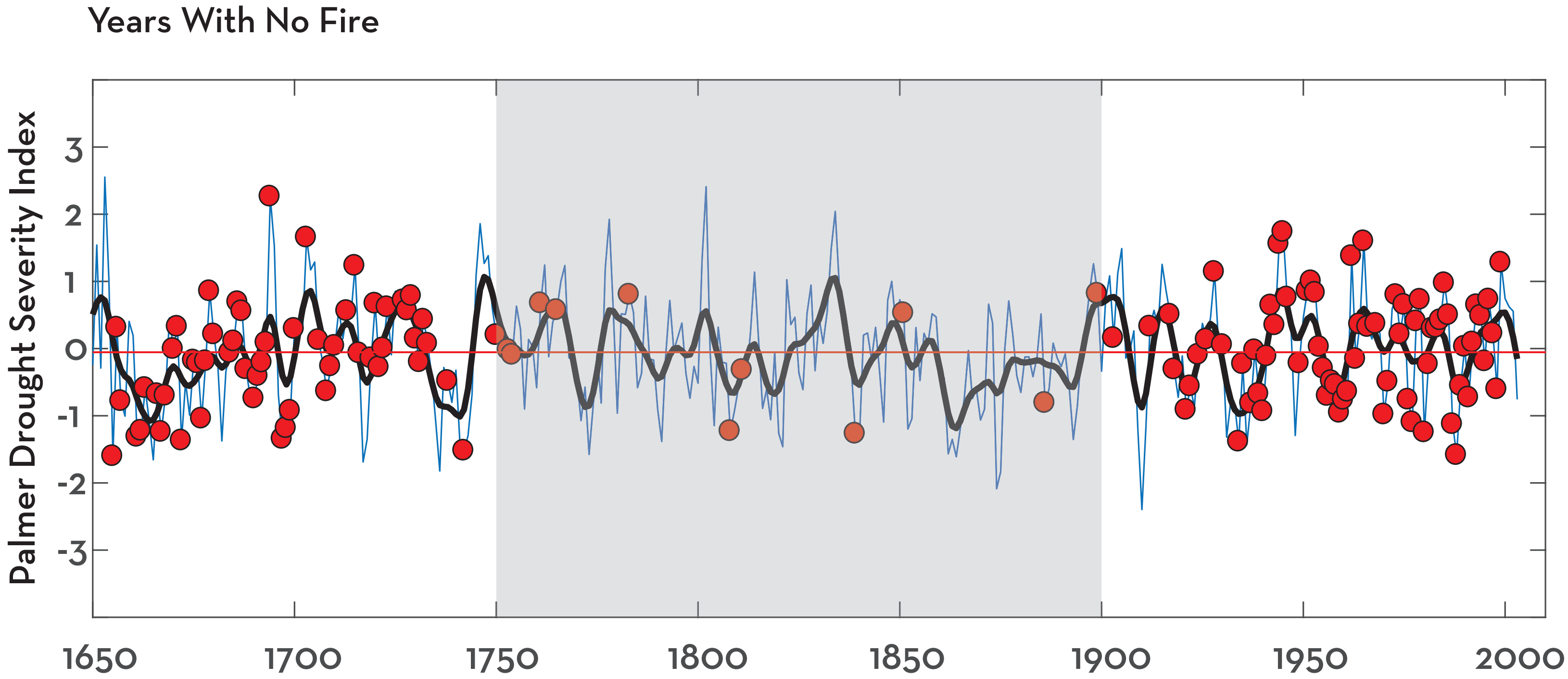

Figure D.3. Years with no fire (red dots) plotted on top of Palmer Drought Severity Index (blue line) and ten year smoothed (black line). Between 1650 and 2003 (length of PDSI record) 143 years recorded no fire events, opposed to 211 years recording fire. Between 1750 and 1900 (grey shaded), 11 years have no recorded fire.

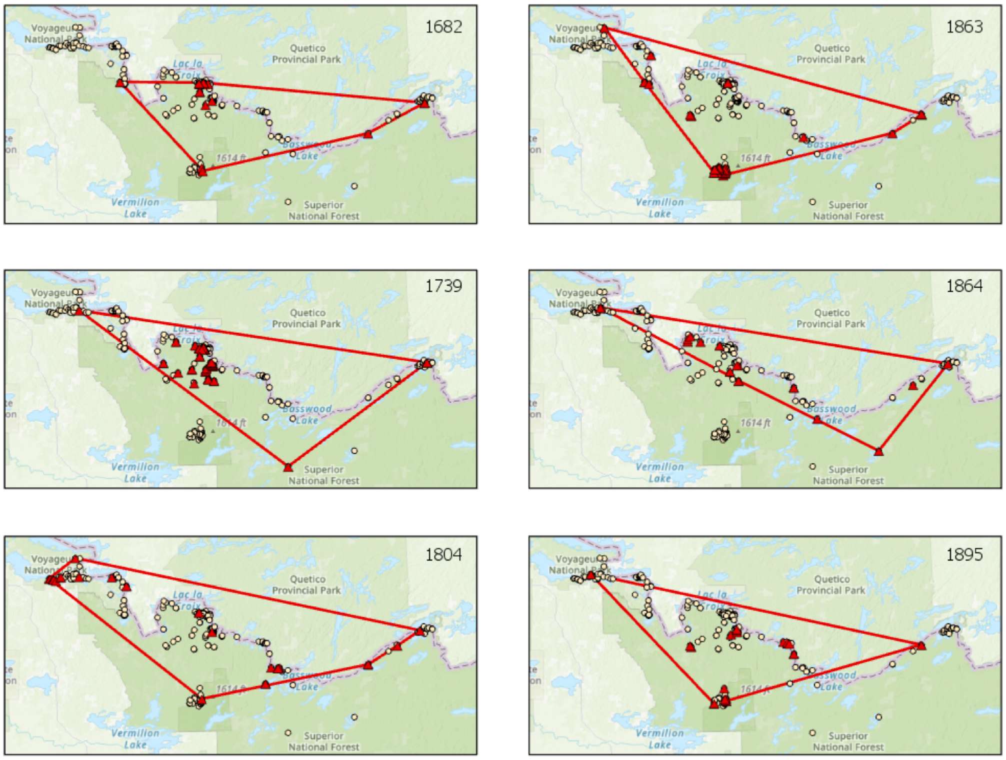

Figure D.4. Convex hull of synchronous fire event years in the Border Lakes Region including 1682, 1739, 1804, 1863, 1864, and 1896.

Decadal Variation in Number of Regions Recording a Fire Event

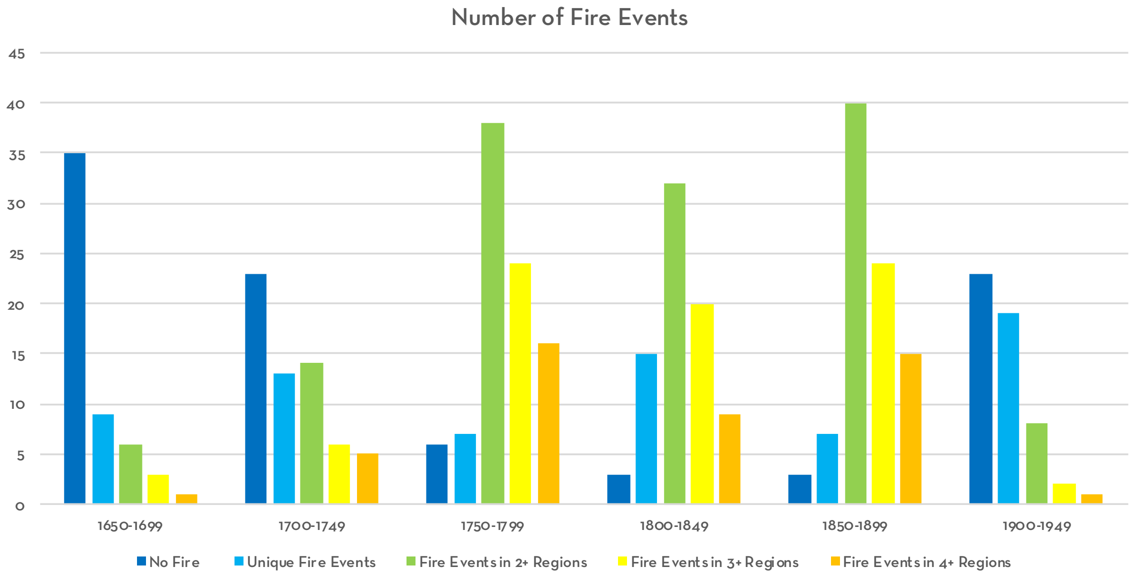

Figure D.5. Fire events occurring by time and by number of regions burned.

Regional Variation in Asynchronous Fire Events

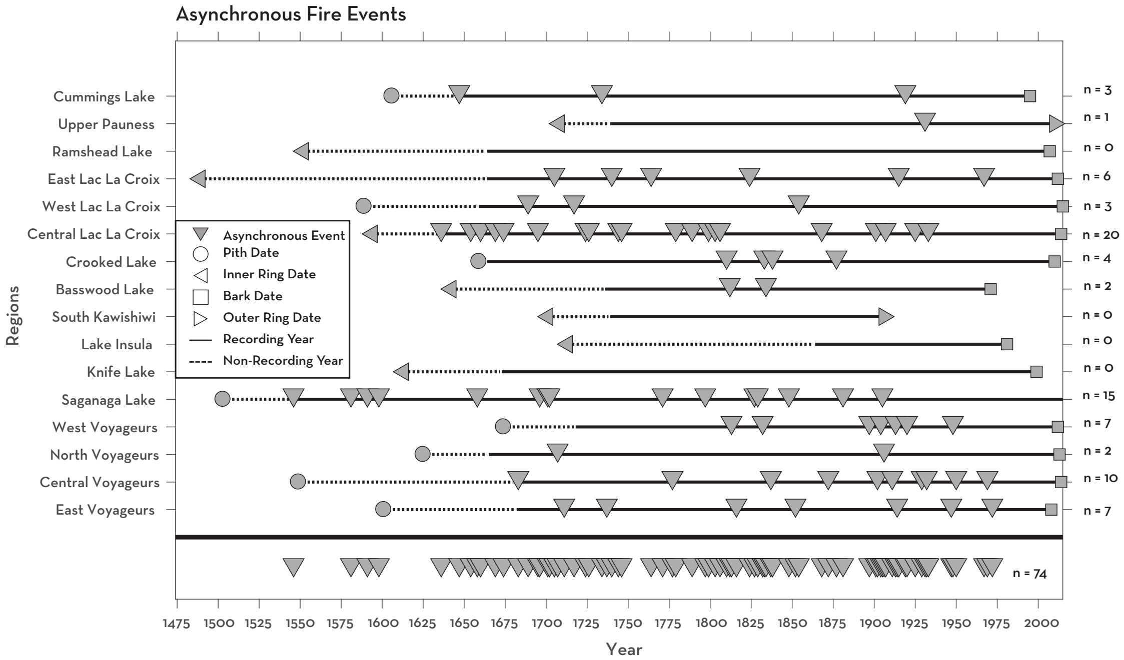

Figure D.6. Fire chart representing only asynchronous fire events for each region (events that are not found in another region, n = 74).

Regional Variation in Synchronous Fire Events

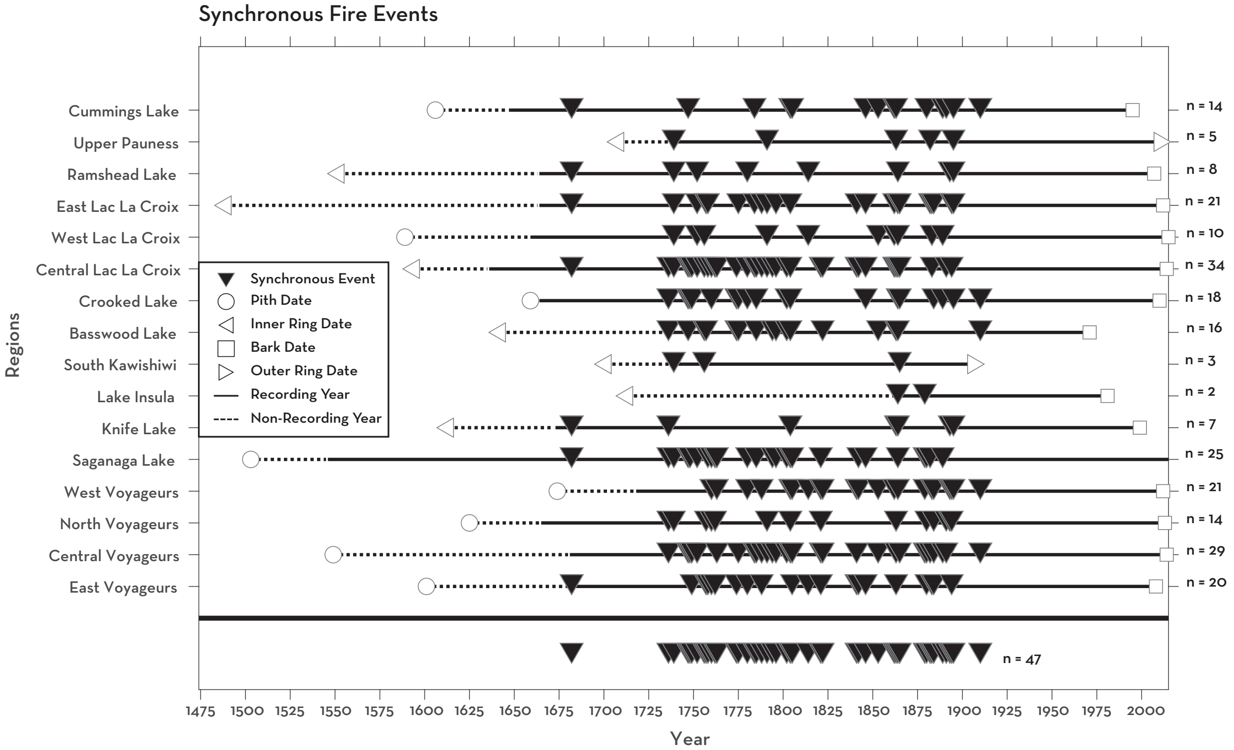

Figure D.7. Fire chart representing only synchronous fire events for each region (events that are not found in four or more regions n=47).

Distribution of PDSI Values in the Year of and Year Before a Fire Event

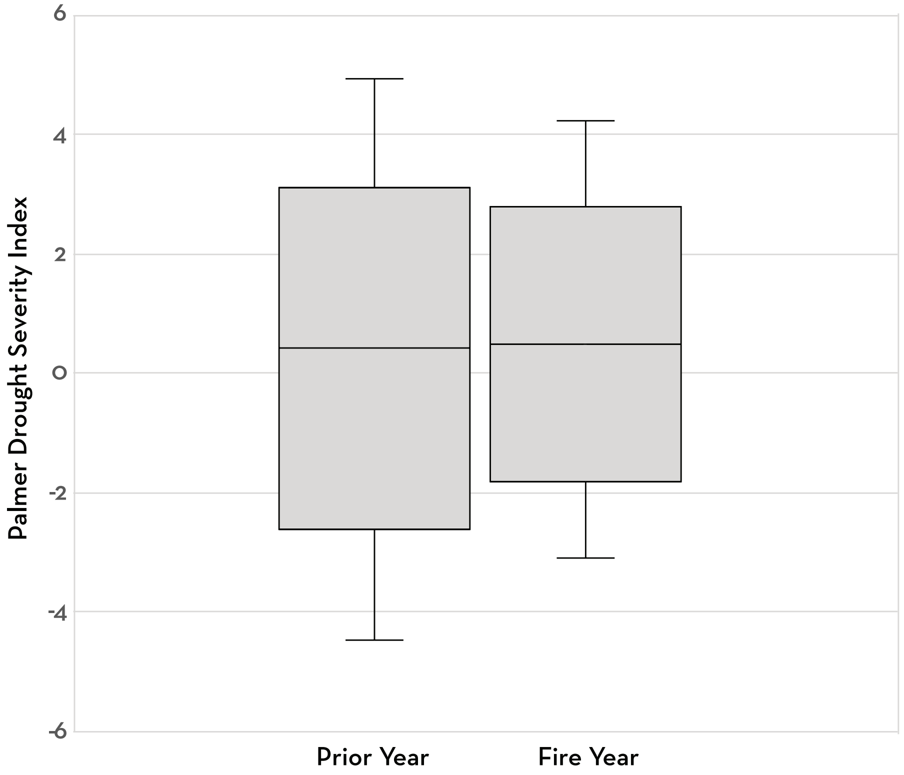

Figure D.8. Variability in PDSI during the years of and the years before all asynchronous fire events (entire record).

Distribution of Jaccard Similarity Values Between Island-Island Sites, Mainland to Mainland Sites, and Island-Mainland Sites

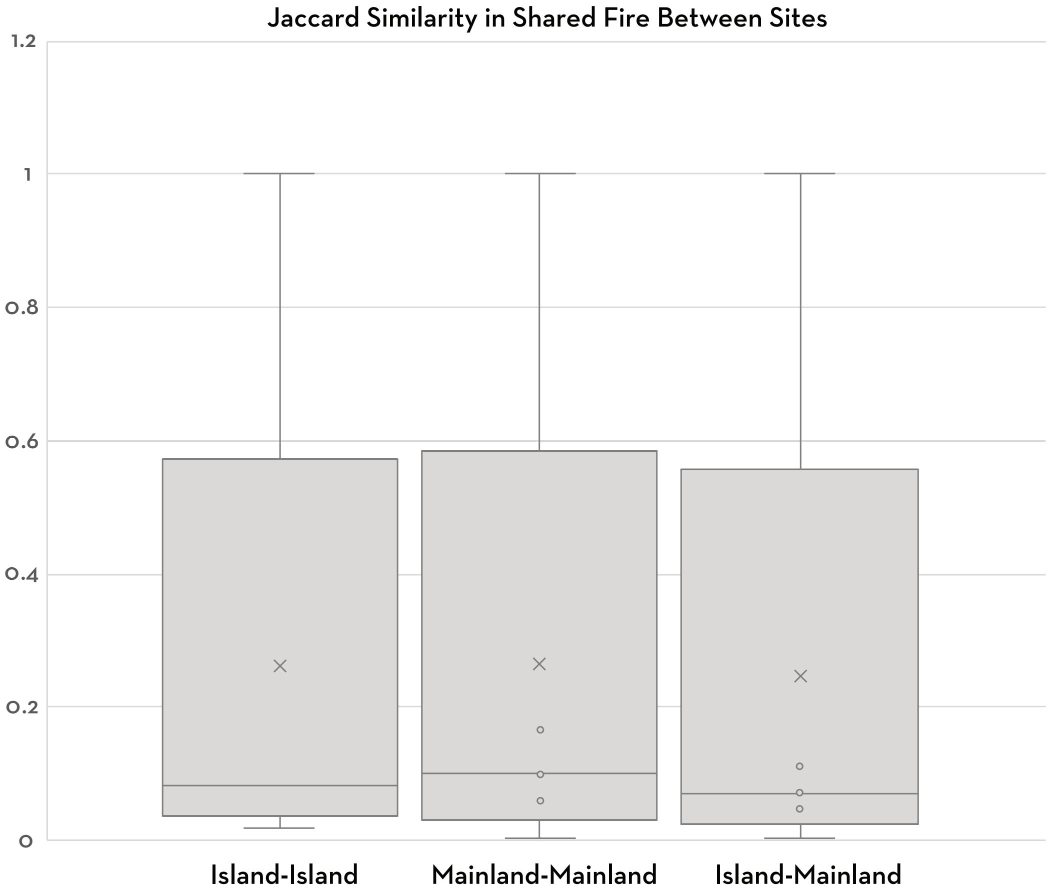

Figure D.9. Boxplots representing the variation in Jaccard similarity values between island sites (island-island), between mainland sites (mainland-mainland), and between island and mainland sites.

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