All fired up: A long-term fire history of the coastal boreal forest of Newfoundland, Canada

by

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Abstract

Little is known about the long-term fire history of coastal boreal forests in Atlantic Canada, particularly of Newfoundland. Establishing historical fire regimes is essential to wildfire management and projecting future wildfire activity. We radiocarbon-dated and botanically identified soil charcoal to resolve the long-term fire history of Terra Nova National Park (TNNP) in eastern Newfoundland. Typically, dendrochronology or lake sediment cores are used to reconstruct fire histories; yet, a soil charcoal approach produces a longer time-scale than dendrochronology and a finer spatial resolution than lacustrine sediment understanding of past fire events. Charcoal ages ranged from 7528 to 64 cal. years BP. The 150 year fire return interval for the park was consistent with other eastern boreal forest stands. We found charcoal of spruce, balsam fir, pine, birch, and maple. The proportion of black spruce increased in the Central Newfoundland Forest, while the proportion of balsam fir increased in the North Shore Forest from the past to present-day. Our results directly inform the wildfire management plan in TNNP to enhance black spruce regeneration, improve overall forest health, and decrease fire risk.

Keywords: fire history, Holocene, boreal forest, ecoregion, soil charcoal, paleoecology, radiocarbon dating, black spruce, balsam fir, Newfoundland

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I would like to respectfully acknowledge the territory in which this study took place as the ancestral homelands of the Beothuk, and the island of Newfoundland as the ancestral homelands of the Mi'kmaq and Beothuk.

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List of Acronyms

CNF	Central Newfoundland forest
FRI	Fire return interval
NSF	North shore forest
TNNP	Terra Nova National Park

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Co-authorship statement

Dr. Carissa Brown is a co-author on Chapter 2 of this thesis. As the principal author, I was the main contributor to the study, including the literature review, project proposal and design, fieldwork and data collection, laboratory work, data analysis, and manuscript preparation. All aspects of the project were done in collaboration with Dr. Brown, who contributed significantly to project design, data analysis, and preparation of the manuscript.

Chapter 1: Introduction and thesis overview

1.1 Fire and the boreal forest

The boreal forest is the fourth largest terrestrial biome on Earth, accounting for nearly 25% of the world's forested area (i.e., approximately 1 billion ha; Burton et al., 2010). In Canada, 56% of the land is covered by boreal forest, and 100% of Newfoundland and Labrador's forest is considered boreal (Burton et al., 2010). The boreal forest is a vital component of the global carbon cycle and climate feedbacks, storing more than one-third of the Earth's terrestrial carbon in organic soil matter and above-ground vegetation biomass (Kasischke, 2000; Mcguire et al., 2002; Tarnocai et al., 2009). However, it can be a carbon source on a local scale due to fires (Kasischke, 2000). Fires are common throughout the boreal due to a combination of climate, vegetation, and ignition-related factors. On average, it is estimated that 5 to 12 million ha of the global boreal forest burns annually (Kasischke, 2000).

Fire is a natural disturbance and a dominant control of ecological processes in the boreal forest, driving regeneration, plant community structure, and nutrient cycling (Johnson, 1992; Payette, 1992; Stocks et al., 2002). Fires occur in irregular spatial and temporal patterns across landscapes due to weather, topography, and fuel (Johnson, 1992; Moritz et al., 2005; Stocks et al., 2002). Weather, such as rain and wind, can affect a fire's ability to ignite, sustain, and spread. Fire and weather can also act as a positive feedback loop. Flammagenitus, also known as a pyrocumulus or fire clouds, form from the heat and smoke plume of a large fire; the hot air from the fire rises and cools to the point of condensation, causing the formation of clouds (American Meteorological Society, 2012a; Lareau and Clements, 2016). These clouds can progress into pyrocumulonimbus clouds, which can generate lightning and, in turn, promote fire growth and spread (American Meteorological Society, 2012b; Lareau and Clements, 2016; Rosenfeld et al., 2007).

Topography (e.g., slope, aspect, elevation, and physical features) can also influence fire spread and ignition (Johnson, 1992). Fires tend to spread faster when travelling upslope; the heat generated from the flames rises upslope first and dries out the vegetation ahead, making it more flammable (Silvani et al., 2012). Aspect and physical features determine how much solar radiation an area receives, which can indirectly control fire by affecting the moisture levels, and type and amount of vegetation (Heyerdahl et al., 2001). Fuel is another factor that influences individual fires. Fuels consist of anything flammable from the forest floor to the canopy (e.g., leaves and needles on the ground, small shrubs, ladder fuels, and snags). The type, amount, and moisture content of the fuels present can affect a fire's ignitability and spread (Johnson, 1992).

Observing the number of individual fire events over a broad landscape and a long temporal scale can provide insight into regional fire patterns, called a fire regime (Table 1.1). Like individual fires, fire regimes vary across landscapes due to climate, ignitions, and vegetation (Flannigan et al., 2009; Johnson, 1992; Kasischke, 2000). Climate has a strong influence on long-term fire patterns; areas that typically experience warm, dry summers are more conducive to fires on a seasonal basis. The boreal forest, on average, does not receive much precipitation and can have temperatures above 30°C in the summertime, creating favourable conditions for fire occurrence (Kasischke, 2000).

However, these conditions are spatially and temporally variable, with some years or locations being hotter and drier than others. Climate is also closely linked to continentality. The influence of maritime air masses does not penetrate deep inland (Foster, 1983; Senici et al., 2010); therefore, locations that are more inland tend to experience drier, more extreme conditions that are conducive to wildfires (Bouchard et al., 2008; Portier et al., 2016).

Fire regimes are also influenced by ignition sources, e.g., type, distribution, and frequency. An ignition source is required for fires to occur. Whether natural or human-caused, Ignition type can influence area burned depending on ignition distribution and density (Erni et al., 2018; Krawchuk et al., 2006; Stocks et al., 2002). Lightning is a natural source of ignition and is the leading cause of fires in the northern Canadian boreal forest (Kasischke, 2000; Stocks et al., 2002). From 1959 – 1997, lightning ignitions accounted for an average of 72% of all fires > 200 ha in Canada, producing 85% of the area burned (Stocks et al., 2002). Once lightning strikes, fuel and weather determine if the fire sparks and how it spreads (Erni et al., 2018; Foster, 1983).

Table 1.1: Definitions of commonly used fire-related terms (Alexander, 1982; Sommers et al., 2011; Turner, 2010).

Term	Definition	Calculation	Examples
Fire frequency/ occurrence	Mean or median number of fire events occurring at a location, or in a defined area, over a specified time	$f = \frac{n}{t} \; OR \; f = \frac{n}{t \cdot A}$ *f* = frequency n = number of fires t = the defined time period (years) A = defined area (m^2, km^2, ha, etc.)	"… a minimum of 22 fire events occurred during the last 3565 cal. years of fire history" (Payette et al., 2012). * Other studies elect to display frequency as a fire return interval or as percent annual area burned (Payette et al., 2012; Stocks et al., 2002)
Fire return interval	Mean or median time between successive fires in a designated area during a specified time; the inverse of frequency.	$FRI = \frac{t}{n}$ FRI = fire return interval (years) *t* = time period (years) *n* = number of fires	"Twenty-six fires occurred at the site over the last 5850 cal. years BP at a mean fire interval of 225 years" (Payette and Frégeau, 2019).
Fire rotation/ cycle	Mean time for an area equal to the entire area of interest to burn (This definition does not imply that the whole area will burn during a cycle; some sites may burn several times and others not at all.)	$Fire\ rotation = \frac{t}{\%\ A} \cdot 100$ *t* = length of study period (years) % A = percent area burned	"For the region as a whole, approximately 21% of the land area has burned in the past 110 years. This represents a fire rotation of approximately 500 years" (Foster, 1983). Also, see Heinselman (1973).
Fire size	Area burned by fire. Most studies report fire size as the fire perimeter area; although not all locations within the perimeter may have burned.	N/A	"For example, at a national scale, 31% of LFDB (Large Fire Database) fires fall in the 200-500 ha size class yet account for only 1.4% of the area burned, while the 2.5% of fires exceeding 50,000 ha represent 44% of the area burned," (Stocks et al., 2002).

Fire intensity	Physical energy or heat released during the burn per length of fire front per time; more intense fires will burn hotter and deeper, representative of the disturbance rather than the ecological effect.	$I = c \cdot m \cdot r$ I = intensity (kW/m, kW = kJ/s) c = heat released per unit mass (kJ/kg) m = mass fuel consumed (kg/m^2) r = rate of spread (m/s)	Alexander (1982)
Fire severity	Linked to fire intensity, severity is a qualitative measure of the fire's impact on the community, ecosystem, or soil. Consequently, high-intensity fires are generally more severe and will have a greater effect on vegetation	N/A	There is no standard method of measuring fire severity since it is a qualitative measure; however, one study used the continuous probability distribution of the differenced Normalized Burn Ratio (Lutz et al., 2011).
Fire seasonality	The time of year and how long the fire season lasts	N/A	"The Canadian forest fire season generally begins in April in the southern regions of the country, and continues through mid-October…" (Stocks et al., 2002)
Fire type	Related to fire severity, an indicator of how much vegetation the fire consumed (e.g., ground fire, surface fire, crown fire)	N/A	
Fire regime	It requires consideration of ecological context, defined by the meteorological, physical, and biological properties of an ecosystem and the spatial, temporal, and behavioural characteristics of the fires that burn in it.	N/A	

Vegetation is another critical component that affects long-term fire patterns. Forested regions can be more fire-prone because of the species present, as certain species are more flammable than others. These combustible species are also typically more fire-adapted, allowing them to survive fires or establish post-fire (Bouchard et al., 2008). In the boreal forest, most understory and tree species are fire-adapted and flammable (e.g., ericaceous shrubs, spruce, pine; Kasischke, 2000). In these cases, vegetation and fire can create a positive feedback loop. For example, some tree species are flammable and require fire for regeneration. These tree species promote fire ignition and spread, and in turn, the fire promotes the post-fire establishment of these species (Bouchard et al., 2008; Moritz et al., 2005). These factors (climate, ignitions, and vegetation), interacting with other disturbances and topography, produce a mosaic of different aged stands (Bergeron and Fenton, 2012; Portier et al., 2016).

Fire regimes are defined by characteristics, such as size, frequency, intensity, severity, seasonality, and type (Table 1.1; Stocks et al., 2002; Weber and Flannigan, 1997), which can be determined using several methods (Table 1.1). One way of quantifying and comparing fire regimes is the fire return interval, i.e., the time between successive fires for a defined location (Table 1.1). Shorter fire return intervals indicate less time between successive fires (i.e., fires are more frequent). Typically, the western regions of the boreal forest experience shorter fire return intervals; Alaska and the Yukon have fire return intervals around 80-150 years (Larsen, 1997; Viereck, 1983). Conversely, longer fire return intervals indicate more time between successive fires (i.e., fires are less frequent). The eastern boreal forest usually experiences longer fire return intervals; Québec has a fire return interval of 270-500 years (Bouchard et al., 2008). To date, a fire return interval has not been calculated for Newfoundland and Labrador. However, the fire cycle (i.e., the mean time for an area equal to the study area to burn; Table 1.1) has been estimated at 500-769 years (Arsenault et al., 2016; Foster, 1983).

Most fire studies aim to determine only the fire frequency. To gain a more comprehensive understanding of fire regimes, it can be useful to understand more than one of the above characteristics. There are different types of fires (e.g., crown, surface, or ground), and each type can vary in intensity and size. These characteristics, in turn, affect fire severity and tree regeneration, for example, how many trees are killed or if serotinous cones open (Heinselman, 1983). The fire return interval for an area might be 250 years, but severe, stand-replacing fires may only occur every 500 years. In a national park, small fires from campsites or cigarettes may occur every ten years but are suppressed quickly. Therefore, these small, frequent fires have a much smaller effect on the landscape than if large, severe fires were to occur every ten years.

Fire regimes of the eastern boreal forest have been well studied in Québec; however, little is known about Newfoundland and Labrador's fire regimes, where the boreal forest reaches its eastern-most extent. In literature, fire regime studies often group Newfoundland and Labrador with Québec (e.g., Bergeron et al., 2004; Hanes et al., 2019; Stocks et al., 2002). However, due to significant variation in fire regimes across eastern Canada (Arsenault, 2015; Bergeron and Fenton, 2012), resulting in part from continental to maritime climatic conditions, Newfoundland and Labrador likely experiences different fire regimes (Arsenault, 2015; Foster, 1983). Fire regimes could also vary within the island of Newfoundland (herein referred to as Newfoundland) due to different ecosystem types (see section 1.5; Damman, 1983).

1.2 Natural and human history of Newfoundland

During the last glacial advance of the Quaternary period, the Laurentide ice sheet reached its maximum extent approximately 23.0-18.0 ka (kilo annum or 10^3 years), covering half of North America (Davis, 1981; Dyke et al., 2002; Mix et al., 2001). Around 16.0 ka, the ice sheets began to retreat rapidly as temperatures started to increase, and by 12.0 ka, the margins of the ice sheets were mostly terrestrial in Atlantic Canada (Dalton et al., 2020; Davis, 1981; Macpherson, 1982; Shaw et al., 2006). There is evidence of deglaciation beginning as early as 12.0 ka in Newfoundland and completing around 10.5 ka near our area of interest (Macpherson, 1982, 1995). This time also marks the beginning of the Holocene, the most recent geological epoch, which started approximately 11.7 thousand years ago.

After deglaciation, pioneer herb-dwarf shrub tundra was the first plant community on the island, followed by a shrub birch heath (Macpherson, 1995). Tree species initially dispersed primarily to the southwest of the island and then spread along the south and west coasts (Macpherson, 1995). The dispersal method is unknown but could have been by wind or animals (e.g., birds) from mainland Atlantic Canada. Deciduous species preceded conifers; aspen (*Populus* spp.) and possibly birch (*Betula* spp.) were the first tree species to arrive shortly before 10.0 ka. Spruce (*Picea* spp.) arrived around 10.0 ka and had expanded to the northeast shore by around 9.5 ka; balsam fir (*Abies balsamea* (L.) Mill) followed within a few centuries (Macpherson, 1995). Pine (*Pinus* spp.) arrived in the northcentral region at around 8.5 ka, and ash (*Fraxinus* spp.) arrived around 7.0 ka (Macpherson, 1995). The proportions of these tree species varied through time with the changing climate and conditions (Figure 1.1). Charcoal was present in lacustrine samples since the early Holocene, indicating the presence of fire. The frequency and severity of the fires would have varied greatly through time, though evidence suggests a peak in charcoal and likely fire occurrence around 6.0 ka (Macpherson, 1995).

Before the presence of humans in Newfoundland, lightning was likely the only ignition source for fires. However, lightning is not common on the island and plays a minor role in ignitions compared to other parts of the boreal forest (Burrows and Kochtubajda, 2010; Shephard et al., 2013; Simpson, 2007). Newfoundland experiences the second-lowest lightning occurrence in the country, primarily due to its proximity to cold water bodies and cool maritime climate (Burrows and Kochtubajda, 2010; Environment Canada, 2019). Along the Newfoundland coast, temperature inversions and cold surface sea temperatures dampen convection and make it difficult for a thunderstorm to form (Burrows and Kochtubajda, 2010; J. Finnis, personal communication, February 22, 2020). When lightning does occur, it is usually accompanied by abundant rain and does not always lead to ignitions. A 19-year study indicates eastern coastal Newfoundland (e.g., St. John's) experiences an average of 4.3 days of lightning per year and 38 cloud-to-ground lightning strikes (Environment Canada, 2019). Lightning is more common inland, but strong vertical wind shear can occur, limiting the development of thunderheads (J. Finnis, personal communication, February 22, 2020). The central and inland areas (e.g., Grand Falls-Windsor and Gander) experience an average of 7.2 days with lightning and 164 lightning strikes per year (Environment Canada, 2019). Western Newfoundland (e.g., Corner Brook) also experiences relatively more lightning at 7.9 days and 150 lightning strikes per year (Environment Canada, 2019).

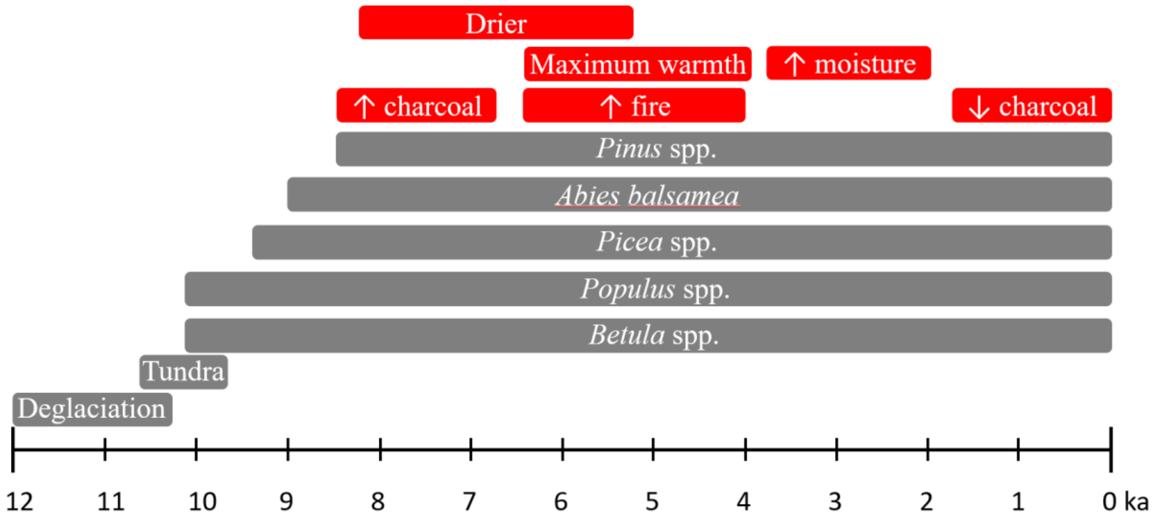

Figure 1.1 Chart depicting the arrival of some of the tree species present on Newfoundland during the Holocene (grey) and indicators of change (red). Figure created from data in Macpherson (1995).

The first evidence of people on the island is approximately 6.0 ka, though people might have been present in Labrador since 9.0 ka (Renouf, 2011; Tuck, 1988). I would like to acknowledge that these dates are based on archeological evidence and that many ideologies of Indigenous Peoples go back to time immemorial (V. Pilgrim, personal communication, March 26, 2020). The earliest and most prominent archeological sites are found on the West Coast of Newfoundland near Port au Choix; however, there is evidence of early people around the island (Renouf, 2011; Tuck, 1988). These archeological sites include hearths with charcoal fragments and cracked rock, indicating Indigenous use of fire and wood as fuel (Renouf, 2011). In TNNP, an archeological assessment revealed indications of intermittent occupation, from sites of major habitation to small stopping points, by early Indigenous Peoples from approximately 5.0 ka – 0.7 ka (Tuck, 1980). It is unknown to what extent early Indigenous Peoples used fire throughout their daily lives in Newfoundland, so accidental or intentional fires were possible (Tuck, 1988). While lightning may have remained the primary ignition source during this time, I did not discount the possibility of anthropogenic ignitions. A study in Ontario detected changes in the fire regime due to human influence, not climate or vegetational changes, before European settlement (Blarquez et al., 2018). Conversely, a study from New England found that human impacts on the landscape before European contact were minimal. They found that climate and vegetation were the main drivers of fire patterns during this period (Oswald et al., 2020).

The first Europeans to arrive and settle on the island were the Vikings circa 1000 CE (all dates hereafter are in the CE, Common Era; Cadigan, 2009; Smallwood and Pitt, 1981a). John Cabot and his crew were the next known group of Europeans to travel to Newfoundland in 1497; although, there might have been earlier, less documented voyages by other explorers (Pope, 1997; Smallwood and Pitt, 1981b). Then, during the 16th century, the Basques frequented the island on a seasonal basis. They would come across the Atlantic only for the summer to fish for cod and harvest whale oil, never forming permanent settlements on land (Smallwood and Pitt, 1981c). For the first 400 years after John Cabot's expedition, the forest was only used to support the fishing industry (e.g., boat repairs; Carroll, 1990). The extent to which these early fishing people impacted forest fire ignitions remains unclear; however, it is known that sometimes fishing people would deliberately destroy tracts of coastal forests by fire to discourage permanent settlement (Carroll, 1990).

In the summer of 1610, John Guy formed the first permanent settlement on Newfoundland, at Cuper's Cove in Conception Bay (i.e., Cupids), marking the beginning of continual permanent European settlement on the island (Carroll, 1990; Smallwood and

Pitt, 1981d). During the early years of colonization, there was little consideration of forest conservation. Many uncontrolled forest fires destroyed extensive areas of forest (Cadigan, 2006; Carroll, 1990). One historian speculates that by ten years after Guy's arrival, fishing people had destroyed all the forest within one mile of the seashore in some locations (Carroll, 1990). Often, fires burned the same tract of land repeatedly, resulting in tree regeneration failure and barren land; repeat burnings are hypothesized to be the cause of much of the barren landscape still seen today on the Avalon and Bonavista Peninsulas (Carroll, 1990).

Newfoundland needed a railway to diversify the economy and open up industry operations in other parts of the island. The Railway Act (1881) was passed in 1881, and construction began that fall (Carroll, 1990; Penny and Kennedy, 2003). The trans-island railway passed through the TNNP region in 1892 and was finally completed in 1898 to Port-aux-Basques (Penny and Kennedy, 2003). The construction and use of the railway mark a point of notably altered forest composition and increased human-caused fires on the island. With an operational railway and a booming forest industry, white pine was nearly eliminated from the island due to selective logging (Carroll, 1990). TNNP was no exception, and there is evidence of many sawmills from the 19th and 20th centuries (Figure 1.2; Tuck, 1980). The railway also caused a considerable increase in fires. Fires started by trains in 1904 had been extremely destructive, burning an area greater than 2,000,000 acres (810,000 hectares; Carroll, 1990). These fires, plus the desire to protect valuable timber resources, prompted the creation of the Forest Fires Act (1905). In the beginning, however, the Forest Fires Act (1905) did little to curb ignitions, likely due to a small workforce and limited resources. At this time, the province-wide Fire Patrol consisted of only four people, and the primary method of fire management was suppression (Carroll, 1990). The Chief Woods Ranger reported that the Fire Patrol extinguished up to 93 fires in one day (Carroll, 1990). Reports also indicated 1193 fires in 1911 and 1166 fires in 1912, of which more than 90% were started by trains and occurred along the railway track (Carroll, 1990). The railway was decommissioned in 1988, concluding the island's largest source of anthropogenic ignitions (Penny and Kennedy, 2003).

Figure 1.2 Old logging equipment in Minchin's Cove, TNNP. It is a wheel from an old mill that was located on Minchin's Brook before the park's establishment. The mill was operated by a seasonal community that lived in the cove (J. Gosse, personal communication, March 6, 2020).

When Terra Nova officially became a national park in 1957, strong fire suppression tactics, plus reduced anthropogenic ignitions, resulted in fewer fires. Since 1961, park management has recorded 15 fires within park boundaries, all caused by human ignitions. Eight of those fires were less than 5 ha (Table 1.2). The largest fire within the park was an 800 ha railway-ignited fire near Pitts Pond in 1961 (Table 1.2).

The largest fire recorded in the greater Terra Nova region (i.e., approximately 20 km surrounding the park) was a 23,045 ha lightning-ignited fire near Gambo Pond in 1979. It was the only high severity (i.e., causing strong ecological impact; Table 1.1) lightning-ignited fire in the area since park formation (Table 1.2). Records indicate that from 1961-2003, anthropogenic fires occurred in the park or surrounding area every 1-4 years. Since 2003, only one spontaneous fire (2017) and three prescribed burns have occurred (Table 1.2). Until 2002, the park's fire management only involved complete suppression of any fires. Park managers then conducted prescribed burns in 2002, 2008, 2015, and 2016 (Table 1.2).

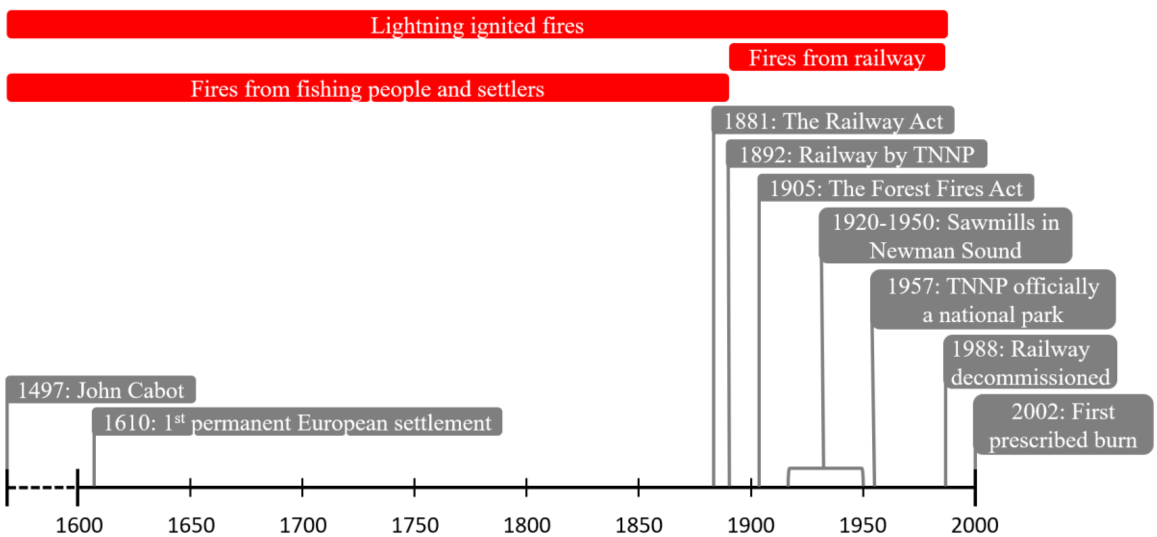

Figure 1.3 Timeline summarizing key events post-European settlement around the Terra Nova region related to fire ignition or suppression (Forest Fires Act, 1905; Railway Act, 1881; Parks Canada, 2009; Penny and Kennedy, 2003; Smallwood and Pitt, 1981b, 1981d).

Table 1.2 Summary of fire occurrence in and surrounding TNNP from 1961 to 2017. Fire occurrence data were collated from unpublished Parks Canada records and provincial fire data by parks staff and independent researchers. Specifically, data are adapted from Power (1996) and Simpson (2007) to include the prescribed burns and most recent 2017 fire (L. Siegwart Collier, personal communication, December 13, 2019).

Location	Date	Total area (ha)	Area within park (ha)	Duration	Comments
Northwest River	July 16, 2017	0.15	0.15	1 day	Unknown
Mill Pond	August 2016	~ 200.0	~ 200.0	1-3 days	Prescribed burn
Spruce Pond	August 28, 2015	93.5	93.5	1-3 days	Prescribed burn
Field Harbour	July 16, 2008	34.2	34.2		Prescribed burn
Terra Nova Village	June 2003				Human Ignition
Big Brook	June 13, 2002	98.0	98	1 day	Park Operations (escaped presc. burn)
Newman Sound Campground	2001	<1	<1	<0.5 day	Charcoal Brickets
Terra Nova Village	June 11, 1999	100.0		3 days	Human Ignition
Ochre Hill	August 11,1999	0.4	0.4	0.5 days	Human Ignition
Spracklin's Road	August 12, 1995	100	5	2 days	Human Ignition
Northwest River	August 1994	< 1.0		1 day	Skidder fire
Arnold's Pond	June 2, 1990	0.1	0.1	Few hours	Defective power line
Thorburn Lake	1990	67.2		Unknown	CNR track removal
Dunphy's Pond	Sept. 21, 1988	< 1	<1	Campfire	Deep burn (0.3-0.6 m)
Newman Sound	1987	2.5	2.5	5 hours	Campfire
Charlottetown	August 22, 1986	5.5	5.0	2 days	Children
Blue Hill West	May 27, 1986	332.0	332.0	4 days	Power line
Bunyan's Cove Road	July 12, 1982	408.8		6 days	Cause unknown
Charlottetown	July 6, 1982	201.6	147.0	Unknown	
Northwest River	July 27, 1981	0.5		Few hours	Campfire

Gambo Pond	July 4, 1979	23,045.0		14 days	Lightning
Port Blandford	1979	18.5		Unknown	
Northwest River	1978	2.0		5 hours	
Terra Nova Road	July 19, 1977	313.6	25.0	2 days	
Terra Nova Dump	August 13, 1976	485.6	25.0	3 days	
Traytown	June 14, 1975	95.0		7 days	
Charlottetown	May 17, 1974	7.2		1 day	
Maccles Lake	July 10, 1973	1.6		1 hour	
Terra Nova	July 13, 1972	48.0		5 days	Railway
Northwest Pond	June 20, 1971	212.0		4 days	
Fox Pond	July 29, 1970	< 2.0	<2.0	4.5 hrs	
Terra Nova River	April 25, 1968	< 2.0		1 day	Farmland
Newman Sound	1967	< 2.0		Unknown	
Traytown	June 14, 1967	10.0		2 hours	
Eastport	June 17, 1965	0.2		5 hours	
Pitts Pond	June 1, 1961	1200.0	800.0	2 days	Start 2 m from railway
TNNP Total			~ 1444 ha		

Although it did not directly impact fire patterns, the introduction of moose (*Alces alces* L.) to the island heavily influenced forest composition within decades. Moose were introduced to the island in 1878 and 1904; by 1907, moose were reported in several parts of the island (Byrne, 2012; Pimlott, 1953). Moose were recorded around the Terra Nova region in 1937 (Pimlott, 1953). Without any natural predators, moose populations reached an island-wide peak of 150,000 by 1960. Populations subsequently declined due to hunting efforts, but a pause on hunting allowed populations to rise again and peak around 1995 (McLaren et al., 2004). Since their introduction, moose have strongly impacted the island's forest composition, decreasing broadleaved species due to preferential feeding (Gosse et al., 2011). They also browse balsam fir saplings, inhibiting balsam fir recruitment (Gosse et al., 2011).

Forest characteristics have also been influenced by a native boreal forest herbivore, the eastern spruce budworm (*Choristoneura fumiferana* Clem., ESB), whose defoliations may have indirectly affected fire patterns. The ESB has caused widespread insect disturbance on the island of Newfoundland. Its populations are cyclic, with outbreaks occurring approximately every 33 years (Arsenault et al., 2016; Morin et al., 2007). The last major outbreak in Newfoundland was from 1972 to 1992, affecting 90% of the productive forest (Arsenault et al., 2016). The relationship between ESB and fire remains unclear, but a growing body of research supports the existence of an interaction (Candau et al., 2018; Fleming et al., 2002; James et al., 2017; Stocks, 1987). These studies suggest that after an ESB outbreak, the large patches of dead fir and spruce trees might create an increased fire risk (Candau et al., 2018). Other studies suggest that the severity of budworm outbreaks increases with time since last fire (Bergeron and Fenton, 2012; Navarro et al., 2018). In contrast, although it is the western spruce budworm (*Choristoneura occidentalis* Freeman), some studies indicate there is no relationship between outbreaks and fires (Flower et al., 2014; Vane et al., 2017). While there have been no studies on the interaction of ESB and fire patterns in Newfoundland, it may have had a potential effect on the historical fire patterns of TNNP.

1.3 Paleoecology

In its broadest sense, paleoecology is the study of the prehistoric occurrence, abundance, distribution, and interactions of species via geologic and biological evidence from fossil deposits (Bottjer, 2016). Paleoecology is a multidisciplinary area of study that employs a variety of methods. To determine wildfire histories, the most common paleoecological methods are dendrochronology and lake sediment cores. Dendrochronology uses direct and indirect data from tree-rings to determine fire events. This method can accurately identify fire events directly by counting tree-rings to date fire scars (Brown, 2013), traumatic resin ducts (Brauning et al., 2016; Schweingruber, 2007), or other changes in tree growth. Dendrochronology can indirectly determine fire events by establishing time-since-last-fire maps (Irulappa Pillai Vijayakumar et al., 2015) or interpolating climatic conditions from the tree rings (Schweingruber, 1988). Dendrochronology can also be used to cross-reference with other methods or determine the “inbuilt error” (see section 2.2 for more on in-built error; Gavin, 2001; Hoffman et al., 2016; Remy et al., 2018).

Lake sediment cores, using pollen-slide charcoal, reconstruct regional fire histories by quantifying charcoal found in the stratified sediment layers from the bottom of a lake (Zimmerman and Myrbo, 2013). A chronology for the core is established by radiocarbon dating relative macrofossils (e.g., plant) in the sediment layers. This method allows for quantifying microscopic charcoal and ash, offering a highly sensitive detection of local and regional fires. Lake sediment cores can detect fire events further back in time than other methods and are more likely to obtain a complete chronology (Remy et al., 2018). In conjunction with palynology (i.e., the study of pollen grains), this method can also be used to reconstruct past forest compositions and approximate climates (Higuera et al., 2009; Macpherson, 1995). Although both these methods have value, they also have limitations. Dendrochronological methods are limited to recent, short-term fire history because they usually rely on living trees. Lake sediment core analyses have typically been limited to regional, landscape-scale fire history because microscopic charcoal can be lofted and blown in from distant fires (Clark, 1988; Remy et al., 2018). Though, recent advances in analytical techniques enable the isolation of peaks in charcoal associated with local fire events (< 1 km; Higuerra et al. 2007), as can the analysis of macrocharcoal (>150 microns) found in sediment.

A third method, pedoanthracology, offers both a longer time-scale than dendrochronology and a finer spatial resolution than lacustrine cores understanding of past fire events through the identification and radiocarbon dating of macroscopic charcoal pieces found in soil. This method can also be used to reconstruct past forest compositions (e.g., Frégeau et al., 2015; García Álvarez et al., 2017). When wood is burned to charcoal, it maintains the unburnt structure and characteristics, allowing its identification. Under a high magnification incident light microscope, charcoal can be identified to tree species or genus by distinctive characteristics (e.g., Figure 1.4; Miszaniec, 2013; Panshin and Zeeuw, 1980; Schoch et al., 2004).

However, pedoanthracology also has biases and limitations. For example, the site locations and charcoal pieces are selected randomly and are not all-inclusive (e.g., some fires may be missed, and the oldest fire may not be detected). Soil charcoal can be destroyed in subsequent high-intensity fires, decreasing available samples over time and potentially underestimating the number of fires detected. Also, because the charcoal samples are not stratified in the soil column as in lake sediments, this method requires more samples to be radiocarbon dated, which is costly (Remy et al., 2018). This method also makes several assumptions, which are detailed in section 2.2.2.

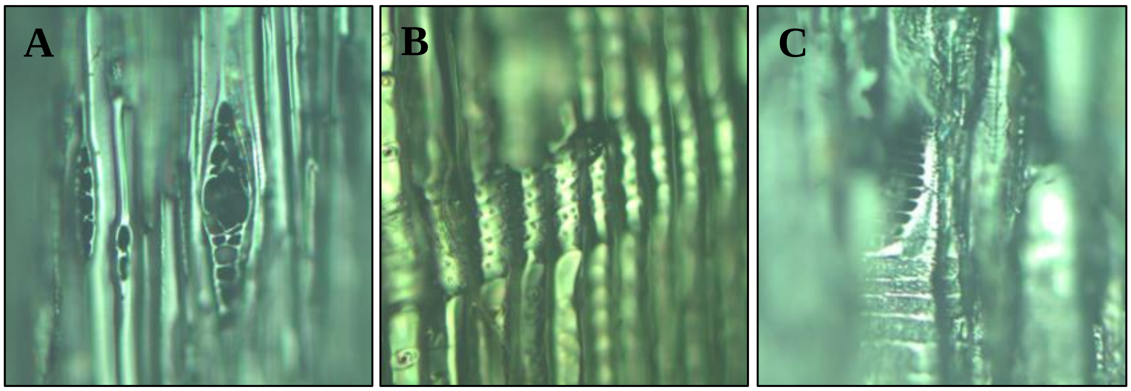

Figure 1.4 Incident light microscope images of (a) two rays and a resin canal (*Picea*), (b) small cross-field pits (*Picea*), and (c) a scalariform perforation plate (*Betula papyrifera* Marsh.; 200x; Photos: L. Walker).

1.4 Thesis rationale

Maintaining ecological integrity is a highly complex management issue and is a challenge currently facing TNNP. Terra Nova, along with all other national parks, has a mandate to maintain or restore ecological integrity (Parks Canada, 2009). In other words, park managers must aim for “a condition that is determined to be characteristic of its natural region and likely to persist, including abiotic components and the composition and abundance of native species and biological communities, rates of change and supporting processes” (*Canada National Parks Act*, 2000). The 2017 State Park Assessment identified the improvement of ecological integrity as a key priority, focusing on the need to preserve forest health (Parks Canada, 2019). Previous and current park management plans and forest monitoring data indicate that forest health is ‘fair,’ but impaired and in decline (Parks Canada, 2009, 2019). Park managers attribute the declining forest health and lack of regeneration to the absence of fire in spruce-dominated, fire-prone stands and herbivory by non-native mammals in fir-dominated stands (Parks Canada, 2009). Therefore, ecological integrity targets will differ based on forest type. Given this context, TNNP has chosen prescribed fire as a forest management tool to improve forest regeneration in black spruce stands and ecological integrity.

The current prescribed burning approach for managing the forests of TNNP depends on the assumption that the lack of fire is the cause of poor forest health in fire-prone black spruce stands. The park is thought to be experiencing a lack of fire because the fire regime occurred in a natural state influenced by only climate and vegetation before European settlement in the area. The pre-settlement fire regime is believed to have been dominated by large, infrequent, intense, and severe fires (Simpson, 2007). Then, during the period of permanent European settlement and, later, the construction and use of the trans-island railway, there was a dramatic increase in fire ignitions in the area. From 1828-1950, there were 189 fires in TNNP and the surrounding area (Power, 1996; Wilton and Evans, 1974). During this period, fire patrols attempted fire control and suppression, but limited resources and workforce meant many fires escaped and burned large areas (Simpson, 2007). Following the national park creation, fires in the park decreased considerably due to increased suppression efforts and decommissioned railway. Provincial and park records indicate that 15 fires occurred from 1961 to present-day (Table 1.2). However, it is unknown if the current fire regime is less active than the unmanaged fire regime that occurred during the Holocene or if it is causing the decline in forest health.

Linking forest health to fire occurrence in TNNP also comes with assumptions. Van Wagner (1978) suggests fire-dependent boreal forest stands should follow a negative exponential age distribution. By this theory, TNNP's spruce forest age distribution is atypical and skewed, with a higher proportion of older age classes (> 100 years; Power, 1996; Simpson, 2007). Past studies have estimated that annually burning 315 ha in the park will reduce the forest's age class structure (Power, 1996; Simpson, 2007). However, the negative exponential age class distribution does not hold true for all forests. Some studies indicate that eastern boreal forest contains at least 30% old-growth trees, providing critical habitat for species at risk and supporting increased understory diversity (Bergeron et al., 2017; Bergeron and Fenton, 2012; Cyr et al., 2009; Parks Canada, 2019b). In this context, old-growth is defined as forest stands older than 100 years. In addition, many fire-prone stands in the eastern boreal forest have fire return intervals well over 100 years (e.g., Bouchard et al., 2008; Couillard et al., 2018; Payette and Frégeau, 2019).

The broad purpose of this thesis is to increase our understanding of past forest dynamics in TNNP and provide science-based information to the park to support management of ecological integrity. Reconstructing the Holocene fire patterns can help forest managers understand the historical range of variation in the fire regime for an area. The assumption is that if forest management activities operate under conditions similar to the natural, historical conditions, the risk of adverse effects on the forest communities will be limited (Arsenault et al., 2016). Although fire regimes have previously been studied in Newfoundland and Labrador (Arsenault et al., 2016; Foster, 1983; Power, 1996; Wilton and Evans, 1974), little is known about the fire history of TNNP during the

Holocene or whether the fire regimes differ between the two ecoregions within the park (described below). Our study will help inform future wildfire management plans in TNNP by reconstructing the park's fire and forest composition history, verifying if previously held assumptions are valid, and determining what management strategies may be appropriate or justified. This research is an important contribution to understanding the ecology of Newfoundland's forests.

1.5 Study area

Field research for Chapter 2 occurred in the fall of 2017 and the summer of 2018 in TNNP, Newfoundland and Labrador. Terra Nova National Park is located in eastern Newfoundland (48° 30' 42.3" N, 53° 56' 56.8" W). Along the Trans-Canada Highway, the park is 225 km northwest of the provincial capital of St. John's (Figure 1.5). The park is approximately 402 km^2 and consists of drumlinoid hills, rocky terrain, and a rugged shoreline with a maximum elevation of 225 m (Blue Hill; Parks Canada, 2009). The park is mostly forested (79%), made up of black spruce (74%), balsam fir (23%), and hardwood species (3%). Occupying the remaining 21% of the park are fens, bogs, and barrens (Simpson, 2007). The soil is primarily a medium textured, stony, sandy-loam formed of glacial origin (Agriculture Canada, 1988). The TNNP region generally experiences a warm-summer continental climate (Peel et al., 2007), with a mean annual temperature of 4.4°C (Environment Canada, 2013). The park's mean monthly temperatures range from -6.9°C in January to 16.4°C in August, and the temperature extremes range from -28.5°C in March to 34.0°C in August (Environment Canada, 2013). Mean monthly precipitation averages 102.8 mm, totalling an average of 1,234 mm annually (Environment Canada, 2013). Precipitation falls mostly as rain from spring through autumn, then as snow in winter (Environment Canada, 2013); spring and early summer fog also contributing notably to overall moisture. However, these specific climatic conditions may differ within the park due to distinct ecoregions: the Central Newfoundland Forest and the North Shore Forest (Figure 1.6; Damman, 1983).

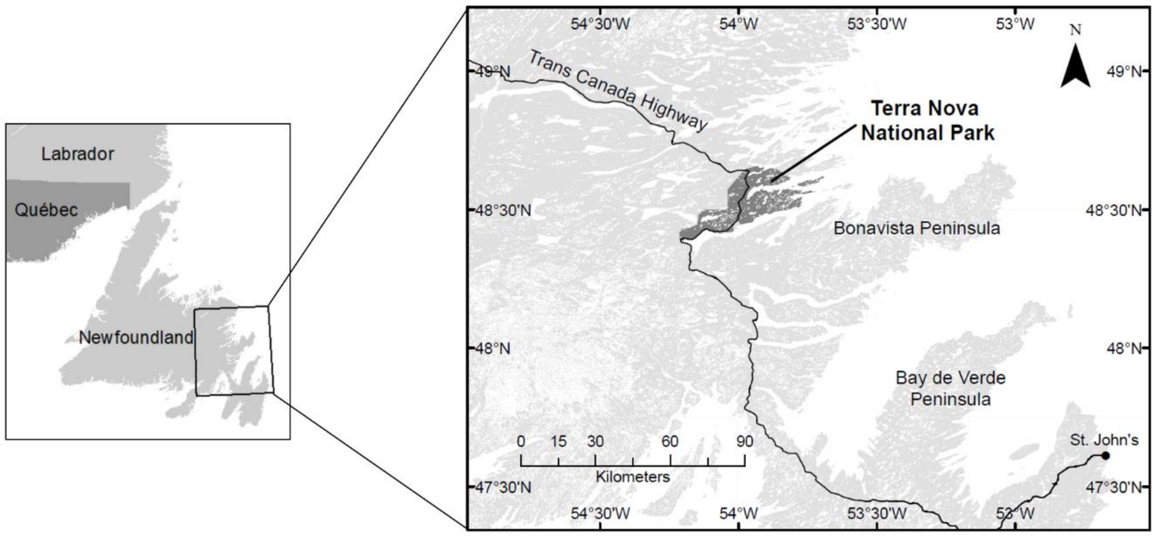

Figure 1.5 Map of Terra Nova National Park in northeastern Newfoundland, Canada. This map indicates the location of the park with respect to the provincial capital, St. John’s.

The Central Newfoundland Forest (Figure 1.6) is inland and has the most continental-like climate of the island, experiencing the highest summer temperatures and lowest winter temperatures (Damman, 1983). Growing degree days (140-160 days) and precipitation are roughly average for the island, although the Northcentral subregion (Figure 1.6), the subregion where TNNP is located, experiences less rainfall than anywhere else on the island (Damman, 1983; Meades and Moores, 1994). This ecoregion is also much drier than other parts of the island with respect to soil moisture; the warm summers result in high evapotranspiration losses causing a soil moisture deficit

(Damman, 1983). This ecoregion is the most characteristically boreal part of the island. The portion within TNNP is heavily forested and dominated by black spruce, and *Kalmia angustifolia* shrub heath is common on nutrient-poor substrate (Damman, 1983). It is thought that fire plays a more important role in the Central Newfoundland forest compared to the other ecoregions, so more fires might occur in this region (Damman, 1983). However, the Central Newfoundland Forest within TNNP is the most eastern and coastal part of this ecoregion. While the ecoregion as a whole may experience a continental climate, the portion within TNNP could have significant coastal influence.

The North Shore Forest (Figure 1.6) is a narrow ecoregion along the island's northeastern coast, reaching only 20-25 km inland (Meades and Moores, 1994). It has a maritime-influenced climate yet experiences the highest summer temperatures of all coastal areas. This ecoregion has a shorter vegetative season but a longer frost-free season than the Central Newfoundland Forest (Damman, 1983). It is mostly forested, dominated by balsam fir, but barrens are present on some of the headlands (Damman, 1983; Meades and Moores, 1994). The North Shore Forest also experiences a soil moisture deficit due to the warm summer temperatures, though to a lesser extent than the Central Newfoundland Forest (Damman, 1983; Meades and Moores, 1994).

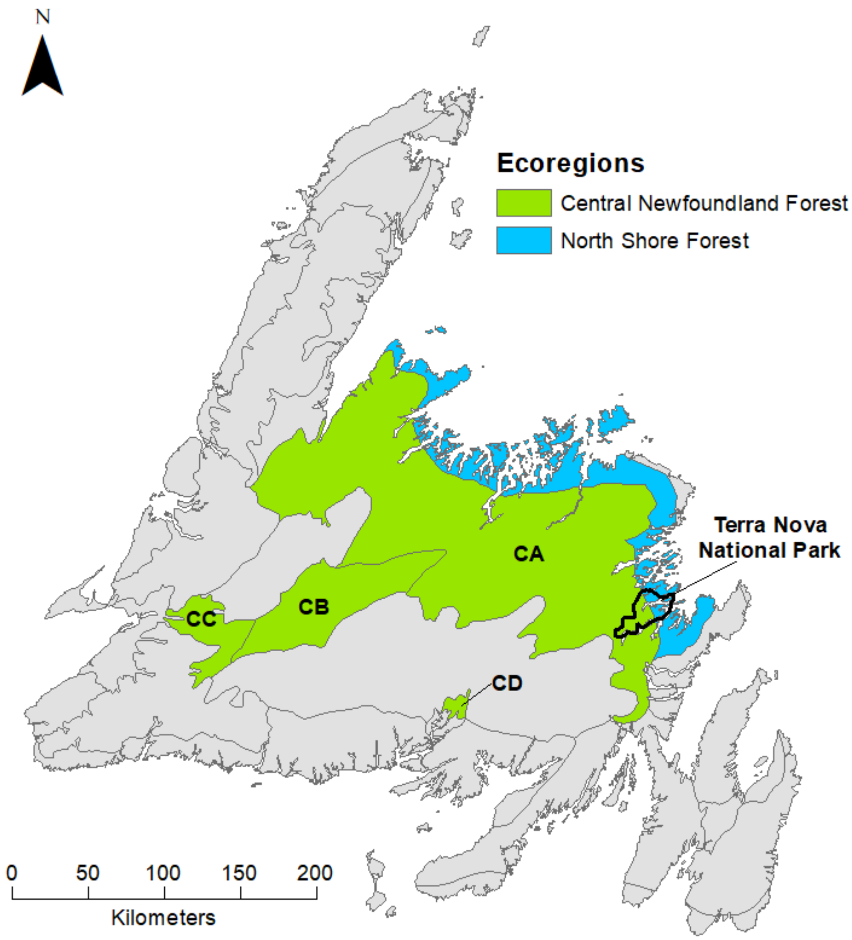

Figure 1.6 Map of the Central Newfoundland Forest (green area) and the North Shore Forest (blue area). The Central Newfoundland Forest has four subregions: 'CA' is the Northcentral subregion, 'CB' is the Red Indian Lake subregion, 'CC' is the Portage Pond subregion, and 'CD' is the Twillick Steady subregion. As defined by Damman (1983) and Meades and Moores (1994). Data from the Government of Newfoundland and Labrador (2017).

1.6 Study species

Black spruce is a coniferous species found all across the North American boreal forest, from Newfoundland to Alaska (Viereck and Johnston, 1990). It is one of the dominant species on the island of Newfoundland. It's also the most common tree species present in TNNP, occupying 74% of the park's forest as the dominant or secondary species (e.g., fir-spruce, birch-spruce; Arsenault et al., 2016; Simpson, 2007). Black spruce is a flammable and fire-adapted species. Its highly resinous needles and branches allow a fire to spread rapidly from the forest floor to the canopy and kill adult individuals (Fryer, 2014). However, black spruce's fire adaptations, such as semi-serotinous cones and aerial seed banks, enable it to regenerate and persist post-fire (Greene et al., 1999; Viereck and Johnston, 1990). Without fire, the cones will partially open and slowly release seeds over time (Viereck and Johnston, 1990). It can also vegetatively reproduce by layering, especially in open, poor-nutrient stands (Viereck and Johnston, 1990). Black spruce can survive in a wide range of environmental conditions but is most commonly found on wet organic soils (Fryer, 2014; Greene et al., 1999). While black spruce grows better on well-drained sites, it is more likely to grow on unfavourable sites than balsam fir because it can better tolerate wet, shallow, and nutrient-poor conditions (Page, 1976). Mineral soil that has had the surface organic layer removed by fire is also a suitable seedbed for black spruce (Viereck and Johnston, 1990).

Balsam fir is also a coniferous species present in the North American boreal forest but only reaches as far westward as Alberta (Frank, 1990). Balsam fir is the second most dominant species on insular Newfoundland and the second most common tree species in the park, accounting for 23% of the forested area (Simpson, 2007). Unlike black spruce, balsam fir regeneration does not benefit from fire and is, in fact, maladapted to fire disturbance. It is found in areas with a cool, humid climate and high rainfall where fire occurrence is low (Frank, 1990; Furyaev et al., 1983; Sirois, 1992). If a prolonged drought and fire occur, balsam fir is not fire resistant and will be destroyed (Furyaev et al., 1983). Low lying branches and mortality from periodic insect outbreaks make it especially susceptible to burning (Furyaev et al., 1983). Balsam fir has a high shade tolerance allowing it to grow under an established canopy and making it an effective late-successional species when fires are absent (Furyaev et al., 1983; Pastor and Mladenoff, 1992). This conifer can grow on a range of inorganic to organic soils, but soil moisture influences its establishment, preferring well-drained sites (Frank, 1990; Page, 1976).

In present-day stands or the charcoal record, the following coniferous species may be present: eastern larch (*Larix laricina* (Du Roi) K. Koch), white spruce (*Picea glauca* (Moench) Voss), white pine (*Pinus strobus* L.), and red pine (*Pinus resinosa* Ait.; Arsenault et al., 2016; Macpherson, 1995; Simpson, 2007). Spruce can only be identified to genus via anatomical wood features, so black spruce could not be differentiated from white spruce in the charcoal samples (Frégeau et al., 2015). However, this issue should not bias the results due to the low presence of white spruce in TNNP (Parks Canada, 2009; Simpson, 2007), although I acknowledge that white spruce might have been more abundant during the Holocene Thermal Maximum.

Hardwood communities are less prominent in TNNP and only occupy 3% of the forest community (Simpson, 2007). In present-day stands, the following deciduous species may be present in small proportions: paper birch (*Betula papyrifera* Marsh.), red maple (*Acer rubrum* L.), and trembling aspen (*Populus tremuloides* Michx.; Parks Canada, 2009). While these species may not be in high abundance at present, they could have been more prevalent in the past due to different climatic conditions and the absence of moose herbivory (Macpherson, 1995). Table 1.3 lists other deciduous species possibly found in present-day stands or the charcoal record.

Table 1.3: List of subdominant coniferous and deciduous tree species that might be found within the park in present-day field surveys or the charcoal record (Arsenault et al., 2016; Macpherson, 1995).

Coniferous	Deciduous
eastern larch	red maple
white spruce	mountain maple (*Acer spicatum* Lamb.)
eastern white pine	speckled alder (*Alnus incana* ssp. *rugosa* (Du Roi) J. Clausen)
red pine	mountain alder (*Alnus incana* ssp. *tenuifolia* (Nutt.) Breit.)
	yellow birch (*Betula alleghaniensis* Britt.)
	mountain white birch (*Betula cordifolia* Regel)
	paper birch
	black ash (*Fraxinus nigra* Marsh.)
	balsam poplar (*Populus balsamifera* L.)
	trembling aspen
	pin cherry (*Prunus pensylvanica* L.f.)
	chokecherry (*Prunus virginiana* L.)
	American mountain ash (*Sorbus americana* Marsh.)
	showy mountain ash (*Sorbus decora* (Sarg.) C.K. Schneid.)

1.7 Thesis overview

In this chapter, I provided an extensive introduction and context for this research. I discussed the possible natural and human influences that could have affected the island's fire history and forest composition. I also delved into fire ecology in the boreal forest and paleoecological methods. What follows are the findings from a soil charcoal analysis (also known as a terrestrial macrocharcoal analysis), examining the differences in historical fire patterns between the Central Newfoundland Forest and North Shore Forest ecoregions in TNNP. The study presented in this thesis offers a novel approach to wildfire history reconstruction in TNNP and Newfoundland. My findings complement previous studies investigating the historical fire regime of TNNP and Newfoundland, providing a spatially explicit long-term fire history of the coastal boreal forest in TNNP. To the best of my knowledge, this study is the first to use a soil charcoal approach to reconstruct Newfoundland's fire history. It is also the first study to empirically compare the fire regimes between the Central Newfoundland Forest and the North Shore Forest within TNNP. This study was developed in conjunction with Parks Canada to meet the needs of TNNP's ecological integrity mandate.

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Chapter 2: The long-term fire history and forest composition of Newfoundland's coastal boreal forest based on soil charcoal

2.1 Introduction

Establishing historical baseline conditions is essential to conservation management (Arsenault et al., 2016; Bottjer, 2016). The historical range of ecological variation from a time before significant human influence can act as a reference or target condition for management purposes. Additionally, understanding how those past ecosystems responded to past environmental change can help predict how they may respond to current and future global climate change (Bottjer, 2016; Willis and Birks, 2006). In the context of wildfire management, an example of baseline conditions could be the fire frequency of an area before the influence of anthropogenic ignitions. Identifying historical fire patterns is critical for planning wildfire management practices (e.g., prescribed burning and fire preparedness) and projecting future wildfire activity (Blarquez et al., 2015; Gavin et al., 2007; Girardin et al., 2013). While there has been a lot of research on the historical range of fire patterns in North America, there remains a lack of consensus (e.g., see Odion et al., 2014, 2016; Stevens et al., 2016). Fire patterns vary through time and space, so it is difficult, if not impossible, to label a large area with one set of conditions. For example, the historical perspective of fire in the boreal forest was simple: fires burned large areas and created monospecific even-aged stands (Arsenault, 2015; Bergeron and Fenton, 2012). More recently, researchers are discovering that fire histories were much more complex than originally thought. The new paradigm suggests a vast range of fire patterns through time (Arsenault, 2015). Varying fire frequencies and severities resulted in complex landscapes where old-growth stands were more common than initially believed (Arsenault, 2015; Bergeron and Fenton, 2012; Cyr et al., 2009). The lack of consensus on fire patterns only increases in areas of low fire frequency, where data are limited. When fire disturbances are low-severity such that the majority of forest remains intact as standing live trees, or fire disturbances are so infrequent that fire scar evidence is lacking, it becomes more difficult to determine long-term, landscape-scale changes in fire patterns (Hoffman et al., 2018).

Fire frequency is locally controlled and heavily influenced by climate (Flannigan et al., 2009; Johnson, 1992; Kasischke, 2000). For example, areas that typically experience warm, dry summers are more conducive to fires on a seasonal basis. Climate is also closely linked to continentality (Bouchard et al., 2008; Foster, 1983). Locations that are more inland tend to experience drier, more extreme conditions that promote wildfires (Arsenault et al., 2016; Bouchard et al., 2008; Portier et al., 2016). Conversely, coastal forests typically experience a lower fire frequency compared to their inland counterparts. While this relationship is true for the North American boreal forest, we acknowledge it does not include fire-prone coastal regions with Mediterranean climate. In Canada, there are scant data on the historical fire occurrence of coastal forests (Arsenault et al., 2016; Hoffman et al., 2016; Ponomarenko, 2009).

Pedoanthracology is one of several paleoecological tools that can be used to determine wildfire histories. It offers both a long time-scale and fine spatial resolution of past fire events directly through the identification and radiocarbon dating of macroscopic charcoal pieces found in the soil layers (Nelle et al., 2013; Remy et al., 2018). However, this method is not without limitations. For example, the site locations and charcoal pieces were selected randomly and not all-inclusive (e.g., some fires may be missed, and the oldest fire may not be detected). Dendrochronology, lake sediment cores, and other methods such as aerial photographs, are commonly used. However, fire-scarred trees are infrequent in our study region, and we aimed to obtain a stand-level fire history on the scale of millennia. Therefore, we chose a soil charcoal approach in this study because it was best suited to meet our research objectives.

Newfoundland and Labrador experiences low fire frequency. The estimated fire cycle for insular Newfoundland and for Labrador is 769 years and 500 years, respectively (Arsenault et al., 2016; Foster, 1983; Wilton and Evans, 1974). However, not all estimates agree; Power (1996) estimated a fire cycle of 98 years using mean stand age. The discrepancies among frequency estimates indicate that we know very little about the province's fire history, creating challenges for contemporary wildfire management. The current fire cycle estimates for Newfoundland and Labrador were derived from present-day evidence (e.g., written records, aerial photographs, and fire scar dating). However, it is problematic to base wildfire management solely on present-day evidence as it does not include the natural range of variation over a longer period. While the contemporary fire regime is still a useful piece of information for fire management, it should not be used in isolation as it could lead to over- or under-estimating fire frequency and result in mismanagement.

The long-term, Holocene fire history of insular Newfoundland (herein referred to as Newfoundland), before significant settler influence, remains poorly understood. Historically, literature has grouped the fire regime of Newfoundland and Labrador with the rest of eastern Canada, mainly Quebec (e.g., Bergeron et al., 2004; Hanes et al., 2019;

Stocks et al., 2002). However, strong maritime air masses and localized weather systems mean that we expect Newfoundland and Labrador to have different regimes compared to other parts of the eastern boreal forest (Arsenault et al., 2016; Foster, 1983). Newfoundland, specifically, experiences a smaller area burned annually than Quebec or Labrador. It has the fourth-smallest area burned across all of Canada (after NS, NB, and coastal BC) and the smallest area burned of the boreal region (Krezek-Hanes et al., 2011). These disharmonies and local fire controls warrant Newfoundland-specific research and tailored management plans.

Fire regimes may not only differ between Newfoundland and the mainland, but they may also differ across the island itself due to varying environmental conditions. Newfoundland has nine distinct ecoregions classified by vegetation and climate (Damman, 1983), two of which are within the boundaries of Terra Nova National Park (TNNP), where this study is focused. Established in 1957, TNNP is in eastern Newfoundland and contains the Central Newfoundland Forest ecoregion to the west and the North Shore Forest ecoregion along the coast to the east (Figure 2.1; Parks Canada, 2009). Since fire frequency is controlled locally by climate, continentality, topography, and vegetation (Flannigan et al., 2009; Johnson, 1992; Kasischke, 2000), the fire regimes likely differ between these two ecoregions. The Central Newfoundland Forest ecoregion has the most continental-like climate of the island and is expected to experience more frequent fires (Damman, 1983; Wilton and Evans, 1974). However, there are no studies empirically comparing the fire regimes between the Central Newfoundland Forest and the North Shore Forest within TNNP. The uneven distribution of the dominant tree species around the park likely also influences fire patterns. Balsam fir (*Abies balsamea* (L.) Mill) is dominant along the coasts and is intolerant of fire, while black spruce (*Picea mariana* (Mill.) B.S.P.) is dominant inland and is highly fire-adapted (Furyaev et al., 1983; Viereck and Johnston, 1990).

Terra Nova National Park managers have a mandate to maintain ecological integrity, with a key priority to preserve forest health (Parks Canada, 2009, 2019). The data from forest monitoring programs indicate that forest health is 'fair,' but impaired and in decline (Parks Canada, 2009, 2019). Park managers attribute the declining forest health and lack of regeneration to the absence of fire, in addition to other factors, such as herbivory by non-native mammals. For example, moose, introduced to the island in 1878, became overabundant and have altered forest composition (Gosse et al., 2011; Parks Canada, 2009). Therefore, TNNP managers chose prescribed fire as a forest management tool to improve regeneration of black spruce stands and improve ecological integrity. The assumption is that reintroducing fire will enhance black spruce regeneration by releasing seeds, creating ideal seedbeds, and reducing plant competition (e.g., *Kalmia angustifolia*; Siegwart Collier and Mallik, 2010; Viereck and Johnston, 1990). Black spruce can release seeds in the absence of fire and regenerate vegetatively, but fire accelerates seed fall, results in immediate reestablishment, and increases regeneration (Viereck and Johnston, 1990). Prescribed burning might also reduce the risk of future catastrophic fires by reducing fuel loads (Parisien et al., 2020). However, this prescribed fire management approach relies on the assumption that fire suppression is the cause of declining forest health and that fire will improve it. Broadly, the aim of this study was to gather more information to validate or reject these assumptions and inform the park of a complex management issue (i.e., maintaining ecological integrity).

The purpose of this study was two-fold; (1) to determine the fire history for TNNP and how it differs between ecoregions; and (2) to compare past and present forest compositions to see if and how they have changed under the potential influence of fire suppression and moose overabundance. We hypothesized that the Central Newfoundland Forest ecoregion would have a shorter fire return interval (i.e., more frequent fires) due to its more continental climate from reduced coastal influence. We also hypothesized that current fire patterns and forest compositions would exhibit a shift away from past patterns due to human intervention. For example, due to lack of fire via fire suppression, we predicted that black spruce stands would successionally shift to balsam fir stands if the conditions were favourable for balsam fir. To test these hypotheses, we established 20 sites distributed throughout TNNP in the Central Newfoundland forest and North Shore forest, in both black spruce-dominated and balsam fir-dominated forest stands, and used a soil charcoal analysis approach. We completed this study with the underlying intention to understand the Holocene wildfire history of TNNP to help inform ecological and wildfire management within the park.

2.2 Methods

2.2.1 Study area

Terra Nova National Park is located 225 km northwest of the provincial capital of St. John's, in the eastern portion of the island of Newfoundland (48° 30' 42.3" N, 53° 56' 56.8" W; (Figure 2.1). The park is approximately 402 km^2 and consists of drumlinoid hills, rocky terrain, and a rugged shoreline with a maximum elevation of 225 m (Parks Canada, 2009). The park is 79% forested, of which 74% is black spruce, 23% is balsam fir, and 3% are hardwood species (paper birch (*Betula papyrifera* Marsh.), red maple (*Acer rubrum* L.), and trembling aspen (*Populus tremuloides* Michx.)). Fens, bogs, and barrens occupy the remaining 21% of the park (Simpson, 2007). Soils of the region are primarily a medium textured, stony, sandy-loam formed of glacial origin (Agriculture Canada, 1988).

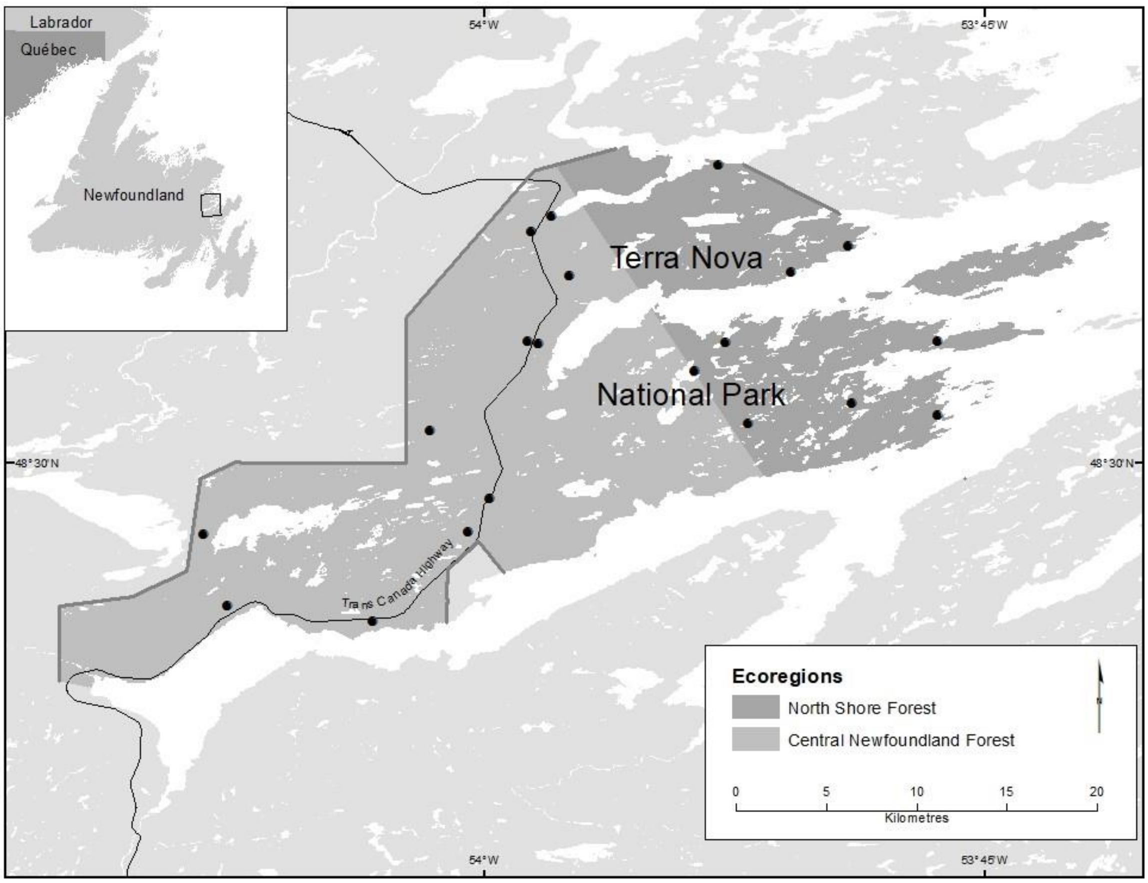

Figure 2.1 Map of Terra Nova National Park in northeastern Newfoundland, Canada. This map indicates the location of the study sites and the boundary between the Central Newfoundland Forest and the North Shore Forest. The black dots indicate sampling locations.

The TNNP region generally experiences a warm-summer continental climate (Peel et al., 2007). The mean annual temperature is 4.4°C and mean monthly temperatures ranging from -6.9°C to 16.4°C in January and August, respectively (Environment Canada, 2013). Mean monthly precipitation averages 102.8 mm, with fog during the spring and early summer also contributing notably to overall moisture (Environment Canada, 2013; Simpson, 2007). However, climatic conditions may differ within the park due to the two distinct ecoregions: Central Newfoundland Forest ecoregion and the North Shore Forest ecoregion (Figure 2.1; Damman, 1983).

The Central Newfoundland Forest ecoregion is inland and has the most continental-like climate of the island, experiencing the widest range of temperature extremes and the lowest amount of precipitation (Damman, 1983). This ecoregion is heavily forested and dominated by black spruce. Black spruce is a fire-adapted species; it is highly flammable and possesses semi-serotinous cones that open with the heat of a fire (Greene et al., 1999; Viereck and Johnston, 1990). The portion of the Central Newfoundland Forest within TNNP is the most eastern and most coastal part of this ecoregion, called the Northcentral subregion. While the ecoregion as a whole may experience a continental climate, the portion within TNNP could have significant coastal influence. The North Shore Forest ecoregion has a maritime-influenced climate yet experiences the highest summer temperatures of all island coastal areas (Damman, 1983). It is mostly forested and dominated by balsam fir (Damman, 1983). Unlike black spruce, balsam fir is maladapted to fire; therefore, balsam fir is found in areas with a maritime climate and low fire occurrence (Furyaev et al., 1983; Sirois, 1992).

2.2.2 Field methods

The soil charcoal sampling method is based on certain assumptions about charcoal formation, burial, and random vertical stratification. Incomplete burning of wood during a fire creates charcoal. After the forest fire, charcoal pieces are fragmented and randomly buried vertically in the soil column due to soil disturbance, such as bioturbation, frost action, surface run-off, and tree uprooting (Bormann et al., 1995; Carcaillet, 2001). Charcoal burial may occur immediately post-fire or decades to hundreds of years later, during which time another fire may burn the same area (Payette et al., 2012). The residence time of charcoal fragments at the surface is related to the number and intensity of soil disturbances post-fire, including subsequent fires that may degrade the charcoal into ash (Payette et al., 2012). For the charcoal that is buried, the random mixing of soil does not favour an increasing age/depth stratification of charcoal in the soil horizons; charcoal fragments can also be resurfaced following disturbances (Carcaillet, 2001; Fesenmyer and Christensen, 2010; Payette et al., 2012). Therefore, samples collected relatively close (e.g., < 20 cm) to the surface of the mineral soil layer are still able to capture a wide age range of charcoal. In addition, in most cases, macroscopic charcoal pieces (≥ 2 mm) can generally be assumed to have formed *in situ* and not blown in from a distant fire, providing evidence for local fire influence (Ohlson and Tryterud, 2000). However, we acknowledge that long-distance travel of charcoal is a possibility and uncertainty in our study, especially in the presence of strong winds (Pisaric, 2002; Tinner et al., 2006). Macroscopic charcoal pieces that are not too severely burnt maintain their anatomical features and can be identified to tree genus or sometimes species (de Lafontaine and Payette, 2012; Frégeau et al., 2015; Talon et al., 2005).

We selected 20 sites within the park. Eleven sites are in the Central Newfoundland Forest, of which eight are in black spruce-dominated stands and three are in balsam fir-dominated stands (Figure 2.1). Nine sites are in the North Shore Forest, of which three are in black spruce-dominated stands and six are in balsam fir-dominated stands (Figure 2.1). Sites were randomly selected from long-term Parks Canada Forest Monitoring sites, providing historical data allowing us to assess forest change over time. However, some sites were preferentially selected based on accessibility.

Each site consisted of a 10 m radius circular plot. At each site, we collected five mineral soil samples: one in the center of the plot and one 10 m in each cardinal direction from the center, resulting in a total of 100 mineral soil samples overall. We obtained the soil samples by removing a 20 cm x 20 cm area of organic matter to expose the mineral soil and taking an 8 cm diameter x 12 cm length (750 cm^3) cylindrical bulk density core of the mineral soil. At the center soil pit, we also measured the soil organic horizon (SOH) thickness, soil moisture, soil pH, and soil texture (Appendix I). We collected the soil samples in the Fall 2017 and Summer 2018. Soil texture classification follows Folk (1954).

To assess current forest composition, we used data collected by Parks Canada in 2014-2018 from the long-term forest monitoring plots. Each plot was an 11.4 m radius circular plot, following Canada-wide Ecological Monitoring and Assessment Network (EMAN) protocol (Roberts-Pichette and Gillespie, 1999). Forest composition was assessed by recording the species of each tree (diameter $\geq$ 4 cm) within the plots. We also took a tree core from five individuals of the dominant species to estimate minimum stand age and measured the slope and aspect of each site (Appendix I).

2.2.3 Laboratory methods

Our charcoal extraction procedure follows Frégeau, Payette, and Grondin (2015). In the laboratory, we soaked the soil samples in a 1% NaOH solution for a minimum of 12 hours, which disperses the soil aggregates. We wet-sieved the soil samples through superimposed 4 mm and 2 mm sieves and carefully extracted the charcoal fragments. Charcoal fragments were abundant (e.g., one 750 cm^3 soil sample could contain up to 400 pieces of charcoal), so for each soil sample, we spread out the charcoal fragments on one or more petri dishes to air-dry. Once dried, we first randomly selected one size-compatible charcoal piece from each soil sample (see below) to be identified and dated (i.e., one charcoal piece per five soil samples per 20 sites = 100 charcoal pieces total for the study). We only identified charcoal pieces ≥ 2 mm and ≥ 5 mg to ensure the charcoal met the weight threshold for radiocarbon dating and was more likely to have formed *in situ* (Ohlson and Tryterud, 2000). On each petri dish, the charcoal pieces were spaced on a 3 x 3 grid. For each soil sample, we used a random number generator to select the (1) petri dish, (2) grid section, and (3) charcoal piece to identify and date. Using an incident light microscope (50x, 100x, 200x, 500x), we identified these 100 charcoal pieces to tree genus, or species when possible, using anatomical wood characteristics defined in identification keys (Miszaniec, 2013; Panshin and Zeeuw, 1980; Schoch et al., 2004). We sent these 100 randomly selected and identified charcoal fragments to an accelerator mass spectrometry (AMS) radiocarbon dating lab. Then, we identified the remaining size compatible charcoal pieces to genus or species (*n* = 300); however, not all samples were identifiable (e.g., indistinguishable features; *n* = 208). Some samples were completely unidentifiable, but some we could partially identify as “coniferous” or “deciduous,” in which case we randomly selected another fragment. We radiocarbon dated eight of the unidentifiable charcoal fragments to assess whether our selection of identifiable pieces biased our age distribution to younger charcoal.

Pre-treatment (i.e., acid-alkali-acid wash following Crann et al., 2017) and radiocarbon dating took place at the A. E. Lalonde AMS Laboratory, University of Ottawa. The $^{14}C \pm 2\sigma$ dates were calibrated using OxCal v4.3 (Bronk Ramsey, 2009) and the IntCal13 or Bomb13 (NH1) calibration curves (Reimer et al., 2013). All dates are presented as calibrated (cal.) years before present (BP), where 0 BP is 1950 CE. Calibration is required to account for the past fluctuations of ^{14}C in the atmosphere due to changes in the production rate, solar activity, etc. (Reimer et al., 2013).

2.2.4 Fire history analysis

Calibration of the ^{14}C dates of a charcoal fragment results in a range of potential calendar years along with an associated probability that the true age of the sample lies within that calibrated date range. Depending on the fluctuations of atmospheric ^{14}C at the time, the calendar year range can be narrow or spread out over a long period (Figure 2.2). There can also be multiple ranges for one sample, each with a respective probability; in this scenario, we used only the date range with the highest probability (Figure 2.3). For analysis purposes, we used the mean of the date range as the sample age in cal. years BP (see Figure 2.2 and 2.3 for examples). With the sample ages of all the dated charcoal samples (n = 108), we created a histogram representing the number of charcoal pieces as a function of time by grouping the sample ages (cal. years BP) into 100-year classes. The first age class, 100-0 cal. years BP, is 1850-1950 CE. We also created histograms for the charcoal dates by ecoregion.

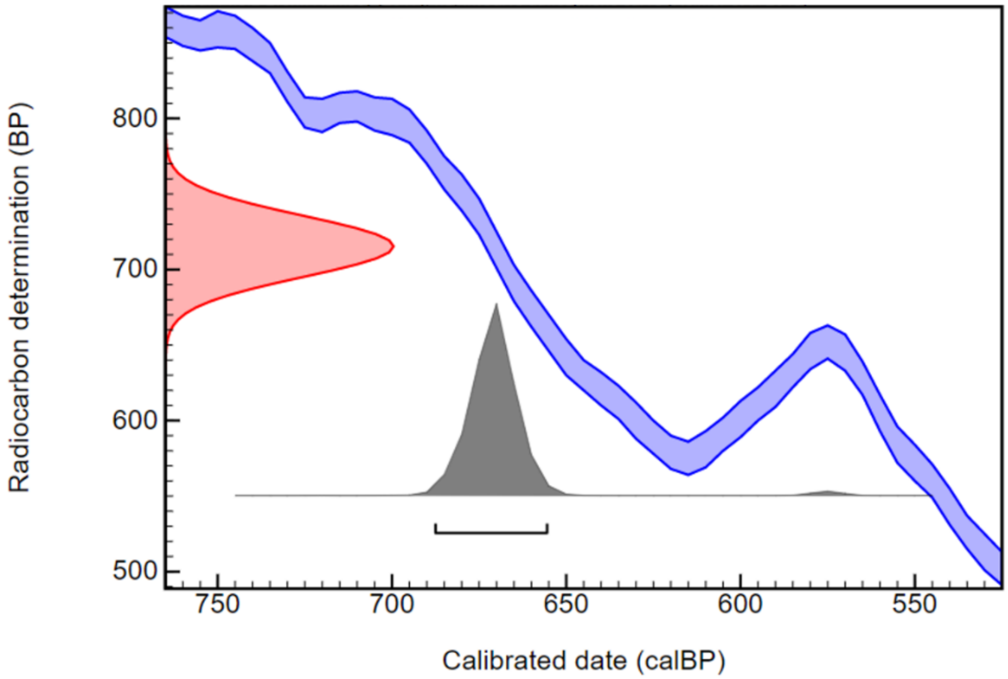

Figure 2.2 An example charcoal fragment calibration resulting in a narrow age range. The radiocarbon determination (i.e., the ^{14}C date derived from the measurement of radiocarbon in the sample) for this fragment was 715 years BP. A normal curve (red) is drawn around the radiocarbon determination to account for measurment uncertainty. This curve (red) is plotted against the calibration curve (blue), a curve of known calendar ages and corresponding amounts of atmospheric ^{14}C, to yield the calibrated date range in calendar years (grey). In this example, the calibrated date range was 656-688 cal. years BP, with a 95.4% probability. The mean of this range, 672 cal. years BP, was chosen for the fire event date. Curve created in OxCal v4.3.2, using the IntCal13 atmospheric curve (Bronk Ramsey, 2009, 2017; Reimer et al., 2013).

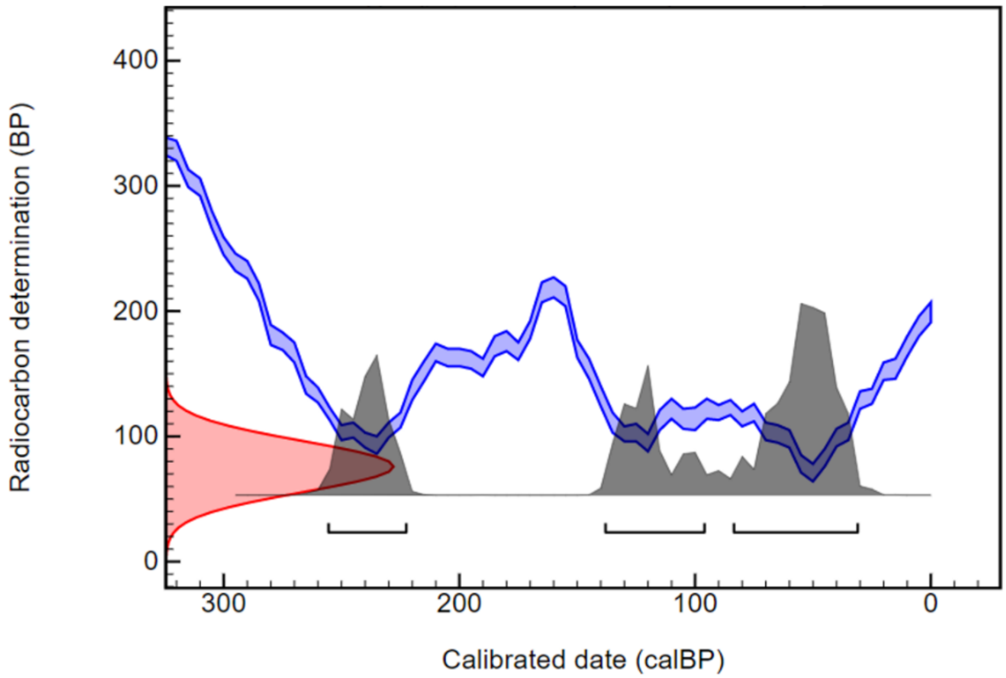

Figure 2.3 An example charcoal fragment calibration resulting in multiple age ranges. The radiocarbon determination (i.e., the ^{14}C date derived from the measurement of radiocarbon in the sample) for this piece was 76 years BP. A normal curve (red) is drawn around the radiocarbon determination to account for measurment uncertainty. This curve (red) is plotted against the calibration curve (blue), a curve of known calendar ages and corresponding amounts of atmospheric ^{14}C, to yield the calibrated date ranges in calendar years (grey). In this example, the calibrated date ranges were 31-84 cal. years BP (48.9% probability), 96-138 cal. years BP (22.3% probability), and 223-256 cal. years BP (24.3% probability). Since this sample has multiple date ranges, the mean of the calibrated date range with the highest probability, 57.5 cal. years BP, was chosen for the fire event date. Curve created in OxCal v4.3.2, using the IntCal13 atmospheric curve (Bronk Ramsey, 2009, 2017; Reimer et al., 2013).

To determine if two or more samples came from the same fire, we once again considered the calibrated date range with the highest probability, not only the mean. Samples were considered to have come from the same fire if (1) the samples were from the same site or the sites were within 6 km of one another, (2) there was no significant geographical barrier between the samples (e.g., a large inlet or mountain), and (3) the calendar year range overlapped by 20 years or more (following Payette and Frégeau, 2019). If we decided two or more samples were from the same fire, we took the average of sample ages (i.e., the mean of the date range with the highest probability) as the fire event date (also fire year). In certain circumstances, given the data and ecological knowledge of the area, samples up to 12 km of one another were considered the same fire (see Appendix II). The 6 km limit was derived from the average size of fires recorded in the TNNP area (Table 1.1). However, the largest fire recorded in the area was 23,450 ha (234.5 km^2), so we assumed fires could be as large. This fire was also the only lightning-ignited fire in recent times. We recognize that the filtering method we choose has a strong impact on the results and interpretations we make from the data, but we feel it was the method best suited to our data and knowledge of the area. We took this as an opportunity to test our assumptions and see how different filtering methods could affect our results. We used the same protocol as above but grouped fires if they were within 3 km and 15 km of each other.

To visualize the fire history, we created a cumulative probability plot for all the charcoal pieces, which sums all the individual calibration probability plots (e.g., Figure 2.2 and Figure 2.3). This plot displays the relative probability that any fire represented by our data set occurred within the park. We constructed the cumulative probability plots in R for the park and each ecoregion using the '*calibrate*' and '*spd*' functions from the package '*rcarbon*' (R Core Team, 2019). We compared the cumulative probability plots of the two ecoregions using the function '*permTest*,' from the same package (R Core Team, 2019). This function performs a permutation test by randomly selecting a subset of samples from both ecoregions to create simulated cumulative probability plots. We performed 1000 Monte Carlo simulations creating 95% confidence intervals. The function then compares the cumulative probability plots for each ecoregion to the 95%

confidence interval from the simulations and highlights areas of positive and negative deviation (Crema et al., 2016; Riris, 2018; Timpson et al., 2014).

With the fire event dates and the cumulative probability plot, we quantified the fire occurrence in the park and within each ecoregion. Following Payette and Frégeau (2019), we calculated the fire return interval for the whole time period by taking the date of the oldest fire and divided it by the number of fires that occurred between that time and present-day. We also calculated fire return intervals for shorter fire periods. We derived the fire periods from the cumulative probability plot, dividing it where there were clear changes in the fire patterns (e.g., from periods of infrequent fires to frequent fires). We emphasize that these are not true fire return intervals because our samples are from sites all around the park, and the uncertainty associated with determining if two pieces of charcoal are from the same fire is too high. Rather, they provide an estimate of how often a fire event occurs within the park boundary. Some studies, such as Fesenmyer and Christensen (2010), did not calculate a fire return interval due to the uncertainties. Similarly, while we can say fire happened historically, calculating a true fire return interval with our data is difficult and may not be possible. We recognize that this area of fire history research remains a point of controversy. Regardless, we attempted to use more contemporary methods to gain a rough quantification of the fire history of TNNP.

It is ideal to radiocarbon date as many samples as possible to gain the most comprehensive fire history of an area. Given funding and logistical limitations, statistical methods can be used to estimate the total number of fires for an area. In our study, the small number of samples per site and the random method of sampling does not guarantee that all fires were detected. Previous studies commonly constructed asymptotic accumulation curves to estimate by extrapolation the total number of fires that theoretically occurred (Couillard et al., 2018; de Lafontaine and Payette, 2011, 2012; Frégeau et al., 2015; Payette et al., 2012, 2016). Similar to a 'species accumulation curve,' this method relates the number of fires detected to the number of charcoal fragments radiocarbon dated, forming a negative exponential curve (de Lafontaine and Payette, 2012; Frégeau et al., 2015). If the curve forms an asymptote, it suggests that the dated samples detected the actual number of fires (Frégeau et al., 2015). Even if the curve does not form an asymptote, we can extrapolate and calculate where the curve would flatten, providing an estimate of the actual number of fires (de Lafontaine and Payette, 2012; Frégeau et al., 2015). However, this method is parametric and assumes that the number of charcoal pieces is equivalent for each fire, which is often not the case due to charcoal decay (M. Frégeau, personal communication, March 20, 2019). Parametric estimators assume that the species accumulation curve follows a statistical model with one or two parameters. This framework is not ideal for empirical data because it depends on knowing the correct form of distribution (Chao and Chiu, 2016). In contrast, non-parametric estimators are more robust, conservative, and make no assumptions about the mathematical form of the distribution (Chao and Chiu, 2016). Therefore, following Payette and Frégeau (2019), we calculated a non-parametric estimator of the total number of fires that are likely to have occurred within the park. This approach uses statistical sampling theory for estimating species richness; it estimates the total number of species (or in this case fires) based on a species-accumulation curve using only presence data (Chao and Chiu, 2016). Using the R software package SpadeR, and the '*Chao1-bc*' method, we calculated the estimate, standard deviation, and the 95% confidence interval of the total number of fires (Chao & Chiu, 2016; R Core Team, 2019).

We determined the past forest composition by calculating the proportion of each tree genus or species from all the identified charcoal, not only the radiocarbon dated samples (n = 300). The past forest composition, in this context, is the past burned forest composition because some tree species are more prone to burning. Therefore, our estimate may be different from the actual past forest composition. Similarly, we calculated the proportion of each species present in the Parks Canada long-term monitoring plots to determine the present forest composition. We used chi-square tests ($\alpha = 0.05$) to determine if the proportions of spruce, fir, or deciduous species were significantly different between ecoregions in the past and from past to present.

There are two sources of error that must be addressed when radiocarbon dating. The first source of error is inherent to the system and can be easily quantified; it is the standard error from measuring the ^{14}C and calibrating the ^{14}C dates to calendar years (Gavin, 2001; Stuiver and Reimer, 1993). The second source of error is the difference between the age of the sample and the actual fire date (Gavin, 2001). When dating charcoal samples, the calibrated dates correspond to the age of wood formation and not the age of the fire event, resulting in the “inbuilt error.” Samples may come from wood that was dead on the ground for some time before being burned (Gavin, 2001). Samples may also come from an interior tree ring, some depth within the tree, and not the most recent growth ring (Gavin, 2001). For example, imagine a piece of charcoal from a tree that was killed by the eastern spruce budworm 400 years BP. This tree stayed upright for 25 years before falling to the ground and remaining there for another 25 years when a fire burned through the area. The age of the charcoal sample would be 400 years BP, but the age of the fire is 350 years BP, so the inbuilt error for this charcoal piece would be 50 years.

Using woody debris decay rates for Newfoundland and Labrador, we assume the inbuilt error for the region is somewhere around 40-60 years for aboveground deadwood (Hagemann et al., 2009; Moroni, 2006), but could be as high as 515 years for deadwood buried by moss (Hagemann et al., 2010; Moroni et al., 2010). Other eastern boreal systems have inbuilt errors that range from 25-140 years (Boulanger and Sirois, 2006; Payette et al., 2012). It is difficult to calculate an estimate of the inbuilt error for our study system, as other studies have done, due to lack of evidence from recent fires, such as fire scars (Hoffman et al., 2016; Payette et al., 2012). Thus, we did not attempt to include the inbuilt error into our analysis. However, it should still be noted that there are approximately 50 years between the ages of the wood that created the charcoal and the ages of the fire events, in addition, to the 70 years between the year 0 BP (1950 CE) and 2020 CE.

2.3 Results

2.3.1 Charcoal samples

Charcoal was present in every soil sample collected; 5280 charcoal pieces were extracted from the mineral soil samples, of which 31% met the *in-situ* formation and radiocarbon dating size requirements (≥ 5 mg and ≥ 2 mm). Of the size-compatible samples, 18% were identified to the species or genus level (n = 300). In the charcoal record, we found spruce (53.3%), balsam fir (26.7%), birch (15.3%), pine (3.0%), and maple (1.7%). Including unidentifiable samples, we found 84.1% coniferous and 15.9% deciduous overall. There was more spruce in the Central Newfoundland Forest than in the North Shore Forest ($X^2 = 5.62$, df = 1, $p = 0.018$; Figure 2.4). However, balsam fir proportions did not differ significantly between the two ecoregions ($X^2 = 1.80$, df = 1, $p = 0.180$; Figure 2.4). There were more deciduous species in the North Shore Forest than in the Central Newfoundland Forest ($X^2 = 7.08$, df = 1, $p = 0.008$; Figure 2.4).

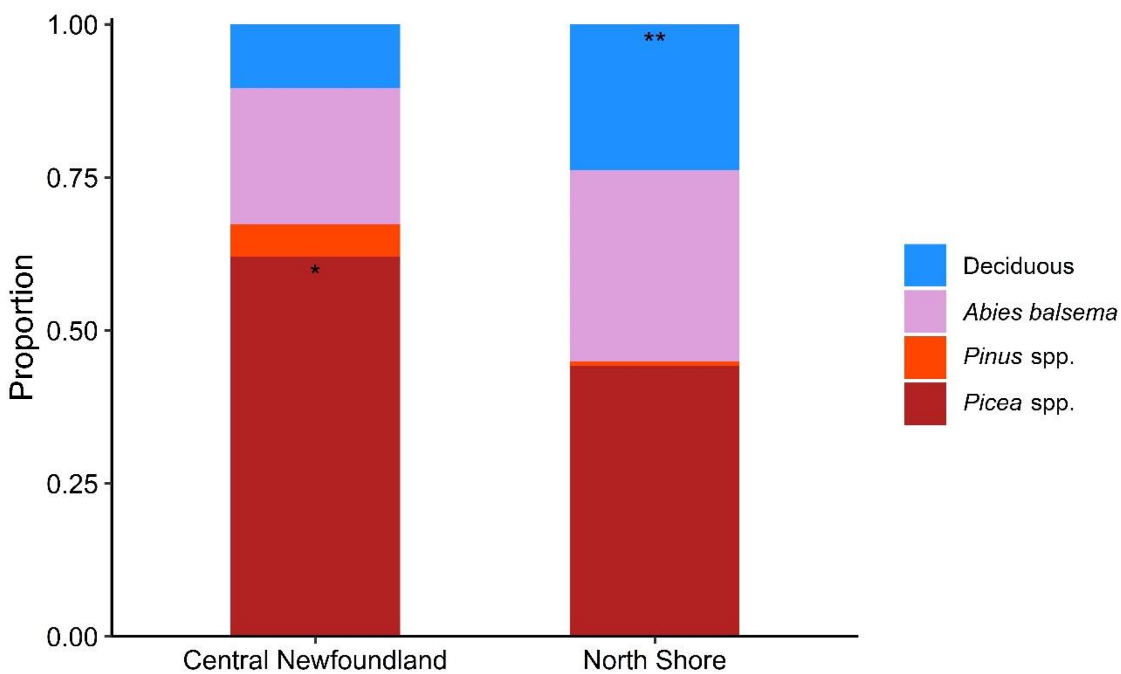

Figure 2.4 Bar plot representing the proportion of each tree genus or species by ecoregion from all the charcoal samples. The deciduous category is made up of *Acer* spp. and *Betula* spp. Comparing the two ecoregions, (*) indicates $p \leq 0.05$ and (**) indicates $p \leq 0.01$.

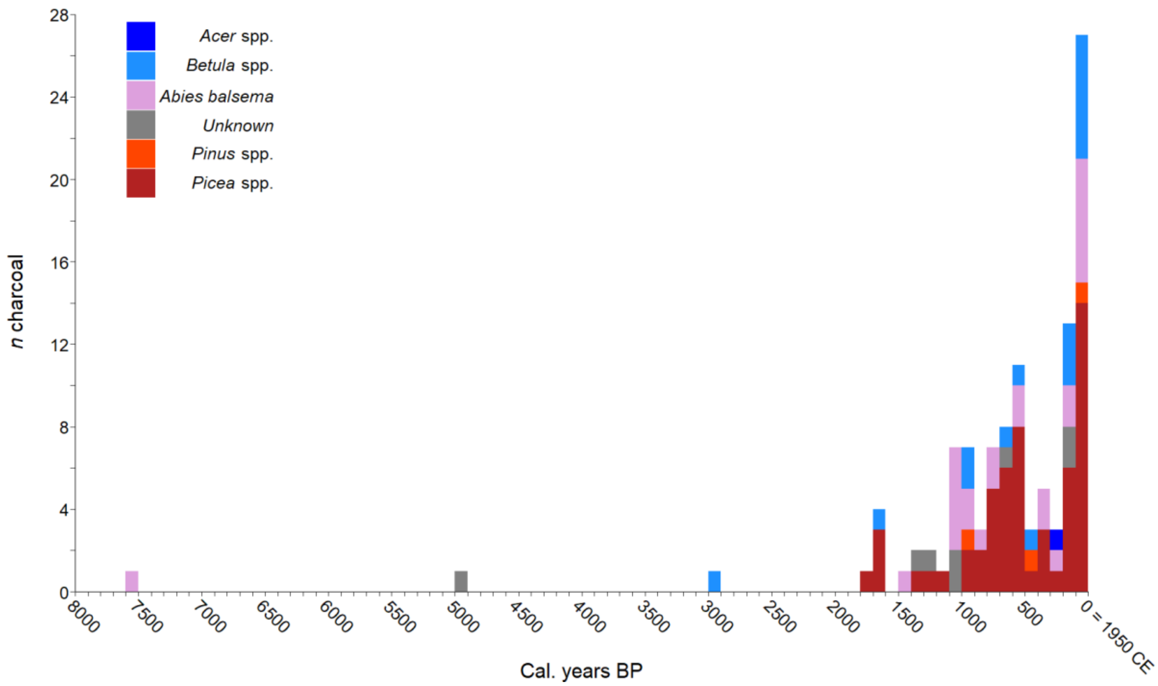

Figure 2.5 The number of charcoal pieces by time for all dated charcoal samples (*n* = 108). The charcoal data are displayed by tree genus or species and distributed in 100-year ages classes. For perspective, the first column, 0-100 cal. years BP, is equivalent to 1850-1950 CE, and 2000 cal. years BP is 50 BCE.

Of the pieces that were radiocarbon dated, the mean charcoal ages spanned from 7528 cal. years BP to 1955 CE (Figure 2.5). Around each mean, the range of cal. years BP varied from two to 198 years. The oldest Central Newfoundland charcoal that we dated was a balsam fir (7528 cal. years BP), and the oldest North Shore charcoal dated was an unidentifiable piece (4905 cal. years BP). The second oldest North Shore charcoal, third oldest overall, was a birch (2922 cal. years BP). There were gaps in the charcoal record from 7528 to 4905 cal. years BP, 4905 to 2922 cal. years BP, and 2922 to 1787 cal. years BP, with 93% of the charcoal < 1500 years old (Figure 2.5). Five out of eight unidentifiable pieces were > 1000 cal. years BP, one of which was > 4500 cal. years BP, indicating our identified samples may be slightly biased to younger ages. The abundance of charcoal decreases steadily through time for both sites (Figure 2.6). Radiocarbon age, calibrated date ranges, and mean and median calibrated years BP with associated probabilities are presented in Appendix II.

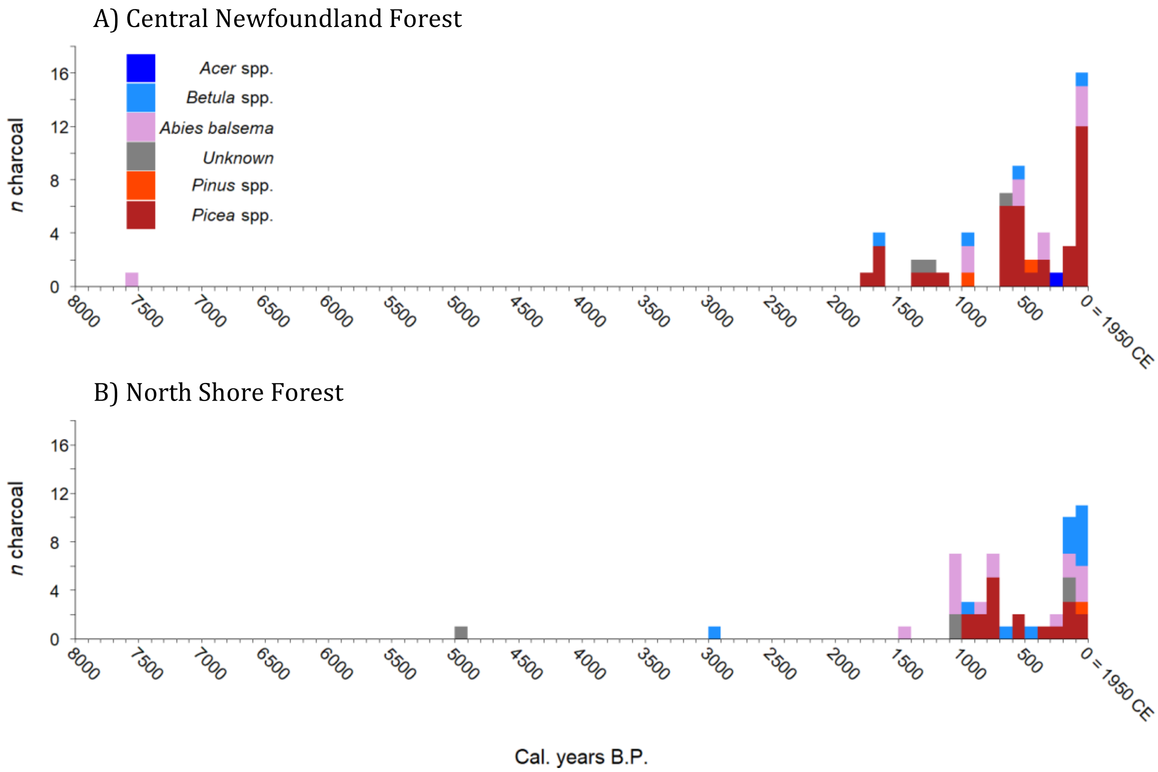

Figure 2.6 The number of charcoal pieces by time for (A) the Central Newfoundland Forest and (B) the North Shore Forest. The charcoal data are displayed by tree genus or species and distributed in 100-year ages classes. Note, 0 cal. years BP is 1950 CE.

2.3.2 Fire history

We defined fire events by samples that were from the same site or within 6-12 km of each other, with no significant barriers, and age ranges overlapping by 20 years or more. Using this protocol, we detected a total of 51 fires throughout the park from the 108 radiocarbon dated charcoal pieces. Those 51 fires occurred over the last 7528 cal. years BP at an average fire interval of 150 years (Figure 2.7a), i.e., a fire occurred somewhere within the park boundary approximately every 150 years. We emphasize that this does not mean a single stand had a fire return interval of 150 years, rather a fire occurred somewhere within the current park boundaries approximately every 150 years. Depending on the assumptions made, the number of fires detected can vary greatly. For example, if we assumed the average size of the fire was 3 km (900 ha), our samples estimate 68 fires within the park. However, if we assumed the average fire size was the same as the largest fire recorded in the park (i.e., 15 km or 22,500 ha), our estimate would be 44 fires.

In the Central Newfoundland Forest, our methods detected that 28 fires occurred over the last 7528 cal. years BP at a mean interval of 270 years (Figure 2.7b). If we look at samples from the past 2000 years, where sample resolution was greatest, the mean interval was 66 years. Seven fires occurred between 1787 and 692 cal. years BP (mean interval: 156 years), eight fires occurred between 692 and 498 cal. years BP (mean interval: 24 years), and 11 fires occurred between 498 cal. years BP and present-day (mean interval: 42 years).

In the North Shore Forest, our methods detected that 23 fires occurred over the last 4904 cal. years BP at a mean interval of 215 years (Figure 2.7c). Focusing on the last 2000 yea A he mean interval was 70 years. One fire occurred between 1464 and 1076 cal. years BP (mean interval: 388 years), eight fires occurred between 1076 and 673 cal. years BP (mean interval: 50 years), three fires occurred between 673 and 295 cal. years BP (mean interval: 126 years), and six fires occurred between 295 cal. years BP and present-day (mean interval: 33 years). We detected areas of statistically significant local deviations between the cumulative probability plots for each ecoregion (Figure 2.8; global p-value = 0.008); although, most of the fire histories are not significantly different. Both ecoregions experience areas of positive and negative deviations, so one region did not experience more fires than the other.

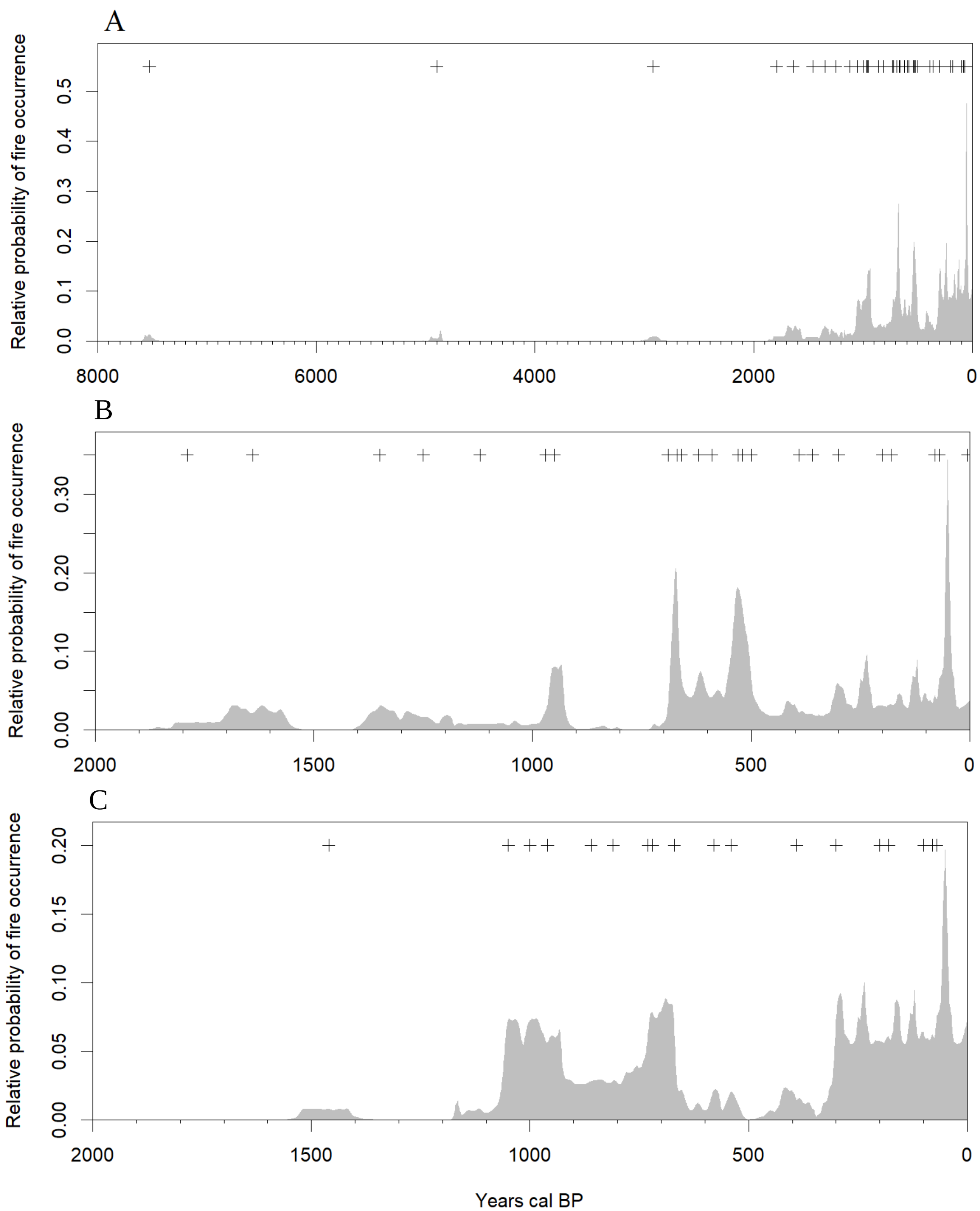

Figure 2.7 The cumulative probability plot for (A) the whole park from 0-8000 cal. years BP. (B) The Central Newfoundland Forest and (C) the North Shore Forest cumulative probability plots are from 0-2000 cal. years BP. The ‘+’ indicates a fire event as determined by our protocol in section 2.2.4. See Appendix II for fire event data.

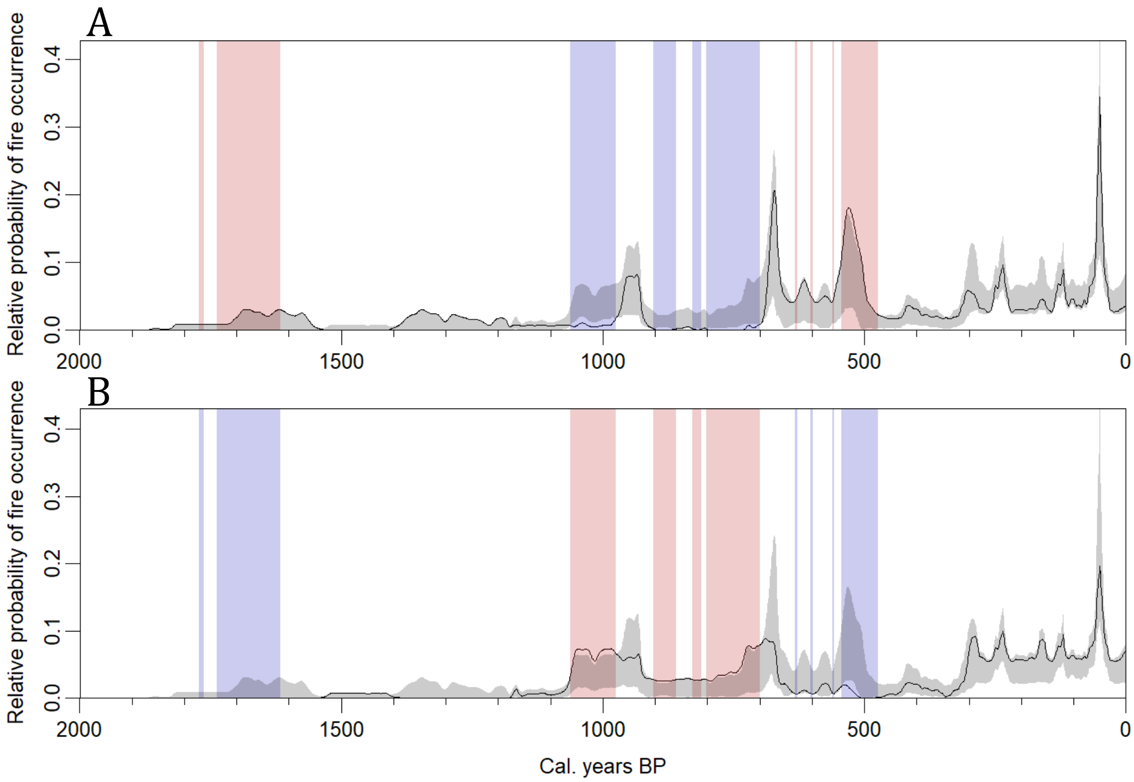

Figure 2.8 The areas of deviation between the cumulative probability plots of the (A) Central Newfoundland ecoregion and (B) North Shore ecoregion. The thin black lines are the respective cumulative probability plots for each ecoregion. The thick grey line is the 95% confidence interval from 1000 Monte Carlo simulations. The red shaded areas are regions of positive deviation from the 95% confidence interval and the blue shaded areas are negative deviations.

Due to the nature of radiocarbon dating, the actual number of fires that occurred is likely greater than the number of fires detected. The non-parametric (*Chao1-bc*) estimate of the total number of fires in the study area was 65.3 ± 8.1. This estimate is 28% larger than the number of fires documented from the charcoal samples we collected, indicating that we did not detect all the historic fires that occurred.

2.3.3 Past and contemporary forest compositions

The current forest composition of our sites is 69.1% black spruce, 23.0% balsam fir, 7.2% paper birch, with red maple, trembling aspen, and eastern larch making up less than 1%. There is no eastern white pine currently present at our sites (i.e., the long-term monitoring plots), though the species does occur in the park. At the park level, proportions of spruce, fir, and deciduous species have not detectably changed from past to present-day (Figure 2.9; Table 2.1). Here, past means the proportion of each tree genus or species from all the identified charcoal (i.e., 8000-0 cal. years BP), not only the radiocarbon dated samples (n = 300). When considering the Central Newfoundland forest specifically, spruce proportions have increased from past to present-day, while balsam fir and deciduous species have decreased (Figure 2.9; Table 2.1). In the North Shore ecoregion, spruce proportions decreased from past to present-day, fir proportions increased, and deciduous proportions did not noticeably change (Figure 2.9; Table 2.1).

Table 2.1 Summary of results from the chi-squared tests between past and present-day species proportions. '↔' indicates that there was no change from past to present-day, '↑' indicates an increase, and '↓' indicates a decrease ($\alpha = 0.05$).

	X^2	df	p	Direction
Park				
Black spruce	2.02	1	0.15	↔
Balsam fir	0.27	1	0.606	↔
Deciduous	3.33	1	0.068	↔
Central Newfoundland				
Black spruce	6.30	1	0.012	↑
Balsam fir	13.60	1	< 0.001	↓
Deciduous	3.99	1	0.046	↓
North Shore				
Black spruce	5.77	1	0.016	↓
Balsam fir	8.47	1	0.004	↑
Deciduous	1.24	1	0.226	↔

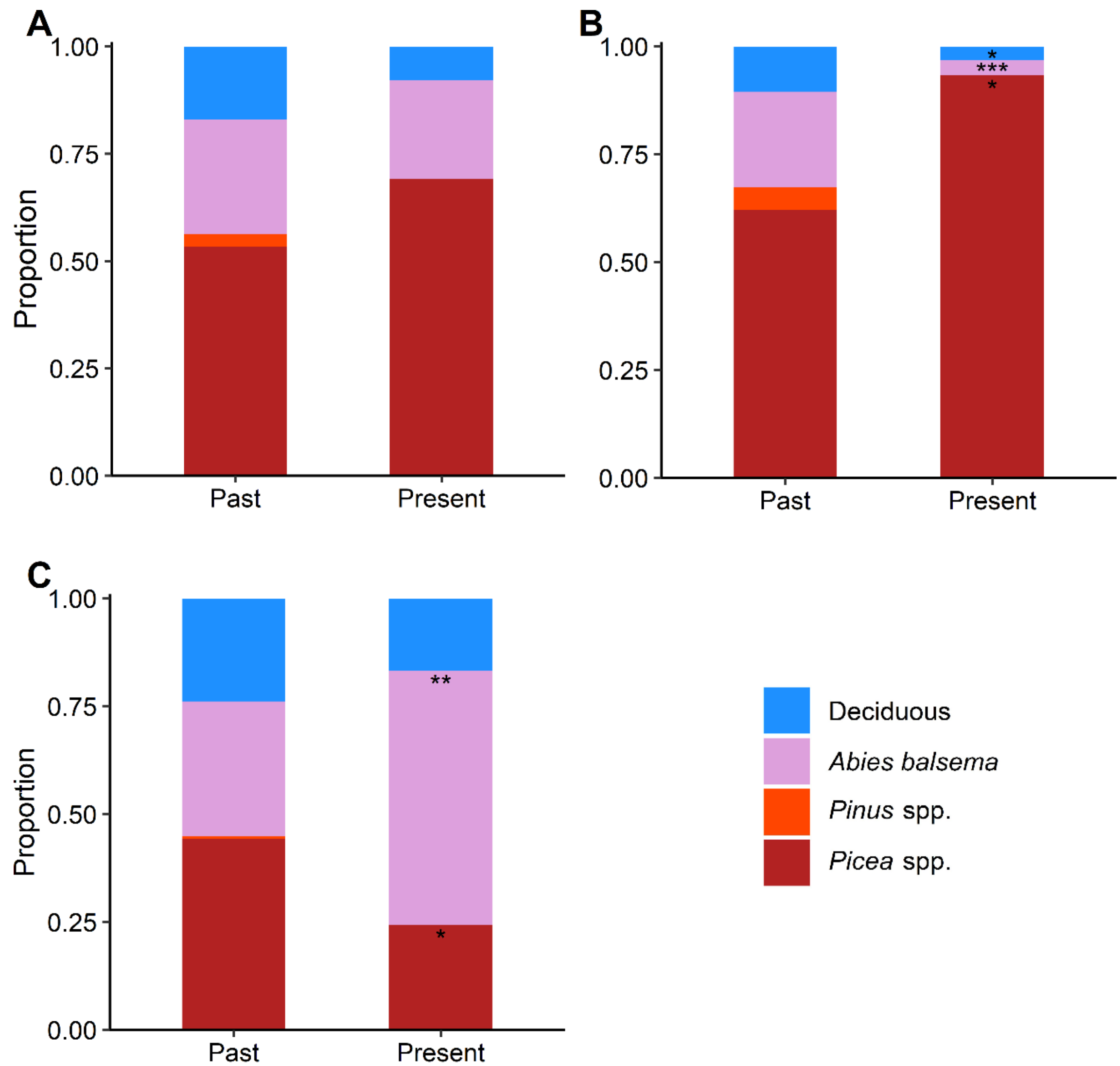

Figure 2.9 This bar plot represents the proportion of each tree genus or species from past to present-day for (A) the park, (B) the Central Newfoundland Forest, and (C) the North Shore Forest. The 'past' columns represent the genus or species proportions from all the identified charcoal samples (n = 300). The 'present' columns represent the genus or species proportions currently observed at the sites. The deciduous category consists of *Acer* spp. and *Betula* spp. (*) indicates $p \leq 0.05$, (**) indicates $p \leq 0.01$, and (***) indicates $p \leq 0.001$ (see Table 2.1).

2.4 Discussion

Our analysis of soil charcoal in TNNP provides direct evidence that fire has been a natural disturbance in Newfoundland's coastal boreal forests since the early Holocene.

We found the presence of consistent fire activity over the past 2000 years in the park, with a drastic increase in fire frequency in the last 100 years. Our estimates of fire occurrence suggest that there are areas of deviation between the fire regimes of the two ecoregions, but overall, the fire regimes are similar. Forest compositions, however, did vary between ecoregions and from past to present-day. Here, we discuss the evidence for these findings and the implications for forest management in coastal eastern boreal forests.

2.4.1 Detection of Holocene fires and species occurrences

Deglaciation of the island began approximately 12.0 ka and completed just after 10.0 ka (Macpherson, 1982; Shaw et al., 2006; Tucker, 1974). After deglaciation, the landscape would have consisted of pioneer herb-dwarf shrub tundra, followed by shrub birch, then finally spruce and fir around 9.5 ka (Macpherson, 1995). The oldest charcoal sample that we analyzed was a balsam fir from 7528 cal. years BP, which corresponds to when other studies detected the presence of balsam fir in the study area (Macpherson, 1995). The gap between the arrival of balsam fir in the study area and our oldest piece of charcoal is likely the result of sampling design and sample size. First, it is very unlikely that we would have sampled the oldest occurrence of balsam fir in the park. Second, the negative exponential distribution of charcoal abundances and extremely low occurrence of charcoal before 1800 cal. years BP is most likely the result of the physical decay of charcoal over time and re-burning (Frégeau et al., 2015). Charcoal is extremely resistant to decay once buried in the mineral soil layer, but it is subjected to decay before burial. Also, if a piece of charcoal is re-burned in a subsequent fire, it would turn to ash and not be detectable in the charcoal record (Payette et al., 2012). These uncertainties mean that we cannot say for certain that lack of charcoal samples means lack of fire. Nonetheless, we want to emphasize the notable absence of charcoal from the early Holocene to 1800 cal. years BP. We cannot ignore that we detected so few fires during this time period compared to 1800 cal. years BP to present-day. It might be that fires were relatively less common during the mid-Holocene. However, it may just be that our sampling design did not allow us to find many samples from that period. A lake sediment core study from the area detected the presence of charcoal beginning in the early Holocene (Macpherson, 1995). While the study site was 150 km to the north west of TNNP, this evidence indicates our lack of charcoal is more likely the result of charcoal decay and not lack of fire. What we can confidently say is fire was irregularly present in the park from 1800 cal. years BP to present.

2.4.2 Fire history of Terra Nova National Park

We estimate the mean fire occurrence within TNNP to be 150 years over the last 8000 years, based on the number of fires detected by our methods. Focusing on the last 2000 years, the mean fire interval was 66 years in the Central Newfoundland ecoregion and 70 years in the North Shore ecoregion. Again, these fire occurrence estimates represent on average how often a fire occurred somewhere within the park boundaries or respective ecoregions. These estimates are a simplification of the fire history; in reality, fire occurrence varies across landscapes and time. We tried to account for spatial variation by calculating the fire return intervals for the two ecoregions. We also attempted to explain the temporal variation by breaking up our data into different fire periods.

However, it is difficult to say if fire frequency variation over a short time is meaningful; if one charcoal sample is missed, it can greatly affect the result. There is a lot of uncertainty and controversy around the calculation and interpretation of fire histories. We made our decisions based on our data and our ecological and historical knowledge of the study area. Another important consideration is that these numbers represent only the fire frequency; they do not indicate fire severity (i.e., ecological effect). While fires might have occurred in the park every 150 years on average, some of those fires may have been small and low severity. It might be that large fires having a lasting effect on the forest and regeneration only happened every 400 or 500 years.

We detected a drastic increase in fire occurrence in the last 100 cal. years BP (1850-1950 CE), with a minor increase in fire occurrence from 200-100 cal. years BP (1750-1850 CE). These increases in fire occurrence correspond with the increased permanent European settlement of the area around the 1800s (Carroll, 1990; Simpson, 2007). However, there was still human influence on fire patterns before this time. Indigenous peoples would have likely contributed to human-caused fires during this time and earlier; however, the extent and use of fire by Indigenous peoples on the island remains unclear. Transient fishers would have also contributed greatly to human-caused fires from as early as 500 cal. years BP. While these European fishermen rarely settled on land, they caused many fires, some of which were purposeful to discourage settlement (Carroll, 1990). During the period of increased fires, 200 cal. years BP to present, increased settlement and development of the area caused anthropogenic ignitions to increase. The single largest source of fire from this time would have been the construction and use of the Newfoundland railway (Carroll, 1990; Parks Canada, 2009). Other sources of fire from this time would have been the early timber industry, accidental domestic fires, construction of roads, etc. (Carroll, 1990; Lundrigan, 1961; Parks Canada, 2009; Penny and Kennedy, 2003; Tuck, 1980).

From 1800-200 cal. years BP, fires occurred in TNNP more frequently than we expected. Even though our samples are from sites all around the park, we observed many fires in an area previously thought to have very little fire occurrence. Even 500 years ago, fires might have occurred as often as every 25 years in the park, when written records only document one lightning fire in the last 60 years (Table 1.1). There are several reasons why we may have observed more fires than expected during this time. Fires may have simply been smaller and more often than previously thought. Alternatively, strong human influence may have begun earlier than we expected. It is also possible that our methods did not properly group the charcoal samples into fire events. If this were the case, fires would have been larger and less frequent, but the uncertainty associated with radiocarbon dating and not knowing the variable sizes of fires did not allow us to detect this.

The high level of uncertainty and error associated with our methods make it hard to infer differences between the two ecoregions. However, our estimates of fire occurrence suggest no meaningful difference between the fire regimes of the two ecoregions within the park. There are areas of significant local deviation between the cumulative probability plots for the two ecoregions, but both have periods of positive and negative deviation. Neither ecoregion experienced exclusively more or less than the other (Figure 2.8). Both ecoregions are surrounded by inlets and ocean, experience fog, and are subjected to the same weather systems resulting in a strong coastal influence over the entire park. While there are distinctive differences in species composition, the coastal climate is the dominant control of the fire regime in the entire Terra Nova region. Other studies on the island, such as Macpherson (1995), group the North Shore ecoregion and the Northcentral subregion (the subregion of the Central Newfoundland Forest that TNNP is in) due to their proximity and similarities in vegetation and climate.

While we cannot directly compare our fire return intervals with those from other portions of the eastern boreal forest, a discussion of our findings would not be complete without it. The average fire return interval for Québec ranges from 270-500 years, calculated at the stand level in plots no larger than 400 m^2 (Bouchard et al., 2008). The estimated fire cycle for coastal Labrador is 500 years and was calculated over almost 50,000 km^2 (Foster, 1983). We expected our fire frequency estimate to be longer than the average fire return interval in Québec due to the maritime air masses and local coastal weather effects in Newfoundland, and shorter than the fire cycle of coastal Labrador since Newfoundland has different ecoregions and generally warmer weather. Qualitatively, our estimates do seem to fall between the two. However, we cannot make a direct comparison with either of these locations due to a difference in the metrics and study area size. In addition, the geographic spread of our sites biases our fire frequency results to a smaller value.

Other studies in the park and on the island have examined historical fire patterns, which found fire cycles ranging from 98 to 769 years (Arsenault et al., 2016; Power, 1996). Once again, we cannot directly compare our results due to the different metrics, methods, and data sources. Arsenault et al. (2016) and Power (1996) used written records, area burnt, and current stand age (or time since last fire). While there is value in these methods, relying on written records and current stand age alone biases the results to a fire history influenced by human observations. It should also be noted that Arsenault (2016) calculated the fire cycle for the entire island and not just the TNNP region. One observation we can make is that Power (1996) also detected an increase in fires from 1850-1950 CE. Our findings complement these studies by contributing to a more comprehensive and rigorous fire history extending back into the Holocene and deepening our understanding of pre-European settlement fires.

2.4.3 Past and contemporary forests

In our comparisons of the past forest composition to contemporary, we did not observe any significant park level changes. It was when observing the ecoregions separately that we were able to see shifts in species proportions. Due to lack of fire from human fire suppression, we expected to see that black spruce-dominated stands would shift successionally to balsam fir stands. Balsam fir seedlings are shade tolerant (Frank, 1990); they remain in the understory until they are released by a canopy opening (e.g., mortality, wind blowdown, insect disturbance). However, this shift from fire-adapted species to non-fire-adapted species was not evident. In contrast to our prediction, we observed an increase in black spruce proportions in the Central Newfoundland Forest accompanied by a decrease in balsam fir and deciduous species. This trend could be a result of higher historical fire activity in this ecoregion, but it could also be explained by other environmental or human-related reasons (e.g., site conditions favouring black spruce, preferential moose browsing of balsam fir and deciduous species, or extensive logging prior to park establishment; Charron and Hermanutz, 2017; Parks Canada, 2009).

We observed the expected trend of increased balsam fir proportions and decreased spruce proportions in the North Shore Forest. This trend may be driven by lower fire activity in the coastal areas, but once again, other environmental factors, such as favourable site conditions, may be the cause of balsam fir dominance.

Overall, we detected a decreasing trend in deciduous species in the park. These results may indicate a decrease in species abundance due to overabundant moose and hare preferential browsing and the long legacy of moose impacts on the regeneration of species, such as birch (McLaren et al., 2004). Unfortunately, due to the resolution of the radiocarbon dating analysis, we cannot say anything about the time of the highest moose impact (i.e., 1960-1990s). However, our analysis still catches the overall past to present-day effect. In addition, while we observed the presence of pine in the past forest composition, there is a complete lack of pine at our sites and limited proportions within the park currently. The lack of pine is not the result of fire-related causes but is due to heavy logging in the area before the formation of the National Park, white pine blister rust, and moose herbivory (Arsenault et al., 2016; Carroll, 1990; ParksCanada, 2009; Simpson, 2007).

2.4.4 Recommendations, implications, and future research

Our study has provided a spatially structured long-term fire history of TNNP, which gives us more information about the wildfire history than previously known. Our results can help inform the future of wildfire management within the park. When advising future wildfire management plans, we must consider several factors. Using data from Parks Canada (Table 1.1), we know that fire has been relatively absent in the landscape since park formation (i.e., 1957 CE), potentially resulting in regeneration failure and poor forest health (Simpson, 2007). Small fires have occurred in the park, but they usually occurred in high visitor use areas and were suppressed quickly. However, our data show that the park has experienced more fires in the past 200 years than ever before (i.e., 1750-1950 CE). This increase in fires was likely the result of anthropogenic ignition sources, pushing the park's fire patterns out of their natural range of variation. In this case, our data might not support or justify the use of prescribed burning. Our data also contest the previously held belief that the park's fire regime during the Holocene was only large, infrequent, intense, and severe fires (Simpson, 2007). Burning too frequently can result in negative consequences. Successive fire disturbances can cause reduced seed load and possibly encourage the increasing presence of *Kalmia* heaths (Siegwart Collier and Mallik, 2010). We must also consider that old-growth forests provide unique ecosystem services, such as increased understory diversity and provision of ecosystems for species at risk (Bergeron and Fenton, 2012; ParksCanada, 2019b). Burning these ecosystems, or reducing their proportion in the landscape too much, could cause more harm than good. From an ecological perspective, a more reasonable approach would be to let burn fires that naturally occur when it is safe and practicable to do.

While prescribed burning in TNNP may not be justified by our findings, it could be justified by other reasons, such as vegetation management or maintaining and improving ecological integrity. Given the anticipated increase in fire weather, season, and severity in Newfoundland, prescribed burns could be used to reduce fuel loads and help mitigate the risk of future catastrophic fires (Flannigan et al., 2013; Natural Resources Canada, 2020). We still cannot exactly say if, where, or how frequently park managers should do prescribed burns. Instead, we would like to emphasize that management plans should aim for ecological integrity and diversity-based goals rather than a specific fire regime target (Odion et al., 2014). There is no single appropriate condition (i.e., fire frequency, size, severity) to aim for, rather a range of conditions is important to maintain successional diversity (Driscoll et al., 2010; Odion et al., 2014). Management plans should also be adaptable to new information and other changes or disturbances, such as wind and insect disturbance (Arsenault et al., 2016; Foster et al., 1996). Finally, we must also consider the surrounding communities' opinions and the risk to personal safety and infrastructure.

Funding constraints limited the total number of samples submitted for radiocarbon dating. With more radiocarbon dated charcoal pieces, we could tell a more comprehensive story about the fire and forest composition history of TNNP. Combining our soil charcoal data with pollen and charcoal data from lake sediment cores in the park would give a more thorough understanding of the local and landscape patterns of fire and forest composition. A critical piece of the fire history that is missing, which would be an excellent future direction for this project, would be to look more into Indigenous use of fire in the area and on the island. There are confirmed archeological sites, once occupied by various Indigenous groups, within the park and around the island (Renouf, 2011; Tuck, 1980). Further studies could investigate the Indigenous use of fire and how Indigenous Peoples have managed the landscape for millennia. It is well understood on the west coast of Canada that Indigenous peoples used fire for cultural, domestic, and sustenance purposes, e.g., to encourage the growth of food sources (Walsh et al., 2015). It is not understood if similar fire practices were used in Newfoundland. A possible approach would be to examine microscopic charcoal deposition in sediment cores from peat bogs or small lakes and compare this data with archeological excavations.

2.4.5 Conclusions

Our study has provided a spatially structured long-term fire history of TNNP, which can help inform wildfire management practices within the park. We have shown that fire has been a natural disturbance in the TNNP region since the mid-Holocene, with fires occurring approximately every 150 years within the park boundary. Fire occurrence increased considerably in the last 100 years, coinciding with the peak of permanent European settlement. Overall, we found changing dominance of black spruce and balsam fir throughout our record and decreased deciduous species from past to present-day, potentially driven by moose and hare herbivory. Our findings increase our understanding of forest and fire dynamics in understudied, coastal boreal forests.

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Chapter 3: Summary and conclusions

3.1 Key findings and future directions

Fire is a natural disturbance and dominant control of ecological processes in the boreal forest, driving regeneration, plant community structure, and nutrient cycling (Johnson, 1992; Payette, 1992; Stocks et al., 2002). Reconstructing the historical fire patterns before significant European settlement is a useful management tool to help forest managers understand a landscape's historical range of variation in fire regime. Moreover, understanding the response of past fire regimes and ecosystems to environmental change can help predict how those same fire regimes and ecosystems may respond to current and future global climate change (Allen et al., 2002; Willis and Birks, 2006). Finally, long-term fire patterns can also be used to inform ecosystem management practices, e.g., determining whether prescribed burning is justified, fire preparedness, and predicting future wildfire activity.

In this thesis, I presented a novel approach to reconstructing the fire history of TNNP's coastal boreal forest on the island of Newfoundland (herein referred to as Newfoundland). I determined an average fire return interval for the park and the two ecoregions within its boundaries. I also reconstructed the past forest composition of the park and compared it to the current forest composition. To achieve these goals, I used a soil charcoal approach (also known as a terrestrial macrocharcoal approach): extracting, identifying, and radiocarbon dating charcoal fragments from soil samples (Payette et al., 2012). This method allowed me to construct a longer time-scale and more spatially precise fire history than previously known. My results show that fire has been a natural disturbance in the coastal boreal forest of TNNP since the early Holocene, and there are periods of minor differences in the fire histories of the two ecoregions in the park. I also found that forest composition varied between the ecoregions and from past to present-day. Here, I discuss these key findings from Chapter 2 and propose future directions for related research.

The deglaciation of Newfoundland began around the start of the Holocene, and fires were likely present not long after the ice retreated and vegetation arrived (Macpherson, 1982, 1995). The oldest fire I detected occurred around 7528 cal. years BP, with limited evidence of fires from 7528 to 1790 cal. years BP. It is not definitive that the lack of charcoal samples during this time is evidence of lack of fire; it is more likely to result from charcoal decay or re-burning (Frégeau et al., 2015; Payette et al., 2012). On average, fires occurred within the park boundaries at an interval of 150 years over the past 8000 years, based on the number of fires detected by our methods. Though, the fire frequency did not remain constant through time, with periods of more and less frequent fires. Since 1790 cal. years BP, fire has been irregularly present throughout TNNP. Over the past 2000 years, fires occurred in the Central Newfoundland Forest and North Shore Forest ecoregions at average intervals of 66 and 70 years, respectively. To be clear, this means that a fire occurred within each region of the park at those intervals and not that individual stands burned every 66-70 years. There was an increase in fire occurrence from 200-100 cal. years BP (1750-1850 CE), then a drastic increase in fire occurrence in the last 100 years (1850-1950 CE). The permanent settlement of Newfoundland by Europeans caused the increase in fire occurrence, with the two primary ignition sources being early fishermen and the railway.

I detected statistically significant local deviations between the historical fire patterns of the Central Newfoundland Forest and the North Shore Forest. However, both ecoregions had periods of positive and negative divergences from one another (i.e., one did not consistently have more or fewer fires than the other). In addition, most of the fire history plots were not significantly different from each other. Forest compositions also differed between ecoregions. Observing the past, burned forest composition, I found more spruce in the Central Newfoundland Forest than in the North Shore Forest and more deciduous species in the North Shore Forest than the Central Newfoundland Forest. From past to present-day, the Central Newfoundland Forest experienced an increase in black spruce proportions but decreased balsam fir and deciduous species proportions. In the North Shore Forest, balsam fir increased, and black spruce decreased from past to present-day. The ecoregion's compositional differences are more likely due to differing site conditions and historical colonization since there was little difference in the historical fire patterns.

Understanding the fire and forest composition history of TNNP is a complex issue, so there are many avenues for future research related to this study. Future studies could start with identifying and radiocarbon dating more charcoal samples from our existing sites. Additional charcoal samples could help tell a more comprehensive story about the park's natural history and improve spatial and temporal comparisons. It would also be interesting to compare our results with data from a lake sediment core study done within the park. This comparison could give us a more thorough understanding of the local versus landscape-scale fire patterns. It could also provide more evidence of early Holocene fires, filling in the gap before 2000 cal. years BP. Finally, looking into the

Indigenous use of fire in the area would fill a critical knowledge gap in the fire history. There are confirmed archeological sites once occupied by various Indigenous groups within the park and around the island (Renouf, 2011; Tuck, 1980). There have also been studies on the island showing that the early Indigenous Peoples in Newfoundland used firewood as fuel (Miszaniec and Bell, 2019; Renouf, 2011). Further studies could examine the Indigenous use of fire as an ecological management tool and how humans have managed Newfoundland's landscape over millennia. On the west coast of Canada, Indigenous Peoples used fire for cultural, domestic, and sustenance purposes, e.g., to encourage the growth of edible plants (Walsh et al., 2015). It is not understood if similar fire practices were used in Newfoundland.

3.2 Management implications

How data are interpreted can have profound environmental and societal ramifications. While it is a valuable piece of information, this study should not be used in isolation when decision making. In Chapter 2, I introduced some management implications of this research but only in the context of our data. Here, I expand this discussion to include recommendations or considerations extrapolated beyond this research but informed by literature.

In Chapter 2, my data showed that fires were more common over the past 200 years, which may not support prescribed burning. Instead, I recommended following a "let it burn" policy for naturally ignited fires. Nevertheless, I suggested that prescribed burning could be justified for vegetation management, such as reducing fire risk or enhancing plant diversity, instead of aiming for a specific burn goal.

A part of the fire history that our data did not capture is from 1950 to present-day. While it is a time when humans strongly influenced fire patterns within the park, it is still part of the fire history and should be considered. Provincial and Parks Canada data indicate that very few forest fires occurred within the park boundaries since its formation in 1957. If fires did occur, they were small, low severity, and suppressed quickly (Simpson, 2007). This lack of fire may have resulted in regeneration failure and poor forest health (Simpson, 2007), but it has not been empirically studied. Regardless, park managers have previously chosen to use prescribed burning as a management technique to help improve forest health. They are in a state of catching up, burning approximately 1% of the forest per year (Simpson, 2007). This practice is rooted in Van Wagner's (1978) theory that fire-dependent forests should exhibit a negative exponential age-class distribution. However, more recent studies have shown that, on average boreal forest stands maintained a minimum of 30% old-growth forest (i.e., > 100 years) throughout the Holocene (Bergeron and Fenton, 2012; Cyr et al., 2009). The implication is burning when it might not be necessary or beneficial, as both young and old-growth forests have value (McCarthy, 2001; McCarthy and Weetman, 2006). Old-growth's unique ecosystem services, such as increased understory diversity and habitat for species at risk (e.g., lichen and Newfoundland pine marten), could be lost if too much forest is burned (Bergeron and Fenton, 2012).

All national parks are mandated to maintain or improve ecological integrity, and prescribed burning may help towards this goal. In addition to our data, I recommend considering several factors informed by literature if prescribed burning will continue to be employed as a management technique. I have already recommended setting goals focused on ecological or biodiversity-based measures and not based solely on a burn target (Odion et al., 2014). Once those goals are established, it may become more apparent if prescribed burning is an appropriate tactic. For example, if the goal is to improve forest regeneration in a coastal, balsam fir-dominated stand, fire will likely not be the best course of action. This implication may involve a revaluation of the current wildfire management zones as seen in Simpson (2007) or the consideration of different management techniques (e.g., moose exclosures, supplemental planting; Charron and Hermanutz, 2016, 2017; Gosse et al., 2011). Currently, the wildfire management zones only allow prescribed burns or "let it burn" fires to occur in remote coastal areas (Simpson, 2007). While our data did not reveal major differences in fire history between the coastal and inland regions, it may be beneficial to target inland areas or forest stands dominated by black spruce. Black spruce will benefit from prescribed fire because it is a fire-adapted species and will regenerate post-fire (Viereck and Johnston, 1990). In contrast, coastal areas have higher proportions of balsam fir and deciduous species, which are not adapted to fire.

Another important consideration is to know if regeneration could occur post-fire (e.g., is sufficient seed available?). If fire disturbance occurs too frequently, before the aerial seed bank can recover or in a senescing stand with little seed, it can result in regeneration failure (Buma et al., 2013; Lamont et al., 1991; Viglas et al., 2013). Emphasis should also be put on burn severity and depth to ensure black spruce seed release, exposure of mineral soil for germination, and reduce the chance of a *Kalmia* heath post-fire, especially in black spruce dominated stands (Jayen et al., 2006; Siegwart Collier and Mallik, 2010; Viereck and Johnston, 1990). I suggest undertaking studies to investigate these factors before doing a prescribed burn.

Reinstating natural disturbance regimes is a complex issue, especially in Newfoundland, where fire, insect, and wind disturbance are present (Arsenault et al., 2016). Management plans must acknowledge and predict future change, monitor management efforts, and adjust as needed (Arsenault et al., 2016; Daniel et al., 2017; Foster et al., 1996). This approach is called adaptive management, an iterative and robust decision-making process involving recurring project design, implementation, monitoring, and adjustment. The TNNP 2007-2017 Wildfire Management Plan states that it already follows this approach, so here I reiterate its importance (Simpson, 2007). There are conflicting opinions in the literature about historical fire regimes in North American forests and the best management techniques. It is imperative that management practices are rooted in evidence, local if possible, and not rely heavily on assumptions, beliefs, or values. Managers should not perform prescribed burns only for the sake of doing burns; they need to set attainable goals. Millions of dollars could be invested in prescribed burning projects without any guarantee of successful outcomes. There is a risk that regeneration will not occur as planned, and habitat loss could occur (Arsenault et al., 2016).

In addition, emulating natural disturbance is challenging, as any emulation is inherently not natural. Many studies use historical reference conditions to determine what forest structure is considered “natural” (i.e., without significant human influence) and model forest management after them (Arsenault et al., 2016; Foster et al., 1996). However, it is difficult to define what “natural” actually is, particularly when many ecosystems operate in a non-equilibrium state, change naturally through time, and have been altered by anthropogenic activities, such as logging (Arsenault et al., 2016; Botkin, 1990; Simpson, 2007; Sprugel, 1991). Thus, it is essential to anchor knowledge of natural disturbance history with robust regional and local information.

3.3 Challenges and limitations

The main challenge I encountered in our study stems from the uncertainties associated with radiocarbon dating and calibration of the ^{14}C dates. The calibration process results in a non-normal curve over a range of calendar years with an associated probability that the true sample age lies within that date range. To perform my analysis, I grouped charcoal samples into fire events if samples were close in location and had overlapping age ranges. With the high level of uncertainty around each sample, I found it difficult to group charcoal pieces into fire events. Even beyond 400 cal. years BP, grouping charcoal pieces was difficult since the size of historical fires is unknown. For example, there were fire events dated to 498 cal. years BP, 518 cal. years BP, and 526 cal. years BP with overlapping date ranges, but they are separated by 10 km or more. It is difficult to say if three smaller fires occurred approximately every 15 years or one large fire. Once the charcoal samples were grouped into fire events, the fire event date was the grouped samples' mean age. Unfortunately, this simplification loses the uncertainty around the date ranges and information from the probability curves. Cumulative probability curves are a good way to maintain each sample's uncertainty. Yet, it is not possible to determine fire events from the cumulative probability plots as far as I know. It is a difficult statistical problem.

Another limitation with fire history reconstruction is that the ignition source is usually unknown (i.e., lightning or human ignited). This issue becomes especially challenging around 500-300 cal. years BP. People could have been present in the area during this time, but it is not clear the extent to which they used the land or ignited (accidental or intentional) fires. This limitation is an issue when differentiating the natural, unmanaged fire regime from human ignited fires. Similarly, radiocarbon dating anything from 400-0 cal. years BP can be problematic. Not only is the source of the fire unknown, but the uncertainty around the radiocarbon dates increases closer to present-day, given anthropogenic effects on the levels of ^{14}C in the atmosphere.

There are also challenges related to the interpretation of fire history reconstructions. These limitations serve as a warning that caution needs to be used when using fire frequency metrics for management purposes. Soil charcoal can determine fire frequency, but there is limited ability to tell the fire's effect on the environment (e.g., severity or size). Fires might have occurred in the park every 150 years on average, but some of those fires may have been small and of low severity. Large fires having a lasting effect on the forest (e.g., tree regeneration) may only happen every 400 or 500 years. Furthermore, fire frequency does not remain constant through time. There are periods of more frequent and less frequent fires, so characterizing the fire regime with one frequency metric misses valuable information.

3.4 Conclusions

Fire has been a natural disturbance present throughout TNNP since the early Holocene. Using a soil charcoal approach, I found charcoal samples as old as 7528 cal. years BP, with fires occurring approximately every 150 years within the park boundary. Fire occurrence increased considerably in the last 100 years, coinciding with the peak of permanent European settlement. The Central Newfoundland Forest and North Shore Forest's fire histories had areas of difference but were mostly indistinguishable. I also found that the proportion of black spruce increased in the Central Newfoundland Forest, while the proportion of balsam fir increased in the North Shore Forest from the past to present-day. While not statistically significant, I observed decreased deciduous species from past to present-day, potentially driven by moose herbivory. Overall, I was able to reconstruct a spatially structured, long-term fire and forest composition history for the park. Our findings increase our understanding of forest and fire dynamics in an understudied, coastal boreal forest.

3.5 References

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Appendix I: Site characteristics

Table AI.1 Characteristics for each site.

Site	Coordinates	Dominant tree species	Aspect	Slope (%)	SOH (cm)	Soil moisture (m^3/m^3)	Soil pH	Soil texture
CS01	N 48° 37.350 W 53° 57.996	bS	S	2	10.1	0.323	5.36	Gravelly muddy sand
CS03	N 48° 35.568 W 53° 57.468	bS	S	6	10.5	0.845	6.13	Muddy sandy gravel
CS18	N 48° 33.540 W 53° 58.392	bS	NE	23	7.0	0.262	5.35	Muddy sandy gravel
CS83	N 48° 36.918 W 53° 58.608	bS	E	9	18.5	0.475	5.85	Muddy sandy gravel
CS84	N 48° 33.612 W 53° 58.728	bS	SSE	3	3.0	0.251	5.45	Gravelly sand
CS90	N 48° 33.594 W 53° 52.794	bF	NW	4	11.5	0.266	4.47	Muddy sandy gravel
bS05	N 48° 27.895 W 54° 0.494	bS	SSE	3	9.0	0.422	5.17	Gravelly muddy sand
bS15	N 48° 25.675 W 54° 7.726	bS	SE	11	18.5	0.457	5.47	Gravelly muddy sand
bS22	N 48° 30.938 W 54° 1.651	bS	NE	1	17.5	0.457	5.50	Gravelly muddy sand
bS25	N 48° 28.910 W 53° 59.848	bS	S	14	8.3	0.493	5.88	Gravelly muddy sand
bF07	N 48° 38.889 W 53° 52.982	bF	NNE	13	2.0	0.701	6.36	Gravelly muddy sand

bF08	N 48° 33.602 W 53° 46.431	bF	NNE	12	11.5	0.298	5.39	Muddy sandy gravel
bF14	N 48° 31.391 W 53° 46.444	bF	SE	4	5.0	0.242	5.47	Gravel
bF20	N 48° 27.825 W 54° 8.425	bF	NE	12	5.0	N.A.	6.86	Muddy sandy gravel
bF24	N 48° 36.451 W 53° 49.018	bF	ESE	13	17.5	0.484	5.1	Muddy sandy gravel
bF26	N 48° 35.702 W 53° 50.807	bF	ESE	3	19.0	0.577	6.17	Muddy sandy gravel
bF27	N 48° 25.207 W 54° 3.345	bS	SE	6	5.5	0.558	6.90	Gravelly muddy sand

Appendix II: Charcoal data

Table AII.1 Lab ID (Identifying label provided by the radiocarbon dating lab), site (see Appendix I), sample (N: north, E: east, S: south, W: west, C: center), ecoregion (CNF: Central Newfoundland Forest, NSF: North Shore Forest), identification (botanical identification of charcoal pieces to genus or species), ^{14}C age BP ± 2σ (radiocarbon determination), interval (calibrated date range of the interval with the highest probability), mean age (mean charcoal age from the interval with the highest probability), median age (median charcoal age derived from all the intervals for each charcoal piece), fire (number of fire events), fire year (calibrate age corresponding to each fire event, rounded to the nearest 10). These fire event groupings were determined using given the data and ecological knowledge of the area. These fire events were grouped using the protocol outlined in section 2.2.4. Fire events indicated with a '*' are over the 6 km threshold, but no further apart than 12 km. I took into account that more recent fires were likely smaller, and older fires were more likely lightening ignited and larger.

Lab ID	Site	Sample	Ecoregion	Identification	^{14}C age BP ± 2σ	Interval	Mean age (cal. yr BP)	Median age (cal. yr BP)	Fire	Fire year (cal. yr BP)
UOC8196	CS84	W	CNF	Picea sp.	>Modern	1954 – 1956 AD	-5	0	1	0
UOC8224	bS25	W	CNF	Picea sp.	>Modern	1954 – 1956 AD	-5	0	2	0
UOC8980	bS05	S	CNF	Abies sp.	193 ± 30	< 6	3	3	3	0
UOC6881	CS18	E	CNF	Picea sp.	3 ± 22	65 – 37	51	51	4	70
UOC8197	CS84	N	CNF	Picea sp.	>Modern	72 – 33	52	54	4	
UOC6889	CS84	C	CNF	Abies sp.	57 ± 20	74 – 32	53	56	4	
UOC8984	CS84	C	CNF	Picea sp.	85 ± 30	142 – 23	82	107	4	
UOC7821	CS18	W	CNF	Betula sp.	90 ± 21	139 – 31	85	107	4	
UOC6880	CS18	S	CNF	Picea sp.	110 ± 20	144 – 54	99	111	4	
UOC8223	bS25	N	CNF	Picea sp.	>Modern	74 – 33	54	56	5	70
UOC8222	bS25	E	CNF	Picea sp.	123 ± 35	151 – 9	80	125	5	
UOC8217	bF14	N	NSF	Betula sp.	1 ± 35	83 – 31	57	57	6	70
UOC6882	CS28	W	NSF	Abies sp.	76 ± 20	84 – 31	58	88	6	
UOC8977	bF14	C	NSF	Picea sp.	120 ± 30	150 – 11	80	119	6	
UOC8226	bF08	C	NSF	Abies sp.	>Modern	74 – 32	53	57	7	70
UOC8215	bF08	E	NSF	Betula sp.	28 ± 35	139 – 31	85	69	7	

UOC8206	bF24	C	NSF	Picea sp.	8 ± 35	83 – 31	57	58	8	70
UOC8975	bF24	N	NSF	Betula sp.	116 ± 30	150 – 11	80	117	8	
UOC8976	bF24	N	NSF	Betula sp.	88 ± 30	143 – 23	83	107	8	
UOC8198	bF27	C	CNF	Abies sp.	6 ± 35	83 – 31	57	58	9	80
UOC8227	bS15	S	CNF	Picea sp.	36 ± 35	139 – 31	85	76	9	
UOC8956	bF20	C	CNF	Picea sp.	50 ± 30	139 – 31	85	75	9	
UOC8957	bF20	N	CNF	Picea sp.	55 ± 30	139 – 31	85	84	9	
UOC8959	bF20	W	CNF	Picea sp.	55 ± 30	139 – 31	85	84	9	
UOC8221	bF07	W	NSF	Pinus sp.	58 ± 35	140 – 25	82	98	10	80
UOC8208	bF07	S	NSF	Betula sp.	49 ± 35	140 – 29	84	91	10	
UOC8209	bF07	N	NSF	Abies sp.	46 ± 35	140 – 30	85	88	10	
UOC6890	CS87	S	NSF	Betula sp.	119 ± 20	146 – 56	101	112	11	100
UOC6894	CS90	C	NSF	Picea sp.	132 ± 20	150 – 59	104	124	11	
UOC7820	CS90	E	NSF	Picea sp.	133 ± 21	151 – 59	105	127	11	
UOC8966	bS05	W	CNF	Picea sp.	211 ± 30	215 – 144	180	179	12	180
UOC9453	bF24	E	NSF	Unknown	199 ± 23	215 – 145	180	174	13	180
UOC8969	bF14	W	NSF	Abies sp.	224 ± 30	215 – 145	180	187	14	180
UOC8216	bF14	C	NSF	Abies sp.	189 ± 35	225 – 136	180	178	14	
UOC8971	CS28	W	NSF	Betula sp.	171 ± 30	226 – 135	180	179	14	
UOC8964	CS28	S	NSF	Betula sp.	196 ± 30	222 – 140	181	178	14	
UOC6892	CS87	W	NSF	Picea sp.	165 ± 20	224 – 166	195	186	15	200
UOC4950	CS35	N	NSF	Unknown	159 ± 23	229 – 165	197	181	15	
UOC6887	CS83	E	CNF	Picea sp.	159 ± 20	225 – 166	196	184	16	200
UOC8950	bS15	W	CNF	Picea sp.	157 ± 30	232 – 166	199	174	17	200
UOC6883	CS35	N	NSF	Abies sp.	236 ± 20	309 – 281	295	288	18	300
UOC8974	CS87	S	NSF	Picea sp.	245 ± 30	320 – 270	295	292	18	
UOC8962	CS03	W	CNF	Acer spp.	250 ± 30	325 – 271	298	295	19	300
UOC8961	CS01	S	CNF	Picea sp.	259 ± 30	331 – 280	306	303	19	
UOC8963	CS03	C	CNF	Picea sp.	354 ± 30	411 – 315	363	401	20	360

UOC8970	bF14	W	NSF	Picea sp.	314 ± 30	466 – 302	384	387	21	390
UOC8972	CS28	W	NSF	Betula sp.	292 ± 30	458 – 348	403	385	21	
UOC7823	CS18	N	CNF	Abies sp.	330 ± 21	463 – 309	386	384	22	390
UOC6878	CS03	S	CNF	Abies sp.	290 ± 20	430 – 358	394	393	22	
UOC8220	bS22	C	CNF	Picea sp.	448 ± 35	540 – 456	498	506	23	500
UOC8192	CS01	E	CNF	Pinus sp.	425 ± 35	532 – 430	481	491	24	520
UOC8193	CS01	N	CNF	Picea sp.	472 ± 35	547 – 480	514	516	24	
UOC6888	CS83	C	CNF	Picea sp.	507 ± 21	545 – 510	528	527	24	
UOC6885	CS83	N	CNF	Picea sp.	524 ± 20	554 – 513	534	534	24	
UOC8194	CS01	C	CNF	Abies sp.	529 ± 35	562 – 507	534	541	24	
UOC8228	bS15	N	CNF	Picea sp.	462 ± 35	544 – 469	506	512	25	530
UOC8958	bF20	S	CNF	Picea sp.	527 ± 30	559 – 508	534	537	25	
UOC8199	bF27	S	CNF	Abies sp.	549 ± 35	565 – 514	540	557	25	
UOC8205	bF24	N	NSF	Picea sp.	538 ± 35	563 – 510	536	547	26	540
UOC6893	CS90	W	NSF	Picea sp.	651 ± 20	598 – 560	579	591	27	580
UOC8981	bF27	C	CNF	Betula sp.	648 ± 30	609 – 555	582	599	28	590*
UOC8952	bS05	S	CNF	Picea sp.	638 ± 30	610 – 554	582	598	28	
UOC8955	bS05	N	CNF	Picea sp.	580 ± 30	651 – 581	616	603	28	
UOC6886	CS83	S	CNF	Picea sp.	572 ± 22	640 – 590	615	604	29	620
UOC8954	bS15	E	CNF	Picea sp.	673 ± 30	678 – 632	655	645	30	660
UOC6877	CS03	N	CNF	Picea sp.	715 ± 20	688 – 656	672	671	31	670
UOC6879	CS03	E	CNF	Picea sp.	724 ± 20	689 – 659	674	673	31	
UOC6891	CS87	E	NSF	Betula sp.	722 ± 20	688 – 658	673	673	32	670
UOC9451	bF27	S	CNF	Unknown	743 ± 23	707 – 661	684	680	33	690*
UOC8949	bS25	S	CNF	Picea sp.	734 ± 30	727 – 656	692	678	33	
UOC7822	CS90	S	NSF	Picea sp.	768 ± 23	729 – 671	700	691	34	720*
UOC8973	CS87	N	NSF	Picea sp.	784 ± 30	745 – 670	708	705	34	
UOC8191	CS90	N	NSF	Picea sp.	794 ± 35	769 – 672	720	712	34	
UOC8213	bF08	N	NSF	Abies sp.	805 ± 35	782 – 677	730	717	34	

UOC8212	bF08	S	NSF	Abies sp.	859 ± 35	804 – 690	747	766	34	
UOC8204	bF24	W	NSF	Picea sp.	814 ± 35	786 – 680	733	724	35	730
UOC8207	bF07	E	NSF	Picea sp.	873 ± 35	833 – 703	768	781	36	810
UOC8211	bF07	E	NSF	Picea sp.	928 ± 35	927 – 766	846	850	36	
UOC8214	bF08	W	NSF	Abies sp.	950 ± 35	930 – 789	860	854	37	860*
UOC8965	CS35	E	NSF	Picea sp.	956 ± 30	929 – 796	862	855	37	
UOC8195	CS84	E	CNF	Abies sp.	1011 ± 35	981 – 898	940	931	38	950*
UOC7819	CS83	W	CNF	Pinus sp.	1030 ± 22	971 – 922	946	945	38	
UOC6876	CS01	W	CNF	Abies sp.	1041 ± 20	976 – 926	951	948	38	
UOC6884	CS35	W	NSF	Picea sp.	1022 ± 20	965 – 920	942	941	39	960
UOC7818	CS35	C	NSF	Picea sp.	1070 ± 23	1006 – 931	968	972	39	
UOC8200	bF27	W	CNF	Betula sp.	1067 ± 35	1012 – 927	970	973	40	970
UOC8202	bF26	C	NSF	Betula sp.	1024 ± 35	998 – 903	950	942	41	1000
UOC8201	bF26	N	NSF	Abies sp.	1107 ± 35	1083 – 932	1008	1013	41	
UOC8203	bF26	W	NSF	Abies sp.	1116 ± 35	1089 – 937	1013	1021	41	
UOC8983	bF26	C	NSF	Abies sp.	1116 ± 30	1082 – 952	1017	1018	41	
UOC8953	bF26	E	NSF	Abies sp.	1116 ± 30	1084 – 954	1019	1018	41	
UOC9452	bF26	C	NSF	Unknown	1106 ± 23	1060 – 962	1011	1009	41	
UOC8968	bF14	S	NSF	Abies sp.	1148 ± 30	1175 – 977	1076	1057	42	1050
UOC9449	CS28	S	NSF	Unknown	1125 ± 23	1074 – 963	1018	1020	42	
UOC8967	bS05	C	CNF	Picea sp.	1180 ± 30	1182 – 1050	1116	1112	43	1120
UOC8218	bS22	N	CNF	Picea sp.	1343 ± 35	1314 – 1227	1270	1279	44	1250
UOC9455	bS22	W	CNF	Unknown	1274 ± 23	1275 – 1180	1227	1230	44	
UOC8948	CS18	C	CNF	Picea sp.	1448 ± 30	1388 – 1299	1344	1338	45	1350
UOC9448	CS18	C	CNF	Unknown	1469 ± 23	1395 – 1308	1352	1353	45	
UOC8978	CS35	W	NSF	Abies sp.	1571 ± 30	1535 – 1394	1464	1467	46	1460
UOC8982	bS22	C	CNF	Betula sp.	1706 ± 30	1699 – 1550	1624	1609	47	1640*
UOC8225	bS22	S	CNF	Picea sp.	1710 ± 35	1704 – 1549	1626	1615	47	
UOC8219	bS22	E	CNF	Picea sp.	1749 ± 35	1738 – 1560	1649	1658	47	

UOC8951	bS15	C	CNF	Picea sp.	1745 ± 30	1720 – 1565	1642	1655	47	
UOC8960	bF20	E	CNF	Picea sp.	1841 ± 30	1865 – 1709	1787	1776	48	1790
UOC8210	bF07	C	NSF	Betula sp.	2811 ± 35	3005 – 2838	2922	2913	49	2920
UOC9454	CS28	C	NSF	Unknown	4328 ± 27	4965 – 4844	4904	4883	50	4900
UOC8979	bS25	S	CNF	Abies sp.	6656 ± 36	7589 – 7466	7528	7533	51	7530