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Samuel Munoz
AUTEUR DE LA THÈSE / AUTHOR OF THESIS

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TITRE DE LA THÈSE / TITLE OF THESIS

Konrad Gajewski
DIRECTEUR (DIRECTRICE) DE LA THÈSE / THESIS SUPERVISOR

CO-DIRECTEUR (CO-DIRECTRICE) DE LA THÈSE / THESIS CO-SUPERVISOR

André Viau

Robert McLeman

Gary W. Slater
Le Doyen de la Faculté des études supérieures et postdoctorales / Dean of the Faculty of Graduate and Postdoctoral Studies

Prehistoric Human-Environment Interaction in Eastern North America

Samuel E. Munoz

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Preface

This dissertation is presented in an 'article format', where chapters 4 and 5 are written as articles ready to be submitted for publication in an appropriate peer-reviewed journal. As such, it is necessary to state the contributions of other authors involved in the development of these articles. For chapter 4, titled 'Synchronous environmental and cultural change in the prehistory of the northeastern United States', Konrad Gajewski and Matthew Peros helped me to write, edit and revise drafts of the article, and will be credited with authorship when the article is published. The article in chapter 5, titled 'Distinguishing prehistoric human influence on late Holocene forests in southern Ontario, Canada' was written with the help of Konrad Gajewski and will be published in *The Holocene* in August 2010, issue 20(5). These articles also directly benefitted from comments made by Robert McLeman and André Viau (University of Ottawa) and Jack Williams (University of Wisconsin-Madison).

Abstract

Industrialized human societies both affect and are vulnerable to environmental change, but the dynamics of human-environment relationships during prehistory are less well understood. Using large databases of accumulated paleoecological and archaeological records, this dissertation explores the relationship between prehistoric humans and environmental change in eastern North America. A synthesis of late Quaternary paleoecological and archaeological data from the northeastern United States shows a close temporal correspondence between changes in climate, terrestrial ecosystems, human culture and population numbers. These synchronous changes occurred at 11.6, 8.2, 5.4 and 3.0 thousand years before present, before the adoption of maize agriculture when human groups in eastern North America subsisted by hunting and gathering. Further examination of these datasets in southern Ontario over the last two thousand years found that clearance of forests by prehistoric Native Americans for agricultural fields significantly altered terrestrial ecosystems at a sub-regional scale (10^2-10^3 m). Together, these results support the hypothesis that prehistoric Native Americans had a greater environmental impact than previously believed, but show that this impact was concentrated around agricultural settlements and was less substantial than that associated with European settlement during the historic period. The methodologies developed in this dissertation provide a means to better understand human-environment relationships in other regions which differ in their environmental and cultural histories.

Résumé

Les sociétés industrialisées affectent et sont également affectées par les changements environnementaux. Parcontre, les dynamiques des relations homme-environnement au cours de la préhistoire sont peu bien connues. Avec l'aide de grandes bases de données de dossiers paléoécologiques et archéologiques accumulées, cette thèse explore la relation entre l'homme préhistorique et les changements environnementaux dans l'est de l'Amérique du Nord. Une synthèse des données paléoécologiques et archéologiques de la fin du Quaternaire des États-Unis du nord-est montre une correspondance temporelle entre les changements du climat, des écosystèmes terrestres et des cultures et des tailles des populations humaines. Ces changements ont eu lieu à 11,6, 8,2, 5,4 et 3,0 mille ans avant le présent, et ce quand les groupes humains dans l'est en Amérique du Nord vivaient de chasse et de cueillette, avant l'adoption de la culture du maïs. Un examen plus approfondi de ces ensembles de données dans le sud de l'Ontario a conclu que la coupe à blanc des forêts préhistoriques par les Amérindiens dans le but de produire des champs agricoles a considérablement modifiée les écosystèmes terrestres à l'échelle sous-régionale (10^2-10^3 m). Ensemble, ces résultats appuient l'hypothèse selon laquelle les Amérindiens préhistoriques avaient un plus grand impact sur l'environnement que l'on avait cru antérieurement. Ces résultats montrent aussi que cette influence des Amérindiens était concentrée autour des villages agricoles et a été moins importante que celle associée à la colonisation européenne au cours de la période historique. Les méthodologies développées dans cette thèse peuvent également aider à la compréhension des relations homme-environnement dans d'autres régions ayant des histoires environnementale et culturelle diverses.

Acknowledgements

There are many people who contributed, both directly and indirectly, to this research. Fist and foremost, many thanks to my supervisor, Konrad Gajewski, who helped me to pursue a research topic of my own interest, despite its basis on a popular science book (I suppose I should also thank Charles C. Mann for writing *1491*). Konrad never showed any doubt that this project could work; he was always willing to help me work through problems I encountered, provide guidance and listen to me think aloud. Thank you!

I would also like to thank the students of the LPC for providing guidance and discussion, especially Matt Peros, Marie-Claude Fortin, Rebecca Ravindra, Matt Ladd and Joan Bunbury. Many faculty members in the department were supportive of my work, and I would especially like to thank my committee members, André Viau and Robert McLeman, for always being open to discussion, exposing me to new ideas, and providing feedback on my work.

The datasets used in this project were all free, the data were graciously donated by dozens of researchers, and subsequently organized and put on the web (or made available to me) by Eric Grimm (NAPD), Mitch Power (GCD) and Matt Betts (CARD). Thanks also to Jim McGrath for taking care of my computer so that I could use these datasets.

In my non-academic life, my parents (David and Eeva Munoz), my sister (Laura Munoz) and my friends were always supportive, interested and inquisitive about my research which helped me to stay grounded and view my project from different perspectives. A special thanks goes to Sierra Pope, who has definitely heard me talk about my work more than anybody else, and has always shown incredible patience, grace and support; thank you.

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1. Introduction

1.1 Purpose

Industrialized societies influence nearly all aspects of Earth's physical and biological systems (Ellis and Ramankutty, 2008). External changes in the environment, such as a drought, soil erosion or climate change, can also seriously impact economies and human welfare (Fraser *et al.*, 2003). A large body of literature documents modern environmental impacts and the implications of these impacts on human populations (e.g. Lambin *et al.*, 2001; Foley *et al.*, 2005), but the dynamics of human-environment relationships in prehistory are less well understood (Goudie, 2006; Pongratz *et al.*, 2008). For example, paleoenvironmental reconstructions have revealed how climatic shifts throughout the late Quaternary have significantly altered ecosystems (MacDonald *et al.*, 2008), but much less is known about how these environmental changes influenced human subsistence, technology and population numbers (Berglund, 2003; Coombes and Barber, 2005; O'Sullivan, 2008). Prehistoric people also hunted, fished, gathered plant foods, built settlements and practiced agriculture (Smith, 2007), but the impact of these activities on the environment is also poorly understood (cf. Clark and Royall, 1995; Campbell and McAndrews, 1995).

A common perception is that prehistoric humans had a negligible impact on ecosystems (Butzer, 1992; Kay, 2002), but some scholars have recently questioned the validity of this model to instead suggest that ecosystems have been influenced by humans for millennia (Denevan, 1992a; Cronon, 1996; Ruddiman, 2003). These claims are disputed (e.g. Vale, 2002), going largely unrecognized by many environmental scientists and policy makers due in large part to a lack of research which clearly addresses the spatial and temporal extent of prehistoric human environmental impacts. Developing a long-term understanding of human-environment relationships provides a context for modern observations and future projections of human vulnerability to environmental change which is crucial to making informed policy decisions and improving systems of natural resource management (Swetnam *et al.*, 1999; Willis and Birks, 2006). Thus, the purpose of this dissertation is to contribute towards an understanding of long-term, prehistoric human-environment interaction by investigating two questions:

(1) How have past changes in climate influenced prehistoric human populations of North America?

(2) To what extent did the practice of agriculture by Native Americans influence terrestrial ecosystems?

The dissertation is presented in the form of two articles, with each article addressing one of these two questions. The articles are followed by a synthesis chapter where the results are interpreted in a broader context.

1.2 Climate change and impact on prehistoric human populations

With improvements in our understanding of environmental and human history, a growing body of literature documents the influence of past climatic changes on a range of human cultures from around the world (deMenocal, 2001), from late Pleistocene hunter-gatherers (Newby *et al.*, 2005) to large stratified agricultural civilizations (Peterson and Huag, 2005; Yancheva *et al.*, 2007). The majority of these studies are performed by physical scientists who derive a long-term record of an environmental variable (e.g. aridity, temperature), and relate changes in this record to cultural changes, particularly societal 'collapses', but make little use of archaeological data (O'Sullivan, 2008). One consequence of this approach is that social scientists treat these temporal associations between environmental and cultural change with skepticism, citing the misuse of 'environmental determinism' during the early 20th century (Willey and Sabloff, 1993) and assert that environmental explanations for cultural change are inconsistent with current knowledge of human societies and behavior (Coombes and Barber, 2005). More recent work, by both social and physical scientists, has considered these criticisms and revised simplistic and deterministic ideas to instead suggest that natural or human-induced environmental changes can, at times, influence human decisions on matters of technology, economy, migration and social structure (Diamond, 2005; Maschner *et al.*, 2009).

Syntheses of environmental and archaeological data are currently few, although such work would greatly improve our understanding of human-environment relationships over millennial time-scales, as human groups have altered their modes of subsistence, technology and social structure. This thesis provides such a synthesis for one region, the northeast United States, where a sufficient understanding of human and environmental history combined with the availability of appropriately scaled archaeological and paleoecological data provide a unique opportunity to generate new insights into the interconnectedness of humans, ecosystems and climate throughout the late Quaternary.

1.3 Prehistoric human influence on ecosystems

The other question explored in this study, the influence of prehistoric agricultural activity on the distribution and development of ecosystems, has also been the subject of considerable scholarly debate (cf. Denevan, 1992a; Vale, 2002). On one side, there are those who argue that the impact of prehistoric human land-use on terrestrial ecosystems was great enough to overwhelm the 'natural' course of development across large spatial scales (Abrams and Nowacki, 2008). For example, humans have been implicated in the extinction of Pleistocene megafauana (Martin, 2002), increasing the incidence of fire in ecosystems (Pyne, 1982), extending grasslands and promoting the growth of certain arboreal taxa (Grimm, 1983; Black *et al.*, 2006). Nearly all of these claims are disputed, with questions concerning the reliability of supporting data (Russell, 1983; Vale, 2002). There is also an extensive literature with evidence supporting the idea that ecosystem development and distribution in prehistory was primarily a function of environmental factors (Shuman *et al.*, 2004; Williams *et al.*, 2004). Yet, analyses of individual sites across North America (Delcourt *et al.*, 1998; McLauchlan, 2003; Lacourse *et al.*, 2007; Springer *et al.*, 2010) and abroad (Birks *et al.*, 1988) show that prehistoric human activities had an impact on the surrounding environment, but because these analyses have been mostly limited to the interpretation of a single record, the spatial extent of this prehistoric human impact remains unclear.

By using a network of many sites, the analysis of prehistoric human impact can be extended across larger spatial scales, making it possible to approximate the spatial extent of this impact. In this study, I focus on one region and one kind of environmental impact which has been disputed, namely prehistoric agriculture in southern Ontario (Clark and

Royall, 1995; Campbell and McAndrews, 1995; Clark, 1995), and develop a technique to better delimit the spatial and temporal extent of this phenomenon.

1.4 Rationale and Approach

Several approaches can be used to study prehistoric human-environment relationships, broadly divided into three categories: modeling, data acquisition and data synthesis. Modeling studies, such as Pongratz *et a*l. (2008) and Kaplan *et al.* (2009), begin with an existing dataset (e.g. human population), and use a set of assumptions (e.g. land clearance per capita) to obtain a result (e.g. total land cleared). Data acquisition, be it archaeological or paleoenvironmental, has been undertaken for decades in North America, although syntheses of these data have only recently emerged (e.g. Anderson, 2001; Williams *et al.*, 2004; Viau *et al.*, 2006; Gajewski *et al.*, 2006). These syntheses have addressed broad anthropological, ecological and climatic questions, but have yet to focus on human-environment relationships. Exploration of the existing datasets towards this end will not only generate new hypotheses and results which can be used in modeling studies, but will also identify where further data acquisition is required.

Thus, this study is based on the analysis of databases of accumulated paleoecological records (sedimentary pollen and charcoal), a database of archaeological radiocarbon dates and paleoclimatic reconstructions derived from proxy-paleoclimate data. Through the mapping of these data in combination with multivariate time-series analysis, spatial and temporal relationships between the archaeological and paleoenvironmental data are explored. The feasibility of this approach depends, in large part, on the amount and quality of data available in a given region. Thus, the regions analyzed in this study reflect the availability of data of an appropriate temporal resolution and spatial distribution to answer the questions posed. Although this study employs a regional-scale approach, the techniques developed can be applied in other regions, and the insights gained contribute to a general understanding of human-environment interaction.

2. Literature Review

2.1 Humans in prehistoric North America

The arrival of humans in North America is commonly accepted to have occurred around 15,000 calendar years before present (yr BP), although the discovery of older sites have led some researchers to postulate arrival dates as early as 40 kyr BP (Meltzer, 2005). Archeological, anatomical and linguistic evidence suggest that the first inhabitants of the Americas migrated from Siberia to Alaska via Beringia during the late Pleistocene (Greenberg *et al.*, 1986), although the precise route of arrival (terrestrial or coastal) remains disputed (Dixon, 2001). Archeological evidence from Cape Horn in southern South America suggests that human occupation of the entire Western Hemisphere had occurred by 12 kyr BP (Fagan, 2000).

The ensuing period of occupation is known as the Paleoindian period, occurring between ~13-10 kyr BP, and is characterized by small bands of nomadic hunter-gatherers (Funk, 1978). During the early Paleoindian period, the Clovis culture, defined by its large fluted spear points, subsisted primarily on Pleistocene mega-fauna such as mastodon (*Mammut spp.*) and bison (*Bison antiquus*) (Kelly and Todd, 1988). Smaller spear points were developed during the middle and late Paleoindian periods probably in response to the extinction of mega-fauna and environmental changes marking the beginning of the Holocene interglacial (Fagan, 2000).

The Archaic period (10-3kyr BP) represents a transition from nomadic large-game hunting to a lifestyle which relied on seasonal exploitation of a wider array of animal and plant resources (Tuck, 1978). Toolkits became progressively more specialized to exploit food resources specific to a given region, and technologies such as the mortar and pestle, the stone axe and fishing weirs were developed or adopted from other regions (Fagan, 2000).

The Eastern Agricultural Complex (EAC), a group of plants which formed the basis for the earliest American agriculture north of Mexico, first emerged during the late Archaic period (~5 kyr BP) in the Mississippi and Ohio River valleys (Smith, 1989). Plants associated with the EAC were early-succession species selected by humans for their oily seeds, including squash (*Cucurbita pepo*), sunflower (*Helianthus annuus*), little barley (*Hordeum pusillum*), goosefoot (*Chenopodium berlandieri*), erect knotweed (*Polygonum erectum*), maygrass (*Phalaris caroliniana*), and marshelder (*Iva annua*). Evidence of plant domestication and agriculture has been demonstrated by changes in key morphological characteristics (e.g. seed size, seed coat thickness). However, populations in others parts of eastern North America, including southern Ontario and the northeastern United States continued to rely on "wild" plant resources, primarily nut mast (e.g. *Carya spp.*, *Castanea spp.*, *Juglans spp.* and *Quercus spp.*) and wild rice (*Zizania palustris*), until maize agriculture was widely practiced around 1 kyr BP (Smith, 1992).

The Woodland period (3,000 – 500yr BP) is identified by the development of firing clay cooking and storage containers, reflecting increased dependence on agriculture and trade (Fitting, 1978). During this time, the bow and arrow replaced the atlatl throughout the continent, greatly improving hunting efficiency (Kowtko, 2006). The Late Woodland saw the adoption throughout eastern North America of maize (*Zea mays*) and other cultigens of Mesoamerican origin, including squashes (*Cucurbita* spp.) and beans (*Phaseolus vulgaris*) (Chilton, 2006). Maize-based agriculture transformed the lifestyle of previously nomadic and non-agricultural people in southern Ontario and the northeastern United States (Doolittle, 1992). In the Midwest and Southeast, Mesoamerican cultigens replaced the EAC and led to development of the Mississippian civilization (Smith, 1992).

European colonization of North America, and the end of the prehistoric period, began in the 16th century with exploration continuing until the 19th century. At the time of European contact, groups throughout much of eastern North America subsisted on a mix of Mesoamerican cultigens and wild animal and plant foods. Agriculture provided a supplementary food source to groups in the Great Plains while hunter-foragers without agriculture lived in California, the Northwest Coast, the Subarctic and Arctic (Doolittle, 1992). The Native American population numbers during the proto-historic period remains highly contentious. Conservative estimates by Ubelaker (2006) suggest a continental population of 2.6 million people, with relatively high population densities throughout much of the continent (31-73 people 100km^{-2}), except the Arctic, Subarctic and Great Basin (1-4 people 100km^{-2}). Other continental population estimates range from less than 1 million people to 18 million (Denevan, 1992b). Native American groups across the continent were significantly altered by contact with Europeans through the spread of disease, social and economic collapse, and the introduction of European flora and fauna (Cronon, 1983; Denevan, 1992b; Whitney, 1994; Crosby, 2004).

2.2 Paleoenvironmental records

Lake sediment, along with various terrigenous and aquatic materials, gradually accumulates through time and can provide an archive of past environmental conditions at a given location. This record can be interpreted by extracting a lake sediment core. Assuming that material at the bottom of the core is older than material at the top (following the law of superposition), and dating organic material (^{14}C) or the sediment itself (^{210}Pb) at several points along the core, a chronology can be established relating core depth to an age. Material contained within the sediment, such as pollen and charcoal, can then be examined along the core to determine vegetation and fire history around the lake (Birks and Birks, 1980).

2.2.1 Pollen and vegetation history

Pollen grains, male gametophyte of gymnosperms and angiosperms, are produced in the anthers of flowering plants and cones of conifers. Pollen grains range in size between 5μm-150μm in diameter. The outer wall of pollen grains is composed of sporopollenin, an extremely resistant material which allows for the preservation of grain structure. Pollen grains produced by different plants are unique in shape, size and surface markings so that they can be associated to a particular family, genus or species. Pollen analysis involves the identification several hundred pollen grains in a particular sample to produce counts of each taxa represented in the sample. These counts can then be converted to a percent of the total sample, or an influx (no. grains / unit volume / unit time) (Faegri and Iversen, 1989).

The identification of pollen grains is typically limited to the generic level in trees, and to the family level in herbaceous plants and shrubs. Pollen analysis is biased towards wind-pollinated species and species which produce copious amounts of pollen, so that these species will be over-represented in the pollen record (Birks and Birks, 1980). Wind-blown pollen can be transported up to several to hundreds of kilometers, and the transport depends on grain morphology and environmental conditions. Animal or insect pollinated taxa typically have larger pollen grains and are underrepresented in the pollen record (Faegri and Iversen, 1989). The source-area for pollen, and thus the scale of vegetation reconstruction, is dependent, among other factors, on the surface area of the lake (Jacobsen and Bradshaw, 1981). In this way, interpretation of a pollen record can be used to approximate the regional-scale vegetation surrounding a lake at a given time, but is not analogous to a vegetation survey.

Nevertheless, pollen analysis has led to a number of insights into the nature of vegetation and climate change from regional to global-scales since the last glacial maximum (LGM, 21 kyr BP). A single pollen record is limited in the spatial extent of its reconstruction, but combining several records in a pollen database increases the scale of analysis. Since their conception in the 1970s and 1980s to test climate models (COHMAP, 1988), pollen databases have allowed for synoptic analyses of vegetation migration since the LGM and provided ecological insight into the nature of biomes and plant associations (Bartlein *et al.*, 1998).

In North America, relatively rapid plant migration and ecological reorganization occurred during the late-glacial period (16-8kyr BP) and after European colonization (500-0yr BP), while biomes have remained more stable during the full glacial (21-17kyr BP) and the mid- to late Holocene (7000-500yr BP) (Williams *et al.*, 2004). Continental-scale vegetation reconstructions often employ lower orders of ecological resolution (biomes and plant functional types) (e.g. Prentice *et al.*, 1996; Prentice and Webb, 1998; Williams *et al.*, 2000). However, a number of vegetation associations and biomes of the late-glacial have no modern analogue (Williams and Jackson, 2007) suggesting that species respond individualistically to environmental change (Huntley and Webb, 1988) and that plant associations and biomes arise through the interaction of individual taxa (Webb, 1988; Williams *et al.*, 2001). At a higher taxonomic resolution, individual taxa display significant shifts in range and abundance which are masked when interpretations are scaled up to the biome level (Williams *et al.*, 2004).

Continental-scale vegetation migration and reorganization is often explained by climatic change because climate exerts a broad and fundamental control on vegetation distribution (Huntley, 1992; Gajewski *et al.*, 2006). Human impact is secondary under this model. However, some paleoecologists have described Europe, for example, as a "cultural landscape" where vegetation has been heavily influenced by millennia of human settlement and agriculture (Birks *et al.*, 1988). Pollen-based reconstructions have identified human-driven vegetation changes using a number of techniques: (1) an increase of "anthropogenic indicator" taxa, pollen of ruderal species related to land clearance, agriculture and grazing (Behr, 1986; Birks *et al.*, 1988); (2) changes in forest pollen taxa (Aaby, 1986); (3) correspondence analysis, examining major patterns of vegetation change (Birks *et al.*, 1988); and (4) rarefaction analysis, a pollen-based measure of biodiversity thought to increase in response to intermediate human disturbance (Birks and Line, 1992; Berglund *et al.*, 2008). However, none of these methods provide unambiguous evidence of human influence. For example, increases in ruderal taxa and changing forest composition may also arise from natural disturbance (Huntley, 1992; Foster and Aber, 2004). Biodiversity estimates from rarefaction analysis may be heavily influenced by pollen richness and concentration (Peros and Gajewski, 2008). Nevertheless, insights gained from studying the "cultural landscape" of Europe have been employed in North America (Delcourt, 1987; Clark and Royall, 1995), although these analyses have been limited to a single pollen record, rather than a network of records. Thus, prehistoric people, particularly those clearing forest for agricultural purposes, may have had a significant impact on vegetation, but the scale of this impact remains unclear (Pongratz *et al.*, 2008). However, continental- to regional-scale vegetation change appears to be predominately influenced by climate (Webb *et al.*, 1983; Shuman *et al.*, 2004; Williams *et al.*, 2004; Gajewski *et al.*, 2006), and these changes would presumably be sufficient to affect the resource base of human populations.

2.2.2 Wildfire and Charcoal

Fire is an important component of terrestrial ecosystems, and occurs where sufficient biomass combines with periods of hot, dry weather and a source of ignition (anthropogenic, lightning, or volcanic) (Whitlock and Bartlein, 2004). In modern North America, fires are common in the Boreal forest, Plains and the California Chaparral (Archibold, 1995) although before European settlement fires may have been common in the eastern temperate forests (Abrams and Nowacki, 2008). Burning of biomass influences terrestrial vegetation as it favours early successional taxa and species with adaptations to the occurrence of fire (e.g. thick bark, epicormic sprouting, serotinous cones, thick seed casing) while reducing the abundance of taxa not adapted to fire, creating openings in the canopy for saplings and herbaceous vegetation (MacDonald, 2003).

In forested regions where frequent wildfire occurs today, ecologists describe the landscape as a diverse "mosaic" of vegetation communities of various ages, structure and species composition (Wade *et al.*, 2000). Native American burning is thought to have influenced forest ecosystems by increasing the frequency of low-intensity fires, creating a mosaic landscape which encouraged grazing by herbivores and the maintenance of fire-adapted trees (Pyne, 1982; Abrams and Nowacki, 2008). The importance of anthropogenic prehistoric fires in altering vegetation has been demonstrated using a vegetation model (Bond *et al.*, 2005) and inferred from witness-tree data (Foster *et al.*, 2004; Black *et al.*, 2006), although these approaches lack the continuous long-term record provided by sedimentary charcoal.

Charcoal is produced by the incomplete combustion of organic material during a fire, and becomes incorporated into lake sediment following a fire. The size of charcoal particles produced varies, and are generally classified into two classes: micro-charcoal (<125μm), capable of long-distance airborne transport and providing a record of regional fire activity; and macro-charcoal (>125μm), typically washed into a lake following a fire, and providing information on the timing and severity of local fires. Charcoal particles in sub-samples of a lake sediment core are counted under a microscope or stereoscope, and the charcoal accumulation rate (CHAR; no. particles / unit volume / unit time) provides a relative measure of fire activity on annual to millennial time scales, where a higher CHAR index is associated with increased fire activity (Whitlock and Larsen, 2001).

Individual sedimentary micro- and macro-charcoal records have recently been amalgamated into the Global Charcoal Database (GCD) to explore large-scale changes in fire regime since the LGM. In order to compare multiple charcoal records, particle accumulations are typically transformed to follow a normal distribution, rescaled and standardized (Power *et al.*, 2008). When scaling up from one site to an amalgamation of several sites, the incidence of individual fire events becomes impossible to resolve as individual peaks may interfere constructively or destructively with each other so only relative increases or decreases in time-series of CHAR are considered in composite records. Nevertheless, studies utilizing GCD composite records display broad-scale trends coherent with insights gained at the local-scale. Over millennial time-scales, insolation exerts a broad influence on climate, the distribution of biomes, the desiccation of biomass and the incidence of fire (Power *et al.*, 2008). Rapid climate changes also coincide with periods of increased fire activity and vegetation change (Marlon *et al.*, 2009). Across North America, charcoal accumulation generally increases during the mid- and late-Holocene (Power *et al.*, 2008). On a global scale, charcoal influx is positively correlated with temperature and human population over the last 2000 years, although this relationship breaks down during the post-industrial era when fire-suppression was common while population increased significantly (Marlon *et al.*, 2008).

3. Materials and Data Assimilation

3.1 The Canadian Archaeological Radiocarbon Database (CARD)

The Canadian Archeological Radiocarbon Database (CARD) was compiled by R.E Morlan of the Canadian Museum of Civilization and consists of over 35,000 archeological and paleobiological radiocarbon dates from across Canada and the United States (Figure 3.1). For each entry, the database provides information regarding its location, radiocarbon age, the type and taxonomy of material dated, archeological significance and context. The majority of artifacts dated are directly related to human culture (~30,000), composed mainly of charcoal, wood and animal bones from hearths and middens. The remaining ~5,000 dates are primarily paleoenvironmental, consisting of radiocarbon-dated paleosols and stratigraphic horizons not directly affiliated with human culture. Subsets of the database were used in the regional studies presented in this thesis (Chapters 4 and 5), with only cultural dates from the selected region used.

To convert normalized ^{14}C dates younger than 21,000 ^{14}C years before present to calibrated years before present (yr BP) I used CALIB 5.0.1 software (Stuiver *et al.*, 2009). Dates were calibrated to the 2σ range, but in all cases the median probability of the calibrated date was used. All material of terrestrial origin was calibrated with the IntCal04 dataset (Reimer *et al.*, 2004). All material of marine origin, including all marine mammals (N=803) and all molluscs, mussels and marine shells (N=848) was calibrated using the Marine04 dataset (Hughen *et al.*, 2004). All marine mammal fossils were corrected for the marine reservoir effect using a standard value of -400 years. The molluscs, mussels and shells were corrected for the marine reservoir effect using values provided by Dyke *et al.* (2003) which range from -800 years in the Pacific to -400 years. In cases where the delta carbon was not provided in the database, we assumed a standard value of -25‰. All dates older than 21,000 ^{14}C yr BP (N=566), the limit of the IntCal04 dataset, were calibrated using the Fairbanks *et al.* (2005) dataset. A substantial proportion of entries could not be calibrated (N=2140; 6.0% of dataset) because (a) dates were beyond the limit of the Fairbanks *et al.* (2005) dataset (>50,000 ^{14}C yr BP), (b) dates were modern (e.g. 0 ^{14}C yr BP), (c) no error was provided with the date or (d) the material was not dated. Uncalibrated dates were not used in any analysis.

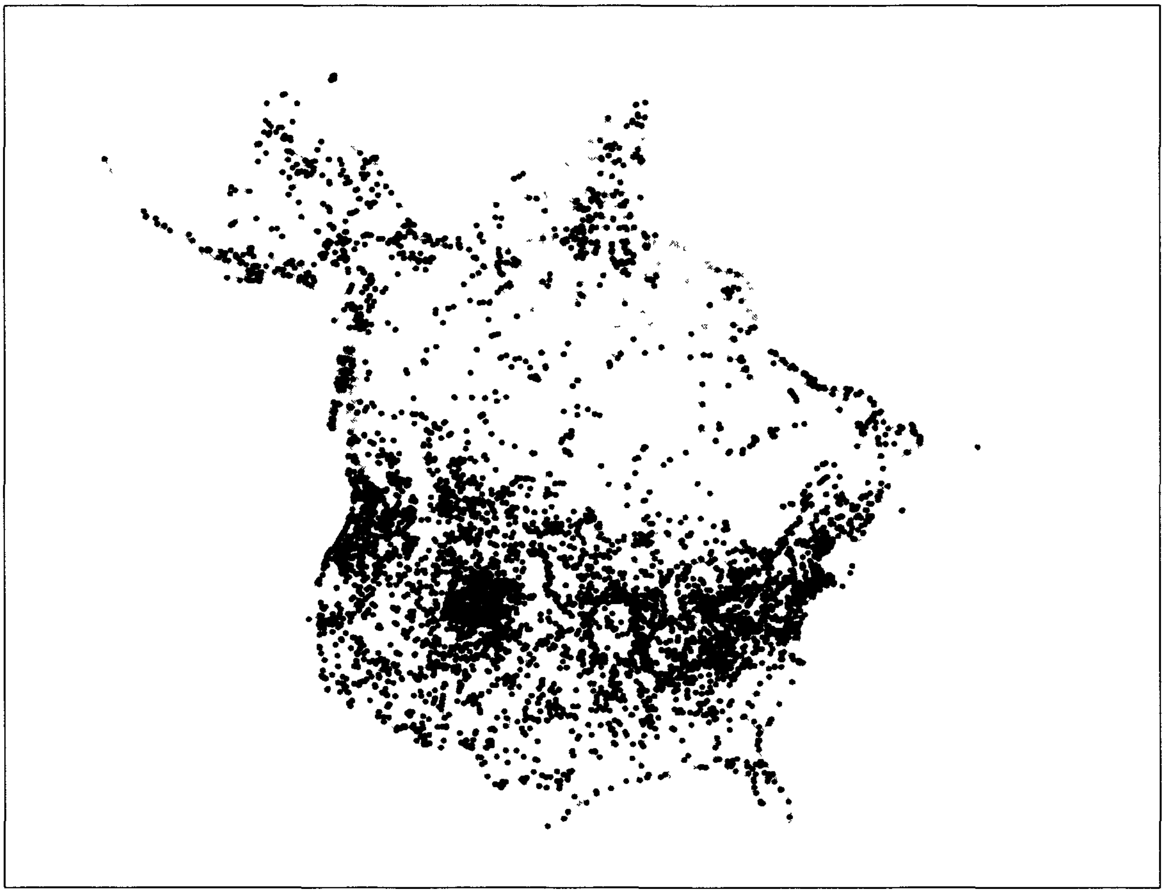

Figure 3.1 The spatial distribution of all ^{14}C dates in the Canadian Archaeological Radiocarbon (CARD; Morlan, 2005)

3.1.1 The CARD as a paleodemographic proxy

The spatial and temporal distributions of archaeological ^{14}C dates are interpreted as a proxy for paleopopulation, based on previous research that has shown that a larger population will result in a greater deposition of cultural carbon (Rick, 1987; Gamble *et al.*, 2005; Buchanan *et al.*, 2008; Surovell *et al.*, 2009; Peros *et al.*, 2010). The spatial density of archaeological sites at a given period of time is interpreted as a proxy for the distribution of human populations at that time. However, because of the way the CARD was developed, the database is currently underrepresented in the southern United States (Morlan, 2005). However, other regions are well represented in the database such that the dates from these regions can be used to approximate the spatial distribution of human populations. This approach can also be biased by heterogeneous geomorphic factors (e.g. dissolution, erosion), modern infrastructure and settlement patterns. To explore the effectiveness of this approach, the spatial density of archaeological sites was compared with historic records which document the locations of Native American settlements (see Appendix). To further validate this approach, the Late Woodland archaeological site density in southern Ontario was plotted alongside pollen assemblages indicative of anthropogenic disturbance.

Temporal frequency distributions of dates are used to delineate periods of demographic change, where relative increases in the frequency of archaeological ^{14}C dates are interpreted as increases in population, and vice-versa. This approach can be biased towards younger material due to the gradual and time-dependent destruction of cultural carbon by erosion or dissolution (Surovell and Brantingham, 2007). The time-dependent destruction of cultural carbon has been modeled empirically by Surovell *et al.* (2009) as a power function:

$$n_t = 5.73\text{x}10^6 (2176.4 + t)^{-1.39} \qquad (3.1)$$

where n_t is the original amount of cultural carbon created at time t, and t is the time elapsed since the initial deposition of the material.

This "taphonomic bias" will be negligible over shorter (10^2 yrs) time periods because the amount of material destroyed at the beginning and end of a short period will not differ substantially. Over longer (10^3-10^4 yrs) periods the destruction of older material can significantly alter temporal frequency distributions, giving the impression of a curvilinear population growth when population may actually have been declining or stationary (Surovell and Brantingham, 2007; Surovell *et al.*, 2009). However, relative peaks and troughs in these long-term population reconstructions are unlikely to be removed by taphonomic bias (Buchanan *et al.* 2008; Peros *et al.* 2010) because the time-dependent destruction of material follows a smooth power function (Equation 3.1).

The interpretation of temporal frequency distributions in this study will be limited to *relative* increases and decreases, which are interpreted as periods of demographic change. To show that relative changes are insensitive to taphonomic bias, the long-term population estimate from the northeast United States was corrected using the model proposed by Surovell *et al.* (2009). In southern Ontario, the study period is recent (Late Holocene) and relatively short (~1500 years) so the taphonomic correction (Equation 3.1) will not alter the population reconstruction. However, in this region an independent population reconstruction was developed by Warrick (2008) using archaeological techniques, which was compared against the regional temporal frequency distribution of ^{14}C dates (Appendix). In the northeastern United State, no such population reconstruction is available for comparison, but several archaeologists have inferred relative increases and decreases in population numbers which are used to validate the temporal frequency reconstruction.

3.2 The North American Pollen Database (NAPD)

The North American Pollen Database (NAPD), stored in the Neotoma database V1.0 (Grimm, 2008), consists of 743 pollen records of various lengths and resolutions spanning the United States and Canada (Figure 3.2). The database contains information regarding site location (longitude, latitude, elevation), lake size, chorological controls and pollen taxonomy. Sites are not distributed evenly across the continent, with the highest density of sites around the Great Lakes and in the northeast United States. The average record length is 10,950 years (standard deviation σ=10,717 years) and the median sampling resolution is 179 years sample^{-1} (σ=1987 years sample^{-1}).

Chronological control is provided by hundreds of ^{14}C and ^{210}Pb dates as well as biostratigraphic and volcanic references. These dates are associated with a given depth in a core, and this information is used to develop a chronology which relates age to depth throughout the entire core. If chronologies were not provided in calendar years, ^{14}C dates were converted to calendar years before present using the IntCal04 dataset (Reimer *et al.*, 2004). The chronologies were re-computed using the median probability of calibrated dates, with the calibrated age of pollen levels obtained by linear interpolation along this chronology.

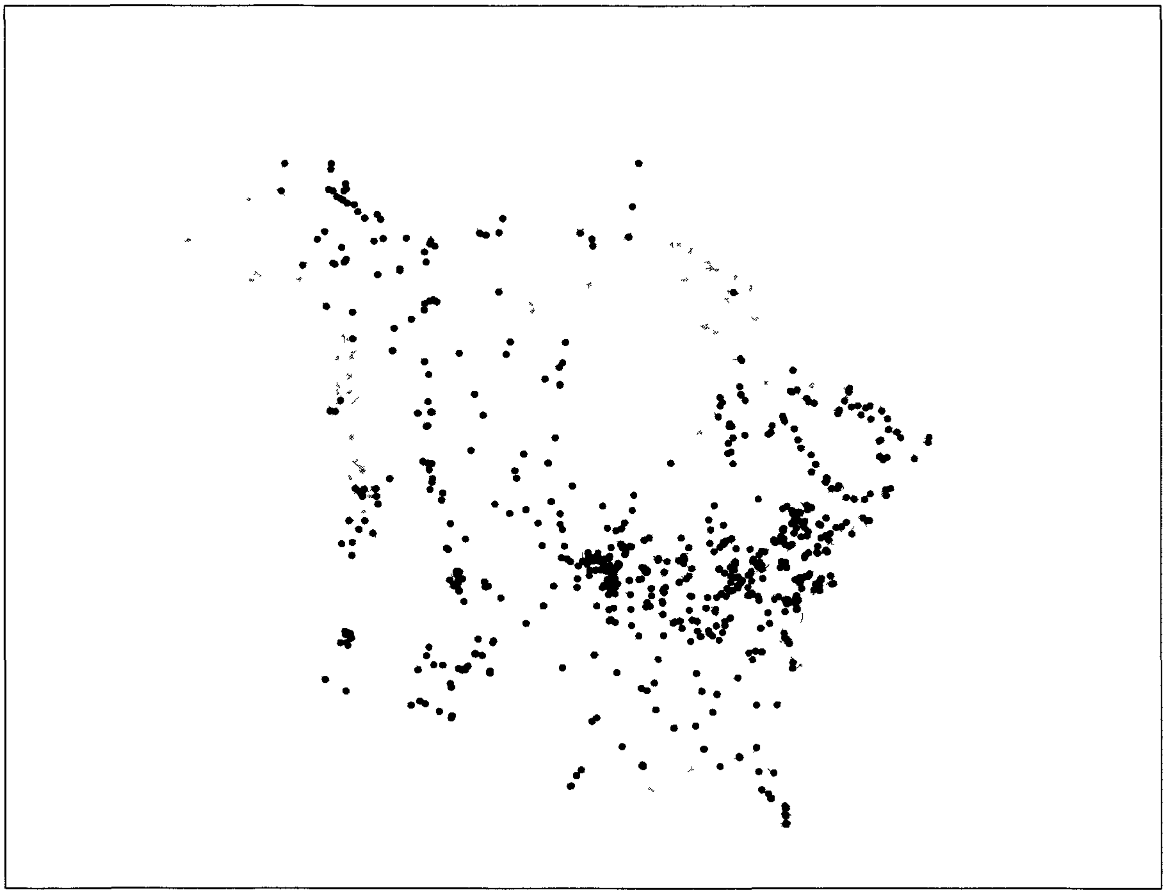

Figure 3.2 The spatial distribution of all pollen records in North America from Neotoma v 1.0 (Grimm, 2008)

3.3 The Global Charcoal Database (GCD)

The Global Charcoal Database (GCD) consists of 405 sedimentary charcoal records from around the world, 166 of which are located in North America (Figure 3.3). The database contains metadata regarding site location, biome, charcoal count method and chronological controls. The spatial distribution of North American sites is not even, with a higher frequency of sites located in the Northeast, Midwest, Rocky Mountains, Northwest Coast and Boreal forest. The average record length is 8971 years (σ=5216) and the median sampling resolution is 64 years sample^{-1} (σ=202 years sample^{1}). All chronologies in the GCD have been converted to calendar years before present using standard methodology described by Power *et al.* (2008). An additional 33 charcoal records not included in the GCD from New England (Chapter 4) and southern Ontario (Chapter 5) were digitized from the paleoecological literature or were provided by David Foster and Wyatt Oswald at Harvard Forest and Konrad Gajewski at the University of Ottawa.

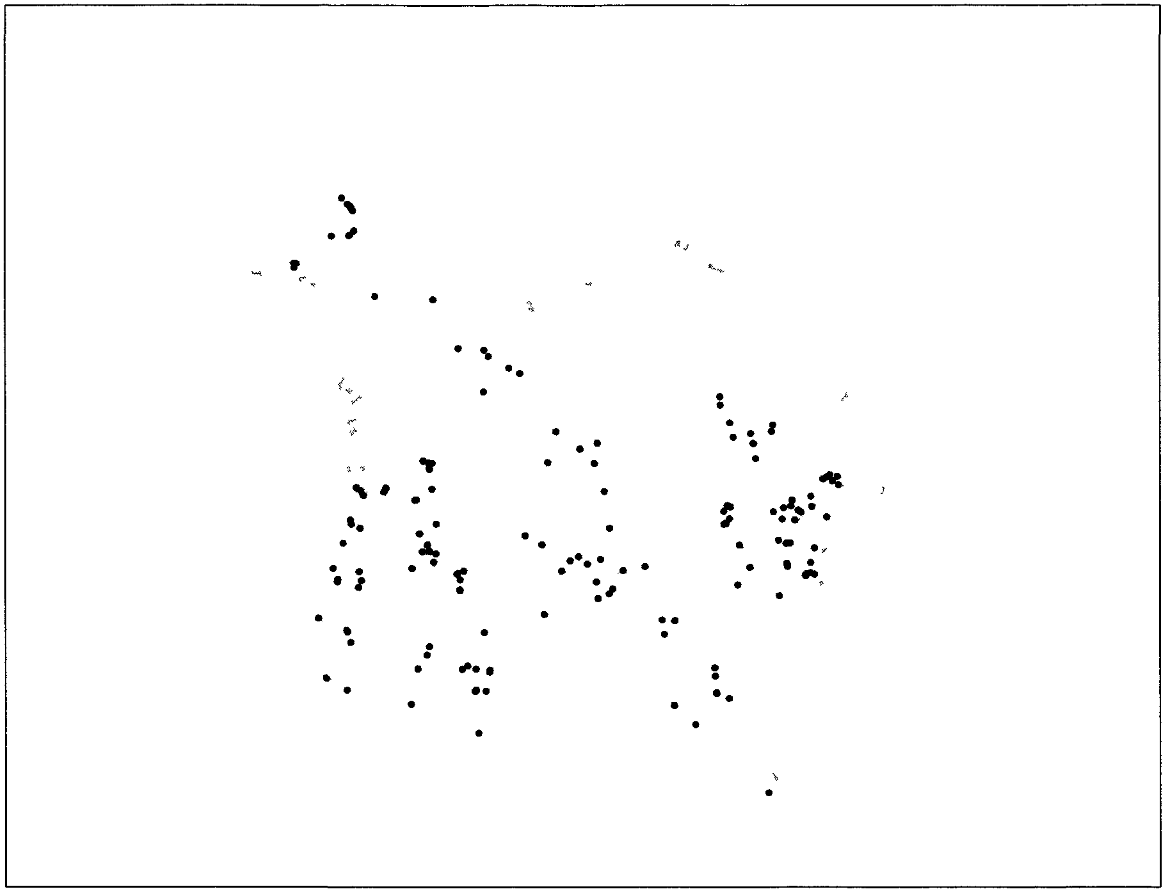

Figure 3.3 The spatial distribution of all charcoal records in North America, from the global charcoal database (GCD, Power *et al*, 2008)

4. Synchronous environmental and cultural change in the prehistory of the northeastern United States

Abstract

Climatic changes during the late Quaternary have resulted in substantial, often abrupt, rearrangements of terrestrial ecosystems, but the relationship between these environmental changes and prehistoric human culture and population numbers remains unclear. Using a database of archaeological radiocarbon dates alongside a network of paleoecological records (sedimentary pollen and charcoal) and paleoclimatic reconstructions, we show that periods of cultural and demographic change in the northeastern United States occur at the same times as major environmental-climatic transitions in the same region. At 11.6, 8.2, 5.4 and 3.0 thousand calendar years before present, changes in forest composition altered the distribution and availability of food resources which resulted in technological adjustments manifested in the archaeological record. Human population level has varied in response to these external changes in ecosystems, but the adoption of maize agriculture during the late Holocene also resulted in a substantial population increase. This study demonstrates the long-term interconnectedness of prehistoric human cultures and the ecosystems they inhabited, and provides a consolidated environmental-cultural framework from which more interdisciplinary research and discussion can develop.

4.1 Introduction

Paleoenvironmental research has demonstrated the role of climate in affecting the distribution and development of ecosystems (Webb *et al.*, 1993; Williams *et al.*, 2004), but the impact of environmental changes on human populations remains contentious (Coombes and Barber, 2005; O'Sullivan, 2008). A growing literature documents the influence of drought and other catastrophic climate changes on past human societies, much of which has focused on environments where human vulnerability to climate change is most pronounced (e.g. deMenocal, 2001; Yancheva *et al.*, 2007). To explore long-term human responses to environmental change in a temperate region, where the relationship between humans and environmental change may not be immediately evident, we integrate newly available and detailed environmental and archaeological records from the northeastern United States that span the initial human settlement of the region ~13.5 kyr BP to the arrival of Europeans 0.5 kyr BP (thousand calendar years before present). Our analysis identifies temporal correspondence between several key cultural transitions, fluctuations in human population, and climate-driven changes in terrestrial ecosystems, generating new insights into environmental factors that influenced cultural change in North American prehistory.

Since initial human occupation, the terrestrial ecosystems of the northeastern United States have undergone large changes in composition and structure, with much change concentrated at several, well defined transitions between climate phases, namely at 13, 11.6, 8.2, 5.4 and 3 kyr BP (Shuman *et al.*, 2004; 2009). These transitions occurred when changes in insolation and ice sheet extent influenced ocean-atmosphere circulation and the energy balance which altered regional patterns of temperature and the timing and magnitude of precipitation (COHMAP, 1988; Bartlein *et al.*, 1998; Yu *et al.*, 1998; Shuman *et al.*, 2002; Viau *et al.*, 2006). The arrangement of the major plant communities has been primarily driven by these changes in climate, and species have responded individualistically to different climate regimes (Prentice *et al.*, 1991; Williams *et al.*, 2004; MacDonald *et al.*, 2008). Thus, periodic transitions between climate regimes in the prehistory of the northeastern United States resulted in different vegetation communities which substantially altered ecosystem services that were used by prehistoric Native American populations.

Through its effects on the development and distribution of terrestrial ecosystems, it is likely that climatic change would also influence human population size as well as modes of prehistoric subsistence dependent on these ecosystems. Although the association of archaeological periods with different ecosystems has long been recognized (Stoltman and Baerreis, 1983), new ideas of the postglacial climate evolution (Viau *et al.*, 2006; Wanner *et al.*, 2008) and more refined dating and specification of the vegetation development, including the presence of non-analogue plant communities (Williams *et al.*, 2004), present an opportunity to re-evaluate the relation between cultural and environmental change. Some previous paleoenvironmental and archaeological studies have suggested links between environmental and cultural change in the study region (Braun, 1974; Fiedel, 2001; Newby *et al.*, 2005), but these have focused on a single cultural/environmental change while the availability of new databases, which can be used to quantify past environmental conditions and cultural and demographic change, now permit a more comprehensive analysis.

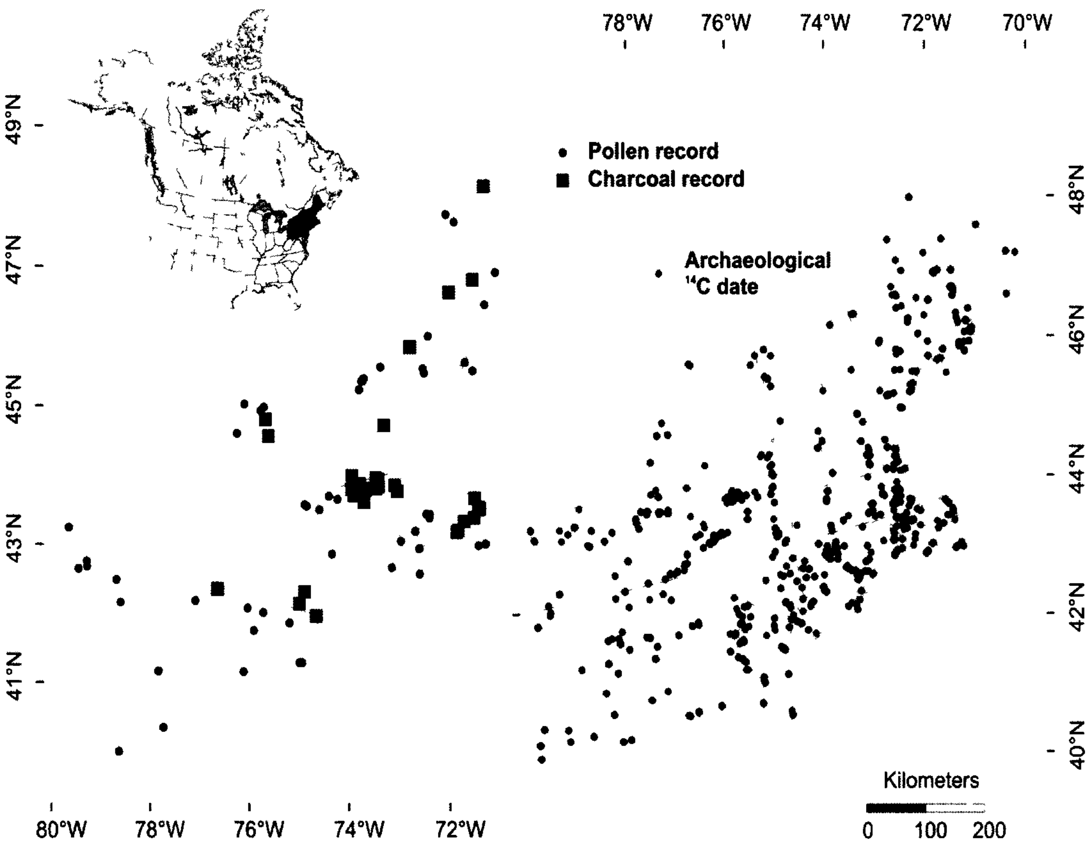

Figure 4.1. Location of study region in relation to modern Canada and the United States (inset). Left: Location of sedimentary pollen (circles) and charcoal (squares) records; see Tables 4.1 and 4.2 for description of records and citations. Right: Location of archaeological radiocarbon dates used in this study; one point may contain multiple archaeological radiocarbon dates

The present study provides a regional-scale synthesis of paleoenvironmental and archaeological data for the entire prehistoric human occupation of sites across the northeastern United States from Maine to Pennsylvania (Figure 4.1). This region has a high density of sedimentary pollen (n=71) and charcoal (n=40) records which provide a regional vegetation and fire history from the Paleoindian to the historic periods. To quantify the magnitude of vegetation change through time we calculated down-core squared-chord distances (SCD) from pollen percentages across 500-year intervals, where a positive change in SCD indicates a shift in vegetation composition (Grimm and Jacobsen, 1992). Hydrogen isotope ratios from lake sediments provide a record of temperature (Huang *et al.,* 2002) and lake-level variations provide a regional record of effective soil moisture (Shuman *et al.*, 2001).

The archaeological data consists of radiocarbon dates extracted from the Canadian Archaeological Radiocarbon Database (CARD; Morlan, 2005), a searchable repository of over 35,000 archaeological and paleontological radiocarbon dates from Canada and the United States. Each datum includes a location (latitude, longitude, elevation), the type and taxonomy of the material dated, and its associated cultural period as determined by the principal investigator. Using archaeological radiocarbon dates (n=1887) from within the study region (Figure 4.1), we determined the timing of regional cultural transitions through the use of temporal frequency distributions (histograms) of the calibrated dates associated with the different cultural periods. A cultural transition was objectively defined as the first time the majority of dates in a histogram bin consists of dates assigned to a later cultural period.

We interpret the temporal frequency distribution of archaeological radiocarbon dates as a proxy of relative population size (scaled from 0 to 1), based on research that has shown that a larger population will result in a greater deposition of cultural carbon (Gamble *et al.*, 2004; Kuzmin and Keates, 2005; Buchanan *et al.*, 2008; Surovell *et al.*, 2009; Peros *et al.*, 2010; Munoz and Gajewski, 2010). However, it has been hypothesized that the distribution of archaeological radiocarbon dates can be influenced by taphonomic bias resulting in the over-representation of younger material in the archaeological record (Surovell and Brantingham, 2007). In a previous study using the CARD to reconstruct relative population changes, Buchanan *et al.* (2008) showed that even at a high rate of site destruction, relative peaks and troughs in frequency distributions of radiocarbon dates are unlikely to be removed. In another analysis of prehistoric population numbers using the CARD, Peros *et al.* (2010) suggested that over-representation of older material, due to varying levels of archaeological interest and radiocarbon dating effort, may offset taphonomic bias in this database. Nevertheless, we corrected our relative population estimate using a taphonomic model proposed by Surovell *et al.* (2009) and found that relative peaks and troughs in our population reconstruction are not affected by implementing this correction (see Supporting Information for details).

4.2 Methods

4.2.1 Archaeological Data

Radiocarbon dates from the Canadian Archeological Radiocarbon Database (CARD; Morlan, 2005) were extracted for the study region. All radiocarbon dates within the study region which were not affiliated with prehistoric humans or whose cultural association was not specified were removed. The remaining radiocarbon dates (n=1887) were converted to calendar years before present using the median probability provided by CALIB v.5.0.2 (Stuiver *et al.,* 2009) and the IntCal04 dataset (Reimer *et al.*, 2004) or the Marine04 dataset for marine shells (Hughen *et al.*, 2004), with marine reservoir corrections following Dyke (2004). To determine the timing and duration of cultural transitions, temporal frequency distributions of calibrated radiocarbon dates using 250-year bins were prepared.

To reconstruct paleo-population, we employ a method similar to that of Peros *et al.* (2010) in which the frequency of radiocarbon dates is used to estimate population through time. To do this, we fit a spline (df=25) to the temporal frequency distribution to smooth high-frequency variability that may result from the calibration process. Because we are only interested in relative changes in population, we re-scaled the smoothed series using a minimax transformation. This transformation rescales a time-series between 0 and 1 by subtracting the minimum value found in the record from each value, and dividing by the total range of values:

$$x' = (x - x_{min}) / (x_{max} - x_{min}) \qquad \textbf{(4.1)}$$

where x is the initial value, x' is the transformed value and x_{min} and x_{max} are the minimum and maximum values in series, respectively.

4.2.2 Pollen Data

To examine changes in vegetation across the study region, all available pollen records (n=71) were extracted from Neotoma v.1.0 (Grimm, 2008; Table 4.1). All chronologies were converted to calibrated years before present by calibrating the radiocarbon dates (median probability from IntCal04; Reimer *et al.*, 2004) which were used in the original chronology. All pollen counts were converted to a percent of the total terrestrial pollen sum, and taxa with a maximum percent <1% were grouped into broader categories. To quantify the magnitude of vegetation change all pollen records were interpolated at 250-year intervals. The 250-year interval is slightly less than the average sampling resolution (310±220 yr sample^{-1}) to avoid aliasing during interpolation. To create a regional-scale composite pollen record, we calculated the average value for major taxa at each interpolated level. Although individual pollen records differ from the regional composite along the region's major environmental gradient (e.g. *Picea* is more abundant in Maine and *Carya* is more abundant in Connecticut) and on a landscape scale (e.g. valleys versus uplands), pollen percentages of each taxa are roughly normally distributed around the regional mean.

To quantify the magnitude of vegetation change through time, we calculated the squared-chord distance (SCD) of the interpolated fossil-pollen spectra (27 taxa) across 500-year intervals (Grimm and Jacobsen 1992). SCDs provide a measure of dissimilarity between two pollen spectra (Overpeck *et al.*, 2008), where a larger SCD indicates a more significant shift in vegetation composition (Grimm and Jacobsen, 1992). We then calculate the mean SCD at 250-year intervals to identify periods of rapid vegetation change.

4.2.3 Charcoal

To examine changes in fire regimes, we extracted all available charcoal records (n=9) across the study region from the Global Charcoal Database (GCD; Power *et al.*, 2008). Additional charcoal records were provided by the Harvard Forest (n=20), our files (n=4) or digitized from the original publication (n=7) to create a network of 40 records which span the study region (Table 4.2). Because charcoal records were prepared and presented differently in their original publication (e.g. influx, percent, ratio) we rescaled each record between 0 and 1 using a minimax transformation (Equation 4.1). Rescaled values were then interpolated at 250-year intervals. To develop a regional-scale charcoal index (CI) we calculated the average charcoal value at each 250-year interval.

4.3 Results and Discussion

The archaeological chronology of the northeast is broadly divided into Paleoindian, Archaic and Woodland periods based on changes in technology, settlement patterns and artistic traditions, with the Archaic and Woodland periods typically divided into early, middle and late subdivisions which denote a particular change of material culture within this framework (Fagan, 2000). Temporal frequency distributions of archaeological radiocarbon dates, stratified by cultural period as identified by the primary archaeological investigator, provide information on changes in relative population size and the rate and timing of regional cultural transitions (Figure 4.2). The chronological overlap of the dates assigned to each cultural period show that some transitions were more gradual than others, although it is possible to determine the most probable time around which each of these transitions was centered. The transition from Paleoindian to Early Archaic period occurred around 11.25 kyr BP. The transitions from Early to Middle Archaic and Middle to Late Archaic were more abrupt, and are dated at 8.25 kyr BP and 5.25 kyr BP, respectively. There is considerable overlap between the Late Archaic and Early Woodland, with the first Early Woodland dates occurring as early as 5.25 kyr BP (the beginning of the Late Archaic), but it is not until 3.0 kyr BP that the majority of dates are associated with Early Woodland cultures. Cultural transitions into the Middle Woodland and Late Woodland occurred at 2.0 kyr BP and 1.0 kyr BP, respectively. Our reconstruction of human population level is consistent with archaeological interpretations of population levels (Ford, 1974; Dincauze, 1974; Snow, 1980; Mulholland, 1988; Fiedel, 2001), and suggests that the Late Archaic and Late Woodland were both periods of rapid population growth, and that population decreased at the Archaic-Woodland transition (3.0 kyr BP).

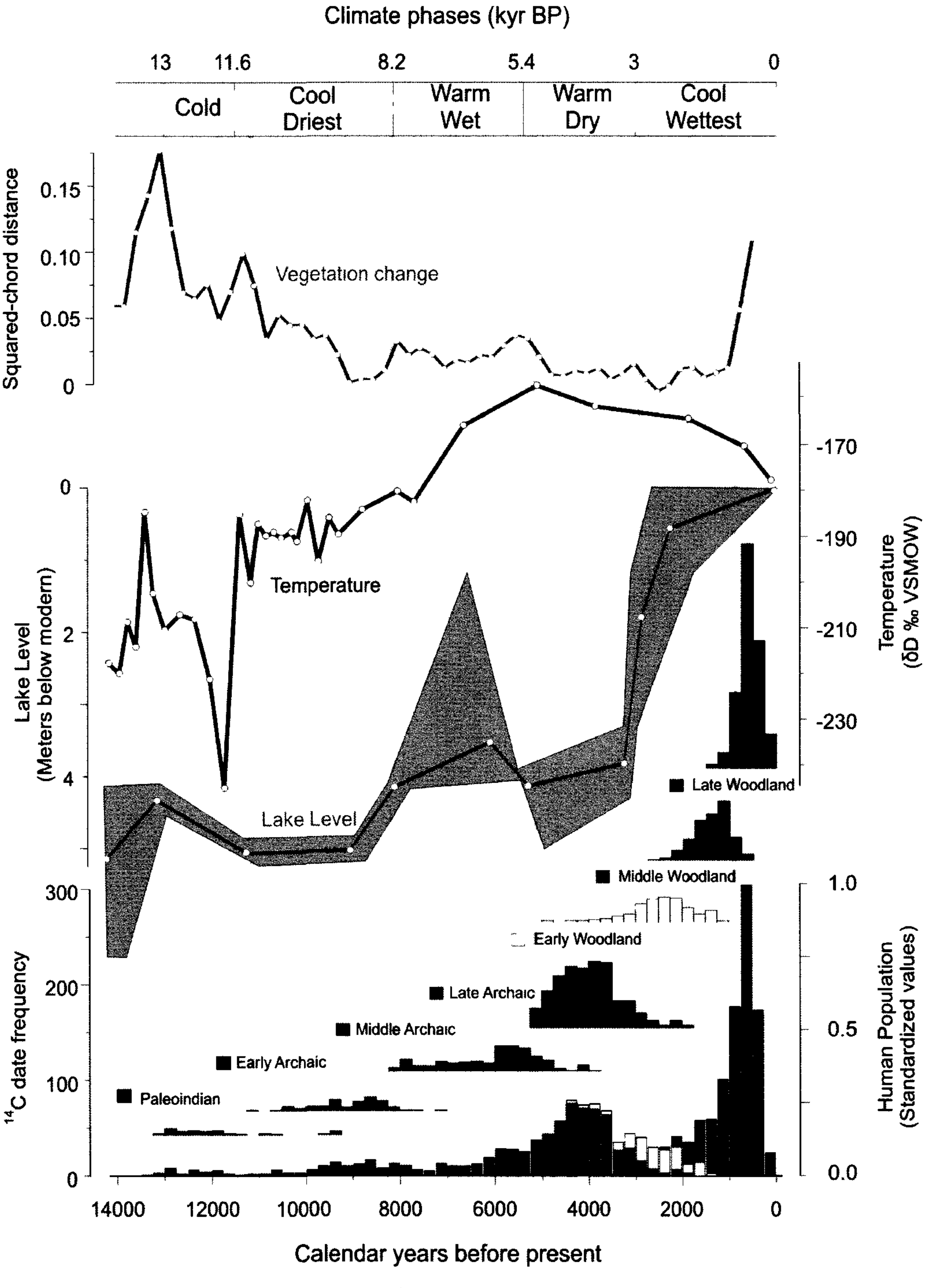

Figure 4.2 Associations between archaeological, climate and vegetation records for northeastern North America from initial settlement (13,500 yr BP) to European contact (500 yr BP). A stacked temporal frequency distribution of archaeological radiocarbon dates (bottom) provides information on the timing of cultural transitions and human population fluctuations. Lake-level (Shuman *et al.*, 2001) and temperature (Huang *et al.*, 2002) reconstructions for the region provide a record of late glacial and Holocene climate. The average of between-sample squared-chord distance (SCD) values from all pollen records in the study region provides a measure of vegetation change through time. Climate phases and transitions derived from paleoenvironmental data are based on Shuman *et al.*, (2004). Grey vertical lines denote cultural transitions defined from the frequency of archaeological ^{14}C dates.

With the exception of the transitions into the Middle and Late Woodland, the latter of which denotes the adoption of maize agriculture (Chilton, 2006), every cultural transition corresponds to a major transition in the climate and vegetation previously identified in this region (Figure 4.2; Shuman *et al.*, 2004). At these transitions, changes in the spatial patterns of temperature and moisture availability caused shifts in vegetation composition, as measured as an increase in squared-chord distance (SCD; Shuman *et al.*, 2009). For pre-agricultural populations in this region who subsisted on wild food resources, these transitions between climate phases changed the abundance and distribution of vegetation communities which would have altered their resource base, site habitability and the carrying capacity of the environment.

Regional pollen and charcoal records describe the changing ecosystems of the region associated with the cultural periods (Figure 4.3). The Paleoindian period (13.5-11.25 kyr BP) was characterized by tundra plants including sedges (Cyperaceae) as well as coniferous spruce (*Picea)* and pine (*Pinus*) and more frequent fire (higher Charcoal Index, CI), the latter possibly due to drier summers (Shuman and Donnelly, 2006; Shuman *et al.*, 2006). During the Early Archaic (11.25-8.25 kyr BP), oak (*Quercus*) increased, pine decreased, and charcoal remained high, consistent with the lake level and temperature data that document a shift toward a drier and warmer climate (Figure 4.2). The Middle Archaic (8.25-5.25 kyr BP) was characterized by an increase in moisture availability, mostly falling in the summer months (Shuman and Donnelly, 2006), low fire frequency, high values of hemlock (*Tsuga*), and increases of other mesic taxa such as beech (*Fagus*) and hickory (*Carya*). During the Late Archaic (5.25-3.0 kyr BP), *Tsuga* decreased abruptly while the percentages of mast trees (*Quercus*, *Carya*) remained high. Charcoal increased again during the Woodland period (3.0-0.5 kyr BP), possibly due to anthropogenic burning (Patterson and Sassaman, 1988) or because the majority of precipitation fell in winter and summers were once again relatively dry (Shuman and Donnelly, 2006), while chestnut (*Castanea*) increased in the southern portion of the study area and spruce (*Picea*) increased in the northern part at the expense of other deciduous taxa (e.g. *Quercus*, *Carya*, *Fagus*). The close correspondence between changes in vegetation and climate, cultural transitions, and population levels suggests that environmental change greatly influenced cultural and demographic change in the northeast, at least until the adoption of maize agriculture around 1.0 kyr BP (Chilton, 2006).

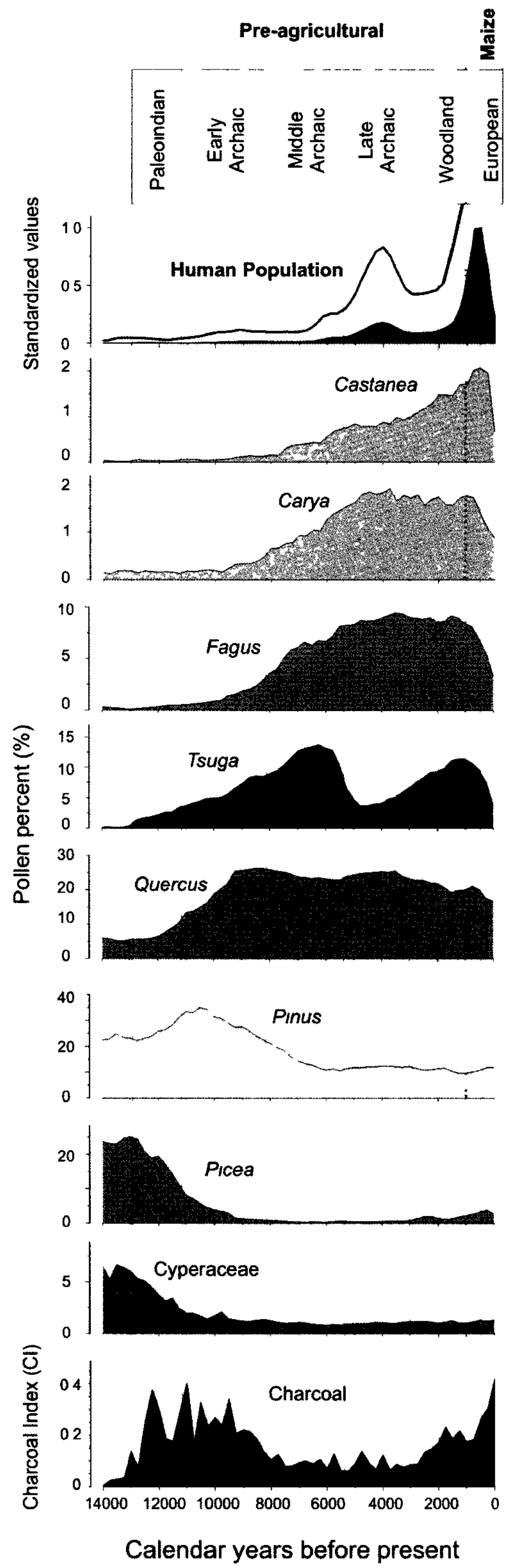

Figure 4.3 Regional-scale pollen and charcoal records in relation to cultural periods. Regional pollen and charcoal records are averaged at 250-year intervals. And charcoal records were rescaled between 0-1 to produce a charcoal index (CI). Solid grey vertical lines denote cultural transitions and dashed line indicates the approximate beginning of maize agriculture in the region (Chilton, 2006). Regional human population numbers, also rescaled from 0-1, was estimated from radiocarbon data using the approach of Peros *et al.* (2010); a 5x exaggeration line appears on the population estimate during the pre-agricultural period.

Several pre-agricultural periods of cultural and demographic change correspond with major and well-documented shifts in climate and ecosystems. For example, the end of the Younger Dryas (~11.6 kyr BP) coincides with the Paleoindian-Archaic transition and the replacement of an open spruce-parkland with a more closed forest consisting mainly of oak (*Quercus*) and pine (*Pinus*) (Newby *et al.*, 2005). A major shift in climate following the collapse of the Laurentide Ice Sheet at 8.2 kyr BP (Alley *et al.*, 1997) resulted in a major change of moisture availability (Shuman *et al.*, 2006) and the expansion of hemlock (*Tsuga*) and beech (*Fagus*) and the Early-Middle Archaic transition. A decline in hemlock (*Tsuga*) at 5.4 kyr BP (Bennett and Fuller, 2002) occurred at the same time as the Middle-Late Archaic transition and population increase. Although this transition has been associated with a pathogenic outbreak that greatly impacted hemlock (Allison *et al.*, 1986), a reevaluation of the paleocological data suggests the hemlock decline may be associated with drier conditions (Shuman *et al.*, 2004; Foster *et al.*, 2006). The Late Archaic is also the period during which mast-producing trees (*Quercus* and *Carya*), an important caloric source for humans and animals, reached their maximum abundance (Figure 4.3). A population decline at the Archaic-Woodland transition (3.0 kyr BP) previously identified by archaeologists (Dincauze, 1974; Snow 1980; Mulholland, 1988; Fiedel, 2001) corresponds with gradual late-Holocene cooling and an increase in lake-level, driven by an increase in winter precipitation (i.e. deeper snowpack) (Shuman and Donnelly, 2006; Shuman *et al.*, 2001; Huang *et al.*, 2002).

More recent cultural and demographic changes are not as easily associated with major climate transitions. For example, the most significant increase in population occurred during the Late Woodland (1.0-0.5 kyr BP). This period is defined by the adoption of maize agriculture, a technology that would have facilitated population growth by increasing the amount of food energy available. Although agricultural production is related to climate, the relatively short length of the Late Woodland period combined with the coarse temporal resolution of many pollen records makes it difficult to discern human-environment associations during this time. Higher-resolution paleobotanical analyses from the region (Gajewski, 1988) have inferred a change in vegetation and climate around 1 kyr BP, and more detailed archaeological-environmental syntheses around this time would provide insight into the importance of climate change at the northern limits of maize agriculture (Demeritt, 1991) as well as the extent of human impact on the landscape (Denevan, 1992).

Given the complexity of human-climate interactions (Coombes and Barber, 2005) and the multifaceted responses of ecosystems to past climate change (COHMAP, 1988; Shuman *et al.*, 2002; Williams *et al.*, 2004) a unidirectional relationship from climatic change to a human response (deMenocal, 2001) may not always emerge, because the resource base of prehistoric hunter-gatherers in a temperate region is controlled by the interaction of many ecological factors which are themselves associated in complex ways with environmental changes. Nevertheless, our work shows a close correspondence between periods of change in ecosystems and the archaeological record, and highlights the complex and multidirectional nature of human-climate relationships. The ecosystems from which prehistoric humans subsisted changed periodically in response to new climatic regimes, and humans adjusted their toolkits accordingly by developing or adopting new or existing technologies. While human population numbers fluctuated in response to changes in the distribution and availability of food resources and site habitability, technological innovation, particularly maize agriculture, likely altered the dynamics of human-environment interaction. These findings provide new insights into the long-term interconnectedness of environmental change, human culture and population in a temperate region, and convey a consolidated environmental framework from which further exploration of the factors that influenced North American prehistory can emerge.

4.4 Supporting Information

4.4.1 Adjusting for Taphonomic Bias

Temporal frequency distributions of archaeological radiocarbon dates are increasingly used as a paleodemography proxy (Kuzmin and Keates, 2005; Buchanan *et al.*, 2008; Peros *et al.*, 2010; Munoz and Gajewski, 2010), but the destruction of cultural carbon by post-depositional processes such as erosion and dissolution may influence these paleodemographic reconstructions (Surovell and Brantingham, 2007). Recently, Surovell *et al.* (2009) proposed a solution to this problem by developing an empirical model to correct for this "taphonomic bias", described as:

$$n_t = 5.73 \times 10^6 (2176.4 + t)^{-1.39} \qquad \textbf{(4.2)}$$

where n_t is the original number of deposits at time t, and t is the time elapsed since the initial deposition of the dated material.

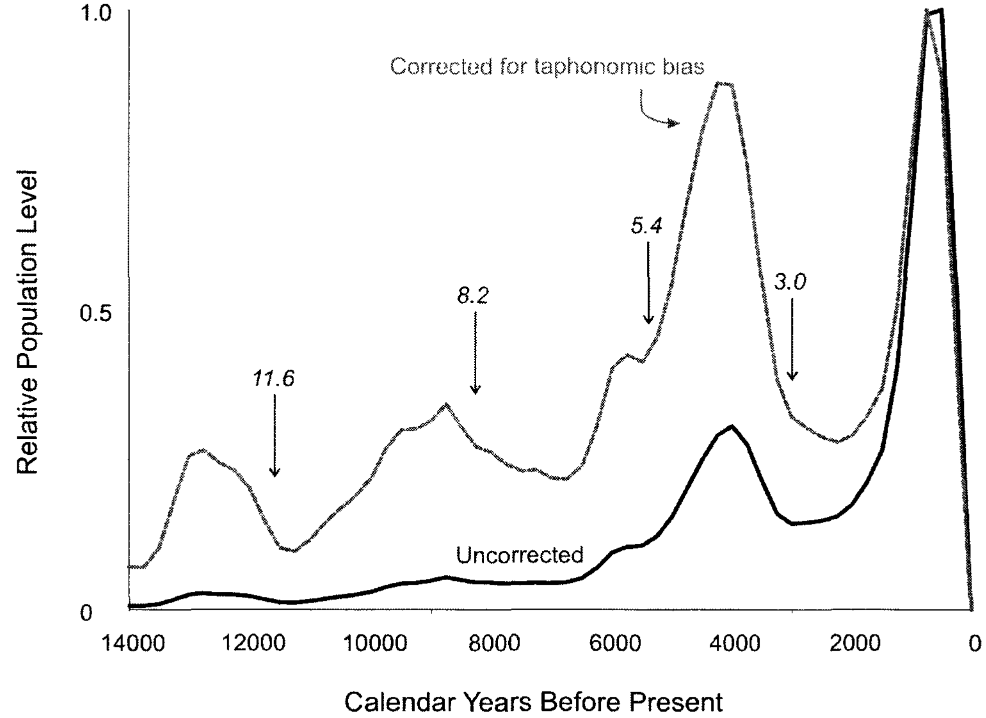

Figure 4.4 Correcting the reconstructed population level for taphonomic bias using the empirical model proposed by Surovell *et al.* (2009). The uncorrected population (black solid line) is the reconstruction which appears in Figure 4.2 and Figure 4.3. When corrected for taphonomic bias (grey dashed line) the timing of relative peaks and troughs remains the same, but the magnitude of these population fluctuations increases.

Although our population reconstruction is consistent with several archaeological interpretations (Ford, 1974; Dincauze, 1974; Snow, 1980; Mulholland, 1988; Fiedel, 2001) we corrected our reconstruction using the model proposed by Surovell *et al.* (2009) to further validate the major demographic changes in our reconstruction (Figure 4.4). The original, uncorrected, population reconstruction presented in the article (Figure 4.2, 4.3) displays marked population increases between 5.4 and 4.0 kyr BP (Late Archaic) and between 1.0 and 0.5 kyr BP (Late Woodland) which straddle a population decline centered around 3.0 kyr BP (Early Woodland). When the original time-series is corrected using Equation 4.2 and re-scaled between 0 and 1 (Equation 4.1) these demographic changes remain, although their magnitude is amplified. This amplification of the original data also magnifies other demographic shifts, more subtle in the uncorrected time-series, which are concurrent with major environmental-climatic transitions discussed in the article at 11.6 kyr BP (the end of the Younger Dryas) and 8.2 kyr BP (the collapse of the Laurentide Ice Sheet). Nevertheless, the timing of relative changes in the original population reconstruction is unaffected when corrected for post-depositional taphonomic bias. This analysis largely agrees with similar population reconstructions using the CARD, which have suggested that (a) the timing of relative changes in reconstructed population level is not influenced by post-depositional destruction of cultural carbon (Buchanan *et al.*, 2008) and (b) older material may be over-represented in this database due to increased interest, which offsets the need for a strong taphonomic correction (Peros *et al.*, 2010).

We chose not to use the corrected population reconstruction because the major features in the original reconstruction (population increase during the Late Archaic and Late Woodland; population decrease during the Early Woodland) are well documented in the archaeological literature (see review by Fiedel, 2001), while the additional features of the corrected reconstruction have not, to the best of our knowledge, been widely discussed in the literature. We hope that the work presented in this study will result in further discussion of prehistoric demography in this region and others, and that other population reconstructions are developed to test the validity of our own (cf. Warrick, 2008; Munoz and Gajewski, 2010).

4.4.2 Sedimentary Pollen and Charcoal Datasets

Tables summarizing key characteristics of the pollen (Table 4.1) and charcoal (Table 4.2) records used in this paper can be found below.

Table 4.1 Sedimentary pollen records used in this study. All records were extracted from Neotoma V1.0 which uses data from the Global Pollen Database. Basal age is given in calendar years before present.

Site Name	Latitude	Longitude	Elevation (m)	Area (ha)	Basal age	Reference
Aino P.	42.680	-71.927	354	1.7	1345	Fuller *et al.* (1998)
Basin P.	44.470	-70.050	124	14	1588	Gajewski *et al.* (1987)
Belmont B.	42.250	-77.917	497	2.0	19543	Spear & Miller (1976)
Berry P.	42.500	-73.317	600	3.9	15144	Whitehead (1979)
Big P.	39.767	-78.550	634		12939	Watts (1979)
Brandreth B.	43.917	-74.683	600	7.0	12485	Overpeck (1985)
Burden L.	42.604	-73.567	192	147	9891	Gaudreau (1986)
Carbuncle P.	41.700	-71.783	342	19.5	998	Bernabo (1977)
Caribou B.	45.933	-68.767	37		10829	Gajewski (1987)
Clear P.	43.750	-74.017	513	10	1898	Gajewski *et al.* (1987)
Conroy L.	46.283	-67.883	140	10	1940	Gajewski *et al.* (1987)
Crider's P.	39.967	-77.550	290		18955	Watts (1979)
Dead Frog P.	42.574	-72.509	80	5.4	3582	Fuller *et al.* (1998)
Deer L. B.	44.033	-71.833	1325	0.09	16163	Spear (1981)
Donut P. B.	41.275	-70.058	4		529	Dunwiddie (1990)
Duck P.	41.933	-70.001	2		13854	Winkler (1985)
Eagle L. B.	44.167	-71.667	1275	0.14	12515	Spear (1981)
Ely L.	41.767	-75.833	384	14.0	2442	Gajewski *et al.* (1987)
Fresh P.	41.158	-71.575	28	50.0	15359	Dunwiddie (1990)
Gould P.	44.983	-69.317	89	3.2	14111	Andersen *et al.* (1992)
Gould's B.	42.533	-72.183	338	0.2	15739	Davis (1958)
Green P. (NJ)	41.004	-74.497	292	201	1447	Russell (1980)
Hawley B. P.	42.566	-72.883	549		13817	Patterson (unpublished)
Heart L.	44.181	-73.968	661	11.2	13854	Whitehead & Jackson (1990)
Helmetta B.	40.383	-74.433	15		11417	Watts (1979)
Houghton B.	42.542	-78.671	428	2	13758	Miller (1973)
Kinsman P.	44.133	-71.733	1140	1.9	13095	Spear (1981)
L. Lacawac	41.382	-75.291	443		696	Russell (1993)
Lockport Gulf Section	43.166	-78.717	109		12999	Miller & Morgan (1982)
Lonesome L.	44.140	-71.701	831	5.2	12553	Davis *et al.* (1980)
Longswamp	40.483	-75.667	192		14698	Watts (1979)
Loon P.	45.033	-68.200	110	2	13750	Jacobson *et al.* (unpublished)
Lost P.	44.247	-71.252	625	1	16011	Davis *et al.* (1980)
Mansell P.	45.042	-68.733	58	4	10328	Almquist-Jacobson & Sanger (1995)
Mashapaug P.	41.783	-71.433	12	36.8	4921	Bernabo (1977)
Mohawk P.	41.817	-73.283	360		18975	Gaudreau (1986)
Monhegan Island Meadow	43.766	-69.300	3	3.3	12020	Bostwick (1978)
Nichols Brook Site	42.545	-78.479	438		14932	Calkin & McAndrews (1980)
No Bottom P.	41.283	-70.209	6		17336	Dunwiddie (1990)
North P.	42.650	-73.050	586	7.1	13208	Whitehead and Crisman (1978)
Panther Run P.	40.800	-77.417	634		16233	Watts (1979)
Pasacaco P.	41.517	-71.450	3	27	1183	Bernabo (1977)

Poland Spring P	44 033	-70 350	94	3	15370	Jacobson *et al* (unpublished)
Protection B	42 622	-78 467	430	6	13284	Miller (1973)
Rogers L	41 367	-72 117	91	107	18597	Davis (1969)
Rose L	41 917	-77 925	690	5 2	17315	Cotter & Crowl (1981)
Ross P	43 922	-69 411	37	7 1	14696	Kellogg (1991)
Silver L (PA)	41 252	-74 987	402		770	Russell *et al* (1993)
Sinkhole P	43 967	70 350	95	2	13117	Jacobson *et al* (unpublished)
Spring L	41 674	-76 350	342		16277	Nickmann (unpublished)
Spruce P	41 240	-74 205	223	2 6	31156	Maenza-Gmelch (1997)
Sutherland P	41 392	-74 038	380	4 05	34645	Maenza-Gmelch (1997)
Szabo P	40 400	-74 483	29		18862	Watts (1979)
Tannersville B	41 033	-75 267	277		19411	Watts (1979)
Taupawshas B	41 275	-70 058	14		12852	Dunwiddie (1989)
Titicut Swamp	41 950	-71 033	20	5	13679	Nelson (1984)
Tom Swamp	42 517	72 213	231	200	16488	Davis (1958)
Upper South Branch P	46 083	-68 900	300	34	10313	Anderson (1979)
Upper Wallface P	44 146	-74 054	948	5 5	14819	Whitehead & Jackson (1990)
Valhalla Hollow	44 309	-74 371	480	0 01	1127	Kearsley & Jackson (1997)
West Sand L Peat B	42 633	-73 600	170		12772	Gaudreau (1986)
Williams Street B	41 900	-71 067	5	10	19098	Davis (1960)
Winneconnet P	41 967	71 117	20	60	16621	Suter (1985)

Table 4.2 Sedimentary charcoal records used in this study Basal age is given in calendar years before present Data source refers to the origin of the data GCD=Global Charcoal Database HF=Harvard Forest website or personal communication, LPC=Laboratory for Paleoclimatology and Climatology, University of Ottawa D=Digitized from original publication Some lakes have multiple charcoal records and we used all available records to reconstruct fire history

Site Name	Latitude	Longitude	Elevation (m)	Area (ha)	Basal age	Data source	Reference
Aino P	42 681	-71 926	354	1 8	1170	GCD	Parhsall & Foster (2002)
Aino P	42 681	-71 926	354	1 8	1327	HF	Fuller *et al* (1998)
Basin P	44 400	70 500	125	14	1678	GCD	Clark & Royall (1996)
Basin P	44 400	-70 500	125	14	1581	LPC	Gajewski *et al* (1985)
Clear P	43 750	-74 017	513	10	1866	LPC	Gajewski *et al* (1985)
Conroy L	46 283	-67 883	140	10	1916	LPC	Gajewski *et al* (1985)
Dead Frog P	42 572	-72 510	80	0 2	3308	HF	Fuller *et al* (1998)
Deep P	41 581	70 580	23	1	2005	HF	Parhsall & Foster (2002)
Duck P	41 800	-70 000	2 5	5 1	14222	D	Winkler (1985)
Eagle P	41 698	-70 137	11	4	3823	HF	Parhsall & Foster (2002)
Ely L	41 760	75 830	384	14	5543	GCD	Clark & Royall (1996)
Ely L	41 760	75 830	384	14	2346	LPC	Gajewski *et al* (1985)
Fresh P	41 594	70 534	7	5 3	2392	HF	Parhsall & Foster (2002)
Gould P	44 980	-69 320	90	3 2	16664	D	Anderson *et al* (1992)
Green P (MA)	42 567	72 511	80	5	2618	HF	Fuller *et al* (1998)
Green P (MA)	42 567	72 511	80	5	414	GCD	Parhsall & Foster (2002)
Ice House P	41 798	69 961	19	1 8	2621	HF	Parhsall & Foster (2002)
Jemima P	41 829	69 985	3	2 2	2147	HF	Parhsall & Foster (2002)
L Pleasant	42 56	-72 514	80	20	1266	HF	Fuller *et al* (1998)
Lily P New Salem	42 418	72 347	303	2 3	3492	D	Foster *et al* (2002)
Lily P Warwick	42 688	-72 337	269	0 8	727	GCD	Parhsall & Foster (2002)
Lily P Warwick	42 688	-72 337	269	0 8	1214	HF	Fuller *et al* (1998)
Little Mirror P	42 525	-71 609	73	5	1043	HF	Fuller *et al* (1998)
Little P Bolton	42 422	71 588	99	5	3677	GCD	Parhsall & Foster (2002)
Little P Bolton	42 422	71 588	99	5	1193	HF	Fuller *et al* (1998)
Mansell P	45 042	-68 733	58		10328	D	Almquist Jacobson & Sanger (1995)
North Round P	42 848	72 452	317	4 3	1534	HF	Francis & Foster (2001)
Otter P	42 656	-72 533	107	3 1	1011	GCD	Parhsall & Foster (2002)
Pecker P	42 713	-71 965	370	16 5	1434	HF	Francis & Foster (2001)
Piedmont Marsh	41 000	-73 917		110	1248	D	Pederson *et al* (2005)
Pout P	43 420	71 500	232		5809	GCD	Clark & Hussey (1996)
Quag P	42 567	-71 957	332	0 8	958	HF	Fuller *et al* (1998)
Round P (NY)	44 000	74 000	548		11891	GCD	Clark (unpublished)
Round P (MA)	41 971	-70 011	4	1 6	3966	HF	Parhsall & Foster (2002)
Sandy Hill P	41 690	-70 365	16	2 4	2562	HF	Parhsall & Foster (2002)

Silver L. (MA)	42.601	-72.229	161	7.1	969	HF	Fuller *et al.* (1998)
Snake P.	42.556	-72.017	282	5	2480	HF	Fuller *et al.* (1998)
Spurce P.	41.239	-74.204	223	2.6	13051	D	Maenza-Gmelch (1997)
Sutherland P.	41.391	-74.038	380	4.05	11522	D	Maenza-Gmelch (1997)
Wickett P.	42.570	-72.432	330	11.5	3152	HF	Francis & Foster (2001)

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5. Distinguishing prehistoric human influence on late Holocene forests in southern Ontario, Canada

Abstract

The influence of Native Americans on late Holocene forests of North America remains a contentious issue, as it is unclear whether vegetation transitions inferred from pollen records are a product of prehistoric human disturbance. In southern Ontario, the adoption of maize agriculture coincides with neoglacial cooling, so distinguishing the relative roles of prehistoric people and climatic change in shaping forest composition requires that pollen records be interpreted in a regional context. In this study, we objectively identify pollen records from the southern Ontario region which exhibit periods of significant pre-European anthropogenic disturbance in the context of the archaeological record. This enables a comparison of pollen records shaped primarily by climatic cooling with those disturbed by prehistoric human forest clearance. Our results suggest that regional-scale late-Holocene cooling resulted in a gradual and synchronous shift from deciduous to boreal taxa. However, forest clearance by Native Americans resulted in a secondary succession characterized by the replacement of late-successional beech-maple forest with ruderal species, grasses and poplar, followed by mid-successional oak and white pine. This transition consistently coincides in space and time with an increase in archeological records of human occupation. The method we have developed here to distinguish significant prehistoric human impacts could be applied to pollen records in other regions, or on a continental scale.

5.1 Introduction

The relative importance of prehistoric human land use, particularly forest clearance associated with maize *(Zea maize)* agriculture, on southern Ontario forest dynamics and composition has been the object of a number of studies (McAndrews and Turton, 2007; Campbell and McAndrews, 1995; Clark, 1995; Clark and Royall, 1995; McAndrews and Boyko-Diankonow, 1989). Debate has focused on whether changes in forest composition interpreted from late Holocene pollen diagrams are responses to natural (climate change) or anthropogenic (land clearance, burning) factors (Wade *et al.*, 2000). At Crawford

Lake, Clark and Royall (1995) suggest that a rapid transition from *Fagus-Acer* to *Quercus-Pinus* forests beginning around 1400 CE is a product of Native American slash-and-burn agriculture, although this transition also occurs during a period of cooling (Campbell and McAndrews, 1991; 1993). Burden *et al.* (1986) found a similar transition at Second Lake near Georgian Bay in conjunction with *Zea* pollen, and also suggest that forests were altered by Native Americans. However, the forests of the region have been continually changing over the past several thousand years, as well as throughout the Holocene (Gajewski *et al.*, 1987; Williams *et al*; 2004; Grimm and Jacobson, 2004; Finkelstein *et al.*, 2005), and determining the cause of a particular transition in a pollen diagram depends in part on understanding the regional to continental context of the transition. For example, a decline of *Fagus* over the last 1,000 years is observed at many sites throughout the northern deciduous forest (Gajewski, 1987), and is synchronous with other changes in forest composition (such as an increase in *Picea* and *Pinus*) that strongly suggest a response to climate variations such as the Little Ice Age and Medieval Warm Period (Pederson *et al.*, 2005). In addition, it is unclear whether prehistoric populations of southern Ontario were high enough to have had a significant impact on the environment (Campbell and Campbell, 1994). The spatial extent and magnitude of prehistoric human influence on forests in southern Ontario, and throughout North America, remains poorly understood in part because previous human-paleoenvironment studies have focused on single locations rather than a regional context (Clark and Royall, 1995; Delcourt *et al.*, 1998).

The debate described above is part of a larger discussion about the environmental history of the 'New World', as it has been suggested that much of what Europeans observed upon arriving in North America was not a 'primeval forest' but a cultural landscape that was a consequence of millennia of human activity (Denevan, 1992a; Delcourt and Delcourt, 2004). Others, however, question the extent of this influence (Russell, 1983; Vale, 1998; 2002). In part, this debate revolves around the difficulty in quantifying paleoenvironmental conditions in the context of current paradigms about ecosystem dynamics and human impacts on the landscape. For example, estimates of population size, which would influence environmental impact, remain under discussion, with some researchers estimating much larger population sizes at European contact than previous estimates (Dobyns, 1983; Denevan, 1992b; Verano and Ubelaker, 1992; Ubelaker, 2006). As a consequence, in North American paleoecological interpretations (e.g. Ritchie, 1987; Bennett, 1993; Williams *et al.*, 2004) the potential for prehistoric human influence on ecosystems is often overlooked entirely (Delcourt, 1987; Butzer, 1992), due, at least in part, to difficulty separating a subtle anthropogenic factor from the other forces, such as climate variability, that cause changes in ecosystems (Fuller *et al.*, 1998; Kay, 2002). Thus, a key approach to resolving these alternate viewpoints is to refocus our approach from the analysis of anthropogenic indicators or impacts on the forests at a single site, as used in previous studies, and use a regional to continental approach. At these scales, sub-regional human impacts should appear as anomalies in relation to larger-scale natural environmental variability (Gajewski *et al.*, 2006; Abrams and Nowacki, 2008).

In this paper, we analyze pollen diagrams from southern Ontario in the context of the archaeological record. We do this by objectively identifying those southern Ontario pollen sites that show significant prehistoric anthropogenic impacts on the pollen record using a temporal scan statistic (Kuldorff, 1997). We then compare these pollen records to others in the region which do not appear to be influenced by Native American activities. We use a database of radiocarbon dates from archeological sites to estimate spatial and temporal patterns of Native American paleo-population. The method used here could be applied to pollen records in other regions with the goal of identifying pollen records significantly influenced by prehistoric human activity. Developing an understanding of when and where human activity may have affected ecosystems in the past is crucial for properly calibrating environmental models, establishing land management goals and deriving quantitative reconstructions of past climate from environmental proxies (Abrams, 1992; Hunter, 1996; Willis and Birks, 2006; Nowacki and Abrams, 2008).

5.1.1 Historical background

During the Early and Middle Woodland periods (800 BCE – 1000 CE; 2750-950 cal. yr. BP), southern Ontario was populated by small mobile bands of primarily hunter-fisher-gatherers living in seasonal villages (Spence *et al.*, 1990). Maize agriculture was introduced to southern Ontario through the Niagara Peninsula around 400-500 CE (1550-1450 cal. yr. BP; Crawford *et al.*, 1997). Isotopic analyses of skeletal populations suggest the transition to agriculture was gradual and that before 1150 CE maize constituted a relatively low proportion of Native American diet (Katzenberg *et al.*, 1995). Over the next several centuries, the intensity and extent of maize agriculture increased, with the addition of other cultigens including squash (*Cucurbita pepo*), sunflower (*Helianthus annuus*) and beans (*Phaseolus vulgaris*) by 1300 CE (Fagan, 2000; Crawford and Smith, 2003; Crawford, 2006). Population growth curves for southern Ontario by Warrick (2008) suggest that populations increased rapidly in response to widespread agriculture, from less than 5,000 persons before 1200 CE to over 30,000 by 1400 CE.

European exploration of the region began in the early 17th century. Ethnohistoric records from the 17th century, primarily the reports of early explorers and missionaries, note the presence of cleared forest and large agricultural fields. These reports also describe specific methods of land preparation (including burning and/or tilling), planting maize seeds and food preparation from harvested crops (Champlain, 1906; Sagard-Théodat, 1964; Lafitau, 1977; reviewed by Doolittle, 2000). European settlement in Ontario was minimal until the late 18th century (Gentilcore, 1969). The region was cleared by logging, and subsequently used for extensive agriculture; European settlement is clearly distinguishable in pollen records throughout this area by a sharp increase in *Ambrosia*-type pollen and a decrease in arboreal taxa (McAndrews, 1988).

5.1.2 Study area

The study area (Figure 5.1a) is southern Ontario, bounded in the north by the latitude of Lake Nipissing, the Ottawa River Valley to the east, Lake Ontario and Lake Erie to the south and Lake Huron in the west. Today, the mean annual temperatures are around 4°C in the north to 8°C in the south, with 800-1000 mm annual precipitation spread evenly throughout the year (Environment Canada, 2009). In the south and along the northern shore of Lake Ontario there are thick surficial deposits of glacial origin (Fulton, 1995). To the north, Precambrian Shield is either completely exposed or covered by a thin veneer of soil which has developed since deglaciation around 14,000 cal. yr. BP (Fulton, 1995; Dyke *et al.*, 2003).

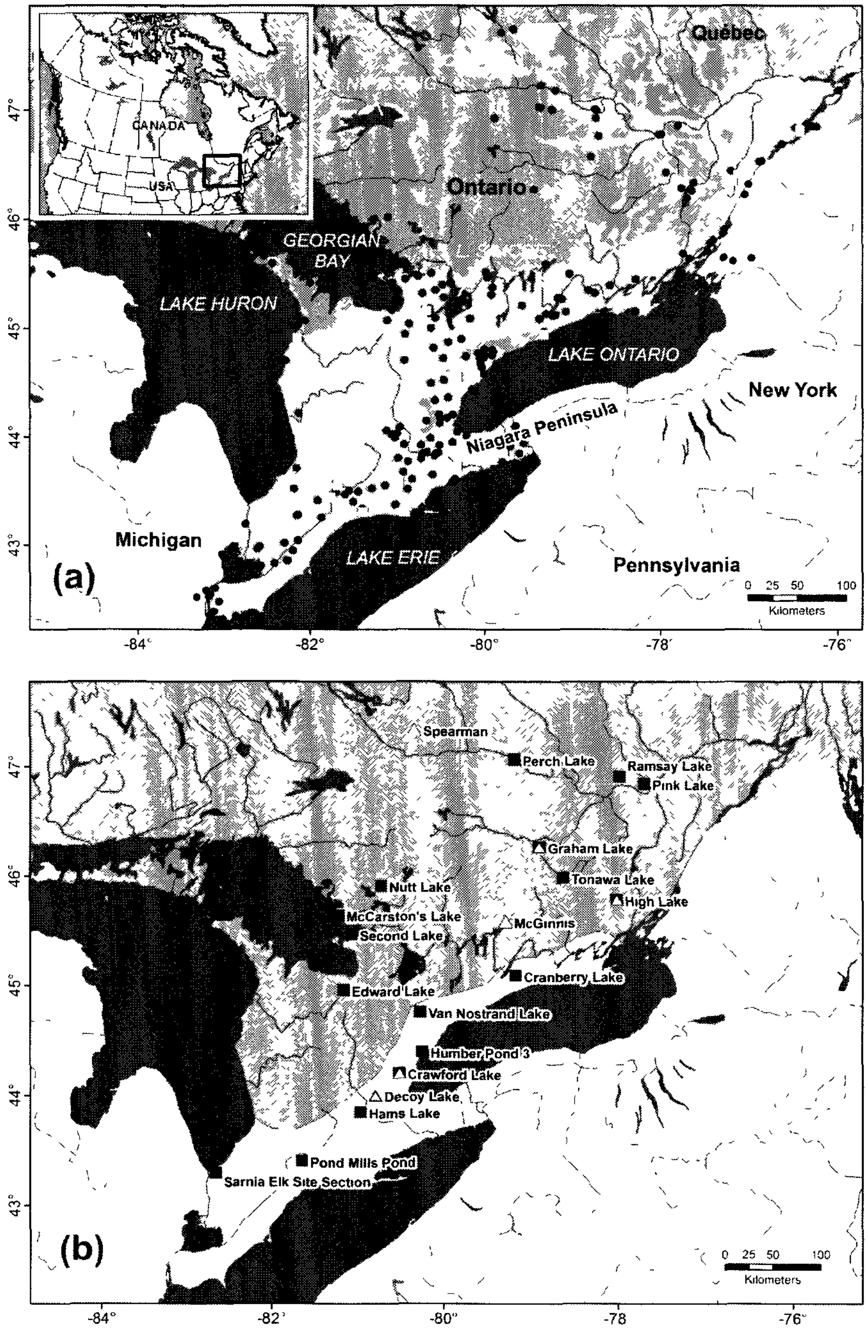


Figure 5.1 Map of southern Ontario, Canada showing (a) surficial materials after Fulton (1995) (dark grey= Precambrian shield; light grey=Glacial deposits) and locations of archaeological sites (black dots) and radiocarbon dated cultigens (white squares) whose calibrated age (median probability) falls within the study period (0-1950 CE; 1950-0 cal. yr. BP), and *(b)* forest regions after Hosie (1979) (dark grey=Great Lakes-St. Lawrence; light grey=Deciduous) and the locations of sedimentary pollen (squares) and charcoal (triangles) records used in this study.

Pollen diagrams from the region indicate that the dominant plant taxa at the beginning of Holocene were *Pinus*, *Picea*, *Populus*, *Betula,* Cyperaceae and Poaceae, with the arrival of *Quercus*, *Acer*, *Tsuga*, *Tilia* and *Fagus* in the mid-Holocene (McAndrews, 1981; Ritchie, 1987). In the southern portion of the study area, several important deciduous taxa (e.g. *Quercus alba*, *Carya ovata*, *Castanea dentata*, *Juglans spp.*) reach their northern limit in the Deciduous Forest region (Hosie, 1979). On the Precambrian Shield, the Great Lakes-St. Lawrence forest region consists of a mixed forest consisting of upland hardwoods (*Fagus grandifolia, Acer rubrum, Acer saccarum, Quercus rubra*) and conifers in mesic sites (*Tsuga canadensis*, *Picea glauca*) with pines (*Pinus strobus*, *Pinus resinosa*) and birch (*Betula alleghaniensis*) found in a variety of habitats (Braun, 1950; Rowe, 1977).

5.2 Methods

5.2.1 Fossil Pollen Records

Neotoma V1.0 is a relational multiproxy paleoenvironmental database freely available to the public (Grimm, 2008). We extracted 17 pollen records within the study area from the Neotoma database (Figure 5.1b; Table 5.1). This study was restricted to the past 2,000 calendar years, the time period before and after the arrival of maize agriculture. A pollen record was excluded if it (a) contained fewer than 15 samples within the study period, (b) contained a hiatus of >500 years within the study period, or (c) had no chronological control (other than the top of the core) within the study period. We used the Neotoma age-depth information for our chronologies, which typically use the European settlement horizon as a chronological control. Where chronologies did not use this marker, we re-interpolated the age-depth curves; where this event was evident near the top of the core (>10X increase in *Ambrosia*-type within a century) we assigned this depth to 1800 CE and used linear interpolation to re-compute sample ages. This had a minimal effect in our analysis because poor chronological control was initially selected against and because most chronologies incorporate the European settlement horizon. All pollen counts were converted to a percent of the total terrestrial pollen sum. Taxonomic resolution of pollen data were reduced to the genus level in arboreal taxa where species-level identification was made (e.g. *Acer saccharum* was reduced to *Acer*) because many records are not resolved beyond the genus level.

Table 5.1 List of sedimentary pollen and charcoal records used in this study. The number of samples includes only those within the study period (0-2000 CE). Surficial material after Fulton (1995); GL=Glaciolacustrine, GF=Glaciofluvial.

Site	Type	No. Samples	Area (Ha)	Elevation (m)	Surficial material	Reference
Deciduous Forest Region						
Sarnia Elk Site	Pollen	22		185	GL (coarse)	McAndrews (n.d.)
Pond Mills P.	Pollen	15		274	Till blanket	McAndrews (1981)
Hams L.	Pollen	16	2.4	301	Till blanket	Bennett (1987)
Decoy L.	Charcoal	11	0.4	260	GF (coarse)	Sceicz & MacDonald (1991)
Crawford L.	Pollen; Charcoal	124	1.5	102	Till blanket	McAndrews & Boyko-Diakonow (1989); Clark & Royall (1996)
Humber P. 3	Pollen	35	4.7	74	GL (coarse)	Wenniger & McAndrews (1989)
Van Nostrand L.	Pollen	15	3.1	297	GF (coarse)	McAndrews (1973)
Cranberry L.	Pollen	36		170	GF (coarse)	McAndrews (n.d.)
Great Lakes-St. Lawrence Forest Region						
Edward L.	Pollen	15	14.7	518	Till blanket	McAndrews (1981)
Second L.	Pollen	30	40.0	196	GL (coarse)	Burden et al. (1986)
McCarstons L.	Pollen	18		433	Till blanket	McAndrews (n.d.)
Nutt L.	Pollen	15	1.2	305	Till veneer	Bennett (1987)
Spearman L.	Charcoal	52		368	Till blanket	Carcaillet & Richard (2000)
McGinnis L.	Charcoal	53	45.0	256	Bedrock	Carcaillet et al. (2006)
Perch L	Pollen	173	0.2	160	Till veneer	Boyko-Diakonow & Terasmae (1975)
Graham L.	Pollen; Charcoal	26	0.2	381	Till veneer	Fuller (1997)
Tonawa L.	Pollen	15	1.6	274	Till veneer	McAndrews (n.d.)
High L.	Pollen; Charcoal	17		192	Till blanket	Fuller (1997)
Ramsay L.	Pollen	13	9.0	200	Till veneer	Mott & Farley-Gill (1981)
Pink L.	Pollen	25	9.4	162	Till veneer	Mott & Farley-Gill (1981)

5.2.2 Anthropogenic Indicators

Anthropogenic indicators are early sucessional ruderal taxa which tend to colonize open habitats disturbed by human activity, such as a settlement clearing or an agricultural field (Behr, 1986). In order to detect human land clearance in pollen records, we developed an anthropogenic plant functional type class (APFT) composed of those taxa which are indicative of human disturbance when found in an archaeological context (Aaby, 1986; Behr, 1988; Delcourt, 1987; Birks *et al.*, 1988). We compiled taxa from a list of anthropogenic indicators provided by Behr (1986), with North American additions from Marks (1983) and Delcourt (1987). Taxa included in the APFT are, in order of decreasing abundance in the pollen records, *Ambrosia*, *Artemisia*, *Rumex*, *Ranunculus*, *Pteridium*, Brassicaceae, *Plantago*, *Urtica*, Caryophyllaceae and *Polygonum*.

5.2.3 Scan Statistics

Scan statistics are used to identify clusters of continuous or discrete variables in space and/or time (Kuldorff, 1997). The temporal scan statistic employed in this analysis uses a series of over-lapping windows of different sizes (length of time) to analyze a time-series. For each window a likelihood function is computed based on the number of observed versus expected observations of the parameter in question (Glaz *et al.*, 2001), in our case pollen percentages of APFT. The window with the maximum likelihood is the most likely cluster, and is thus least expected to have occurred by chance. The significance of this cluster is established through Monte Carlo replications, where the maximum likelihood from the real data is compared with that of 999 permuted datasets (Kuldorff, 2009). The significance (p-value) assigned to a window is inversely proportional to (a) the maximum log likelihood ratio, (b) the difference between the mean inside and outside the window and (c) the number of samples falling inside the window. The scan statistic is an ideal approach for detecting human impacts from pollen percentages because this method (a) does not require samples to be evenly spaced in time or space, (b) works with continuous variables which are not normally distributed and (c) does not require a null distribution to be defined by the user, but instead calculates the expected frequency based on the data itself (Kuldorff, 1997; Jacquez, 2008).

Using SatScan v8.0 (Kuldorff, 2009) we ran a temporal scan statistic using the normal model (Huang *et al.*, 2009) on the APFT from each site to identify periods of statistically significant ($p<0.100$) increases in these taxa. The data were truncated at 1600 CE, which corresponds to the first significant European colonization of North America. Although this date is well before the major European settlement of Ontario (late 18th century), using this older date ensured that pollen transported from the coastal colonies did not affect the analysis. It is expected that if land were cleared for agriculture near a pollen site, then a relative increase in the APFT should occur at that site (Behr, 1986; Birks *et al.*, 1988). We then compared the complete pollen records of those sites identified by the scan statistic as having a significant increase in APFT with neighbouring sites at which no such increase was identified. Comparison was accomplished by creating two composite records; the first is composed of the sites identified by the scan statistic as significant, and the second of the remaining sites in the study area. Composite records were produced by first interpolating each record at 50-year intervals to avoid over-representation of high-resolution sites. We then computed the average pollen percentage for all major taxa at each interpolated point, separating the sites with a significant (p<0.100) human influence from those which did not exhibit a significant increase in APFT (p>0.100).

5.2.4 Fossil Charcoal Records

The Global Charcoal Database (GCD; Power *et al.*, 2008) compiles late Quaternary sedimentary charcoal records of lakes and bogs from across the globe which can be used to infer fire history (e.g. Marlon *et al.*, 2008). To explore the relationship between charcoal, pollen and archaeological records, we extracted all charcoal records in southern Ontario (Crawford Lake, McGinnis Lake and Spearman Lake) from the GCD. We also digitized charcoal influx diagrams from Decoy Lake (Szeicz and MacDonald, 1991), Graham Lake and High Lake (Fuller, 1997) from their original publications (Table 1) as these were not included in the GCD. All records were smoothed using a kernel smoother with a bandwidth of 100 years to summarize regional-scale trends in charcoal influx. Kernel smoothers calculate a weighted average at each observation, with a decreasing weight at greater distances from the focus (Wand and Jones, 1995). Charcoal influx diagrams were plotted alongside each other to compare fire histories across gradients of anthropogenic disturbance, as determined by archaeological site density and the results of the scan statistic. Due to the scarcity of charcoal records in this region, we placed no limitations to the inclusion of a charcoal record in this study. All diagrams are based on the influx of micro-charcoal (particle diameter <125μm), which are used to infer regional-scale trends in fire occurrence.

5.2.5 Archaeological Radiocarbon Dates

The Canadian Archaeological Radiocarbon Database (CARD; Morlan, 2005) consists of over 35,000 radiocarbon dates from archaeological sites in Canada and the United States. The database provides all relevant information for a date, including its radiocarbon age, location and the material dated. To illustrate the relationship between archaeological data in southern Ontario and sedimentary pollen and charcoal records, we extracted all archaeological radiocarbon dates from CARD from within the study area (Figure 5.1a). Radiocarbon dates were calibrated using CALIB 5.0.1 (Stuiver et al., 2009). We selected all dates (N=633) whose median probability fell between 0-1900 CE (1950-50 cal. yr. BP). Within these dates, 18 were directly dated cultigens (e.g. maize kernels) found in an archaeological context. We assume that the presence of a cultigen implies that agriculture was practiced nearby at that time. From our set of individual radiocarbon dates, we considered all unique locations (latitude and longitude) to be an archaeological site (N=228). We explored the spatial and temporal relationships between the southern Ontario archaeological data and sedimentary pollen and charcoal records, and noted patterns in space and time of the radiocarbon-dated cultigens. The spatial distribution of archaeological sites was used to calculate archaeological site density and individual dates were used to plot temporal frequency distributions.

To determine spatial relationships between southern Ontario archaeological sites and pollen and charcoal records, we compared the density of archaeological dates across the study region with the locations of pollen and charcoal records. We assume that higher densities of archaeological sites imply a higher population density, and a greater probability of a human impact on vegetation and pollen percentages (Rick, 1987; Surovell *et al.*, 2009; Peros *et al.*, 2010). The density of archaeological sites was estimated using a kernel density function (Silverman, 1986) which fits a smoothed surface over each point (archaeological site). The value of this surface is highest at a point and decreases with increasing distance from this point, reaching zero at a specified search radius (in this case, 50 km). Archaeological site densities are given in units of number of sites km^{-2}.

To determine temporal relationships between archaeological dates and pollen records we extracted archaeological radiocarbon dates within a 50 km radius of each pollen record and plotted temporal frequency distributions (number of dates century^{-1}) of these dates alongside the pollen data. Prehistoric population estimates from southern Ontario by Warrick (2008) suggest that rapid population growth occurred in response to the arrival of agriculture. We use the temporal frequency of archaeological radiocarbon dates as a proxy for local paleo-population and assume that a relative increase in the number of dates implies an increase in population and settlement intensity (Peros *et al.*, 2010). This approach has been employed elsewhere to infer prehistoric demography and settlement intensity based on the assumption that a larger population will result in a greater production and deposition of cultural carbon (e.g. Delcourt and Delcourt, 2004; Gamble *et al.*, 2004; Kuzmin and Keates, 2005; Buchannan *et al.*, 2008).

5.3 Results

5.3.1 Scan Statistics

The scan statistics identified five sites that had a period of significantly ($p<0.100$) elevated APFT values (Table 5.2). Three of these sites (Hams Lake, Crawford Lake and Humber Pond 3) are located near the Niagara Peninsula, the fourth (Cranberry Lake) is on the northern shore of Lake Ontario and the fifth (Second Lake) is located on the southern shore of Georgian Bay (Figure 5.2). Crawford Lake and Second Lake, both previously believed to have been influenced by Native American agriculture (McAndrews and Boyko-Diakonow, 1989; Burden *et al.*, 1986), are identified as having a highly significant ($p=0.001$) period of increased APFT values between 1195-1591 and 1446-1545 CE, respectively. The other three sites (Hams Lake, Humber Pond 3 and Cranberry Lake) have not been previously associated with prehistoric anthropogenic disturbance (Bennett, 1987; Weninger and McAndrews, 1989; McAndrews, unpublished). All sites are located on thick glacial deposits, and with the exception of Second Lake, are located in the deciduous forest region. Cranberry Lake, Second Lake and Humber Pond are located on coarse-grained surficial materials, while Crawford Lake and Hams Lake are surrounded by a glacial till diamict. The time periods identified as significant (between 1000-1600 CE) coincide with the widespread adoption of agriculture in southern Ontario (Crawford and Smith, 2003). Records where a statistically significant window of higher APFT was identified also tended to have higher temporal-resolution pollen data.

Table 5.2 Results of temporal scan statistic. Sites italicized are those we considered to be statistically significant ($p<0.100$).

Site	Log-likelihood ratio	Max likelihood window (years CE)	Mean inside window	Mean outside window	Significance (p)	No. samples/Total samples
Sarnia Elk Site	3.19	1548-1572	3.84	1.46	0.779	2/14
Pond Mills P.	3.51	1176-1455	2.76	1.08	0.307	3/8
Hams L.	*5.38*	*985-1580*	*2.04*	*0.56*	*0.001*	*6/12*
Crawford L.	*22.48*	*1195-1591*	*1.15*	*0.42*	*0.001*	*29/71*
Humber P. 3	*8.22*	*1313-1530*	*2.55*	*0.49*	*0.062*	*3/11*
Van Nostrand L.	4.96	1033-1224	0.67	0.36	0.321	2/8
Cranberry L.	*17.51*	*1169-1284*	*3.64*	*0.70*	*0.007*	*3/27*
Edward L.	0.53	1372-1501	0.96	0.55	0.978	2/9
Second L.	*16.49*	*1446-1545*	*5.04*	*0.90*	*0.001*	*6/22*
McCarston's L.	5.10	1365-1425	1.28	0.50	0.229	2/11
Nutt L.	3.06	1421-1524	1.29	0.67	0.564	2/12
Perch L.	6.58	621-768	1.88	0.50	0.172	2/11
Graham L.	3.48	590-611	2.22	1.34	0.366	2/22
Tonawa L.	1.49	1444-1576	0.93	0.27	1.000	2/12
High L.	2.33	620-1327	1.43	0.97	0.558	7/14
Ramsay L.	3.66	10-210	0.84	0.39	0.487	2/8
Pink L.	3.13	1217-1393	0.72	0.24	0.554	2/8

5.3.2 Pollen

A comparison of the five sites identified by the scan statistics (Figure 5.3a) with the remaining sites in the study area (Figure 5.3b) reveal general differences between these pollen records. At sites with a prehistoric human influence there is: (1) a decline in *Acer*, *Fagus* and *Ulmus* pollen percentages beginning at 1100 CE that is more abrupt than other sites; (2) a concurrent increase in *Quercus* pollen, (3) an increase in anthropogenic indicator taxa (APFT), (4) an increase in *Populus* and Poaceae pollen percentages, not observed at other sites; and (5) several samples with pollen of cultigens (*Zea mays* and

Helianthus) after 1300 CE. A decline of *Fagus* pollen percentages began around 900 CE and is apparent in both composite records. At sites not identified as influenced by human activity, the increases in *Pinus*, *Picea* and *Betula* pollen percentages also began at 900 CE but accelerated around 1500 CE, at the same time as a decrease in *Tsuga* pollen percentages.

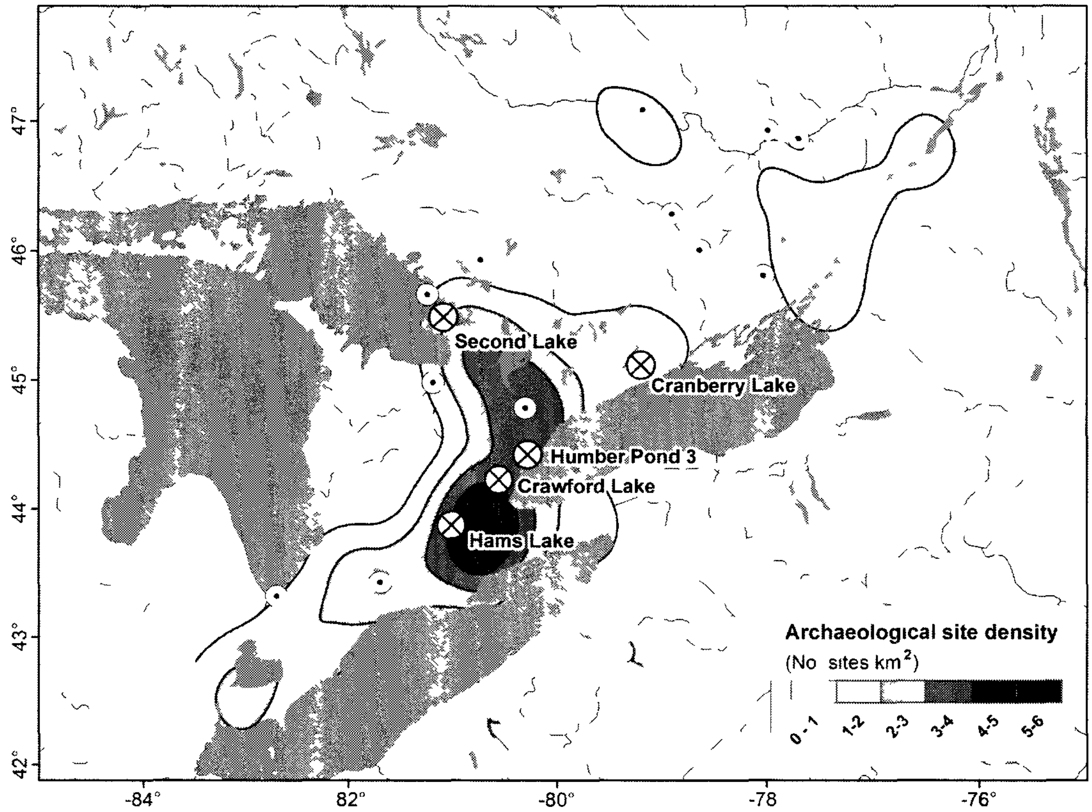


Figure 5.2 Kernel density of archaeological sites, expressed as the number of sites km^{-2}, and the locations of sedimentary pollen records identified as being significantly ($p<0.100$) influenced by human activity (white circles with X) and those where human disturbance was not significant ($p>0.100$, white circles with •)

5.3.3 Archaeological Radiocarbon Dates

The archaeological sites included in our study are clustered around the Niagara Peninsula, near the shores of Lake Ontario and Lake Erie, and around Lake Simcoe and Georgian Bay (Figure 5.2). This main cluster is located on deep surficial deposits of glacial origin, occupying much of the deciduous forest region, although sites around Lake Simcoe and Georgian Bay are in the Great Lakes-St. Lawrence forest region. Smaller clusters of sites are found in the western St. Lawrence Valley and the Ottawa River Valley.

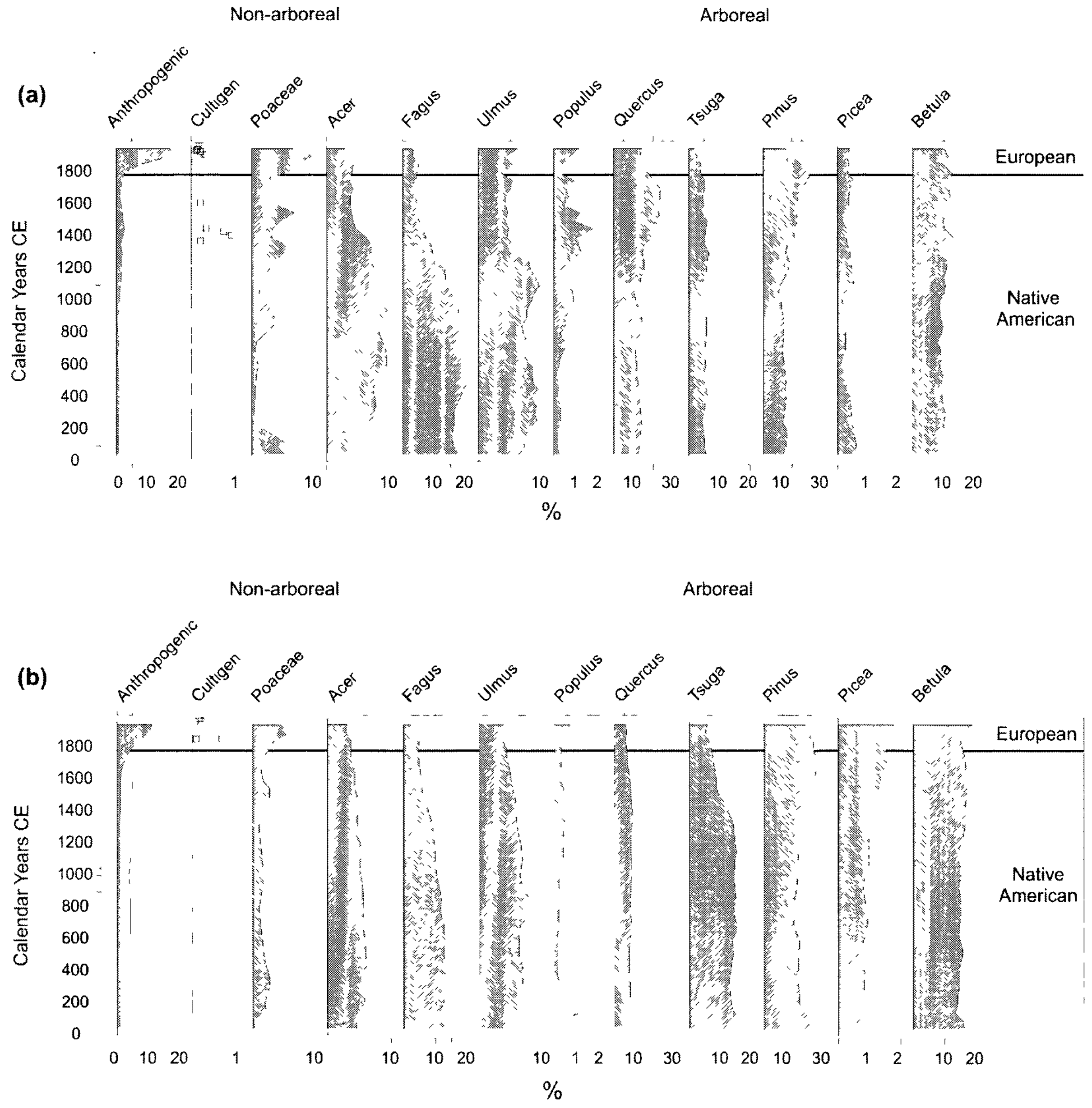


Figure 5.3 Averages of major pollen taxa interpolated at 50-year intervals from (a) sites identified as significantly (p<0.100) influenced by prehistoric human activity (Hams Lake, Crawford Lake, Humber Pond 3, Cranberry Lake and Second Lake) and (b) neighbouring sites which do not appear to be influenced by Native Americans. The anthropogenic pollen type (APFT) has a 5X exaggeration line. The pollen of cultigens (*Zea mays* and *Helianthus*) is expressed as a percent of the pollen sum from the sample from which it originates.

The five pollen records exhibiting significant disturbance by human activity are located within the main cluster of archaeological sites (Figure 5.2). The kernel density of archaeological sites tended to be higher at sites where a significant increase in APFT was identified by the scan statistic (Figure 5.4). Archaeological site density is relatively high at Hams Lake (3.92 sites km^{-2}), Crawford Lake (3.62 sites km^{-2}) and Humber Pond (3.41 sites km^{-2}) and lower at Second Lake (1.73 sites km^{-2}) and Cranberry Lake (1.65 sites km^{-2}). The average density of archaeological sites surrounding these five sites considered to have a significant anthropogenic impact is greater (2.9±1.1 sites km^{-2}) than at sites where no significant increase in APFT was found (1.1±1.0 sites km^{-2}). Although Van Nostrand Lake and Pond Mills Pond are in areas of relatively high settlement density (3.70 and 2.49 sites km^{-2}, respectively), the significance of increases in APFT at these sites is relatively low (p=0.321 and 0.307, respectively).

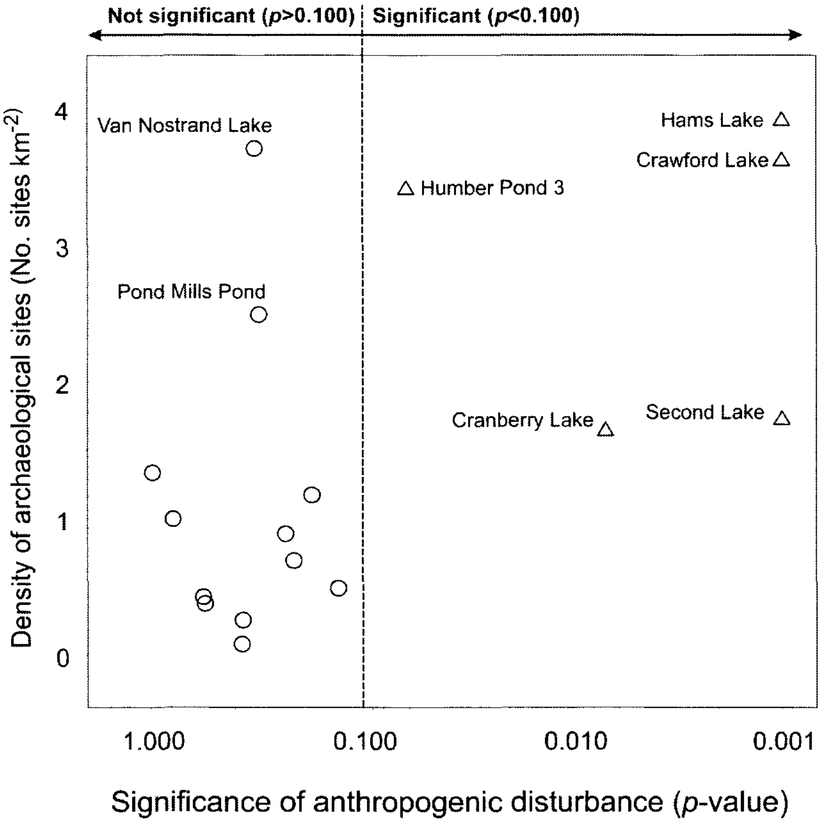
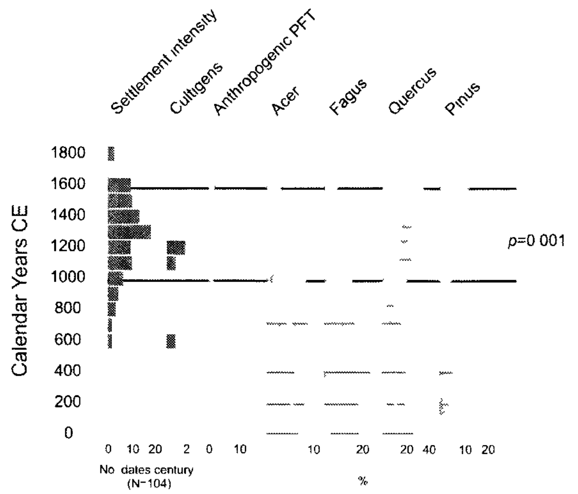
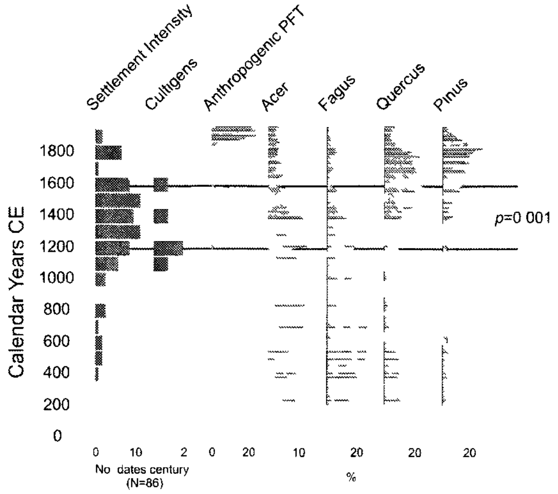


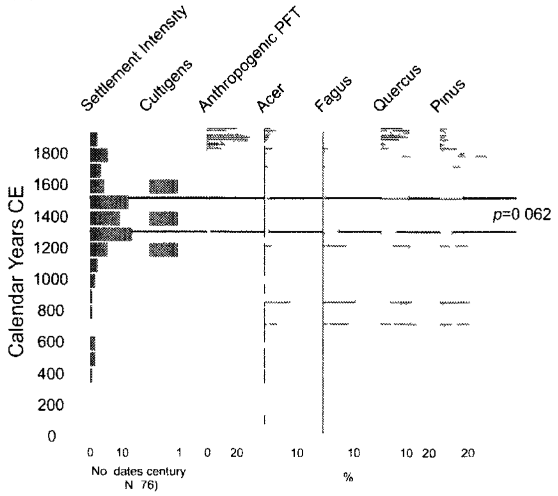
Figure 5.4 Spatial relationship between archaeological site density and the significance (p) of anthropogenic disturbance identified in pollen records. Triangles represent pollen records where disturbance was considered significant (p<0.100) and circles are sites where disturbance was not found to be significant (p>0.100).



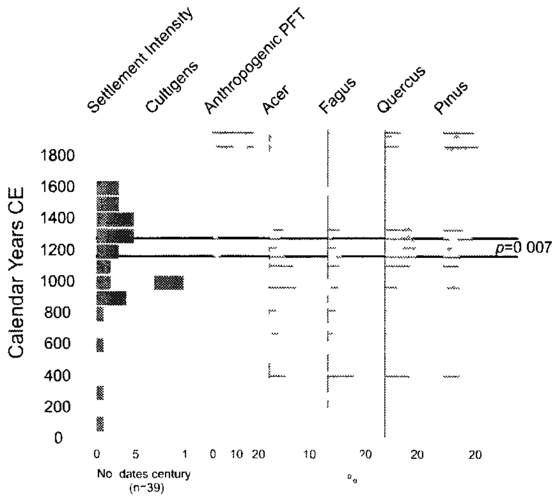
(a) Hams Lake



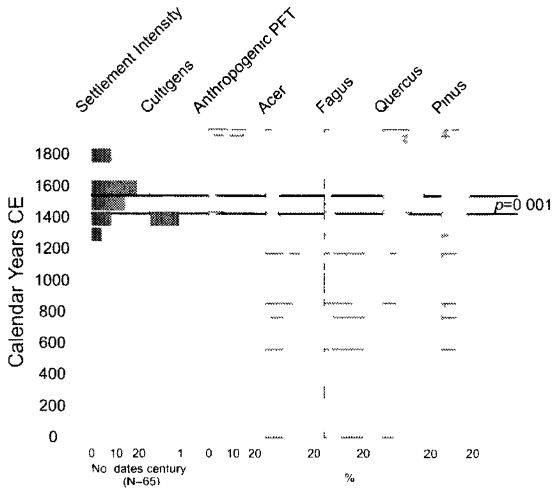
(b) Crawford Lake



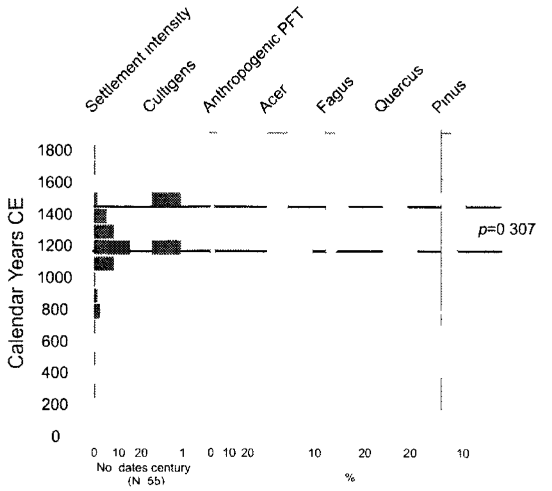
(c) Humber Pond 3



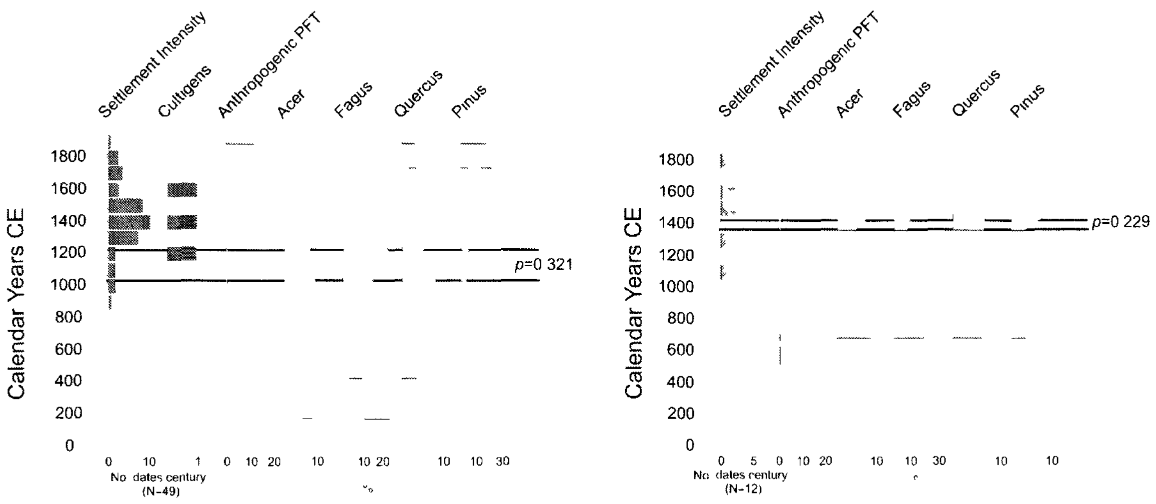
(d) Cranberry Lake



(e) Second Lake

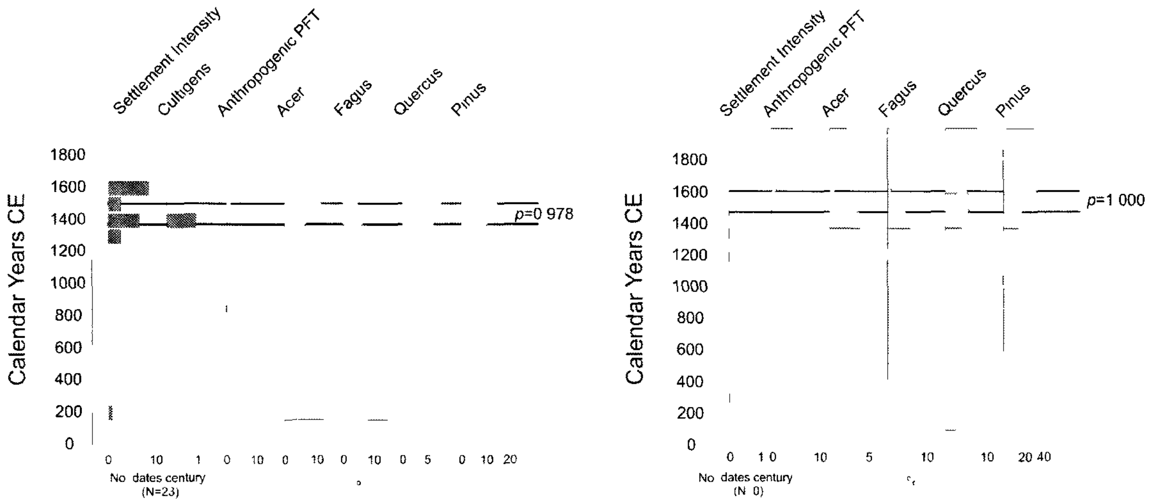


(f) Pond Mills Pond



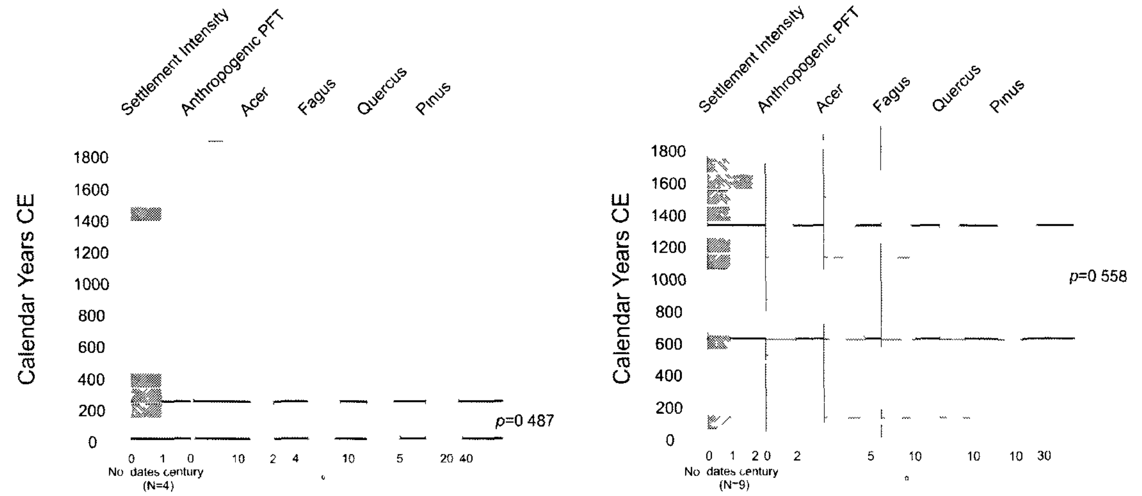
(g) Van Nostrand Lake

(h) McCarston's Lake



(i) Edward Lake

(j) Tonawa Lake



(k) Ramsay Lake

(l) High Lake

Figure 5.5 Temporal associations between archaeological data (bars) and select pollen taxa. Frequency distributions of archaeological radiocarbon dates (dates century $^{-1}$) within 50 km of a pollen site serve as a proxy for human settlement intensity, and cultigens (agricultural macrofossils from archaeological sites) indicate the local presence of agriculture. Thick lines indicate the period of elevated anthropogenic indicator taxa identified by the scan statistic, and the significance (p-value) assigned to this period.

Temporal relationships between pollen records and frequency distributions of archaeological radiocarbon dates (a proxy for settlement intensity) differ from site to site, although some general patterns are apparent (Figure 5.5). For example, periods of elevated APFT identified by the scan statistic generally coincide with periods of greater settlement intensity and the presence of agricultural macrofossils (cultigens). At sites where the increase in APFT is significant (Figures 5.5a-e) decreases in *Fagus* and *Acer* and increases in *Quercus* and *Pinus* pollen percentages occur at the same time as the significant disturbance events. The timing of this transition occurs earlier at sites near Lake Ontario (Hams Lake, Crawford Lake, Humber Pond 3 and Cranberry Lake) than at Second Lake, but remains consistent with significantly elevated APFT values. At other sites (Figures 5.5f-l), where increases in APFT were not found to be significant, increases in *Quercus* pollen are not apparent. The exception to this is Van Nostrand Lake (Figure 5.5g), where no increase in APFT is observed during an increase in settlement intensity and *Quercus* pollen. At all sites not influenced by human disturbance, an increase in *Pinus* is observed after 1500 CE. A decline of *Fagus* begins around 900 CE at most sites and predates significant increases in APFT and settlement intensity.

5.3.4 Charcoal

Charcoal influx diagrams from southern Ontario display significant variability between sites (Figure 5.6). Sampling resolution varies from annual (1 sample yr^{-1}) at Crawford Lake to one sample every 350 years at Spearman Lake. Influx values are generally low (between 0-1 mm^2 cm^{-2} yr^{-1}), although they are higher at Crawford Lake (2-10 mm^2 cm^{-2} yr^{-1}). Decoy Lake and Crawford Lake are located in areas of high archaeological settlement density (4.12 and 3.62 sites km^{-2}, respectively), with intermediate density values for McGinnis Lake (0.87 sites km^{-2}) and High Lake (0.69 sites km^{-2}) and low density values at Graham Lake (0.25 sites km^{-2}) and Spearman Lake (0.07 sites km^{-2}). The pollen record from Crawford Lake was identified as being significantly influenced by human disturbance. Decoy Lake is 5 km away from Hams Lake and McGinnis Lake is 50 km to the north of Cranberry Lake, both of which have pollen records exhibiting significant human disturbance. At Decoy Lake, McGinnis Lake, Graham Lake and Spearman Lake, higher influx values occur at the beginning of the study period (0-500

CE). After 1200 CE a relative increase in charcoal influx occurs at Decoy Lake, Crawford Lake and McGinnis Lake, while charcoal accumulation decreases or is absent (0 mm^2 cm^2 yr^{-1}) at the remaining sites.

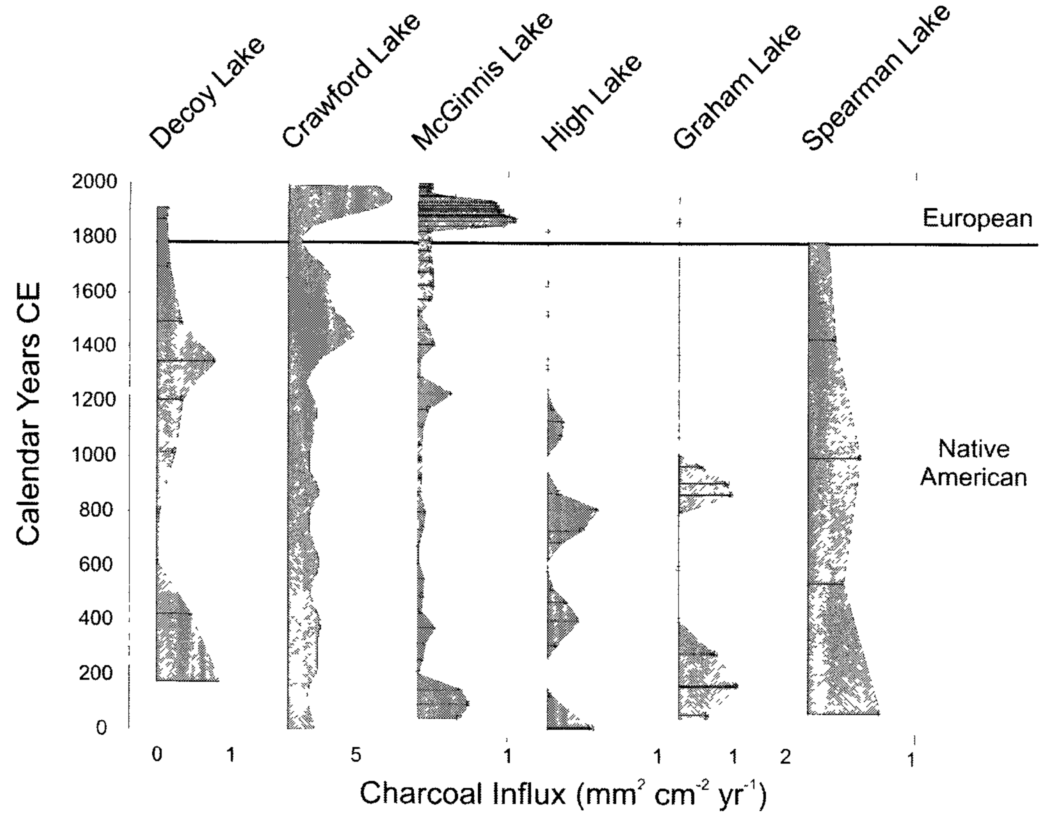


Figure 5.6 Smoothed charcoal influx diagrams from southern Ontario. Horizontal lines and squares represent sample levels, except for Crawford Lake where resolution site is annual (1 sample year^{-1}).

5.4 Discussion

5.4.1 Vegetation Response to Late Holocene Climatic Change

Late Holocene changes in forest composition at regional to sub-continental scales, prior to the European settlement of North America, are generally considered to be the result of factors such as climatic change or on rare occasions, a pathogenic outbreak (Ritchie, 1987; Bennett, 1993; Fuller, 1998; Schuman *et al.*, 2004). General changes in pollen percentages across southern Ontario over the last 2,000 years include (a) declines of *Fagus*, *Acer*, *Ulmus* and *Tsuga* and (b) increases in *Picea*, *Pinus* and *Betula* (Figure 5.3).

Paleoclimatic reconstructions from southern Ontario based on isotopic (Edwards and Fritz, 1986; 1988) and pollen analyses (McAndrews, 1981; Liu, 1990; Finkelstein and Davis, 2005) suggest that cooler and wetter conditions have occurred over the last 2,000 years. In our analysis, both the ecology of the taxa involved and the spatial scale at which this transition occurs also suggest that it is a product of late-Holocene cooling. *Picea, Pinus* and *Betula papyrifera* are prominent trees of boreal forest, with more northern ranges than hardwoods and *Tsuga* (Hosie, 1979; Tardiff *et al.*, 2001). An increase in abundance of these more cold-tolerant taxa occurred throughout the region (Figure 5.3b) and we therefore interpret these changes as independent of human influence because Native American settlements were not ubiquitous in the region, but clustered (Figure 5.2). Campbell and McAndrews (1991) found a regional-scale southward shift of arboreal taxa, particularly an increase in *Pinus,* in response to late-Holocene climatic cooling in Ontario pollen records. At a sub-continental scale, a general shift towards more cold-tolerant taxa during the late Holocene has been observed across the mixed forest of northeastern North America (e.g. Gajewski, 1988; Lavoie and Richard, 2000). The relatively gradual replacement of northern hardwood (*Acer*, *Fagus, Ulmus*) and coniferous (*Tsuga*) trees with boreal taxa (*Picea*, *Pinus*, *Betula*) observed in pollen records uninfluenced by human activity (Figure 5.3b) suggest that this is the regional-scale vegetation response to neoglacial cooling.

5.4.2 Vegetation Response to Native Americans

In Europe, there is an extensive literature that documents changes in pollen records at sites influenced by anthropogenic activity (Birks *et al.*, 1988; Bell and Walker, 1992; Parker *et al.*, 2002). In North America, several studies have suggested comparable impacts (e.g. McAndrews, 1988; Butzer, 1992; Delcourt and Delcourt, 1997; 1998). A defining characteristic of southern Ontario pollen records influenced by human activity (Figure 5.3a) is the replacement of *Acer* and *Fagus* with *Quercus* and *Pinus.* This transition occurs at the same time as an increase in anthropogenic indicators, increases in settlement intensity and the presence of agricultural macrofossils at each of the five sites where a significant increase in APFT occurs (Figure 5.5a-e). Moreover, pollen sites objectively identified as being influenced by human activity are located within clusters of contemporaneous archaeological sites (Figure 5.2; Figure 5.4).

An increase in *Quercus* at sites influenced by human activity is anomalous given the general interpretation of cooler and wetter climatic conditions of the late Holocene (see above). Oaks present in southern Ontario (predominately *Q. alba* and *Q. rubra*) are mid-successional species typically found in warmer, drier locations where fires are more frequent (Abrams, 1992; McShea and Healy, 2002). Oaks exhibit physiological characteristics adapted to periodic fire and drought (e.g. deep roots, thick bark, sprouting ability, acorns) and are poor competitors with other hardwoods in the absence of disturbance (McDonald et al., 2002; Abrams, 1998; 2003). Similarly, *Pinus* in this region (*P. strobus and P. resinosa*) are shade-intolerant taxa that are associated with drier conditions (Scott, 1983; Szeicz and MacDonald, 1991) and exhibit tolerance to recurring fires (Swan, 1970; Wade *et al.*, 2002). Conversely, beech-maple forests are characteristic of the northern hardwood forest (Braun, 1950), and develop in the absence of large-scale disturbance (Aber and Melillo, 1991) because maple (*A. saccharum*) and beech (*Fagus grandifolia*) saplings are shade tolerant and the mature trees are poorly adapted to fire (Abrams, 1992). This suggests that the replacement of a late-successional forest (*Fagus-Acer*) by *Quercus* and *Pinus* cannot be driven exclusively by cooling because (a) observed late Holocene cooling is inconsistent with an increase in oak, and (b) this transition occurs exclusively in areas influenced by human activity. Instead, we propose that this transition is a product of both anthropogenic disturbance and cooling: Under natural conditions, *Fagus-Acer* forests gradually gave way in more marginal habitats to cold-adapted species such as *Picea* and *Betula*; Native American clearance of *Fagus-Acer* forests for agriculture accelerated their decline and initiated a secondary succession which provided an open habitat ideal for *Populus* spp. and Poaceae, followed by *Pinus strobus* and *Quercus* spp.

Although old-field succession sequences vary significantly between sites (Blatt *et al.*, 2005), changes recorded in southern Ontario pollen diagrams influenced by human land clearance are broadly consistent with observations of old-field succession from across the eastern deciduous forest (Chapman, 1937; Braun, 1950; Den Uyl, 1951; Bard, 1952; Bazzaz, 1968; Heidenreich, 1971; Williamson, 1975), where shade intolerant annuals and arboreal taxa adapted to more xeric conditions are established following forest clearance. In the absence of further disturbance, these are eventually replaced by late-succession arboreal taxa capable of growing under a forest canopy (Brubaker, 1975). However, at well-drained sites underlain by coarse-grained surficial materials, dry conditions may restrict the development of more mesic tree species, such as *Acer saccharum* and *Fagus grandifolia* (Szeicz and MacDonald, 1991). Although several of the sites we identify as being influenced by human disturbance are underlain by coarse-grained substrates, others are not (Table 5.1), and we observe no clear connection between coarse-grained surficial materials and the changes in forest composition we attribute to human forest clearance.

Ethnohistoric accounts suggest that Late Woodland agricultural fields in Ontario were cleared by girdling trees (removing bark) and using branches and bark to burn and kill the tree (Doolittle, 2000). Fields were cleared and expanded for 10-30 years, and subsequently abandoned, probably due to soil exhaustion and increasing distance of the village to suitable firewood and construction material (Sagard-Théodat, 1939; Sykes, 1980). With populations increasing rapidly in response to the introduction of agriculture (Warrick, 2008), the amount of land cleared would have increased. Campbell and Campbell (1994) calculated that 403,000 ha of forest could have been cleared by Native Americans, which represents only 5% of the land south of the Canadian Shield, and 12% of the area where contemporaneous archaeological sites are most concentrated (estimated as 3.4 x 10^6 ha from Figure 5.2). When compared to post-European land clearance, the impact of Native American agriculture was relatively small, but our results suggest that it was not negligible. The result of this land clearance is that pollen records in proximity to horticultural village sites exhibit an old-field succession which is manifested in the pollen records as an increase in ruderals and early-successional arboreal taxa (e.g. *Populus*) followed by mid-successional taxa (*Pinus* and *Quercus*). The eventual recovery of late-successional beech-maple forest following site abandonment is also observed in the pollen records as a slight increase in these taxa, although interpretation of the pollen diagrams becomes more complicated after the arrival of Europeans due to significant changes caused by intensive land use (McAndrews, 1988; Williams *et al.*, 2004).

5.4.3 Native Americans and Fire

There has been speculation that Native American use of fire to facilitate travel, clear forests and manipulate flora and fauna was as a major factor in prehistoric forest ecology (Day, 1953; Lorimer, 1977; Pyne, 1982; Denevan, 1992a; Kay, 2000; Krech, 2000; Mann, 2005; Abrams and Nowacki, 2008), although clear paleoecological evidence from sedimentary charcoal records of this influence are sparse (Clark and Royall, 1996). As with the interpretation of vegetation changes, uncertainty on this subject is partly due to the problem of attributing a particular shift in charcoal accumulation to anthropogenic activity, especially when charcoal accumulation in sediments is influenced by several factors (e.g. vegetation type, basin morphology, transportation vectors) (Millspaugh and Whitlock, 1995; Pisaric, 2002; Peters and Higuera, 2007). At Crawford Lake, Clark and Royall (1995) found an increase in charcoal influx which coincided with Native American occupation of the site. However, this analysis provided no comparison with other records in the region to determine whether the charcoal record at Crawford Lake is anomalous. If anthropogenic fires were a factor in the transition to *Quercus-Pinus* dominated forests, we would expect an increase in charcoal accumulation in these areas which should deviate from the regional trend. Under the cooler and more mesic climatic conditions of the late Holocene, fire frequency is expected to have decreased.

A comparison of all available charcoal diagrams from southern Ontario suggests that charcoal influx increased after 1200 CE in proximity to Native American settlements (Figure 5.6). Crawford Lake and Decoy Lake are both within an area of high archaeological site density and near pollen sites identified as disturbed by Native Americans; these two records show an increase in charcoal influx beginning around 1300 CE and 1100 CE, respectively, although values were even higher in Decoy Lake prior to AD 600. Charcoal influx also increased slightly after 1000 CE at McGinnis Lake, which is about 50 km to the north of Cranberry Lake, a pollen site significantly influenced by human activity. Conversely, charcoal records which are more distant from Native

American settlements (High Lake, Graham Lake and Spearman) show decreased influx after 1000 CE. This may explain the dominance and persistence of oak near Native American settlements, because white oak (*Q. alba*) and red oak (*Q. rubra*) have morphological adaptations enabling survival in the presence of recurring fire which lead them to out compete other deciduous taxa at sites were fire is frequent (Abrams, 1992; 2003; McShea and Healy, 2002). Although these results are suggestive, charcoal records in southern Ontario are too few to be conclusive; our analysis provides a hypothesis that can be tested when more data from the region becomes available.

5.4.4 Detecting Prehistoric Disturbance from Pollen Records

The technique described in this paper successfully identified periods of anthropogenic disturbance from fossil pollen records in southern Ontario and may therefore be used in other regions, to eventually identify the impact of Native Americans on North American ecosystems across the continent. However, there are several limitations to consider. For example, Pond Mills Pond and Van Nostrand Lake are both found in areas where the density of archaeological sites is relatively high, but the scan statistic did not identify periods of high values of agricultural indicators (p=0.307 and 0.321, respectively) (Figure 5.4). Possible reasons for this include: (1) Both of these records have few pollen levels during the study period. Because low resolution pollen records may only contain few samples during a period of human disturbance the statistical significance of the increase in APFT during these periods is low, as one anomalous observation has a greater probability of being produced by chance. Thus, this technique is best suited to higher resolution records. More research is required to determine the minimum number of pollen levels needed to apply the methodology. (2) Both of these lakes have small surface areas (Table 5.1), so that the majority of pollen presumably originates from local sources (Jacobson and Bradshaw, 1981). If forest clearance did not occur in the area immediately surrounding these small lakes, then its influence on the pollen record may be smaller. (3) If a record contains more than one period of disturbance and/or human occupation the significance of the scan statistic may be reduced because windows must be continuous periods. Thus, a large number of sites are needed at a regional scale to more firmly identify human impacts on the forests, and more high-resolution pollen records are needed.

5.5 Conclusions

We attempted to objectively identify southern Ontario pollen records influenced by prehistoric human activity. For each pollen record, scan statistics were used to distinguish statistically significant periods of heightened anthropogenic indicators. Highly significant (p<0.100) increases in anthropogenic indicators were identified at five pollen sites in the region and shown to be associated with contemporaneous Native American settlements in both space and time. Comparison of these five sites with the remaining 12 sites in the region suggests that pollen records influenced by prehistoric anthropogenic disturbance differ from those which were shaped primarily by late Holocene cooling. Across the region, northern boreal taxa gradually increased their presence at the expense of deciduous trees from the conifer-hardwood forests to the south. At sites influenced by human activity this climate-induced change is super-imposed on changes in forest dynamics associated with clearance for agricultural fields. This clearance served as a major disturbance that provided more open habitat for herbaceous plants, early- and mid-succession arboreal taxa such as *Populus*, *Pinus strobus* and *Quercus*. An analysis of available charcoal records in the region suggests that increased fire frequency in proximity to Native American agricultural settlements at a time when fires were becoming less frequent as a result of cooler and wetter conditions. Our results suggest that the prehistoric human influence on forests in southern Ontario is relatively widespread, but localized around areas of higher settlement density following the widespread adoption of maize agriculture after 1000 CE.

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6. Summary and Synthesis

Although modern industrialized nations exert a tremendous influence on nearly all aspects of the environment, the history of the human-environment relationship before industrialization or even before agriculture, is poorly understood (cf. Goudie, 2006). This subject has more recently gained attention because of work by Denevan (1992), Cronon (1996) and Ruddiman (2003), who propose that human impacts on the environment have been substantial throughout much of the Holocene. These authors present a new way of looking at modern landscapes: instead of industrialization transforming a pristine wilderness, this new perspective holds that humans have modified Earth's physical and biological systems for millennia. These claims are disputed, with other authors arguing that pre-industrial human land-use had a negligible impact on the environment (Russell, 1993; Vale, 1998; 2002). The magnitude and extent of this pre-industrial modification would have varied in space and time as human population, culture and technology changed (Ehrlich and Holdren, 1971; Moran, 2006). Thus, the purpose of this dissertation is to develop an improved understanding of this variability though the examination of prehistoric human-environment relationships in two regions of eastern North America. These studies are based on the analysis of large datasets of accumulated paleoenvironmental and archaeological records.

Databases of accumulated paleoenvironmental and archaeological records have tremendous potential to answer questions for which these data were not originally intended, but the current distribution and quality of these data will guide the questions which can be answered. For example, in eastern North America, particularly the Midwest, southern Ontario and New England, there is a high density of pollen records which have been used to better understand the late Quaternary migrations of vegetation and the response of vegetation to climatic change. In this dissertation, many of these same records were successfully used to infer the prehistoric human impact on vegetation. There is no shortage of other questions which could be explored, at almost no cost to the researcher, by using this same dataset. There are, of course, limits to this dataset such as the spatial density of pollen records, the temporal resolution, and the age limits of the record, which will constrain the types of questions which can be answered.

The results from the two studies in this dissertation were guided by the quality and types of data readily available in the databases. In southern Ontario, there are several pollen records which are of a high enough resolution for the late Holocene and are taken in proximity to prehistoric agricultural villages. Archaeological radiocarbon dates in this region are sparse for the Palaeoindian and Archaic periods. In contrast, pollen records in New England are of lower resolution and are not near the coasts, where the majority of agricultural groups are thought to have lived. However, New England has an abundance of low resolution pollen records which span the late Quaternary, reconstructions of regional climate, and an excellent understanding of the factors that controlled long-term ecosystem development. Archaeological radiocarbon dates in this region from all cultural periods are well represented. By exploring the distribution and quality of data available, it was clear that the approach taken in one region could not simply be copied for another. Instead, by making use of the data that were available, two distinct studies were developed which, together, provide an improved understanding of prehistoric human-environment relationships.

In Chapter 4, a long-term temporal analysis of paleoenvironmental and archaeological records from across the northeastern United States revealed that periodic changes in climate throughout the Holocene resulted in synchronous changes in terrestrial ecosystems, human culture and population numbers. Temporal correspondence between changes in humans and ecosystems was strongest when groups in this region were hunter-gatherers. After the adoption of maize agriculture ca. 1 kyr BP human population and culture changed in the absence of a substantial change in climate or ecosystems. These results suggest that the material culture and population level of hunter-gatherers, who rely entirely on 'wild' food resources provided by the surrounding environment, are highly sensitive to external changes in ecosystems. Agricultural groups, however, transform the surrounding ecosystem to supplement their diet with cultigens, increasing the carrying capacity of the landscape and altering the dynamics of human-environment relations. Thus, climatic changes in the past resulted in rearrangements of terrestrial ecosystems which greatly influenced material culture and population numbers throughout much of prehistory.

This study was based on the analysis of temporal patterns, with the spatial extent fixed at a broad regional scale, but provides some insight into the impact of humans on the landscape. At a regional scale, prehistoric changes in vegetation closely track changes in climate, specifically the magnitude and seasonality of temperature and precipitation (Shuman *et al.*, 2004; Zhao *et al.*, 2010). Adding the archaeological data onto this regional environmental framework, it is clear that humans were also greatly influenced by these external climatic changes (Figure 4.2). This suggests that at a regional scale, the prehistoric human influence on the environment did not overwhelm the impact of climatic change on ecosystems. Prehistoric hunter-gatherers would have altered the demographics of their prey, cut down certain trees for firewood or building material and facilitated the dispersal and establishment of preferred plant foods (Goudie, 2006), but this influence was not substantial enough to alter regional ecosystem dynamics. In contrast, the arrival of Europeans to this region in the 16th century had a sufficient impact to be recorded in the regional pollen and charcoal records as a decrease in arboreal pollen taxa and an increase in non-arboreal pollen and charcoal (Fuller *et al.*, 1998; Russell and Davis, 2001; Parshall and Foster, 2002; Foster and Aber, 2004). In order to distinguish the prehistoric human impact on the environment in eastern North America, the focus must be shifted from regional-scale impacts to sub-regional scales.

In Chapter 5, the adoption of maize agriculture in southern Ontario was used as an opportunity to identify sub-regional scale human impacts on the environment and better delineate the spatial and temporal extent of this impact. By identifying those pollen records which document an increase in anthropogenic indicator pollen types from those which do not show such a change, this study distinguishes sub-regions where ecosystems were substantially influenced by human activity (Figures 5.2 and 5.3). These sub-regions correspond with archaeological and historical data that document where Native Americans practiced maize agriculture (Figure 5.1; Doolittle, 2000). The pollen data show that in proximity to prehistoric agricultural villages in southern Ontario there was a replacement of beech-maple forest with a successional forest composed mainly of oak and pine. Thus, the environmental impact of prehistoric agriculture was substantial at a sub-regional scale (10^2-10^3 m), localized around contemporaneous village sites but large enough to significantly alter pollen records (Jacobson and Bradshaw, 1981). The environmental impact of European colonization is prevalent at regional and even continental scales (Russell and Davis, 2001; Williams *et al.*, 2004), but the prehistoric Native American impact is only distinguishable when scaling down to sub-regions where populations were most concentrated.

The nature and dynamics of the prehistoric human-environment relationships discussed in this dissertation are not representative of all prehistoric people, nor of all Native North Americans. There was a tremendous amount of cultural and environmental diversity across prehistoric North America, and the relationships between these cultures and their environment would vary considerably as a function of culture, population and technology. For example, in the Mississippi and Ohio River Valleys, and much of the southeastern United States, there were larger, stratified agricultural societies during the late Holocene which likely had a more substantial impact on the environment than groups in southern Ontario (Olendorff, 1993; Pauketat, 2004). There were also non-agricultural groups in California and along the Pacific coast whose populations are thought to have been quite large, stratified, and who may have practiced forms of agro-forestry to improve site habitability (Anderson, 2006). These regions were not studied in this thesis due to lack of sufficient data in the regions in the databases. However, the methods developed here could be adapted for use in these other regions to develop a broader understanding of the human role in past, present and future environmental change.

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Appendix: Exploration of the CARD as a paleodemographic proxy

The use of large datasets of archaeological radiocarbon dates as a paleodemographic proxy is still in its infancy, and few studies have attempted to validate demographic reconstructions derived from radiocarbon data with comparable reconstructions from other sources. Such a validation would strengthen the basic argument behind this technique, that a greater population will deposit a larger amount of cultural carbon (Surovell *et al.*, 2009; Peros *et al.*, 2010). Here, I provide two examples of comparisons between independent demographic reconstructions, based on historical and archaeological records, against reconstructions derived from the CARD.

Spatial Distribution of Proto-Historic Population

If a larger population results in a greater deposition of cultural carbon, and if archaeological radiocarbon sampling is representative of the population as a whole, then the density of archaeological radiocarbon dates should approximate the population density at a corresponding time. To test these assumptions, the spatial density of proto-historic archaeological radiocarbon dates was compared with a dataset of early-historic population estimates derived from written recordings of European explorers.

The historical dataset, compiled by the Historical Atlas of Canada (Heidenreich and Wright, 1987) provides an absolute contact-era population estimate for 96 Native American groups across much of the Northeast cultural area (Figure A1). These population estimates were originally provided in discrete categories, and they have been kept in this format. To compare this historical data with the archaeological data, all cultural dates from the last 1000 years (primarily Late Woodland and variants) were extracted from the CARD and used to calculate the kernel density (search radius of 75 km) of proto-historic archaeological dates (Figure A1). Finally, to quantify the correspondence between these two population reconstructions the kernel density of proto-historic archaeological dates was extracted at each point where a historical population estimate is available (Figure A2).

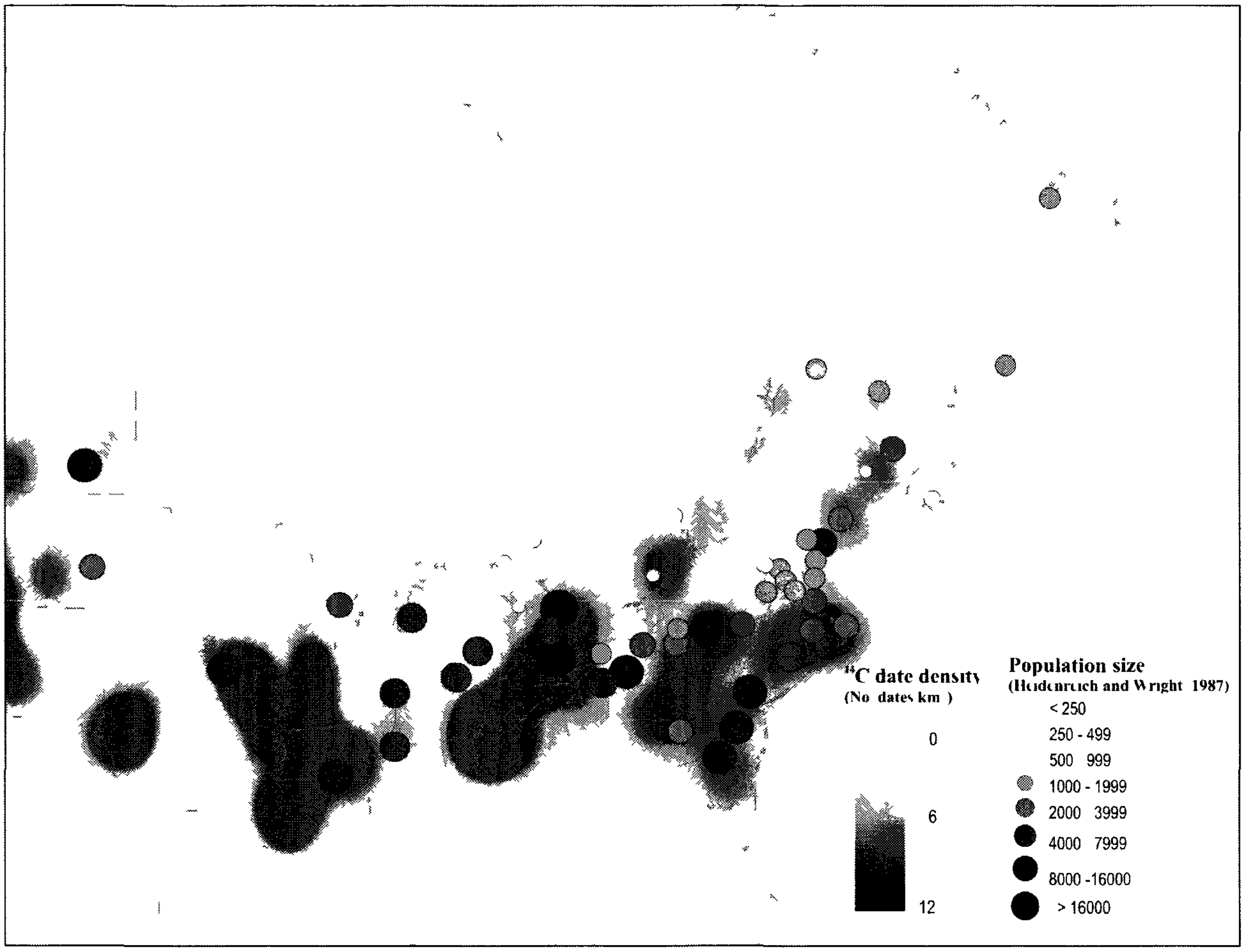

Figure A1 Comparison of protohistoric ^{14}C date density and 17th century Native American population size derived from historical records (Heidenreich and Wright, 1987)

At a very broad spatial scale, the historical data suggest that early historic populations were smaller in northern Ontario and northern Quebec, and larger in the Midwest, southern Ontario, New England and Maritimes. A similar pattern can be seen in the density of archaeological dates, where there are fewer dates in the northern part of the study area, and higher densities concentrated in several areas in the southern part of the study area. At a finer spatial scale, several areas with a high density of archaeological dates correspond with larger populations recorded historically, namely: along the coast of Maine, southern New England, southern Ontario, northern Ohio, northern Illinois and Wisconsin. However, other areas of relatively large populations in the historical record correspond with lower densities of archaeological dates, most notably the agricultural Iroquois groups in upstate New York.

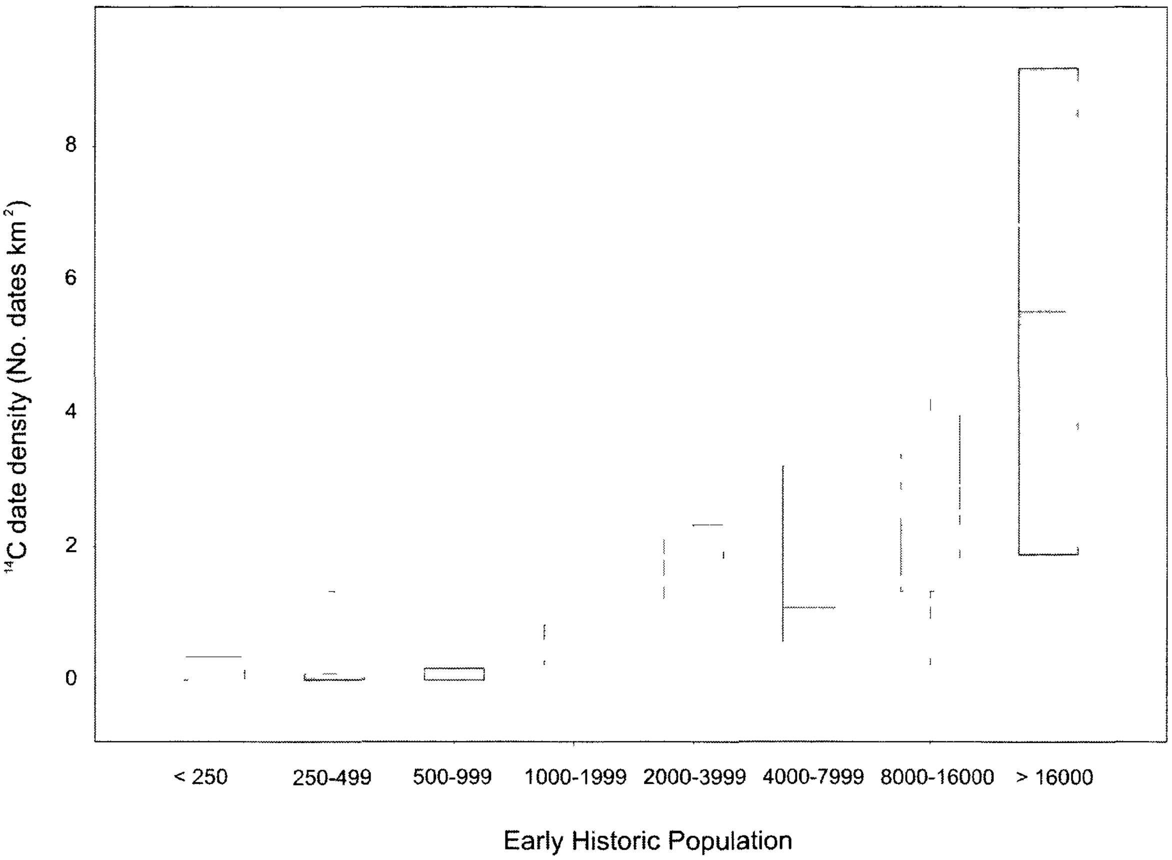

Figure A2 Box-plot of the kernel density of ^{14}C dates versus ^{17}th century Native American population estimates by Heidenreich and Wright (1987). The kernel density was extracted for each population estimate point in Figure A1.

Several problems exist with this analysis, most notably the use of a point estimate for the population of a group. Native American groups did not occupy a single site, but occupied several sites within a territory. Ideally, the historic population estimates would correspond with polygons (not points) to delineate the population of a group. Few data points in some population classes also hinder the power of this analysis. Ideally, population estimates would be provided on a continuous scale of measurement to avoid this problem. Finally, archaeological sampling in some regions may not be representative of the population as a whole, or the data may not have been incorporated into the CARD, or the historical population estimates may be erroneous in some cases.

Nevertheless, there is a broad-scale correspondence between population density inferred from radiocarbon data and the historical record where both records suggest smaller populations in northern Ontario and northern Quebec and larger populations throughout much of the southern part of the study area. At a finer spatial scale, there are several regions where a close correspondence between these records emerges, especially southern Ontario and New England. In other regions, such as upstate New York, the relationship between these records is less clear. Thus, the use of archaeological radiocarbon date density to approximate the spatial distribution of past populations is supported in some regions, but not in others. The causes of this disparity may be related to political, geomorphic or logistic factors.

Temporal Population Change

The use of archaeological radiocarbon dates to reconstruct population change through time is based on the same assumptions as the use of these data to reconstruct the spatial distribution of past populations. If a larger population results in a greater deposition of cultural carbon, and if archaeological sampling is representative of the population as a whole, then the frequency of radiocarbon dates should increase and population increases, and vice-versa. To test the validity of this approach a temporal frequency distribution of archaeological radiocarbon dates from southern Ontario was compared against a comparable and independent population reconstruction by Warrick (2008). The latter population reconstruction documents the population growth of the Huron and Petun Iroquois after the adoption of maize agriculture and their population decline associated with European contact. This reconstruction is based on both archaeological data and written records, using data such as the number of villages, the number of houses in a village and the number of hearths in a village to estimate population change through time. Warrick (2008) provides three population estimates using different methods, but because all three were similar, the average population reconstruction was used. Warrick (2008) recognizes three major periods, pre-contact, indirect contact and direct contact with Europeans, and argues that the population of the Huron-Petun did not decline until direct Euorpean contact.

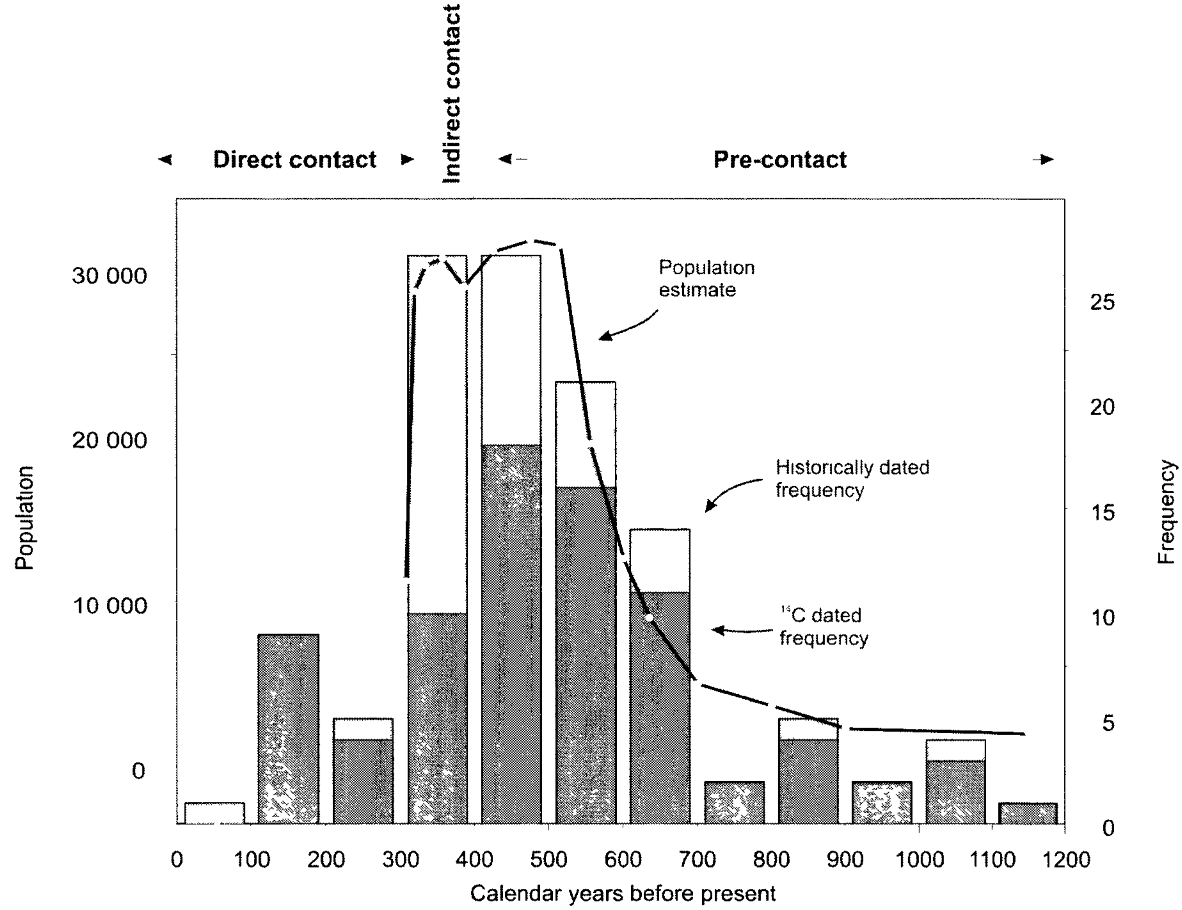

Figure A3 Comparing two reconstructions of temporal population change. Line: Population reconstruction by Warrick (2008) using archaeological surveys. Bars: Temporal frequency distribution of archaeological artifacts in CARD. Dark bars represent the frequency of ^{14}C dated artifacts, and light bars represent the frequency of artifacts whose age was estimated by the primary investigator based on its association with other materials.

All archaeological radiocarbon dates dating to the last 1200 years and within the study area of Warrick (2008) were extracted from the CARD (n=116), and a temporal frequency distribution with 100 year bins was prepared with these dates. Several entries (n=39) primarily from the 15th and 16th centuries in this subset of the CARD were materials which were not radiocarbon dated because the principal investigator was able to date the object based on European goods associated with this material. Using the investigator's "suggested age" of these materials, they were also included in the frequency distribution. By comparing the frequency distribution of archaeological data with Warrick's (2008) population reconstruction the validity of these reconstructions can be tested.

The population estimate by Warrick (2008) shows before 900 yr BP the population of the Huron was 5,000, but with the adoption of maize agriculture rapidly increased to over 30,000 by 500 yr BP. Population decreased rapidly after direct contact with Europeans around 340 yr BP. The temporal frequency distribution of archaeological data from the CARD shows a very similar pattern to the population estimate (Figure A3). The number of radiocarbon dated artefacts drops off during the period of indirect contact, but the number of artefacts dated using historical records (e.g. found in association with European goods) increases during this period. After direct contact, the frequency of artefacts in the CARD drops off rapidly. The close correspondence between these two independent records of population change suggests that temporal frequency distributions of archaeological dates are truly providing an accurate demographic measurement.

This analysis supports the hypothesis that the temporal frequency distribution of archaeological data provides information on the timing and magnitude of population change (Peros *et al.*, 2010). Future work should explore other opportunities to compare the radiocarbon-database approach with independent reconstructions of demographic change with the goal of improving methods to reconstruct paleo-populations.