Millennial fire history reconstruction in the boreal forest of south-central Canada using lake-sediment charcoal, tree-ring and archival records

By

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Abstract

The Canadian boreal forest has been developing since the end of the last glaciation approximately 10,000 years ago. During this time, fire has modified the development of the forest by altering species distribution, stand structure and forest regeneration. With future climate changes, the fire frequency and annual area burned (AAB) are expected to increase with increasing temperatures. It remains unclear what effect this increase in fire frequency will have on the forest. Current projections of future fire are often based on relatively short environmental records and longer records are needed to capture variability in fire occurrence over millennia. In this study, a multi-millennial fire history was reconstructed for eight lakes from the Lake of the Woods Ecoregion (LWE) within the boreal forest of central North America using a combination of archival, tree-ring and lake sediment charcoal records.

The archival record provided fire dates and area burned information for the period 1920 to 2010. A tree-ring fire history reconstruction was developed around eight lakes for the period 1690-2010 from stand initiation dates and fire scars. The fire history reconstruction was extended through lake sediment charcoal records obtained from overlapping sediment cores collected from eight lakes. For each lake, the sediment fire history reconstruction was obtained from macroscopic charcoal particles with an area >150 micrometers. Calculation of the Charcoal Accumulation Rate (CHAR) and subsequent peak analysis of the CHAR record allowed for the examination of changes in fire regime dating back to 2500 BP (500 BCE).

The archival and tree-ring records revealed recent large fires (>200 ha) in 1948, 1980 and 1989. An additional 17 fires were identified by the fire-scar record. Fire events in 1805, 1840, 1863, and the 1890's were identified in numerous locations around multiple lakes suggesting that they were of large extents. In accordance with the tree-ring record, the CHAR peak record generally identified the major fires, with identification becoming less accurate for smaller fires and those in close succession. The CHAR record also tended to lag behind fires identified from tree-ring records by several decades. Within the LWE, the long-term charcoal record revealed that CHAR was higher for each lake in the earlier portion of the record followed by a progressive decrease towards the more recent record. Multi-millennial fluctuations in CHAR suggested that modern temperature increases could lead to higher fire frequency than that observed over the last two millennia.

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1.0 General Introduction

1.1 Boreal forest dynamics

The boreal forest is a globally important biome that covers approximately 11 percent of the Earth's land surface (Bonan and Shugart 1989; Bourgeau-Chavez *et al*. 2000). The distribution of the boreal forest is predominantly in Eurasia and North America, containing approximately 65 and 35 percent of the forest, respectively (Chen and Popadiouk 2002; Brassard and Chen 2006; de Groot *et al.* 2013). Covering approximately 500 million hectares, the boreal forest of North America is an important component of global biogeochemical and atmospheric cycles (Bonan and Shugart 1989; Brassard and Chen 2006). Moreover, the heterogeneous stand structure and age distribution within the boreal forest is an important component for wildlife habitat and for maintaining biodiversity (Rowe and Scotter 1973; Van Wagner 1978; Brassard and Chen 2006).

The current distribution of boreal forest tree species is the result of a series of changes to the physical system that began with the onset of the Holocene, corresponding to the end of the most recent glaciation approximately 10,000 years ago (Harrington 1987; Stocks and Ward 2011). Over time, the dominant tree species in the boreal forest have come to include jack pine (*Pinus banksiana* Lamb.), black spruce (*Picea mariana* (Mill) B.S.P.), white spruce (*Picea glauca* (Moench) Voss), northern white-cedar (*Thuja occidentalis* L.), trembling aspen (*Populus tremuloides* Michx.), paper birch (*Betula papyrifera* Marsh.), balsam fir (*Abies balsamea* (L.) Mill), eastern larch (*Larix laricina* (Du Roi) K.Koch), and balsam poplar (*Populus balsamifera* Michx.). Throughout the

Holocene, fire and climate have been important factors contributing to the distribution of species and to the structure of the forest. For example, fires between 1959 and 1997 burned an average of two million hectares of North American boreal forest every year (Stocks *et al*. 2003). Brassard *et al.* (2008) indicated that this occurrence of fire was important for the stand structural diversity and for tree species distribution. In turn, Bessie and Johnson (1995) revealed that stand structural diversity and composition were important contributors to fire ignition and spread. However, the limitations to burning imposed by vegetation structure and composition can be overcome by large-scale climate conditions (Bessie and Johnson 1995; Flannigan *et al*. 2009).

In North America, climate has an influence on the distribution of the boreal forest through control of temperature and moisture conditions. Temperature limitations are largely responsible for the northern limit of the boreal forest as well as the latitudinal species gradient (Bonan and Shugart 1989). For example, Asselin and Payette (2006) indicated that black spruce establishment and growth in the forest-tundra was limited by climatic conditions and that increased temperatures associated with climate change were expected to improve growing conditions. In contrast, annual moisture conditions limit the southern distribution of the boreal forest (Larsen 1980; Bonan and Shugart 1989; Brassard and Chen 2006). For example, Hogg (1994) reported that the southern boundary between the boreal forest and prairies was maintained by low precipitation and that the associated high fire frequency limited the establishment of tree species. Similarly, in the eastern boreal forest, Gauthier *et al.* (2000) indicated that increased precipitation and corresponding decrease in fire frequency at the southern limit of the boreal forest contributed to a forest transition to hardwood species.

In North America a west to east moisture gradient is also observed on the leeward (downwind) side of the Rocky Mountains. The gradient is established through moisture discharge onto the Rocky Mountains (orographic precipitation) as prevailing winds push moisture bearing systems eastward, which leads to decreased moisture availability for the western and central boreal forest (Bonan and Shugart 1989). This moisture gradient also contributes to a west to east species gradient observed within the boreal forest (Larsen 1980; Bonan and Shugart 1989; Brassard and Chen 2006). In addition, atmospheric pressure systems can further affect moisture conditions through the establishment of pressure ridging and troughing that can alter the path of moisture bearing weather systems (Larsen 1980; Skinner *et al*. 1999; Flannigan and Wotton 2001; Skinner *et al*. 2002; Fauria and Johnson 2006; Whitlock *et al*. 2010). Although the boundaries and species gradient of the boreal forest are largely determined by climate, the characteristic heterogeneous stand structure and distribution of age classes are the result of periodic disturbance events, such as fire (Rowe and Scotter 1973; Van Wagner 1978; Bonan and Shugart 1989; Bergeron and Dubuc 1989; Larsen 1980; Engelmark *et al*. 1993; Linder *et al*. 1997; Weber and Stocks 1998; Greene *et al*. 1999; Bergeron 2000; De Grandpré *et al*. 2000; Chen and Popadiouk 2002; Gauthier *et al*. 2009).

1.2 Disturbances in the North American boreal forest

Within the boreal forest, natural disturbances are important for initiating regeneration as well as for maintaining the heterogeneous distribution of species and stand structure throughout North America (Rowe and Scotter 1973; Van Wagner 1978; Larsen 1980; Bonan and Shugart 1989; Brassard and Chen 2006). The predominant sources of natural disturbance in the boreal forest are severe weather, insect outbreaks and fire events (Bonan and Shugart 1989; Engelmark *et al*. 1993; De Grandpré *et al*. 2000; Brassard and Chen 2006; Vaillancourt *et al*. 2009). Although severe weather events and insect outbreaks can cause damage to a large area of forest, they also leave the majority of the biomass on the landscape and its accumulation can lead to increased risk of fire (Stocks 1987; Vaillancourt *et al*. 2009). Among these disturbances, fire has the potential to affect the largest changes and has been an important disturbance shaping the boreal forest since the end of the last glaciation (Bonan and Shugart 1989; Larsen 1980; Engelmark *et al*. 1993; Stocks *et al*. 2003; Whitlock *et al*. 2010; Stocks and Ward 2011).

As a physical process, fire is the result of a chemical reaction leading to combustion of organic material (Johnson 1992; Michaletz and Johnson 2007). Combustion is a two-fold process whereby endothermic reactions first break down complex molecules which are then further broken down by exothermic oxidation of endothermic products (Johnson 1992; Michaletz and Johnson 2007). The endothermic reaction begins with the addition of heat that breaks complex molecules apart and dries fuels. The smaller molecules facilitate the onset of the exothermic oxidation reaction which leads to the flaming phase of combustion followed by a smoldering phase associated with the decreasing rate of oxidation (Michaletz and Johnson 2007). Although the process is the same for each fire event, the variability in extent and severity results in a heterogeneous fire imprint across the landscape.

Fire occurrence in the boreal forest is described through the fire regime concept that encompasses the type of fire (ground, surface, crown) and its spatial (size, severity, intensity) and temporal (frequency, seasonality) characteristics (Bonan and Shugart 1989; Weber and Flannigan 1997; Stocks *et al*. 2003; Vaillancourt *et al*. 2009; Bowman *et al.* 2013). On the long-term, this spatiotemporal variability is an important characteristic contributing to the heterogeneous age and stand structure of the boreal forest. For example, Bergeron and Dubuc (1989) reported that even-aged stands of early succession species (pine, aspen) were maintained by stand replacing fires every 200 years or less on average. In contrast, persistence of late successional species (white spruce, balsam fir, northern white-cedar) and mixed-age stands resulted from infrequent fire events every 300 years or more on average. Similarly, Johnson *et al*. (1998) reported that the mosaic of even-aged patches in the western boreal forest was maintained by fire events that returned every 200 years on average, with virtually no forest going unburned for longer than 400 years.

In the boreal forest, fire events and local landscape conditions contribute to stand heterogeneity on a small scale (Cyr *et al*. 2007). For example, upon ignition of fire, the size and direction of burn is influenced by local landscape characteristics such as slope and fire barriers (Heinselman 1973; Rowe and Scotter 1973; Bonan and Shugart 1989; Turner and Romme 1994; Larsen 1997; Cyr *et al*. 2007). Homogenization of stand and age structure is attributable to the widespread occurrence of large fires with high annual area burned (AAB) related to broad-scale climatic patterns (Flannigan and Wotton 2001). Johnson and Wowchuck (1993) reported that in the western boreal forest of North America hundreds of thousands of hectares could be affected by fire in years with persistent atmospheric blocking ridges. Further, Kasischke and Turetsky (2006) indicated that fires in the western boreal forest were larger and occurred more frequently compared to the eastern boreal forest. Asselin *et al*. (2001) also indicated that in the eastern boreal forest large fires had a homogenizing effect on the landscape, although regeneration and final stand structure were strongly related to seed source availability.

The heterogeneity of the boreal forest is also influenced by the temporal distribution of fire and fire conditions (Weber and Stocks 1998; Stocks *et al*. 2003; Shabbar and Skinner 2004: Flannigan *et al*. 2005). In North America, the conditions necessary for the ignition and spread of fire generally occur between April and September (Weber and Stocks 1998; Stocks *et al*. 2003: Kasischke and Turetsky 2006; Fauria and Johnson 2008). However, on an annual basis temporal heterogeneity is also partially related to the cumulative effect of climatic influences that leads to more frequent fire in the west and central boreal forest and less frequent fire in the east (Fauria and Johnson 2008). Beverly and Martell (2005) reported that prolonged dry periods associated with atmospheric conditions contributed to fire severity in the central boreal forest with fire occurring once every decade in the western portion of the study area and once every century in the eastern portion. Following a fire event, the length of time before another fire can burn (fire interval) is dependent on the rate of fuel buildup combined with weather conditions that promote ignition (Bessie and Johnson 1995; Héon *et al*. 2014).

1.3 Methodological background

1.3.1 Archival records of fire in the boreal forest

Archival records can provide information on past fires through a direct record of events or conditions (written and instrumental accounts of climate and fire data) or through interpretation of forest structure (aerial photographs/remote sensing). Fire history reconstructions' utilization of archival records, such as continuous temperature, precipitation and fire event data, can help to establish patterns of past fire occurrence (Grissino-Mayer and Swetnam 2000; Whitlock *et al*. 2010). Written records provide the longest account of weather and fire data but the resolution is dependent on whether an area was settled, events were recorded and that records survived to the present day. In North America, the earliest written records of weather and fire events are sporadic and often associated with established fur trade posts (Alexander 1981; Fritz *et al*. 1993; Weber and Stocks 1998; Zhang *et al*. 2000; Rannie 2001; Zhang *et al*. 2001; Stocks *et al*. 2003; Rannie 2006). However, records became more spatially dispersed and continuous with the advent of systematic record collection by national institutions (Van Wagner 1988; Stocks *et al*. 2003).

In North America additional instrumental records, such as those obtained from weather stations, can span multiple centuries and provide important information on past forest conditions (Weber and Stocks 1998; Zhang *et al*. 2000; Zhang *et al.* 2001). More recent fire record composites, such as the Large Fire Database (Stocks *et al*. 2003; Kasischke and Turetsky 2006), those linked to outputs from General Circulation Models (de Groot *et al*. 2013; Flannigan *et al*. 2013) and fire analyses based on ecological classifications (Beverly and Martell 2005; Boulanger *et al*. 2012) are largely constructed from records beginning in the 1970's (Weber and Stocks 1998; Stocks *et al*. 2003; Fauria and Johnson 2006). Although these records are important for placing boreal forest-fires in an historical context, the relatively short duration of these records compared to the history of boreal forest development requires analysis of proxy records that can be used to obtain longer records of past fire occurrence.

1.3.2 Dendroecological records

Dendroecology is the science related to the interpretation of the environmental record stored in tree rings (Fritts 1976; Schweingruber 1988; Speer 2010). Throughout the lifespan of a tree, changes to environmental conditions can result in ring-width variations and anomalous growth features that can be accurately dated (Fritts 1976; Schweingruber 1988; Larsen and MacDonald 1995; Girardin and Tardif 2005; Speer 2010; Waito *et al*. 2013). Through comparison between the tree-ring and archival records, the determination of the causes of ring-width variations and anomalous growth features can allow inferences to be made regarding past forest conditions whenever these growth characteristics are observed (Larsen 1996; Grissino-Mayer and Swetnam 2000). The tree-rings' record of environmental conditions, combined with the slow decomposition of the wood from several boreal tree-species results in the potential for a long record of fire conditions and events to be retained in the form of stand regeneration, growth suppression/release and fire scarring (Arno and Sneck 1977; McBride 1983; Dansereau and Bergeron 1993; Tardif 2004; Brassard and Chen 2006).

Stand initiation in the boreal forest is typically related to stand-replacing crown fires and can be used as an indicator of past fire events because a number of boreal species have specific adaptations to facilitate post-fire regeneration (Johnson 1992; Johnson and Gutsell 1994; Whitlock and Bartlein 2003; Whitlock *et al*. 2010; Bowman *et al*. 2013). Jack pine and black spruce have serotinous and semi-serotinous cones, respectively, that enable rapid seeding of fire-exposed soil. A post-fire regeneration method characteristic of paper birch and trembling aspen is an ability to regrow from the stump or root system, respectively (Rowe and Scotter 1973; Tardif 2004). Although the regeneration of the forest generally occurs rapidly following a fire event, differential rates of recruitment may lead to an underestimation of the age of the fire cohort and thus of the fire date itself (Johnson and Gutsell 1994; Senici *et al*. 2010). The possibility of obtaining information from fire cohorts is also diminished as successive fire events remove older cohorts from the landscape (Johnson and Gutsell 1994) and in situations where forests transition from pioneer succession (Bergeron and Charron 1994).

The tree-ring record also provides information on environmental conditions through growth fluctuations. The changes in growth are generally related to temperature and precipitation signals and are observed as increased or decreased annual ring-width (Larsen and MacDonald 1995; Girardin and Tardif 2005). This variation in tree-ring width can become an indicator of fire conditions in situations where tree growth is suppressed, as growth suppression is often related to drought conditions (St. George *et al*. 2008). However, given the spatial heterogeneity of drought conditions, fire reconstructions from ring widths are commonly used to infer broad trends in AAB, rather than individual fire events (Girardin and Tardif 2005; Girardin 2007; Girardin and Sauchyn 2008; Knapp and Soulé 2011).

One of the most common fire records used in fire history reconstructions from trees is fire scars (Arno and Sneck 1977; Swetnam 1993; Johnson and Gutsell 1994; Whitlock and Bartlein 2003; Whitlock *et al*. 2004; Whitlock *et al*. 2010). Fire scar formation occurs in situations where the tree is exposed to temperatures above 60°C in the presence of wind conditions favourable to their formation (McBride 1983; Gutsell and Johnson 1996; Falk *et al*. 2011). Surviving the fire event and continued tree growth can be used to determine the year and season of burn. Fire scars are typical of low severity surface fires or along the lower severity edges of high severity crown fires (Arno and Sneck 1977; Falk *et al*. 2011).

In the forest, fire scars often appear as a triangular shape with the stem missing the bark. The triangular shape is the result of decreasing stem damage as temperature decreases further away from the ground (Gutsell and Johnson 1996). The scar often occurs on the leeward side of the stem where airflow conditions sustain the high temperatures long enough to kill tissues (Gutsell and Johnson 1996). Fire scars can also be concealed within trees and are observed internally as damaged tissue from the time of fire, associated with abnormally large growth rings covering the wound (McBride 1983).

Fire-scar formation exhibits age and species trends as fire scars tend to appear on older, fire tolerant species with younger trees, or species not well adapted to surviving fire, often not containing fire scars as the fire causes mortality (McBride 1983).

The regeneration, growth and scarring traits of trees, combined with the persistence of successive cohorts within the forest, allows for the determination of the spatiotemporal trends in fire occurrence (Heinselman 1973; Swain 1973; Clark 1990; Johnson and Gutsell 1994; Weir *et al*. 2000; Falk *et al*. 2011). For example, frequency of fire can be determined from cohort regeneration in situations where successive cohorts are established following fire events (Johnson 1992; Johnson and Gutsell 1994; Whitlock and Bartlein 2003; Whitlock *et al*. 2010; Bowman *et al*. 2013). Similarly, a widespread drought signal within the tree-rings can be used to infer fire conditions over a large area (Larsen and MacDonald 1995; Girardin and Tardif 2005; Girardin 2007; Girardin and Sauchyn 2008). Further, comparison of samples with fire scars of the same year provides spatial context of individual fires whereas comparison of multiple fire scar years provides the frequency of fire in a given area (Arno and Sneck 1977; Clark 1990; Swetnam 1993; Falk *et al*. 2011).

1.3.3 Lake sediment records

In addition to tree-rings, paleoecological investigations have used a number of environmental proxy records including ice cores, soils, sand dunes, peat and lake sediments (Carcaillet *et al*. 2001a; Laird *et al*. 2003; Carcaillet *et al.* 2006; Ali *et al.* 2008; Fauria and Johnson 2008). The lake sediment record is particularly suited to fire history reconstructions and can extend the record beyond that provided by archival and tree-ring records (Whitlock and Larsen 2001). Proxy records from lake sediments commonly used in fire history reconstructions include charcoal particles, pollen and plant macroremains (Long *et al*. 2007, Ali *et al*. 2008). The charcoal record, in particular, can be utilized to infer fire events and changes in fire frequency over time (MacDonald *et al*. 1991a; Larsen 1980; Larsen and MacDonald 1998ab; Pitkanen *et al*. 1999; Carcaillet *et al*. 2001a; Asselin and Payette 2005; Marlon *et al*. 2006; Long *et al*. 2007).

The analysis of charcoal records is facilitated by the incomplete combustion of organic matter at temperatures between 250-500°C (Chandler *et al*. 1983). Upon production, charcoal particle transportation to the lake can be classified as of primary or secondary origin (Patterson III *et al.* 1987; Clark 1988ab; Clark 1990; Nichols *et al*. 2000; Higuera *et al*. 2007). Primary charcoal transport refers to the movement of particles during, or immediately after, a fire event. Secondary charcoal transport refers to the continued transport of charcoal following a fire event that can occur for many years through slope-wash or redeposition within the lake (Bradbury 1996; Whitlock and Larsen 2001). Whitlock and Millspaugh (1996) determined that secondary transport of charcoal occurred for up to 20 years following a fire event, potentially obscuring the actual fire date during peak analysis. Larsen and MacDonald (1993) reported that, once in the lake, charcoal could continue to be resuspended through such mechanisms as wave action and sediment slumping. However, Bradbury (1996) indicated that charcoal resuspension within a lake only continued until the charcoal particles settled below the portion of the lake profile that experiences thermal inversions (thermocline).

The deposition of macroscopic charcoal into lake sediments can be particularly useful in reconstructing past fire conditions. Macroscopic charcoal particles are classified as those with a diameter >150 micrometers (μm) based on empirical evidence that charcoal particles above this size class represent local fires occurring within the watershed while excluding records of fires that occurred tens to hundreds of kilometers (km) away (Whitlock and Millspaugh 1996; Whitlock and Larsen 2001; Higuera *et al*. 2007). Although 150 μm is the accepted standard, Millspaugh and Whitlock (1995) indicated that analysis of charcoal particles between 125 and 250 μm provided a good record of fires occurring in the watershed. Enumeration of smaller particles (<125 μm) was deemed impractical and larger particles (>250 μm) were assessed as being too infrequent (Millspaugh and Whitlock 1995). Gardner and Whitlock (2001) also confirmed that particles >125 μm represented local fires, but that lake characteristics and position in relation to wind direction determined the distance to which an event could be recorded. Lynch *et al*. (2004a) reported that aerial charcoal transport was particularly high within 10 m of the burn edge with transport progressively decreasing between 10-200 m, thus indicating that fires in closer proximity to the lake are better recorded than those >200 m from shore.

In addition to charcoal size, an understanding of charcoal transport and deposition can be enhanced through an analysis of charcoal morphotypes. Different charcoal morphotypes are present within lake sediment as a result of the different types of vegetation being burned during a fire event. Enache and Cumming (2006) were able to identify seven different charcoal morphotypes and suggested that particularly fragile types, such as those with high porosity, were best suited to fire history reconstructions as they were mainly moved via primary transportation. Similarly, Jensen *et al*. (2007) were able to distinguish between charcoal produced from grass, conifer or deciduous trees which allowed them to infer changes in vegetation composition and fire intensity over time. More recently, Aleman *et al*. (2013) examined the width to length relationship within charcoal particles and were able to infer land-use changes based on grass and wood morphologies. Therefore, examination of charcoal morphotypes within a lake can provide important information regarding vegetation cover and source area of charcoal.

The analysis of charcoal from lake sediments requires extraction and isolation of the record. Within a lake, sedimentation can either be laminated (layers) or non-laminated (Larsen and MacDonald 1993; Glew *et al*. 2001) and methods have been developed to extract sediment from lakes based on this difference in sedimentation. The main technique for collecting laminated sediments is the freeze corer that preserves layers by freezing the sediment in place before extraction (Glew *et al*. 2001). For non-laminated sediments, two types of coring devices have been developed based on the differences in bulk density within the sediment profile (Glew *et al*. 2001; Cohen 2003). The gravity corer (i.e. Kajak-Brinkhurst) enables extraction of the more fluid upper sediments near the water-sediment interface, whereas the piston corer (i.e. Livingstone) is designed to extract progressively deeper sediments while minimizing the mixing of sediment through the profile (Glew 1991; Glew *et al*. 2001; Whitlock and Anderson 2003).

Upon extraction, the sediment is prepared for analysis on the basis of whether the regional or local record is required. In studies that seek to examine the regional fire record, the sediment is generally mounted on a pollen slide (Clark 1988a; Clark and Royall 1995; Clark and Hussey 1996; Blackford 2000; Carcaillet *et al*. 2001a; Asselin and Payette 2005) or made into a thin section (Clark 1988ab; Clark and Royall 1995; Clark and Hussey 1996; Ali *et al*. 2009a). In situations where the local record of fire is required, charcoal particles are isolated from sediment by sieving the samples to obtain the desired size class (often >150 μm) from the sediment and enables a number of measurements to be performed (Clark and Hussey 1996; Whitlock and Millspaugh 1996; Laird and Campbell 2000; Carcaillet *et al*. 2001a; Lynch *et al*. 2003; Asselin and Payette 2005; Carcaillet *et al*. 2006; Ali *et al*. 2009a; Ali *et al*. 2009b).

The procedure for sediment sieving begins with sub-sampling continuous sediment cores. The frequency of the sub-samples provides different temporal resolution and is determined based on the purpose of any given study. Ali *et al*. (2009a) suggested that sub-sampling at intervals of 1 centimeter (cm) or less was appropriate when attempting to maintain equal temporal resolution. Whitlock and Anderson (2003) indicated that sub-sampling sediment cores at 0.5-1 cm intervals represented 5-20 years of sedimentation. However, the sedimentation rate for individual lakes is ultimately dependent on such factors as lake depth and area, as well as the type of aquatic vegetation (Gasiorowski 2008). Following sub-sampling of the sediment core, extraction of the charcoal record through the sieving technique requires further sub-sampling of the sediment slice. Whitlock and Anderson (2003) indicated that removal of 1-10 cm^3 of sediment may be required based on the type of analysis being done. More often, 1 cm^3 is typically removed for analysis (Whitlock and Anderson 2003; Ali *et al*. 2009a; Brossier *et al*. 2014). Sediment sub-samples are then generally soaked in a deflocculant (such as sodium hexametaphosphate) to facilitate the sieving process (Whitlock and Anderson 2003; Ali *et al*. 2009a)

Charcoal production, transport and deposition during and following a fire event can be used to infer fire activity through time (Patterson III *et al*. 1987; Clark 1988ab; Laird and Campbell 2000; Whitlock and Bartlein 2003; Asselin and Payette 2005; Higuera *et al*. 2007; Long *et al*. 2007; Kelly *et al*. 2011). Fire inferences are commonly made through a decompositional approach that separates the charcoal accumulation rate (CHAR) into a background and peak component (Whitlock and Larsen 2001; Whitlock and Anderson 2003; Higuera *et al*. 2010; Brossier *et al*. 2014). Within the CHAR record the slowly varying background component is related to such things as changes in biomass distribution and burning, secondary transport of charcoal and transport of extra-local charcoal (Long *et al*. 1998; Whitlock and Larsen 2001; Whitlock and Anderson 2003). The peak component of the CHAR record is related to primary transport and deposition directly associated with a fire event in the vicinity of the watershed (Long *et al*. 1998; Whitlock and Larsen 2001). Direct relation of charcoal peaks to fire events means that repeated occurrence over time can provide the long-term fire regime.

Separation of the CHAR record into the background and peak component is commonly determined by establishing a threshold, with values above the threshold representative of fire events (Millspaugh and Whitlock 1995; Long *et al.* 1998). A number of techniques have been utilized for determining the threshold. For example, Millspaugh and Whitlock (1995) calculated the threshold in relation to known fires using a weighted running mean. Building on this approach, Long *et al*. (1998) also determined the threshold between the background and peak components against known fires but employed a locally weighted moving window to smooth the variability. More recently, Higuera *et al*. (2010) suggested that the determination of the threshold between the background and peak components is best represented by the 95th, 99th or 99.9th percentiles of the distribution. In addition, a high signal (peak) to noise (background) index should be used to help determine the appropriateness of chosen parameters (Higuera *et al*. 2010; Kelly *et al.* 2011). Based on these findings, Higuera *et al*. (2010) developed the statistical program CHARAnalysis that enables a separation of CHAR peaks from the background based on a threshold determined by the best signal to noise index.

Along with the extraction of the charcoal record, chronological control and the discussion of fire occurrence through time requires the determination of the approximate date of sediment deposition. Commonly, ^{210}Pb and ^{14}C isotopic dating methods are used to estimate when sediments were deposited on the lake bottom (Carcaillet *et al*. 2001a; Carcaillet *et al*. 2001b; Whitlock and Larsen 2001; Whitlock and Bartlein 2003; Higuera *et al.* 2009; Brossier *et al*. 2014). The ^{210}Pb isotope is a product of the uranium decay series and is used for dating samples up to 150-200 years old based on a half-life of 22.3 years (Appleby 2001; Cohen 2003). In ^{210}Pb dating, the constant rate of supply (CRS) model is often used to describe ^{210}Pb activity and assumes that the production and deposition of atmospheric ^{210}Pb, along with *in situ* production (background), is relatively constant on a year to year basis (Appleby 2001; Cohen 2003). Obtaining older dates from sediments is commonly through radiocarbon dating. Radiocarbon dating is made possible because carbon isotopes ^{12}C, ^{13}C and ^{14}C are differentially incorporated into plant and animal tissues (fractionation) and exist in relatively stable proportions over the lifetime of most organisms (Björk and Wohlfarth 2001). The ^{14}C isotope, in particular, is formed in the atmosphere through interaction with cosmic rays and has a half-life of 5568 years (Björk and Wohlfarth 2001). The ratio between ^{14}C compared to ^{12}C and ^{13}C isotopes, combined with the availability of long-term reference materials of past isotopic ratios, enables the determination of the age of a sample up to 40,000 years old (MacDonald *et al*. 1991b; Björk and Wohlfarth 2001).

1.4 Boreal forest development during the Holocene

1.4.1 Vegetation trends

At the onset of the Holocene the margins of the glaciers retreated northward followed closely by pro-glacial lakes (Wright 1968; Björk 1985; Overpeck *et al*. 1989; Marlon *et al*. 2009; Genries *et al*. 2012; Johnson and Miyanishi 2012). The subsequent draining of these lakes allowed vegetation to migrate into the newly exposed areas. Reconstructions of post-glacial environmental conditions reveal that the climate has been variable through time with periods of climatic shift punctuated by periods of relative stability (Björk 1985; Bowman *et al.* 2013). Broad trends in vegetation migration are reported between 10000-8000 BP, 8000-4000 BP, and 4000 BP-present (Genries *et al*. 2012).

Between 10000-8000 BP the climate of North America was characterized by rapidly warming temperatures (Viau *et al.* 2006*)*. Within central North America, paleoecological results indicate that the first tree-species to become established included eastern larch, black spruce, jack pine and paper birch (Love 1959; Wright 1968; Ritchie 1976; Bjork 1985; Liu 1990; McLeod and MacDonald 1997; Dyke 2005; Genries *et al*. 2012; Senici *et al*. 2013). Persistence of favourable growing conditions allowed the initial forest to transition from spruce dominated to increasing presence of pine and deciduous species as the ice and lake margins retreated (Love 1959; Dyke 2005; Senici *et al.* 2013).

The environmental conditions from 8000-4000 BP occurred during a climatic period known as the Hypsithermal (Last and Teller 1983; Bjork 1985; Viau *et al.* 2006). The climate of the Hypsithermal was characterized by the continued increase in temperatures from 8000 BP up to the Holocene maximum around 6000-4000 BP (Love 1959; Wright 1968; Swain 1973; Björk 1985; Long *et al*. 1998; Carcaillet and Richard 2000; Carcaillet *et al*. 2001b; Lynch *et al*. 2003; Whitlock and Bartlein 2003; Lynch *et al*. 2004b; Viau *et al.* 2006; Long *et al*. 2007; Ali *et al*. 2008; Genries *et al.* 2012). Bjork (1985) indicated that in central North America, the maximum temperature around 6000 BP corresponded to the maximum northward distribution of eastern white pine (*Pinus strobus* L.) which was approximately 200 km north of its present location. Similarly, Teller *et al*. (2008) reported that increased deposition of pollen from pine and deciduous trees into lake sediments was closely related to warmer temperatures within central North America. The pollen records also indicate that climatic cooling between 6000 and 4000

BP translated into a decrease in the distribution of eastern white pine populations (Wright 1968; Björk 1985; Viau *et al.* 2006; Genries *et al.* 2012) and the rapid expansion of spruce and jack pine (Wright 1968; Björk 1985; Liu 1990; McLeod and MacDonald 1997; Genries *et al.* 2012).

During the period between 4000 BP-present, the climate has been cooler and moister than the period between 8000-4000 BP (Swain 1973; Genries *et al.* 2012). The development of the forest continued towards increasing jack pine and paper birch dominance and the forest has generally maintained its current distribution since approximately 4000 BP (Love 1959; Carcaillet and Richard 2000; Carcaillet *et al*. 2001b; Teller *et al*. 2008; Genries *et al*. 2012; Senici *et al*. 2013). In addition, within central North America, pollen records revealed that conditions became particularly moist from 2000-1700 BP (Swain 1978; Larsen and MacDonald 1998ab; Campbell and Campbell 2000). Love (1959) indicated that this period of increased moisture led to an expansion of the southern boundary of the boreal forest. Following this period of increased moisture, Laird *et al*. (2003) reported that dry conditions prevailed from approximately 1700-600 BP.

1.4.2 Fire during the Holocene

The northward retreat of the glaciers and glacial lakes that enabled the migration of plants, animals and people into the newly exposed areas also corresponded to the introduction of fire onto the landscape (Whitlock and Bartlein 2003; Carcaillet *et al*. 2006). Throughout the Holocene, the climatic variability that shaped the distribution of vegetation was also a contributing factor in determining the size and frequency of fire (Ali *et al*. 2008). In addition to climate and vegetation as important components of fire occurrence, local conditions have an important role in determining when and where a fire will burn (Ali *et al*. 2008; Higuera *et al*. 2009). Similar to vegetation trends, broad trends in fire occurrence are reported between 8000-4000 BP, 4000-1000 BP and 1000 BP-present (Ali *et al*. 2009b; Higuera *et al*. 2009; Genries *et al*. 2012; Senici *et al*. 2013).

During the period between 8000-4000 BP, fire frequency generally increased as temperatures became warmer. Higuera *et al*. (2009) reported that fire return intervals (FRI) of the boreal forest of western North America became shorter, increasing in frequency to an average of once every 145 years compared to an average 251 years for the period between 10000-8000 BP. They attributed this increase in fire frequency to climatic conditions that favoured the increased presence of highly flammable species, such as spruce and pine. Similarly, in the boreal forest of eastern North America, Ali *et al*. (2009b) reported that climatic changes towards dryer conditions contributed to a shortening of mean FRI after 5800 BP from 230 years to 110 years. Moos and Cumming (2012) reported a similar trend in central North America, indicating that fire frequency increased from 190 years to an average 119 years between 8000-4000 BP and also implicated climate and vegetation changes as responsible.

During the period 4000-1000 BP a number of studies have indicated a change in fire frequency compared to the Hypsithermal (8000-4000 BP) period (Ali *et al*. 2009b; Kelly *et al*. 2013; Senici *et al*. 2013). For example, Kelly *et al*. (2013) indicated that warm, dry conditions in western North America allowed fire frequency to increase up until approximately 800 BP. They attributed the decrease in fire frequency since 800 BP to cooler, wetter conditions that were unfavourable to fire ignition and spread. Within eastern North America, Ali *et al.* (2009b) reported that FRI remained short up until 1000 BP before experiencing a large decrease in fire frequency. Although FRI remained short during this period, a shift towards decreasing fire frequency around 4000 BP was attributed to the increasing influence of local factors on the start and spread of fire. Similarly, Senici *et al*. (2013) indicated that a decrease in relative fire frequency within their study area in central North America was observed around 4000 BP that could be attributed to the increased importance of changes to the species composition and abundance at local scales.

During the most recent 1,000 years, fire frequency in the boreal forest has been decreasing compared to previous fire conditions (Lynch *et al*. 2003). Within the last 1,000 years both the Medieval Climate Anomaly (MCA; 900-1200 CE) and the Little Ice Age (LIA; 1400-1850 CE) exhibited unique fire conditions within North America. For example, Kelly *et al*. (2013) indicated that fire frequency was higher during the MCA associated with hot, dry conditions and that it has decreased since the end of the MCA. Haig *et al*. (2013) reported that the MCA received the lowest amount of moisture in North America for the last 1,000 years. Similarly, Ali *et al*. (2009a) indicated that the fire frequency decreased in eastern North America at the end of the MCA and increased at the end of the LIA. Within the boreal forest of central North America, Moos and Cumming

(2012) reported that the fire frequency has generally decreased during the most recent 1000 years.

During the last 600 years, climate records reconstructed from tree rings revealed that the average climatic conditions were cool and wet (St George and Nielsen 2002; Girardin and Sauchyn 2008; St. George *et al.* 2009), punctuated by periodic drought (St George and Nielsen 2002; Tardif 2004; Girardin and Sauchyn 2008; St. George *et al.* 2009). Since the onset of the LIA fire frequency has been variable, reported as intermediate between the years 1640 and 1720 CE, high between 1720 and 1810 CE and low between 1820 and 1863 CE (Clark 1988b; Clark 1990; Millspaugh and Whitlock 1995). With the end of the LIA, conditions were more moist with higher fire frequency between 1863 and 1920 CE and lower between 1920 and 1970 CE (Heinselman 1973; Swain 1978; Gajewski *et al.* 1985; Clark 1988b; Clark 1990; Clark and Royall 1995; Millspaugh and Whitlock 1995; Stocks *et al*. 2003; Tardif 2004; Girardin *et al*. 2006b; Girardin *et al.* 2006c; Girardin 2007; Girardin and Sauchyn 2008).

1.4.3 Human influences

Superimposed over post-glacial vegetation and fire trends are complex social conditions that potentially influenced the pattern of fire and vegetation on the landscape. Within central North America archaeological evidence suggests that people first arrived approximately 9,000 years ago (Love 1959; McMillan 1995; Johnson and Miyanishi 2012). This arrival of human populations onto the landscape contributed to an increase in fire frequency as fire has long been a tool used to stimulate vegetation growth and alter the landscape (Heinselman 1973; Alexander 1981; White 1985; Murphey *et al.* 2000; Miller and Davidson-Hunt 2010; Archibald *et al*. 2012; Johnson and Miyanishi 2012; Girardin *et al.* 2013).

The arrival and migration of European settlers in North America during the 17th century also had important implications for vegetation, wildlife and fire (White 1985; Schwimmer *et al.* 1998; Johnson and Miyanishi 2012; Johnson and Kipfmueller 2016). This influence began with the onset of the fur trade and was intensified as improved infrastructure opened up large areas to development (Heinselman 1973; Alexander 1981; White 1985; Johnson and Miyanishi 2012). The widespread construction of the railways exposed previously isolated areas to increased fire hazard associated with the development of agriculture, forestry and mining activities (McMillan 1995; Johnson and Miyanishi 2012; Bowman *et al.* 2013). Despite this increased human activity, studies have revealed that fire frequency has generally decreased since 1850 CE compared to the period before (Weir *et al*. 2000; Tardif 2004; Girardin *et al*. 2006b; 2006c; 2006d). In contrast, others indicated that fire frequency has increased since 1850 CE (Senici *et al.* 2010). In addition, fire frequency has been reported to have increased since the 1970's (Skinner *et al*. 1999; Skinner *et al*. 2002; Beverly and Martell 2005; Fauria and Johnson 2006; Gillett *et al*. 2004; Girardin *et al*. 2006b; Kasischke and Turetsky 2006; Girardin 2007; Fauria and Johnson 2008; Shabbar *et al*. 2011; Bowman *et al*. 2013).

Forest management practices and climate changes have the potential to alter the fire regime of the boreal forest and, subsequently, species distribution and stand structure

(Weber and Flannigan 1997; Weber and Stocks 1998; Bergeron *et al*. 2001; Bergeron *et al*. 2002; Lesieur *et al*. 2002; Flannigan *et al*. 2005; Girardin *et al*. 2010). One issue confronting forest management objectives is a lack of information regarding past fire regimes (Girardin *et al*. 2010). This can be resolved through analysis of archival and paleoecological proxy records that can be used to infer past fire events and environmental conditions (Hughes and Diaz 1994; Weber and Flannigan 1997; Flannigan *et al*. 2001; Willis and Birks 2006; Fauria and Johnson 2008; Girardin *et al*. 2010; Whitlock *et al*. 2010; Girardin *et al.* 2012). In addition to archival records, two records that are particularly suited to fire reconstructions are tree rings and lake sediment charcoal (Whitlock *et al*. 2004; Whitlock *et al*. 2010).

1.5 Thesis rationale and objective

The impact of climate change on fire occurrence and forest distribution has become a growing concern. Many studies have reported that fire frequency and intensity are expected to increase in association with increasing temperatures (Girardin *et al*. 2012; Flannigan *et al.* 2013). An increase in fire frequency and size could have important consequences for species distribution and forest composition. As fire is an important process in the boreal forest and a major contributor to nutrient cycling, carbon balance, stand regeneration and heterogeneous forest structure, the integration of fire into management strategies is necessary. A number of management strategies thought to replicate fire as a disturbance include clear-cut (crown fire) and selective (surface fire) harvesting techniques, as well as prescribed burns of various intensities. However, decisions regarding the appropriate timing, frequency and size of management projects require the natural pattern of fire for the area in question to be known. There is a general consensus that more research is needed across the boreal forest to determine the historic fire cycle and factors contributing to its variability. A number of archival and proxy records have been identified that are suitable for determining past fire size and frequency, with proxy records contained in tree rings and lake sediments particularly suited to long-term fire history reconstructions. The main objective of this thesis was to reconstruct a multi-millennial fire history for a portion of the south-central boreal forest. The study area is located at the transition between the Boreal Shield, Prairies and Great Lakes-St. Lawrence Ecozones where the maintenance of the southern boundary of the boreal forest is potentially sensitive to predicted climate changes (Weber and Flannigan 1997). Establishment of a fire history in the area is necessary to provide information on long-term changes in fire-climate associations and the potential effect that Aboriginal and European land-use had on the fire cycle (Johnson and Miyanishi 2012).

2.0 Multi-proxy fire history reconstruction in the boreal forest of south-central Canada

2.1 Introduction

2.1.1 Fire in the boreal forest

Fire is an important disturbance agent in the boreal forest of North America with an average of two to seven million hectares burned on an annual basis (Stocks *et al.* 2003; de Groot *et al*. 2013). Recent studies have reported that climatic changes could lead to greater fire frequency with important implications for forest composition, forest dynamics and management objectives (Flannigan *et al*. 2005; Girardin and Mudelsee 2008; Girardin *et al.* 2013). For example, Flannigan *et al*. (2005) indicated that the annual area burned (AAB) could increase by 74-118 percent in a $3xCO_2$ environment. Girardin *et al*. (2012) reported that such a large increase in AAB would lead to conditions beyond that observed throughout the entire post-glacial period in the boreal forest of eastern North America. However, the lack of continuous long-term fire records across the Canadian boreal forest makes it difficult to assess the impact of future climate change on AAB and its consequences.

The relatively short fire records that currently exist within the boreal forest are problematic for use in interpreting recent and future fire frequency because they were collected during a period of widespread landscape development and fire suppression that may not accurately represent natural conditions (Murphy *et al*. 2000). Currently, the boreal forest of central North America is largely dominated by a crown fire regime (Senici *et al*. 2013). However, millennial-scale reconstructions of fire activity reveal a complex interaction between vegetation, climatic conditions and fire activity (Ali *et al*. 2009a; Ali *et al*. 2009b; Senici *et al*. 2013). Therefore the determination of past forest fire variability is an important area of research that enables placement of current and future fire observations into historical context and aids in the prediction and interpretation of future fire projections (Bergeron *et al*. 2001; Girardin and Mudelsee 2008; Girardin *et al.* 2012). In addition to archival records, fire history and vegetation assemblages can be reconstructed through paleoecological investigations using tree rings and lake sediments, each providing a distinct proxy record of past conditions.

2.1.2 Fire history records

2.1.2.1 Archival records

A number of archival records provide information on past fires through a direct record of events or conditions (written and instrumental accounts of climate and fire events) or through interpretation of forest structure (aerial photographs/remote sensing). For example, Fritz *et al*. (1993) examined written records of fire events from fur trade posts as a proxy record for explaining fluctuations in ungulate populations in northwestern Ontario since 1786. In addition, fire history reconstructions can also use instrumental records such as continuous temperature and precipitation data to help establish patterns of past fire frequency (Grissino-Mayer and Swetnam 2000; Whitlock *et al*. 2010). For example, Clark (1989) used temperature and precipitation data spanning 150 years to analyze the water balance within the forests of northern Minnesota and was able to establish periods of increased fire frequency in relation to moisture deficits. Similarly, Newark (1975) utilized weather records to elucidate the relationship between atmospheric pressure systems and fire events in northwestern Ontario. Within North

America, the spatiotemporal coverage of archival records is generally limited to the last few centuries.

Archival records became more spatially dispersed and continuous with the advent of systematic record keeping by national institutions and are particularly detailed for the period beginning around the 1970's (Van Wagner 1988; Murphy *et al*. 2000; Stocks *et al*. 2003). For example, the development of the Large Fire Database by Stocks *et al*. (2003) was based on records collected between 1959 and 1997 and provided a record of fires >200 ha across the boreal region of North America. Similarly, the development of fire prediction models linked to outputs from General Circulation Models are based on recent records and it enabled Flannigan *et al*. (2005) to provide predictions of future fire conditions across the boreal forest in response to climate changes. More recently, Boulanger *et al*. (2012) used fire data from 1980-99 to develop a fire zonation scheme that more accurately grouped areas with similar fire traits than obtained from ecological classification systems. Although these records are important for placing the boreal forest into an historical context, their relatively short duration compared to the history of boreal forest development requires analysis of proxy records that can be used to obtain longer records of past fire occurrence.

2.1.2.2 Tree-ring records

Fire history reconstructions based on tree-ring records have been extensively conducted throughout the boreal forest of North America using ring-width chronologies (Girardin 2007; Girardin and Sauchyn 2008), stand initiation dates, fire scars or a combination of these records (Bergeron 1991, Johnson and Gutsell 1994; Tardif 2004). Archival fire history records can be extended through analysis of tree rings because they commonly provide a temporal record of 3-4 centuries within the boreal forest (Bergeron 1991; Tardif 2004; Girardin *et al*. 2006b). For example, Girardin and Sauchyn (2008) used tree-ring width chronologies spanning 300 years to infer annual area burned from drought induced growth suppression in the boreal forest of North America. Despite the length of the record, it is difficult to assess long-term trends of past fire variability because many periods of climatic changes and climatic stability occur over longer time-spans than the temporal range of the tree-ring record (Girardin *et al*. 2012). As a result, analyses of additional fire proxies, such as the charcoal record from lake sediments, have been undertaken to obtain longer fire records.

2.1.2.3 Lake sediment records

Lake sediment records have been used extensively throughout the boreal forest to determine past climate, vegetation and fire conditions. Björk (1985) was able to reconstruct the post-glacial migration of vegetation in northwestern Ontario using pollen records obtained from lake sediments and, through changes in relative pollen abundance, was able to infer climatic changes. Similarly, Carcaillet *et al*. (2001b) were able to reconstruct post-glacial climate and vegetation dynamics in the boreal forest of eastern North America and indicated that vegetation distribution was largely determined by fire as assessed through charcoal records. Senici *et al*. (2013) also used macroscopic charcoal particles (>125 μm) to reconstruct fire frequency within the boreal forest of northwestern Ontario over the last 10,000 years. Similarly, Brossier *et al*. (2014) used macroscopic charcoal particles to reconstruct fire history over 7,000 years in the eastern boreal forest. Therefore, the lake sediment charcoal record is particularly suited to fire history reconstructions and can extend the record beyond that provided by the archival and tree-ring records (Whitlock and Larsen 2001).

2.1.3 Post-glacial boreal forest development of central North America

The boreal forest of central North America has been developing during a geologic period known as the Holocene that began with the end of the most recent glaciation approximately 10,000 years ago (Wright 1968; Björk 1985; Overpeck *et al*. 1989; Marlon *et al*. 2009; Johnson and Miyanishi 2012). Between 10000 and 8500 years BP (BP=before present; present =1950 CE) the northward retreat of the glaciers and glacial Lake Agassiz enabled the migration of plants, animals and people into the newly exposed areas (Björk 1985; McMillan 1995; Thornleifson 1996; Johnson and Miyanishi 2012). Paleoecological results indicated that the first tree-species to migrate into central North America were eastern larch (*Larix laricina* (Du Roi) K.Koch), black spruce (*Picea mariana* (Mill) B.S.P.), jack pine (*Pinus banksiana* Lamb.) and paper birch (*Betula papyrifera* Marsh.) (Love 1959; Ritchie 1976; Björk 1985; McLeod and MacDonald 1997; Dyke 2005; Senici *et al*. 2013). Persistence of favourable growing conditions allowed the initial forest to transition from spruce dominated to an increased presence of pine and deciduous species as the ice and lake margins retreated (Love 1959; Dyke 2005; Senici *et al.* 2013). The forests reached their maximum northward extent in association with peak temperatures about 6,000 years ago (Hypsithermal) followed by the gradual expansion of species more tolerant of the cooler temperatures that prevailed during the most recent 4,000 years (Neoglacial). Modern forest conditions and species distribution are similar to those that prevailed during the most recent 4,000 years, but with a trend towards increasing spruce and aspen and a retraction of the northern tree-line (Love 1959; Dyke 2005).

The migration of vegetation into newly deglaciated areas also allowed for the occurrence of fire. Within the boreal forest of central North America paleoecological reconstruction of post-glacial environmental conditions have revealed that fire occurrence generally reflected vegetation migration, with broad trends in fire frequency and area burned between 8000-4000 BP and 4000 BP-present (Moos and Cumming 2012; Senici *et al*. 2013). The period between 8000-4000 BP was characterized by higher than average fire frequency in association with increasing temperature and the northward expansion of pine species. The maximum post-glacial fire frequency occurred approximately 6000 BP and was associated with the dominance of pine species and conditions that were warmer and drier than present (Vance *et al*. 1995; Viau and Gajewski 2009; Moos and Cumming 2012; Senici *et al.* 2013). The frequency of fire within central North America gradually decreased during the most recent 4,500 years with the prevalence of cooler and wetter conditions and the expansion of deciduous species (Senici *et al*. 2013).

More recently, climatic conditions associated with the Medieval Climate Anomaly (MCA; 900-1300 CE) and the Little Ice Age (LIA; 1400-1850 CE) has enabled reconstruction of fire frequency and area burned on a finer scale. Paleoecological analyses indicated that climate was warmer and drier during the MCA compared to the

LIA (Viau and Gajewski 2009; Laird *et al*. 2012; Moos and Cumming 2012; Haig *et al*. 2013). The warmer, dryer conditions associated with the MCA would have contributed to increased fire frequency in the boreal forest of central North America as periods of drought are related to increased fire risk (Girardin and Wotton 2009). During the most recent 600 years, diatom records indicated that the average LIA climate of the central North American boreal forest was wetter than that of the MCA (Haig *et al*. 2013). Further, climate records obtained from tree rings indicated that the wetter conditions of the last 600 years were punctuated by periodic drought events (St. George and Nielsen 2002; St. George *et al.* 2009). The association between drought induced ring-width variations and area burned indicated that variability in AAB increased towards the end of the LIA and again during the most recent 50 years (Girardin *et al*. 2006b; Girardin and Sauchyn 2008).

Superimposed over post-glacial vegetation and fire trends are complex social conditions that potentially influenced the pattern of fire and vegetation on the landscape. Within central North America archaeological evidence suggests that people first arrived approximately 9,000 years ago (McMillan 1995; Johnson and Miyanishi 2012). This arrival of human populations onto the landscape would likely have contributed to an increase in fire frequency as fire has long been a tool used to stimulate vegetation growth and alter the landscape (Heinselman 1973; Murphy *et al*. 2000; Miller and Davidson-Hunt 2010; Archibald *et al*. 2012; Johnson and Miyanishi 2012; Girardin *et al.* 2013; Johnson and Kipfmueller 2016). Day (1953) revealed that fire was used by Aboriginal peoples throughout North America for a number of purposes, such as clearing land, improving hunting conditions and stimulating vegetation growth. Similarly, Miller and Davidson-Hunt (2010) reported that Aboriginals in northwestern Ontario identified fire as a crucial forest process and utilized it in land management when deemed necessary and appropriate. Within central North America, Anderton (1999) indicated that fire was a tool used by Aboriginals to maintain blueberry patches throughout the forests around Lake Superior.

During the most recent three centuries the human influence on fire frequency increased with the migration of European settlers beginning in the early 17th century as fur-trade routes and posts were established and land cleared for settlement (Heinselman 1973; White 1985; Johnson and Miyanishi 2012). In addition, the European influence on fire occurrence was enhanced with the advent of industrialization and the construction of the railways beginning in the 19th century (White 1985; McMillan 1995). Several studies indicated that this increased activity resulted in increased fire frequency but decreased area burned since 1850 CE compared to the period before (Weir *et al*. 2000; Tardif 2004; Girardin *et al*. 2006b; Girardin *et al*. 2006c; Girardin *et al*. 2006d). Similarly, other results confirmed an increase in fire frequency but that it did not occur until the 1920's (Senici *et al.* 2010). The 1920's also marks the beginning of active fire suppression throughout the boreal forest of North America (Baker 1992). However, it remains uncertain whether fire suppression has (Martell and Sun 2008) or has not (Baker 1992) had a significant effect on reducing the area burned. For example, area burned has been reported to have increased throughout the boreal forest region of North America since the 1970's despite modern fire suppression practices (Skinner *et al*. 1999; Skinner *et al*.

2002; Beverly and Martell 2005; Fauria and Johnson 2006; Gillett *et al*. 2004; Girardin *et al*. 2006b; Kasischke and Turetsky 2006; Girardin 2007; Fauria and Johnson 2008; Senici *et al*. 2010; Shabbar *et al*. 2011).

2.1.4 The need for multi-proxy comparisons

The potential for error in the interpretation of fire events from periods of increased charcoal accumulation in sediment, such as those resulting from sediment redeposition or erosion events, has led to the realization that better controls were needed to help differentiate actual fire events from noise (Higuera *et al*. 2005; Higuera *et al.* 2011; Brossier *et al.* 2014). For example, Bradbury (1996) reported that wind and lake currents were responsible for the resuspension and redeposition of charcoal particles into deeper water over time. This potential for error has resulted in an increased number of studies that compared charcoal records and tree-ring fire records to provide a more detailed record of past fire than is possible with either record alone (Whitlock and Larsen 2001; Whitlock *et al*. 2003; Higuera *et al*. 2005; Higuera *et al.* 2011; Girardin *et al*. 2012; Brossier *et al*. 2014). Although studies comparing fire events reconstructed from tree-ring and charcoal records have become increasingly common, their spatial coverage is still limited, with study areas located predominantly in the eastern Boreal Shield and Taiga Shield ecozones within eastern Canada (Asselin and Payette 2005; Girardin *et al*. 2012; Brossier *et al*. 2014), and the Humid Temperate Domain (Clark 1988b; Clark 1990; Millspaugh and Whitlock 1995; Whitlock *et al*. 2004; Higuera *et al*. 2011) and Dry Domain (Gavin *et al*. 2003; Higuera *et al*. 2005) of the United States. Within the boreal forest of central North America only a small number of studies have assessed the long-term fire trends using lake sediment records and even fewer have used a multi-proxy methodology (Moos and Cumming 2012; Senici *et al.* 2013). Furthermore, no long-term fire history reconstruction has been conducted at the southern margin of the central Canadian boreal forest. This region and its fire regime may be particularly susceptible to climate changes as it marks the transition between the boreal forest, the prairies to the southwest, and the temperate forest to the southeast (Genries *et al*. 2012; Haig *et al*. 2013).

2.1.5 Objectives and Hypotheses

From a forest management perspective, the importance of fire to the functioning of forest ecosystems necessitates that the conditions that led to the current distribution and composition be understood. In this study the long-term fire history was reconstructed for a portion of Lake of the Woods Ecoregion, an area of the south-central Boreal Shield Ecozone situated along the transition between the Boreal Plains and Prairie Ecozones to the west and the Humid Temperate Domain to the south and southeast. Two objectives were put forward for the fire history reconstruction. The first objective was to compare the reconstructed recent fire history around eight lakes using proxy records that are obtained from archival, tree-ring and lake sediment charcoal records. The second objective was to reconstruct a multi-millennial fire history from the charcoal records contained in lake sediment and compare it with results from other North American studies. It was hypothesized that charcoal accumulation would increase in association with known fire events identified from the archival and tree-ring records. Further, it was hypothesized that European settlement and modern climate changes have influenced the fire frequency. Contained within the reconstruction period are a number of well documented climate anomalies (MCA, LIA) and periods of severe, widespread fire. It remains unclear whether the modern fire regime (frequency, size) of the central boreal forest falls within the historic range of variability.

2.2 Materials and Methods

2.2.1 Study area

The study area is located in the southern boreal forest of central Canada in the Lake of the Woods Ecoregion (LWE) along the border between the provinces of Manitoba and Ontario (Figure 1; Appendix I). The LWE occupies the southern-most portion of the central Boreal Shield Ecozone (Ecological Stratification Working Group 1996). At a finer scale, the study area is located within both the Kenora Ecodistrict and along the border between the Kenora Ecodistrict and the Pinawa Ecodistrict (Smith *et al*. 1998, Crins *et al*. 2009). The entire LWE was extensively covered by glaciers during the last glaciation up until approximately 12,000 years ago, followed by the transition to coverage by glacial Lake Agassiz (Thornleifson 1996; Yang and Teller 2005). The presence of glacial Lake Agassiz within the study area ended around 8000 BP.

The geology of the LWE is comprised mainly of massive crystalline Archean rocks and limestone (Ecological Stratification Working Group 1996; Smith *et al.* 1998; Crins *et al.* 2009). Bedrock is overlain with thick to thin glacial till, fluvioglacial, and glacial Lake Agassiz deposits (Ecological Stratification Working Group 1996; Smith *et al.* 1998; Crins *et al.* 2009). Soils of the region consist of poorly drained Organic Mesisols, Fibrisols, Brunisols, Luvisols and Chernozems within the low lying areas and little to no soil covering the rock outcrops (Ecological Stratification Working Group 1996; Smith *et al.* 1998; Crins *et al.* 2009). The topography of the region is comprised of undulating terrain alternating between upland bedrock outcrops and lowlands (Ecological Stratification Working Group 1996). The elevation of the LWE ranges between 215 and

Figure 1: Map of the study area. The inset figure represents the limits of the Boreal Shield Ecozone (grey shaded area) and the Lake of the Woods Ecoregion (LWE; black line). The eight study lakes are indicated by the black triangles. The main figure provides a detailed view of the study area. The black dot indicates the city of Kenora for context.

390 meters (m) above sea level (Smith *et al*. 1998). The Pinawa Ecodistrict marks the transition from the Canadian Shield to the east (Kenora Ecodistrict) and the Lake Agassiz deposit dominated Ecodistricts to the west.

The continental climate of the LWE is characterized by a gradient between the Subhumid Transitional Low Boreal in the north (Crins *et al*. 2009) and the Moist Lower Boreal in the south (Scott 1995). Within the LWE the climate is characterized by short, warm summers and long, cold winters (Ecological Stratification Working Group 1996; Smith *et al.* 1998; Crins *et al.* 2009). For the period 1981-2010 the mean annual temperature ranged between 2.5 degrees Celsius (°C) and 3.1°C at Kenora. For Indian Bay and Kenora, the highest mean July temperature ranged from 19.1°C to 19.7°C and the lowest mean January temperature ranged from -17°C to -16°C, respectively (Government of Canada Climate Normals 2016). Mean annual precipitation ranged between 630 millimeters (mm) at Indian Bay and 715 mm at Kenora, of which approximately 536 mm falls as rain (Government of Canada Climate Normals 2016). A moisture gradient exists within the LWE with higher precipitation and lower moisture deficits in the Kenora Ecodistrict compared to the Pinawa Ecodistrict (Smith *et al*. 1998).

The vegetation in the LWE forms part of the transition between the Northern Coniferous boreal forest to the north, the Great Lakes-St. Lawrence forest to the southeast and the Manitoba Lowlands to the southwest (Rowe 1972; Ecological Stratification Working Group 1996; Smith *et al*. 1998; Crins *et al*. 2009). Dominant tree-species in the ecoregion include black spruce, jack pine, white spruce (*Picea glauca*

(Moench) Voss), northern white-cedar (*Thuja occidentalis* L.), balsam fir (*Abies balsamea* (L.) Mill), trembling aspen (*Populus tremuloides* Michx.), paper birch, and other hardwoods (Rowe 1972; Ecological Stratification Working Group 1996; Smith *et al*. 1998; Crins *et al*. 2009). This area also represents the northwestern limit of red pine (*Pinus resinosa* Ait.) and eastern white pine (*Pinus strobus* L.) distribution (Rowe 1972; Ecological Stratification Working Group 1996). The distribution of vegetation in the LWE has also been influenced by human activities through extensive land-clearing for agriculture, forestry activities and altered fire conditions throughout human habitation by both Aboriginal and European populations (Rowe 1972; Scott 1995).

2.2.2 History of human activities

Evidence for the presence of human populations indicates an arrival and spread of Aboriginals throughout North America approximately 14,000-8,000 years ago (Dickason 1992; McMillan 1995). Within the LWE, archaeological evidence suggests that people first arrived approximately 8,000 years ago (Dickason 1992; McMillan 1995). For the period between the initial arrival and European contact, there was widespread manipulation of the landscape for agricultural and hunting purposes throughout North America (Dickason 1992). At the time of European contact, the boreal forest region of central North America was occupied by Native Americans of Anishinaabe heritage (Dickason 1992). The Anishinaabe practiced limited slash-and-burn agriculture and largely subsisted on hunting and gathering activities. The arrival and expansion of European settlement into central North America began during the 17th century in relation to the fur trade (McMillan 1995). During this period, Anishinaabe people migrated into the LWE along with European fur traders (Davidson-Hunt 2003). The Anishinaabe provided support to the fur traders through provision of supplies and often managed resources through the application of fire (Davidson-Hunt 2003). In 1873, the signing of Treaty #3 enabled the westward expansion of European colonization (Davidson-Hunt 2003).

The earliest establishment of a modern transportation network through the area was the Dawson Road constructed in the 1860's that linked Thunder Bay to Winnipeg through a series of land and water connections (Wightman and Wightman 1997; Davidson-Hunt 2003). Railway construction through the area began in 1874 and the connection between Thunder Bay and Winnipeg was completed in 1885. Within the study area large-scale logging began in the 1880's and was sustained until a sharp decline in the 1930's (Wightman and Wightman 1997; Davidson-Hunt 2003). A period of road construction occurred in the 1930's that began to open up the northern portions of Ontario. Connection between Manitoba and Ontario via road was established for the first time in 1934. A number of additional roads were constructed over time that came near the study lakes, including highway 596 from Kenora to Minaki (passing by Lake O6) that was completed between 1958 and 1966 (Appendix II) and Highway 525 from Minaki to Whitedog that was begun in 1956 and paved beginning in 1982. Cygnet Lake road passing by Lakes O14 and O15 (Appendix III and IV) and Sherwood Lake road passing by Lake O4 (Appendix V) were constructed for resource extraction and recreational purposes. In the 1950's the first systematic Forest Resource Inventories (FRI) were undertaken by Provincial governments and the forest industry with the objective of extensively cataloging the forest resource through aerial and ground surveys (Wightman and Wightman 1997). With the advent of industrial forest harvesting in the 1970's, clear-cut harvesting increased followed by a decline in the latter portion of the 20th century (Wightman and Wightman 1997).

The Manitoba portion of the study area is located entirely within the Whiteshell Provincial Park (WPP) which was established in 1961 and encompasses 2,729 km^2 (Manitoba Department of Mines, Natural Resources and Environment-Parks Division 1978). Prior to the designation as a park a number of roads and railways were constructed through WPP. In the northern portion of the study area near Lake M34, a tramway was built from the Pointe du Bois generating station in 1929 (Appendix VI) to facilitate construction of the Slave Falls generating station (Lacey 1996). In 2009, the tramway was replaced with an all-weather road (Wyatt 2015; Manitoba Hydro 2016). In the southern portion of the study area near Lake M16, construction of highway 44 was completed in 1933 (Appendix VII). The road network in WPP was further enhanced by the construction of Provincial Route 307 and 309 between 1933 and 1948 with the latter passing near Lake M14 (Appendix VIII; Manitoba Infrastructure and Transportation 2016). In 1950 a gravel road was constructed past Lake M15 (Appendix IX; Manitoba Infrastructure and Transportation 2016) to allow cottage development around West Hawk Lake (Manitoba Infrastructure and Transportation 2016).

2.2.3 Lake sediment field and laboratory work

2.2.3.1 Lake selection and sediment extraction

In the summer of 2009 an initial reconnaissance was conducted to select lakes suitable for fire history reconstruction. During this survey, 30 candidate lakes were pre-selected based on size and accessibility criteria using Google Earth. Final selection of suitable lakes was determined by visiting each lake to ensure that they had no inflowing streams, a minimum water depth of 1 m, no evidence of aquatic plant growth at the centre, and minimal evidence of beaver activity (Carcaillet *et al*. 2001b; Whitlock and Anderson 2003). Of the 30 lakes surveyed, 14 were deemed suitable for fire history reconstruction, nine from southeastern Manitoba and four from northwestern Ontario.

During February 2010, eight of the 14 lakes were revisited for sediment extraction (Figure 1; Appendices I-IX; Table 1), the others having been discarded mainly due to time constraints. The collection of the sediment cores from the eight selected lakes included removal of the sediment profile from the sediment-water interface down to the sediment-clay interface (Appendix X) that represented the total post-glacial period of sediment accumulation. Lake sediments were extracted using a Kajak-Brinkhurst (KB) gravity corer (Glew *et al*. 2001) and a modified Livingstone piston corer (Glew *et al*. 2001) operated through holes drilled into the ice surface. The coring procedure required an overlap between successive cores and a minimum 20 centimeter (cm) of overlap was retained to this end. The extracted KB cores were sub-sectioned into 1 cm thick slices in the field and stored in labelled plastic bags (Figure 2 A-B). The Livingstone cores were extruded onto labelled poly-vinyl chloride tubes lined with aluminum foil and vinylidene chloride plastic (Saran™) wrap and transported to the laboratory (Figure 2 C). All samples were stored at 4°C in the laboratory while awaiting further analysis.

Table 1: The location and physical characteristics of the eight sampled lakes and the general condition of the surrounding landscape. The relief column represents general topography ranging from low-lying areas surrounded by low elevation rock outcrops (Low) through to lakes bordered by steep outcrops and extensive undulating terrain (High).

Lake	Latitude (N)	Longitude (W)	Elevation (masl)	Maximum Water Depth (m)	Maximum Length (m)	Maximum Width (m)	Area (ha)	KB Core Length (cm)	Livingstone Core Length (cm)	Relief	General Moisture
M14	50°04'32”	95°24'08”	330	1.2	400	345	8.6	51	97	Low	Hydric
M15	49°47'09”	95°11'25”	337	5.7	513	125	5.3	41	96	Med	Xeric
M16	49°48'57”	95°15'56”	341	2.5	485	124	5.0	26	90	High	Xeric-mesic
M34	50°13'48”	95°34'40”	290	4.5	300	200	4.3	39	-	Low	Mesic
O4	49°45'27”	94°52'40”	366	7.2	710	230	14.6	37	98	High	Xeric
O6	49°49'17”	94°47'01”	361	3.3	436	208	6.3	44	93	Med	Xeric
O14	50°01'42”	94°49'28”	332	8.3	360	120	7.0	36	99	Med	Xeric
O15	50°00'29”	94°58'57”	339	3.9	461	192	6.2	22	97	High	Xeric-mesic

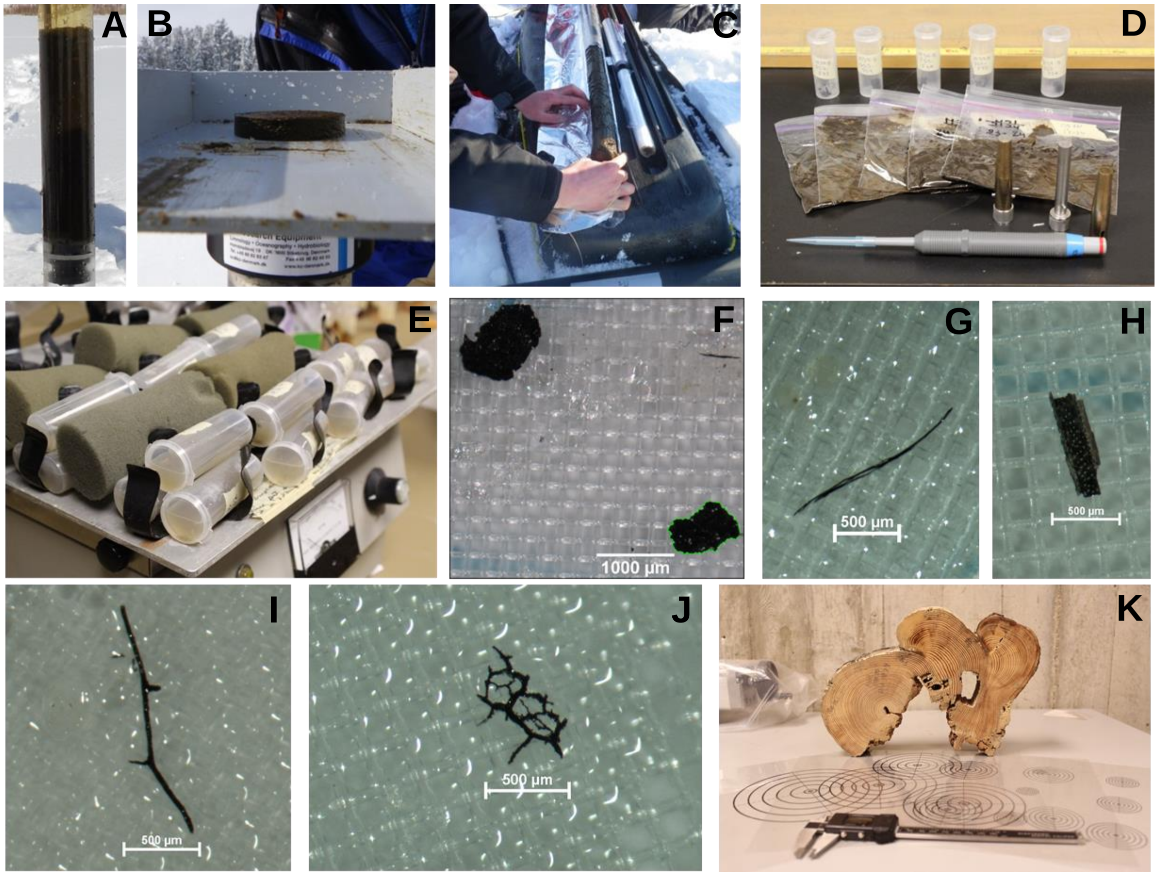


Figure 2: General procedure for the tree-ring and lake sediment sampling and methodology. The KB core extracted from the lake (A). 1 cm thick KB sediment slice in the field (B).The Livingstone core extracted from the lake (C). Vials containing 1 cm^3 subsample, bags containing 1 cm sediment slices and the 1 cm^3 Livingstone brass subsampler and 1 cm^3 KB volumetric syringe (D). Vials containing sediment solution on shake table (E). Charcoal particles on the sieve (F). The image contains three pieces of charcoal, one of which is being measured (green outline). In the background of the image, under the sieve, is the graph paper reference grid. Charcoal particle of narrow grass morphotype (G). Grass particle of wide grass morphotype (H). Charcoal particle of wood (branch) morphotype (I). Charcoal particle of wood (leaf) morphotype (J). Laminated paper and digital caliper for pith estimation (foreground) and tree cross-section (background) containing the 1863 and 1894 fire scar (K).

2.2.3.2 Sediment dating (^{210}Pb and ^{14}C) and age-depth model

Dating of the upper sediments (KB core) was undertaken using standard methods of the ^{210}Pb Constant Rate of Supply (CRS) technique (Binford 1990; Carcaillet *et al*. 2001a; Brossier *et al*. 2014). The CRS technique assumes that the ^{210}Pb content in sediments is composed of a 'supported' fraction that is supplied from *in situ* radioactive decay and an 'unsupported' fraction that is supplied from the atmosphere. The supply of the unsupported and supported ^{210}Pb is assumed to be constant in the CRS technique. The ^{210}Pb isotope is a product of the uranium decay series and is used for dating samples up to 150-200 years old based on a half-life of 22.3 years (Appleby 2001; Cohen 2003). The procedure followed in ^{210}Pb preparation was that outlined by Mycore Scientific Inc. (http://mycore.ca) and through consultation with Dr. A. Ali (Université Montpellier 2) where the initial wet weight of the homogenized sediment was obtained followed by removal of a 1 cm^3 subsample for charcoal analysis with an additional 1 cm^3 set aside for future pollen analysis (Figure 2 D). The sediment was reweighed following removal of the two 1 cm^3 subsamples and each unsealed bag of sediment was placed into an oven and dried at 40°C for an average of four days. Dry sediment was weighed, disaggregated with a mortar and pestle and sealed in new relabelled plastic bags until further analysis. For each lake, the upper 20 to 25 cm was submitted and all dating completed by MyCore Scientific Inc. The submitted samples enabled dates to be obtained for between 13 and 19 cm, depending on the lake.

Dating of the deeper (Livingstone core) sediments were undertaken on organic material or bulk sediments using the ^{14}C Accelerator Mass Spectrometry (AMS) method

(Björk and Wohlfarth 2001; Carcaillet *et al*. 2001a; Ali *et al.* 2008; Ali *et al*. 2009a). The procedure followed in ^{14}C preparation was that outlined by Beta Analytic (http://www.radiocarbon.com) and through consultation with Dr. A. Ali (Université Montpellier 2). Prior to ^{14}C dating two 1 cm^3 sub-samples were removed from the middle of each 1 cm Livingstone core sediment slice for charcoal and pollen analysis (Figure 2 D). For each core, ^{14}C sampling locations were selected at two separate portions along the Livingstone core that were located at least 50 cm apart with a 10 cm maximum established in order to help constrain the dating range (Table 2). Next, the samples that were selected for dating were soaked in sodium hexametaphosphate ($(NaPO_3)_6$) to disaggregate particles and left for 24 hours. After 24 hours the sediment was poured into a petri dish and plant macroremains identified and removed with the aid of a dissecting microscope and a pair of fine tweezers. Identification of plant material was aided by reference books (Martin and Barkley 1961; Lévesque *et al*. 1988) and through correspondence with Dr. A. Ali. If material could be confirmed as plant material it was included in the sample, otherwise it was discarded. Macroremains included needles, leaves, roots, seeds, wood and bark.

The isolated plant material was placed in an oven and dried at 40°C for approximately 48 hours. Dried macroremains were then weighed and failure to obtain the required minimum weight (>10 milligrams (mg)) resulted in processing of bulk sediments. The procedure for bulk sediment dating of Livingstone core sections entailed oven-drying 3-4 cm of bulk sediment and combining successive sediment slices until at least two grams were obtained, which is the minimum weight required for this type of

Table 2: Radiocarbon (^{14}C) summary table for AMS dating. Reported ages and standard deviation were determined on Livingstone cores using the Calib computer software. Dating attempts with potentially unreliable dates and that were subsequently re-dated are indicated by [a] and a ^{14}C dating attempt on a KB sample is indicated by [b].

Site and Depth (cm)	Age BP (Conv.)	13C:12C Ratio (%)	Cal. BP (2σ)	Material	Reference
M14					
60-63[a]	650+/-30	-19.5	720-660	Macroremains	Beta-365469
100-106[a]	560+/-30	-24.0	650-530	Macroremains	Beta-365470
40-43[b]	350+/-30	-24.3	500-310	Macroremains	Beta-373078
48-51	530+/-30	-26.0	555-515	Macroremains	Beta-373079
128-133	1240+/-30	-25.8	1270-1070	Macroremains	Beta-373080
M15					
51-61	780+/-30	-18.7	740-670	Macroremains	Beta-360844
91-101	1300+/-30	-29.2	1290-1180	Macroremains	Beta-360845
M16					
55-62[a]	1830 +/- 30	-31.2	1600-1420	Macroremains	Beta-365471
95-103[a]	1640 +/- 30	-34.9	1860-1700	Macroremains	Beta-365472
32-35	1040+/-30	-31.2	980-925	Gyttja	Beta-373081
102-105	1640+/-30	-29.1	1605-1520	Macroremains	Beta-373082
M34					
35-37	670+/-30	-29.8	670-560	Gyttja	Beta-365473
O4					
59-61	1760+/-30	-33.7	1729-1573	Gyttja	Beta-365474
99-101	2530+/-30	-30.6	2740-2490	Gyttja	Beta-365475
O6					
62-64	1460+/-30	-30.5	1400-1300	Gyttja	Beta-360846
100-102	2080+/-30	-23.0	2130-1950	Macroremains	Beta-360847
O14					
66-68	1670+/-30	-30.7	1690-1520	Gyttja	Beta-360848
96-106	2270+/-30	-27.3	2350-2160	Macroremains	Beta-360849
O15					
46-56	1840+/-30	-25.5	1860-1710	Macroremains	Beta-360850
86-96	2360+/-30	-24.7	2430-2340	Macroremains	Beta-360851

dating (Björk and Wohlfarth 2001). For each lake at least two ^{14}C samples were prepared for dating except for Lake M34 which only had one ^{14}C sample that was obtained from the KB core as the Livingstone 'A' core was unable to be extracted due to the fluidity of the sediment (Table 2). Lakes M14 and M16 had a total of five and four ^{14}C samples, respectively, as a result of resubmission of additional samples in order to resolve dating issues from the initial submission.

The dating (^{210}Pb and ^{14}C) of the sediment allowed the development of age-depth models that provided a date of deposition for each centimeter of sediment. The age-depth models first required the measured radiocarbon dates to be calibrated using the program CALIB 7.0 (Stuiver and Reimer 1993) based on IntCal13 (Reimer *et al*. 2013). Calibration between the measured radiocarbon dates and calibration datasets of known ^{14}C concentrations, obtained from tree-rings and sedimentary rocks, is necessary to convert the radiocarbon sample dates to calendar years BP. Following calibration, age-depth models were developed using the MCAgeDepth 0.1 computer program in which Monte Carlo simulations generated probability age distributions based on ^{210}Pb and ^{14}C information (Higuera 2008). The age-depth model for each of the eight lakes was calculated using 1000 Monte Carlo simulations with the parameters set as follows: a natural cubic spline with stiffness set at 0.05; an alpha value of 0.05 to generate confidence intervals; a fixed depth of 150 cm; and a variable time span that was dependant on the calibrated age. The final output of the model provided dates for each centimeter based on the initial dates and depths from the ^{210}Pb and ^{14}C samples. In addition, sediment accumulation rates (cm yr^{-1}) were provided and represented the amount of sediment accumulated in a given year, calculated by dividing a given centimeter by the number of years represented by that centimeter (sample resolution). The CALIB and MCAgeDepth programs are widely used in paleoecology (Ali *et al*. 2009b; Higuera *et al*. 2011; Brossier *et al*. 2014) and are freely available online (http://calib.qub.ac.uk/calib/, https://code.google.com/p/mcagedepth/).

2.2.3.3 Charcoal particle extraction, measurement and morphology

The analysis of the local charcoal record began with sub-sampling 1 cm^3 from the homogenized KB core sediment slice and from the middle of each Livingstone core sediment slice (1 cm thick), and the sub-sample placed into pre-labelled polypropylene hinge topped vials (Figure 2 D). Sub-sampling of the 1 cm^3 was aided by a micropipette for sampling fluid sediments and a specialized brass volumetric tool for sampling the solid sediments (Figure 2 D). The sediment in the vials was treated with a 5 percent sodium hexametaphosphate ($(NaPO_3)_6$) and 6 percent sodium hypochlorite solution to deflocculate aggregates and bleach non-charcoal material, respectively (Ali *et al*. 2008). The vials were left for 48 hours with the sediment kept in suspension on a shake table set at the minimum setting (Figure 2 E). After 48 hours the sediment was gently wet sieved through a 160 µm nylon mesh (Figure 2 F-J) in order to retain charcoal particles >160 µm (Ali *et al*. 2008). In this study only charcoal particles >160 µm in size were retained based on empirical evidence that charcoal particles above this size class represent local fires occurring within the watershed while excluding records of fires that occurred tens to hundreds of kilometers away (Whitlock and Millspaugh 1996; Whitlock and Larsen 2001; Higuera *et al*. 2007).

Following wet sieving, a section of laminated graph paper was placed on the bottom of the sieve to facilitate identification of charcoal particles and image capture. For each 1 cm^3 of sediment processed, images of every charcoal particle on the sieve were captured at 20X magnification using a Nikon DS-FI1 digital camera attached to a Nikon Eclipse 200 dissecting microscope connected to a computer with the NIS Elements Basic Research Imaging Software 3.0 (Nikon Instruments Inc. 2008). For each sample, the sieve was visually scanned following the grid lines and images captured of identified charcoal particles. Charcoal was identified based on colour and, when in doubt, particles were tested for fragility by attempting to break them with a dissecting probe (Whitlock and Larsen 2001). When this procedure was used, the image was frozen prior to breaking particles in order to retain the original structure in the event that the particle was confirmed as charcoal. All images were labelled with the Lake ID, sample depth, image number and number of charcoal particles contained within each image as part of the quality control protocol. In total, charcoal particle extraction from 976 1 cm^3 subsamples yielded in 13,752 images and 27,582 identified pieces of charcoal from the eight lakes (Appendix XI).

Following image acquisition the next step was to measure individual charcoal particles from the captured images (Figure 2 F). The charcoal images were imported into NIS Elements where a wide variety of variables could be measured including Area, Perimeter, Length, Width, Length over Width, Width over Length, Maxferet (largest value of a set of diameters), Maxferet90 (largest value of a set of diameters at 90° of MaxFeret), Minferet (minimal value of a set of diameters), Circularity (how close it approximated a circle), Elongation (ratio of Minferet to Maxferet), Linelength (length of an elongated object), and Shapefactor (roughness of an object). To facilitate automation of the measurement process a macro was developed within the program that enhanced the contrast between the charcoal particles and the surrounding background. All charcoal measurements were conducted by one of three people. In order to ensure quality control each person was trained through a series of sample images designed to span the range of difficulty inherent in charcoal identification and image quality. Measurement and identification uncertainties encountered by any of the people measuring were addressed through consultation until a consensus could be reached.

The measurement data pertaining to each charcoal particle was exported to an Excel spreadsheet where the charcoal measurements were merged to obtain the charcoal record per centimeter for each lake. Exploratory analysis of the charcoal measurements were then undertaken based on the charcoal area and count in order to facilitate comparison to the existing literature as these are the two most commonly examined parameters (Carcaillet *et al*. 2001a; Ali *et al*. 2008; Ali *et al*. 2009a; Brossier *et al*. 2014). Robust Scale regression was employed to examine the relation between charcoal count and area per cm, taking into account the effect of potential outliers which were estimated and removed using the scale-estimation procedure in Systat 12 (Systat Software Inc. 2008). The parameters used to estimate outliers in the Scale-regression were a cutoff of five (residual that is > five standard deviations from regression) based on the 95 percent confidence intervals. Although a cutoff based on three standard deviations is the standard in regression statistics (Gotelli and Ellison 2004), a conservative cutoff of five was selected to only remove the most extreme outliers from the regression. The exploratory regression analysis revealed that charcoal area and count had a highly significant ($p<0.001$) relationship (r-square=0.35-0.93) with a large charcoal particle area generally corresponding to a high number of charcoal particles (Appendix XII). Situations where a 1 cm^3 sample had a large charcoal area but a low charcoal count (ex: Lake M16) may be indicative of a fire event that occurred very close to the shore as empirical results indicated these large particles are generally transported a short distance (Clark *et al*. 1998; Lynch *et al*. 2004a). In contrast, high charcoal count without an associated high charcoal area (ex: Lake O14) may indicate a fire event that occurred within 1 km of the lakeshore, however it has been reported that a high charcoal number may also result from the breakage of larger particles (Moos and Cumming 2012).

Previous studies have shown that charcoal particles could be sub-divided into different morphotypes that could be indicative of long-term vegetation changes (Umbanhowar and Mcgrath 1998; Jensen *et al.* 2007; Aleman *et al.* 2013). For example, Aleman *et al*. (2013) examined the grass and wood component of lake sediment charcoal to determine changes in fuel type, land cover and land use over time. In this study, the classification of morphotypes began with visual identification of 300 grass-type (hereafter grass) and 300 wood-type (hereafter wood) particles from 450 images. Charcoal particles of the grass morphotype were characteristically long and slim (Figure 2 G). A smaller subset of the grass morphotype was more rectangular in shape and had visible stomata, structural elements and parallel venation (Figure 2 H). Charcoal particles of the wood morphotype were characteristically wider and more round than the grass type and included material of branch, leaf and stem origin (Figure 2 I-J). Although grass and wood morphotypes were generally easily distinguishable, confirmation of certain types was aided by consultation with reference material (Umbanhowar and Mcgrath 1998; Jensen *et al.* 2007; Aleman *et al.* 2013).

Following selection of the 600 charcoal particles a classical linear discriminant analysis was undertaken with Systat 12 to determine which measurement variables obtained from NIS Elements could be used to accurately classify particles into their respective visually identified grass or wood group. The discriminant analysis was run using a forward stepwise selection with alpha-to-enter of 0.05 and alpha-to-remove of 0.1. Of the initial measurement variables (Area, Perimeter, Length, Width, Length over Width, Width over Length, Maxferet, Maxferet90, Minferet, Circularity, Elongation, Linelength, Shapefactor) it was found that eight variables (Area, Perimeter, Width over Length, Minferet, Elongation, Length over Width, Width and Maxferet) were able to correctly classify 90 percent of the charcoal particles and so the other variables were excluded from further analysis.

Following the visual identification and classification of the 300 grass and 300 wood particles a multinomial logistic regression model was developed within Systat 12 that could be applied to classify all remaining charcoal particles as either wood or grass morphotypes. The model was developed using the independent variables identified from the discriminant analysis (Area, Perimeter, Width/Length, Minferet, Elongation, Length/Width, Width, and Maxferet). During the development of the model a forward stepwise procedure was used to determine the minimum number of variables that best classified grass and wood charcoal based on the maximization of Akaike's Information Criterion (AIC) values. Of the initial independent variables, the final model was based on the charcoal measurement variables of Width over Length, Minferet, Elongation and Perimeter (Table 3). Every charcoal particle for each lake was then classified as either grass or wood morphotype using the equation;

$$\text{Morphotype} = (\text{WoL}*5.451) + (\text{Minferet}*-0.024) + (\text{Elongation}*0.272) + (\text{Perimeter}*0.001) + 0.407$$

The classification procedure from the model resulted in grass particles (Group 1) represented as positive values and wood particles (Group 2) represented as negative values. Attributing a charcoal particle to a particular class enabled the separation of measurement variables obtained for each centimeter into the relative contribution from grass and wood. Both the grass and wood contribution to the charcoal record were converted to a ratio by dividing each by the total charcoal area for a particular centimeter. Of the two ratios, the wood contribution divided by the total charcoal area was used for all graphing and analysis.

2.2.3.4 Merging sediment cores and general procedure for converting raw charcoal data to charcoal accumulation rate (CHAR)

The next step in the analysis was to merge the charcoal data from the KB and Livingstone cores into one continuous record for each lake. This was undertaken by

Table 3: Multinomial logistic model results for determining the wood and grass morphotype component of the charcoal record. Each group was based on 300 charcoal particles obtained from 450 images. The variables comprising the final model are width over length (WOL), minferet (shortest measured axis), elongation and perimeter. Group 1 represents grass particles and Group 2 represents wood particles.

Variable	**Estimate**	**Group 1 Mean**	**Group 2 Mean**	**Standard error**	**z-ratio**	**p-value**
WOL	5.451	0.037	0.089	2.483	2.195	0.028
Minferet	-0.024	85.73	309.87	0.005	-5.012	0.000
Elongation	0272	9.756	3.109	0.091	2.974	0.003
Perimeter	0.001	2090.23	3025.26	0.000	2.786	0.005
Constant	0.407	-	-	0.793	0.513	0.608
Model χ^2	-415.888	P<0.000				
R^2	0.757					
n=	600					

examining the pattern of charcoal area and number contained within the KB and Livingstone cores and determining the best overlapping position (Ali *et al*. 2009a). The procedure for merging cores into a continuous record entailed plotting the KB and Livingstone core on separate graphs based on the initial overlap established in the field and determining if the data needed to be adjusted relative to each other based on the pattern of charcoal deposition (Appendix XIII). This procedure revealed that charcoal count was better suited than charcoal area for determining the best overlap, however both were retained here to illustrate the procedure. Once it was established how much the data should be shifted, the entire length of the KB was kept (because KB had more robust dating by ^{210}Pb) and the Livingstone core adjusted, with overlapping Livingstone data dropped, producing a continuous record from the two merged datasets. It was often observed that the KB core contained lower amounts of charcoal compared to the Livingstone core and was attributed to differential sediment compaction resulting from natural processes and sampling effects that led to more charcoal per centimeter in Livingstone cores due to lower sample resolution at greater depths (Glew *et al*. 2001).

Following the merging of the data into a continuous record the identification of fire events from charcoal contained within the lake sediments required conversion of raw charcoal data (e.g. mm^2cm^{-1}; Figure 3 A-B) to charcoal accumulation rate (CHAR; $mm^2cm^{-2}year^{-1}$; Figure 3 C-E). The general sequence of data transformation from raw charcoal to charcoal accumulation rate (CHAR) is discussed here, illustrated in Figure 3 A-E, and detailed procedures presented. Charcoal analysis first involved obtaining charcoal measurements for each centimeter (Figure 3 A). Next, the date of deposition,

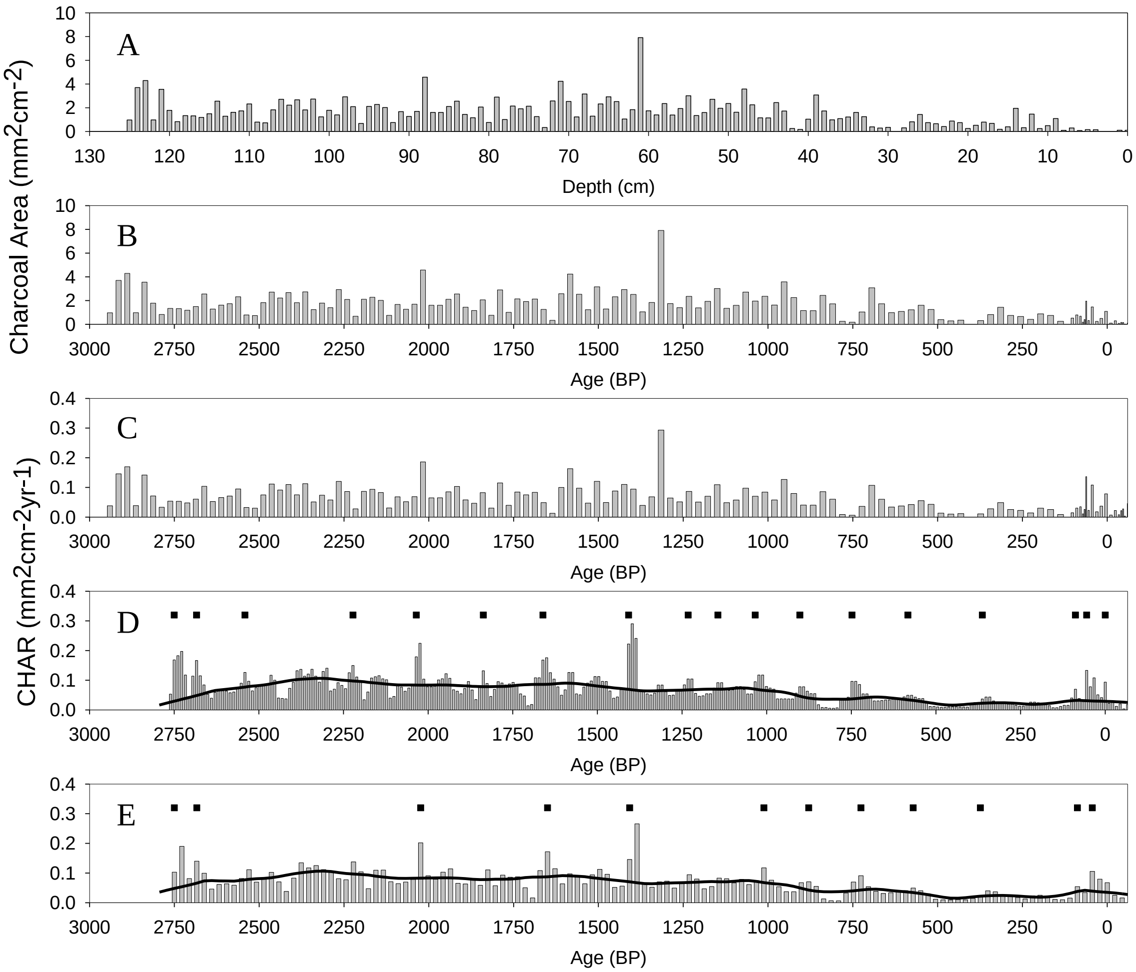


Figure 3: The procedure for converting raw charcoal measurements to CHAR for Lake O14. The figure shows the charcoal measurements per centimeter (A), the same measurements following date allocation from age-depth models (B), manually calculated CHAR (charcoal area * sediment accumulation rate) (C) and the interpolated CHAR ($C_{interpolated}$) for the recent sequence (D) and entire sequence (E). The recent (D) and entire (E) record is interpolated to 11 and 22 year time steps, respectively, based on the median resolution of the charcoal series for this lake. The low frequency variation in CHAR ($C_{background}$) is represented as values below the line determined using a 300 year smoothing window. The peak CHAR component (C_{peak}) is represented by values above the line. The CHAR peaks that were identified as significant, based on the 99 percent confidence intervals, are indicated by the black squares.

determined from the MCAgeDepth model, was attributed to each centimeter (Figure 3 B). Dating resulted in a charcoal redistribution compared to depth because of different temporal resolution for each centimeter of sediments (Figure 3 A-B). The CHAR was then calculated manually by multiplying the sedimentation rate obtained from the MCAgeDepth model by the raw charcoal area (mm^2cm^{-1}) measurements (Figure 3 C). This allowed a better understanding of the automatic procedure performed by the CHARAnalysis program. Finally, sediment detrending from CHARAnalysis ($C_{interpolated}$, $C_{background}$, C_{peak}) is depicted (Figure 3 D-E). Detrending began with the conversion of the charcoal record to equal time steps ($C_{interpolated}$) based on the median sample resolution of the charcoal series. Brossier *et al*. (2014) reported that the median resolution based on the recent sediment (~300 years; Figure 3 D) or the entire sequence (Figure 3 E) can produce different CHAR distributions and so both are presented here, with a respective median age of 11 and 22 years. The interpolation results in some redistribution of the CHAR record (Figure 3 D-E) compared to manual calculation of CHAR (Figure 3 C). From $C_{interpolated,}$ the $C_{background}$ could be estimated to remove low-frequency CHAR variability (Figure 3 D-E). Finally, CHAR peaks were isolated by removing the effects of $C_{background}$ from the $C_{interpolated}$ series (Figure 3 D-E). The isolated CHAR peaks consist of a noise (C_{noise}) and fire (C_{fire}) signal that is separated and significant peaks identified throughout the CHAR sequence (Figure 3 D-E).

2.2.3.5 Analysis of CHAR and identification of fires through peak analysis

For each of the eight lakes, the CHAR series was interpolated ($C_{interpolated}$) to equal time steps, containing a low frequency ($C_{background}$) and a high frequency (C_{peak})

component (Higuera *et al*. 2010; Brossier *et al*. 2014). The entire CHAR series was interpolated using the median sample resolution given by the recent sediment as determined by the length of the tree-ring record (1670-2010; ex: Figure 3 D). Each lake thus had a unique median age determined (Lake M14=9, M15=11, M13=9, O4=12, O6=8, O14=11, O15=10 years) for the recent period (1670-2010) that was calculated using the time span covered by each centimeter of sediment. The use of the median age derived from the most recent 300 years (1670-2010) and applied to the entire record was based on results by Brossier *et al*. (2014) who reported that the interpolation based on the temporal resolution of the recent charcoal sequence (in their case ~150 years) provided the best fit with the tree-ring fire record.

After determining the $C_{interpolated}$ series for each lake, separation of C_{peak} from $C_{background}$ was required to identify fire events. To this end, the $C_{background}$ component was modelled for each lake using a Lowess smoother robust to outliers with a 300 year smoothing window. We used a smoothing window width of 300 years based on reports by Brossier *et al*. (2014) that a 300 year window provided comparable results to longer window widths that are commonly used (Ali *et al*. 2008; Higuera *et al*. 2010; Senici *et al*. 2013), thus enabling comparison with other studies. Brossier *et al*. (2014) also reported that using a shorter smoothing window width (100 years) resulted in a low Signal to Noise Index (SNI). The C_{peak} component was then calculated by subtracting $C_{background}$ from $C_{interpolated}$ ($C_{interpolated}$ - $C_{background}$; Figure 3 D-E). The isolated C_{peak} contains a C_{noise} and a C_{fire} component representing sediment mixing, sampling error and naturally occurring variation over time, and charcoal peaks from local fires, respectively (Kelly *et* *al*. 2011; Brossier *et al*. 2014). The C_{noise} distribution was calculated using a locally defined Gaussian mixture model (Higuera *et al*. 2010; Brossier *et al*. 2014). Thresholds for peak detection were calculated for the 95^{th}, 99^{th} and 99.9^{th} percentile to separate C_{noise} into a fire (C_{fire}) and non-fire component with the 99^{th} percentile used to identify significant charcoal peaks in the charcoal record and to reconstruct the fire histories within the study area. The final determination of the peak analysis parameters were based on maximization of the signal to noise (SNI) index (typically >3) and goodness of fit (GOF; $p<0.05$) (Kelly *et al*. 2011; Brossier *et al*. 2014). A p-value >0.05 from the GOF analysis suggests that empirical and modelled C_{noise} populations are from the same distribution (Brossier *et al*. 2014).

In this study, the analysis of the entire CHAR sequence was used to 1) compare peak identification with the tree-ring record of fire history and 2) analyse changes in the fire regime recorded in the upper sediment of each lake [minimum of 0.4 m representing approximately 700 years (Lake M34); maximum of 1.5 m representing approximately 2,500 years (Lake O4)]. The CHAR procedure was specific to the unique temporal resolution of the recent sediments for each lake selected based on the length of the tree-ring record (1670-2010). The analysis of the charcoal record was also sub-divided into five periods; pre-MCA (<900 CE); MCA-LIA (900-1200 CE); end of MCA to beginning of LIA (1200-1400 CE); LIA (1400-1850 CE); and post-LIA (1850-present) in order to obtain additional fire frequency statistics from CHARAnalysis. This approach provided an analysis of changes to the fire free interval (FFI) over time within these widely reported periods of climatic variability. Analysis of the CHAR with and without subdivisions provided the same results, but returned different summary statistics. All statistical treatments were conducted with CHARAnalysis 1.1 (Higuera 2009, http://sites.google.com/site/charanalysis/).

2.2.4 Tree-ring records: field sampling and laboratory work

2.2.4.1 Collection of tree-ring records

In the summer of 2012 and 2013, the eight lakes (Figure 1; Appendix I-IX) were visited to collect the tree-ring record for fire history reconstruction. Prior to tree-ring sampling, the fire history and forest resource inventory information was obtained from the Manitoba Land Initiative (MLI) and Land Information Ontario (LIO) data warehouses, each providing a record from 1920 to present. There were three components to the tree-ring sampling: first, a systematic survey of the lake shore was done to obtain the tree-ring record immediately adjacent to the lake; second, a survey up to the 1 km limit from the shore was conducted to obtain the local tree-ring record; and third, a regional record of fire was obtained by sampling from between 1 to 20 km of the lake. To collect the local and regional record of fire each lake was divided into six equal portions (hereafter sectors) by drawing lines 1 km in length from their shoreline (Appendix II-IX). Samples collected within the 1 km limit of the lake comprised the local record and samples collected beyond 1 km comprised the regional record. Tree-ring sampling locations were informally pre-selected on Google Earth based on archival and FRI information, but final sample locations were selected based on “on-the-ground” observations. Pre-selection of sample locations favoured areas that were more likely to retain past fire information such as around fire breaks, areas with particular topographical characteristics or vegetation transition areas.

The sampling of the tree-ring records followed standard methods with both cores and cross-sections collected (Heinselman 1973; Arno and Sneck 1977; Tardif 2004). The collection of samples had the aim of 1) determining the time-since-last-fire date (stand initiation age), 2) developing a fire scar event chronology and 3) developing long tree-ring chronologies. The stand initiation age was largely determined from pioneer species, such as jack pine and trembling aspen. Jack pine and trembling aspen represented 68 and 14 percent of all samples, respectively (Table 4) and the synchronous regeneration of these species following fire can provide the approximate date of a fire event (Dansereau and Bergeron 1993; Tardif 2004; Brassard and Chen 2006). Development of long tree-ring and fire-scar chronologies from pioneer species were largely based on jack pine, as it was common around the lakes, is well adapted to regenerating after fire, can regenerate on the extensive areas of exposed rock of the study area, is susceptible to fire scarring, and is resistant to decay (Alexander 1981; Tardif 2004). At each lake tree-rings were collected within a site or a checkpoint and a record made of the GPS coordinates, elevation, number of samples collected, general forest structure, general soil characteristics, cardinal direction of fire scars, species composition, topography, and general comments.

Obtaining the stand initiation age for the local record around a lake (<1 km) was based on the establishment of a site for each species encountered. Tree-ring sampling

Table 4: Some characteristics of the tree-ring data collected for each lake. The number of sample locations represents either sites or checkpoints. Total number of trees represents a sampled tree that had either cores or a cross section removed. Chronology length and jack pine series intercorrelation represent the longest records and agreement between measurement series, respectively. Series intercorrelation was calculated within COFECHA. Samples per species represent the percent that each species contributed to the tree-ring record.

Lake		**M14**	**M15**	**M16**	**M34**	**O4**	**O6**	**O14**	**O15**
Number of sample locations		100	43	50	105	49	40	45	37
Total number of trees		381	135	273	275	218	176	246	190
Jack pine chronology length		1787-2012	1811-2012	1772-2012	1807-2012	1693-2012	1740-2012	1763-2012	1779-2012
Series intercorrelation		0.602	0.556	0.573	0.598	0.531	0.569	0.502	0.541
Percent of samples per species	*Betula papyrifera*	2	2	<1	0	2	<1	3	1
	Larix laricina	<1	0	0	0	0	0	0	3
	Picea glauca	0	0	0	0	0	<1	3	<1
	Picea mariana	37	3	3	5	0	4	5	12
	Pinus banksiana	46	82	86	40	56	86	78	69
	Pinus resinosa	1	0	0	0	26	2	<1	1
	Pinus strobus	0	<1	0	0	4	4	0	0
	Populus tremuloides	13	11	10	46	11	1	9	12
	Populus balsamifera	0	0	0	0	1	0	<1	0
	Quercus macrocarpa	0	0	0	9	0	0	0	0
	Abies balsamea	0	<1	0	0	0	0	<1	<1

within a site required the collection of two cores from the base of at least ten living trees to obtain the earliest growth rings of the tree (pith). Within a checkpoint tree-ring sampling was based on the collection of two cores from the base of at least two living trees with the aim of verifying the forest age. Obtaining the forest age for the regional record (1 to 20 km) of each lake was based on removing two cores from at least 4 living trees at each regional sample site. In general, the two cores removed from each tree in a site, checkpoint and regional site were extracted at least 90 degrees apart and were stored in labelled plastic straws. Extraction of cores from paper birch involved removal of four cores due to the prevalence of missing rings in this species.

The development of longer tree-ring and fire-scar chronologies in sites, checkpoints and regional sites was based on the collection of samples from living fire scarred trees, dead snags and downed trees and logs (Arno and Sneck 1977; Dansereau and Bergeron 1993; Tardif 2004). Collection of fire scars from living trees entailed removal of a wedge that contained the scar and the pith if possible, whereas the collection of material from snags, downed trees and logs entailed removing a full cross-section. Within 1 km of the lake the age and structure of the forest was usually relatively homogeneous and so the majority of checkpoints were associated with areas where fire scars were sampled. Checkpoints that were based on fire scar samples usually had similar forest characteristics as earlier sample locations and so often only the fire scar was collected with a record of GPS coordinates, elevation, list of samples obtained and a note made to reference an earlier site for forest and landscape conditions. All cross-sections were labelled and brought back to the laboratory for further processing.

2.2.4.2 Sample preparation and data collection

In the laboratory, the preparation and analysis of the dendrochronological samples followed standard methods (Arno and Sneck 1977; Tardif 2004; Speer 2010). The tree cores were first mounted on labelled wood moulding and allowed to dry for several days. The cores were secured to the moulding with tape and warping was prevented by applying weight. Once dry, all of the samples were sanded using a progression of sandpaper grits, beginning with 80 and ending with 600, so as to enhance the tree-rings. A similar procedure was applied for cross-sections, however only fragile and broken sections were mounted on wood.

Following sanding, the samples were visually crossdated, beginning with the cores extracted from living trees, in order to establish a master chronology. The crossdating procedure followed a modified list method (Yamaguchi 1991) that entailed comparison of tree-ring widths and abnormal growth features across many samples, ensuring the accuracy of dating. Visual crossdating was also aided by existing chronologies previously developed from the laboratory (Tardif unpublished; Girardin *et al*. 2006c). The cross-sections were also visually crossdated using the existing chronologies and the chronologies developed from the tree-cores. Crossdating of cross-sections also included identification and dating of scars, with fire scars identified based on field observations and scar morphology (Figure 2 K). During crossdating, internal fire scars that were hidden by wound closure were also identified based on similar growth characteristics as exposed fire scars.

Following crossdating, measurement of tree-ring widths was undertaken to establish long master tree-ring width chronologies for the study area that could be used to validate the crossdating. Measurement of the tree-ring widths from cores and cross-sections preferentially focussed on older samples and samples that would extend the ring-width chronology. All tree-ring measurements were obtained to an accuracy of 0.01mm using a Velmex measuring table attached to a computer containing the J2X measuring software. Measured series were imported into COFECHA in order to statistically validate both measurement and crossdating of the samples through comparison of measured segments against the master chronology (Holmes 1983). The COFECHA program statistically examines the correlation between individual tree-ring series (50 year segments) against a reference chronology and also calculates the best statistical fit within a lag of -10 and +10 years. All cross-dating, chronology development, fire scar identification, measurements and analysis were done in collaboration with F. Conciatori.

Prior to determination of the stand initiation date of each sampling site/checkpoint, the number of years to the tree-centre (pith) was estimated for samples missing the pith (Figure 2 K). The pith estimation protocol was developed with Dr. J. Tardif and was facilitated by overlaying each sample with embedded concentric circles (targets) printed onto transparency film (Figure 2 K). Tree-ring samples that contained sufficient ring arc for the innermost complete ring were first overlaid with the transparency paper and the target that best matched the curve identified. Second, the distance between the latewood of the innermost (incomplete) ring and the predicted centre (pith) of the tree was measured using a digital caliper. Third, a database of average ring-width measurements was constructed from samples that contained the pith for each species. Within the database, the pith year of each sample was set to zero and the width of the first year (and each subsequent year) from each sample was averaged together. As an example, suppose the tenth year of growth was measured to be an average of five centimeters from the pith; then if a sample without the pith was estimated to be five centimeters from the pith it would have 10 years added to its inside date. To assess the accuracy of the pith estimation procedure, measurements were periodically obtained for trees that contained one core with the pith and one core without to ensure that the estimation procedure correctly predicted the pith age. Of the 1592 trees used in this project, 859 (54%) had their pith estimated. For the trees that required pith estimation the average age adjustment was 7.6 years.

2.2.4.3 Data analysis

In order to reconstruct the tree-ring fire history three datasets were used: stand initiation dates, fire scar dates, and regional jack pine ring-width chronology. The stand initiation database for each lake was largely obtained by assessing the regeneration date of pioneer species in even-aged forest stands (cohort). Brassard and Chen (2006) reported that shade intolerant pioneer species, such as jack pine, trembling aspen and paper birch are generally some of the first to colonize a post-fire area and quickly establish an even-aged cohort. To establish the date of post-fire cohorts we dated the 1) origin of the living trees and 2) origin of the dead trees. This procedure allowed us to establish the date of stand initiation for the cohort originating from the most recent stand replacing fire (living trees) as well as for cohorts originating from past fire events (dead trees). For each site and checkpoint, a stand initiation database was developed from the living and dead material. The age determination for a particular cohort was preferentially based on the oldest tree that provided a pith age. In the absence of a pith date the oldest estimated pith-age of a cohort was taken as the time of regeneration. The stand initiation age data were then binned into 10 year age classes to obtain initiation dates for a given stand.

For each lake, a fire-scar database was constructed by recording the date of every scar within a sample and the approximate season (position in ring) of burn (dormant period, the earlywood, or the latewood). Fire scars recorded in the dormant period were attributed to a spring fire as opposed to the fall of the previous year because of the higher prevalence of spring fires in the boreal forest (Fauria and Johnson 2008). Fire scars attributable to severe fire years were the easiest to identify based on classic morphology and location in multiple sites and checkpoints. A number of scars were recorded around each lake where the cause was not certain and were often observed as additional scars on an earlier fire scar. Erring on the side of caution resulted in scars of uncertain origin to be excluded from the final analysis.

In this study a regional standard chronology was developed from the ring-width measurements of all jack pine trees for each lake based on reports from Girardin and Tardif (2005) that revealed drought conditions negatively impacted jack pine ring-width. In turn, drought conditions were often conducive to the occurrence of fire (Girardin *et al.* 2004a). Therefore, periods of growth suppression identified in the jack pine ring-width chronology can be examined to provide additional support for identified fire events. For the chronology construction, it is necessary to remove age/size related growth trends (Girardin *et al*. 2006b; Girardin and Sauchyn 2008). In this project, the jack pine tree-ring widths for each lake were standardized using a cubic smoothing spline calculated from 66 percent of the series length with a 50 percent frequency response (Girardin *et al*. 2006b; Girardin and Sauchyn 2008). Standardization of the tree-rings was undertaken using the ARSTAN 41d computer program (Cook and Holmes 1999). The standardized chronology was fitted with a 25 year running average smoother in Sigmaplot 11 (Systat Software Inc. 2008) to help decipher variability in the data. Data from the Canadian Drought Code (CDC) from Girardin *et al*. (2006b) was also obtained in order to examine the tree-ring records against moisture availability.

2.2.5 Comparing tree-ring and lake sediment fire history

The fire history derived from tree-ring data and lake sediment charcoal data were compared following two strategies. The first strategy was to examine the regional record of fire by combining the fire history data from all eight lakes into a single LWE dataset for each of the following components: stand initiation, ring width, fire scar and charcoal record. The development of the regional tree-ring fire record was done in three stages: first the stand initiation distribution for each lake was averaged after standardization to remove the influence of differential sample sizes; second, a LWE standardized ring-width chronology was developed for jack pine trees from the entire study area; third, fire scar dates obtained for each site and checkpoint were combined to obtain the frequency across the study area; fourth, was to transform the CHAR record using the standard composite approach outlined in Power *et al*. (2008), Marlon *et al*. (2008) and Blarquez *et al*. (2014) to examine CHAR regionally. Briefly, CHAR was rescaled using a minimax transformation, variance was homogenized using the Box-Cox transformation followed by transformation into Z-scores, and smoothed using a Lowess smoother (Blarquez *et al*. 2014). The short-term record was obtained using the pftransform command which bins data for rescaling and transformations, whereas the long-term record was obtained using the pftransformLF command that bins the data and smooths it using a predetermined window width (500 years in this project) during rescaling and transformations. The transformation was undertaken using the paleofire package in the RStudio (2014) application for R 3.0.2 (Blarquez *et al*. 2014; R Core Team 2014).

The second strategy for comparing the tree-ring and lake sediment charcoal record of fire was to examine the records for each lake individually to identify regional variability. Two approaches were developed with one based on examining the tree-ring record in relation to the distance from the lake edge (<500 m, 500 m-1 km, >1 km) and the other approach based on the representation of the samples around the lake (sector 1-6). The development of the charcoal record of fire for each lake consisted of three steps; interpolate the CHAR record ($C_{interpolated}$) to equal time steps based on the unique median temporal resolution for the recent sediments for each lake; isolate the background ($C_{background}$) and peak (C_{peak}) component from $C_{interpolated}$; differentiate significant CHAR peaks from noise based on the 99 percent confidence intervals.

2.2.6 Long-term fire history reconstruction from lake sediment charcoal

To compare the variability of fire in the LWE over the last millennia, two strategies were pursued. The first strategy was to examine the identified fire events (peaks) and fire-free intervals (FFI) from CHARAnalysis for the entire record and between five periods; pre-MCA (<900 CE); MCA-LIA (900-1200 CE); end of MCA to beginning of LIA (1200-1400 CE); LIA (1400-1850 CE); and post-LIA (1850-present). The establishment of the five periods was justified based on findings that the climate of central North America has been variable over time, particularly during the MCA (Laird *et al*. 2012) and during the LIA (Laird *et al*. 2003). Based on the work by Ali *et al*. (2009b) and Brossier *et al*. (2014) the fire histories of the lakes were compared using median fire free intervals (mFFI) with the non-parametric two-sample Mann-Whitney U test and examine the long-term FFI distributions (FFId) using the non-parametric Kolmogorov-Smirnov test. The second strategy was to examine changes to the relative proportion of grass and wood charcoal within the charcoal record over time. Variability in the relative contribution of grass and wood charcoal to the record could provide additional information as to how the interaction between climate and vegetation potentially contributed to changes in the fire regime (Umbanhowar and Mcgrath 1998; Jensen *et al.* 2007; Aleman *et al.* 2013). Based on the work by Jensen *et al*. (2007) a decrease in charcoal of grass morphotype will be interpreted as either a shift from lower severity surface fires to higher severity crown fires or a shift towards forest closure.

2.3 Results

2.3.1 Dating and chronological settings

The age-depth model developed for each lake revealed similar sediment depositional trends as indicated by the relative ^{210}Pb and ^{14}C activity (Appendix XIV; Figure 4). Dating based on ^{210}Pb activity also revealed that the recent rate of sediment deposition within a lake was relatively uniform over time (Figure 4). A high level of ^{210}Pb decay (Bq/kg) was initially observed in the recent sediments that decreased as the unsupported (atmospheric fraction) approached the supported (*in situ*) fraction (Appendix XIV). This decrease resulted in larger confidence intervals for deeper sediments from the decreasing ability to differentiate the unsupported and supported ^{210}Pb fractions (Figure 4). Poorer dating accuracy for deeper ^{210}Pb samples may have contributed to the abrupt change in sedimentation for ^{14}C dated samples for most lakes. The level of ^{210}Pb decay where the supported and unsupported fractions were no longer able to be differentiated within a particular lake occurred between 77 and 379 Bq/kg (Lake O6 and M34, respectively).

The long-term rate of sediment deposition, determined based on ^{210}Pb and ^{14}C dates, confirmed that sedimentation was relatively uniform over time for most lakes with the exception of Lake O15 that appeared to have a period of increased deposition between 2500-2000 BP (see Table 2; Figure 4). A slope change at the transition from ^{210}Pb to ^{14}C dated sediments was also commonly observed within lakes indicating that sedimentation was faster for the KB core compared to the Livingstone core. Each lake

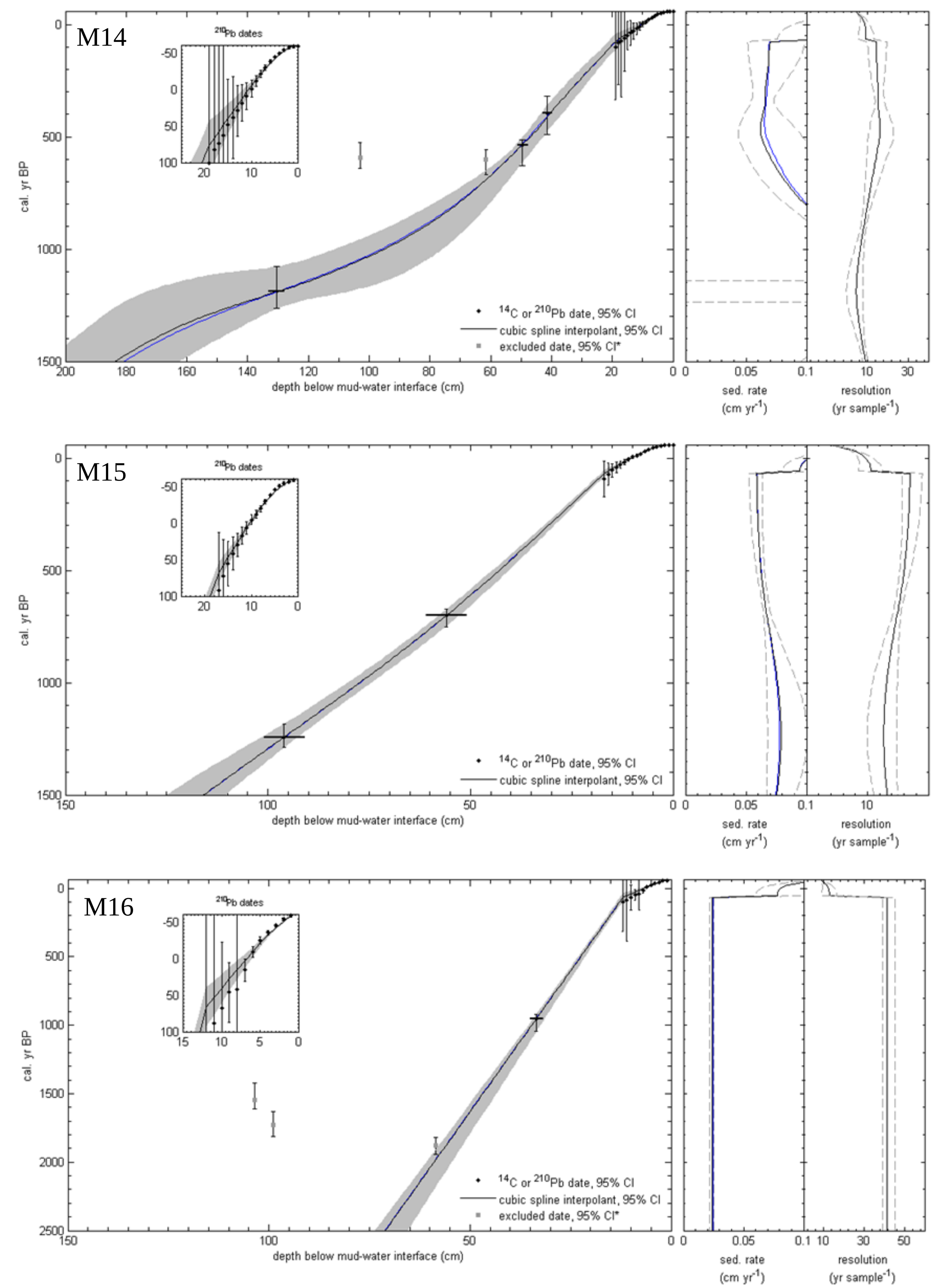
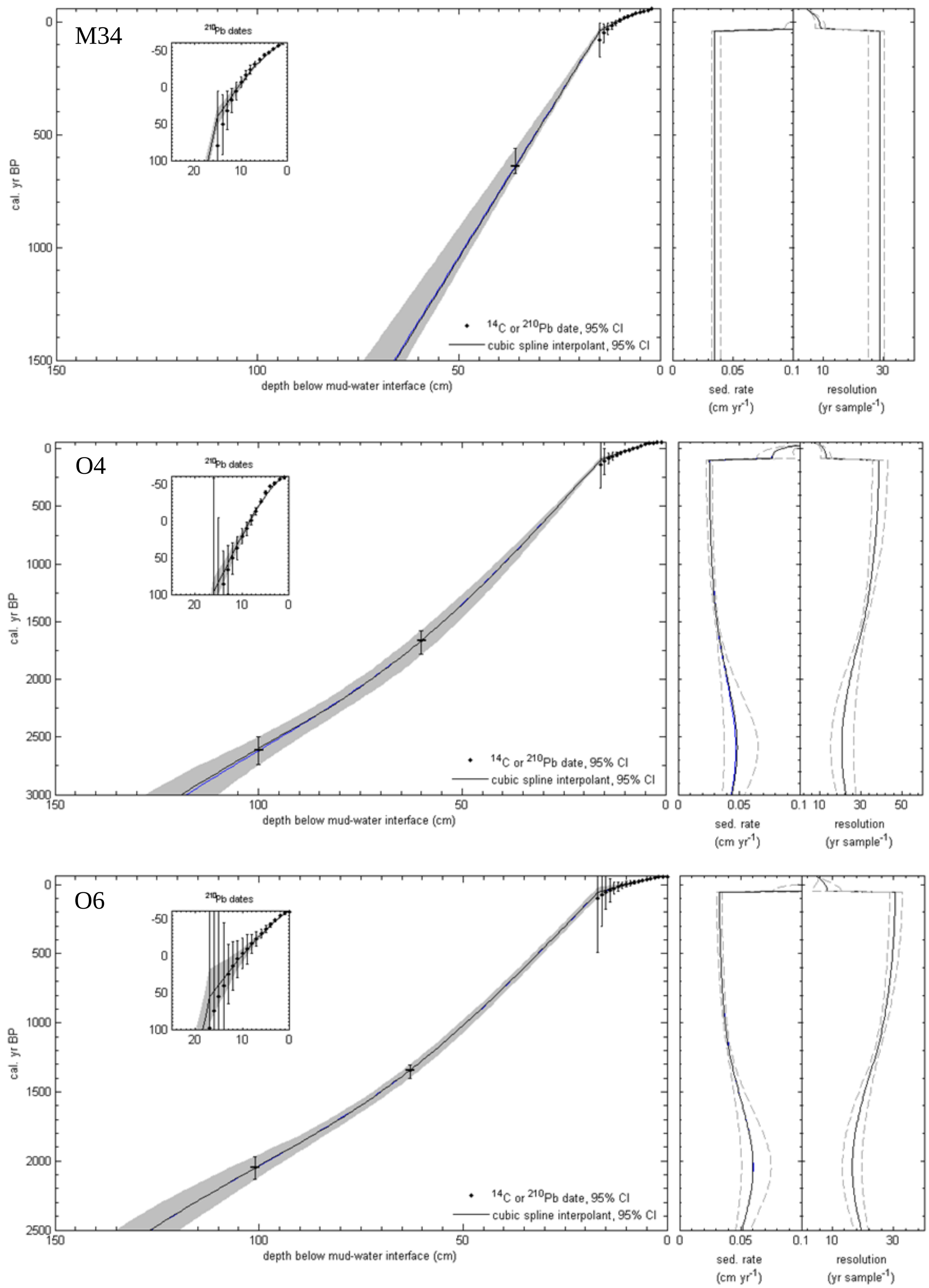


Figure 4: Age-depth models for the eight lakes. The main figure shows the age-depth model based on the ^{210}Pb and ^{14}C isotope dates. The two sub-figures on the right show the sediment accumulation rate and corresponding sample resolution. Note the different scales on the axes. All age-depth modelling was performed using the MCAgeDepth computer program (Higuera 2009).

Figure 4 Continued.



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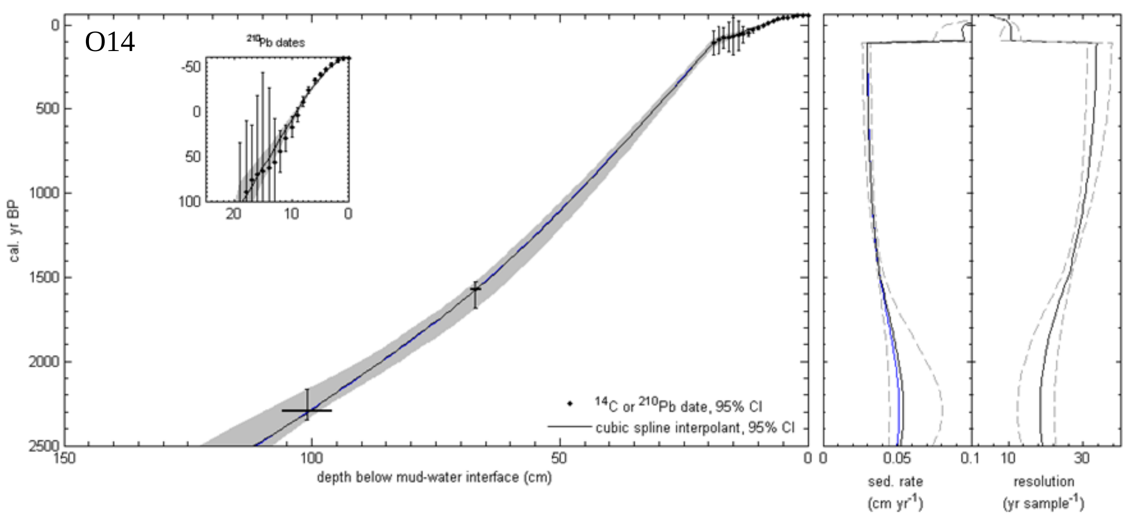

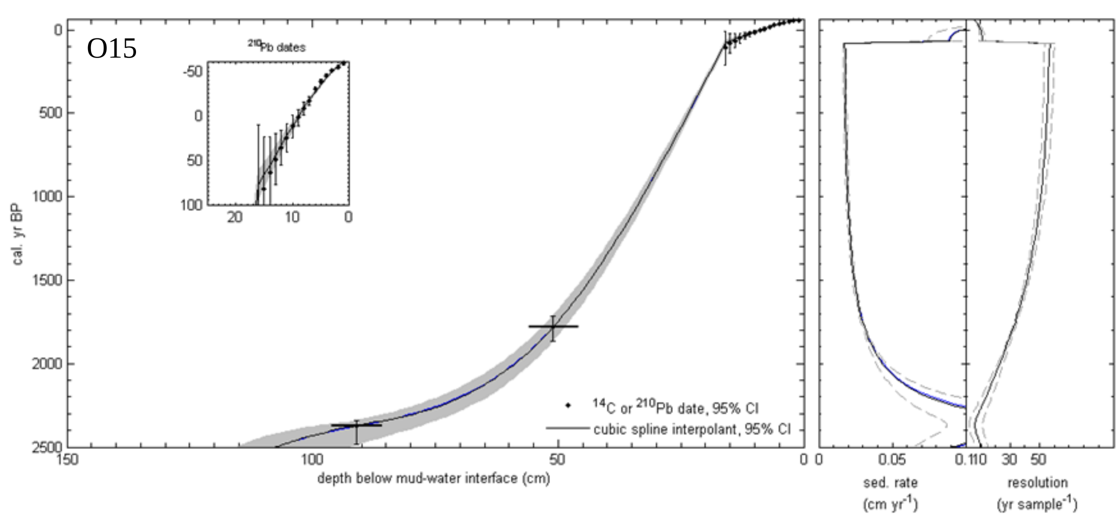

contained at least two ^{14}C dates except Lake M34 which had only one ^{14}C date because of the sediment gap during field sampling (see Table 2; Figure 4). Although Lake M16 had more than one ^{14}C date, the record was truncated at 50 cm because of an apparent period of sediment mixing approximately 1,500 years ago. Similarly, Lake M14 had two ^{14}C dates excluded based on additional dating that better fit the expected profile. The lakes from Manitoba generally had a faster sedimentation rate compared to Ontario lakes, as indicated by the respective shorter and longer timespan contained within the upper 1.5 m of sediment. For example, at 100 cm depth, Lake M15 was dated to approximately 1250 BP (700 CE) compared to 2000 BP (50 BCE) for Lake O6 (see Table 2; Figure 4).

2.3.2 Recent fire history of the central Lake of the Woods Ecoregion

2.3.2.1 Archival record

The archival records for the recent period indicated that large fires have occurred throughout the Lake of the Woods Ecoregion (hereafter LWE) in almost every decade since systematic recording began in the 1920's (Figure 5; Appendix XV). In the Manitoba portion of the study area, the archival record indicated no local (within 1 km) large fires for any of the four study lakes since 1920 (Figure 5; Appendix XV; Table 5). Within Manitoba, the closest large archival fire event to a lake occurred in 1952 for Lake M34 and 1956 for Lake M14 (approximate distance of 2 km and 5 km, respectively) and 2002 for Lake M15 and Lake M16 (approximate distance of 2.5 km and 3.5 km, respectively). The size of the fires recorded near these lakes in the 1950's and 2000's was small compared to other fires within the archival record (Figure 5; Appendix XV). In the Ontario portion of the study area large fires (>200 ha) in the archival record were

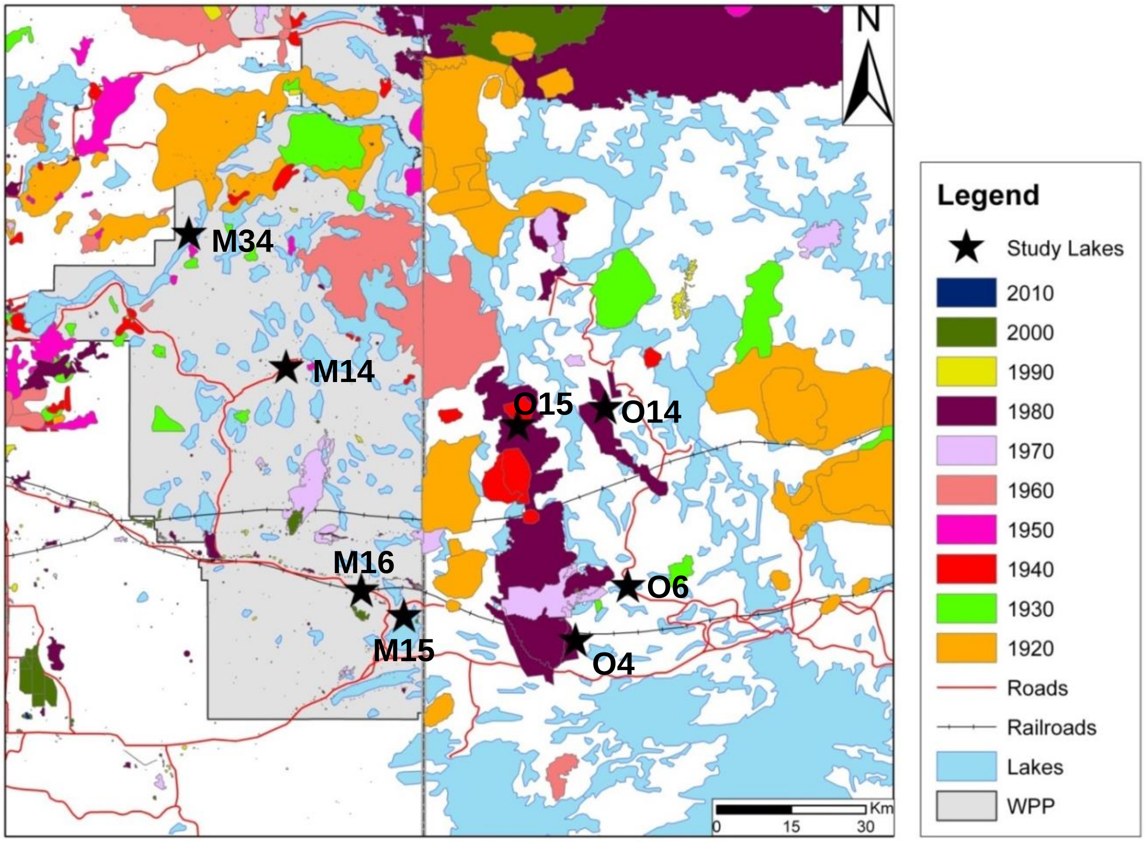

Figure 5: The historical record of fires that occurred since 1920 in the study area. The Ontario record only contains fires >200 ha in size, whereas the Manitoba record contains all recorded fires regardless of size. Data were obtained from the Manitoba and Ontario provincial fire database. The study lakes are indicated by the black stars. The extent of Whiteshell Provincial Park (WPP) is shown by the grey shading.

Table 5: Archival and associated tree-ring fire records for the eight lakes. For each fire date the presence of an archival record is indicated (Y=yes, N=no), as well as whether a fire scar was identified (Y) or not (N) along with the percentage of the stand initiation (SI) recorded. The asterisk (*) denotes fires that were identified within 1 km whereas the plus sign (+) indicates stand initiation that may represent more than one fire. For example, the 1805 fire around Lake M14 did not contain an archival record (N), but there was a fire scar (Y) and two percent of total stand initiation (2), both of which were observed within 1 km of the lake (*). The archival record for each lake represents fires (>200 ha) that occurred within 1 km of the lake, or the closest fire (>200 ha) if no archival fire was recorded within 1 km. Fire events identified through fire scars and stand initiation include those recorded at any distance.

Fire Date	Archival Record	M14	M15	M16	M34	O4	O6	O14	O15
		Scar (SI)	Scar (SI)	Scar (SI)	Scar (SI)	Scar (SI)	Scar (SI)	Scar (SI)	Scar (SI)
1756	N	-	-	-	-	Y (4)	-	-	-
1805	N	Y* (2*)	-	-	-	-	Y* (10*)	-	Y* (32*)
1820	N	-	-	-	-	-	-	-	Y* (35*+)
1840	N	-	-	-	Y* (15*)	Y* (12*+)	Y* (5+)	Y* (60*)	-
1842	N	-	-	-	-	Y (12*+)	Y (5+)	-	-
1863	N	Y* (1*)	Y (14*)	Y (2*)	-	Y* (51*)	Y* (11*)	-	-
1881	N	-	-	Y (16*)	-	-	-	-	-
1886	N	-	Y (23*)	-	-	-	-	-	-
1888	N	-	-	-	-	Y* (39*+)	-	-	-
1894	N	-	-	-	-	Y* (55*+)	Y (68*)	-	-
1906	N	-	Y (63*)	-	-	-	-	-	-
1917	N	-	-	-	-	Y* (16*)	-	-	-
1926	N	-	-	Y (32*+)	-	-	-	-	-
1930	N	-	-	Y* (32*+)	-	-	Y (5*+)	-	-
1932	N	-	-	-	-	-	Y* (5*+)	-	-
1936	N	Y* (4*)	-	-	-	-	-	-	-
1949	Y*	-	-	-	-	-	-	-	Y (27*)
1951	N	-	-	-	-	-	-	Y (16*)	-
1952	Y	-	-	-	N (19*)	-	-	-	-
1956	Y	N (5*)	-	-	-	-	-	-	-
1977	N	-	-	Y* (0)	-	-	-	-	-
1980	Y*	-	-	-	-	-	-	Y* (24*)	-
1989	Y*	-	-	-	-	N (0)	N (0)	-	N (14*)
2002	Y	-	N (0)	N (0)	-	-	-	-	-

Note: The 1949 archival and fire scar record was interpreted as a late season 1948 fire occurring after tree growth had ceased.

recorded within 1 km of Lake O15 in 1948 and 1989, of Lake O14 in 1980, and of Lake O4 in 1989 (Figure 5; Appendix XV; Table 5). In relation to the size of the fires that occurred around the lakes, the 1989 fire burned approximately 22,600 ha, the 1980 fire burned 3,900 ha, and the 1948 fire burned about 900 ha. The closest recorded fire to Lake O6 was the 1989 fire located 4 km to the west. A large fire in 1976 also burned approximately 6 km and 5 km away from Lake O4 and O6, respectively. For ELA 320 and Northwest Lake, archival fire events >200 ha were recorded within 1 km of the lakes in 1929 and 1985, respectively (Appendix XV).

2.3.2.2 Tree-ring record

In this project, 1592 trees sampled from 469 sampling locations were used to develop a tree-ring fire history from fire scars, stand initiation and ring-width measurements. Of the 469 sample locations, there was an average of 59 per lake with a minimum of 37 and a maximum of 105 (Table 4). The tree-ring record covered the last ~350 years (1670-2010) with jack pine providing the longest record (eight lake chronology averaged 243 years) for each lake (Table 4; Figure 6). The fire history represented by stand initiation of trees (Figure 6A) was largely obtained from fire adapted species, such as jack pine and trembling aspen (Table 4). Similarly, the fire history reconstruction from fire-scarred trees (Figure 6B) was largely from jack pine, red pine or white pine samples collected from within 66 (14 percent) of the sample locations and represented by 133 (53 percent) of 253 scars found. From these 133 fire scars, 20 fire years were identified with 12 located within 1 km of the lakes (Figure 6B; Table 5). One hundred and twenty of the 253 scars that could not definitively be attributed to fire events

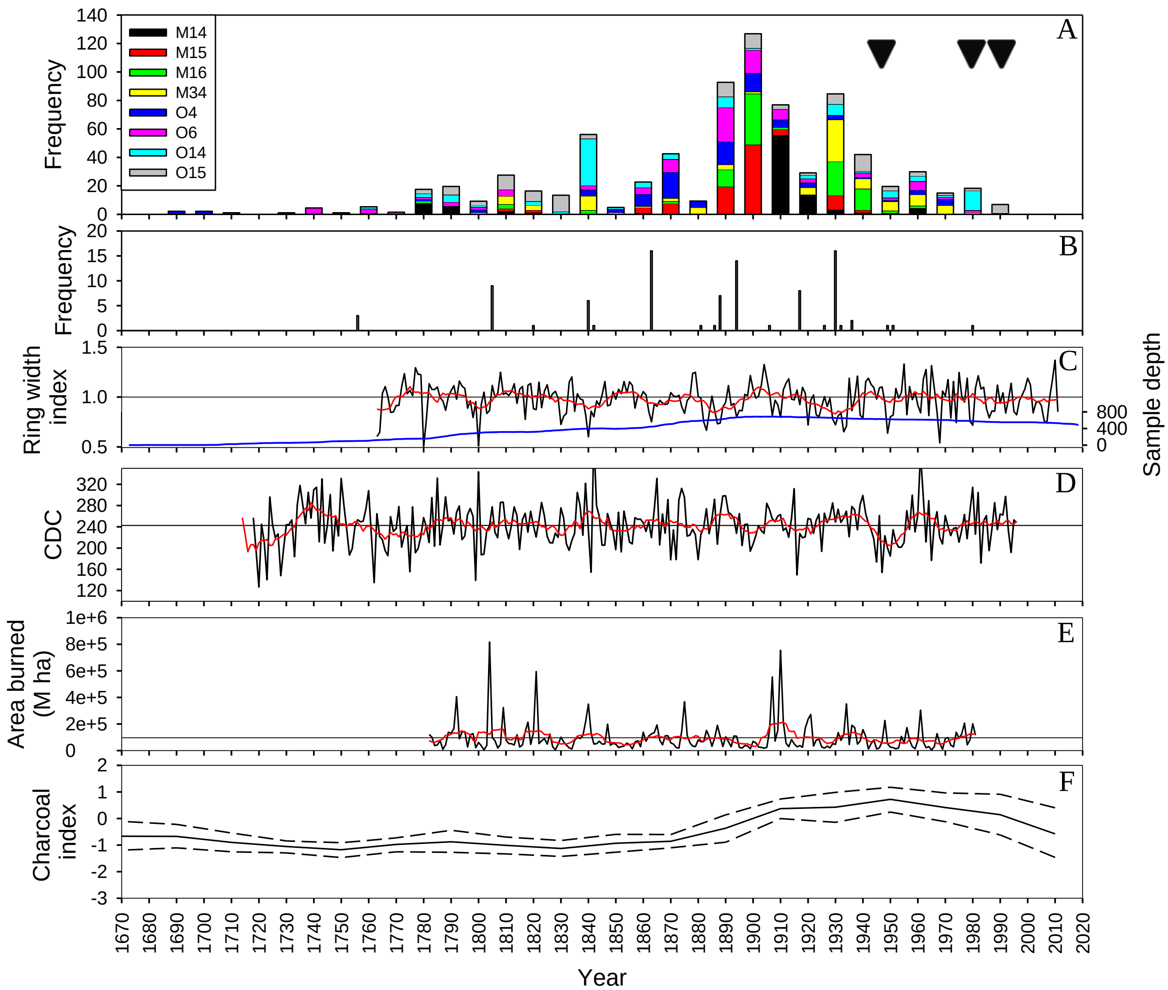

Figure 6: Composite stand initiation (A), fire scar frequency (B), standardized jack pine ring-width chronology (C), Canadian Drought Code (CDC) for the Boreal Plains (Girardin *et al*. 2006c) record (D), reconstructed Area Burned for the boreal forest of North America (Girardin 2007) record (E) and composite CHAR for the study region (F). The stand initiation data (A) represent 10 year classes (ex. 1890 = 1890-1899) and were standardized to 100 percent for each lake. The black triangles represent the fires that were recorded in the archival record (1920-2010) within 1 km of the lakes. The red line in the ring width index (C), CDC (D), and Area Burned (E) were obtained by smoothing the data with a 10 year moving average. The blue line (C) represents the number of ring-width measurements contributing to the tree-ring width index. For the composite CHAR (F) the solid line represents the CHAR index based on 20 year binning and the dashed lines represent the 95 percent confidence intervals.

were omitted from the analysis. A jack pine ring-width index chronology was also examined as the association between reduced ring-widths and drought conditions enables annual growth to be a proxy for climatic conditions associated with fire and can support observations of fire from other records. Jack pine inter-series correlation of 0.497 (specific lake value ranged between 0.502 and 0.602) confirmed that tree growth was largely influenced by common factors in our area (Table 4) and ring-width measurements from jack pine samples were used to construct a reference chronology for the most recent 248 years (Table 4; Figure 6C).

The regional tree-ring fire history of the LWE was reconstructed by compositing the standardized stand initiation distribution (Figure 6A), fire scar dates (Figure 6B), and jack pine ring-width index chronology (Figure 6C) for the eight lakes. The comparison between the regional tree-ring record and the archival record revealed that archived fires occurring in 1948, 1952, 1956, 1980 and 1989 had corresponding tree-ring records (Table 5). For example, the 1948 fire around Lake O15, the 1952 fire located 2 km to the south of Lake M34, and the 1956 fire located 5 km to the east of Lake M14 had a corresponding period of stand initiation in the 1950's (Figure 6A; Table 5) and a reduced ring-width index (Figure 6C) for the fire events, with trees around Lake O15 also recording a fire scar (Figure 6B; Table 5). The decadal resolution of the stand initiation records, compared to the annual resolution of the fire scar and ring-width records, often resulted in a delayed response between fire events and their identification within the stand initiation data. Similarly, the 1980 archival record of fire around Lake O14 had a corresponding period of stand initiation in the 1980's (Figure 6A; Table 5), a corresponding fire scar dated to 1980 (Figure 6B; Table 5), and was also supported by a period of decreased ring-width index (Figure 6C). The 1989 fire around Lake O15 had a corresponding pulse of stand recruitment in the 1990's (Figure 6A; Table 5), whereas the archived 1989 fire around Lake O4 and the 2002 fire around Lakes M15 and M16 did not contain an associated tree-ring record. However, it should be noted that in this study, a focus on obtaining older fire records means that stand initiation from more recent fire events, such as local fires in 1948, 1980, and 1989 were generally under-represented in the tree-ring record. Additional fire scar events recorded around Lake O14 in 1951 and Lake M16 in 1977 were each located in only one sample site and did not contain an associated archival record (Table 5).

The stand initiation results revealed that tree recruitment occurred for almost every decade throughout the entire record (Figure 6A). Major periods of stand initiation centered around 1810, 1840, 1860-70, 1890-1910, 1930-40 and 1950-60 were indicative of high intensity fire events (Figure 6A). Except for the 1950's-60's, these periods were also characterized by numerous fire scars and were often synchronous between lakes suggesting widespread distribution of fire conditions (Figure 6B; Table 5). Fire scar years were also associated with decreased ring widths suggesting decreased moisture availability and increased risk of fire over large areas (Figure 6B-C). Support for this is provided by the Canadian Drought Code (hereafter CDC) and the Annual Area Burned (hereafter AAB) that revealed an increase in area burned was often associated with an increase in the CDC (Figure 6D-E). The ring-width index and the CDC were significantly correlated for the common period 1768-1987 (-0.460; $p<0.000$). Moreover, both the ring-width index and CDC values were significantly different between fire and non-fire years indicating that fire years were characterized by widespread ring-width reduction associated with higher CDC values (i.e. dryer conditions) compared to the non-fire years (Figure 6C-D; Table 6). However, the agreement between the ring-width index and the CDC and AAB indices became less clear around the 1950's where an absence of prolonged above or below average ring widths was observed in the ring-width index compared to the earlier ring-width index. The regional CHAR record generally supported the tree-ring, CDC and AAB records for the LWE although a lag between the records was observed. For example, the CHAR increase since the 1870's relative to the period 1670-1870, and subsequent decrease around 1950, match the increase in fire activity during the 1800's observed in the stand initiation and fire scar records and the subsequent decrease in fire activity around 1900 (Figure 6F).

2.3.3 Tree-ring and CHAR fire history across the LWE

The LWE fire history reconstruction revealed that fire occurrence has been variable across the region with individual lakes recording both common and unique fire events (Figure 7, Appendix XVI). The tree-ring records revealed that the 19th century was characterized by widespread fire occurring in 1805, 1840, 1863 and the 1890's as indicated by major stand recruitment and/or fire scar distribution (Table 5; Figure 7, Appendix XVI). The 1890's, in particular, have been characterized by high severity crown fires that were responsible for stand recruitment. The widespread fire years identified by the tree-ring stand initiation data and/or fire scar records contained a corresponding CHAR increase/peak associated with the 1840 (Lakes M34, O4, O14),

Table 6: Tree ring-width index for years that did not contain a fire record (Non-fire) and those that did (Fire) based on the fire dates obtained from fire scars (Table 5). Also provided is an analysis between fire (Fire-b) and non-fire (Non-fire-b) years that included additional archival fire events >200 ha that occurred in the LWE (ex: 1929, 1961 and 1976). The 1756 and 1989 fire events were excluded from the analysis because they were outside the range of the CDC record. The tree-ring index was analyzed against the Canadian Drought Code (CDC) for the Boreal Plains reconstructed by Girardin *et al*. (2006a) for the period 1768-1987. For each group, the mean and standard deviation is provided, along with the results from the Kruskall-Wallis test ($p<0.05$). The tree-ring index and the CDC record were analyzed over a common period from 1768-1987.

	Non-fire n=201	Fire n=19	p-value	Non-fire-b n=196	Fire-b n=24	p-value
Ring-width						
Mean	0.990	0.861	0.000	0.994	0.858	0.000
Standard deviation	0.154	0.128		0.152	0.135	
CDC						
Mean	179.850	197.084	0.019	179.107	199.600	0.003
Standard deviation	26.510	30.793		25.691	33.040	

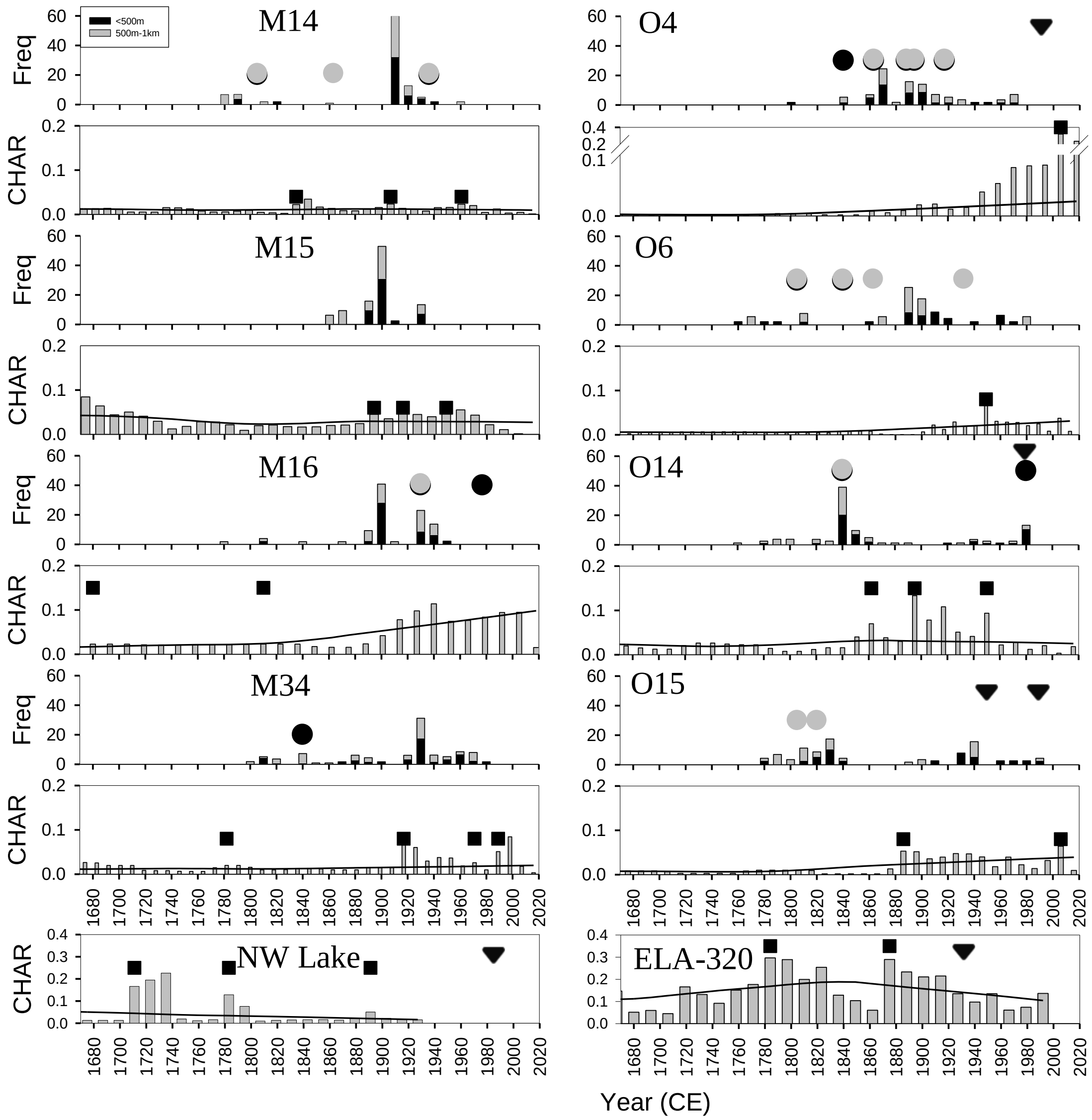

Figure 7: Individual lake fire record with tree-ring (top) and CHAR (bottom) data indicated for their overlap period. In the top panel for each lake, the local (within 1 km) stand initiation is represented by bars, whereas fire scar years are indicated by the circles. The black triangles represent archival fire records that occurred within 1 km of the lake. In the bottom panel, the bars, line and symbols represent CHAR, CHAR background and CHAR peaks (black squares), respectively. For comparison, the CHAR for Northwest Lake (NW Lake) and ELA-320 were obtained from the Global Charcoal Database and were originally sampled by Lynch *et al*. (2004a). The CHAR for all lakes was calculated using the same parameters based on lake specific median ages. Note the different scale for the y-axes.

1863 (Lakes M14, M15, M16, O4, O6) and the 1890's (Lakes M14, M15, M16, M34, O4, O14) fire events. Similarly, increased CHAR/peak identification corresponding to fire events localized around individual lakes was also observed for the 1805 (Lake M14), 1820 (Lake O15), 1930 (Lake O6), 1932 (Lake O6) and 1936 (Lake M14) fire events. Within each lake the CHAR response was often lagged by 10-30 years in relation to the tree-ring record of fire. This is well illustrated within Lake M14 where the three separate fire events identified by fire scars had corresponding CHAR peaks identified approximately 20 years after the fire event (Figure 7; Appendix XVI). More generally, an increase in the short-term CHAR composite from the mid-1800's to the mid to late 1900's revealed a lagged response to the increased frequency of fire identified from the stand initiation and fire scar records between 1800 and 1940. Charcoal data obtained for ELA-320 and Northwest Lake (Lynch *et al*. 2004a) further confirmed that CHAR is highly variable among lakes (Figure 7; Appendix XVI). In addition, the timing of increased CHAR and peak detection in ELA-320 and Northwest Lake often followed similar trends as observed for the study lakes (ex: increased CHAR and CHAR peaks identified around 1880).

Identification of fire events through peak analysis of the CHAR record of individual lakes revealed that the amount of forest that burned around a lake was an important determinant as to whether an event was recorded (Figure 7; Appendix XVI). The large fires contained within the archival record (ex: 1980 in Lake O14 and 1989 in Lake O15) that occurred in close proximity to a lake were generally associated with a CHAR peak (Figure 7), whereas the smaller archival fires (ex: 1948) did not have an associated CHAR peak (Figure 7; Appendix XVI). Further, large scale fires suggested by pronounced stand initiation or widespread fire scars were often in closer association with CHAR peaks than fires identified by smaller stand recruitment peaks or less frequent fire scars. In relation to fire size, peak analysis of larger fire events appeared to overestimate the amount of fires that occurred (ex: Lake M16 and Lake M34). In contrast, peak analysis for fire events that occurred in close succession around a lake (ex: Lake O4 and Lake O6) appeared to underestimate the fire history (Figure 7; Appendix XVI).

In contrast to fire size and timing, proximity of fire to a lake had a limited effect on peak detection (i.e. <500 m or 500 m-1 km; cardinal direction). For instance, all CHAR peaks were associated with fires that occurred within 500 m of the lake, however not all fires occurring within 500 m of the lake were identified as a CHAR peak (Figure 7). Notably, there were multiple fires identified by fire scars around Lakes O4 and O6 that did not contain an associated CHAR peak. Further, the direction of a fire in relation to the lake also appeared to have a limited influence compared to fire size. For example, the 1840 and 1863 fire years were identified by fire scars to the west of Lake O6 but did not translate into a CHAR peak as would be expected with prevailing westerly winds (Appendix XVI). Similarly, the distance between lakes had little explanatory effect as lakes in close proximity (ex: Lakes M15 and M16; Lakes O14 and O15) often contained heterogeneous CHAR records and a unique record of fire events. For example Lake M15 generally contained higher CHAR values and more CHAR peaks compared to Lake M16, despite only being located 6 km apart. The peaks identified for the ELA-320 and Northwest Lake dataset (Lynch *et al*. 2004a) also contained unique records of fire as well as detected peaks consistent with fire events identified within other lakes, particularly for the 1890's-1900's (Figure 7; Appendix XVI).

2.3.4 Multi-millennial fire history reconstruction from CHAR

The multi-millennial CHAR composite record revealed that charcoal accumulation has been variable over time (Figure 8A). Beginning in 1000 BCE, CHAR generally increased until approximately 300 BCE, suggesting that fire occurrence increased during this period. Between 500 BCE to 200 CE the maximum CHAR within the record was observed suggesting it was a period of maximum area or biomass burned. Following this maximum, a continuous decline in CHAR was observed between 200-1000 CE where CHAR values approximated those observed prior to 500 BCE. After 1000 CE another decrease in CHAR was noticed that was sustained until approximately 1600 CE, suggesting that conditions were becoming increasingly unfavourable for fire. This sustained decrease was followed by an increase in CHAR from 1600-2000 CE. Although the CHAR increased since 1600 CE, it has remained at a lower value than that observed prior to 1000 CE. Comparison between the regional CHAR record (Figure 8A) and the North American (herafter NAm) composite (Figure 8B) from Marlon *et al*. (2013) revealed that CHAR was generally similar between the two records (Figure 8). The NAm composite CHAR record supported observations of increasing fire during the early record, followed by a fire decrease around 0 CE. In the NAm CHAR composite, the sustained CHAR decrease until 1600 CE, and subsequent increase until 2000 CE, followed a similar pattern as observed for the study area composite (Figure 8). The different composite CHAR records in Figure 6 and Figure 8 were a result of the

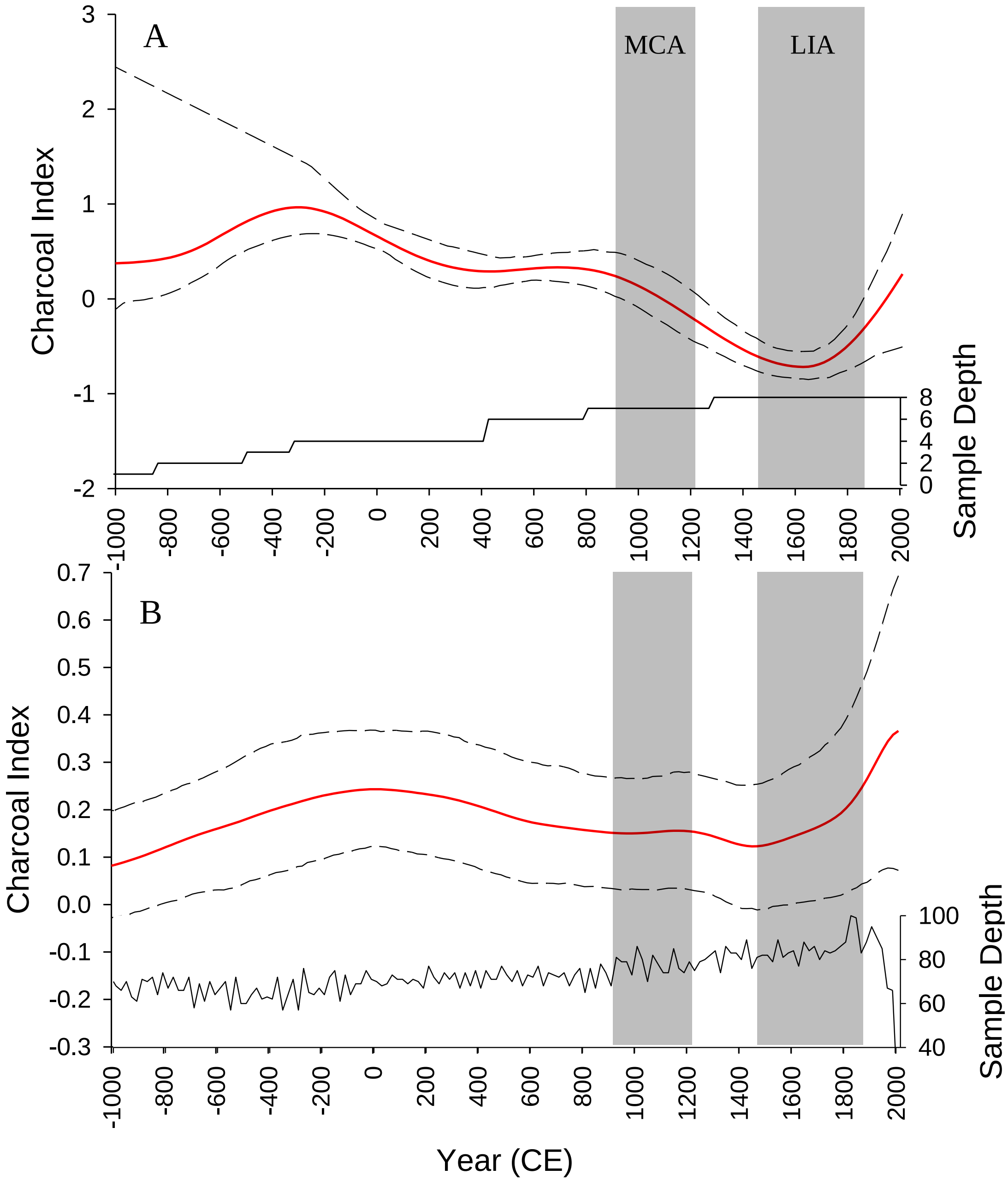

Figure 8: Composite CHAR record for the eight lakes (A) and for North America (B) from Marlon *et al*. (2013). Subfigure A is constructed by calculating charcoal influx using charcoal area from the eight lakes, whereas subfigure B is constructed from Marlon *et al*. (2013) using influx values of any type (i.e. charcoal area, count, weight) obtained from the Global Charcoal Database (GCD), Mooney *et al*. (2011) and 25 sites from other publications. The solid line represents the CHAR index based on 20 year binning and filtered through a 500 year window and the dashed lines represent the 95 percent confidence intervals. Gray shaded areas represent the MCA (900-1200 CE) and LIA (1450-1850). The composite CHAR were calculated using the procedure outlined in the paleofire package for R by Blarquez *et al*. (2014). Note the different scale for the y-axes.

variability observed in Figure 6 being removed by the smoothing procedure for Figure 8 using a 500 year window.

Within the study area, individual lakes exhibited a combination of shared and unique spatial trends (Figure 9). For example, the records obtained from the Ontario lakes were generally longer than those of the Manitoba lakes indicating that the sedimentation rate was slower in Ontario (Figure 9). Further, the Manitoba lakes revealed that CHAR decreased abruptly around the end of the MCA (~1200 CE). Peak analysis of the CHAR record identified 12 (M14), 14 (M15), 8 (M16), 7 (M34), 11 (O4), 9 (O6), 18 (O14), and 15 (O15) fire events (Figure 9; Table 7). The similarity in the number of recorded peaks among lakes, combined with the shorter record for the Manitoba lakes, indicated that more fires were identified in the Manitoba portion of the study area. Comparison of the CHAR peaks from ELA-320 (18) and Northwest Lake (15) revealed that they generally contained a similar number and distribution of peaks as that observed for the study lakes and also confirmed the heterogeneity between lakes in relatively close proximity in relation to the number and distribution of CHAR peaks (Figure 9). The distribution of CHAR peaks and of fluctuations in CHAR amount indicated that widespread fire conditions affected multiple lakes simultaneously. For example, around 1600 CE fire events observed for Lakes M14, M15, M34, O4, O6, O14, ELA-320, and Northwest Lake indicated that widespread fire conditions may have prevailed. In contrast, fluctuations in CHAR amount between multiple lakes often indicated that a shift in the fire regime may have occurred, such as that implied by lower CHAR amount and CHAR peak distribution

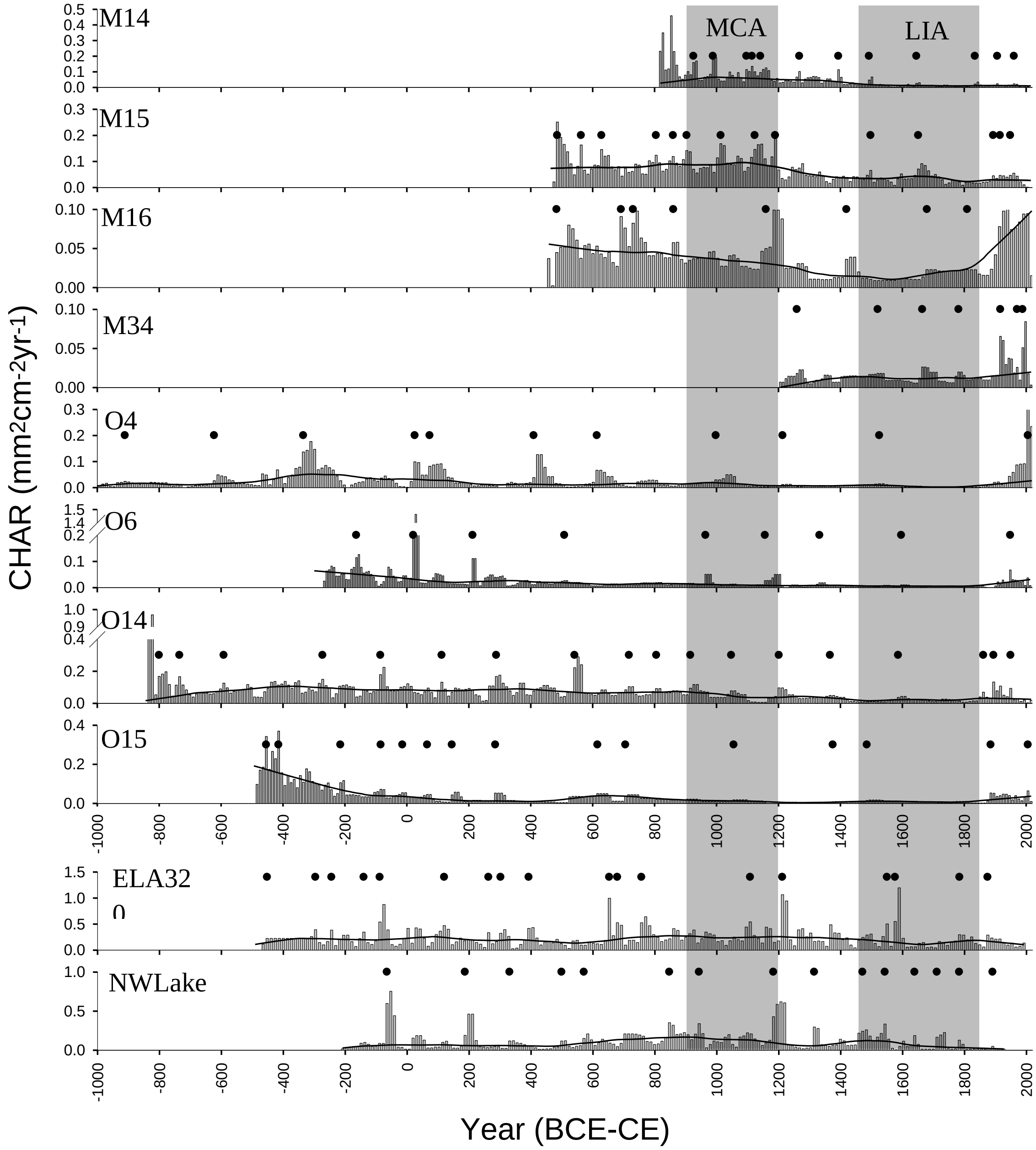

Figure 9: The millennial CHAR record for the eight lakes. The bars, black line and black dots represent CHAR, CHAR background, and fire events determined through peak analysis, respectively. The shaded areas represent the Medieval Climate Anomaly (900-1200 CE) and the Little Ice Age (1450-1850 CE), respectively. The data from ELA-320 and Northwest Lake (NW Lake) were obtained from the Global Charcoal Database and these lakes were originally sampled by Lynch *et al*. (2004a). The CHAR for all lakes was calculated using the same parameters based on lake specific median ages. Note the different scales on the y-axes.

Table 7: Median fire free interval (mFFI) and fire free interval distribution (FFId) for the eight lakes. The data presented includes the entire record without any sub-division into periods. Each record begins with the first detected peak for a particular lake with the oldest fire at the bottom of the column.

Lake	M14			M15			M16			M34		
Median age	9			11			13			9		
Record length	1132			1464			1492			744		
Fire event	Fire year (CE)	mFFI	FFId	Fire year (CE)	mFFI	FFId	Fire year (CE)	mFFI	FFId	Fire year (CE)	mFFI	FFId
1	1961	23	45	1949	28	55	1810	98	195	1989	9	18
2	1907	23	45	1916	11	22	1680	59	117	1971	5	9
3	1835	32	63	1894	6	11	1420	124	247	1917	23	45
4	1646	90	9	1652	116	231	1160	124	247	1791	63	126
5	1493	72	180	1498	72	143	861	143	286	1665	54	108
6	1394	45	144	1190	149	297	731	59	117	1521	68	135
7	1269	59	90	1124	28	55	692	13	26	1260	126	252
8	1142	59	117	1014	50	99	484	98	195			
9	1115	9	117	904	50	99						
10	1097	5	18	860	17	33						
11	989	50	99	805	22	44						
12	926	27	54	629	83	165						
13				563	28	55						
14				486	33	66						
Average		41.2	81.8		49.5	98.2		89.8	178.8		49.7	99.0
St. Dev		25.9	51.8		41.9	83.6		43.3	86.4		42.3	84.8

Table 7 continued

Lake	O4			O6			O14			O15		
Median age	12			8			11			10		
Record length	2992			2249			2794			2444		
Fire event	Fire year (CE)	mFFI	FFId	Fire year (CE)	mFFI	FFId	Fire year (CE)	mFFI	FFId	Fire year (CE)	mFFI	FFId
1	2006	12	12	1949	28	56	1950	28	55	2006	10	10
2	1526	234	468	1597	172	344	1895	22	44	1886	55	110
3	1214	150	300	1333	128	256	1862	11	22	1486	195	390
4	998	102	204	1157	84	168	1587	132	264	1376	50	100
5	614	186	372	965	92	184	1367	105	209	1056	155	310
6	410	96	192	509	224	448	1202	77	154	706	170	340
7	74	162	324	213	144	288	1048	72	143	616	40	80
8	26	18	36	21	92	184	916	61	121	286	160	320
9	-334	174	348	-163	88	176	806	50	99	146	65	130
10	-622	138	276				718	39	77	66	35	70
11	-910	138	276				542	83	165	-14	35	70
12							289	121	242	-84	30	60
13							113	83	165	-214	60	120
14							-85	94	187	-414	95	190
15							-272	88	176	-454	15	30
16							-591	154	308			
17							-734	66	132			
18							-800	28	55			
Average		128.2	255.3		116.9	233.8		73.0	145.4		78.0	155.3
St. Dev		67.7	137.5		57.5	115.0		39.6	79.3		61.5	123.8

during the LIA compared to the MCA for Lakes M14, M15, M16, O4, O14, O15, and Northwest Lake.

The long-term CHAR record also revealed a combination of shared and unique temporal trends. For this analysis, comparisons between lakes were based on the record lengths of a particular lake (Table 7). For example, all lakes were compared against Lake M34 only for the shared record of the last 744 years. Similarly, only the last 2790 years of Lake O4's 2992 year record was used based on the second longest record of Lake O14 (2790 years). The examination of the median fire free interval (mFFI) and fire free interval distribution (FFId) confirmed that lakes contained unique fire frequency and distribution records (Table 7; Figure 10). The mFFI revealed that fire occurrence ranged from 5-234 years (eight lakes averaged 78.3 years) whereas the FFId ranged from 9-468 years (eight lakes averaged 155.9 years) and revealed that lakes experienced 0-2 fire events per century (Table 7; Figure 10). The distribution of fire revealed a broad northwestern (Lakes M14, M15, M34, O14 and O15) and northeastern (Lakes M16, M34, O4, O6, O14 and O15) grouping based on statistical differences between lakes (Figure 10; Table 8). Lakes M14, M15 and M34 represented the shortest average mFFI, Lakes M16, O14 and O15 an intermediate average mFFI, and Lakes O4 and O6 represented the longest average mFFI. Statistical analysis of the mFFI revealed that Lakes M16, O4, and O6 were significantly different from Lake M14, with Lake M16 and O6 also significantly different from Lake M15 (Table 8). Lake M34 was not significantly different from any lakes in regards to mFFI (Table 8). In comparison, the examination of the FFId revealed that Lakes M14 and M15 were significantly different than Lakes M16, O4, and O6. Lake

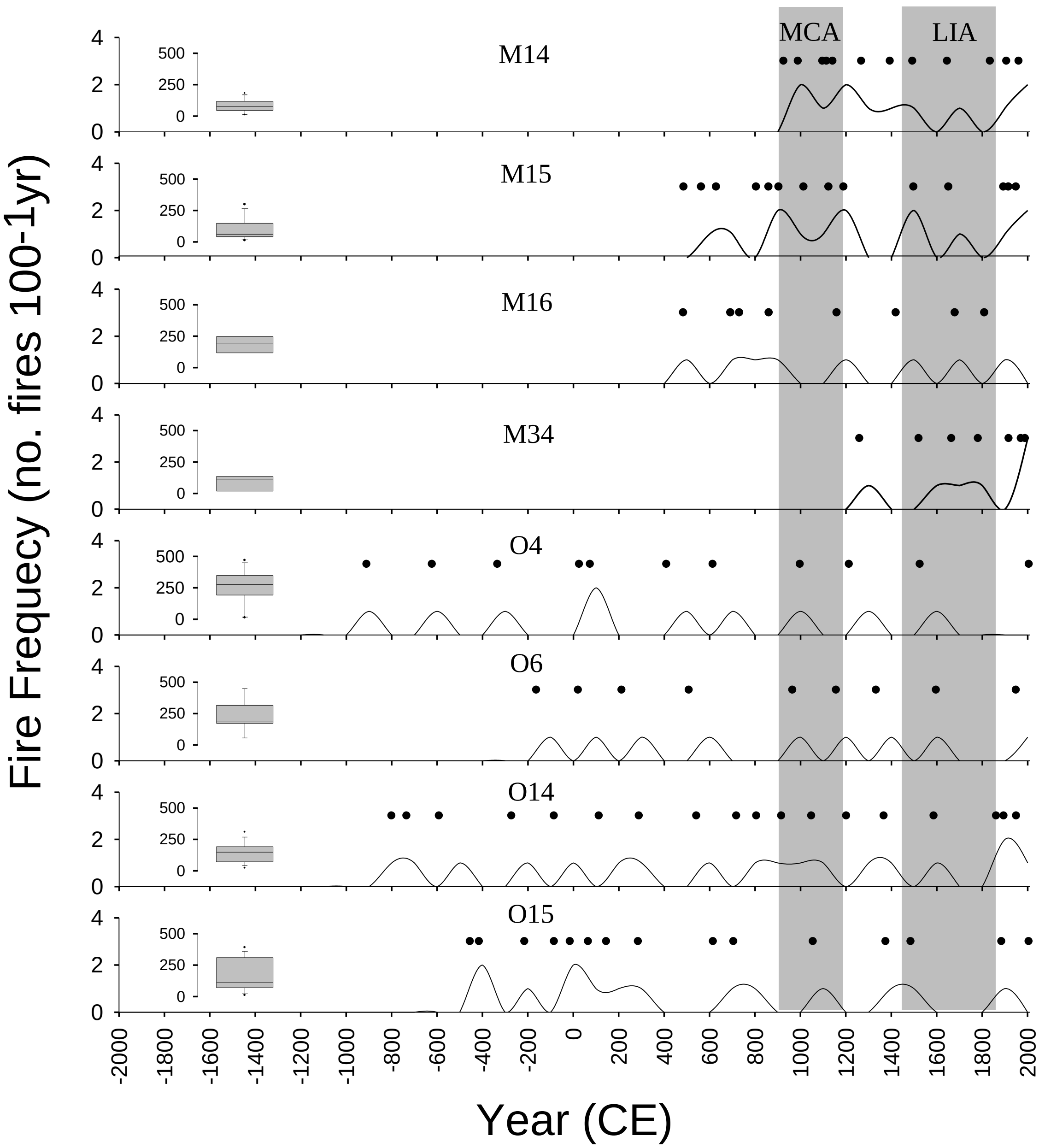

Figure 10: Fire series (black circles), fire frequency (line), and distribution of fire free intervals (box plot) for the eight lakes. The fire frequency is represented as the number of fires per 100 years. The shaded areas represent the Medieval Climate Anomaly (900-1200 CE) and the Little Ice Age (1450-1850 CE), respectively.

Table 8: Two sample Mann Whitney U test comparisons of median fire free intervals (mFFI) and fire-free interval distributions (FFId) for Lake M14, M15, M16, M34, O4, O6, O14, and O15 using the data from Table 7. Comparison between lakes for mFFI and FFId was based on the length of record for a particular lake with a minimum timespan of 744 (Lake M34) and 2792 (Lake O14) years. The grey shading represents significant differences between lakes (p≤0.05). The results for the mFFI are displayed below the line and the FFId is displayed above the line. Shading is provided to help see significant differences.

	M14	M15	M16	M34	O4	O6	O14	O15
M14	-	0.885	0.004	0.636	0.043	0.008	0.229	0.114
M15	0.908	-	0.047	0.873	0.039	0.007	0.206	0.056
M16	0.004	0.047	-	0.199	0.300	0.246	0.247	0.752
M34	0.727	0.568	0.130	-	0.439	0.136	0.749	0.715
O4	0.034	0.051	0.300	0.131	-	0.453	0.017	0.120
O6	0.008	0.018	0.246	0.089	0.369	-	0.051	0.186
O14	0.216	0.206	0.247	0.338	0.053	0.030	-	0.722
O15	0.104	0.055	0.752	0.372	0.023	0.178	0.766	-

O14 was also significantly different than Lake O4. Lakes M14, M15 and M34 represented the shortest average FFId, Lakes M16, O14 and O15 an intermediate average FFId, and Lakes O4 and O6 represented the longest FFId. For the different periods (pre-MCA (<900 CE), MCA (900-1200 CE), end of MCA to beginning of LIA (1200-1400 CE), LIA (1400-1850CE), and post- LIA (1850-present)), the examination of the mFFI and FFId revealed that there were no significant differences between lakes (not shown).

2.3.5 Charcoal morphology

The relative proportion of wood and grass type charcoal, obtained by determining the contribution of wood charcoal to the total, indicated that wood charcoal dominated the record of most lakes with the exception of Lakes M15, M34 and O14 that often contained more grass charcoal (Figure 11). For lakes with longer records (Lakes O4, O6, O14, O15) there was a decrease in wood charcoal around 200 BCE suggesting that a shift in charcoal production/deposition may have occurred that affected the entire eastern region. Although the four lakes had sustained wood CHAR increases until the end of the MCA, Lakes O6 and O14 saw pulses of decreased wood CHAR around 300 CE and 700 CE implying that conditions were more heterogeneous in the easternmost portion of the study area. Lakes M15 and M16 also had a decrease in wood CHAR around 700 CE and 600 CE, respectively, and suggested the change in conditions was widespread during this time. For the more recent record, (~900 CE-present), charcoal morphotypes revealed the pattern of accumulation diverged and became more spatiotemporally heterogeneous across the study area. Wood charcoal revealed that lakes in close proximity exhibited similar fluctuations within a northwestern (Lakes M14, M34), southwestern (Lakes M15,

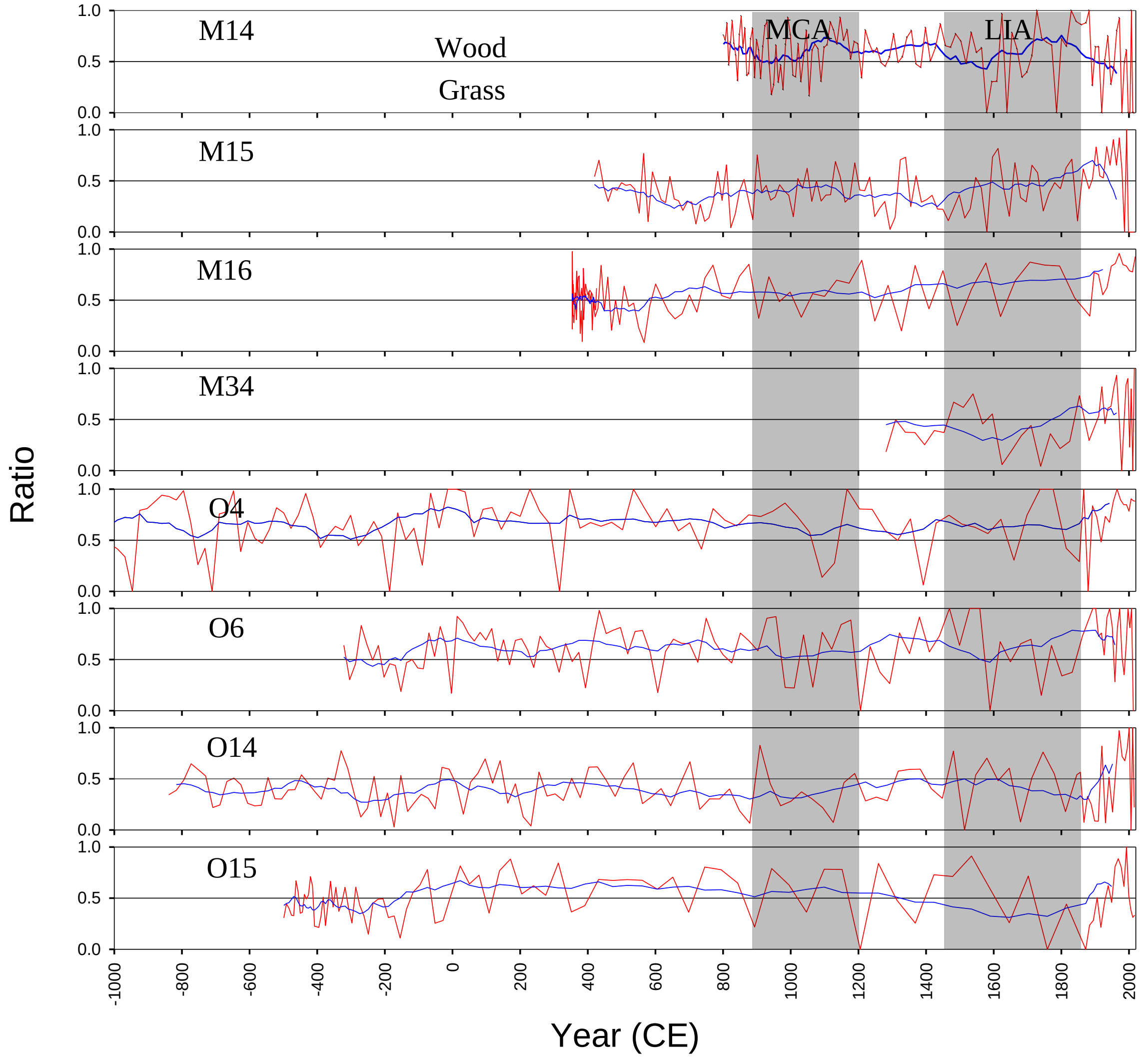

Figure 11: The relative proportion of the contribution of wood and grass charcoal types to the charcoal record. The Manitoba lakes are the top four subfigures and the Ontario lakes are the bottom four subfigures. The values above the reference line represent samples that contained more wood type charcoal. The blue line was calculated using a 10 year running average. The shaded areas represent the Medieval Climate Anomaly (900-1200 CE) and the Little Ice Age (1450-1850 CE).

M16), southeastern (Lakes O4, O6) or northeastern (Lakes O14, O15) grouping. For example, Lakes M15 and M16 generally had increasing wood CHAR throughout the recent record compared to Lakes O4 and O6 that remained relatively stable.

2.4 Discussion

2.4.1 Lake of the Woods Ecoregion modern fire history (1670-2010)

2.4.1.1 Tree-ring and archival records

Within the LWE, the period 1920-2010 provided the longest overlap between archival, tree-ring, and charcoal records of fire. The beginning of the 1920's also marks a shift in human activities towards improved record collection, active fire suppression, and industrialized agricultural, construction, and forestry techniques (Alexander 1981; Beverly 1998; Senici *et al*. 2010). This monitoring and suppression effort was implemented on a large scale beginning in the 1950's (Murphy *et al*. 2000). In general, the multi-proxy fire history reconstruction of the LWE revealed that the archival records were in better agreement with the tree-ring fire records for the latter part of the 20th century compared to the early record. For example, large (>200 ha) local (within 1 km) fires that were recorded within the archival record in 1948 (Lake O15), 1980 (Lake O14) and 1989 (Lake O15) generally had corresponding tree-ring fire records. Within central North America the 1980's fires, in particular, corresponded to reports of increased fire activity (Stocks *et al*. 2003; Blais *et al*. 1998; Fauria and Johnson 2008; Girardin and Sauchyn 2008) associated with decreased precipitation and increased temperature (Blais *et al*. 1998; Fauria and Johnson 2008; St. George *et al*. 2008; Bonsal *et al*. 2013). In some situations, the fire scar record did not have an equivalent archival fire record. An absence of an archival record in association with stand initiation or fire scars suggested that the early archival records do not contain a complete record of larger fire events. Further, lower severity fires implied by lower stand initiation and fewer fire scars indicated that the early archival record also underestimated lower severity fires. In relation to an absence of archival records for fire events in the central portion of North America, Beverly (1998) and Senici *et al*. (2010) have suggested that reduced detection associated with relatively limited transportation networks (ex: roads) and fire monitoring networks (ex: fire towers, aerial reconnaissance) may have been a contributing factor for incomplete early archival records. Murphy *et al*. (2000) reported that a similar monitoring situation existed across Canada and Alaska. Therefore, the lack of archival fire records within the LWE may have been related to poorer access to the areas prior to construction of infrastructure. Expansion of transportation networks may have even contributed to fire as suggested by the close association between the 1926 and 1930 fire events around Lake M16 and increased human activity associated with road construction of Highway 44 during this time (Wightman and Wightman 1997). Senici *et al*. (2010) observed a similar association between increased human activities, in the form of forest harvesting during the 1920's, and one of the highest periods of recent fire activity within their study area near Thunder Bay, Ontario.

2.4.1.2 Tree-ring fire records

Prior to 1920, the regional LWE tree-ring fire history reconstruction revealed that widespread fires occurred in 1805 (Lakes M14, O6, O15), 1840 (Lakes M34, O4, O6, O14), 1863 (Lakes M14, M15, M16, O4, O6), and 1894 (Lakes O4, O6), with the 1890's marking the last period of widespread stand replacing fires around the lakes until those observed in the 1980's. These widespread fire years corresponded to periods of increased drought identified within the Boreal Plains CDC reconstruction (Girardin *et al*. 2006c) and increased fire identified within the North American AAB reconstruction (Girardin

2007). Within the LWE the fire activity in 1805 occurred in association with a period of widespread drought throughout central North America in the early 1800's (Sauchyn and Skinner 2001) that also corresponded to reports of increased fire occurrence in adjacent areas of Ontario (Alexander 1981; Fritz *et al*. 1993; Girardin *et al*. 2006b), northern Minnesota (Frissell 1973; Swain 1973; Alexander 1981; Clark 1990), Manitoba (Tardif 2004; Girardin *et al*. 2006b) and western Canada (Sauchyn *et al*. 2015). The 1805 fire year also occurred during a period of increased fire activity recorded within Hudson Bay Company (hereafter HBC) archival records of northwestern Ontario between 1790 and 1805 (Fritz *et al*. 1993). Within central North America, Girardin *et al*. (2006b) identified 1804 as the year with the highest area burned for the period 1781-1982. Rannie (2001) also indicated that HBC records reported severe drought and late-season fire activity in 1804 south of modern-day Winnipeg, and so the 1805 fire year may be a late season 1804 fire or represent a multiyear drought event within central North America. Within the LWE the 1840 fire year occurred during a period between the 1830's and 1860's that the HBC archival records reported as containing lower fire activity (Fritz *et al*. 1993). However, reports of increased drought during the 1840's, identified through decreased ring-widths (St. George and Nielson 2002; Tardif 2004; St George *et al*. 2008) and increased AAB (Girardin and Sauchyn 2008) throughout central and western North America, suggested that the 1840 fire event in the LWE may have been more widespread than the HBC archival records implied. The 1863 fire event within the LWE occurred during a period of particularly severe drought in the 1860's identified across North America (Alexander 1981; Sauchyn and Skinner 2001; Herweijer *et al*. 2006; St George *et al*. 2008; St George *et al*. 2009). This drought period was also associated with widespread fire in 1863/64 reported throughout northern Minnesota (Frissell 1973; Heinselman 1973; Swain 1973; Clark 1989; Clark 1990), northwestern Ontario (Alexander 1981; Fritz *et al*. 1993; Girardin *et al*. 2006d; Scoular 2008), and Manitoba (Girardin *et al*. 2006d). Within central North America, Fritz *et al*. (1993) indicated HBC archival records reported the 1860's as a transition towards increasing fires up to the end of the 19th century. Similar to the other widespread fires, the conditions responsible for fires in the 1880's and the widespread 1894 fire event appear to be related to prolonged drought over a large area of central and western North America (Sauchyn and Beaudoin 1998; Sauchyn and Skinner 2001; Herweijer *et al*. 2006; St George *et al*. 2008; Sauchyn *et al*. 2015). The widespread drought in the 1880's and 1890's contributed to increased fire in northern Minnesota (Frissell 1973; Heinselman 1973; Clark 1989; Clark 1990), Manitoba (Tardif 2004; Girardin *et al*. 2006d; Tardif *et al*. 2016), northwestern Ontario (Alexander 1981; Fritz *et al*. 1993; Girardin *et al*. 2006d; Scoular 2008) and western North America (Rowe 1955; Tande 1979; Johnson *et al*. 1998). Following the 1890's fires, HBC archival records revealed that fire activity declined into the 1900's (Fritz *et al*. 1993).

In addition to the widespread fires identified within the LWE tree-ring records, fire events in 1756 (Lake O4), 1820 (Lake O15), 1842 (Lake O4), and 1906 (Lake M15) were potentially larger than the tree-ring record suggested as a result of the diminishing tree-ring record through time. For example, the limited distribution of the 1820 fire event implied by the tree-ring record occurred at a time of widespread drought reported throughout central and western North America during the 1820's (Sauchyn and Beaudoin

1998; Sauchyn and Skinner 2001; Girardin *et al*. 2006b; Girardin *et al*. 2006d). Further, the 1820's drought contributed to increased fire reported within northern Minnesota (Frissell 1973), northwestern Ontario (Fritz *et al*. 1993), western Manitoba (Rowe 1955; Caners and Kenkel 2003), and western North America (Sauchyn and Beaudoin 1998). Similarly, the 1842 fire year was not widely reported within North America, but did occur in association with the increased drought of the 1840's throughout central and western North America (St. George and Nielson 2002; Tardif 2004; Girardin and Sauchyn 2008; St George *et al*. 2008). The limited fire distribution suggested by the LWE tree-ring record for the 1906 fire event also appeared to be associated with more widespread occurrence of drought and fires in central (Swain 1973; Heinselman 1973; Clark 1990) and eastern North America (Bergeron and Brisson1990; Girardin *et al*. 2006d; St. George *et al.* 2009). The 1756 (Lake O4) fire event was only located at one site and its poor representation within the tree-ring record is likely an artefact of the diminishing record further back in time. However, it too corresponds to a period of increased drought in central North America reported for the 1750's-60's (Sauchyn and Skinner 2001). Within the LWE the general agreement between fire events and periods of widespread drought and fire activity suggested that the limited distribution of fire events in 1756, 1820, 1842, 1906, 1926, 1930, 1932, 1936, 1951, and 1977 indicated that tree-ring records may provide an underestimation of fire occurrence. A multi-proxy fire history reconstruction that includes charcoal analysis can therefore help verify fire periods, identify additional fire events, and extend the length of the record. An important first step in charcoal reconstructions of fire is comparison with the archival and tree-ring-records (Whitlock and Larsen 2001; Whitlock and Anderson 2003).

2.4.1.3 Charcoal records and the modern fire history reconstruction

In relation to archival and tree-ring records, the modern charcoal records revealed that the agreement between identified fire events and CHAR peaks was variable. For example, more recent large (>200 ha) local (within 1 km) fires that were recorded within the archival and tree-ring record for 1989 contained a corresponding CHAR peak (Lakes O4 and O15). In contrast, the 1948 (Lake O15) and 1980 (O14) fire events identified in the archival and tree-ring record did not contain a corresponding CHAR peak. Therefore, based on findings by Higuera *et al*. (2005) peak identification of fire events may suggest that CHAR peaks are associated with high severity events that produced a large amount of charcoal. For example, Krezek-Hanes *et al*. (2011) revealed that the 1980's decade contained the highest fire activity across North America for the 1959-2007 period, burning over 25 million ha. The 1989 fire year was found to be particularly severe, burning over 2.5 million ha of forest (Krezek-Hanes *et al*. 2011). Senici *et al*. (2010) also identified the 1980's as one of two periods of increased fire activity within central North America during the 20th century. Similarly, Tardif *et al*. (2016) indicated that 1980 was the year of the most recent large fire in Riding Mountain National Park. However, an absence of CHAR peaks for the 1980 and 1948 fire events suggested that they were smaller and that peak detection of fires may be more difficult for less severe fire events.

For the period preceding the archival records, CHAR peak identification was also variable in relation to fires identified by the LWE fire-scar record. Similar to the archival period, CHAR peaks were generally better observed for the larger, more widespread fire events in 1840 (Lakes M34, O4, O14), 1863 (Lakes M14, M15, M16, O4, O6) and the 1890's (Lakes M14, M15, M16, M34, O4, O14). This result is consistent with other studies (Higuera *et al*. 2005; Higuera *et al*. 2010) which confirmed that large, low frequency, high severity fires were best suited for peak detection. Further, CHAR peaks potentially related to the fire events localized around individual lakes in 1805 (Lake M14), and 1820 (Lake O15) suggested that these fires may have been more widespread than the tree-ring record implied. Further, peak analysis has been observed to be better suited to areas where fire events occur at intervals of at least 5 times the sediment sample resolution and poorer peak identification may occur for areas with more frequent fires (Higuera *et al*. 2010). Therefore, poorer peak analysis for lakes with frequent tree-ring fire records, such as Lakes O4 and O6, may be a result of fires occurring approximately every 30 years rather than the optimum 5 times the sampling resolution (~80 years for Lakes O4 and O6) reported for charcoal fire history reconstructions (Whitlock and Larsen 2001; Higuera *et al*. 2010).

For fire events that were identified through both tree-ring and CHAR records, many of the CHAR peaks appeared to lag behind tree-ring records by several decades and is a common occurrence related to the timing of charcoal transport and deposition (Higuera *et al*. 2005; Conedera *et al*. 2009; Brossier *et al*. 2014). For example, Higuera *et al*. (2005) observed that a CHAR peak associated with a severe 1890 fire identified within tree-rings occurred 36 years after the actual fire event. Within the LWE, the lagged response is well illustrated by Lake M14 where CHAR peaks in the 1830's, 1900's, and 1960's may be associated with fire events that occurred several decades before. The lagged effect is particularly evident for the CHAR composite record where a CHAR increase beginning near the end of the 19th century is contrary to tree-ring records showing a decrease in widespread fire beginning in the 1900's and can only be reconciled if related to a lag between actual fire events and the transport and deposition of charcoal. Despite some incongruities, the relative agreement between archival, tree-ring and CHAR records provides an opportunity to assess the modern fire history in relation to human activities and climatic changes. However, before proceeding, several inconsistencies among the records must first be examined.

2.4.1.4 Discrepancy among fire history records

Inconsistencies between tree-ring records and CHAR peaks is a common issue in charcoal analyses and has been related to a number of factors including fire size, severity, intensity, biomass availability, and wind direction (Conedera *et al*. 2009; Higuera *et al*. 2011; Brossier *et al*. 2014). For example, Higuera *et al*. (2005) reported that missed fire events may have been a function of fire severity, where small fires had limited charcoal production and large fires could produce strong updrafts that resulted in a skip distance. Whitlock and Millspaugh (1996) further revealed that wind direction was an important component as to which lakes recorded a particular fire event with lakes downwind of a fire containing a better record of the event. Underrepresentation of fire events during peak analysis also has the potential to occur for fire events in close temporal proximity (Higuera *et al*. 2005; Conedera *et al*. 2009). Higuera *et al*. (2005) reported a situation where peak analysis identified one CHAR peak in relation to two fires recorded within the tree-ring records. Within the LWE, an example of this can be seen for the 1960's

CHAR peak in Lake M14 that was identified in relation to a fire implied by the 1910's period of stand initiation and a fire identified by the 1936 fire scar. Similarly, five fires that occurred in close succession around Lake O4 were only identified as one fire within the CHAR record. Although peak analysis of fires in close succession remains an unresolved issue, methodological solutions have been suggested, such as finer sample resolution (Whitlock and Larsen 2001; Whitlock and Anderson 2003), and refined peak analysis parameters (Higuera *et al*. 2011; Brossier *et al*. 2014).

Inconsistencies between tree-ring records and CHAR peaks can also be a reflection of the parameters selected during peak analysis. For instance, peak detection in LWE lakes using the median sample resolution of the recent record better identified fire events within the tree-ring record than did the median resolution of the entire record (not shown). This is consistent with Brossier *et al*. (2014) who reported that interpolated CHAR ($C_{interpolated}$), containing the background ($C_{background}$) and peak (C_{peak}) component, was in better agreement with tree-ring records when the median resolution for the recent record was used rather than that of the entire record. Therefore, arbitrarily selected sample resolution or those calculated from the entire record may lead to an underestimation of the occurrence of fire. Further, Brossier *et al*. (2014) revealed that the selection of smoothing window width can result in different interpretations of fire history from the CHAR record. For example, they reported that longer window widths failed to detect recent fires identified within the tree-ring records compared to shorter window widths. However, shorter window widths can also result in lower signal-to-noise (SNI) ratios within the CHAR peak (C_{peak}) component and poorer separation of the fire signal

(C_{fire}) from noise (C_{noise}) (Kelly *et al*. 2011; Brossier *et al*. 2014). Brossier *et al*. (2014) indicated that a 300 year window width provided the best balance between peak detection of known fires, higher SNI values, and comparability to other studies. Therefore, missed fire events within the LWE may partially be a function of the 300 year window width that was selected. Selection of shorter window widths in the LWE (not shown), although violating the SNI threshold requirement (SNI>3), did produce a better fit with tree-ring records of fire and peak analysis may be better informed from comparison to actual fire events in the tree-ring record rather than attempting to maximize the SNI threshold.

The lagged effect between tree-ring and CHAR records could have occurred in direct relation to increased charcoal production and deposition from fire events (primary transport) or indirectly through continued transport over time (secondary transport) (Patterson III *et al*. 1987; Bradbury 1996; Whitlock and Millspaugh 1996). For primary transport, most charcoal is deposited into a lake relatively quickly. However, aquatic vegetation and the rate of sediment slumping within a lake can delay the movement of charcoal to the centre of the lake which can offset the fire record by several decades (Patterson III *et al*. 1987; Whitlock and Millspaugh 1996). For example, within the LWE, lagged CHAR increase in the 20th century, compared to decreased fire indicated in the tree-ring records, appears to be a function of these well-known taphonomic processes controlling the transport and deposition of charcoal to deeper portions of the lake (Patterson III *et al*. 1987; Whitlock and Millspaugh 1996).

Increases in CHAR could have also occurred indirectly through increased transport and deposition associated with remobilization of charcoal (secondary transport). This process can influence CHAR particularly during periods of increased or decreased moisture availability (Patterson III *et al*. 1987; Bradbury 1996; Whitlock and Millspaugh 1996). As the 20th century is generally reported as having a similar amount of precipitation, albeit distributed more heterogeneously, as the 19th century (Sauchyn and Beaudoin 1998; St. George and Nielsen 2002), it appeared that increased CHAR during the 20th century was not related to increased secondary transport associated with increased precipitation. It has also been suggested that drought conditions have the potential to cause increased secondary transport of charcoal through water level changes that can lead to CHAR increases/peaks that have no direct relation to fire events (Laird *et al*. 2012). Laird *et al*. (2012) reported that changes to relative diatom populations can help identify periods of drought that may contribute to remobilized charcoal. Inclusion of this method in CHAR analyses may provide additional information towards identifying issues and resolving inconsistencies in identification of fire events. The relative importance of these factors for charcoal production, transport and deposition is still unclear and represents an area that needs additional work.

It is also possible that the lagged effect between records is an artefact caused by the dating process. For example, increased error for ^{210}Pb dating of deeper sediment means that CHAR peaks could conceivably have occurred earlier or later than the date provided by the median age (Higuera *et al*. 2005; Higuera *et al*. 2011). A shifted date would put many CHAR peaks in better alignment with tree-ring records. Further, assigning dates to sediment samples through extrapolation between widely spaced dates may miss important periods of sediment fluctuation that could change the date assigned to a particular sample based on a particular sedimentation rate (Whitlock and Anderson 2003). Additional dating may also help resolve the abrupt change in sedimentation rate between ^{210}Pb and ^{14}C dated cores (Tardif *et al*. 2016). However, despite being observed within other studies (Haig *et al*. 2013; Brossier *et al*. 2014; Tardif *et al*. 2016), the abrupt transition between ^{210}Pb and ^{14}C dated sediment is generally not acknowledged and requires further examination. Recent studies that use only ^{14}C dating for sediments (Ali *et al*. 2009b; Ali *et al*. 2012; Senici *et al*. 2013) have also been conducted and this method may be needed for the LWE lakes to try and resolve some of the dating inconsistencies. In relation to ^{14}C dates that were omitted from the age-depth model (Lakes M14 and M16), rather than being errors, may have been indicative of variation in sediment deposition which would lead to a different fire history interpretation. These methodological issues are well documented and remain an unresolved problem inherent in fire history reconstruction from lake sediments (Whitlock and Anderson 2003; Higuera *et al*. 2005; Higuera *et al*. 2011). These results highlight the importance of multi-proxy record comparison when reconstructing fire events and indicate the reconstruction of the long-term CHAR record may provide a conservative estimate of the fire occurrence.

2.4.1.5 Modern fire history, human activities, and climatic conditions

The archaeological evidence for central North America suggested that permanent settlement had not occurred within the LWE until the arrival of the fur trade around 1600 CE (Fritz *et al*. 1993; Davidson-Hunt 2003). A subsequent increase in settlement throughout North America beginning in the 17th century brought an increase in fire occurrence (Bowman *et al*. 2013) and corresponded with a CHAR increase in the LWE beginning in the mid-LIA (~1600 CE). Continued settlement expansion (Davidson-Hunt 2003; Johnson and Miyanishi 2012; Bowman *et al*. 2013) and increasing CHAR through the 19th century suggested that fire events identified in the tree-ring record may have been related to increased ignition sources associated with agricultural, forestry, and transportation related activities. For example, Rannie (2001) indicated that HBC archival records from the Prairies contained numerous references to grass-fires associated with fur trade activities followed by a decrease around the 1880's associated with advanced European settlement. Similarly, several authors (Tardif 2004; Weir *et al*. 2000; Tardif *et al*. 2016) have reported that European settlement was associated with a lengthening of the 20th century fire cycle in western Manitoba and eastern Saskatchewan, respectively. Therefore, changes in settlement and its relation to fire may have contributed to a decrease in widespread LWE fire events after 1900 CE identified within the tree-ring records. Davidson-Hunt (2003) further suggested that the reduction in fire ~1900 CE may also have been related to the adoption of policies aimed to both discourage/penalize human activities responsible for fire occurrences, combined with a move towards active fire suppression. However, modern transportation networks, and fire monitoring and suppression techniques were well established at the time of large fire events during the 1980's suggesting that climate has also played an important role in fire occurrence.

Within the LWE, many of the major fire events have been related to climatic conditions leading to major drought. For example, LWE fire events in 1980 and 1989 are consistent with reports of increased drought occurrence beginning in the 1980's that have been linked to atmospheric pressure ridging across the boreal forest of North America (Brotak and Reifsnyder 1977; Skinner *et al*. 1999; Flannigan and Wotton 2001; Skinner *et al*. 2002; Girardin *et al*. 2004b; Girardin and Tardif 2005; Girardin *et al*. 2006c; Fauria and Johnson 2008). The dryer conditions combined with increased ignition sources associated with ridge breakdown (Newark 1975; Fauria and Johnson 2008) have also been linked to increased AAB across North America since 1980 (Skinner *et al*. 1999; Skinner *et al*. 2002; Stocks *et al*. 2003; Gillett *et al*. 2004; Girardin *et al*. 2004b; Beverly and Martell 2005; Fauria and Johnson 2006; Girardin *et al*. 2006b; Kasischke and Turetsky 2006; Skinner *et al*. 2006; Girardin 2007; Le Goff *et al*. 2007; Fauria and Johnson 2008; Girardin and Sauchyn 2008; Senici *et al*. 2010; Shabbar *et al*. 2011). For example, within central North America, Senici *et al*. (2010) observed the 1980's to be a decade of severe fires, with over 180,000 ha of their study area burning. Similarly, the LWE fire events in 1926 and the 1930's that occurred in relation to increased drought during the 1920's and 1930's (Heinselman 1973; Tardif 2004; LeFort *et al*. 2003; Girardin *et al*. 2006a; Girardin *et al*. 2006d; St. George *et al.* 2009) have also been linked to increased atmospheric pressure ridging (LeFort *et al*. 2003; Girardin *et al*. 2006a; Girardin *et al*. 2006d; St. George *et al.* 2009). Despite the appearance that the 1930's fires were not particularly severe within the LWE, Senici *et al*. (2010) have reported that AAB within their study area was actually higher than that observed for the 1980's. As increased pressure ridging has been linked to many of the LWE fire events it is possible that the longer-term fire history reconstruction may provide a record of past climatic fluctuations.

2.4.2 Millennial Lake of the Woods fire history

2.4.2.1 Long-term CHAR record

Despite some incongruity between fire events identified from archival, tree-ring and CHAR records over the last 2-3 centuries, the CHAR and peak analysis over longer periods may provide important insight into fire occurrence and frequency through time. Within the LWE, the CHAR was highest in the earlier portion of the record and lowest towards the end of the LIA. This may indicate that fire frequency or area burned has been decreasing through the latter portion of the Holocene. The long-term composite CHAR record, in particular, revealed the highest CHAR occurrence was around 200 BCE and was broadly consistent with the North American CHAR composite results of Marlon *et al*. (2013). This increased CHAR around 200 BCE corresponds with other studies from central North America (Senici *et al*. 2013; Senici *et al*. 2015) as well as with the highest temperatures of North America for the last 2,000 years (Marlon *et al*. 2008). The maximum CHAR around 200 BCE is also consistent with a period of decreased moisture availability in central North America. For example, Haig *et al*. (2013) examined diatom species assemblages within their sediment cores and revealed that the presence of shallower water species in a deep-water lake sediment core around 2000 BP indicated that lake water levels were over a meter below the Holocene average. In relation to fire occurrence, Senici *et al*. (2013) observed that the increased CHAR around 200 BCE in the Thunder Bay area was associated with a longer-term pattern of decreased median fire return interval (hereafter mFRI) between 4000-2000 BP (~2000-0 BCE). Following the maximum CHAR, the prolonged CHAR decrease within the long-term composite record until the mid to late Little Ice Age (LIA), with the exception of the Medieval Climate Anomaly (MCA), is consistent with reports of cooler conditions, decreased biomass burning (Marlon *et al*. 2008), and longer mFRI for central North America (Senici *et al*. 2013; Senici *et al*. 2015). For the recent (1670-2010) period the long-term charcoal composite record showed that CHAR has been continually increasing, whereas the short-term charcoal composite record revealed that CHAR decreased following the tree-ring record of large fires in the 19th century. This discrepancy was a result of variability within the recent composite record being removed through the 500 year smoothing procedure of the long-term composite record and suggested that this method provided an underestimation of past-fire variability. Additional work examining how different parameters for charcoal composite record construction influence the long-term CHAR profile is suggested.

In relation to LWE fire activity, the fire free interval distribution (FFId) and median fire free interval (mFFI) records revealed that lakes were broadly grouped along a west to east gradient. Within the LWE, the northwestern and northeastern FFId and mFFI grouping was also reflected in sedimentation rates that were broadly similar among Manitoba lakes and among Ontario lakes. This grouping was observed despite variable topographical and vegetation characteristics between lakes and suggested large-scale climatic conditions were important for frequent fire occurrence. Within eastern North America, Carcaillet *et al*. (2001b) also revealed that climatic fluctuations ~2000 years BP had a larger influence on the fire regime than did fluctuations in vegetation composition. Within central North America Senici *et al*. (2015) also observed that climate was the predominant driver of fire frequency, particularly for the latter half of the Holocene, with vegetation connectivity playing a larger role in fire frequency for the earlier half of the Holocene. Within the LWE the influence of the fire regime on vegetation distribution is also evident through the presence of red pine only within the two sites with the longest mFFI (Lakes O4 and O6) and their exclusion around lakes with shorter mFFI. The association between CHAR peaks and larger fire events suggested that the area around Lakes O4 and O6 was characterized by more frequent fire associated with a surface or mixed fire regime rather than a crown fire regime. Flannigan and Bergeron (1998) observed a similar trend in eastern North America where red pine was excluded from northern regions by higher fire activity.

In relation to vegetation composition, studies have revealed that increases and decreases in relative wood and grass type charcoal may be indicative of changes in fire frequency or type (Jensen *et al*. 2007; Aleman *et al*. 2013; Blarquez *et al*. 2015). For example, Jensen *et al*. (2007) observed that increased wood morphotypes were associated with closed forest canopies, whereas increased grass morphotypes were associated with forest canopies that were more open. This implied that lakes with higher wood charcoal, such as Lakes M14, M16, O4, O6, and O15 may have been characterized by more closed forests with Lakes M15, M34 and O14 characterized by more open forests. Further, Enache and Cumming (2006) indicated that an increase of wood morphotypes was a good indicator of fire activity, particularly for high intensity crown fires. This suggested that additional research comparing charcoal morphotypes to pollen records is needed to better understand the vegetation signal contained within the charcoal morphotype record.

Similarly, transformation of the charcoal morphotype record to a CHAR morphotype record and comparison to the multi-millennial CHAR record is needed to better understand the fire signal contained within the charcoal morphotype record. Although still relatively new, the analysis of charcoal morphotypes is a promising area of research that has the potential to provide supplementary information for the reconstruction of forest composition and structure, as well as fire type, severity and frequency over time.

2.4.2.2 CHAR record in relation to the Medieval Climate Anomaly and Little Ice Age

Within the long-term CHAR record, there was no sustained increase in CHAR values in association with the MCA that would suggest that fire activity was higher. The CHAR composite record revealed that fire activity may have even decreased at the beginning of the MCA. However, the CHAR record suggested that fire activity during the MCA was generally higher than that observed for the post-MCA period. Mann *et al*. (2009) have revealed that the MCA was a climatic anomaly that did not occur everywhere on earth and that it did not show a consistent temperature increase for the entire period. However, Haig *et al*. (2013) reported that MCA conditions resulted in lower water levels within northwestern Ontario. Within the LWE it appeared MCA CHAR was an extension of conditions that prevailed between ~1600 to 800 BP and was consistent with results from ELA-320 and Northwest Lake of Lynch *et al*. (2004a). This suggested that, although LWE temperatures may not have increased during the MCA, moisture conditions may have decreased, potentially leading to increased fire frequency.

Following the MCA, the CHAR resumed its progressive decrease where the composite record revealed the lowest CHAR values for the entire record occurred during the LIA around 1600 CE. Haig *et al*. (2013) revealed that, following the MCA, lake water levels in northwestern Ontario returned to their higher, pre-MCA, levels around the beginning of the LIA. Therefore, the cooler wetter conditions responsible for this lake level change may also have contributed to the decrease in fire occurrence during the LIA reported within central North America (Swain 1973; Marlon *et al*. 2013; Senici *et al*. 2013). Following the lowest CHAR values around 1600 CE, the trend towards decreasing CHAR shifted to one where CHAR was increasing and suggested fire occurrence within the LWE began to increase midway through the LIA. Senici *et al*. (2013) and Senici *et al*. (2015) observed a similar trend in the Thunder Bay area where mFRI was generally shorter towards the end of the record implying that fire activity has been increasing.

Near the end of the LIA (~1900 CE), LWE CHAR and tree-ring records suggested that fire occurrence shifted from large, widespread crown fires to a period characterized by smaller fire events. The observation of short-term drought and increased climatic heterogeneity during the 20th century is supported by the tree ring-width index where an absence of prolonged above or below average ring-widths beginning in the 1930's suggested that fluctuations in climatic conditions were of shorter duration. This shift is consistent with reports of a transition to warmer temperatures (Viau *et al*. 2012), a shorter duration of drought conditions (Fauria and Johnson 2008), and a more heterogeneous distribution of prolonged wet and dry periods compared to the MCA and LIA (Sauchyn and Skinner 2001; Laird *et al*. 2003; St. George *et al*. 2009). Although the general correspondence between the long-term CHAR record and climatic fluctuations suggested that past climate changes were responsible for changes in long-term fire frequency and severity, the long-term fire regime may also have been influenced by human activities and requires further examination.

2.4.2.3 Millennial fire history in relation to human history

The archaeological evidence suggests Aboriginal populations have been present in North America for at least 9,000 years (Johnson and Miyanishi 2012). During this time, fire has routinely been applied across North America for a variety of purposes, including maintenance of berry patches (Ferguson 2011; Anderton 1999; Davidson-Hunt 2003), improvement of grazing for hunting purposes (Day 1953; Ferguson 2011; Boyd 2002; Davidson-Hunt 2003; Johnson and Miyanishi 2012), and in inter-tribal warfare (Davidson-Hunt 2003). Modern burning practices of the Anishinaabe people of central North America (Miller and Davidson-Hunt 2010) and the Slave people of northern Alberta (Ferguson 2011) indicate that traditional methods of lighting fires during periods of low fire risk allowed the extent of purposefully set fires to be limited. For example, Ferguson (2011) revealed that the burning practices of the Slave people were to leave campfires burning in the fall when vacating an area with the expectation that sufficient fall snow-cover would limit the extent and severity of the burn. Davidson-Hunt (2003) revealed that written reports of these fire events indicated that the intention of purposely set fires was to occasionally burn an extensive area. Although traditional burning practices may have been effective at limiting area burned in the majority of cases, there would have existed the possibility of a particular fire becoming much larger than intended or of fires occurring accidentally. For example, Rannie (2001) referenced documentation from HBC records of a severe prairie fire that was accidentally set on December 1, 1800 and revealed that a fire could become very large despite ignition so late in the fire season. However, situations like this may have been limited to the prairies as forested areas burned less easily because of a better ability of preventing snowfall from blowing away (Ferguson 2011). Purposeful ignition of fire would potentially be expected to rarely result in an unanticipated widespread fire as it would not have been lit if the conditions were not appropriate. Although Aboriginal populations have routinely applied fire to the landscape (Davidson-Hunt 2003), and assuming that fire application was relatively constant through time, the progressive decrease in fire occurrence within the LWE during the last 2,500 years suggests that fire usage by aboriginal populations had a limited effect on the overall fire record. Therefore, the decreasing fire occurrence over the last few millennia appeared to be primarily related to climatic conditions.

2.4.3 Conclusion

The focus of this research was to reconstruct a 1) recent fire history for a portion of the Lake of the Woods Ecoregion (LWE) using archival, tree-ring, and lake sediment charcoal records, and 2) multi-millennial fire history using the long-term charcoal record. To this end, overlapping sediment cores collected from eight lakes were dated and analyzed to obtain the fire history from charcoal particles >160 µm in size. The modern fire history, reconstructed from tree rings using stand initiation, ring widths and fire-scar records, revealed that major fires occurred in 1805, 1840, 1863 and the 1890’s, with the 1890’s representing the last period of widespread stand replacing fires around the lakes until the 1980's. The archival and tree-ring records revealed additional large (>200 ha) fires in 1948, 1980 and 1989, whereas fires were also identified by the fire-scar record in 1756, 1820, 1842, 1881, 1886, 1888, 1906, 1926, 1930, 1932, 1936, 1951, and 1977. Many of the archival and tree-ring fire records corresponded to periods of drought and increased fire activity reported throughout central and western North America suggesting that climate has been a predominant driver of fire activity.

In relation to the tree-ring record, peak analysis of the CHAR record better reflected high severity, low frequency fire events. Peak analysis parameters that used the recent median sample resolution produced better results than the sample resolution for the entire record. Similarly, a shorter smoothing window better identified CHAR peaks than a longer window. Peak analysis of the CHAR record failed to identify several fire events, particularly those occurring in close succession. This suggested that peak analysis is more adequate when detecting infrequent fires compared to more frequent ones. Fire events may also have been missed because of a lack of charcoal deposition associated with unfavourable wind direction or in association with a skip distance that can occur in relation to high intensity fires. The CHAR record also tended to lag behind fires identified from tree-ring data by several decades and was potentially related to taphonomic processes and/or to artefacts associated with the sampling and dating processes. Therefore, fire events identified in the CHAR record provided a conservative estimate of fire occurrence.

The analysis of the multi-millennial charcoal record revealed that CHAR was higher for each lake in the earlier portion of the record followed by a progressive decrease towards the more recent record. The highest CHAR was observed ~200 BCE, with the lowest observed ~1600 CE. In relation to LWE fire activity, the fire free interval distribution (FFId), median fire free interval (mFFI), and sedimentation rate revealed that records were generally similar among Manitoba lakes, among Ontario lakes, and among ELA-320 and Northwest Lake. In relation to vegetation composition and structure, charcoal morphology may indicate that Lakes M14, M16, O4, O6, and O15 have been characterized by more closed forests with Lakes M15, M34 and O14 characterized by more open forests.

Within the long-term composite CHAR record, higher CHAR values occurred in association with the MCA compared to the post-MCA period. Following the MCA, the CHAR decreased to the lowest values for the entire record around 1600 CE. Following the lowest CHAR values, CHAR began increasing after 1600 CE and suggested fire occurrence within the LWE began to increase midway through the LIA. Near the end of the LIA (~1900 CE), fire occurrence appeared to have shifted from large, widespread crown fires to a period characterized by smaller fire events that coincided with changes in settlement and climate changes associated with the end of the LIA. The long-term fire history record and climatic fluctuations suggested that past climate changes were more influential on long-term fire frequency and severity compared to the influence of human activities.

The archival, tree-ring and CHAR records generally provided a fire history reconstruction that agreed with reported long-term changes in climate and land-use within central North America. The general agreement with reported long-term climate and fire, as well as the spatial heterogeneity between lakes present several opportunities for future research:

1) Complete the CHAR analysis for the eight lakes to assess the long-term Holocene fire record in order to better place modern fire regimes into a post-glacial context.

2) Examine how additional dating at the transition between ^{210}Pb and ^{14}C dated cores, as well as the omission of ^{210}Pb dated sediments affects peak analysis and the fit among archival, tree-ring, and CHAR records.

3) Conduct the pollen analysis to examine changes in vegetation and how they contributed to changes in the long-term fire regime.

4) Examine the charcoal morphology record in greater depth to better assess the record against pollen reconstructions of vegetation changes and the relationship of both records to the long-term CHAR reconstruction of fire events.

5) It is recommended that fire history reconstructions from CHAR be conducted using multi-lake and multi-proxy records so as to better decipher signals from noise and sort out variability among lakes. The variability in the CHAR record among lakes and in relation to the archival and tree-ring data suggest that fire histories conducted through CHAR alone, or from a limited number of lakes may be overlooking considerable variability across relatively small spatial scales.

6) The potential for diatom analyses to identify periods of drought and potential remobilization of charcoal in relation to periods of water level changes may also be a powerful tool for fire history reconstructions.

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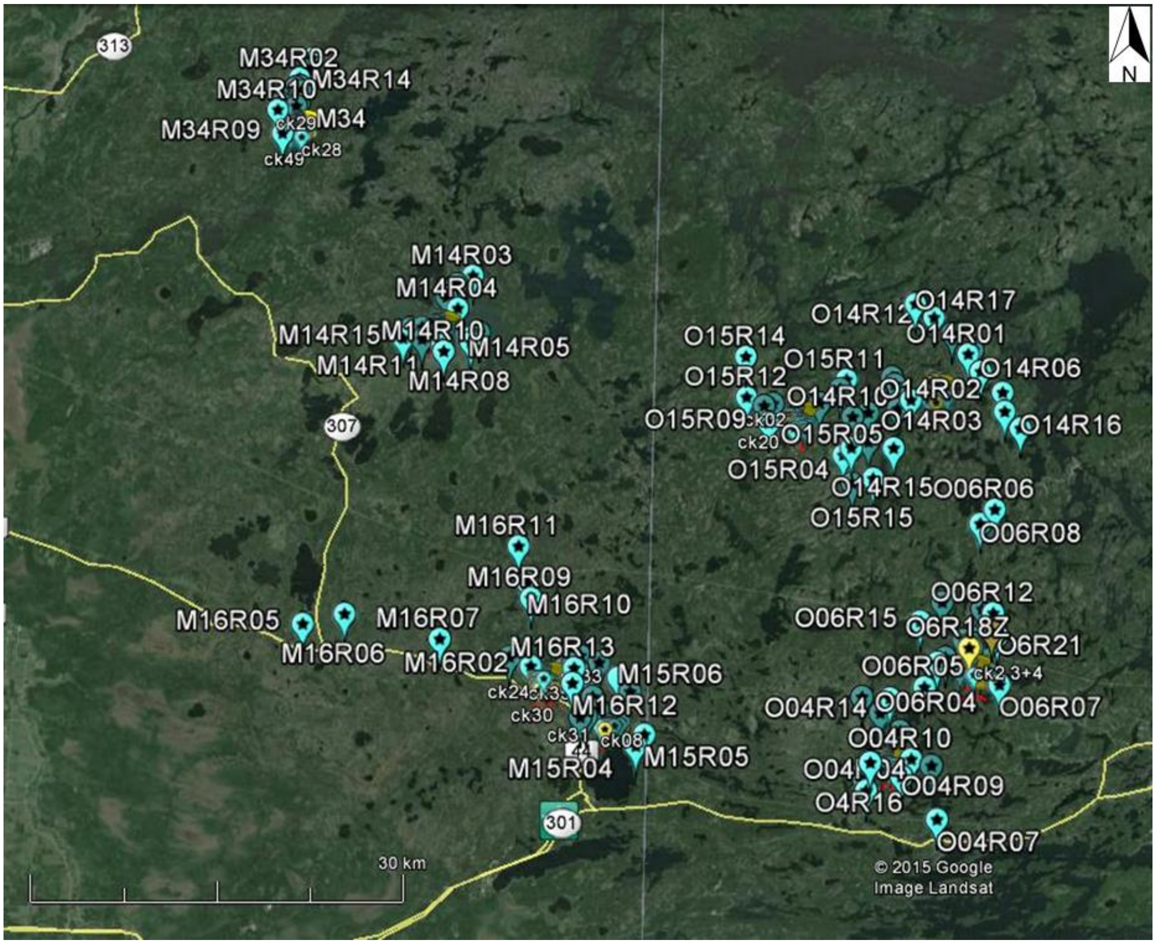
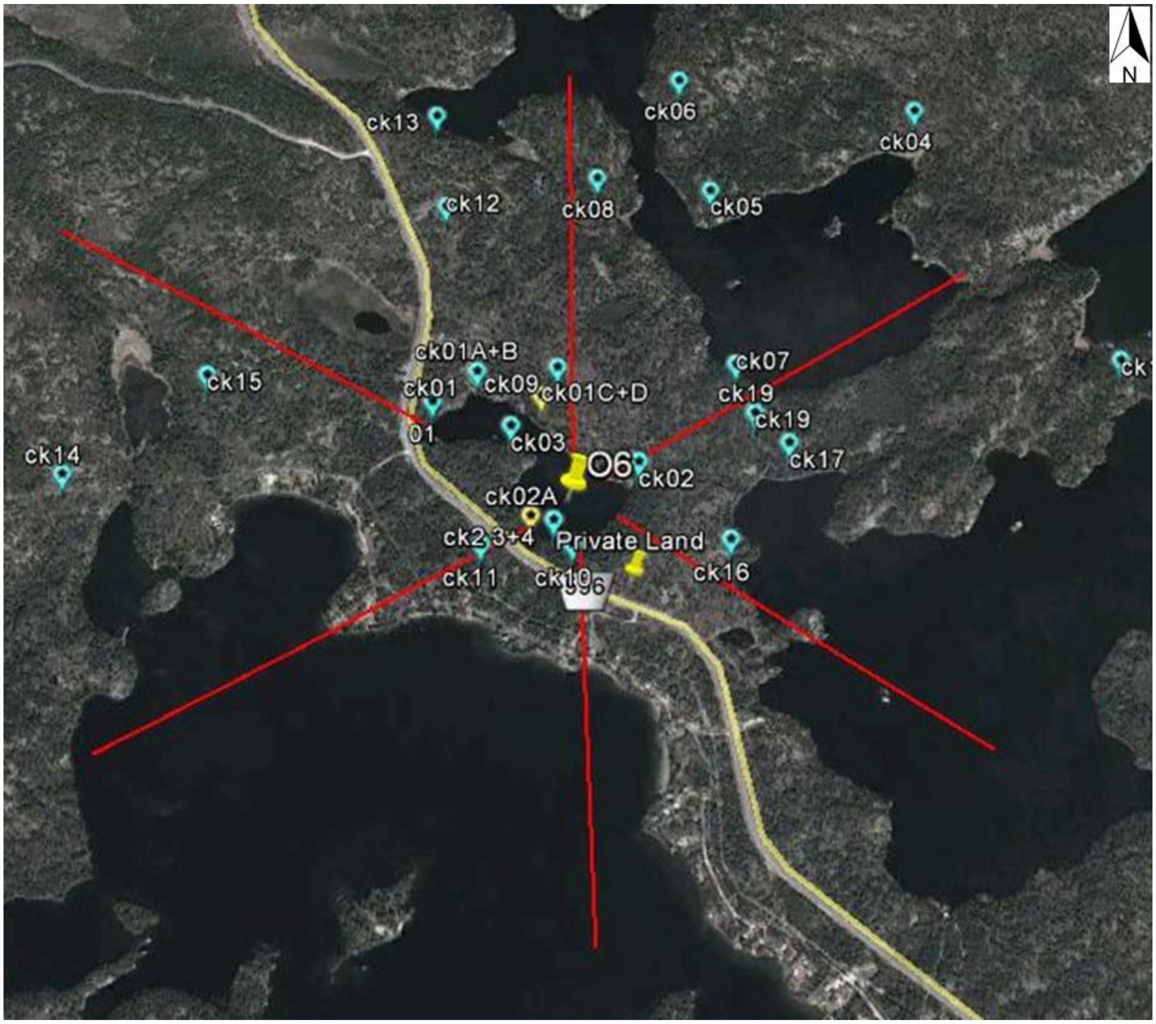
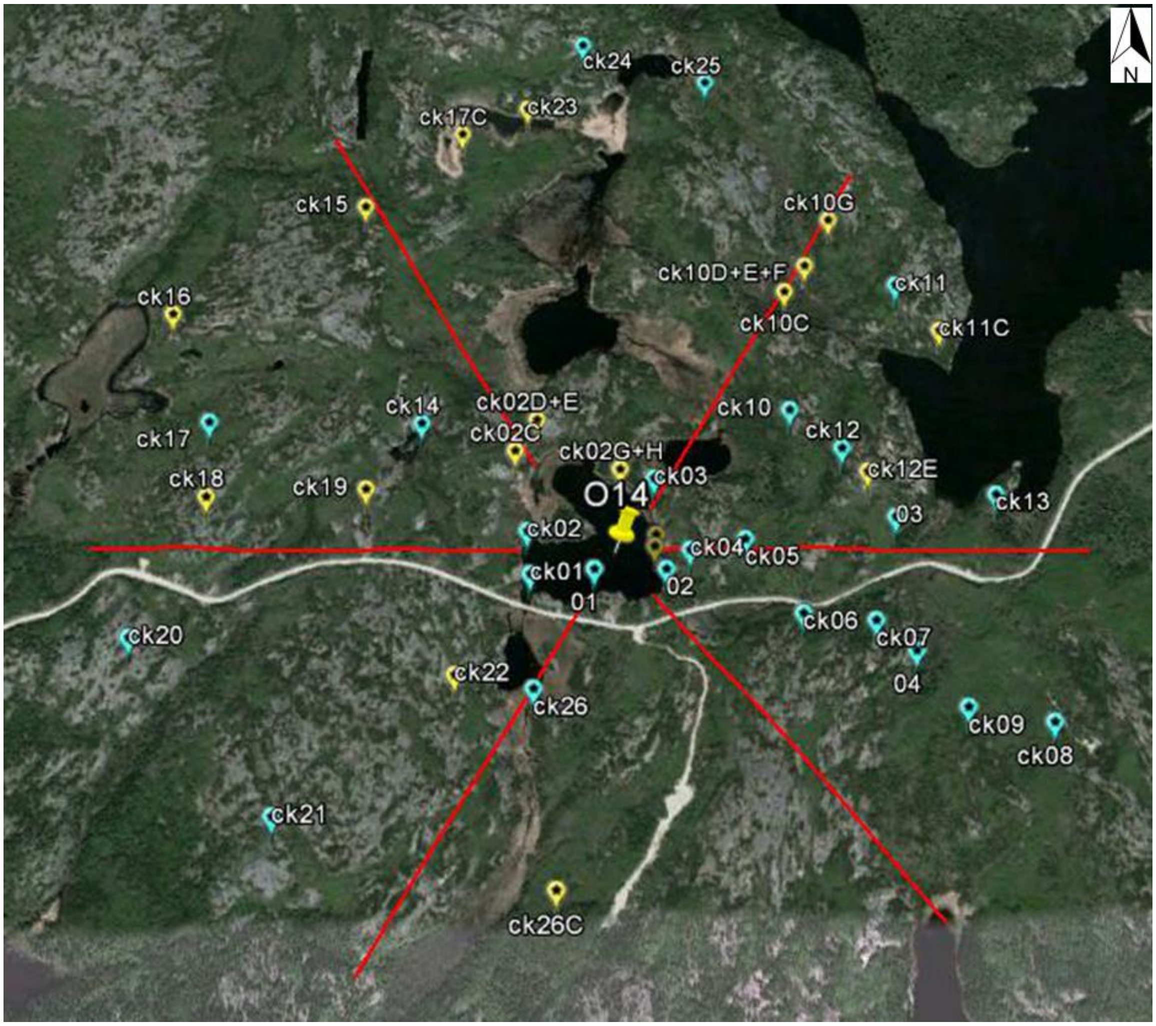
4.0 Appendices



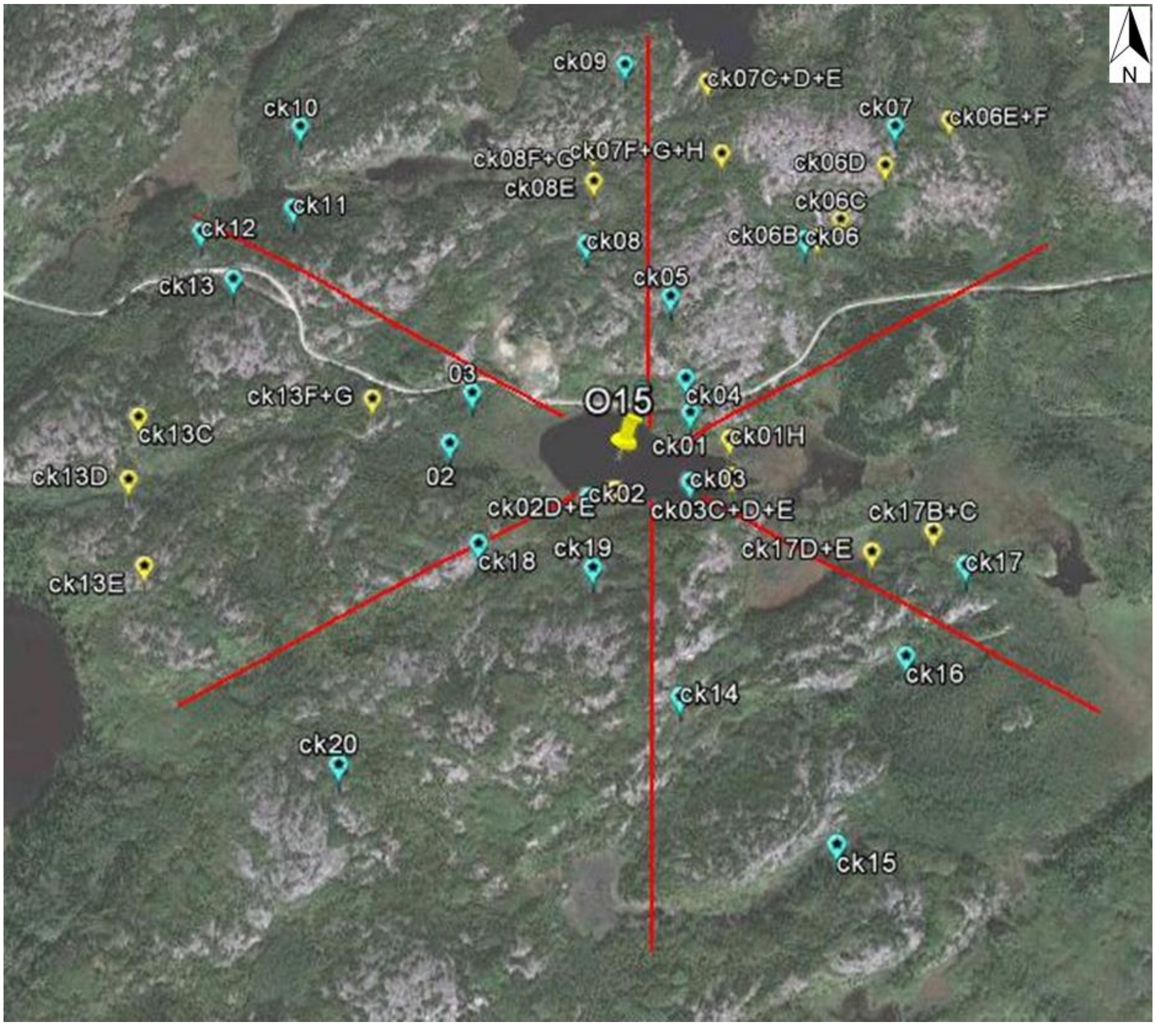
Appendix I: The sample locations for each of the 8 sampled lakes within the Lake of the Woods Ecoregion. The sample locations labelled 'R' represent those that are >1 km from the lake and so represent a regional rather than local record of fire. Sample locations indicated by the yellow place-markers represent places where only a cross-section was collected.



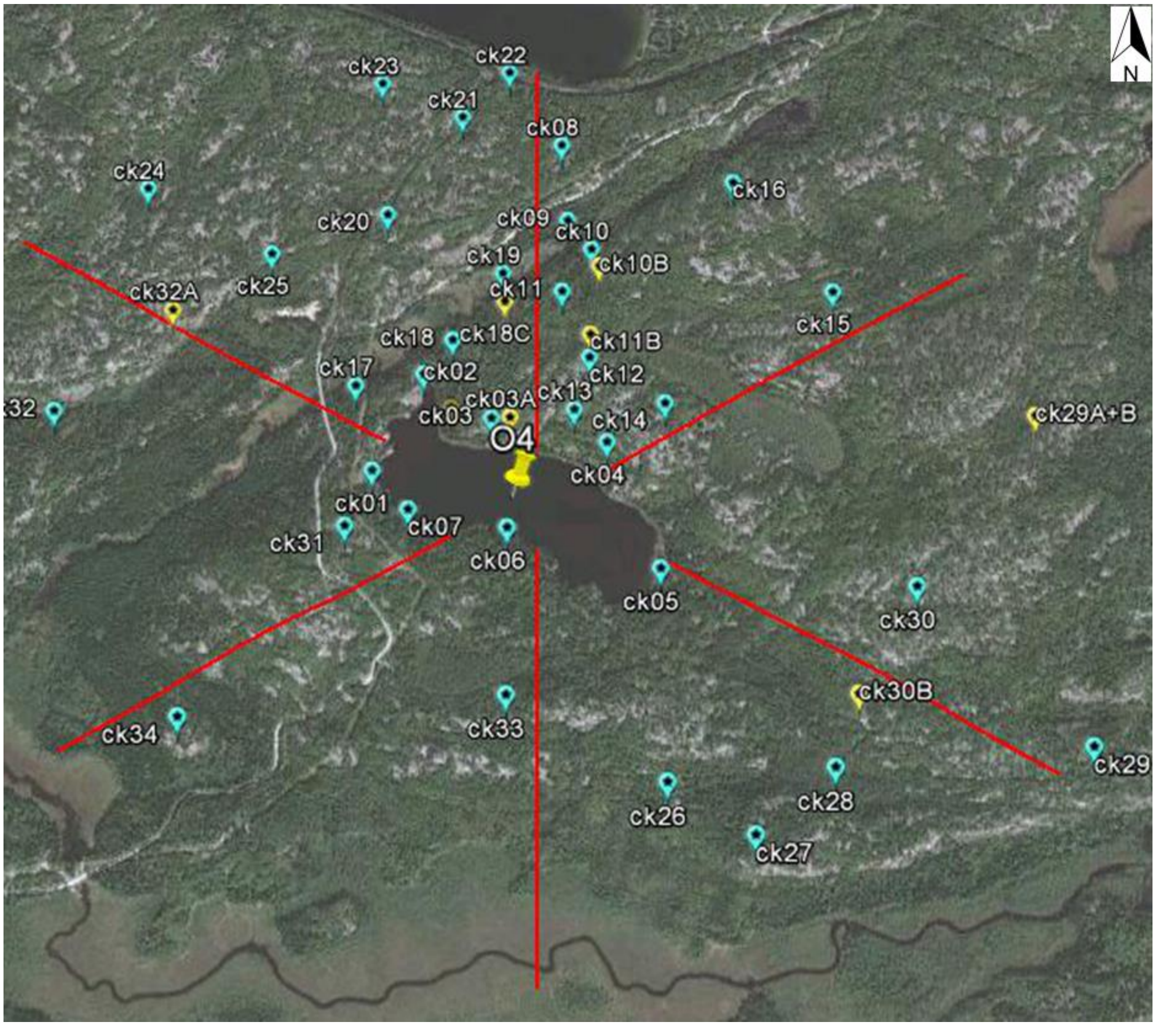
Appendix II: Lake O6 shoreline subdivided into six 1 km sectors. For scale, the maximum length of the red lines represents 1 km. The blue symbols show sites and checkpoints where living and dead materials were collected. The yellow symbols represent checkpoints where only dead material was collected. Highway 596 is indicated by the yellow line and passes along the southwestern side of the lake. Highway 596 was constructed between 1958 and 1966 (Wikipedia 2016).



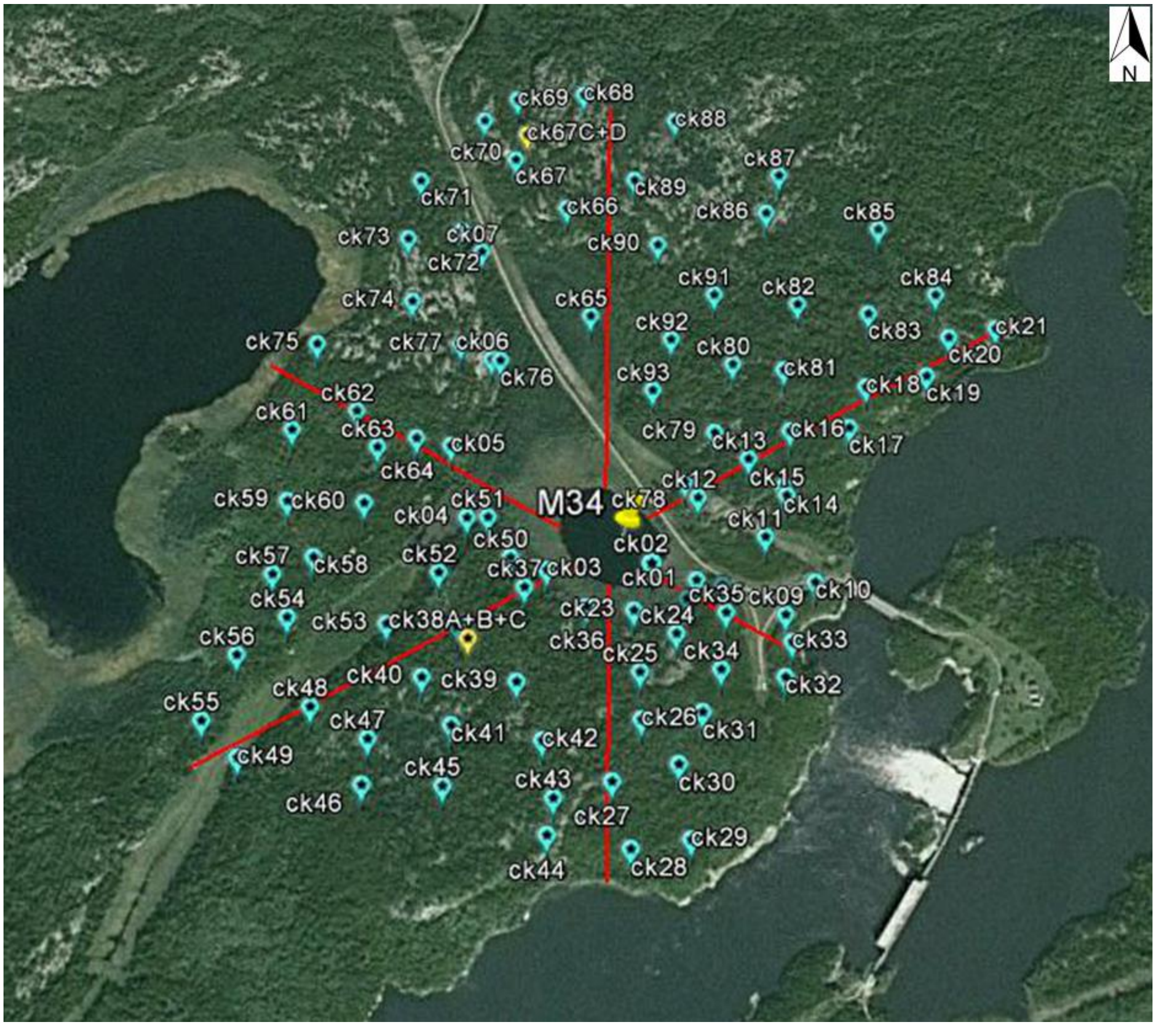
Appendix III: Lake O14 shoreline subdivided into six 1 km sectors. For scale, the maximum length of the red lines represents 1 km. The blue symbols show sites and checkpoints where living and dead materials were collected. The yellow symbols represent checkpoints where only dead material was collected. Cygnet lake road passes along the southern edge of the lake.



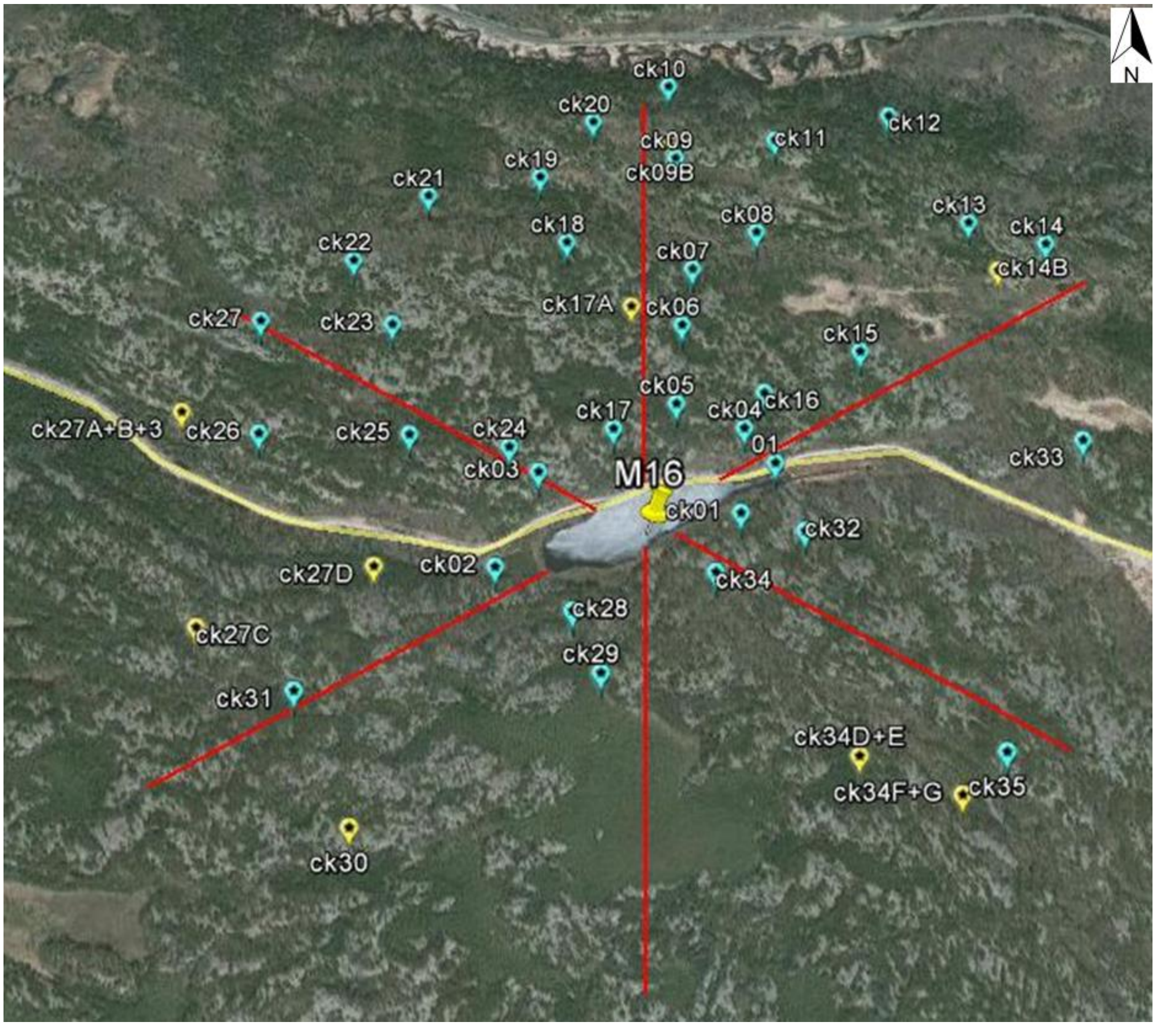
Appendix IV: Lake O15 shoreline subdivided into six 1 km sectors. For scale, the maximum length of the red lines represents 1 km. The blue symbols show sites and checkpoints where living and dead materials were collected. The yellow symbols represent checkpoints where only dead material was collected. Cygnet Lake road passes along the northern edge of the lake.



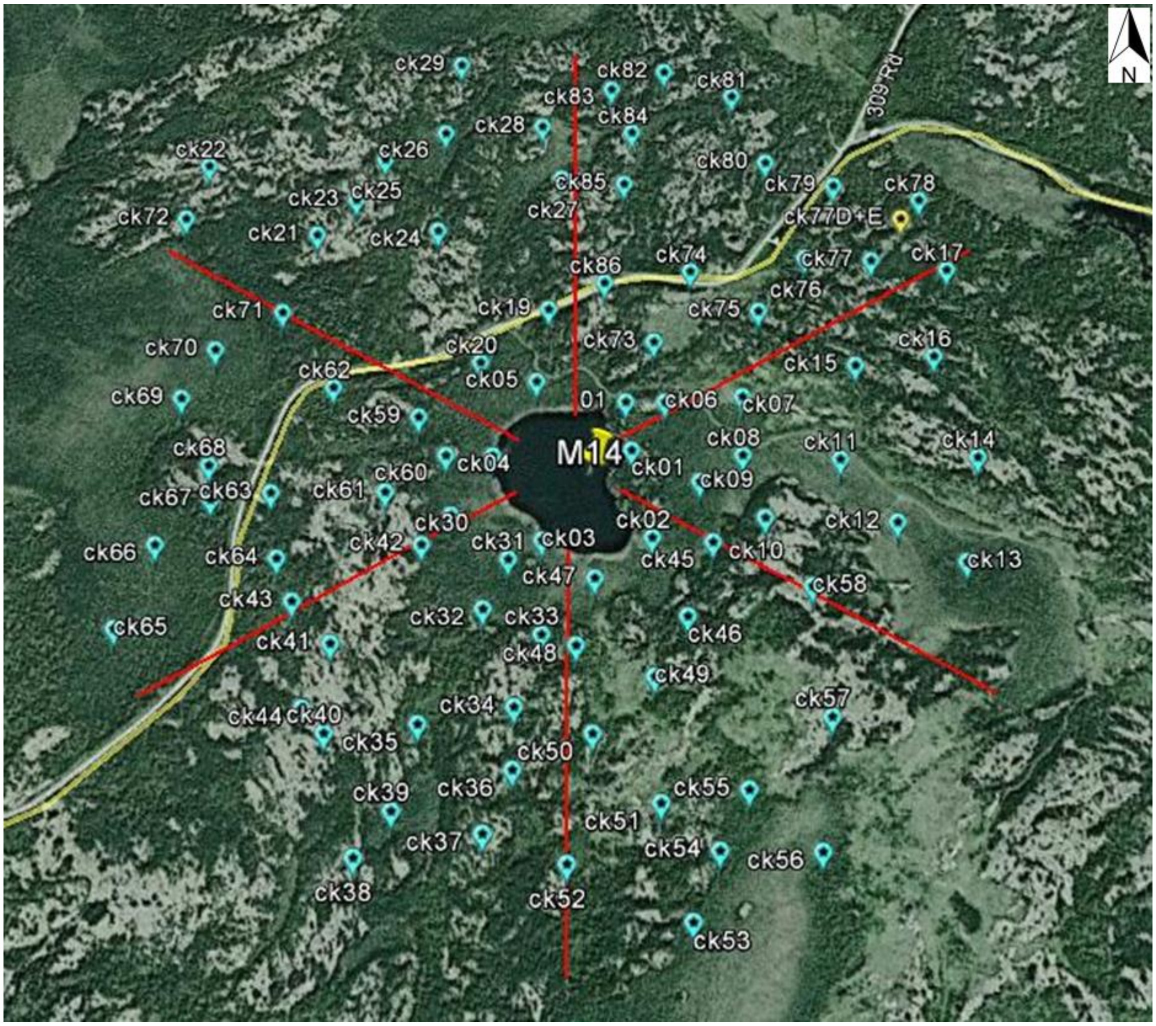
Appendix V: Lake O4 shoreline subdivided into six 1 km sectors. For scale, the maximum length of the red lines represents 1 km. The blue symbols show sites and checkpoints where living and dead materials were collected. The yellow symbols represent checkpoints where only dead material was collected. Sherwood Lake road passes within 500 m of the west side of the lake and the railway passes about 1 km along the northern end of the lake.



Appendix VI: Lake M34 shoreline subdivided into six 1 km sectors. For scale, the maximum length of the red lines represents 1 km. The blue symbols show sites and checkpoints where living and dead materials were collected. The yellow symbols represent checkpoints where only dead material was collected. Construction of a tramway began in 1928 to provide access to the Slave Falls generating station and was completed in 1948 (Manitoba Hydro 2016). The tramway was replaced with an all season road in 2009.

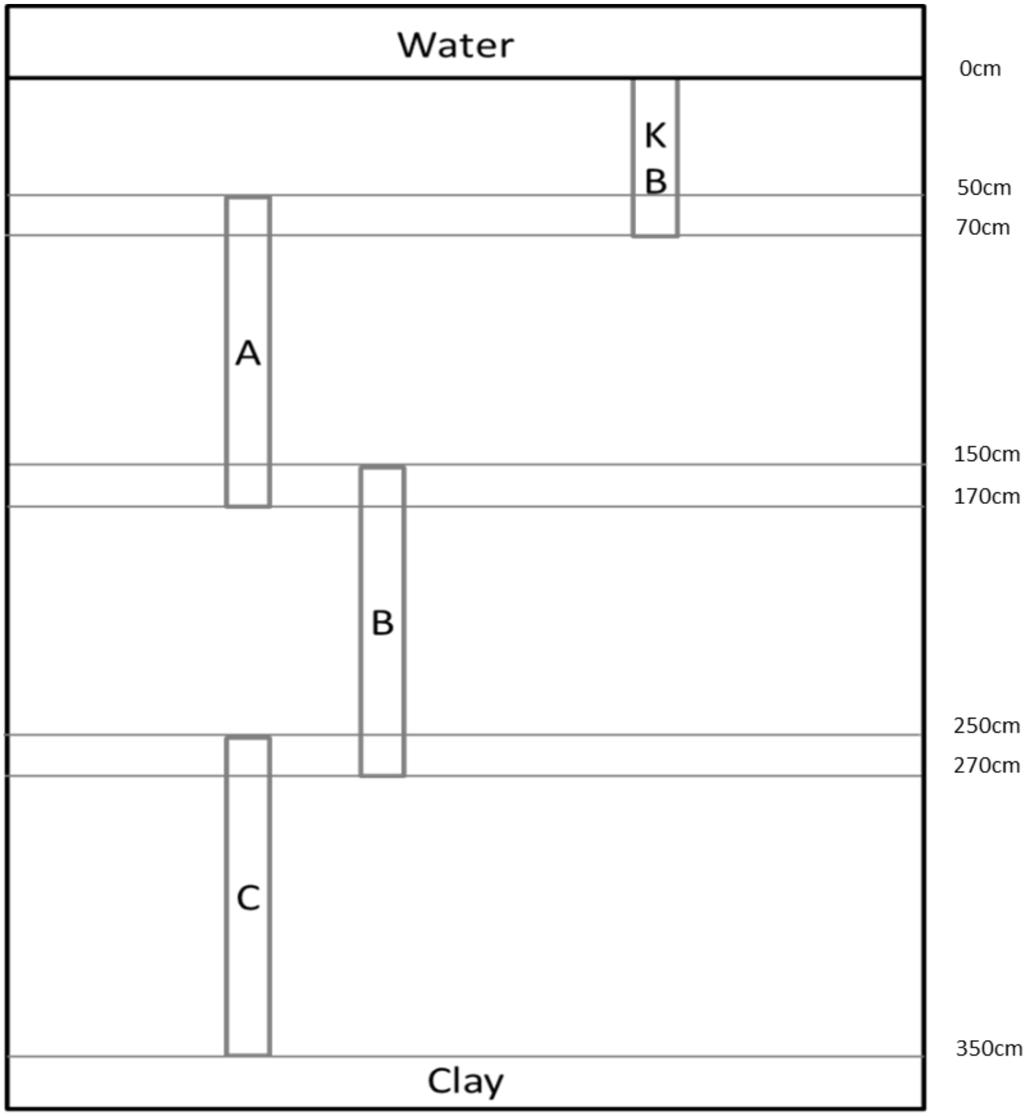


Appendix VII: Lake M15 shoreline subdivided into six 1 km sectors. For scale, the maximum length of the red lines represents 1 km. The blue symbols show sites and checkpoints where living and dead materials were collected. The yellow symbols represent checkpoints where only dead material was collected. Highway 44 is indicated by the yellow line and was constructed in 1933. A railway runs by the lake about 1km north of the lake and was initially constructed in 1885.

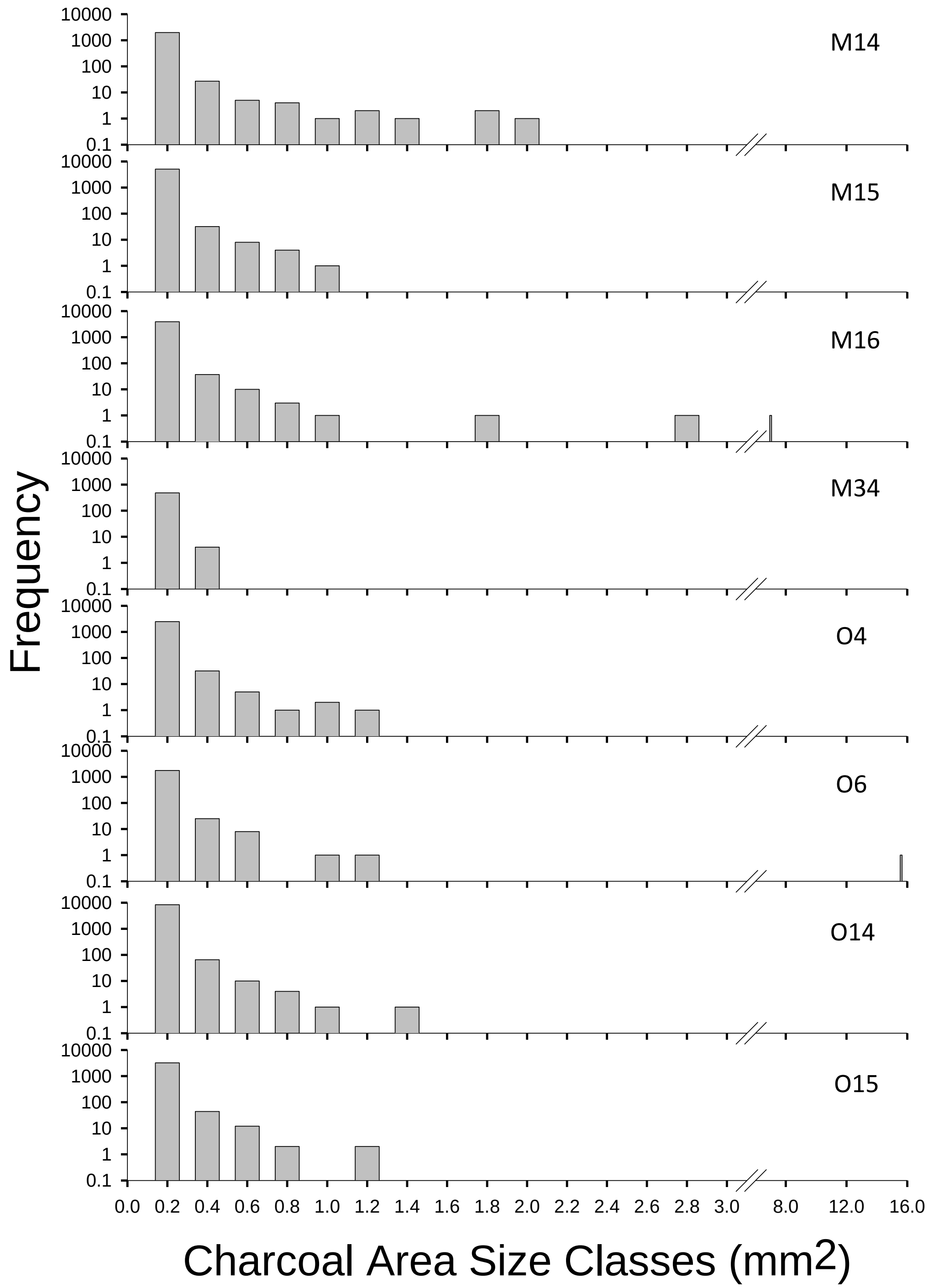


Appendix VIII: Lake M14 shoreline subdivided into six 1 km sectors. For scale, the maximum length of the red lines represents 1 km. The blue symbols show sites and checkpoints where living and dead materials were collected. The yellow symbols represent checkpoints where only dead material was collected. PR 309 is indicated by the yellow line and was constructed between 1933 and 1948 (Historical Highway Maps of Manitoba 2016).

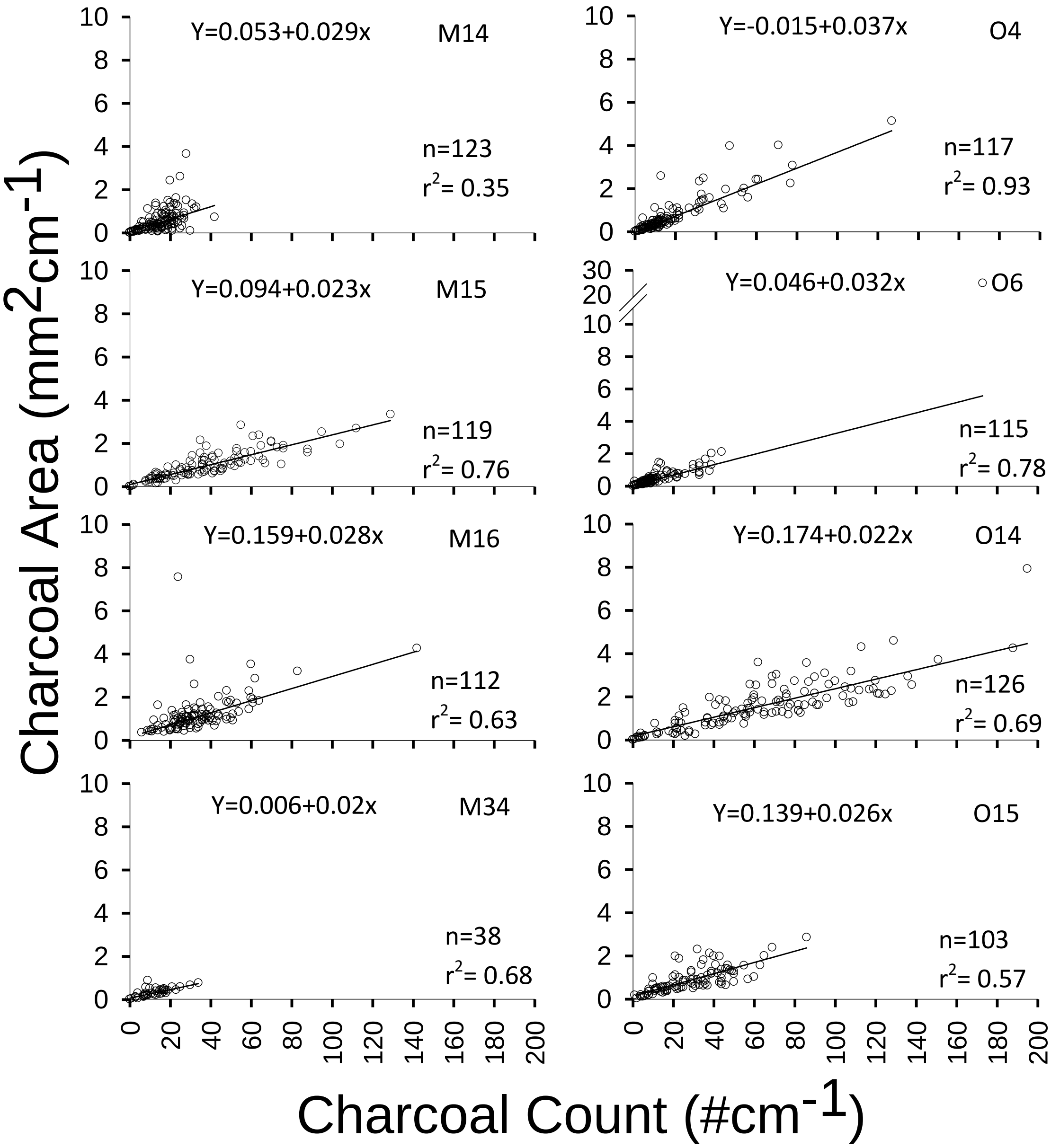
Appendix IX: Lake M15 shoreline subdivided into six 1 km sectors. For scale, the maximum length of the red lines represents 1 km. The blue symbols show sites and checkpoints where living and dead materials were collected. The yellow symbols represent checkpoints where only dead material was collected. The road (Big Island Landing) was constructed in the 1950's to facilitate development around West Hawk Lake.



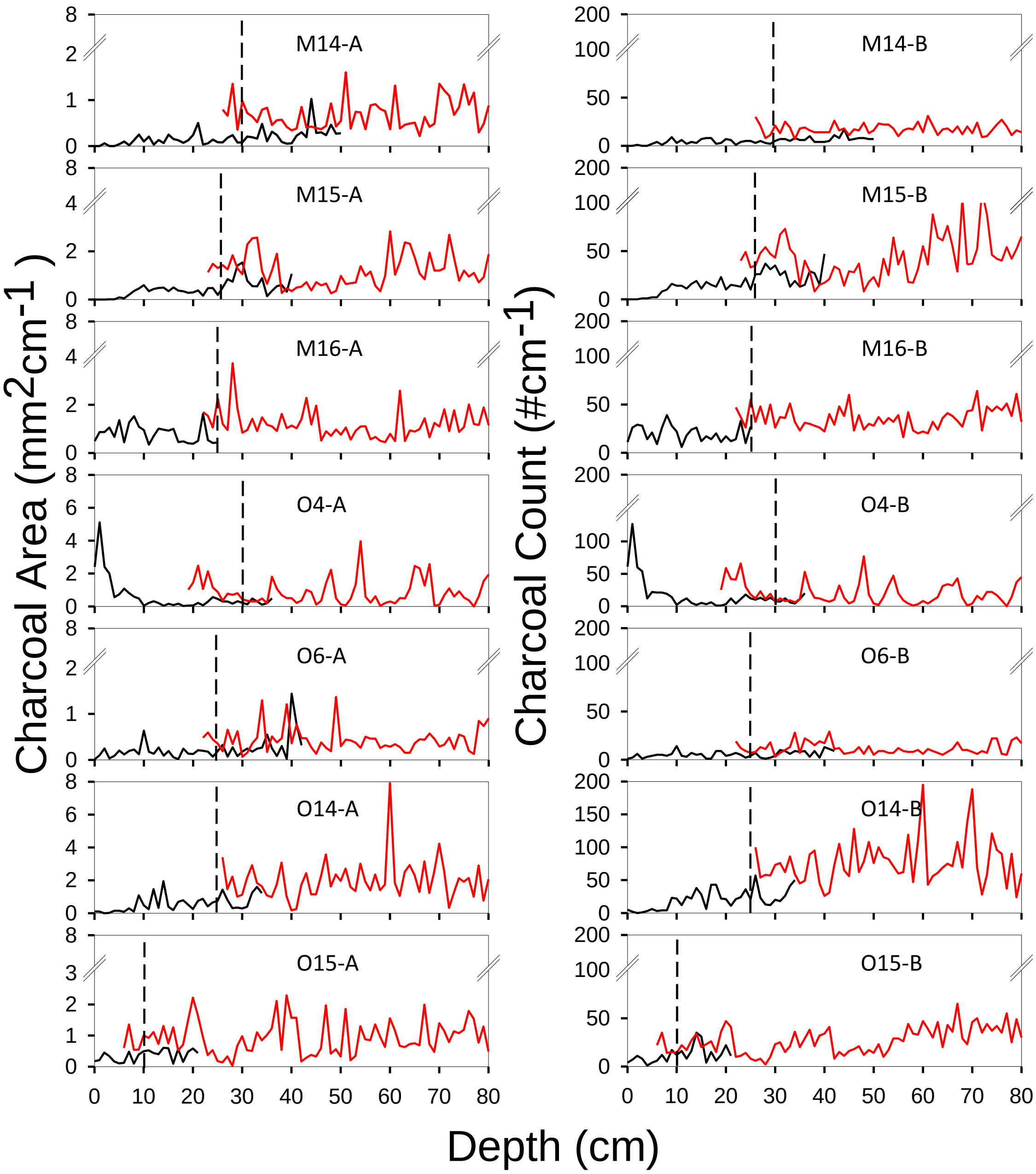
Appendix X: Theoretical sampling procedure for extracting successive sediment cores from the lake bottom. The Kajack Brinkhurst core is depicted as KB and the Livingstone cores are depicted as A, B, and C. During field sampling the 20 cm overlap is to enable merging the cores into a single continuous record.



Appendix XI: The log-frequency of charcoal size classes for each lake. The charcoal particles represent the local record of fire (within 1 km) as represented by particles >160 µm. The large particle area recorded for M16 was the result of one charcoal particle located at a depth of 82 cm and was dated to 1595 BP (354 CE). The large particle area recorded for O6 was the result of a large particle at a depth of 94 cm and was dated to 1936 BP (14 CE).



Appendix XII: Robust S-regression comparing charcoal area and count for the eight lakes. A conservative estimate of >5 standard deviations was used to identify and remove outliers as part of the robust regression procedure. Each dot represents the total area and count data obtained from each 1 cm^3 subsample. The Manitoba lakes are presented on the left and the Ontario lakes are presented on the right.



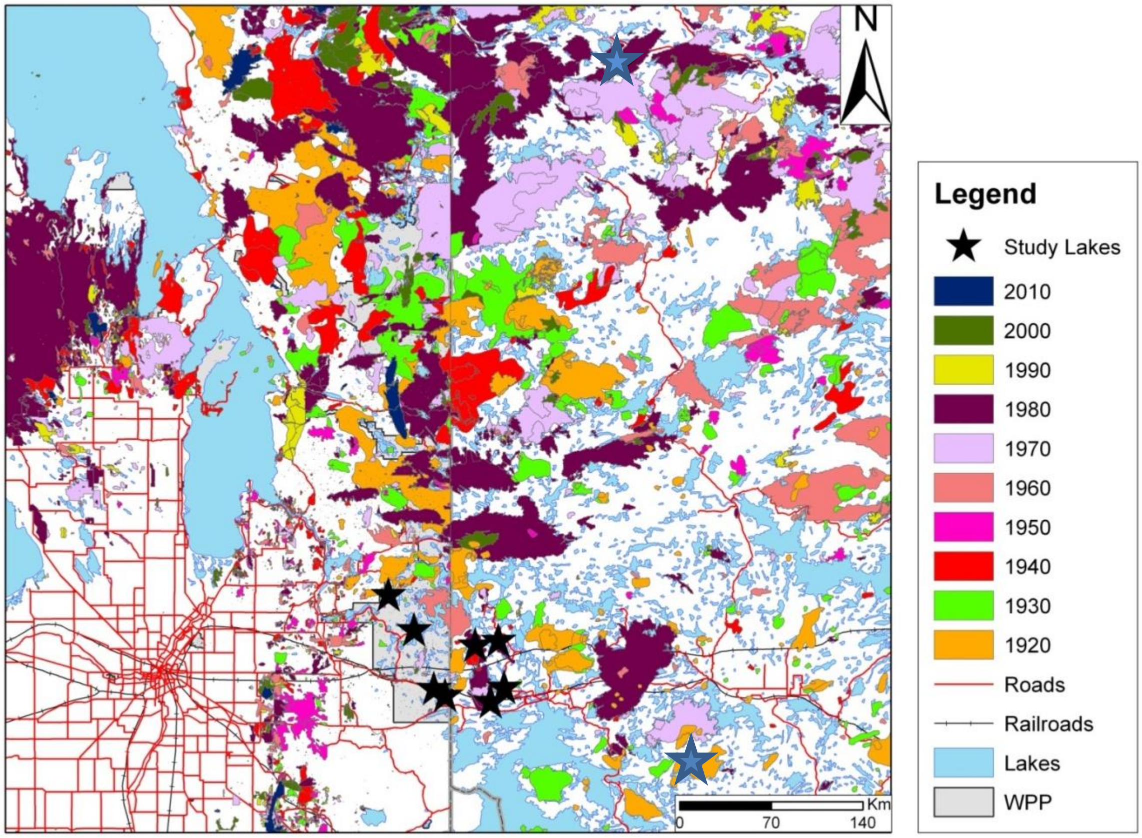
Appendix XIII: Adjusted overlap depth between the KB and Livingstone cores from the eight lakes. The graphs indicate the KB (black line) and Livingstone (red line) graphically determined overlap for charcoal count (A) and area (B) for each lake. The vertical black dashed line represents the initial field determined overlap of the KB and Livingstone core. Lake M34 is not shown as there was no Livingstone core.

Appendix XIV: Lead 210 activity in recent sediments from the eight lakes. The level of activity is measured as Bequerels per kilogram (Bq/kg) and represents the number of disintegrations per second. Samples marked 'na' (not available) signify samples for which the minimum weight required for dating was not obtained. DE represents dating error and SD represents standard deviation.

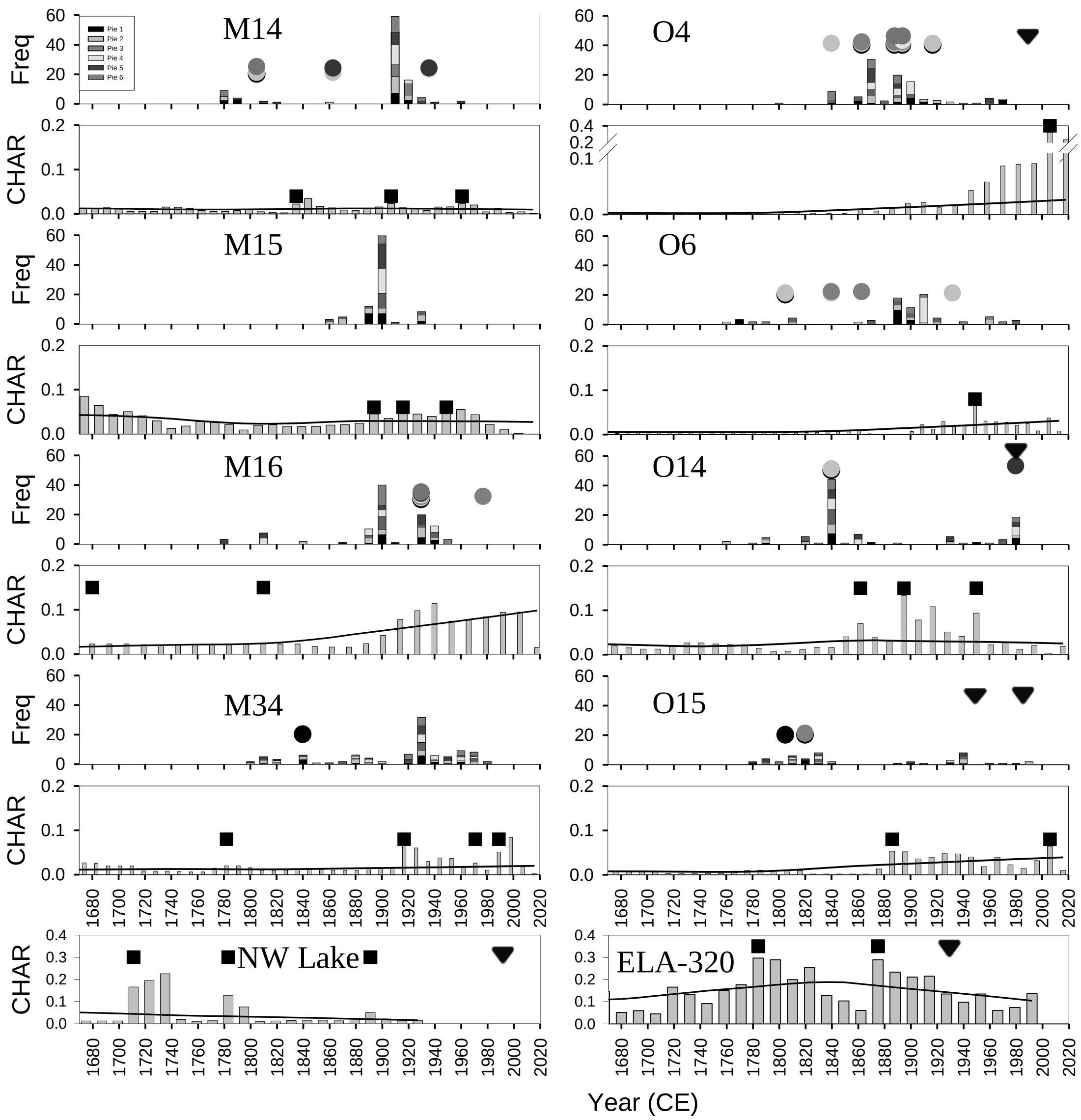
Lake	**M14**				**M15**				**M16**				**M34**			
Sample depth (cm)	Date	DE (years)	^{210}Pb activity (Bq/kg)	SD (%)	Date	DE (years)	^{210}Pb activity (Bq/kg)	SD (%)	Date	DE (years)	^{210}Pb activity (Bq/kg)	SD (%)	Date	DE (years)	^{210}Pb activity (Bq/kg)	SD (%)
0	na				na				na				na			
1	2009	0	1143	3.5	2009	0	2358	2.6	2012	0	760	2.8	2012	0	1894	2.5
2	2008	0	1133	2.6	2007	0	2526	2.8	2009	0	720	3.0	2010	0	2038	2.7
3	2004	0	916	2.7	2004	0	2406	2.6	2004	0	734	3.0	2007	0	2013	2.6
4	2000	1	984	3.0	2001	0	2545	2.7	1996	1	593	3.3	2002	1	1499	2.7
5	1995	1	901	2.7	1996	1	2247	2.6	1986	2	476	3.3	1997	1	1020	2.6
6	1988	1	882	2.6	1988	1	1945	2.4	1975	2	432	3.2	1994	1	1198	2.8
7	1980	2	729	2.8	1979	2	1412	3.0	1960	4	322	4.2	1987	1	1078	2.9
8	1972	3	582	3.0	1970	2	896	3.0	1934	8	228	5.1	1981	2	1005	3.4
9	1961	4	488	3.2	1962	3	649	3.2	1909	57	92	4.5	1974	3	830	2.9
10	1951	6	353	3.2	1955	3	636	3.3	1904	20	133	4.8	1967	3	867	2.9
11	1941	9	275	3.9	1944	4	481	3.0	1882	45	103	6.3	1957	4	817	3.3
12	1932	13	224	3.6	1933	6	399	3.2	1861	149	85	5.1	1945	6	636	3.3
13	1921	17	198	3.6	1920	8	323	3.6	1847	105	89	6.4	1932	8	544	4.1
14	1911	28	162	3.8	1908	11	237	3.3					1918	13	504	4.3
15	1901	31	161	4.0	1895	15	211	3.7					1899	20	438	4.5
16	1887	73	123	4.1	1878	25	166	3.9					1870	38	379	5.0
17	1876	125	110	4.1	1857	40	138	3.9								
18	1868	93	119	3.8												
19	1849	117	117	4.5												

Appendix XIV continued.

Lake	**O4**				**O6**				**O14**				**O15**			
Sample depth (cm)	Date	DE (years)	^{210}Pb activity (Bq/kg)	SD (%)	Date	DE (years)	^{210}Pb activity (Bq/kg)	SD (%)	Date	DE (years)	^{210}Pb activity (Bq/kg)	SD (%)	Date	DE (years)	^{210}Pb activity (Bq/kg)	SD (%)
0	na			na	2010	0	792	5.0	2010	0	768	3.2	2012	0	1272	3.0
1	2009	0	2749	2.2	2008	0	738	4.1	2009	0	868	2.5	2009	0	1244	2.7
2	2006	0	1952	2.5	2004	0	585	4.2	2007	0	985	2.5	2005	0	1036	3.3
3	2001	0	2048	2.8	1998	1	492	4.2	2002	0	849	3.5	2000	1	945	3.1
4	1997	1	1803	2.4	1992	2	396	4.0	1997	1	740	3.1	1995	1	891	2.9
5	1989	1	1567	2.6	1986	2	349	3.9	1991	1	798	3.5	1989	1	890	2.6
6	1977	2	1258	2.5	1980	3	340	4.0	1984	1	835	3.2	1980	2	740	2.6
7	1963	3	677	2.8	1972	5	264	4.5	1974	2	852	3.1	1967	2	502	2.7
8	1951	3	542	2.6	1966	7	232	4.9	1961	3	546	3.1	1958	4	405	3.1
9	1939	4	430	3.0	1959	10	181	4.8	1946	4	341	3.3	1948	5	334	3.1
10	1929	5	403	3.0	1953	11	189	4.8	1933	6	235	3.6	1938	6	295	3.5
11	1913	8	295	3.3	1946	12	186	5.0	1920	7	209	3.7	1925	8	231	2.9
12	1899	11	239	3.3	1936	17	157	3.8	1905	11	145	3.9	1915	10	210	2.8
13	1884	16	206	3.9	1925	20	152	3.8	1893	25	104	5.2	1901	14	183	3.1
14	1864	23	173	3.5	1909	43	110	4.5	1888	44	82	4.7	1886	20	168	3.3
15	1839	58	142	4.6	1895	60	101	4.4	1883	55	79	5.1	1868	29	150	3.4
16	1809	100	131	4.5	1875	113	85	4.2	1879	44	83	4.7	1841	50	135	3.7
17					1852	197	77	4.7	1873	31	92	4.1				
18									1861	40	87	4.0				
19									1845	35	97	4.5				



Appendix XV: The historical record of fires that occurred since 1920 in the study area. The Ontario portion contains fires >200 ha in size, whereas the Manitoba portion contains all recorded fires regardless of size. Data were obtained from the Manitoba and Ontario provincial fire database. The study lakes are indicated by the black stars. The southeast and northeast most lakes are ELA-320 and Northwest Lake (Lynch *et al*. 2004a), respectively and are indicated by blue stars. The extent of Whiteshell Provincial Park (WPP) is shown by the grey shading.



Appendix XVI: Individual lake fire record with tree-ring (top) and CHAR (bottom) data indicated for their overlap period. In the top panel for each lake, stand initiation is represented by bars, whereas fire-scar years are indicated by the circles. In this figure, the local (within 1 km) record is presented based on what direction the fire was located in relation to the lake. The black triangles represent archival fire records that occurred within 1 km of the lake. In the bottom panel, the bars, line and symbols represent CHAR, CHAR background and charcoal peaks (black squares), respectively. For comparison, the CHAR for Northwest Lake (NW Lake) and ELA-320 were obtained from the Global Charcoal Database and were originally sampled by Lynch *et al*. (2004a). The CHAR for all lakes was calculated using the same parameters based on lake specific median ages. Note the different scale for the y-axes.