LAKEHEAD UNIVERSITY
FACULTY OF NATURAL RESOURCE MANAGEMENT

# FROM FOREST TO FARMLAND: PALAEOECOLOGICAL AND GEOSPATIAL RECONSTRUCTION OF LAND-USE CHANGE IN THE LAKE SIMCOE WATERSHED, ONTARIO

BY
LILY EDMUNDS

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**COMMITTEE MEMBERS:**
**DR. FLORIN PENDEA (SUPERVISOR)**
**DR. BRIGITTE LEBLON (SUPERVISOR)**
**DR. SEUNG-IL LEE (COMMITTEE MEMBER)**
**DR. ELISABETH LEVAC (EXTERNAL EXAMINER)**

# *Abstract*

Reconstructing long-term land-use change and its ecological consequences requires integrating archaeological, historical, and palaeoecological evidence across spatial and temporal scales. This thesis applies a nested palaeoecological and historical aerial photo and GIS-based framework to the Lake Simcoe watershed (southern Ontario, Canada), combining a continuous Holocene sediment record from Bass Lake (Langman) with high-resolution twentieth-century records from three hydrologically open wetlands spanning an urban–rural gradient (Beaver River, Rogers Reservoir, and Baileys Ecopark). Pollen, microscopic charcoal, and non-pollen palynomorph (NPP) analyses, supported by radiocarbon and radionuclide chronologies and historical aerial photograph reconstruction, are used to evaluate how Indigenous and Euro-Canadian land-use regimes are recorded in sedimentary archives and to test the extent to which recent pollen assemblages track independently documented landscape change. The long-term Bass Lake (Langman) record documents gradual Holocene forest succession punctuated by subtle late pre-contact agricultural indicators, including repeated low-abundance occurrences of *Zea mays* and *Cucurbita*-type pollen. These signals occur without sustained arboreal collapse or prolonged charcoal elevation, indicating spatially focused Indigenous land use embedded within a resilient forested landscape. In contrast, nineteenth- and early twentieth-century Euro-Canadian settlement is marked by coherent multi-proxy reorganization across sites, including increases in herbaceous and ruderal taxa, elevated disturbance indicators, and pronounced shifts in pollen assemblage structure. Independently constrained *Ambrosia* maxima demonstrate spatial variability in the timing and expression of agricultural expansion across the basin. North–south contrasts further indicate that closed northern basins retain clearer forested baselines, whereas hydrologically connected southern systems record persistent openness and amplified disturbance associated with agriculture, drainage, and urbanization (Chapter 2**).** GIS-based reconstruction of historical aerial photographs (1920s–2025) reveals divergent land-use trajectories, ranging from rapid urban expansion at Baileys Ecopark to relatively stable agricultural landscapes at Beaver River, with intermediate conditions at Bass Lake (Langman) and Rogers Reservoir. A taxon-to-land-use crosswalk linking pollen taxa to mapped land-use classes demonstrates that agricultural indicators exhibit the strongest and most consistent correspondence with reconstructed land use, while forest signals are more sensitive to fragmentation and source-area effects. Multivariate analyses show significant concordance between pollen assemblages and aerial photo-derived land-use patterns at most sites (Mantel $r$ = 0.66–0.77; Procrustes correlation = 0.76–0.85), with reduced agreement at Bass Lake (Langman) reflecting chronological uncertainty and landscape complexity (Chapter 3**).** Together, these results demonstrate that Indigenous land use produced detectable but localized ecological signals, whereas Euro-Canadian land use generated broader, more persistent transformations that restructured regional ecosystems. This thesis advances a transferable framework for linking palaeoecological records with spatially explicit land-use data and provides new insight into the interpretation of ecological baselines and anthropogenic change in temperate landscapes.

**Keywords:** palaeoecology; land-use change; Lake Simcoe watershed; pollen analysis; charcoal analysis; geospatial analysis; multi-scale analysis; Holocene reconstruction; Indigenous land-use; Euro-Canadian settlement

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## *Notes*

This research was conducted within the Lake Simcoe watershed, on the traditional territories of the Anishinaabeg, including the Ojibwe and Chippewa peoples. Laboratory work and thesis writing were completed on these same lands. I acknowledge and respect the enduring presence and knowledge of Indigenous peoples in this region.

All analyses were completed by the author, and the writing presented in this thesis is original. GenAi (ChatGPT, Claude) was used to support editing, including improving clarity, reducing repetition, and assisting with the synthesis of key points in the conclusion chapter. Generative AI tools were also used when needed to help troubleshoot R code.

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# Chapter 1 – Thesis Introduction

## *1.1 Research Objectives and Thesis Overview*

Understanding how land-use change is recorded across ecological and temporal scales requires the integration of long-term environmental archives with independently reconstructed landscape data. This thesis combines palaeoecological and geospatial approaches to examine how human land-use has shaped vegetation, disturbance regimes, and landscape processes within the Lake Simcoe watershed.

The primary objective of this research is to reconstruct land-use change from prehistoric to modern periods using a nested palaeoecological framework that integrates a continuous Holocene sediment record with multiple high-resolution records from contrasting depositional environments. This design enables comparison across spatial scales and landscape contexts, allowing for the evaluation of how land-use signals are expressed in both closed and hydrologically open systems.

A central focus of this thesis is the differentiation of Indigenous and Euro-Canadian land-use regimes within a long-term ecological context. Indigenous land stewardship in southern Ontario has been characterized by controlled burning, rotational horticulture, and settlement mobility, producing recurring but spatially constrained ecological disturbances (McAndrews, 1988; Crawford & Smith, 2003; Williamson, 2010). These practices are expected to be reflected in palaeoecological records as low-abundance but persistent indicators of cultivation and disturbance embedded within largely forested systems. In contrast, Euro-Canadian settlement introduced widespread deforestation, agricultural intensification, wetland drainage, and permanent landscape modification, resulting in more extensive and synchronous ecological change (McAndrews, 1988; Butt *et al*., 2012). This thesis evaluates how these contrasting land-use regimes are expressed in sedimentary records and how their ecological impacts vary across the Lake Simcoe basin.

A second objective is to assess the transferability and limitations of long-term palaeoecological baselines across modern landscapes. Baselines derived from closed-basin records are frequently used to define reference conditions for conservation and restoration; however, their applicability to hydrologically open or urban-influenced systems remains uncertain. By comparing the long-term record from Bass Lake with high-resolution records from Beaver River, Rogers Reservoir, and Baileys Ecopark, this research evaluates how basin characteristics, hydrological connectivity, and landscape context influence the recording and interpretation of ecological signals.

Building on these long-term reconstructions, this thesis further integrates palaeoecological data with land-use reconstructions derived from historical aerial imagery to examine landscape change over the twentieth and early twenty-first centuries. Land-use trajectories are reconstructed across sites spanning an urban–rural gradient, and their relationship to pollen assemblages is evaluated using both indicator-based and multivariate approaches. Pollen taxa are grouped into land-use-relevant functional categories to assess whether specific indicators covary with mapped land-use classes, while ordination and distance-based methods are used to test whether overall pollen assemblage turnover parallels reconstructed landscape change.

This integrative framework is based on the premise that pollen records do not directly capture land-use but instead reflect the vegetation expression of land-use filtered through processes of production, dispersal, and deposition (Bunting *et al*., 2004; Sugita, 2007a). As such, this thesis evaluates the extent to which pollen assemblages track broad patterns of landscape composition and reorganization rather than discrete land-use states.

These objectives are addressed through the following research questions:

1) How are Indigenous and Euro-Canadian land-use practices expressed in palaeoecological records from the Lake Simcoe watershed, and how do their ecological impacts differ?
2) How does the expression of land-use impacts vary spatially across the watershed, particularly between northern and southern regions and among sites with differing hydrological characteristics?
3) To what extent can long-term palaeoecological baselines derived from closed-basin systems be applied to interpreting land-use impacts in hydrologically open and urban-influenced environments?
4) How well do pollen assemblages reflect reconstructed land-use patterns over the twentieth and early twenty-first centuries?
5) To what extent does multivariate turnover in pollen assemblages correspond to independently reconstructed landscape change?

### *1.1.1 Overview of Chapter 2*

Chapter 2 presents a long-term palaeoecological reconstruction based on sediment cores from Bass Lake (Langman), supplemented by short-core records from Beaver River, Rogers Reservoir, and Baileys Ecopark. This chapter applies a nested palaeoecological approach, in which multiple sedimentary records are analyzed across different spatial scales, basin types, and temporal resolutions to capture hierarchical patterns of ecological change.

Within this framework, the long-term record from Bass Lake (Langman), a closed-basin system, provides a regional baseline spanning the Holocene, while shorter, higher-resolution records from Beaver River, Rogers Reservoir, and Baileys Ecopark, which are hydrologically open and span an urban–rural gradient, capture more localized and recent landscape dynamics. By integrating these records, this approach enables comparison of site-specific signals within a broader regional context and allows differences in hydrological connectivity and landscape setting to be directly linked to variation in palaeoecological signal expression.

This chapter examines vegetation dynamics and disturbance indicators from the Holocene through the historical period, highlighting recurring, low-frequency signals of cultivated plants and other disturbances associated with localized land-use.

### *1.1.2 Overview of Chapter 3*

Chapter 3 integrates palaeoecological records with land-use reconstructions derived from historical aerial photographs and satellite imagery spanning the late 1920s to the present. This chapter evaluates the alignment between sedimentary proxies and mapped land-use categories, assessing the reliability of pollen and related indicators for reconstructing recent landscape changes.

## *1.2 Background and Literature Review*

### *1.2.1* Palaeoecology *and Environmental Reconstruction*

Palaeoecology provides a framework for reconstructing past environmental conditions using biological, physical, and geochemical indicators preserved in natural archives. Lake and wetland sediments are particularly valuable due to their continuous accumulation and ability to preserve signals of vegetation composition, disturbance, and ecosystem processes over long timescales (Birks & Birks, 1980).

The capacity of pollen records to document human influence on vegetation was first systematically demonstrated in foundational European studies. Johannes Iversen (1949) identified widespread declines in *Ulmus* pollen across northwestern Europe and linked these shifts to Neolithic forest disturbance and early agricultural activity, establishing one of the earliest connections between pollen stratigraphy and anthropogenic landscape change. Subsequent syntheses by Harry Godwin (1975) further formalized the use of pollen analysis in reconstructing Holocene vegetation dynamics and human impacts.

These approaches were later extended through regional syntheses and quantitative analyses that refined the interpretation of anthropogenic signals in pollen records (Behre, 1981; Berglund, 1991). In North America, similar frameworks were applied to postglacial vegetation histories, with increasing emphasis on distinguishing climatic drivers from anthropogenic disturbance during the late Holocene (Davis, 1963; Webb, 1986). In southern Ontario, early Holocene vegetation patterns were largely governed by postglacial succession and climate, while later records increasingly reflect human influence during the Late Woodland and post-contact periods

Interpretation of sedimentary records requires careful consideration of proxy behaviour, including production, dispersal, and preservation. Wind-pollinated taxa such as *Pinus* are often overrepresented due to high pollen productivity and long-distance transport, whereas taxa such as *Fagus* and *Acer* are underrepresented relative to their actual abundance. These biases must be accounted for when linking pollen assemblages to vegetation composition (Andersen, 1970; Broström *et al*., 2004).

The spatial scale represented in sedimentary records is strongly influenced by basin size and hydrological connectivity. Larger lakes integrate vegetation signals over broad regional areas, whereas smaller basins are more sensitive to local and catchment-scale processes (Prentice, 1985; Nielsen & Sugita, 2005; Sugita, 2007a). This distinction reflects differences in the relevant source area of pollen (RSAP), which varies as a function of basin size, landscape structure, and dispersal processes (Sugita, 1994; Hellman *et al*., 2009). As a result, the spatial representativeness of sedimentary records must be considered when comparing pollen assemblages to independently reconstructed land-use patterns.

### *1.2.2 Pollen, Non-Pollen Palynomorphs, and Charcoal*

Pollen analysis is a foundational method in Palaeoecology, enabling reconstruction of past vegetation through identification and quantification of pollen grains preserved in sediments (Faegri & Iversen, 1989; Moore et al., 1991). Because pollen production and dispersal vary among taxa, assemblages reflect a combination of local and regional vegetation signals (Sugita, 2007a).

The interpretation of pollen as an indicator of land-use has been strengthened through the identification of anthropogenic indicator taxa. Johannes Iversen (1949) demonstrated that cereal pollen could be linked to early agricultural activity, while Karl-Ernst Behre (1981) formalized the use of associated disturbance taxa such as Plantago lanceolata and Rumex acetosella as indicators of cultivation and grazing. Subsequent work confirmed that even low percentages of cereal-type pollen can indicate nearby cultivation when consistently present within sediment sequences (Moore & Webb, 1978; Gaillard *et al*., 1994; Josefsson, 2014).

Non-pollen palynomorphs (NPPs) provide complementary evidence of environmental processes that are not captured by pollen alone. Fungal spores such as Glomus are associated with soil disturbance and erosion and often increase in response to land clearance (van Geel, 2006). At Crawford Lake, Ontario, fungal remains associated with crop pathogens, including Ustilago maydis and Puccinia species, exceed the abundance of their corresponding host pollen and provide strong evidence of cultivation during both Indigenous and Euro-Canadian agricultural phases (McAndrews & Turton, 2010). These findings highlight that fungal indicators can provide a more direct signal of agricultural activity than pollen alone.

Charcoal preserved in sediments provides a record of past fire activity, reflecting both natural processes and human influence (Whitlock & Larsen, 2001). In southern Ontario, charcoal records indicate low-intensity, localized burning during the Late Archaic and Woodland periods associated with Indigenous land management practices, while more sustained charcoal increases correspond with widespread land clearance and agricultural expansion during Euro-Canadian settlement (McAndrews, 1988; Yu *et al*., 1996).

The integration of pollen, NPPs, and charcoal supports a multi-proxy approach that improves interpretation of vegetation dynamics, disturbance regimes, and land-use processes.

### *1.2.3 Indigenous Land-use and Ecological Expression*

Indigenous peoples have shaped landscapes across North America for millennia through practices such as controlled burning, cultivation, harvesting, and ecosystem stewardship (McAndrews, 1988; Ellis & Deller, 1990). In southern Ontario, these practices intensified during the Late Woodland period with the development of Iroquoian horticultural systems.

Palaeoecological records from the region demonstrate that Indigenous land-use produced detectable but spatially constrained ecological signals. Sediment records from Crawford Lake document increases in *Zea mays, Phaseolus, and Cucurbita* pollen alongside charcoal and disturbance indicators during periods of Iroquoian agricultural activity (McAndrews & Turton, 2010). These signals reflect localized cultivation and settlement rather than extensive forest clearance.

Archaeological evidence indicates that Iroquoian agricultural systems were rotational, with settlements relocating every 12–25 years to allow for soil recovery and forest regeneration (Williamson, 1990; Crawford & Smith, 2003). As a result, ecological impacts were spatially heterogeneous and temporally intermittent.

This period of land-use was also shaped by broader socio-political dynamics, including the seventeenth-century Beaver Wars, which led to the displacement and reorganization of Indigenous populations across the Great Lakes region (White, 1974; Sutton, 1999). These disruptions influenced settlement patterns and land-use, contributing to shifts in cultivation intensity and landscape use that may be reflected in palaeoecological records through changes in disturbance indicators and site occupancy.

### *1.2.4 Euro-Canadian Settlement and Landscape Transformation*

Euro-Canadian settlement in southern Ontario introduced a fundamentally different land-use regime characterized by permanent settlement, widespread deforestation, agricultural expansion, wetland drainage, and infrastructure development (Foster *et al*., 2003; Williams *et al*., 2010; Bowley, 2015).

By the late nineteenth century, extensive forest clearance and agricultural expansion had transformed much of the region, with large proportions of arable land converted to agriculture and wetlands extensively modified or drained. These changes resulted in accelerated soil erosion, altered hydrological systems, and long-term shifts in ecosystem function (McAndrews, 1988; Butt *et al*., 2012).

In sedimentary records, these transformations are expressed as abrupt and sustained changes in vegetation composition and disturbance indicators. The rapid increase of *Ambrosia* pollen is widely recognized as a stratigraphic marker of land clearance and agricultural expansion across eastern North America (McAndrews, 1988; Yu *et al*., 1996).

Multi-proxy records show concurrent increases in herbaceous pollen, disturbance-associated NPPs, and charcoal, alongside declines in arboreal taxa, indicating a shift toward permanently altered landscapes (McAndrews, 1988; Yu *et al*., 1996; Williams *et al*., 2010). These changes occur at broader spatial scales and with greater synchronicity than those associated with earlier Indigenous land-use practices (Foster *et al*., 2003; Williams *et al*., 2010).

### *1.2.5 Linking Palaeoecological Records with Geospatial Land-use Reconstruction*

The integration of palaeoecological data with geospatial land-use reconstruction provides a framework for directly comparing ecological responses preserved in sedimentary archives with independently documented landscape change. Historical aerial photography represents one of the most valuable spatial archives for reconstructing twentieth-century landscapes. Since the early decades of the twentieth century, systematic aerial surveys have documented land cover across large regions, providing high-resolution records of agricultural patterns, urban expansion, forest cover, and wetland extent (Grossinger et al., 2007; Morgan et al., 2010). In Ontario, the National Air Photo Library (NAPL) archive provides continuous aerial coverage extending to the late 1920s for many parts of the province, offering an unusually long baseline for quantitative landscape reconstruction (Thurston, 1991). When georeferenced and digitized within a geographic information system (GIS), these records enable detailed examination of land-use trajectories across multiple decades and allow for the delineation of land-use categories through polygon-based interpretation (Bender et al., 2005; Plieninger et al., 2006).

Geospatial land-use reconstruction from aerial imagery typically involves the manual delineation of land-use polygons and their classification into standardized categories representing agricultural, forest, wetland, and urban land uses. This approach produces spatially explicit representations of landscape composition that can be quantified and compared through time. However, these reconstructions are subject to several sources of uncertainty, including variation in image resolution, georeferencing error, interpreter consistency, and the clarity of land-use boundaries within historical imagery. These limitations must be considered when interpreting relationships between mapped land-use data and ecological proxies (Cousins, 2001; Petit and Lambin, 2002; Bürgi et al., 2004).

Palaeoecological records preserved in lake and wetland sediments provide a complementary, temporally continuous archive of ecological change, capturing vegetation dynamics, disturbance regimes, and anthropogenic activity over decadal to centennial timescales. Fossil pollen, non-pollen palynomorphs, and charcoal record the vegetation expression of land-use rather than land-use itself, filtered through differences in pollen production, dispersal, source area, and sedimentary time-averaging (Davis, 2000; Bunting et al., 2004; Sugita, 2007a, 2007b). As a result, pollen assemblages are most effective at capturing broad patterns in vegetation cover and land-use intensity, with signal strength influenced by basin characteristics and landscape heterogeneity (Hellman et al., 2009; Mazier et al., 2012).

A key challenge in integrating palaeoecological and geospatial datasets lies in the fundamental differences in how these records represent time and space. Historical aerial photographs provide discrete spatial snapshots at irregular intervals, whereas sedimentary records represent time-integrated ecological averages with variable temporal resolution. Reconciling these differing data structures requires explicit consideration of the temporal mismatch between instantaneous spatial observations and temporally averaged ecological signals (Bürgi et al., 2004). This mismatch is particularly important when evaluating rapid land-use change, which may be smoothed or lagged in sedimentary records.

Despite these challenges, integrating spatial reconstruction with palaeoecological data provides a powerful framework for understanding landscape change. Historical GIS approaches based on aerial photography or maps provide detailed spatial reconstructions but limited ecological insight, while palaeoecological records provide continuous ecological archives but lack spatial specificity (Birks and Birks, 2006; Goring et al., 2013). Combining these complementary data sources allows both the spatial structure and ecological consequences of land-use change to be evaluated within a single analytical framework (Swetnam et al., 1999; Froyd and Willis, 2008; Szabó, 2015). However, systematic comparisons between pollen records and land-use trajectories derived from sequential aerial photography remain relatively rare, particularly across multiple sites and landscape contexts. This thesis addresses that gap by developing a hybrid framework to evaluate the correspondence between palaeoecological indicators and reconstructed land-use change across sites spanning an urban–rural gradient.

### *1.2.6 Regional Context and Research Significance*

The Lake Simcoe watershed in southern Ontario comprises a heterogeneous landscape of forests, wetlands, agricultural land, and urban development shaped by both long-term ecological processes and successive phases of human land-use. The region has a documented history of Indigenous occupation followed by extensive Euro-Canadian settlement beginning in the nineteenth century, resulting in substantial and persistent landscape transformation (McAndrews, 1988; Butt *et al*., 2012). Marked spatial variability across the watershed, including contrasts between relatively forested northern areas and more intensively developed southern regions, provides an effective framework for examining how landscape context influences the expression of ecological signals.

Building on this landscape complexity, this research examines how human land-use is recorded in sedimentary archives and how these records can be used to interpret ecological change across multiple temporal scales (Jackson & Hobbs, 2009). By integrating long-term palaeoecological data with geospatial land-use reconstruction, this thesis evaluates the extent to which commonly used proxies reflect independently reconstructed landscape dynamics.

Although environmental change within the Lake Simcoe watershed has been documented, relatively few studies have directly linked sedimentary records with reconstructed land-use patterns across multiple sites. This thesis addresses that gap through a combined palaeoecological and historical imagery analysis framework, enabling assessment of both the sensitivity and limitations of pollen, non-pollen palynomorphs, and charcoal as indicators of land-use change.

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# Chapter 2 – Nested Palaeoecological Reconstruction of Prehistoric to Historic Landscapes in the Lake Simcoe Region (Central Ontario, Canada)

## *2.1 Introduction*

Southern Ontario represents a long-occupied landscape in which human land-use has exerted ecological forcing throughout the Holocene. Archaeological evidence, including fluted projectile points and lithic scatters recovered from proglacial lake margins, indicates that occupation of the region began following Deglaciation, with Palaeo-Indigenous groups present by 12,700-12,100 cal BP (Ellis & Deller, 1990; Roberts, 1984). Early land use practices during this period were largely seasonal and mobile (e.g., short-term hunting camps and seasonal fishing stations), with ecological changes resulting from postglacial climate dynamics and vegetation succession rather than direct human disturbance (McAndrews, 1988; Yu *et al*., 1996).

During the Middle to Late Archaic period (9,500-2,900 cal BP), Indigenous land-use intensified along river corridors and within the broader Lake Simcoe basin (MacKinnon, 2020). Archaeological indicators such as ground stone tools and net sinkers reflect evolution in diverse subsistence strategies, while palaeoecological records document localized increases in charcoal deposition. These patterns are consistent with low intensity and spatially limited burning practices that influenced vegetation structure without producing sustained impacts (Ellis & Deller, 1990; McAndrews, 1988).

A more pronounced shift in land-use occurred during the Late Woodland period with the emergence of Iroquoian horticulture. Cultivation of *Zea mays* (maize) was introduced to southern Ontario by approximately 1,300-1,150 cal BP, initially as part of mixed subsistence systems rather than intensive agriculture (Crawford *et al*., 1997; Crawford & Smith, 2002). Pollen and charcoal records from southern Ontario kettle lakes, including Crawford Lake, record increases in disturbance indicator taxa and fire activity linked to small-scale field clearance during this interval (McAndrews, 1988; Yu *et al*., 1996). Importantly, Iroquoian land-use systems were rotational and regenerative, with villages typically relocated every 12-25 years, this allowed for soil recovery and forest regrowth (Williamson, 1990; Crawford & Smith, 2003).

Euro-Canadian settlement began in the late eighteenth and early nineteenth centuries, which introduced a different kind of land-use regime. Fixed cadastral surveys, permanent farmsteads, and plough-based monoculture agriculture replaced Indigenous mobility and long rotation systems (Williamson, 2010; Archives of Ontario, 2013). By the late nineteenth century, historical records indicate widespread wetland drainages and channel modifications as well as the clearing for agriculture on more than 70% of arable land of southern Ontario (Zavitz, 1916; Bowley, 2015). These changes resulted in accelerated soil erosion, altered hydrological regimes, and long-term ecological degradation that exceeded the spatial extent and persistence of pre-contact disturbances (McAndrews, 1988; Butt *et al*., 2012).

At the Holocene scale, these different land-use practices show that human influence has been a continuous but variable ecological forcing in southern Ontario. Indigenous land stewardship shaped landscapes through repeated, spatially limited disturbances embedded within long-term cycles of recovery, whereas Euro-Canadian land-use imposed abrupt and extensive transformations. Distinguishing between these practices is needed when interpreting palaeoecological records and understanding the long-term effects observed in modern-day ecosystems.

Historical records represent an important but incomplete foundation for the reconstruction of land-use changes in southern Ontario. Early documentation, such as Euro-Canadian maps and land surveys, broadly describes settlement patterns and agricultural practices, though these documents can be spatially and temporally uneven and often written in a colonial perspective rather than an ecological or land-based standpoint. (Williamson & Robertson, 1998; Archives of Ontario, 2013). Explorers and surveyors, including John Graves Simcoe, Augustus Jones, and early Loyalist and Crown surveyors, upon arrival in the late eighteenth to early nineteenth century, described the encountered landscapes within the Lake Simcoe region as "burnt," "waste," or "abandoned." These interpretations served to obscure the presence of Indigenous-managed agroecosystems and misrepresented the fallow phases of long-rotation land-use systems as ecological degradation (Heidenreich, 1973; Doolittle, 2000; Birch & Williamson, 2013). Written records are subject to the limitation in their ability to document ecological processes such as fire regimes, soil disturbance, and vegetation succession. While historical accounts note the presence of clearings or agricultural fields, they often fail to capture the timing, frequency, or extent of disturbance as well as the periods of recovery or resilience following land-use changes (McAndrews, 1988).

Palaeoecological records offer consistent archives that can greatly complement existing historical records. Pollen assemblages record changes in vegetation composition, microscopic charcoal, which reflects fire activity, and non-pollen palynomorphs (NPPs), which provide evidence for processes such as soil erosion, nutrient loading, and agricultural activity that may not be visible in pollen data alone (McAndrews, 1988; van Geel, 2006; McAndrews & Turton, 2010). In southern Ontario, the nineteenth century rise in *Ambrosia* (ragweed) pollen serves as a strong palaeoecological marker of Euro-Canadian Forest clearance, often used as an independent way to date historical land-use transition periods (McAndrews, 1988). Despite their strengths, palaeoecological records also involve methodological constraints. Long sedimentary sequences allow reconstruction of long-term land-use change but are typically derived from a limited number of sites and/or may not capture spatial variability across heterogeneous landscapes (Prentice, 1985; Sugita, 1994). In comparison, short, high-resolution records from multiple locations improve spatial replication but lack deep time context and baseline conditions against which recent change can be evaluated (Jackson, 1990; Nielsen & Sugita, 2005). Recognizing these strengths and limitations helps to design studies that integrate both temporal depth and spatial coverage. Palaeoecology is therefore not a replacement for historical records but a necessary counterpart, providing continuous ecological context through which historical documented evidence can be evaluated.

To address the limitations of temporal continuity and spatial replication often present in palaeoecological studies, this study adopts what is known as a nested palaeoecological approach, which combines records of differing lengths and spatial extents within a single framework (Birks & Birks, 1980; Jackson & Williams, 2004). This design prioritizes long-term continuity at one site and spatial contrast across multiple high-resolution short records. The Bass Lake core (Langman) (Fig. 1) provides a continuous Holocene record spanning pre-contact, Indigenous land-use, and Euro-Canadian settlement, and functions as the long-term baseline within a nested palaeoecological framework used to interpret shorter, high-resolution records.

By nesting spatially distributed historic records within a single long-term archive, this approach enables analysis of how land-use signals appear across landscapes with contrasting hydrologic and land-use settings. It also allows testing of whether palaeoecological baselines derived from closed basin systems can be meaningfully transferred to more open, urban influenced environments which is an issue of growing importance in anthropogenically modified landscapes.

## *2.2 The Lake Simcoe Watershed*

The Lake Simcoe watershed is located in south central Ontario (Fig. 1) and encompasses about 3,400 km$^2$, draining south through the Holland River into Lake Ontario (LSRCA, 2020). The basin occupies a transitional ecological zone between the Great Lakes-St. Lawrence Forest region and the southern edge of the Canadian Shield, which results in high ecological diversity (Johnson, 1997; LSRCA, 2020).

Retreating ice margins produced landforms such as kettle depressions, outwash plains, moraines, and riparian corridors. Prominent features such as the Oak Ridges Moraine act as a hydrological divide that regulates groundwater recharge and allows surface water to flow into Lake Simcoe and its tributaries (Chapman & Putnam, 1984; LSRCA, 2020). These landforms have a strong influence on sedimentation patterns, wetland distribution, and vegetation structure across the watershed.

Prior to large-scale Euro-Canadian settlement, regional vegetation was dominated by mixed hardwood forests including species such as *Acer* (maple), *Quercus* (oak), *Fagus grandifolia* (beech), and *Tsuga canadensis* (hemlock), with scattered wetlands and open areas maintained only through natural processes and Indigenous land-use (McAndrews, 1988; Yu *et al*., 1996). Palaeoecological records from southern Ontario document postglacial vegetation succession from early *Picea* (spruce) dominated assemblages to increasingly diverse temperate forests during the early to mid-Holocene (McAndrews, 1988).

Human occupation of the Lake Simcoe basin began shortly after deglaciation and further intensified throughout the Holocene (Ellis & Deller, 1990; Williamson & Steiss, 2003). The subsequent land-use practices contributed to localized forest clearance, controlled burning, and the creation of anthropogenic landscape mosaics.

Euro-Canadian settlement beginning in the late eighteenth century initiated rapid landscape transformation. Forest clearance, wetland drainage, channel modification, and agricultural expansion reshaped Lake Simcoe watersheds' hydrology and vegetation, especially in the southern portions of the watershed more heavily affected by larger scale anthropogenic disturbance (Zavitz, 1916; Butt *et al.*, 2012; Bowley, 2015). Subsequent urban and industrial development further altered sediment dynamics and ecological connectivity, producing a heterogeneous modern landscape in which effects of past land-use remain preserved in soils, wetlands, and aquatic systems to this day. (Johnson, 1997; LSRCA, 2024).

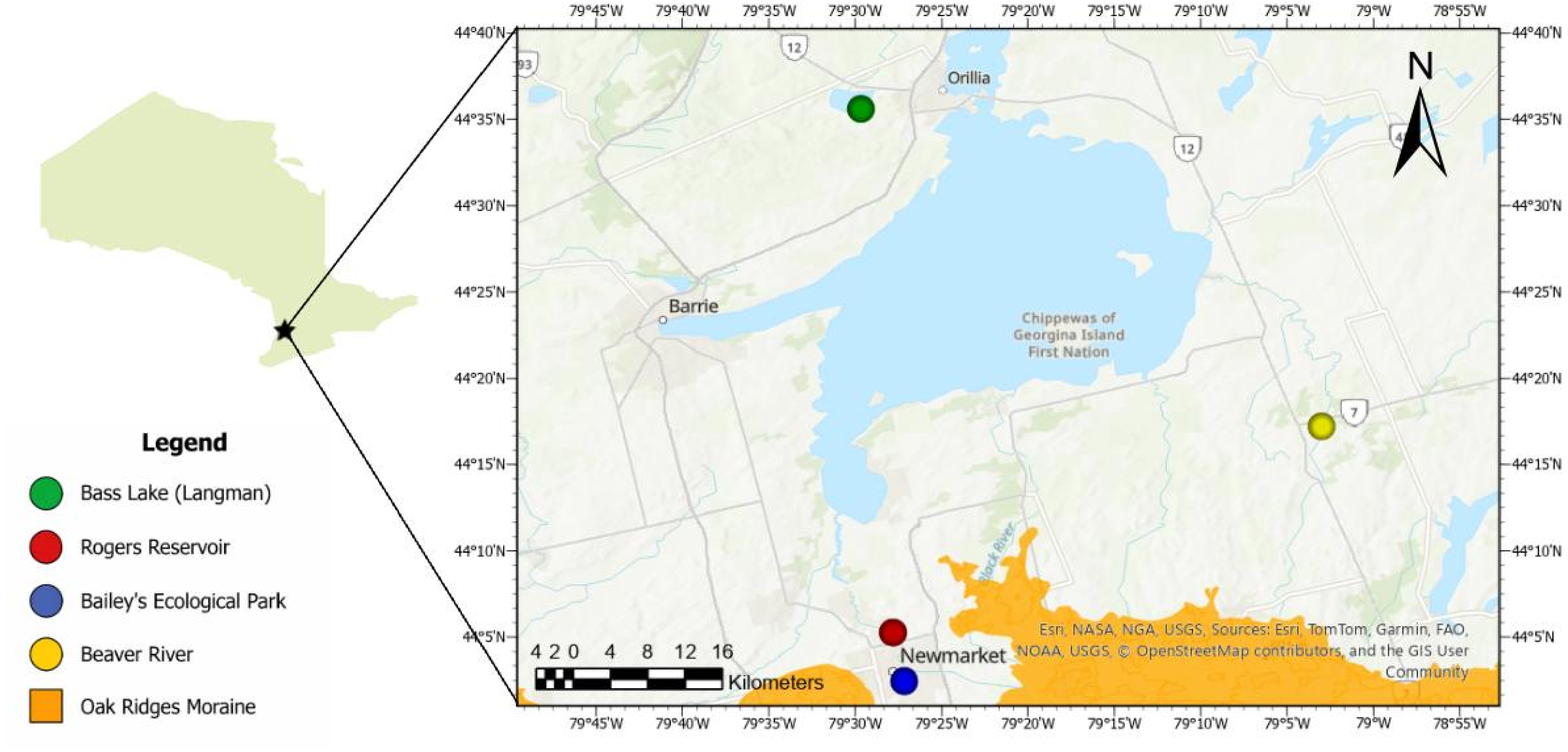

*Figure 1. Figure 1. Location of study sites within the Lake Simcoe watershed, south-central Ontario, Canada. The map shows the positions of Bass Lake (Langman), Rogers Reservoir, Baileys Ecopark, and Beaver River relative to Lake Simcoe and the Oak Ridges Moraine, as delineated by the provincial Oak Ridges Moraine land-use designation layer (Government of Ontario, 2002).*

## *2.3 Site Selection*

The four study sites were selected in a way that would provide contrasts in both land-use history and spatial context within the Lake Simcoe watershed (Fig. 1) while remaining comparable within a single palaeoecological framework. Together, the sites represent gradients of north versus south basin position, rural versus urban land-use, and closed versus hydrologically open depositional systems.

Bass Lake (Langman) was selected as the sole long-term archive because it is a small, closed-basin system with continuous Holocene sediment accumulation and minimal direct hydrologic connectivity. Closed basins are particularly effective at preserving locally derived pollen and charcoal signals due to continuous sedimentation and limited external input, making them highly sensitive to local vegetation change and fire activity (Prentice, 1985; Faegri & Iversen, 1989). In southern Ontario, such records have been widely used to distinguish climate-driven vegetation change from anthropogenic disturbance over millennial timescales (McAndrews, 1988; Yu *et al.*, 1996).

The remaining three sites were selected to provide spatially distributed, high-resolution records focused on the contact period to modern day. The Beaver River Wetland Complex, located within the northern end of the Lake Simcoe watershed, represents a large rural fluvial system, its large wetland area and open hydrology integrate signals from upstream catchments and surrounding agricultural land, making it well-suited for examining Euro-Canadian agricultural impacts in a non-urban context (LSRCA, 2023A).

In comparison, Baileys Ecopark and Rogers Reservoir are in the southern portion of the watershed, where early settlement and subsequent urbanization have strongly altered the land cover and hydrology. Baileys Ecopark represents an urban stormwater-influenced system constructed to intercept runoff from surrounding developed areas, while Rogers Reservoir is a peri-urban riparian system shaped by early twentieth-century canal construction and long-term hydrologic modification (Carter, 1996; LSRCA, 2013). These sites were selected to capture the impacts of urbanization and to assess how hydrologic connectivity influences the expression of land-use signals in sedimentary records.

The pairing of northern versus southern and rural versus urban sites allows for the analysis of spatial heterogeneity in historic land-use impacts across the watershed. The inclusion of both closed and open basins further enables evaluation of how depositional context can change palaeoecological signals, particularly during periods of major land-use change (Prentice, 1985; Jackson, 1990; Nielsen & Sugita, 2005). Rather than treating all sites as equivalent, the methods used in this study recognize the differing capacities to record local versus catchment-scale processes. By combining one long Holocene archive with three spatially distributed historic records, this site selection strategy supports the direct comparison of land-use signals across contrasting environments while maintaining a temporal framework for further interpretation. This site selection strategy reflects the nested palaeoecological framework applied in this study, in which records spanning different basin types, spatial contexts, and temporal resolutions are integrated to evaluate how ecological signals vary across the landscape.

### *2.3.1 Bass Lake (Simcoe North)*

The Bass Lake (Langman) kettle basin is located within the northern region of the Lake Simcoe watershed in the township of Oro Medonte near Orillia, within the George Langman Sanctuary. This site is characterised by a closed basin wetland system with sustained sediment accumulation and limited hydrologic connectivity to surrounding surface waters. George Langman Sanctuary is a private wildlife reserve and contains open water areas with aquatic vegetation, the surrounding wetlands transitioning into a swamp forest where shrubs, ferns, mosses, and understory graminoids are common. This vegetation structure mirrors that of a relatively undisturbed wetland complex. Land use surrounding Bass Lake is relatively low intensity compared to the southern portions of the watershed, although it is close to the early Euro-Canadian urban centre of Orillia. This spatial context limits direct modern disturbance to the wetland areas while still allowing sensitivity to localized land-use change. As such, Bass Lake serves as the primary long-term reference archive in this study, documenting Holocene vegetation succession and land-use dynamics within the northern Lake Simcoe region.

### *2.3.2 Beaver River Wetland Complex (Simcoe North, Rural)*

The Beaver River Wetland Complex is located in the northern Lake Simcoe watershed between Cannington and Uxbridge, encompassing roughly 1,300 ha of wetland habitat (LSRCA, 2023A). The system is hydrologically open, receiving inputs from the Beaver River and its tributaries, which results in the integration of sediments and ecological signals from the broader upstream catchment (LSRCA, 2024).

Vegetation within the wetland includes *Typha* (cattail) marshes, sedge meadows, and swamp forests dominated by *Thuja occidentalis* (eastern white cedar), *Picea spp*, *Abies balsamea* (balsam fir) , and *Acer rubrum* (red maple) (LSRCA, 2023A). The surrounding land-use is mainly rural, with agriculture representing a majority of the catchment influence and contributing to sediment and nutrient inputs during periods of intensified land-use change (LSRCA, 2024), although the area is currently protected as part of the Lake Simcoe Region Conservation Authority. As a large, hydrologically connected system, sediments from the Beaver River Wetland Complex are expected to record catchment-scale pollen, charcoal, and NPP signals rather than only local disturbance. In this study, the site provides a rural, open system which provides a contrast to more closed basin archives in the northern Lake Simcoe region (Jackson, 1990; Nielsen & Sugita, 2005).

### *2.3.3 Baileys Ecopark (Simcoe South, Urban)*

Baileys Ecopark is located in the southern Lake Simcoe watershed within the Town of Newmarket. The site covers 10 ha and was developed as a stormwater management and ecological restoration project made to intercept urban runoff before outflowing to the East Holland River (LSRCA, n.dA ). The park contains many constructed wetlands and ponds that are hydrologically connected to urban drainage infrastructure. Vegetation within the wetland areas is dominated by *Typha* marshes, while upland areas include regenerating meadows, mixed hardwood stands, and conifer plantations associated with restoration activities (LSRCA, n.dA). The surrounding catchment is highly urbanized; as a result, sediments deposited within the park's wetlands are heavily influenced by urban runoff, modified flow regimes, and anthropogenic nutrient and contaminant inputs. (LSRCA, 2024).

Sediments from Baileys Ecopark are expected to reflect its function as an urban stormwater interception system with integration of land-use signals from across a developed catchment. In this study, the site provides an urban, open system perspective.

### *2.3.4 Rogers Reservoir (Simcoe South, Peri-Urban Riparian)*

Rogers Reservoir is located in East Gwillimbury, along the East Holland River in the southern Lake Simcoe watershed. This 84 ha site forms part of a linear riparian system that is hydrologically connected to the East Holland River, allowing for a constant exchange of water, sediment, and organic matter (LSRCA, 2013).

The current landscape has faced substantial modifications associated with early twentieth-century infrastructure development, particularly the Newmarket Canal project (1906–1911). Although the canal was never completed, aspects of it including channelization, lock construction, and floodplain alteration, permanently impacted river morphology and local hydrology, causing changes in sediment deposition patterns within the reservoir (Carter, 1996; LSRCA, 2013).

Vegetation within the site includes riparian wetlands and *Typha* marshes, willow thickets, floodplain forest, upland meadows, and mixed hardwood stands with local pine plantations (LSRCA, 2013). The surrounding areas are mixed urban and rural land-use with agricultural activity upstream and urban development associated with Newmarket and East Gwillimbury contributing to anthropogenic inputs to the East Holland River system (LSRCA, 2023b; LSRCA, 2024). Sediments deposited within Rogers Reservoir are expected to contain signals from both local riparian vegetation and upstream catchment processes. In this study, Rogers Reservoir serves as a peri-urban riparian site for examining how mixed land-use signals are expressed within a hydrologically connected depositional environment.

## *2.4 Core collection and Stratigraphy*

At Bass Lake (Langman), an 8 m-long, 5 cm-diameter sediment core was extracted from the swamp basin using a Macaulay corer.  In this study we only used the upper 5 m which corresponds to the Holocene sequence. Following collection, the core was wrapped in plastic film, encased in lengthwise cut PVC piping for protection, and stored frozen to preserve sediment integrity prior to laboratory processing.

In the laboratory, the Bass Lake core was subsampled at 1 cm thickness, taken at 10 cm intervals, with finer subsampling (1-2 cm) for the upper 60 cm. Sediment texture, structure, organic content, and stratigraphic features were described visually in the field and verified during laboratory preparation.

At Beaver River Wetland Complex, Baileys Ecopark, and Rogers Reservoir, coring procedures followed the standardized methods described by Pendea *et al*. (2023). At each site, a 50 cm long, 5 cm diameter sediment core was collected using a sharpened steel pipe driven vertically into the sediment. Sampling locations were selected to represent dominant wetland conditions while minimizing edge effects. Core compaction during extraction was estimated by comparing recovered core length with penetration depth and did not exceed 4%. In the laboratory, cores were sectioned into 1 cm increments, with interval thickness adjusted where necessary to account for sediment compaction or friable material. Where sediments were powdery or unconsolidated, larger increments were used to prevent material loss during processing. Stratigraphic descriptions were based on visual assessment of sediment colour, texture, and organic content. These descriptions provided a framework for subsequent chronological modelling and palaeoecological analyses.

## 2.5 Palaeoecological Analyses

### 2.5.1 Pollen Analysis

Sediment subsamples from all sites were prepared for pollen analysis following palynological procedures outlined by Moore *et al*. (1991). Micro-ceramic marker particles (Kitaba and Nakagawa, 2017) were added to each sample to allow calculation of palynomorph concentrations.

Chemical preparation began with treatment in hydrochloric acid (HCl) to remove carbonates, followed by potassium hydroxide (KOH) to remove humic acids, with rinsing in deionized water between steps. Samples were sieved at 125 µm to retain coarse material for macrofossil analysis, and the finer fraction was passed through a 7 µm nylon mesh to remove clay-sized particles. Samples were dehydrated using glacial acetic acid before acetolysis in a mixture of acetic anhydride and sulfuric acid (Moore *et al*., 1991). Following acetolysis, samples were treated with hydrofluoric acid (HF) to remove silicate minerals, neutralized with HCl, and rinsed twice with deionized water. Samples were then sieved again through 125 µm and 7 µm meshes until the supernatant appeared clear, indicating removal of residual particles. Following sieving, samples were mounted on microscope slides, and pollen and spores were identified using microscopy and regional reference keys (Moore *et al*., 1991). For each sample, we attempted to count a minimum sum of 500 terrestrial pollen and spore grains (henceforth Main Sum); in ~15% of the samples, the pollen concentration was low and thus for these we counted a minimum of 300 grains. Taxonomic identification was conducted to the lowest possible level, with some taxa grouped where morphological distinction was not reliable. Pollen was identified using published keys (Faegri *et al*., 1989; Moore *et al*., 1991; Kapp *et al*., 2000). For Betulaceae and Asteraceae we followed Punt *et al*. (2003) and Punt and Hoen (2009), respectively.

Cerealia-type (Poaceae) pollen was identified as large monoporate grass grains ≥45 µm in diameter, with a prominent circular pore surrounded by a distinct thickened annulus and a psilate to finely scabrate exine. These grains exceed the size range typical of most wild temperate Poaceae and are consistent with cultivated cereal morphotypes. (Behre, 1981; Moore *et al*., 1991).

### *2.5.2 Charcoal Analysis*

Microscopic charcoal particles were counted alongside pollen and NPP during palynological analysis. Charcoal was identified visually as opaque, angular, black fragments following standard practice in regional palaeoecological studies (McAndrews, 1988; Whitlock & Larsen, 2001). Charcoal counts were converted to concentrations (particles $cm^{-3}$) using the sample volume as a representation of relative charcoal abundance within each sediment sample and serve as a proxy for local fire activity (McAndrews, 1988; Whitlock & Larsen, 2001).

### *2.5.3 Non-Pollen Palynomorphs (NPPs)*

Non-pollen palynomorphs (NPPs) were counted alongside pollen and microscopic charcoal during palynological analysis. NPPs include a range of microscopic remains such as fungal spores, algal remains, and other organic microfossils that provide information on ecological processes not captured by pollen data alone (van Geel, 2006). NPPs were analyzed from the same palynological samples prepared for pollen analysis, and no additional methodologies were applied beyond standard pollen preparation procedures (Moore *et al*., 1991). Identification of NPPs was conducted using microscopy and published reference keys (van Geel 1978; van Geel et al. 1981, 2003, 2011; van Geel and Aptroot 2006; Cugny et al. 2010; Shumilovskikh & van Geel 2022). NPP types recorded in this study include fungal spores, aquatic algae and some testate amoeba, all of which are commonly used as indicators of decomposition processes, hydrologic conditions, and disturbance (van Geel, 2006). The relative proportion of NPP was expressed as % of the palynomorph sum (Main Sum + NPP sum).

### *2.5.4. Palynomorph Data Treatment*

In addition to standard palynological taxonomy, we derived several taxonomic groups, namely Trees, Shrubs, Herbs, and Disturbance Indicators, and these are presented with the main palaeoecological diagrams. The latter group includes charcoal particle relative abundance (% of the Main Sum+Charcoal counts), and disturbance and/or agriculture-related fungal spores (Henry, 2020), namely arbuscular mycorrhizal fungi (*Glomus)*, predominantly coprophilous fungi (*Sordaria*, *Podospora, Sporormiella*, and *Delitschia),* and parasitic fungi (*Ustilago*-type, *Pucinnia sorghi, Pucinnia graminis*) identified in other southern Ontario prehistoric or historic contexts (McAndrews and Turton, 2010).

## *2.6 Statistical Analyses and Chronological Framework*

Stratigraphic zonation of pollen and non-pollen palynomorph (NPP) assemblages was performed using stratigraphically constrained hierarchical clustering by incremental sum-of-squares (CONISS), which restricts cluster amalgamation to adjacent stratigraphic levels (Grimm, 1987). Dissimilarity among samples for CONISS was calculated using chord distance, which reduces the influence of dominant taxa and is appropriate for compositional percentage data (Orlóci, 1967; Legendre & Gallagher, 2001). The number of statistically meaningful assemblage zones was evaluated using the broken-stick model as an objective stopping rule (Bennett, 1996). To summarize major gradients in assemblage composition through time and facilitate comparison among sites, principal components analysis (PCA) was conducted on Hellinger-transformed percentage data, a transformation recommended for community composition datasets to make them suitable for linear ordination methods (Legendre & Gallagher, 2001). In this study, PCA axis 1 (PCA1) is interpreted as the primary compositional gradient in the pollen assemblage rather than a direct index of disturbance intensity. Within-sample diversity was quantified using Shannon entropy (Shannon, 1948) and Simpson diversity (Simpson, 1949), capturing complementary aspects of richness and evenness. All statistical analyses and diagram production were performed in R (R Core Team, 2025). Stratigraphic plotting and zonation were implemented using the riojaPlot and rioja packages (Juggins, 2024, 2025), while ordination and diversity metrics were calculated using the vegan package (Oksanen *et al.*, 2024).

To establish the chronological framework we used radiocarbon and radionuclide ($^{210}$Pb and $^{137}$Cs) dating to construct age-depth models for cores, which provided continual temporal frameworks for each core, allowing data to be aligned and compared on a common time axis (Appleby, 2001; Blaauw & Christen, 2011; Reimer *et al.*, 2020). In addition to radiometric dating, we used relative/contextual dating based on pollen markers (*Ambrosia*, Cerealia-type, *Taraxacum*) for the start of the Euro-Canadian signal along the palaeoecological records and available historical records of first substantial settlement in the local areas.

## *2.7 Radiocarbon Dating*

For the Bass Lake (Langman) core we conducted Accelerated Mass Spectrometry (AMS) radiocarbon measurements exclusively on macrofossils including seeds, twigs, and leaves. AMS radiocarbon analyses were performed by Beta Analytic Inc. (Miami, USA) and the André E. Lalonde AMS Lab at University of Ottawa (Canada). Quoted errors represent one relative standard deviation statistics (68% probability) and counting errors are based on the combined measurements of the sample, background, and modern reference standards. Radiocarbon ages were corrected for isotopic fractionation and were calibrated using the IntCal20 curve (Reimer, *et al*., 2020). Calibrated ranges are reported as two standard deviations. The age-depth model was derived using the *rbacon* package in the R platform (Blaauw and Christen, 2011), which divides a dated sequence into many short sections for which accumulation rates (in yr $cm^{-1}$) are modelled. The accumulation rate of any individual section "*i*" depends both on the adjacent radiocarbon age estimates and, to a certain degree, on the accumulation rate of previous section (*i*-1). In this way, a "memory" of accumulation rate throughout time is obtained, that seeks to reflect environmental conditions that might change gradually over time.

### *2.7.1 Radionuclide (Lead-210 and Cesium-137) and Palaeoecological Dating*

For the Beaver River, Baileys Ecopark, and Rogers Reservoir cores we used a combination of radionuclide dating ($^{210}$Pb and $^{137}$Cs) and relative dating based on continuous *Ambrosia* and other European cultural indicators (Cerealia-type and/or *Taraxacum*) signals as relative palynological biostratigraphic tie-points to support the recent (post-contact) age framework.

Unsupported $^{210}$Pb activities were modeled using the mixed model approach (Pendea *et al*., 2023), and $^{137}$Cs profiles were used to identify the 1963–1964 fallout maximum and, where present, the ca. 1954 onset of atmospheric deposition, providing absolute chronological control for the upper sediments. For a full description of radionuclide dating including the raw metadata please refer to Pendea *et al*. (2023).

Below the depth of reliable radionuclide constraint, we used pollen-based settlement-horizon indicators to support late 19th century age assignments. A sustained rise in *Ambrosia* (ragweed) pollen was treated as the principal biostratigraphic marker of Euro-American land clearance and agricultural expansion, consistent with its widespread use as a settlement-horizon indicator in eastern North America (e.g., Bassett & Terasmae, 1962; Grimm, 1987). Because the stratigraphic expression of this horizon can vary with land-use history, basin size, sediment focusing, and sampling resolution, the *Ambrosia* rise was interpreted as an approximate chronological tie-point rather than a fixed calendar date. Occurrences of Cerealia-type pollen were considered supportive evidence of agricultural activity but interpreted cautiously due to taxonomic ambiguity with large wild Poaceae. In addition, increases in *Taraxacum* (dandelion), a European-introduced ruderal species associated with anthropogenic disturbance (National Agri-Environmental Standards Initiative Report no. 2-29, 2006), were treated as supplementary contextual indicators when co-occurring with *Ambrosia* and other disturbance taxa. This multi-proxy framework reduces reliance on any single palynological signal and provides a conservative age interpretation below the radionuclide-dated interval.

## *2.8 Results*

### *2.8.1 Geochronology of Bass-Lake (Langman)*

The Bass Lake (Langman) core chronology is based on a series of accelerator mass spectrometry (AMS) radiocarbon dates obtained from terrestrial macrofossils and discrete organic fractions (Table 1). Radiocarbon ages were calibrated using the IntCal calibration curve (Reimer *et al*., 2020), and age–depth relationships were modeled using a Bayesian age–depth framework. The resulting model indicates continuous sediment accumulation throughout the Holocene, with no major stratigraphic hiatuses (Figure 2 and 3). Modeled accumulation rates are broadly consistent with regional lacustrine sedimentation rates (Byun *et al*., 2022) and show moderate variability through time, with higher apparent rates in the late Holocene relative to the early–mid Holocene. Age uncertainties increase with depth, as expected, but remain within acceptable limits for centennial- to millennial-scale interpretation. The uppermost sediments correspond to the last ~250–300 calibrated years, providing direct overlap with the short-core chronologies.

*Table 1. Radiocarbon chronology for the Bass Lake (Langman) site, including laboratory ID, depth, material type, conventional radiocarbon age (yr BP), and calibrated 2σ probability ranges (cal yr BP).*

| BETA / Lalonde lab ID# | Depth (cm) | Sample Material | Radiocarbon age (years BP) | 2σ Probability cal age (yr BP) | | |
|---|---|---|---|---|---|---|
| | | | | 1st | 2nd | 3rd |
| UOC-29-240 | 13 | Wood | 100 ± 35 | 268–14 (95.4%) | n/a | n/a |
| UOC-29-241 | 29 | Plant | 200 ± 35 | 306–… (95.4%) | n/a | n/a |
| Beta-664900 | 67 | Plant | 1240 ± 30 | 1192–1070 (55.8%) | 1271–1204 (39.6%) | n/a |
| UOC-29-242 | 90 | Wood | 1340 ± 35 | 1305–1176 (95.4%) | n/a | n/a |
| Beta-664901 | 167 | Plant | 3000 ± 30 | 3255–3073 (86%) | 3330–3293 (9.4%) | n/a |
| UOC-29-243 | 239 | Plant | 4510 ± 40 | 5310–4992 (95.4%) | n/a | n/a |
| Beta-664903 | 442 | Peat | 10020 ± 30 | 11652–11387 (79.4%) | 11381–11324 (8.6%) | 11709–11663 (7.4%) |

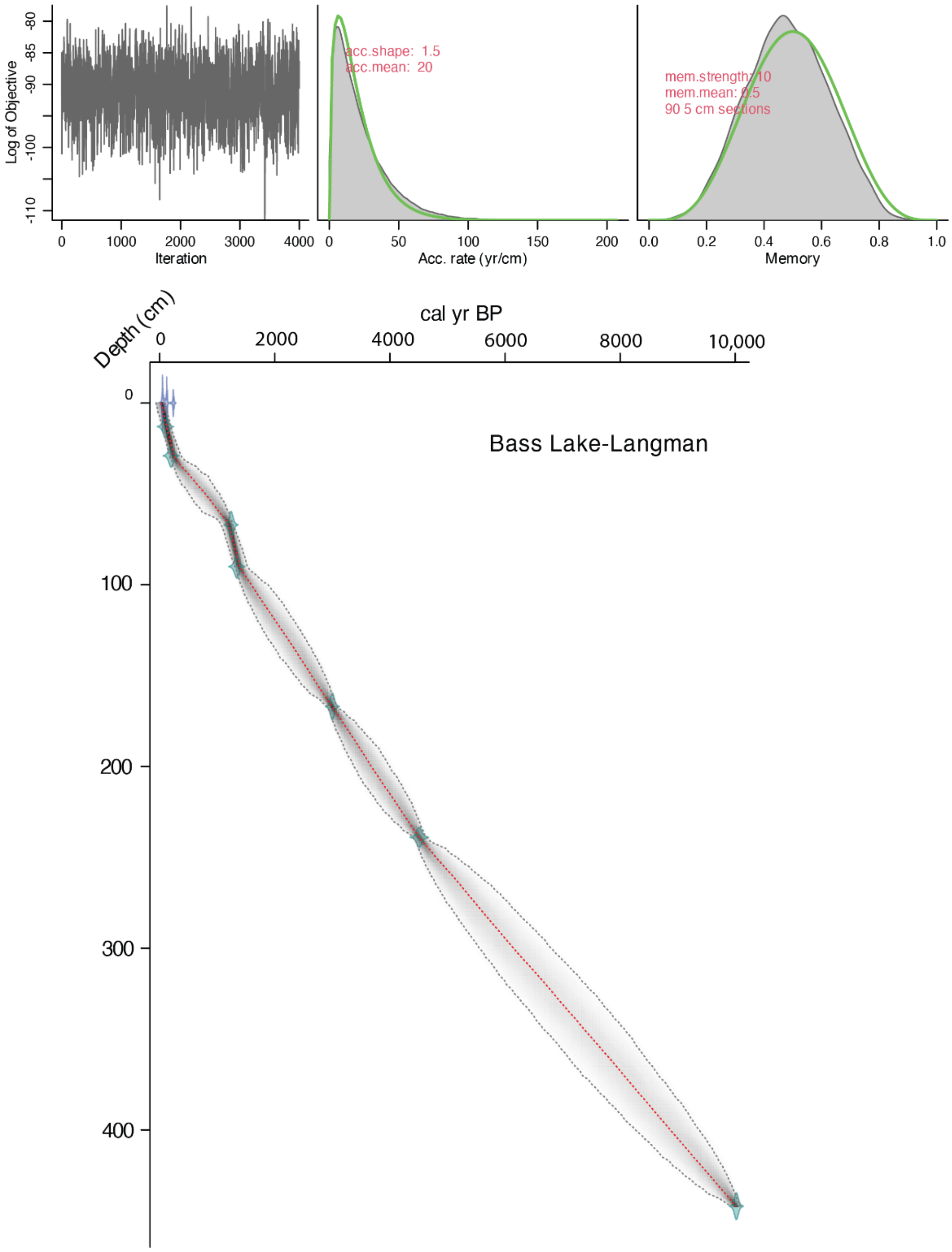

*Figure 2. Age–depth model for the Bass Lake (Langman) sediment core. The upper panels display model diagnostics, including a trace plot of iterations (left) and parameter distributions (Centre and right). The lower panel shows the modelled age-depth relationship with the red line representing the mean modelled age and the grey shading indicating model uncertainty. Blue points represent calibrated radiocarbon ages used to constrain the chronology.*

### *2.8.2. Geochronology of Beaver River*

The Beaver River short core chronology is based primarily on unsupported $^{210}$Pb measurements, supplemented by $^{137}$Cs activity profiles (Table 2, Figure 5). Unsupported $^{210}$Pb inventories were modeled using a constant rate of supply (CRS) approach (Appleby and Oldfield, 1978; Appleby, 2001), generating continuous age–depth relationships for approximately the past 100–150 years. The $^{137}$Cs profile exhibits a distinct mid-20th century activity peak consistent with global atmospheric fallout maxima, providing an independent chronological marker that is in good agreement with the $^{210}$Pb-derived ages (Appleby, 2001). Below the limit of reliable $^{210}$Pb chronology, age control is constrained using stratigraphic markers associated with regional settlement history. In particular, the initial sustained rise in *Ambrosia* pollen (~5%) and associated agricultural indicators beginning at 30 cm-depth is assigned to the period of early Euro-Canadian land clearance in the Beaver River catchment, corresponding to the establishment of timber extraction and agricultural settlement in the mid-19th century (ca. 1830 CE) (Farewell and Fitzgerald, 1887; Johnson, 1997). This pollen-based marker provides a stratigraphic anchor linking the radionuclide chronology to documented historical land-use expansion

*Table 2. Radionuclide-derived chronologies, age–depth relationships, and sedimentation rates for the Beaver River Wetlands, Baileys Ecopark, and Rogers Reservoir sediment cores.*

| Beaver River Wetland core | | | | | | | |
|---|---|---|---|---|---|---|---|
| Depth | | Chronology | | | Sedimentation Rate | | |
| cm | g $cm^{-2}$ | Date AD | Age y | ± | g $cm^{-2}$ $y^{-1}$ | $cm^{-2}$ $y^{-1}$ | ± (%) |
| 0 | 0 | 2017 | 0 | 0 | | | |
| 1 | 0.11 | 2015 | 2 | 2 | 0.053 | 0.58 | 6.6 |
| 3.55 | 0.31 | 2011 | 6 | 2 | 0.036 | 0.38 | 5.4 |
| 5.95 | 0.53 | 2002 | 15 | 2 | 0.018 | 0.15 | 5.5 |
| 8.4 | 0.9 | 1978 | 39 | 3 | 0.013 | 0.09 | 7.2 |
| 9.6 | 1.1 | 1963 | 54 | 5 | 0.013 | 0.07 | 7.2 |
| 10.8 | 1.33 | 1944 | 73 | 8 | 0.013 | 0.06 | 7.2 |
| 13-Jan | 1.93 | 1900 | 117 | 12 | 0.013 | 0.06 | 7.2 |
| 14.1 | 2.08 | 1890 | 127 | 13 | 0.013 | 0.07 | 7.2 |
| 15.75 | 2.53 | | | | | | |
| 18.05 | 3.09 | | Episode of rapid sedimentation | | | | |
| 18.6 | 3.24 | 1880 | 137 | | 0.013 | | |
| 19.2 | 3.36 | 1872 | 145 | 14 | 0.013 | 0.07 | |
| Baileys Ecopark core | | | | | | | |
| 0 | 0 | 2017 | 0 | 0 | | | |
| 0.5 | 0.2 | 2016 | 1 | 0 | 0.2 | 0.44 | 12 |
| 2.5 | 1.1 | 2011 | 6 | 1 | 0.2 | 0.32 | 12 |
| 4.5 | 2.7 | 2004 | 13 | 2 | 0.2 | 0.25 | 12 |
| 6.5 | 4.3 | 1995 | 22 | 3 | 0.2 | 0.24 | 12 |
| 8.5 | 6.1 | 1987 | 30 | 4 | 0.2 | 0.22 | 12 |
| 10.5 | 8 | 1977 | 40 | 5 | 0.2 | 0.22 | 12 |
| 12.5 | 9.8 | 1968 | 49 | 6 | 0.2 | 0.23 | 12 |
| 14.5 | 11.6 | 1959 | 58 | 7 | 0.2 | 0.22 | 12 |
| 16.5 | 13.5 | 1950 | 67 | 8 | 0.2 | 0.19 | 12 |
| 18.5 | 15.7 | 1939 | 78 | 9 | 0.2 | 0.18 | 12 |
| 20.5 | 17.9 | 1928 | 89 | 11 | 0.2 | 0.18 | 12 |
| Rogers Reservoir core | | | | | | | |
| 0 | 0 | 2017 | 0 | 0 | | | |
| 0.65 | 0.47 | 2015 | 2 | 1 | 0.23 | 0.29 | 10.8 |
| 2.75 | 2.25 | 2007 | 10 | 2 | 0.21 | 0.25 | 12.4 |
| 4.7 | 3.89 | 1999 | 18 | 2 | 0.18 | 0.22 | 14.3 |
| 6.55 | 5.33 | 1991 | 26 | 3 | 0.16 | 0.19 | 18 |
| 8.5 | 6.93 | 1980 | 37 | 4 | 0.13 | 0.16 | 18.8 |
| 9.5 | 7.72 | 1972 | 45 | 5 | 0.1 | 0.12 | 22 |
| 10.75 | 8.78 | 1961 | 56 | 6 | 0.1 | 0.1 | 21.4 |
| 13 | 11.03 | 1938 | 79 | 11 | 0.1 | 0.1 | |
| 15.1 | 13.16 | 1916 | 101 | 16 | 0.1 | 0.1 | |

An important feature of both northern records (Bass Lake and Beaver River) is that maximum *Ambrosia* pollen abundance (10–20%) is independently constrained by radiocarbon dating at Bass Lake (Langman) and by radionuclide chronology at Beaver River. At Bass Lake (Langman), the *Ambrosia* increase above 10% falls between 1878 and 1909 CE, while the single peak above 10% at Beaver River is constrained to 1891–1940 CE. These dates are somewhat later than the initial *Ambrosia* rise commonly reported for parts of eastern North America and southern Ontario, where major forest clearance and agricultural expansion often produce ragweed increases during the early to mid-nineteenth century (e.g., McAndrews, 1988; Williams *et al*., 2004). Together, these independently constrained maxima indicate that ragweed thresholds are spatially variable and may lag initial forest clearance in northern basins. The later timing at the northern sites likely reflects delayed and spatially heterogeneous land clearance in the Lake Simcoe north basin.

In contrast, at the two southern sites (Rogers Reservoir and Baileys Ecopark), *Ambrosia* remains a comparatively minor component of the pollen assemblage, while Cerealia, *Taraxacum*, and Poaceae reach substantially higher abundances. This difference suggests that historic land-use in the southern basin is expressed less as a classic ragweed-dominated clearance pulse and more as sustained agricultural and urban disturbance

### *2.8.3. Geochronology of Rogers Reservoir*

The Rogers Reservoir core chronology similarly relies on unsupported $^{210}$Pb measurements modeled using the CRS approach, with $^{137}$Cs activity providing an independent mid-20th century reference horizon (Table 2, Figure 6). The $^{210}$Pb-derived age–depth model indicates rapid sediment accumulation during the twentieth century, consistent with the hydrologically open and highly disturbed character of the site. Below the $^{210}$Pb-supported interval, chronological control is guided by pollen stratigraphy. Here *Ambrosia* pollen never rise above trace levels. Instead, broadly synchronous, sustained appearance and increase of Cerealia and *Taraxacum* pollen is cautiously interpreted to correspond with the expansion of agricultural activity and infrastructure development in the Rogers Reservoir catchment during the early nineteenth century (ca. 1800 CE; Mulvany, 1885 and Armstrong, 1985). This combined radionuclide–pollen framework provides internally consistent age assignments for the historic interval.

### *2.8.4. Geochronology of Baileys Ecopark.*

Chronological control for the Baileys Ecopark core is based on unsupported $^{210}$Pb measurements modeled using the CRS method, supplemented by $^{137}$Cs activity profiles (Table 2, Figure 7). The $^{137}$Cs peak corresponding to mid-20th century fallout is clearly expressed and aligns with the $^{210}$Pb-derived age model, supporting the reliability of the radionuclide chronology for the upper portion of the core.

Below the depth of measurable unsupported $^{210}$Pb (Figure 7), age assignments are more difficult to constrain than at the other sites because pollen markers show inconsistent stratigraphic behavior. Baileys Ecopark therefore provides the weakest pollen-based chronological constraint below radionuclide control. *Ambrosia* pollen occurs continuously at low proportions slightly below the 1927 CE radionuclide date, broadly consistent with maximum *Ambrosia* rise at the northern sites, although overall abundance remains substantially lower. In contrast, increases in Cerealia and *Taraxacum* do not coincide stratigraphically, limiting their utility as precise chronological markers. Together, these signals suggest probable nineteenth-century deposition for the lowest part of the core, consistent with historical records of early settlement in the area (Mulvany, 1885; Armstrong, 1985; Rayburn, 1997).

## *2.9 Palaeoecological Reconstruction*

The Bass Lake record was used to establish long-term baseline conditions and the timing of major land-use transitions, while the three other records which were shorter were evaluated relative to shared historic intervals, particularly the nineteenth and twentieth centuries. This approach allows spatial variability in land-use expression to be assessed without assuming uniform baseline conditions across depositional environments (Sugita, 1994; Nielsen & Sugita, 2005).

Hydrologic context was considered during cross site comparison. Closed basin systems were interpreted as a reflection of local vegetation and disturbance signals, whereas open and fluvially connected systems were expected to integrate broader catchment scale inputs (Jackson, 1990). Differences among sites were therefore evaluated in relation to basin type and land-use context.

### *2.9.1 Bass Lake (Langman): The Holocene Context*

Pollen percentages grouped pollen curves, non-pollen palynomorphs, microscopic charcoal (percentages), principal components analysis (PCA1 axis scores), and diversity indices for the Bass Lake (Langman) core are shown in Figs. 3-4. The record is divided into five local pollen assemblage zones (LPAZ 1–5) based on constrained cluster analysis by sum-of-squares (CONISS), with zones defined as significant clusters using the broken stick method (Grimm, 1987). Results are presented by zone, from oldest to youngest.

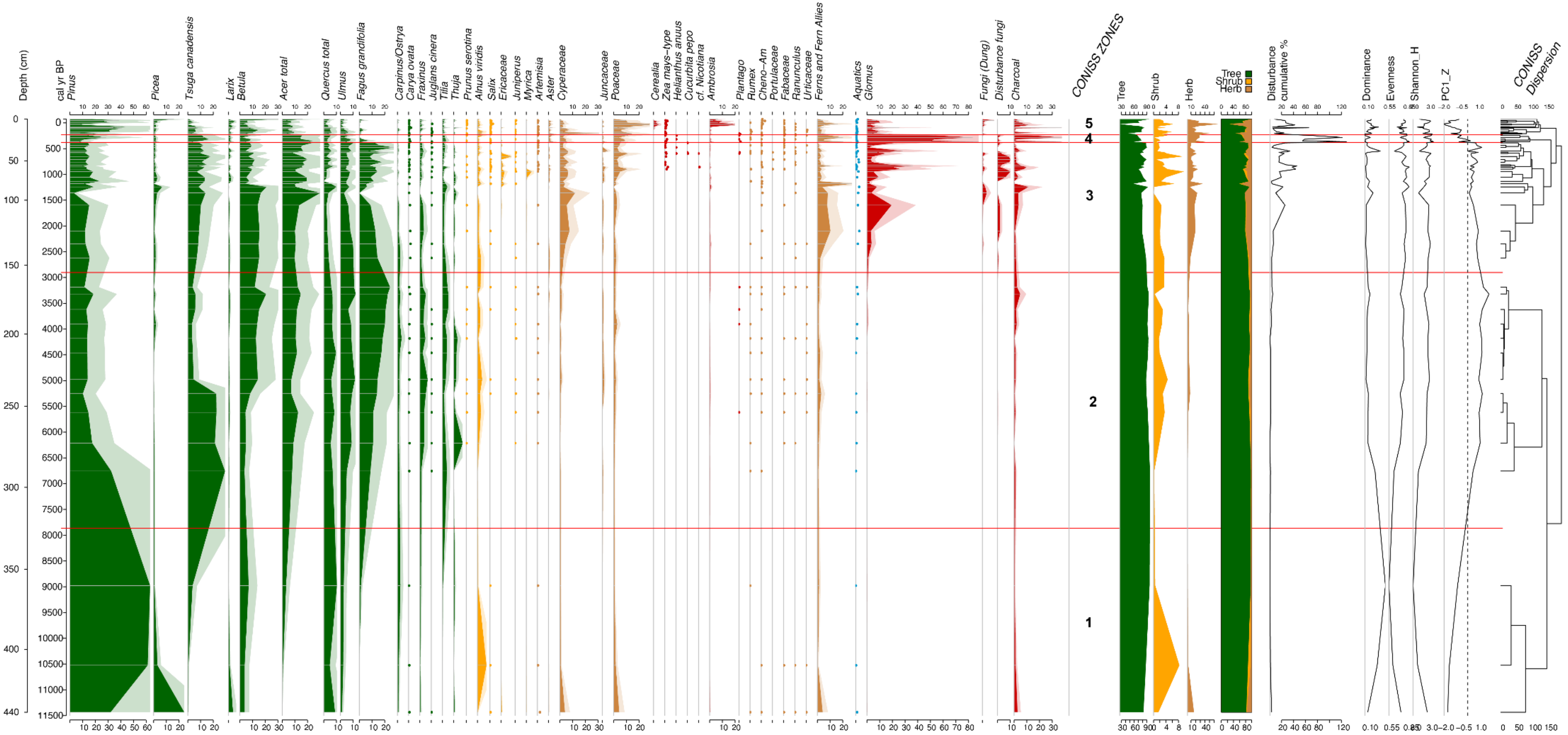

*Figure 3. Holocene multi-proxy diagram (pollen, plant spores, fungal spores, and charcoal accumulation rates) for the Bass Lake (Langman) core plotted against radiocarbon calibrated age estimates (cal yr BP), including derived diversity indices and principal component axis (PCI) scores. Stratigraphic zones are defined using constrained hierarchical clustering by incremental sum-of-squares (CONISS) with significant clusters isolated using the Broken stick method (Grimm, 1987) All statistical analysis and diagram production were performed in R (R Core Team, 2025). Stratigraphic plotting and zonation were implemented using the riojaPlot and rioja packages (Juggins, 2024, 2025) while ordination and diversity metrics were calculated using the vegan package (Oksanen, et al, 2024).*

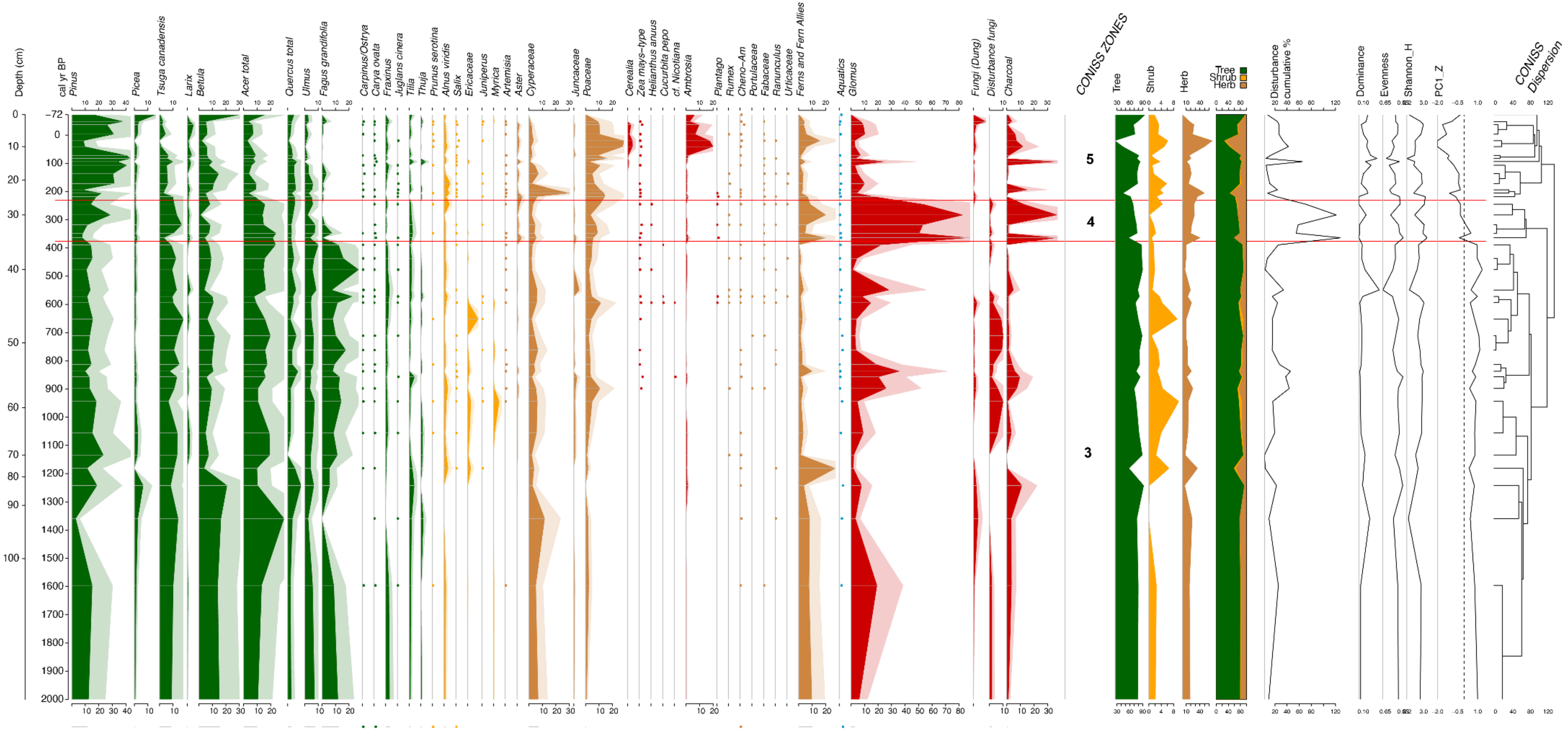

*Figure 4. Late Holocene (last 2,000 years) multi-proxy diagram (pollen, plant spores, fungal spores, and charcoal accumulation rates) for the Bass Lake (Langman) core plotted against radiocarbon calibrated age estimates (cal yr BP), including derived diversity indices and principal component axis 1 (PC1) scores. Stratigraphic zones are defined using constrained hierarchical clustering by incremental sum-of-squares (CONISS) with significant clusters isolated using the Broken stick method (Grimm,1987). All statistical analysis and diagram production were performed in R (R Core Team, 2025). Stratigraphic plotting and zonation were implemented using the riojaPlot and Rioja packages (Juggins, 2024, 2025) while ordination and diversity metrics were calculated using the vegan package (Oksanen, et al, 2024).*

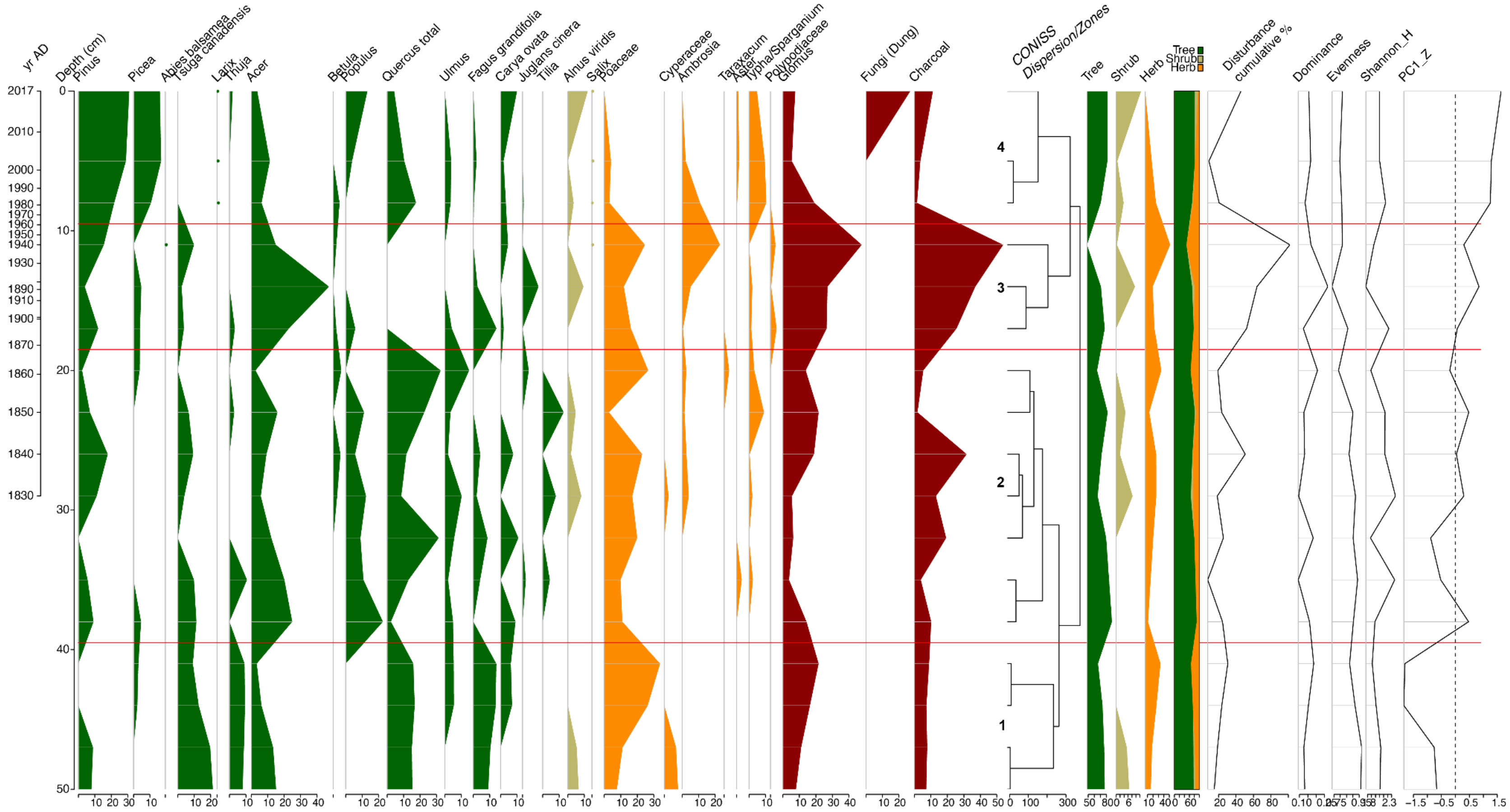

*Figure 5. Multi-proxy diagram for the Beaver River Wetlands core (pollen, plant spores, fungal spores, and charcoal accumulation rates) plotted against age (210Pb-137Cs and biostratigraphic marker chronology in years CE), including derived diversity indices and principal component axis 1 (PC1) scores. Stratigraphic zones are defined using constrained hierarchical clustering by incremental sum-of-squares (CONISS) with significant clusters isolated using the Broken stick method (Grimm,1987). All statistical analysis and diagram production were performed in R (R Core Team, 2025). Stratigraphic plotting and zonation were implemented using the riojaPlot and Rioja packages (Juggins, 2024, 2025) while ordination and diversity metrics were calculated using the vegan package (Oksanen, et al, 2024).*

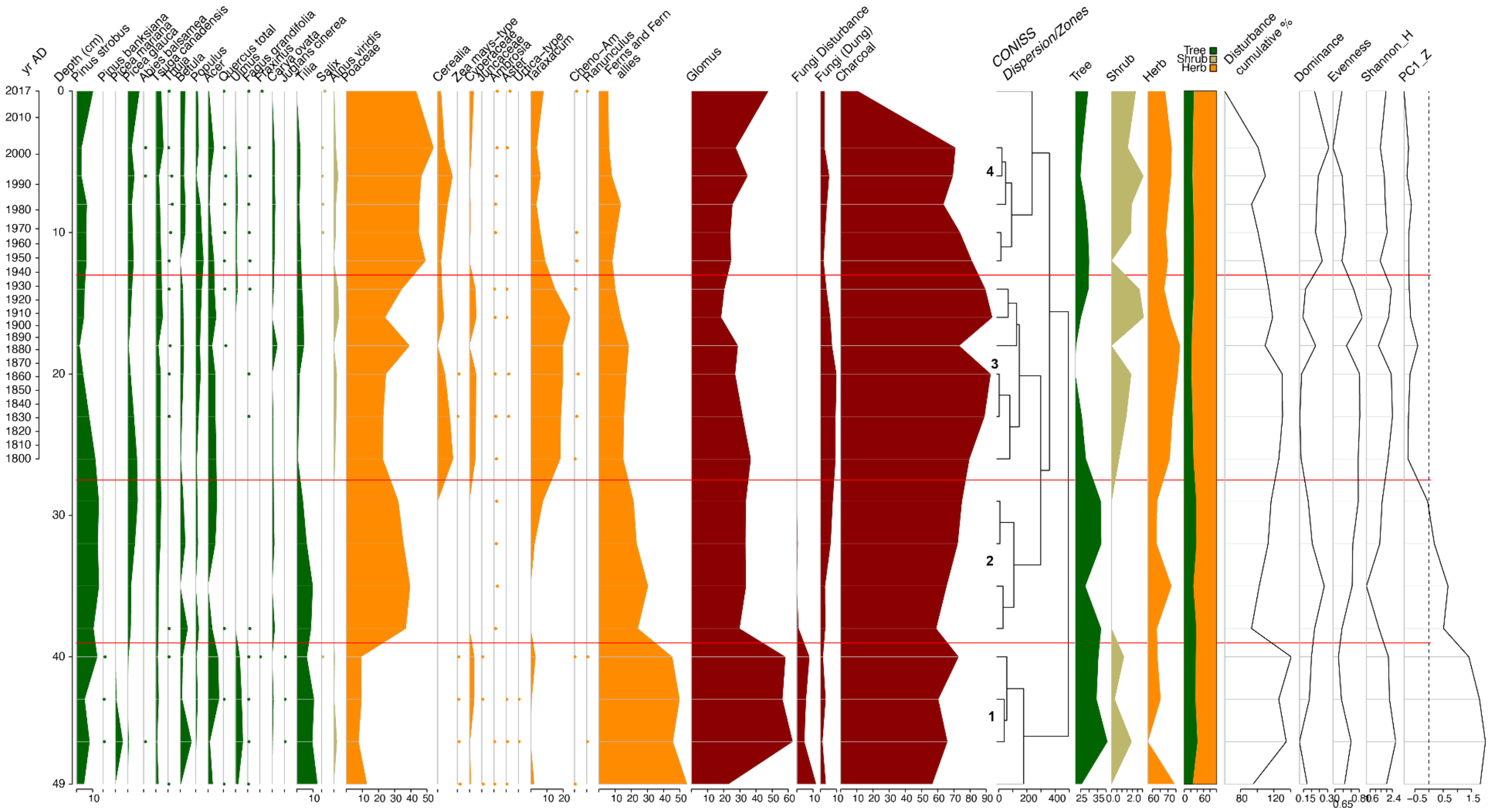

*Figure 6. Multi-proxy diagram for the Rogers Reservoir core (pollen, plant spores, fungal spores, and charcoal accumulation rates) plotted against age (210Pb-137Cs and biostratigraphic marker chronology in years CE), including derived diversity indices and principal component axis 1 (PC1) scores. Stratigraphic zones are defined using constrained hierarchical clustering by incremental sum-of-squares (CONISS) with significant clusters isolated using the Broken stick method (Grimm,1987). All statistical analysis and diagram production were performed in R (R Core Team, 2025). Stratigraphic plotting and zonation were implemented using the riojaPlot and Rioja packages (Juggins, 2024, 2025) while ordination and diversity metrics were calculated using the vegan package (Oksanen, et al, 2024).*

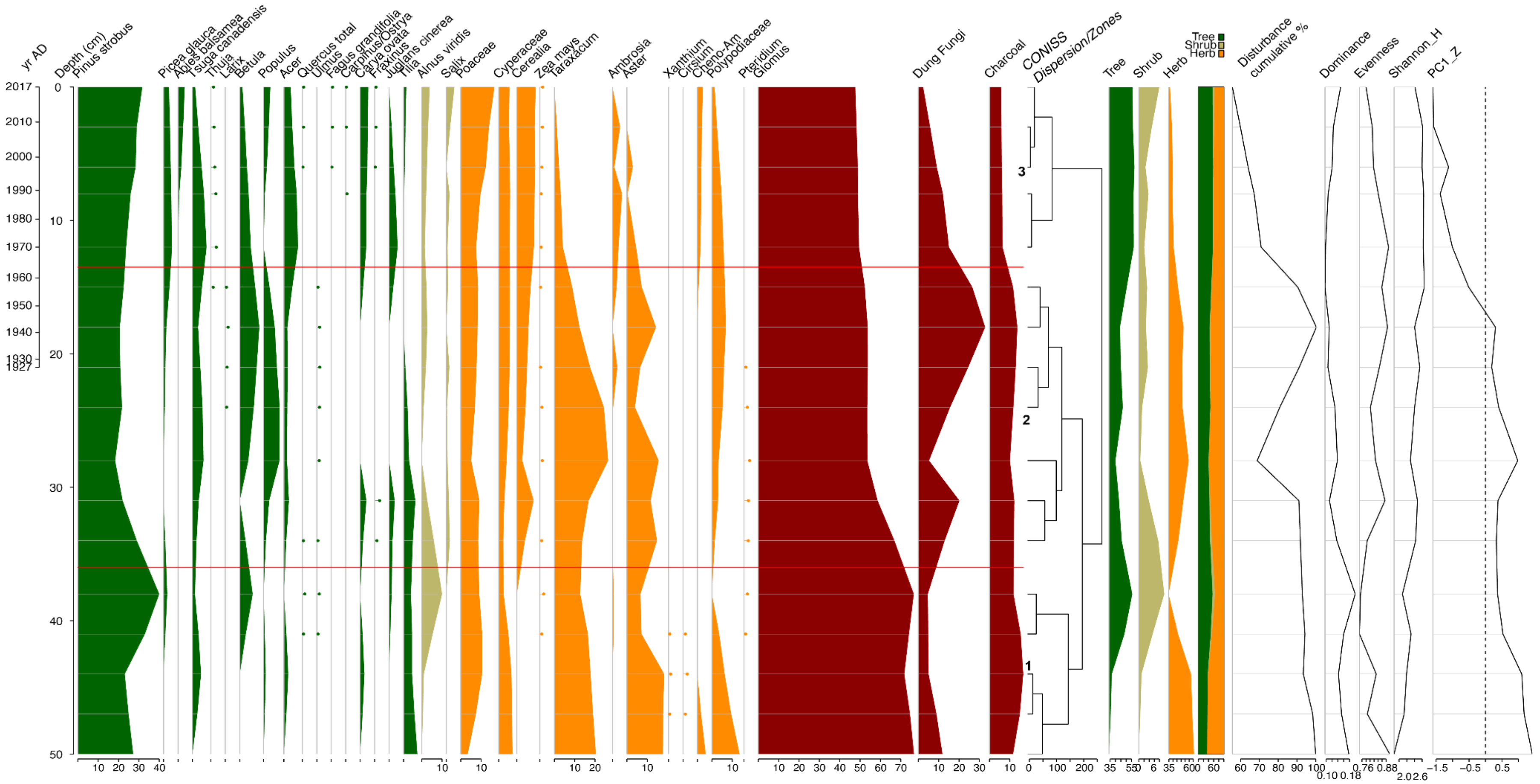

*Figure 7. Multi-proxy diagram for the Baileys Ecopark core (pollen, plant spores, fungal spores, and charcoal accumulation rates) plotted against age (210Pb-137Cs chronology in years CE), including derived diversity indices and principal component axis 1 (PC1) scores. Stratigraphic zones are defined using constrained hierarchical clustering by incremental sum-of-squares (CONISS) with significant clusters isolated using the Broken stick method (Grimm,1987). All statistical analysis and diagram production were performed in R (R Core Team, 2025). Stratigraphic plotting and zonation were implemented using the riojaPlot and Rioja packages (Juggins, 2024, 2025) while ordination and diversity metrics were calculated using the vegan package (Oksanen, et al, 2024).*

#### *2.9.1.1 LPAZ 1 (ca. 11,400-7,800 cal years BP) (Figure 3)*

Zone 1 is characterized by increasing arboreal pollen (AP), from 77% at the beginning of this zone to almost 100% at the end. The arboreal assemblage is dominated by *Pinus* (30 to 60%), while *Picea* declines from a co-dominant status (~25%) at the beginning of the zone to background levels thereafter. *Tsuga canadensis* pollen appears ca 10,000 cal years BP, reaching ~8% at the end of this zone. Among hardwoods, only *Quercus* maintains sustained abundances (~10%), followed by *Ulmus* and *Carpinus/Ostrya* (<5%), and towards the end of the zone, by *Fagus grandifolia* and *Acer* (5-10%). Non-arboreal pollen (NAP) values are highest at the beginning of the zone (~15%) and are composed primarily of Poaceae and Cyperaceae. Minor taxa not presented in the diagram and a series of forbs collectively reach up to 10% of the spectra. Disturbance-associated elements (*Ambrosia*, *Glomus* spores, and microscopic charcoal) occur at very low or trace levels. PCA1 scores remain strongly negative throughout Zone 1. Increasing dominance values and decreasing evenness and Shannon's indexes characterize zone 1, mirroring the increasing role of *Pinus* pollen in the zone 2 assemblage.

#### *2.9.1.2 LPAZ 2 (ca. 7,800 to 1,900 cal years BP) (Figures 3-4)*

Within Zone 2, CONISS revealed two non-significant subclusters (LPAZ2a and LPAZ2b) featuring two relatively different plant communities. In the LPAZ2a (ca. 7,800 to 5,000 cal years BP), the *Pinus* pollen decreases progressively but dramatically from 60% in zone 1 to ~15% at the end of LPAZ2a, with concomitant increases in pollen from *Tsuga canadensis* and a variety of hardwoods such as *Acer, Quercus, Fagus grandifolia, Ulmus, Fraxinus, Betula*, and *Tilia*. A small but non-trivial shrub component (*Alnus viridis*-type) adds to the complexity of the woody pollen spectra during this time. Herbaceous taxa pollen is rare (trace levels), although it increases to above trace levels (~3-5%) at the end of LPAZ2a. In the LPAZ2b subcluster, although pollen taxa composition remains the same, the relative abundance of taxa changes in one significant way: *Tsuga canadensis* declines considerably being replaced primarily by increasing values of pollen from *Betula*, *Fagus grandifolia* and, to a lesser extent *Ulmus*. All other taxa abundances remain broadly similar to those of LPAZ2a. Disturbance indicators (*Glomus* and charcoal) are largely absent or at trace levels throughout this zone, except towards the end (after 3,500 cal years BP) when they increase slightly.

The PCA 1 scores of Zone 2 mirror the broad vegetational change from the *Pinus*-dominated forest to a mixed assemblage of *Tsuga canadensis* and hardwoods with a switch from weakly negative loadings at the beginning of LPAZ2 to positive loadings thereafter. The declining role of the *Pinus* pollen, concomitant with the rise of a diverse assemblage drive diversity indexes in Zone 2, with dominance rapidly decreasing at the beginning of this zone, in parallel with an increasing evenness and Shannon’s values.

#### *2.9.1.3 LPAZ 3 (ca. 1,900 to 400 cal years BP) (Figure 4)*

Compared to Zone 2, the pollen assemblage of Zone 3 is defined by several major palynological changes. First, herbaceous taxa increase substantially (from ~5 to maximum 34%), led by increases in Cyperaceae, Poaceae, and Ferns and Fern allies. In the first half of this period, the tree pollen assemblage features a resurgence of *Tsuga canadensis* largely concomitant with a progressive decline in *Ulmus*, *Quercus*, and *Fagus grandifolia*. In the second half of this period (after ca. 1,350 cal years BP), *Fagus grandifolia* and *Acer* pollen exhibit increasing abundance, this time to the detriment of *Betula*, which declines sharply between ca. 1,350 and 1,150 cal years BP (ca. 700 CE). Shrub pollen (mainly *Alnus viridis*-type, Ericaceae, and *Salix*) increased as well, following the same *Betula* decline.

In addition to the *Betula* decline, the pollen assemblages during the interval ca. 1,350 to 1150 cal years BP (700-900 CE) show two short-lived developments that are noteworthy. At ca. 1,350 cal years BP, *Pinus* pollen declines considerably (<3%; the only time this taxon declines below 10%) together with a decline in *Fagus grandifolia*, which briefly becomes palynologically invisible. This shift seems to be associated with a rise in *Acer* and Cyperaceae, all other taxa remaining relatively unchanged. This is followed, at ca 1,150 cal years BP by the first Holocene decline in tree pollen below 60% (most taxa, but particularly *Betula*), corresponding with a sharp rise in fern spores and shrub pollen.

One of the most important palynological elements of this zone is the appearance of clear signs of cultivar pollen, namely maize (*Zea mays*-type) and squash (*Cucurbita pepo*) beginning at ca. 900 cal years BP (1,050 CE). These elements are associated with a variety of disturbance indicators such as higher charcoal influx, coprophilous fungi, plant parasites (e.g., *Ustilago mayidis*-type, *Pseudoperonospora cubensis*-type, *Alternaria helianthi*-type ), and particularly *Glomus* and other soil erosion fungi (e.g., type UAB30 B).

Throughout Zone 3, PCA1 values remain positive and relatively stable but show increased short-term variability. Diversity indices are relatively stable throughout this zone except for two episodes of increased dominance and decreased evenness and Shannon's, at ca. 1,350 and 600 cal years BP, respectively.

#### *2.9.1.4 LPAZ 4 (ca. 400 - 250 cal years BP) (Figure 4)*

Zone 4 is marked by a pronounced reorganization of the pollen assemblage. Arboreal pollen declines to ~60, coincident with a severe reduction in *Fagus grandifolia* and to a lesser extent *Acer.* The tree decline is mirrored by a rise in ferns, fern allies and grasses, as well as a

Holocene maximum in disturbance indicators, mainly charcoal and *Glomus* spores. PCA1 scores turn negative during this zone, while diversity indices remain relatively unchanged compared to zone 3.

#### *2.9.1.5 LPAZ 5 (ca. 250 cal years BP to Present) (Figure 4)*

The local pollen assemblage Zone 5 starts ca. 1,700 CE and represents the last stage in the development of the local environment of the Bass Lake (Langman) area. The period debuts with a decline in arboreal pollen below 50% at ca. 200 cal years BP (1750 CE), a first in the site's Holocene history, followed by a recovery until the period between the two World Wars (ca. 20 cal years BP or 1930 CE), when it sharply deepens to ~20%. The relative abundance of tree pollen covaries tightly with that of herbs, primarily *Ambrosia* (which reaches ~20%), Poaceae (up to 30%), ferns and fern allies (up to 15%). Sustained high *Ambrosia* abundance, starting ca. 40 cal years BP (beginning of the 20th century), corresponds with the first Cerealia pollen above trace levels. Disturbance indicators such as Glomus spores and charcoal decrease substantially compared to zone 4 but remain at relatively elevated levels. The last three decades of the site's history are defined by a dramatic increase in tree pollen and a decrease in herbs and disturbance indicators.

PCA1 values decline to strongly negative values towards the beginning of the 20th century but increase to near 0 at present. Diversity indices are variable and show a slightly increased dominance and lower evenness and Shannon's compared to Zone 4.

In summary, the Bass Lake (Langman) record documents a long interval of Holocene forest dominance characterized by high arboreal pollen and warm-affiliated hardwood taxa (Zones 1–3), followed by two intervals of increased openness and disturbance (Zones 4 and 5). These shifts are expressed consistently across pollen percentages, grouped taxa, PCA1 trajectories, and diversity indices, with the most abrupt and sustained changes occurring in the uppermost zone.

## *2.10 European Land-use Signals Across Sites (last ~300 years)*

Pollen percentages, grouped pollen curves, non-pollen palynomorphs, microscopic charcoal (percentages), PCA1 trajectories, and diversity indices for the three short cores are shown in Figs. 5-7. For consistency with the Bass Lake (Langman) record, results are presented by site and by significant pollen assemblage zones, focusing on the historic interval spanning approximately the last 250–300 years.

### *2.10.1 Beaver River (BRWTHS; Simcoe North, Rural)*

The Beaver River record is divided into four principal pollen zones spanning the early 19th century to the present.

#### *2.10.1.1 LPAZ 1 (below 39 cm; Pre-European/Contact) (Figure 5)*

The lower zone is characterized by high arboreal pollen (AP), generally ranging between ~65 and 75%. Assemblages are dominated by a mixed conifer–hardwood forest with *Tsuga canadensis, Quercus, Fagus grandifolia, Acer,* and *Thuja*, as the most palynologically visible taxa. *Pinus* is a minor component, accounting for <10% of the pollen sum. Herbaceous pollen varies between 15 and 30%, comprising grasses (Poaceae) and to a lesser extent *Cyperaceae. Alnus viridis-type* (shrub) reaches ~7% in the first half of this zone. Among the disturbance indicators, *Glomus* spores follow broadly the Poaceae curve, while charcoal concentration is low throughout. PCA1 scores are moderately to strongly negative in this zone, while the diversity indices display low dominance, high evenness and moderate Shannon's diversity.

#### *2.10.1.2 LPAZ 2 (Contact to ca. 1,870 CE) (Figure 5)*

Zone 2 is characterized by high arboreal pollen (AP), generally ranging between ~70 and 85%. Assemblages are dominated by a mixed conifer–hardwood forest with *Quercus*, *Acer,* and *Populus,* with *Fagus grandifolia, Tsuga canadensis, Thuja*, and *Carya* playing low or diminishing roles. *Pinus* rises briefly to 20% ca 1840 CE but is largely <10% of the pollen sum.

Non-arboreal pollen (NAP) values are generally <20%, with Poaceae as the only major, continuous herb signal. *Ambrosia* pollen appears and displays a low (<5%) but continuous signal beginning with the depth of 30 cm, which is tentatively dated as 1,830 CE based on records of the first substantial European presence and activity in the Beaver River Basin (Farewell and Fitzgerald, 1887; Johnson, 1997). Disturbance indicators (*Glomus* spores and charcoal) are generally low, although charcoal increased slightly during the early 1800s. PCA1 scores vary around the zero mark, while diversity indices are more variable but broadly unchanged relative to Zone 1.

#### *2.10.1.3 LPAZ 3 (ca. 1,870 CE – 1,960 CE) (Figure 5)*

The third zone records a decline in arboreal pollen from ~80 to 45%, accompanied by an increase in herbaceous pollen to ~25–40%, with a maximum above 50% during the period between the two World Wars. Poaceae remain the dominant herb taxa throughout except during the same inter-World Wars period when *Ambrosia* reaches a maximum of 23% of the pollen sum. The arboreal pollen assemblage is characterized by a substantial transformation compared to zones 1 and 2 mixed forest, with *Acer* the most abundant taxa, particularly at the turn of the 20th century. Disturbance indicators (*Glomus* spores and charcoal) reached an all-time high during the Second World War, corresponding with the rise in herbs and particularly the ruderal *Ambrosia*.

PCA1 scores shift from zero at the beginning of the zone to slightly positive values at the end of the zone. Diversity indices indicate marginal changes compared to Zone 2, although an increase in dominance and decrease in evenness are obvious after 1,900 CE.

#### *2.10.1.4 LPAZ 4 (ca. 1,960 CE to Present) (Figure 5)*

The uppermost local pollen zone corresponds to the last several decades and is defined by a substantial recovery of the arboreal pollen assemblage from 50% in zone 3 to 80% at present. *Pinus* (25-30%) and *Picea* (~10%) are the dominant taxa, followed by several broadleaves such as *Quercus, Acer, Populus* and *Carya,* all at or below 5%. The previously dominant herbs (Poaceae and *Ambrosia*) decline to trace levels, while the emergent aquatic Typha/Sparganium reaches a maximum proportion during this period. Disturbance indicators are very low except in the surface sample, where coprophilous fungi reach a high concentration.

PCA1 scores become strongly positive in this zone mirroring the rise in arboreal pollen. Diversity indices are less variable than in Zone 3, with a decreased dominance and an increase in Shannon's index.

### *2.10.2 Rogers Reservoir (RRR; Simcoe South, Peri Urban Riparian)*

The Rogers Reservoir record is divided into four significant local pollen zones spanning at least the last 250 years.

#### *2.10.2.1 LPAZ 1 (Pre-European/Contact) (Figure 6)*

Zone 1 is characterized by relatively low arboreal pollen (AP) values, typically ~25–35%, although the upper value represents maximum AP recorded at this site. The AP spectra is dominated by *Tilia, Acer*, and *Pinus*, as well as minor taxa such as *Ulmus*, *Betula*, and *Tsuga canadensis,* just slightly above trace levels. Herbaceous taxa dominate the assemblage, largely comprising fern and fern allies spores (40-50%) with Poaceae as a secondary taxa group (<15%). Disturbance indicators such as charcoal, *Glomus* and other fungal spores with disturbance affinities (*Alternaria, Ustilago*-type, type UAB30 A and B) reach high values although ruderal taxa such as *Ambrosia* and *Taraxacum* appear only at trace or very low values.  PCA1 values are near zero to moderately positive. Diversity indices show reduced dominance, moderate evenness, and high Shannon's.

#### *2.10.2.2 LPAZ 2 (Pre-European/Contact) (Figure 6)*

Zone 2 starts with a sharp rise in Poaceae (from 10 to ~40%) pollen concomitant with a decrease of similar magnitude in ferns and fern allies. Arboreal pollen abundance remains the same as in  Zone 1, although the assemblage structure shows a higher abundance of conifers (mainly *Pinus* and *Picea*) to the detriment of *Tilia*, which decreases from 10% to ~3% at the end of the zone. Disturbance indicators are marginally less abundant than zone 1, mainly due to a reduction in Glomus, while charcoal abundance shows progressively increasing concentration within this zone. A noteworthy appearance at the end of this zone is the ruderal *Taraxacum* pollen (~3-7%). PCA1 scores decrease from strongly positive in zone 1 to ~0 at the end of zone 2. Diversity indices show an increased dominance and evenness, but a decreased Shannon's index compared to Zone 1.

#### *2.10.2.3 LPAZ 3 (ca. 1,800 to 1,940 CE) (Figure 6)*

Zone 3 is defined by a substantial reduction in arboreal pollen (the only period below 25%) concomitant with a rise in herbs to a maximum of 75% at the end of the 19th century CE. The herb assemblage is dominated by Poaceae and *Taraxacum* as co-dominants (~20% each), followed by ferns and fern allies, and Cyperaceae. A significant development in this zone is the appearance of a quasi-continuous Cerealia signal, which rises to 5-10% of the pollen spectra. Arboreal pollen taxa remain largely the same as in Zone 2, although with the exception of *Pinus*, none rise above 5%. Shrubs (*Alnus viridis*-type) rise above trace levels in this zone. Disturbance indicators increase in this zone compared to Zone 2, mostly because of a substantial rise in charcoal and to a lesser extent, of coprophilous fungi. PCA1 scores turn negative in this zone while diversity indices show an increased evenness and Shannon's index, but a decreased dominance compared to Zone 2.

#### *2.10.2.4 LPAZ 4 (ca. 1,940 CE to present) (Figure 6)*

The last local pollen zone at Rogers Reservoir is defined by a slight recovery in arboreal pollen (25-35%), with relative proportions of tree taxa largely unchanged compared to zone 3. The rise in tree pollen is mirrored by a slight decline in herbs, which display a relative abundance shift with Poaceae now the only dominant taxa group while the ruderal *Taraxacum* declines to <10%. Disturbance indicators decline relative to Zone 3, driven primarily by a marked reduction in charcoal concentrations, which decrease from approximately 90% at the end of Zone 3 (ca. 1930s CE) to 10% or less during the past decade.

### *2.10.3 Baileys Ecopark (BEP; Simcoe South, Urban)*

The BEP core is divided into three local pollen zones (significant clusters) spanning the late 18th century to the present.

### *2.10.3.1 LPAZ 1 (before 1,800 CE) (Figure 7)*

The lowermost zone is characterized by high non-arboreal pollen (~65%) in the first half of the zone, after which it declines to 35% concomitant with a rise in tree and shrub pollen. Taraxacum, Aster, and Poaceae are the dominant herbs (10-20% each), followed by ferns and Cyperaceae, typically below 10%.

*Pinus* is the dominant arboreal taxa followed by *Tilia* (5-10%) and minor taxa (e.g., *Tsuga* canadensis, *Betula*), typically <5%. Disturbance indicators are very high, led by very high abundance of *Glomus* spores and a moderate abundance of charcoal. PCA1 values vary from strongly to marginally positive loadings, while diversity indices show minimum Shannon diversity and relatively high dominance.

### *2.10.3.2 LPAZ 2 (ca. 1,800 to 1,965 CE) (Figure 7)*

The second pollen zone at Baileys Ecopark is defined by a slightly lower arboreal component (~40–55%) compared to the end of Zone 1 comprising a diminished *Pinus* abundance and higher proportions of *Betula, Populus*, and *Tsuga canadensis*, all between 5 and 10%. *Tilia* pollen, an important part of the arboreal spectra in zone 1, becomes palynologically invisible after 1950 CE. The non-arboreal pollen represents ~50% of the pollen spectra, being dominated by Taraxacum (15-25%) and Aster (5-20%). The signature palynological signal in Zone 2 is the appearance of Cerealia pollen (5-8%) and a continuous *Ambrosia* signal, above trace levels. Disturbance indicators abundance remains elevated with lower Glomus but much higher coprophilous fungi proportions compared to Zone 1. PCA1 scores decline from marginally positive in the first half of this period to negative loadings at the end. Evenness and Shannon’s indices increase slightly compared to Zone 1, while dominance is lower.

#### *2.10.3.3 LPAZ 3 (ca. 1,965 CE to Present) (Figure 7)*

During the last several decades, the arboreal pollen assemblage has increased considerably (60-65%), being dominated by *Pinus* (20-30%) and a mix of minor conifers (*Tsuga canadensis* and *Picea*) and hardwoods (e.g., *Acer*, *Betula, Carya*). The herbaceous component declines but remains important (35-45%) and is now dominated by Poaceae, Cerealia, and *Cyperaceae*, while the previously dominant *Taraxacum* and *Aster* all but disappear. Shrub pollen (*Alnus viridis*-type and *Salix*) increased to ~5%. Disturbance indicators decline to a minimum for this site, led by sharply declining coprophilous fungi and lower charcoal. PCA1 shows a strong and sustained negative loading. Diversity indices are broadly similar to those of Zone 2 although there is a moderate increase in dominance and a decrease in evenness towards the surface.

### *2.10.4 Synthesis of European Land-use Signals Across Sites*

In summary, across the four sites, historic landscape change is expressed consistently through shifts in arboreal and non-arboreal pollen proportions, increases in ruderal and disturbance-associated taxa, and parallel changes in non-pollen palynomorphs, charcoal, ordination structure, and diversity metrics. Taken together, these records document a basin-wide transition toward increased landscape openness and disturbance during the nineteenth and early twentieth centuries, with the timing, magnitude, and persistence of this transition varying among sites.

In the northern basin, both Bass Lake (Langman) and Beaver River record marked historic departures from forest-dominated conditions, but with contrasting expressions. At Bass Lake (Langman), the European-period interval (ca. AD 1750–present) is characterized by a sustained decline in arboreal pollen relative to its Holocene baseline, elevated *Ambrosia* and Poaceae, increased disturbance indicators, and strong multivariate reorganization. In contrast, Beaver River retains higher arboreal pollen through the early historic period, with a more abrupt and temporally constrained disturbance peak centred on the late nineteenth to mid-twentieth centuries, followed by substantial late-century arboreal recovery.

In the southern basin, both Rogers Reservoir and Baileys Ecopark record persistently open landscapes throughout much of their sequences, with strong dominance of herbaceous taxa and pronounced expression of ruderal and agricultural indicators. At Rogers Reservoir, sustained herb dominance and quasi-continuous Cerealia characterize much of the nineteenth and early twentieth centuries, whereas Baileys Ecopark records a highly disturbed urban assemblage marked by shifting dominance among herb taxa, strong fungal and charcoal signals, and partial reorganization in the late twentieth century.

Across all sites, PCA1 trajectories capture major assemblage reorganizations within each record rather than absolute disturbance intensity, while diversity indices respond most strongly at sites with pronounced herb dominance and taxonomic homogenization. Diversity metrics respond most strongly where herb dominance produces compositional homogenization. Collectively, the four records provide complementary perspectives on historic land-use change across the Lake Simcoe basin, setting the stage for interpretation of spatial gradients and legacy effects.

## *2.11 Discussion*

### *2.11.1 Northern basin: Urban Versus Rural Expressions of European Land-use*

Comparison of the two northern records highlights strong contrasts between urban-proximal and rural landscape histories. At Bass Lake (Langman), European-period land-use produced the most pronounced and persistent reduction in arboreal pollen observed in the entire Holocene sequence (Fig. 2), accompanied by sustained increases in herbaceous and ruderal taxa, disturbance fungi, charcoal, and multivariate variability. This signal reflects a prolonged departure from pre-contact conditions, extending well beyond the period of maximum disturbance into the late twentieth century. In contrast, the Beaver River record preserves a more muted and temporally constrained disturbance signature (Fig. 5). Although the late nineteenth to mid-twentieth centuries are marked by strong *Ambrosia* maxima and elevated charcoal and Glomus, arboreal pollen recovers rapidly after ca. AD 1960, returning to levels comparable to the early historic period. This divergence suggests that, within the northern basin, proximity to population centers and sustained landscape modification exerted a stronger influence on long-term ecological trajectories than did agriculture alone. Importantly, Bass Lake (Langman) also records low abundance but repeated occurrences of cultigen indicators during the late pre-contact interval (Fig. 3), a signal absent from Beaver River. While these occurrences remain below conventional percentage thresholds, their stratigraphic coherence suggests that Bass Lake (Langman) integrates localized Indigenous land-use activities that are not captured in the rural fluvial setting. The Beaver River served as part of Huron-Wendat trade and travel networks linking Lake Simcoe to Georgian Bay, with less intensive settlement focused on fishing and mobility rather than villages, enabling quicker post-disturbance recovery (Trigger, 1976; Heidenreich, 1973). Archaeological evidence shows minimal village sites here compared to Bass Lake's proximity to horticultural zones near Oro-Medonte (Warrick, 2008). Rapid arboreal recovery aligns with 1920s Simcoe County reforestation to stabilize soils (Bowley, 2015). Hydrological connectivity in the Beaver wetland likely diluted signals relative to Bass Lake's closed basin (LSRCA, 2023a).

### *2.11.2 Southern basin: Persistence and Amplification in Open, Connected Systems*

The two southern records reflect landscapes that were already open or highly modified at the onset of the historic period, but they differ in how disturbance signals are amplified and reorganized through time. At Rogers Reservoir, sustained herb dominance and continuous agricultural indicators point to a catchment-integrating system that records prolonged and spatially extensive land-use (Fig. 6). The persistence of Cerealia and high herbaceous proportions through much of the nineteenth and early twentieth centuries suggests limited buffering by arboreal cover. Baileys Ecopark, by contrast, records a strongly urbanized disturbance regime characterized by rapid shifts among dominant herb taxa, extreme values of disturbance fungi, and marked changes in charcoal abundance (Fig. 7). Although arboreal pollen increases in the late twentieth century, the assemblage does not return to a pre-disturbance structure, indicating reorganization rather than recovery. Together, the southern records illustrate how hydrologic connectivity and urban infrastructure can amplify and prolong disturbance signals, even in small basins, producing pollen assemblages that differ fundamentally from those observed at rural or closed northern sites. Rogers Reservoir's position along the Holland River allows it to integrate sediment and pollen inputs from a broad upstream catchment shaped by nineteenth-century wetland drainage and sustained agricultural land-use, reinforcing prolonged and spatially extensive disturbance signals within the record (LSRCA, 2013; Johnson, 1997). In contrast, Baileys Ecopark reflects a disturbance regime driven by localized urban development within the East Holland River corridor in Newmarket, where twentieth-century land clearing, infrastructure expansion, and episodic burning contributed to elevated charcoal inputs and rapid shifts in herbaceous taxa (LSRCA, 2013). Although recent restoration initiatives correspond with modest increases in arboreal pollen, the assemblage remains structured by persistent soil disturbance and urban legacy effects rather than true ecological recovery (Bowley, 2015). The long-standing openness of the southern basin is further rooted in pre-contact Huron-Wendat river-valley use for trade, travel, and fishing, which preconditioned these landscapes prior to Euro-Canadian settlement (Williamson, 2010).

### *2.11.3 North–South Gradients and the Limits of Baseline Transferability*

Taken together, the four records demonstrate a pronounced north–south gradient in the expression of historic land-use impacts across the Lake Simcoe basin. Northern sites retain clearer forested baselines and express disturbance as deviations from those baselines, whereas southern sites record persistently open conditions in which disturbance is expressed primarily through changes in herb composition, dominance, and associated non-pollen indicators. These contrasts underscore the importance of spatial context when interpreting palaeoecological baselines. While the Bass Lake (Langman) record provides a robust long-term reference for distinguishing Indigenous-era variability from Euro-Canadian disturbance (Fig. 2), its European-period trajectory is not directly transferable to either rural northern or southern urban systems. The nested design adopted here demonstrates that combining long temporal records with spatially distributed historic cores is essential for resolving how land-use intensity, settlement history, and basin characteristics interact to shape ecological legacies.

The gradient reflects Huron-Wendat settlement concentration in the north around Lake Simcoe (Warrick, 2008). Trade routes via the Beaver and Holland Rivers connected sites to Georgian Bay, influencing pollen sources (Heidenreich, 1973). Southern proximity to Lake Ontario networks amplified openness under later Euro-Canadian use (Birch & Williamson, 2013). Southern connected systems like Rogers Reservoir show prolonged eutrophication from runoff, unlike northern closed basins (LSRCA, 2013).

## *2.12 Indigenous Land-use in a Holocene Context*

The Bass Lake (Langman) record provides a rare opportunity to evaluate Indigenous land-use within a continuous Holocene framework, allowing late pre-contact signals to be assessed relative to long-term background variability (Fig. 2). Across most of the Holocene, vegetation dynamics at Bass Lake (Langman) are characterized by gradual compositional change within a predominantly forested system, punctuated by short-lived disturbances that are limited in magnitude and duration. Against this backdrop, the late pre-contact interval stands out not because of large-scale transformation, but because of the appearance of subtle, stratigraphically coherent indicators that are unlikely to arise from natural processes alone. Within pollen assemblage Zone 3 (pre-AD 1550), a non-significant but persistent compositional shift is observed beginning around AD 1000–950. This interval is marked by repeated low-abundance occurrences of cultigen indicators, most notably *Cucurbita*, alongside *Zea mays* and *Helianthus*-type pollen (Fig. 3). Although these taxa remain well below conventional percentage thresholds, their repeated presence over multiple contiguous samples distinguishes them from background noise or long-distance transport and contrasts sharply with their complete absence in the rural northern Beaver River record. Among these indicators, Cucurbita pollen represents the strongest and most unambiguous evidence of Indigenous agricultural activity in proximity to the Bass Lake (Langman) site. Unlike maize pollen, which can occasionally be transported over moderate distances (Jones & Newell, 1946; Raynor *et al*., 1971; Aylor, 2003), Cucurbita pollen is large, heavy, and poorly dispersed (Holst *et al*., 2007; McAndrews & Turton, 2007; Whitney *et al*., 2012), and its occurrence is widely interpreted as reflecting cultivation or processing activities within the local catchment. The Bass Lake (Langman) record, therefore, indicates that Wendat farmers were active in the immediate landscape during the late pre-contact period, even though the overall vegetation structure remained forest dominated. Importantly, this evidence for Indigenous land-use is not accompanied by sustained increases in disturbance indicators, large reductions in arboreal pollen, or major shifts in multivariate structure. Arboreal pollen proportions remain high through Zone 3, charcoal percentages do not show prolonged elevation, and PCA trajectories indicate continuity with earlier Holocene assemblages. These patterns suggest that Indigenous land-use at Bass Lake (Langman) was spatially focused and ecologically integrated within a broader forest matrix, producing detectable but low-magnitude signals rather than multi-proxy coherence across basins. The contrast between Bass Lake (Langman) and Beaver River further underscores the spatial specificity of Indigenous land-use. While both sites share similar regional vegetation histories, only Bass Lake (Langman) preserves cultigen indicators during the late pre-contact interval. This divergence highlights the importance of site context—particularly proximity to population centres and settlement landscapes—in determining whether Indigenous land-use becomes visible in palaeoecological records. The Bass Lake (Langman) record supports an interpretation of Indigenous land-use that is both detectable and limited in scale. The data provide clear evidence for agricultural activity in the surrounding landscape during the late pre-contact period, while simultaneously indicating that activity did not fundamentally alter basin-scale vegetation structure or long-term ecological trajectories. This stands in marked contrast to the magnitude, persistence, and spatial coherence of Euro-Canadian land-use impacts documented in the historic portion of the record.

This pattern of low magnitude but coherent agricultural signals is consistent with the known historical and archaeological context of the Bass Lake area. Bass Lake (Langman)'s proximity to major Huron-Wendat village clusters in Oro-Medonte likely supported rotational agriculture integrated with forest management practices, including small clearings and controlled burning (Sykes, 2001; Crawford & Smith, 2003). The continuity and scale of these activities were abruptly disrupted during the Beaver Wars of the mid-seventeenth century, approximately the 1640s to 1650s, when Haudenosaunee offensives led to the destruction of nearby villages, including Cahiagué near present-day Warminster and Orillia. The burning of longhouses and cultivated fields, combined with rapid Wendat dispersal and severe population decline exacerbated by introduced diseases, curtailed sustained land management in the Bass Lake catchment (Trigger, 1985; Warrick, 2008). This disruption provides a clear explanation for why Zone 3 lacks prolonged charcoal elevation, significant reductions in arboreal pollen, or major multivariate shifts despite the repeated presence of cultigen indicators. Although Wendat agricultural practices were spatially focused and locally detectable, villages were typically relocated every 10 to 15 years to allow soil recovery, and regional conflict increasingly constrained trade routes and settlement stability prior to final abandonment (Heidenreich, 1973). The broader ecological legacy of the Beaver Wars, including rapid forest regrowth following village destruction, declining land-use intensity, and the cessation of Indigenous cultivation in the basin, aligns closely with the sustained arboreal pollen dominance and low disturbance observed through the end of Zone 3 (Jennings, 1984; Warrick, 2008).

## *2.13 Regional Context Links with the Southern Ontario* Palaeoecology *and the European Transformation*

Interpreting land-use legacies in the Lake Simcoe basin requires situating the results within the broader palaeoecological record of southern Ontario, where differences in basin morphology, sedimentation, and proxy preservation strongly influence the detectability of human activity. Comparison with pollen and non-pollen proxy records across the region highlights two consistent patterns: (i) Indigenous land-use is detectable but spatially constrained and archive dependent, and (ii) Euro-Canadian land-use produces a longer residence time of the disturbance signal and a more persistent ecological signal that is coherent across basin types and proxy systems. Indigenous land use across southern Ontario produced detectable but highly localized signals, such as low-abundance cultigen pollen, such as *Zea mays* and *Cucurbita*, as well as minor charcoal or nutrient pulses, often preserved only in high-resolution or proximity-sensitive archives like Bass Lake (Ekdahl *et al*., 2004; McAndrews & Turton, 2010). In sharp contrast, Euro-Canadian settlement from the early 19th century onward initiated a profound, region-wide ecological transformation through extensive deforestation, systematic wetland drainage, plough-based monoculture, road and canal construction, and continuous cropping that crossed clear ecological thresholds. The rapid, synchronous rise of *Ambrosia* (ragweed) pollen consistently dated to the mid-19th century in pollen records across southern Ontario serves as a recognized stratigraphic marker of this shift, reflecting large-scale land clearance for agriculture and the proliferation of ruderal weeds on newly opened landscapes (Yu *et al*., 1996; McAndrews, 1988; Ekdahl *et al*., 2004).

### *2.13.1 Detectability, scale, and Indigenous Land-use Across Southern Ontario*

Within this regional pattern, Lake Simcoe provides an opportunity to evaluate how archive sensitivity and spatial scale influence the visibility of Indigenous land-use. The Bass Lake (Langman) record extends this framework northward into the Lake Simcoe basin, where pollen archives integrate broader catchments and preservation conditions are less favourable (Fig. 2). At Bass Lake (Langman), the late pre-contact interval is characterized by repeated low-abundance occurrences of cultivation-related indicators, including *Zea mays*, *Cucurbita*, *Helianthus*-type pollen, and disturbance-associated non-pollen palynomorphs (Fig. 3). Individually subtle, their stratigraphic coherence distinguishes them from background variability and long-distance transport. Importantly, these signals occur without sustained reductions in arboreal pollen, prolonged charcoal enrichment, or major multivariate reorganization, indicating that Indigenous land-use was spatially focused and ecologically embedded within a largely forested landscape.

High-resolution archives such as Crawford Lake illustrate how Indigenous agricultural signals can be resolved where preservation conditions are optimal (Ekdahl *et al.*, 2004; McAndrews & Turton, 2010). However, such sensitivity represents an upper bound of detectability. In more spatially integrated basins such as Bass Lake (Langman) and Beaver River, the visibility of Indigenous land-use depends strongly on proximity to settlement and depositional context rather than on its absence.

In contrast, the Beaver River record, representing a rural fluvial system removed from major settlement centres, does not preserve comparable cultigen or disturbance indicators despite sharing similar regional vegetation histories (Fig. 5). Archaeological and historical evidence from Huronia supports this spatial interpretation, indicating that cultivation was concentrated around village landscapes and well-drained soils, while extensive surrounding areas remained forested (White, 1974; Sutton, 1999). Together, these patterns emphasize that the detectability of Indigenous land-use reflects spatial scale and archive sensitivity rather than the presence or absence of land-use itself.

### *2.13.2 Euro-Canadian Land-use and Threshold-scale Ecological Change*

In comparison to the spatially constrained and archive-sensitive signals of Indigenous land-use, Euro-Canadian settlement produced a basin-wide ecological transformation that is consistently expressed across southern Ontario palaeoecological records. At Bass Lake (Langman), the European period marks the most pronounced departure from Holocene baseline conditions, with sustained reductions in arboreal pollen, strong increases in ruderal taxa, elevated disturbance indicators, and persistent multivariate reorganization extending into the twentieth century (Fig. 2). Comparable signals are observed across the short cores from both northern and southern portions of the Lake Simcoe basin, despite differences in basin type and hydrologic connectivity. Regional comparisons indicate that Euro-Canadian land-use crossed a qualitative ecological threshold. The widespread rise of ragweed, increased sediment and nutrient delivery, and long-lasting changes in aquatic and terrestrial communities are recorded not only in small lakes and wetlands, but also in deep-water basin archives.

Historical land surveys and reconstructions quantify this scale: pre-settlement forest cover in southern Ontario exceeded 80-90% but plummeted to approximately 20-30% by the late 19th to early 20th century through aggressive timber extraction, agricultural clearance, and infrastructure expansion (Zavitz, 1916; Bowley, 2015). At the same time, wetlands, which are critical for hydrology and sediment retention suffered losses of 68–85% across the region, with drainage for tile-based farming contributing 81–85% of this impact, particularly in fertile lowlands near Lake Ontario and within the Lake Simcoe watershed itself (Ducks Unlimited Canada, 2010; Bowley, 2015; LSRCA, 2018). Historical records document the rapid expansion of road networks, drainage infrastructure, timber extraction, and continuous agricultural clearance during the nineteenth century, producing spatially extensive and cumulative impacts that differ fundamentally from earlier land-use regimes (White, 1974; Sutton, 1999).

In the Lake Simcoe basin, southern sub watersheds, including the East Holland River, experienced increased impacts, with ongoing legacy effects like eutrophication persisting despite 20th-century reforestation efforts in Simcoe County, which recovered about 10-15% of lost cover by the 1920s-1930s (Bowley, 2015; LSRCA, 2023). This hydrological rewiring via channelization and tile drains, produced coherent proxy signals across closed Bass Lake

(Langman) and open systems (Baileys, Rogers), unlike the localized Indigenous traces. Within this regional context, debates surrounding the Anthropocene hinge less on the presence of pre-contact human activity—which is now well established—than on the magnitude, persistence, and reversibility of ecological change. Palaeoecological evidence from Lake Simcoe and comparable sites indicates that Indigenous land-use did not fundamentally alter basin-scale vegetation structure or long-term ecological trajectories, whereas Euro-Canadian land-use initiated enduring transformations that continue to shape ecosystems today.

### *2.13.3 Implications for Baseline Definition and Regional Synthesis*

Taken together, southern Ontario palaeoecological records demonstrate that defining ecological baselines requires careful consideration of both temporal depth and spatial scale. High-resolution sites such as Crawford Lake reveal fine-grained expressions of Indigenous land-use, while broader, less sensitive archives capture the cumulative and threshold-scale effects of European settlement (Ekdahl *et al.*, 2004; McAndrews & Turton, 2010). The nested approach adopted in this study—combining a long Holocene record with spatially distributed historic cores—provides a framework for reconciling these perspectives and for distinguishing between ecologically integrated land-use and persistent transformation. This regional synthesis underscores the value of integrating palaeoecological, archaeological, and historical evidence when interpreting human–environment interactions in southern Ontario, and highlights the importance of archive sensitivity in shaping what aspects of past land-use are preserved in the sedimentary record. Importantly, these results demonstrate that baseline conditions are better conceptualized as ranges of variability constrained by land-use system structure rather than as fixed pre-disturbance states (McAndrews, 1988; Jackson & Hobbs, 2009). In southern Ontario, attempts to project baselines across space or archive type risk conflating ecologically integrated land-use with threshold-driven transformation, particularly where hydrologic connectivity and infrastructure have altered sediment and nutrient pathways (Zavitz, 1916; Bowley, 2015). A regionally grounded, multi-archive approach therefore provides the most reliable means of distinguishing reversible landscape modification from enduring ecological reorganization in human-dominated systems (Ekdahl *et al*., 2004; McAndrews & Turton, 2010).

## *2.14 Conclusions*

This chapter shows the value of a nested palaeoecological framework for reconstructing land-use legacies across contrasting depositional environments within the Lake Simcoe watershed. By integrating a continuous Holocene archive with spatially distributed historic cores, we resolve both the long-term ecological context of Indigenous land use and the spatial heterogeneity of Euro-Canadian transformation.

The Bass Lake (Langman) record reveals that late pre-contact agricultural activity is detectable through repeated cultigen pollen and disturbance indicators yet occurs without sustained forest collapse or multivariate reorganization. Indigenous land-use was therefore spatially focused and ecologically integrated within a resilient forest matrix. In contrast, Euro-Canadian settlement initiated multi-proxy, basin-wide transformations characterized by increased herb dominance, ruderal taxa expansion, elevated erosion indicators, and persistent compositional shifts. These signals are coherent across both closed and hydrologically open systems, though their magnitude and expression vary along a north–south gradient shaped by settlement intensity and basin connectivity. Independently dated *Ambrosia* maxima highlight that settlement-horizon markers are spatially variable within northern basins, underscoring the need for cautious chronological interpretation when transferring regional pollen thresholds. More broadly, the results demonstrate that ecological baselines are not fixed pre-disturbance states, but ranges of variability structured by land-use regime and archive sensitivity.

By situating Lake Simcoe within the broader southern Ontario palaeoecological context, this study clarifies the differing magnitude, persistence, and spatial coherence of pre-contact and Euro-Canadian land-use impacts. The approach provides a replicable framework for distinguishing ecologically integrated landscape modification from greater magnitude and persistence in other human-dominated regions.

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# Integration of Chapters 2 and 3

The two manuscript chapters in this thesis address complementary aspects of the same research problem: how is land-use change recorded in the palaeoecological archives of the Lake Simcoe watershed, and how reliably do those archives reflect independently documented landscape transformation?

Chapter 2 establishes the long-term palaeoecological context. Using a continuous Holocene record from Bass Lake (Langman) and three high-resolution short cores from contrasting depositional environments, it reconstructs vegetation dynamics, disturbance regimes, and anthropogenic signals from pre-contact through Euro-Canadian settlement. The central finding of Chapter 2 is that Indigenous land-use produced detectable but spatially focused ecological signals embedded within a resilient forested landscape, whereas Euro-Canadian settlement initiated a qualitatively different regime of persistent, basin-wide ecological transformation. Chapter 2 also demonstrates that the expression of these signals varies systematically along a north–south gradient and between closed and hydrologically open basins, establishing that site context is a critical determinant of palaeoecological signal preservation.

Chapter 3 builds directly on this foundation by asking a question that Chapter 2 cannot answer on its own: do the pollen assemblages from these sites actually track the land-use changes that are independently documented in the historical record? To address this, Chapter 3 reconstructs twentieth-century land-use trajectories from historical aerial photographs and GIS analysis, then tests the correspondence between these spatial reconstructions and the pollen records from the same sites. The taxon-to-land-use crosswalk, correlation analyses, and multivariate comparisons in Chapter 3 provide an empirical validation of the pollen signals that Chapter 2 interprets qualitatively.

Together, the two chapters form a coherent analytical framework: Chapter 2 provides the temporal depth and ecological interpretation, while Chapter 3 provides the spatial specificity and quantitative validation. The sites, cores, and pollen data are shared between the two chapters, but the analytical questions, methods, and interpretive frameworks are distinct and complementary.

# Chapter 3 – Landscape Change Across an Urban–Rural Gradient in the Lake Simcoe Region Since the Early Twentieth Century: A Hybrid Analysis of Historical Air Photos, GIS Data, and Palaeoecological Records

## *3.1 Introduction*

Land-use change represents one of the most pervasive drivers of ecological transformation in the Anthropocene (Foley *et al*., 2005; Ellis *et al*., 2010). Across much of the temperate world, twentieth-century landscapes experienced rapid shifts associated with agricultural intensification, urban expansion, and infrastructure development, often accompanied by substantial alterations to hydrological systems and wetland ecosystems (Ramankutty and Foley, 1999; Lambin *et al*., 2001). In eastern North America specifically, these transformations were superimposed on landscapes already profoundly altered by nineteenth-century European settlement, which converted extensive forests and wetlands into an agricultural mosaic within a few generations (Foster *et al*., 2003; Drummond and Loveland, 2010). Understanding the timing and magnitude of these landscape transformations is essential for interpreting contemporary ecosystem structure and function, as well as for informing conservation and land-management strategies.

In southern Ontario specifically, the scale of post-European settlement landscape conversion has been among the most extreme in temperate North America. Pre- European Forest cover exceeded 80% across much of the region, but by the mid-twentieth century less than 20% of the original forest remained (Larson *et al*., 1999; Butt *et al*., 2012). Wetland losses in the lower Great Lakes basin have exceeded 70% in many catchments, with particularly severe losses in the Lake Simcoe and Lake Ontario drainages (Snell, 1987; Ducks Unlimited

Canada, 2010). These losses have had cascading consequences for hydrological regulation, nutrient cycling, biodiversity, and the capacity of landscapes to provide ecosystem services (Schindler, 2006; Palmer *et al*., 2011).

Reconstructing historical land-use change, however, presents significant methodological challenges. Historical geographic information system (GIS) approaches based on aerial photography or historical maps provide detailed spatial reconstructions of land-use but typically offer limited insight into ecological responses within landscapes (Cousins, 2001; Petit and Lambin, 2002; Bürgi *et al*., 2004). In contrast, palaeoecological records preserved in lake and wetland sediments provide continuous ecological archives, capturing vegetation dynamics, disturbance regimes, and environmental change through time, but often lack the spatial specificity required to reconstruct landscape configuration directly (Birks and Birks, 2006; Goring *et al*., 2013). Integrating these complementary sources of information — combining the spatial precision of historical mapping with the temporal continuity of sedimentary records — offers a promising framework for understanding both the spatial structure and ecological consequences of historical land-use change (Swetnam *et al*., 1999; Szabó, 2015; Froyd and Willis, 2008).

Historical aerial photography represents one of the most valuable spatial archives for reconstructing twentieth-century landscapes. Since the early decades of the twentieth century, systematic aerial surveys have documented land cover across large regions, providing high-resolution records of agricultural patterns, urban expansion, forest cover, and wetland extent (Morgan *et al*., 2010; Grossinger *et al*., 2007). In Ontario, the National Air Photo Library (NAPL) archive provides continuous aerial coverage extending to the late 1920s for many parts of the province, offering an unusually long baseline for quantitative landscape reconstruction (Thurston, 1991). When digitized and analyzed within a GIS environment, these records enable detailed examination of land-use trajectories across multiple decades, supporting the kind of spatially explicit historical reconstruction that is difficult to achieve through other means (Bender *et al*., 2005; Plieninger *et al*., 2006).

Palaeoecological archives preserved in lake and wetland sediments provide an independent record of ecological change that can complement spatial reconstructions derived from historical imagery. Fossil pollen, non-pollen palynomorphs (NPPs), and charcoal fragments preserved in sediment sequences record vegetation dynamics, disturbance events, and anthropogenic activity over decadal to centennial timescales (van Geel, 2001; Whitlock and Larsen, 2001; Birks and Birks, 2006). Critically, however, pollen does not record land-use directly. Rather, it captures the vegetation expression of land-use, filtered through differences in pollen production, dispersal distance, source area, and sedimentary time-averaging (Davis, 2000; Bunting *et al*., 2004; Sugita, 2007a, 2007b). Understanding these filters is essential for interpreting pollen–landscape relationships, particularly in heterogeneous landscapes where multiple land-use types contribute to the pollen source area (Hellman *et al*., 2009; Mazier *et al*., 2012).

The conceptual and quantitative relationship between pollen assemblages and surrounding vegetation has been the subject of extensive research, particularly within the POLLANDCAL and LandClim frameworks developed in Scandinavian and western European settings (Gaillard *et al*., 2008; Broström *et al*., 2008; Fyfe *et al*., 2013). These studies have demonstrated that pollen assemblages can predict broad vegetation cover types with reasonable accuracy when appropriate source-area models are applied, and that anthropogenic pollen indicators (sensu Behre, 1981) — including Cerealia-type pollen, Plantago, Rumex, and coprophilous fungal spores — provide reliable markers of agricultural and pastoral land-use across a range of European landscapes (Gaillard *et al*., 2008; Baker *et al*., 2013; Perrotti and van Asperen, 2019). In North American temperate landscapes, however, comparatively fewer pollen–landscape calibration studies exist, and the empirical correspondence between pollen signals and land-use classes derived from historical mapping remains underexplored, particularly at the decadal timescales relevant to twentieth-century change (Fuller *et al*., 1998; Goring *et al*., 2013; McLauchlan *et al*., 2014). This gap is particularly notable in rapidly urbanizing landscapes of the Great Lakes region, where the pace and intensity of land-use transformation during the twentieth century may outstrip the temporal resolution of many palaeoecological records.

A small but growing number of studies have attempted to bridge the divide between spatial reconstruction and palaeoecological analysis. Swetnam *et al*. (1999) articulated the conceptual foundations of "applied historical ecology," emphasizing the complementarity of archival, instrumental, and palaeoecological records. Szabó (2015) reviewed the intellectual history of historical ecology and its integration with landscape science. In a few notable cases, researchers have directly compared pollen or charcoal records with independently documented land-use change, for example matching fire-scar chronologies with charcoal stratigraphy (Whitlock and Larsen, 2001) or comparing pollen assemblages with land-survey vegetation data (Cogbill *et al*., 2002). However, systematic comparisons between pollen records and GIS-reconstructed land-use trajectories derived from sequential air-photo interpretation remain rare, and to our knowledge no study has attempted this across a gradient of landscape contexts within a single region using the indicator-group correlation approach adopted here.

The Lake Simcoe region of southern Ontario provides an ideal setting for examining the interaction between landscape transformation and ecological response. Over the twentieth century, this region experienced substantial land-use change driven by agricultural development, urban expansion associated with the northward sprawl of the Greater Toronto Area (GTA), and evolving conservation efforts aimed at protecting wetlands and water resources (LSRCA, 2009; Palmer *et al*., 2011; North *et al*., 2013). The Lake Simcoe watershed has been the subject of sustained management and scientific attention, owing to longstanding concerns over nutrient loading, declining cold-water fisheries, and invasive species (Eimers *et al*., 2005). Within this region, landscapes spanning an urban–rural gradient provide contrasting contexts in which to evaluate historical land-use trajectories and their ecological expression in the palaeoecological record.

In this study, we integrate historical aerial photography to create a remote sensing-based land-use reconstruction, and palaeoecological records to examine landscape change since the early twentieth century across four sites within the Lake Simcoe region. Specifically, we aim to: (1) reconstruct land-use trajectories from historical aerial photographs using GIS across four sites spanning an urban–rural gradient; (2) evaluate whether pollen assemblage composition captures differences in landscape structure among sites using ordination; (3) test whether specific pollen indicator groups — defined through a taxon-to-land-use crosswalk — track corresponding mapped land-use classes through time; and (4) assess the multivariate correspondence between pollen assemblage turnover and reconstructed landscape change using Mantel and Procrustes comparisons. By combining spatially explicit historical reconstruction with ecological archives, this study provides a hybrid framework for understanding landscape transformation across rapidly changing temperate landscapes and evaluates the conditions under which pollen records can be meaningfully linked to documented land-use histories.

This integrative approach is summarized conceptually in Figure 8, which illustrates how historical imagery, GIS-based land-use reconstruction and palaeoecological indicators are combined to evaluate landscape change through time. Historical aerial photographs and archival spatial data are digitized within a GIS environment to produce spatially explicit land-use maps through time. In parallel, sediment records from nearby wetlands provide independent palaeoecological indicators, including pollen, fungal spores, charcoal, and anthropogenic indicator taxa (e.g., *Zea mays, Ambrosia*), that record vegetation change, fire activity, and agricultural land-use. The integration of these complementary datasets allows land-use trajectories derived from aerial photo reconstruction to be evaluated and refined using ecological evidence preserved in sediments, resulting in a hybrid GIS–palaeoecological framework for reconstructing historical landscape transformation (Fig. 8). The figure was created by the author in Adobe Illustrator (v.30.1) based on an original conceptual design, incorporating original graphics and AI-assisted artwork generated using Adobe Firefly (v.26.3).

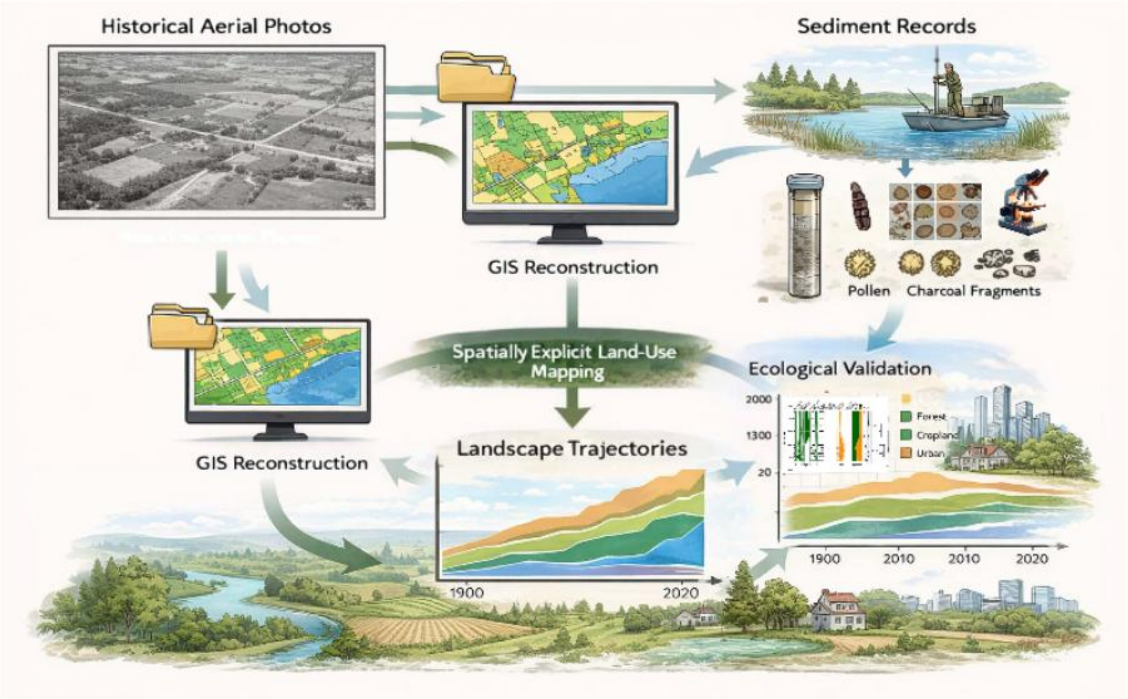

*Figure 8. Conceptual framework for integrating historical GIS reconstruction with palaeoecological validation to reconstruct land-use trajectories.*

## *3.2 Study Area*

The study sites are located within the Lake Simcoe watershed in southern Ontario, Canada (Fig. 1). The region is characterized by a humid continental climate (Köppen Dfb) with warm summers (mean July temperature ~20°C) and cold winters (mean January temperature ~−8°C), and receives approximately 850–950 mm of annual precipitation (Environment and Climate Change Canada, 2023). The physiographic setting spans the Oak Ridges Moraine to the south and the Simcoe Lowlands to the north (Chapman and Putnam, 1984), and includes a diverse mosaic of agricultural lands, forests, wetlands, and rapidly expanding urban areas. Over the twentieth century, the region has experienced substantial land-use change associated with agricultural intensification and suburban expansion linked to the growth of the Greater Toronto Area (LSRCA, 2009; Palmer *et al*., 2011). Four sites representing different positions along an urban–rural gradient were selected for analysis; their geographic, environmental, and landscape characteristics are summarized in Table 3, and their spatial distribution is shown in Fig. 2 (Chapter 2).

Baileys Ecopark is located within the municipality of Newmarket (~44.03419°N, -79.4643°W), where suburban expansion has accelerated during recent decades. Historically dominated by agricultural land-use, the surrounding landscape has undergone rapid transformation associated with residential development and urban infrastructure. The site lies within the physiographic context of the Oak Ridges Moraine, an area of particular hydrological and conservation significance in southern Ontario (Gerber and Howard, 2002).

Beaver River represents a predominantly rural landscape within the northern portion of the Lake Simcoe watershed (~44.28783°N, -79.4643°W). Land-use in this catchment remains largely agricultural, with relatively limited urban development and comparatively higher retention of forest cover.

Bass Lake (Langman) is situated within a complex wetland system (~44.55°N, 79.38°W) surrounded by a heterogeneous landscape of agricultural land, forest patches, and urban development. The marsh itself and adjacent areas have benefited from conservation initiatives aimed at protecting wetland ecosystems within the region. However, urban pressures began early in the vicinity of the site, related to the historical urban centre of Orillia, Ontario. Rogers Reservoir is a managed wetland-upland landscape (~44.24°N, 79.40°W) associated with water-level control infrastructure and wetland conservation initiatives. Although surrounded by agricultural land, the site exhibits relatively stable wetland conditions through time.

*Table 3. Summary of geographic and landscape characteristics for the four study sites in the Lake Simcoe watershed, including location, elevation, basin type, mapped landscape extent, surrounding landscape context, and proximity to the nearest urban centre.*

| Site Name | Latitude | Longitude | Elevation (m) | Basin Type | Mapped Landscape Extent (km²) | Dominant Landscape Context | Distance to Nearest Urban Centre (km) | Nearest Urban Centre |
|---|---|---|---|---|---|---|---|---|
| Bass Lake (Langman) | 44.59407 | -79.4939 | 266 | Closed | 8.26 | Forested wetland basin within a predominantly rural agricultural–forest matrix | 6 | Orillia |
| Beaver River Wetland Complex | 44.28783 | -79.05 | 264 | Open | 11.7 | Large wetland complex embedded in a rural agricultural landscape. | 3 | Sunderland |
| Baileys Ecopark | 44.03419 | -79.4643 | 244 | Open | 4.68 | Urbanizing suburban landscape with remnant forest and wetland patches | 2.6 | Newmarket |
| Rogers Reservoir | 44.08831 | -79.463 | 230 | Open | 8.65 | Mixed peri-urban landscape with agricultural land, suburban development, and forest patches | 2 | East Gwillimbury |

## *3.3 Study Design and Analytical Rationale*

This study was designed to evaluate whether and to what extent twentieth- and early twenty-first-century pollen assemblages track land-use change reconstructed from historical aerial photography in the Lake Simcoe region. The analysis focused on four sites spanning a north–south gradient and contrasting landscape settings. These sites differ in the relative importance of forest cover, agricultural land use, wetland complexity, and urban or peri-urban development, providing a useful regional test of pollen–landscape relationships.

The central premise of the analysis was that pollen does not record land-use directly, but rather records the vegetation expression of land-use, filtered through differences in pollen production, dispersal, source area, and sedimentary time-averaging (Davis, 2000; Bunting *et al.*, 2004; Sugita, 2007a). Accordingly, the statistical framework was designed to test whether pollen assemblages track broad landscape composition and its temporal reorganization, rather than whether individual pollen samples correspond exactly to discrete land-use snapshots from aerial photographs.

Two complementary analytical approaches were used. First, pollen taxa were grouped into land-use-relevant functional indicators in order to test whether specific pollen signals covaried with mapped land-use classes through time. Second, pollen and land-use data were treated as multivariate compositional datasets and compared using ordination- and distance-based methods to determine whether overall pollen assemblage turnover paralleled mapped landscape turnover.

### *3.3.1 Historical Aerial Photography*

Historical aerial photographs spanning the twentieth and early twenty-first centuries were obtained from multiple archival and online sources. Imagery covering the late 1920s through

2025 was accessed through the Earth Observation Data Management System (EODMS), including the National Air Photo Library and the Canada Lands Air Photos Collection. Additional aerial imagery for the Beaver River site was obtained from the Lake Simcoe Region Conservation Authority, while supplementary imagery and historical basemaps were accessed through Esri World Imagery Wayback and a York Region WMS service, with multiple photographic surveys capturing landscape conditions at each study site (Appendix Table 1).

Aerial photographs were georeferenced in ArcGIS Pro using ground control points identifiable across time periods (e.g., road intersections, permanent structures, and shoreline features). Root mean square error (RMSE) values for georeferencing ranged from 2.54 m to 15.28 m across the dataset, with individual image RMSE values reported in Appendix table 1. Land-cover features were manually delineated as polygons through visual interpretation of each georeferenced image. Because polygons were digitized manually rather than generated through automated classification, a fixed minimum mapping unit (MMU) was not applied; polygon size instead reflected the smallest features that could be reliably interpreted from the aerial imagery.

All digitization and land-use classification were performed by a single operator following standardized classification criteria applied consistently across all sites and time periods. No formal classification accuracy assessment was conducted; however, classification decisions were reviewed iteratively against the original imagery during digitization. The temporal coverage of the imagery varied slightly among sites, reflecting the availability of aerial survey data.

### *3.3.2 GIS Land-use Mapping*

Historical aerial photographs were assembled for each site to reconstruct land-use composition over the interval covered by the pollen records. Because photo availability differed among sites, the sequence of mapped years was site-specific. Air photographs were georeferenced and digitized using ArcGIS pro, land-use polygons were classified into a standardized set of land-use categories (Table 4). The classification scheme included agricultural categories (AG1: crop; AG2: hay; AG3: pasture; AG4: fallow; AG5: mixed anthropogenic land cover), forest categories (F1: deciduous; F2: conifer; F3: mixed forest; F4: plantation), aquatic features (lakes, ponds, streams), wetland environments (W1: graminoid marsh; W2/W3: swamp wetland; poor fen), residential categories (R1: residential/impervious; R2: buildings and trees; R3: buildings and turf), and limited infrastructure elements such as solar installations. The resulting attribute dataset for each site contained, for each mapped year and land-use class, the number of polygons and total surface area (m²).

*Table 4. Land cover classification scheme used for manual polygon delineation from historical aerial imagery in the Lake Simcoe watershed study sites. Categories, associated codes, and descriptions outline the land cover types interpreted during image analysis, including agricultural classes (AG1-AG5), forest classes (F1-F4), hydrological features (H1-H2), wetland types (W1-W4), residential land uses (R1-R3) and infrastructure (I1)*

| Category | Codes | Description |
|---|---|---|
| Agriculture | AG1–AG5 | (1) cultivated crops, (2) hayfields, (3) pasture, (4) fallow land, (5) mixed agricultural use |
| Forest | F1–F4 | (1) deciduous forest, (2) conifer forest, (3) mixed forest, (4) plantation forest |
| Hydrology | H1–H2 | (1) lakes/ponds, (2) rivers/streams |
| Wetlands | W1–W4 | (1) open water wetlands, (2) marsh wetlands, (3) swamp wetlands, (4) poor fens |
| Residential | R1–R3 | (1) buildings/paved areas, (2) residential with tree canopy, (3) residential turf |
| Infrastructure | I1 | (1) solar farm |

### *3.3.3 Reconstruction of Land-use Trajectories and Visualization of Landscape Change*

To facilitate comparison among sites and time periods, land-use surface areas were standardized as proportions of the total mapped landscape for each year. The proportional contribution of each land-use class was calculated as:

$P_i = A_i / A_{total}$

Where $A_i$represents the surface area of land-use class $i$, and $A_{total}$represents the total mapped surface area for a given site in a given year (i.e., the sum of all mapped land-use classes within the defined study boundary for that year).

Temporal land-use trajectories were visualized using time-series maps and a stacked area diagram (Figs. 9–13) representing the proportional contribution of each land-use class through time. In this diagram, land-use areas are expressed as percentages of the total mapped area for each individual year, such that all classes sum to 100% annually. This normalization ensures that comparisons reflect relative changes in land-use composition rather than differences in total mapped area, allowing consistent comparison among sites and across aerial photograph series.

## *3.4 Palaeoecological Records and Chronological Framework*

Palaeoecological data were obtained from sediment cores collected near each study site (see Edmunds *et al*., Chapter 2, for full descriptions of core collection, palynological processing, and detailed chronological results; key chronological parameters are summarized here for reference). Fossil pollen, non-pollen palynomorphs (NPPs), and charcoal fragments preserved in the sediment sequences provide a record of vegetation dynamics, disturbance events, and environmental change through time.

Chronological control for the three short cores (Beaver River, Rogers Reservoir, and Baileys Ecopark) was established using $^{210}$Pb and $^{137}$Cs radionuclide dating performed at the Environmental Radioactivity Research Centre, University of Liverpool (Appleby and Piliposian, in Pendea *et al.*, 2023). Unsupported $^{210}$Pb activities were modelled using the constant rate of supply (CRS) approach (Appleby and Oldfield, 1978), with the exception of Baileys Ecopark, where the constant initial concentration (CIC) model was used in conjunction with the $^{137}$Cs-derived 1963 reference point due to a slight CRS–$^{137}$Cs discrepancy (Appleby, 2001). At all three sites, $^{137}$Cs activity profiles provided an independent mid-twentieth-century chronological marker corresponding to the 1963–1964 atmospheric fallout maximum; at Beaver River, this was further confirmed by a coincident $^{241}$Am peak. Radionuclide-derived chronologies extend to approximately 1872 CE at Beaver River, 1916 CE at Rogers Reservoir, and 1928 CE at Baileys Ecopark. Below the limit of reliable radionuclide constraint, age assignments are guided by pollen-based biostratigraphic markers, principally the sustained rise of *Ambrosia* pollen associated with Euro-Canadian land clearance, supplemented where applicable by the appearance of Cerealia-type and Taraxacum pollen (see Edmunds *et al.*, Chapter 2, for full discussion). Age uncertainties for the $^{210}$Pb-dated intervals are typically ±2–5 years in the upper portions and ±10–16 years near the base of reliable radionuclide constraint (Table 5).

Chronological control for the Bass Lake (Langman) core was established using seven AMS radiocarbon dates on terrestrial macrofossils (wood, plant material, and peat), analyzed at Beta Analytic Inc. (Miami, USA) and the André E. Lalonde AMS Laboratory (University of Ottawa, Canada). Radiocarbon ages were calibrated using the IntCal20 curve (Reimer *et al.*, 2020) and age–depth relationships were modelled using the Bayesian framework implemented in the *rbacon* package (Blaauw and Christen, 2011). The resulting model indicates continuous sediment accumulation throughout the Holocene with no major hiatuses.

For the twentieth-century interval used in the present analysis, the *rbacon* model yields median age estimates with reasonable decadal-scale spacing (e.g., 0 cm ≈ 2022 CE; 5 cm ≈ 1964 CE; 8 cm ≈ 1930 CE). The formal 95% confidence envelopes are substantially wider than at the radionuclide-dated sites, spanning approximately 80–150 years per sample in the upper 5–8 cm (Table 5; Appendix Table 2), reflecting the well-known flattening of the radiocarbon calibration curve during the last ~300 years. However, the reliability of the *rbacon* median chronology in the twentieth-century interval is independently supported by a biostratigraphic cross-validation: the sustained rise of *Ambrosia* pollen at Bass Lake (Langman) corresponds to a modelled age of approximately 1909 CE, while the same *Ambrosia* inception at the nearby Beaver River site — which shares a similar regional settlement history — is independently dated by $^{210}$Pb to approximately 1915 CE. The close agreement (~6 years) between these two independent chronological frameworks for the same ecological event indicates that the *rbacon* median ages at Bass Lake (Langman) produce ecologically plausible and regionally consistent dates for the early twentieth-century portion of the record, despite the wide formal confidence envelopes. The implications of the remaining chronological uncertainty for pollen–remote sensing comparisons at Bass Lake (Langman) are discussed in the conclusions of this chapter.

*Table 5. Summary of chronological control for sediment cores used in the present study.*

| Parameter | Bass Lake (Langman) | Beaver River | Rogers Reservoir | Baileys Ecopark |
|---|---|---|---|---|
| Dating method | AMS $^{14}$C on macrofossils | $^{210}$Pb + $^{137}$Cs + $^{241}$Am | $^{210}$Pb + $^{137}$Cs | $^{210}$Pb + $^{137}$Cs |
| Dating laboratory | Beta Analytic; Lalonde AMS (uOttawa) | Univ. Liverpool ERRC | Univ. Liverpool ERRC | Univ. Liverpool ERRC |
| No. dated horizons | 7 AMS $^{14}$C dates | 12 $^{210}$Pb + $^{137}$Cs peak | 10 $^{210}$Pb + $^{137}$Cs peak | 14 $^{210}$Pb + $^{137}$Cs peak |
| $^{210}$Pb model | n/a | CRS (piecewise, $^{137}$Cs-constrained) | CRS | CIC ($^{137}$Cs-constrained) |

| Parameter | Bass Lake (Langman) | Beaver River | Rogers Reservoir | Baileys Ecopark |
|---|---|---|---|---|
| Age-depth model | *rbacon* (Bayesian) | Direct from CRS | CRS + CIC hybrid | CIC constant sed. rate |
| $^{137}$Cs 1963 depth | n/a | 9.0–10.2 cm ($^{241}$Am confirmed) | 10–11.5 cm | 14–15 cm |
| Radionuclide base date | n/a | ~1872 CE | ~1916 CE | ~1928 CE |
| 20th-c. age uncertainty | 95% CI ~80–150 yr ($^{14}$C plateau) | ±2–14 yr | ±1–16 yr | ±0–11 yr |
| Mean sed. rate (20th c.) | ~0.05–0.08 cm yr$^{-1}$ | 0.065 cm yr$^{-1}$ | 0.10–0.23 cm yr$^{-1}$ | 0.23 cm yr$^{-1}$ |
| No. pollen samples used | 5 | 6 | 7 | 8 |
| Reference | This study; Reimer *et al.* (2020); Blaauw and Christen (2011) | Pendea et al. (2023) | Pendea *et al.* (2023) | Pendea *et al.* (2023) |

† The reliability of the Bass Lake (Langman) *rbacon* median chronology in the twentieth-century interval is supported by cross-validation with the *Ambrosia* rise biostratigraphic marker: *Ambrosia* inception at Langman = ~1909 CE (*rbacon* median); at Beaver River = ~1915 CE ($^{210}$Pb-dated). Agreement within ~6 years.

### *3.4.1 Taxon-to-land-use Crosswalk*

The taxon-to-land-use crosswalk was established a priori, before any correlation or multivariate analyses were performed. Taxa were assigned to land-use classes based on their known autecology in southern Ontario landscapes, direct field observations of vegetation composition within mapped land-use classes at the study sites, and established palynological indicator frameworks (Behre, 1981; McAndrews, 1988; Fuller *et al.*, 1998). The full crosswalk is provided in Appendix Table 3.

For some land-use classes, the expected pollen expression is straightforward. Cropland (AG1) was linked to Cerealia-type and *Zea mays* pollen, which are produced exclusively by cultivated plants. Forest classes (F1, F2) were linked to their corresponding arboreal pollen types (deciduous and conifer taxa, respectively). Hay fields (AG2) were linked primarily to

Poaceae, reflecting the well-known effect of repeated mowing in selecting against forbs and favouring grass dominance in managed hayfields.

For other classes, the expected pollen expression is more complex and the assignments draw on field observation. Pasture (AG3) was linked to a suite of ruderal and disturbance-associated taxa — including Plantago, Rumex, Taraxacum-type, and coprophilous fungal spores (e.g., Sordaria, Podospora; see Appendix plate 1 and 2) — reflecting the characteristic vegetation of grazed landscapes in southern Ontario. Fallow land (AG4) was linked to early-successional and disturbance taxa whose presence was confirmed by field inspection of fallow parcels at the study sites. Mixed anthropogenic land cover (AG5) and residential subclasses (R2, R3) were assigned based on direct observation of the vegetation present within these land-use polygons during fieldwork.

Where a taxon was ecologically associated with multiple land-use classes, multiple-class assignments were retained (for example AG3+AG4). In these cases, the corresponding mapped land-use classes were summed before comparison with the pollen data. This approach was preferred over fractional assignment because it preserved ecological ambiguity explicitly and avoided imposing arbitrary weights on taxa with broad disturbance affinities. The subsequent correlation analyses therefore constitute a test of these a priori predictions rather than a circular confirmation of post hoc assignments. The fact that several predicted associations did not hold up — including non-significant or bootstrap-fragile correlations at Beaver River, Rogers Reservoir, and Bass Lake (Langman) — demonstrates that the framework does not automatically produce positive results and can identify both strong and weak pollen–land-use linkages.

## *3.5 Linked Pollen Indicator Groups*

For each sampled pollen level, grouped pollen indices were calculated by summing the percentages of all taxa linked to a given land-use class. Equivalent land-use variables were generated by summing the mapped area proportions of the corresponding GIS classes and linearly interpolating those values to pollen sample ages. Each pollen level was assigned to the calendar year of the nearest air-photo survey where possible; additional pollen levels were included between air-photo dates where stratigraphic evidence indicated compositional change, and GIS values for these levels were obtained by linear interpolation between adjacent mapped years. This produced paired pollen–land-use variables such as: AG1 (cultivated land) pollen index representing combined pollen from Cerealia-type and *Zea mays;* AG2 (hay) pollen index formed by abundances of Poaceae; AG3 (pasture) pollen index including *Plantago*, *Rumex*, *Taraxacum*-type, coprophilous fungi, and mycorrhizal fungi *Glomus* (see Appendix Table 3 for complete crosswalk).

Preliminary site-level analyses showed that strict one-to-one comparisons between deciduous pollen and deciduous forest polygons, or between conifer pollen and conifer polygons, could underestimate pollen–forest relationships in mixed landscapes. This was especially evident at Beaver River, where mapped forest was dominated by mixed forest rather than discrete deciduous or conifer classes. To address this, a broad forest variable, Forest_all, was calculated as the sum of mapped forest classes (F1 + F2 + F3 + F4). On the pollen side, Forest_all was calculated as the sum of conifer and deciduous arboreal pollen groups. This broad forest metric was intended to test the hypothesis that arboreal pollen tracks total forest cover more reliably than individual mapped forest subclasses. This treatment is consistent with the fact that pollen integrates multiple forest types within its source area and is not expected to reproduce cartographic distinctions between mixed, deciduous, and conifer forest with equal precision (Bunting *et al*., 2004; Hellman *et al*., 2009).

Residential subclasses required special treatment because these land-use classes contain a mixture of vegetated and impervious surfaces, and only the vegetated fraction contributes to the pollen signal. Visual inspection of residential polygons across the air-photo time series indicated that approximately half of the area within typical R2 (buildings and trees) and R3 (buildings and turf) parcels was occupied by impervious surfaces (buildings, driveways, roads), with the remainder comprising tree canopy (R2) or turf grass (R3). To account for the pollen-silent impervious fraction, a weighting factor of 0.5 was applied: R2 area was weighted at 0.5 and added to the mixed forest metric (F3), reflecting the tree canopy component of residential parcels, while R3 area was weighted at 0.5 and added to the mixed open-land metric (AG5), reflecting the turf grass component. These adjustments were applied conservatively and are intended to approximate the effective pollen-producing area within residential land-use classes rather than to precisely quantify vegetation cover. The 0.5 weighting represents a first-order estimate; sensitivity to this parameter is discussed in this chapter's conclusions.

## *3.6 Multivariate Analyses*

Because individual taxa or grouped indicators do not capture the full ecological structure of landscape change, pollen and GIS data were also compared as multivariate compositional datasets.

### *3.6.1 Data Transformation*

Pollen-group and land-use-group matrices were Hellinger-transformed prior to ordination and distance analyses. Hellinger transformation is widely recommended for ecological community data because it reduces the disproportionate influence of dominant variables while retaining Euclidean properties suitable for ordination (Legendre and Gallagher, 2001).

It is especially appropriate where the data are compositional or semi-compositional and contain many zeros.

### *3.6.2 Correlation and Indirect Gradient Analyses*

Linked palynological-GIS variables were compared using both Pearson and Spearman correlations. Pearson correlation was used to evaluate linear association in magnitude, whereas Spearman rank correlation was used to assess monotonic agreement independent of strict linearity. Using both statistics allowed the analysis to distinguish between relationships that were directionally consistent but potentially non-linear, and relationships that were both directionally and proportionally coherent.

Given the small sample sizes per site ($n = 5–8$), only strong correlations ($|r| > 0.75–0.88$, depending on n) are detectable at conventional significance thresholds. The use of both Pearson and Spearman statistics, combined with multivariate tests (Mantel, Procrustes) that assess overall dataset concordance rather than individual variable pairs, provides mutual reinforcement and reduces the risk of Type II error at any single site. Non-significant Spearman results at sites with $n \leq 6$ should be interpreted cautiously, as statistical power at these sample sizes is insufficient to detect moderate-strength rank correlations.

To assess the robustness of correlations at these small per-site sample sizes, nonparametric bootstrap 95% confidence intervals were calculated for all Pearson and Spearman coefficients reported in Table 7 (10,000 paired resamples, percentile method; Efron and Tibshirani, 1993). Bootstrap confidence intervals that do not include zero indicate that the observed correlation is robust to the resampling of individual observations, whereas intervals that include zero indicate sensitivity to one or more influential data points.

Principal Components Analysis (PCA) was performed on Hellinger-transformed pollen percentage data to evaluate differences in pollen assemblage composition among sites.

### *3.6.3 Mantel and Procrustes comparisons*

Mantel tests were used to compare Bray–Curtis dissimilarity matrices calculated separately from the pollen and land-use datasets. Mantel r therefore measured whether pollen samples that were more dissimilar from one another were also associated with greater differences in mapped land-use composition. Significance was assessed using 999 permutations.

Procrustes analysis was used to compare the configuration of pollen and land-use datasets in reduced multivariate space. Separate principal component ordinations were first calculated for the Hellinger-transformed pollen and land-use matrices. Procrustes rotation was then used to superimpose the pollen ordination onto the land-use ordination. The resulting Procrustes correlation provided a measure of the degree to which pollen assemblage structure matched landscape composition structure through time (See Appendix Figures 17-20). Significance was evaluated via the PROTEST procedure (Peres-Neto and Jackson, 2001) with 999 permutations.

## *3.7 Site-level Versus Regional Framework*

All analyses were first carried out separately for each site in order to preserve the ecological distinctiveness of individual landscapes and to identify site-specific response modes. This step proved especially important because the dominant pollen–land-use relationship varied among sites: for example, forest cover was the strongest organizing variable at Beaver River, whereas disturbance and agricultural indicators were more important at Bass Lake (Langman) and Baileys, and urbanizing disturbance was more characteristic of Rogers Reservoir.

After site-level analyses, results were compared across sites to identify regionally robust indicator groups. The strongest cross-site signals were ranked by the absolute magnitude of

Spearman correlation coefficients, allowing identification of pollen groups that consistently tracked land-use change despite differences in local landscape context. This two-step design prevented strong site-specific relationships from being obscured by pooling and, conversely, prevented regional conclusions from being drawn solely from a single local trajectory.

## *3.8 Special Note on Bass Lake (Langman)*

Bass Lake (Langman) represents a particularly heterogeneous wetland landscape, including marsh, swamp, upland forest, and adjacent agricultural and urban land-uses. In contrast to the other sites, parts of the surrounding vegetation mosaic do not lend themselves easily to broad polygon classification, particularly where mixed upland forest and wetland transitions are spatially complex. This likely reduces the degree of direct correspondence between mapped land-use classes and the integrated pollen signal relative to sites with simpler or more clearly partitioned landscape structure. The relevant pollen source area at Bass Lake (Langman) may also extend substantially beyond the mapped air-photo extent, particularly for wind-pollinated arboreal taxa (cf. Sugita, 2007a). Chronological uncertainty further contributes to this mismatch. Although the radiocarbon-based chronology for Bass Lake (Langman) carries wider formal age uncertainties in the twentieth-century interval than the radionuclide-dated short cores, the rbacon median ages are independently corroborated by Ambrosia biostratigraphic cross-validation with Beaver River (approximately 6 years agreement). This supports the overall reliability of the chronology, but the wider confidence envelopes mean that precise temporal alignment between individual pollen samples and specific air-photo dates remains less certain than at the other sites. In addition, the low sedimentation rate at Bass Lake (Langman) means that standard 1 cm sediment slices integrate a longer period of pollen rain, producing temporal averaging that does not correspond directly to discrete cartographic snapshots. Short-term disturbance processes that pre-date the aerial photograph record may also contribute to the observed mismatch, as sedimentary signals can reflect ecological responses to earlier, short-lived landscape disruptions that are not represented in twentieth-century land-use data (Trigger, 1987; Warrick, 2000; Birch, 2015). These combined factors contribute to the observed mismatch between pollen assemblages and aerial photo-derived land-use patterns at Bass Lake (Langman).

### *3.9 Software*

All data processing, interpolation, and statistical analyses were carried out in R (R Core Team, 2025). Data import and reshaping were performed using packages *readxl, dplyr, tidyr*, and *stringr*; ordination and community analyses were performed with *vegan* (Oksanen *et al*., 2024); bootstrap analyses used base R; and plots were produced using *ggplot2* (Wickham, 2016), with label placement assisted by *ggrepel*.

### *3.10 Results*

To examine how landscape structure and vegetation composition varied across the study region, we first reconstructed land-use trajectories using historical air-photo GIS analysis and then compared these patterns with pollen assemblage composition and multivariate correspondence between the two datasets.

## 3.11 Historical Landscape Change Reconstructed from Aerial Imagery

Interpretation of historical aerial photographs reveals clear divergence in landscape trajectories among the four study sites from the late 1920s to the present (Figures 9–12), with full temporal sequences for each site shown in Appendix Figures 1–12.

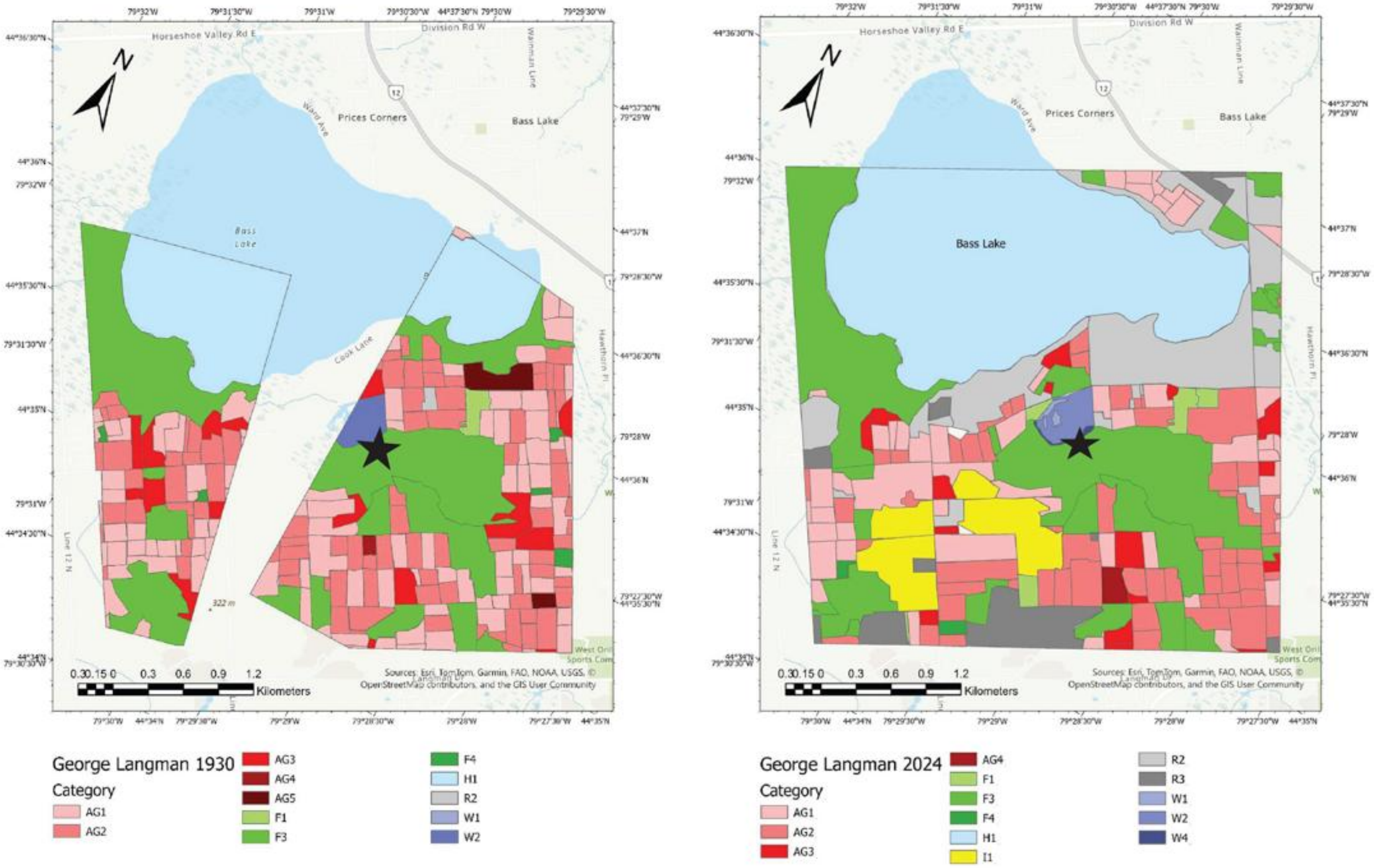

*Figure 9. Land-use classification maps for the Bass Lake (Langman) study area in 1930 and 2024 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1-F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3) and infrastructure (I1) These maps depict land-use change surrounding the core site (black star) for the 1930-2024 period.*

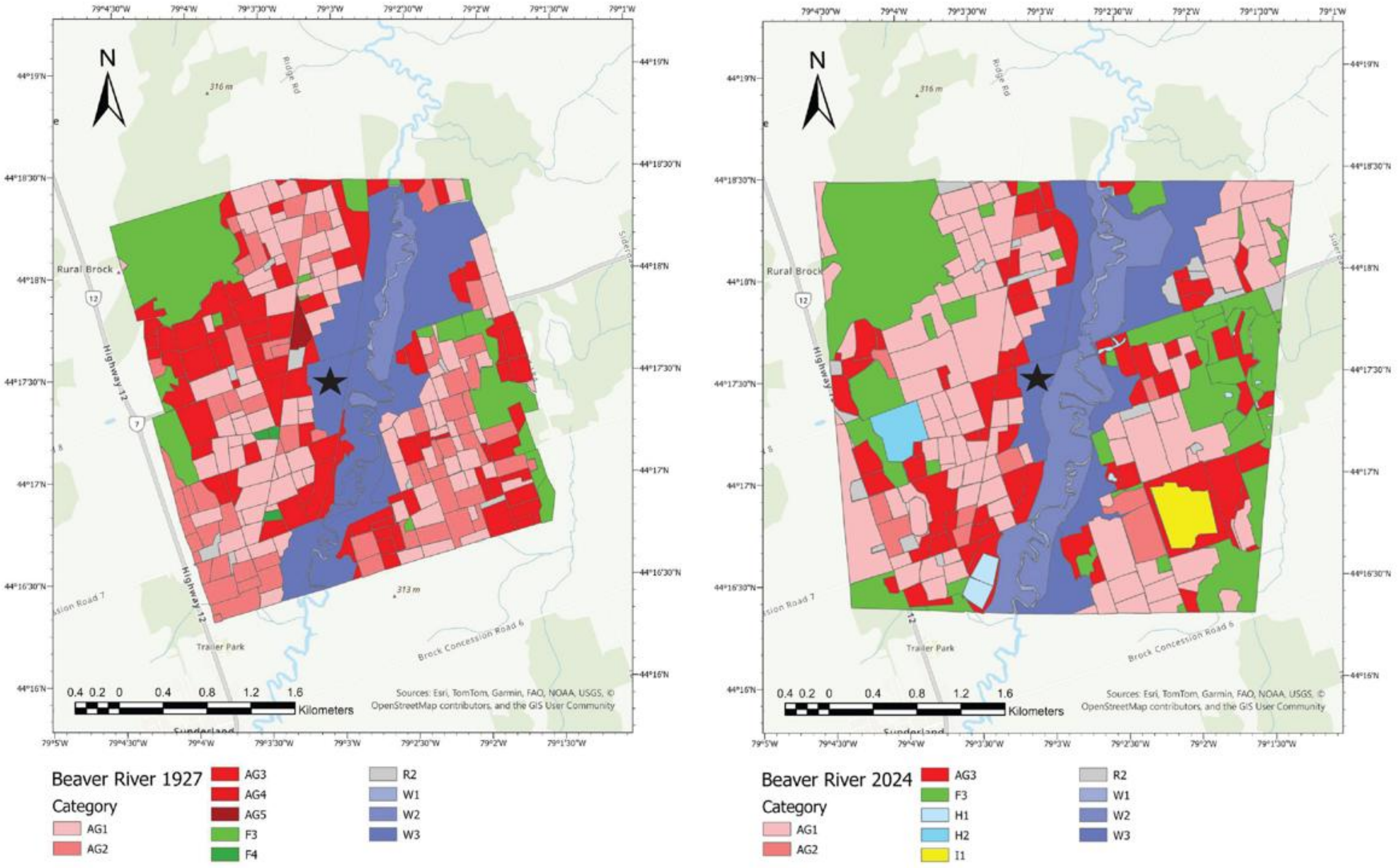

*Figure 10. Land-use classification maps for the Beaver River study area in 1927 and 2024 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1-F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). These maps depict land-use change surrounding the core site (black star) for the 1927-2024 period.*

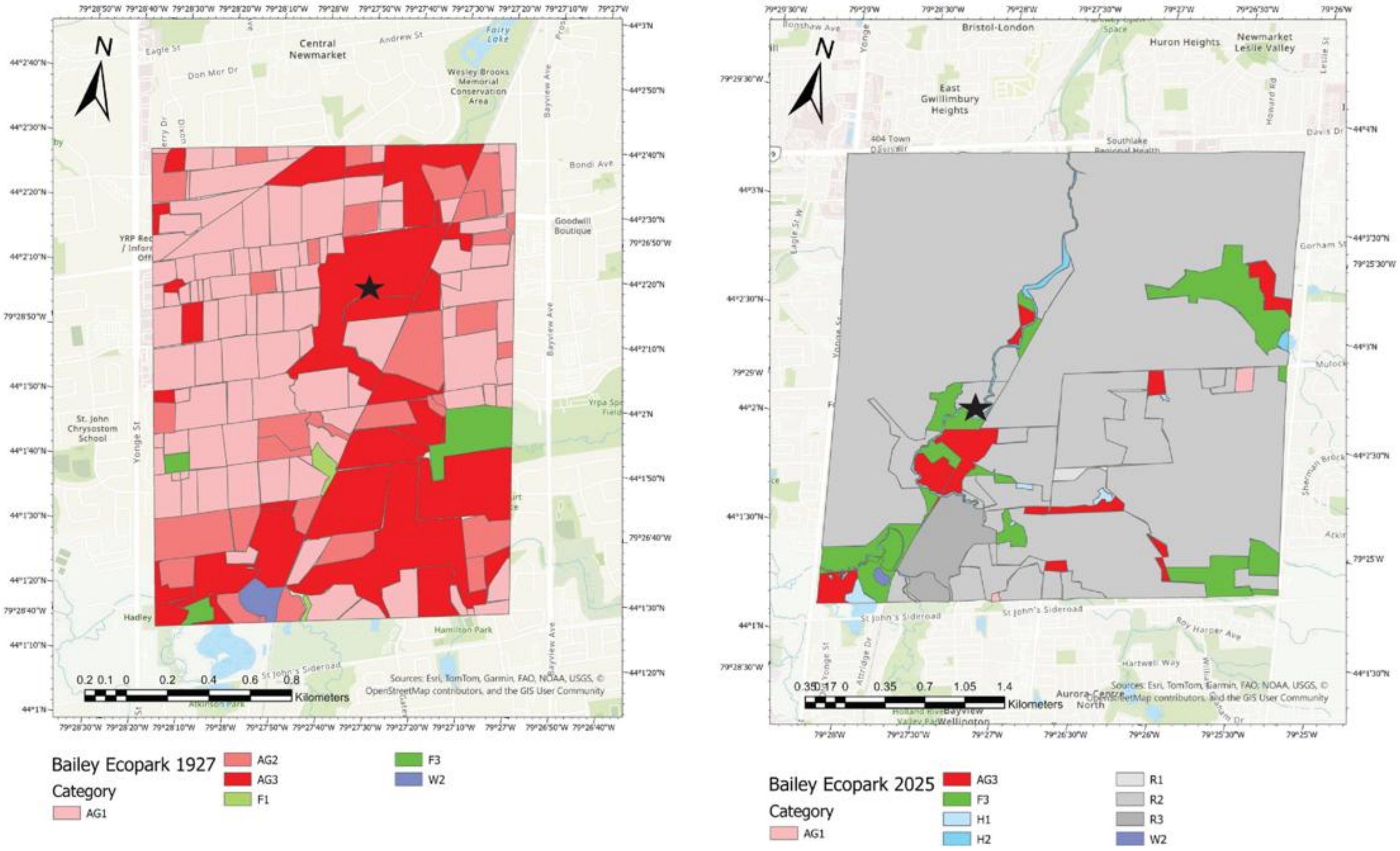

*Figure 11. Land-use classification maps for the Baileys Ecopark study area in 1927 and 2025 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1-F3) wetlands (W1-W4), hydrology (H1-H3), residentials (R1-R3), and infrastructure (I1). These maps depict land-use change surrounding the core site (black star) for the 1927-2025 period.*

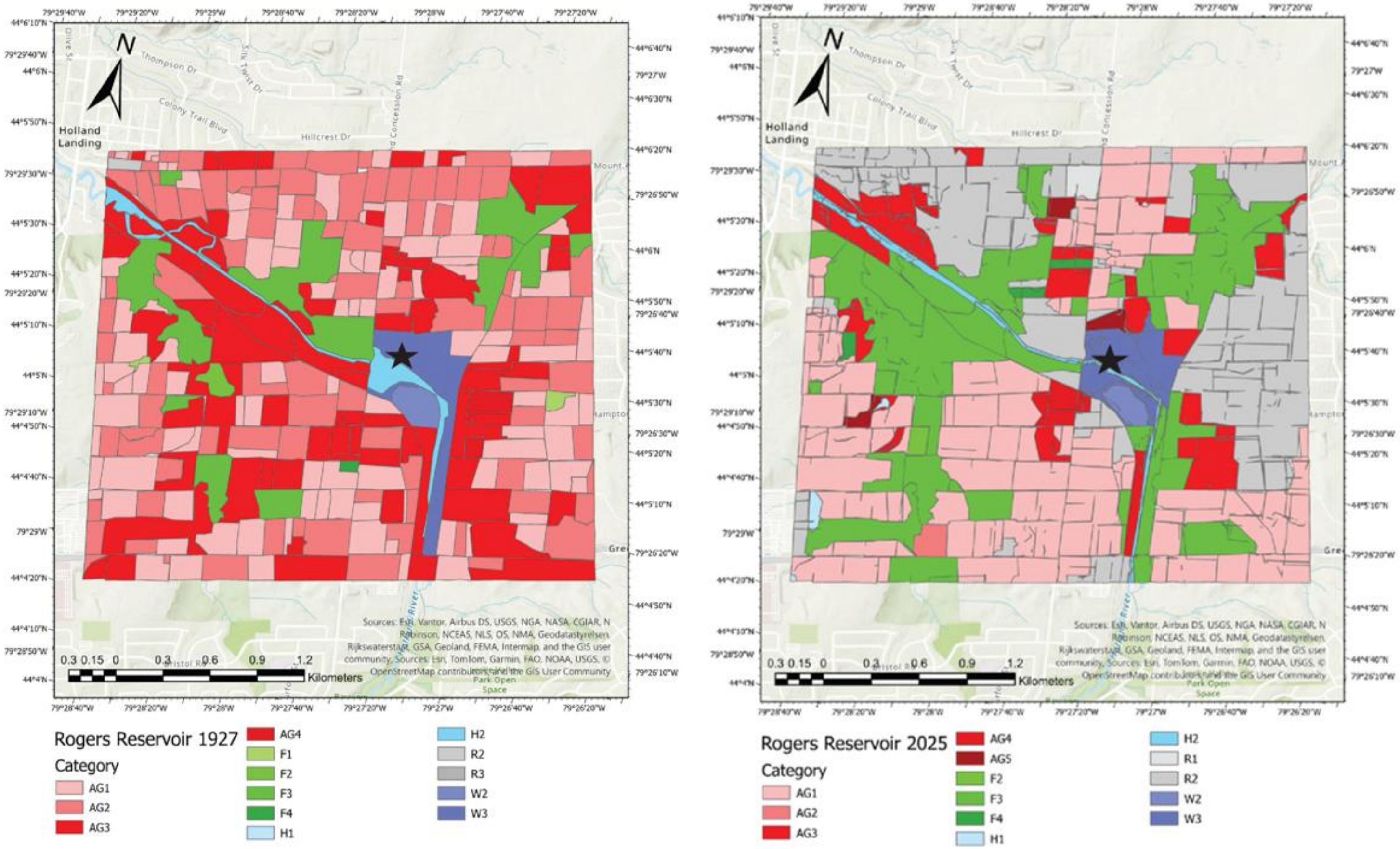

*Figure 12. Land-use classification maps for the Rogers Reservoir study area in 1927 and 2025 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1-F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). These maps depict land-use change surrounding the core site (black star) for the 1927-2025 period.*

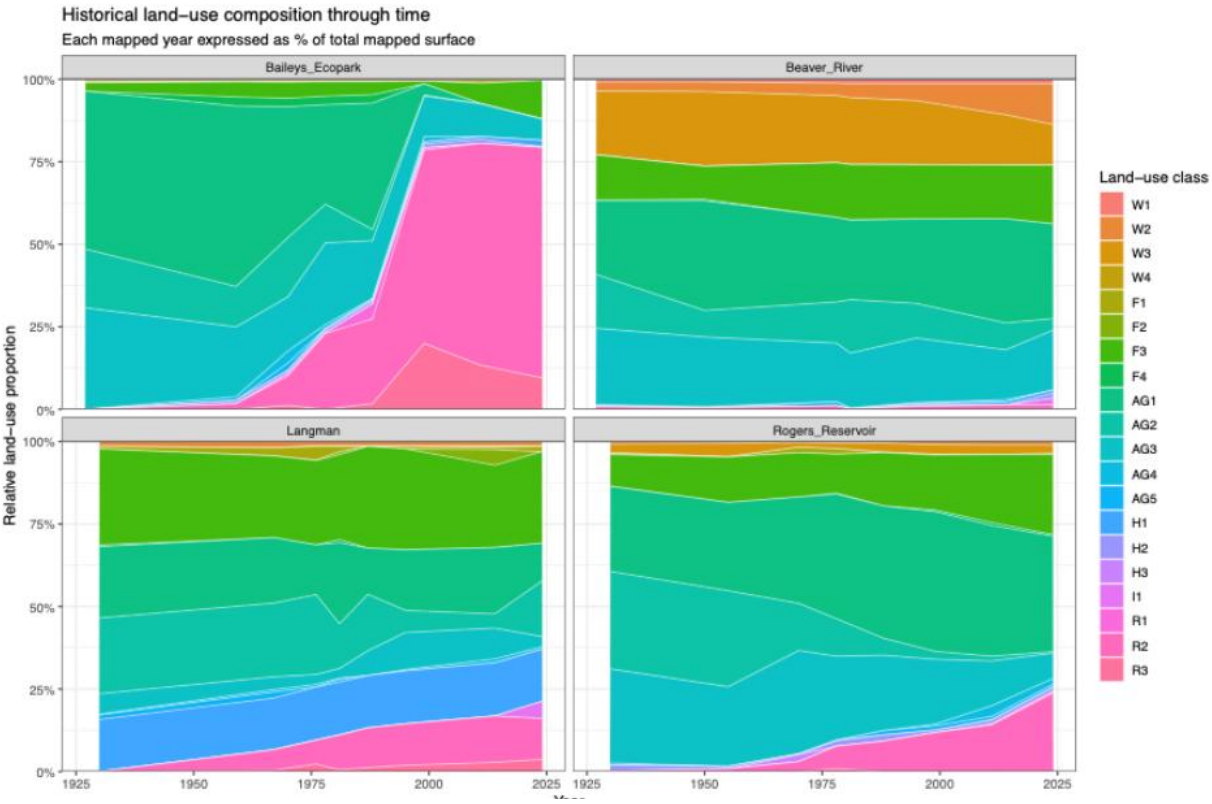

*Figure 13. Historical land-use trajectories reconstructed from digitized aerial photographs for the four study sites. Each mapped year is expressed as 100% of the total mapped surface area for that site, allowing comparison of relative land-use composition through time.*

Baileys Ecopark (Fig. 11, 13 and Appendix Figures 7-9) shows the most pronounced transformation, characterized by a marked expansion of mixed anthropogenic land cover (AG5) beginning in the late twentieth century and accelerating toward the present. This increase corresponds with a decline in several agricultural classes, particularly crop and hay fields, reflecting the rapid urban expansion of the Newmarket area during recent decades. In contrast, Beaver River (Fig. 10, 13 and Appendix Figures 4-6) displays comparatively stable land-use composition through time, with agriculture remaining the dominant component and only modest shifts among crop, hay, and pasture categories. Forest cover remains present but does not show major directional change across the mapped sequence.

Bass Lake (Langman) and Rogers Reservoir occupy intermediate positions between these two extremes. At Bass Lake (Langman) (Figs. 9 and 13; Appendix Figures 1–3), agricultural classes gradually decline while mixed forest (F3) and deciduous forest (F1) increase in relative importance through time, reflecting partial reforestation and the persistence of a heterogeneous wetland–upland mosaic surrounding the site. Wetland classes, including swamp wetland (W3) and graminoid marsh (W2), remain consistently present across the record, reinforcing the complex ecological setting of the basin.

Rogers Reservoir (Figs. 12 and 13; Appendix Figures 10–12) shows more moderate land-use shifts overall, with forest and agricultural categories fluctuating through time but without the dramatic urban expansion observed at Baileys Ecopark.

Together, these reconstructions highlight a regional gradient of landscape change, ranging from strong urbanization to relatively stable rural land-use. Full land-use composition data are provided in Appendix Tables 6–9. Summary values for the earliest and most recent mapped time intervals are presented in Table 6.

*Table 6. Summary of land-use composition at earliest and most recent mapped dates for each site. Values represent the proportional contribution (%) of aggregated land-use categories with AG representing agriculture, F representing forests, H representing hydrology, W representing wetlands, R representing residentials and I representing infrastructure.*

| Site | Earliest year | AG (%) | F (%) | H (%) | W (%) | R (%) | I (%) | Most recent year | AG (%) | F (%) | H (%) | W (%) | R (%) | I (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Baileys Ecopark | 1927 | 96.37 | 2.99 | 0 | 0.64 | 0 | 0 | 2025 | 6.53 | 11.69 | 2.13 | 0.31 | 79.35 | 0 |
| Beaver River | 1927 | 62.31 | 13.94 | 0 | 22.92 | 0.83 | 0 | 2024 | 50.34 | 17.8 | 2.48 | 26.02 | 1.37 | 1.99 |
| Bass Lake (Langman) | 1930 | 52.35 | 30.37 | 15.76 | 0.03 | 1.48 | 0 | 2024 | 32.12 | 29.33 | 15.8 | 16.09 | 1.5 | 5.16 |
| Rogers Reservoir | 1930 | 84.43 | 10.16 | 1.81 | 3.44 | 0.17 | 0 | 2025 | 45.63 | 24.96 | 1.43 | 3.72 | 24.26 | 0 |

## 3.12 Ordination of Pollen Assemblages

To evaluate whether pollen assemblages reflect these contrasting landscape contexts, we examined the multivariate structure of pollen data across all sites using Principal Components Analysis (PCA) of Hellinger-transformed pollen percentages (Fig. 14). The first two axes explain 33.1% and 22.4% of the total variance in assemblage composition, respectively, accounting for 55.5% of the total variation in the dataset (full PCA axis loadings are provided in Appendix Table 4). Samples from each site form distinct clusters in ordination space with limited overlap, indicating that pollen assemblages capture consistent compositional differences among the study landscapes.

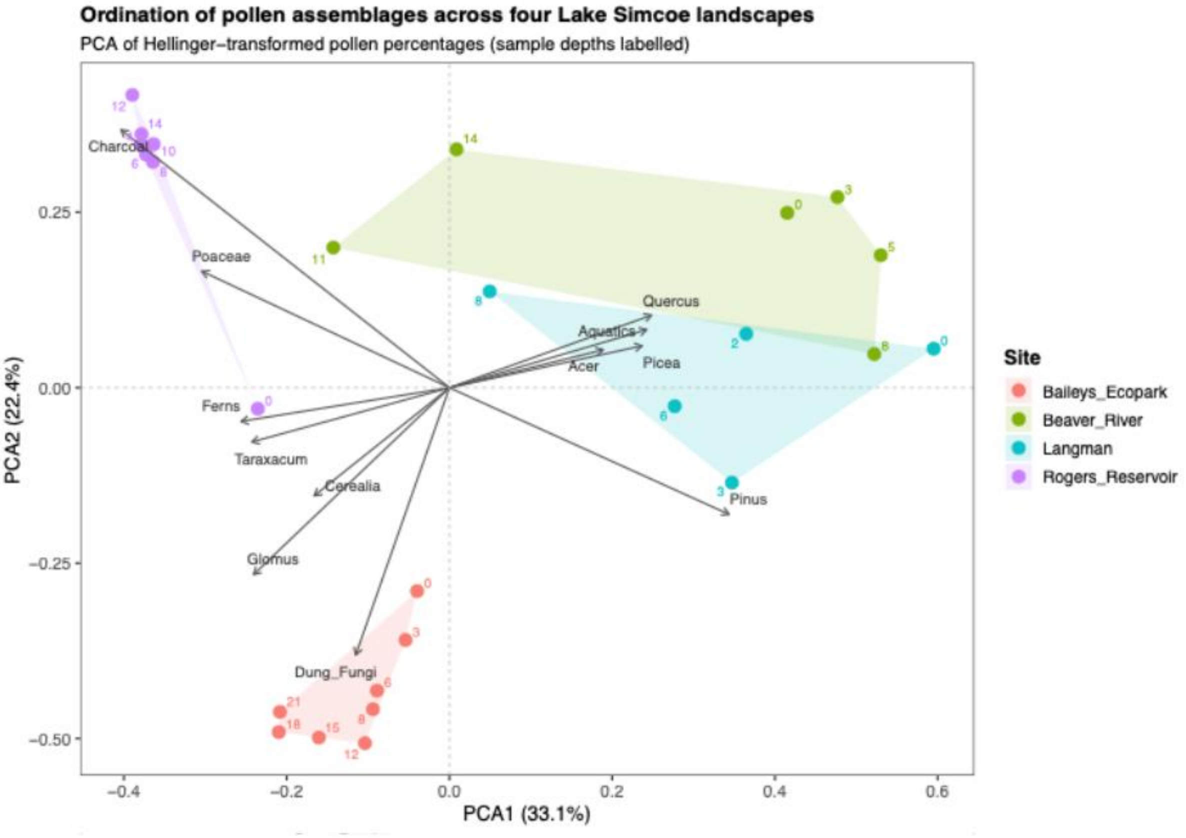

*Figure 14. Principal Components Analysis (PCA) of Hellinger-transformed pollen percentages from sediment cores collected across four landscapes in the Lake Simcoe region. The first two axes explain 33.1% and 22.4% of the total variance in pollen assemblage composition, respectively. Samples are colored by site, and convex hulls outline the*

*distribution of samples from each location. Species arrows indicate the direction and strength of taxon loadings.*

Beaver River samples plot strongly along the positive portion of PCA1 and are associated with arboreal taxa including *Quercus, Acer*, and *Picea*, reflecting the predominance of forest vegetation in the surrounding rural landscape. Bass Lake (Langman) samples occupy an intermediate position on PCA1 and cluster slightly positive on PCA2, corresponding with mixed forest taxa and aquatic indicators, consistent with the heterogeneous wetland–upland mosaic surrounding the site. Rogers Reservoir samples plot toward the negative portion of PCA1 and are associated with charcoal and Poaceae, suggesting a stronger influence of open vegetation and disturbance-related taxa. In contrast, Baileys Ecopark samples form a tight cluster at strongly negative PCA2 values and are associated with disturbance-related indicators including coprophilous fungal spores (e.g., *Sordaria, Podospora, Delitschia;* see Appendix plate.1 and 2), *Glomus*, and cultivated taxa such as Cerealia-type. The separation of site clusters demonstrates that pollen assemblages record distinct vegetation signals corresponding to the differing landscape contexts documented in the GIS reconstruction.

## *3.13 Strongest Pollen–Land-use Relationships*

Pearson and Spearman correlation analyses were used to evaluate relationships between linked pollen indicator groups and interpolated land-use proportions. Both statistics produced similar rankings of the strongest pollen–land-use associations (Table 7). A complete matrix of all calculated correlation coefficients and associated p-values for each site is available in Appendix Table 5. Detailed time-series comparisons of these scaled pollen indicator groups against their corresponding mapped land-use trajectories for each individual site are presented in Appendix Figures 13 through 16. Analysis of these linked pollen groups revealed several strong relationships between pollen assemblages and mapped land-use classes (Fig. 15). The strongest relationships involved pasture-related disturbance (AG3), combined pasture–fallow indicators (AG3+AG4), crop indicators (AG1), hay indicators (AG2), and broad forest cover (Forest_all). The direction and strength of these relationships varied among sites. For example, forest pollen indicators showed strong positive relationships with mapped forest cover at Beaver River and Baileys Ecopark, whereas agricultural indicators tracked land-use change more strongly at Bass Lake (Langman) and Baileys Ecopark. These results indicate that some pollen indicator groups track mapped land-use classes consistently across sites, whereas others vary depending on local landscape context.

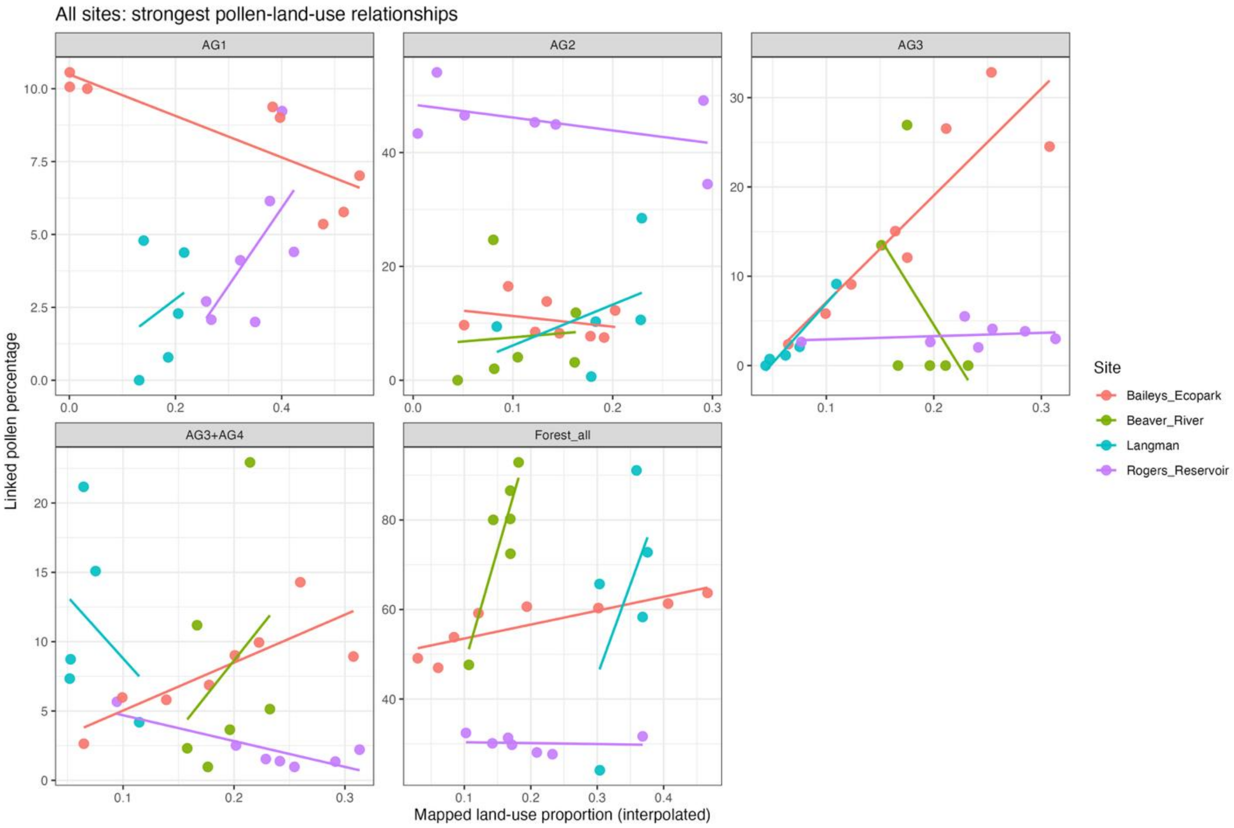

*Figure 15. Strongest linked pollen–land-use relationships across all sites based on the highest-ranked pollen groups in the cross-site analysis. Panels show relationships between linked pollen percentages and interpolated mapped land-use proportions for AG1 (crop), AG2 (hay), AG3 (pasture), AG3+AG4 (pasture plus fallow/disturbance), and Forest_all. Colors indicate site identity.*

*Table 7. Strongest correlations between pollen indicator groups and corresponding land-use classes across the four study sites. n = number of paired pollen–GIS observations. Bootstrap 95% CIs (10,000 resamples, percentile method) are shown alongside parametric p-values. Bold Cis indicate intervals that do not include zero.*

| **Site** | **Pollen group** | **Land-use class** | **n** | **Pearson r** | **p** | **Boot 95% CI** | **Spearman ρ** | **p** | **Boot 95% CI** |
|---|---|---|---|---|---|---|---|---|---|
| Bass Lake (Langman) | AG3 | Pasture | 5 | 0.956 | 0.011 | **[0.91, 1]** | 1 | 0.017 | **[1, 1]** |
| Bass Lake (Langman) | AG2 | Hay | 5 | 0.418 | 0.484 | [-0.525, 1] | 0.9 | 0.083 | **[0.111, 1]** |
| Beaver River | Forest_all | Forest cover | 6 | 0.889 | 0.018 | [-0.366, 0.999] | 0.6 | 0.242 | [-0.8, 1] |
| Rogers Reservoir | AG3+ AG4 | Pasture + fallow | 7 | −0.828 | 0.021 | [-0.999, 0.724] | −0.607 | 0.167 | [-1, 0.407] |
| Baileys Ecopark | AG1 | Cropland | 8 | −0.835 | 0.01 | **[-0.991, -0.686]** | −0.881 | 0.007 | **[-1, -0.241]** |
| Baileys Ecopark | AG3 | Pasture | 8 | 0.894 | 0.003 | **[0.743, 0.997]** | 0.905 | 0.005 | **[0.407, 1]** |
| Baileys Ecopark | AG3+ AG4 | Pasture + fallow | 8 | 0.811 | 0.015 | **[0.504, 0.987]** | 0.833 | 0.015 | **[0.289, 1]** |
| Baileys Ecopark | Forest_all | Forest cover | 8 | 0.834 | 0.01 | **[0.688, 0.976]** | 0.952 | 0.001 | **[0.62, 1]** |

Bootstrap analysis confirmed that the strongest reported correlations are robust to resampling (Table 7). All four correlations at Baileys Ecopark produced bootstrap 95% confidence intervals that excluded zero for both Pearson and Spearman statistics, indicating that these relationships are not driven by individual influential observations. The Bass Lake (Langman) AG3 (pasture) correlation was similarly robust at both statistics despite the small sample size (n = 5), confirming a strong and stable pollen–land-use relationship for pasture indicators at this site. In contrast, the Forest_all correlation at Beaver River (n = 6) and the AG3+AG4 correlation at Rogers Reservoir (n = 7) produced bootstrap confidence intervals that included zero, indicating that these individual-group correlations are sensitive to specific observations. However, the significant Mantel and Procrustes results at both sites (Table 8) confirm that the overall multivariate concordance between pollen and GIS datasets remains robust even where individual indicator-group correlations are sample-size-limited.

## *3.14 Multivariate Correspondence Between Land-use Types and Pollen Assemblages*

To quantitatively evaluate the relationship between reconstructed land-use composition and pollen assemblage structure, we compared the GIS-derived land-use matrices with pollen assemblage data using Mantel tests and Procrustes analysis (Table 8).

*Table 8. Multivariate correspondence between GIS-derived land-use composition and pollen assemblage structure. Mantel tests compare Bray–Curtis dissimilarity matrices; Procrustes analyses compare PCA configurations. Significant results ($p < 0.05$) in bold.*

| Site | n | Mantel r | Mantel p | Procrustes correlation | Procrustes p |
|---|---|---|---|---|---|
| Beaver River | 6 | 0.77 | **0.008** | 0.85 | **0.018** |
| Rogers Reservoir | 7 | 0.77 | **0.012** | 0.82 | **0.018** |
| Baileys Ecopark | 8 | 0.66 | **0.007** | 0.76 | **0.025** |

| Site | n | Mantel r | Mantel p | Procrustes correlation | Procrustes p |
|---|---|---|---|---|---|
| Bass Lake (Langman) | 5 | −0.54 | 0.875 | 0.48 | 0.825 |

Significant correlations between the two datasets were detected at three of the four sites. Mantel tests indicated strong correspondence between landscape composition and pollen assemblages at Beaver River ($r = 0.77$, $p = 0.008$), Rogers Reservoir ($r = 0.77$, $p = 0.012$), and Baileys Ecopark ($r = 0.66$, $p = 0.007$). Procrustes analyses produced consistent results at the same three sites.

In contrast, Bass Lake (Langman) did not exhibit a significant relationship between the two datasets (Mantel $r = -0.54$, $p = 0.875$; Procrustes correlation = 0.48, $p = 0.825$). The negative Mantel r indicates that samples close in pollen composition are dissimilar in land-use composition, and vice versa — a result that cannot be attributed to weak signal alone but suggests an active decorrelation between the two data streams at this site. Although the Bass Lake (Langman) *rbacon* chronology is independently supported by cross-validation with the $^{210}$Pb-dated *Ambrosia* rise at Beaver River, the wider formal age uncertainties and the small sample size ($n = 5$) at this site reduce the power of the multivariate tests. The potential causes of this result, including landscape complexity, pollen source-area effects, and pollen sample temporal compounding, are explored in section 3.15.4.

## *3.15 Discussion*

The landscapes of southern Ontario have undergone profound transformation since European settlement, when extensive forest clearing, wetland drainage, and agricultural expansion converted a predominantly forested region into a highly modified agricultural and urban landscape (Kelly, 1974; McAndrews, 1988). Historical reconstructions based on early surveyor records indicate that pre-settlement forest cover exceeded 80% across much of southern Ontario, whereas modern landscapes retain less than 20% forest cover and substantially reduced wetland area (Larson *et al.*, 1999; Butt *et al.*, 2012). These long-term changes have reshaped regional vegetation patterns and ecological processes, but their expression in palaeoecological records remains uneven and site-dependent (Ekdahl *et al.*, 2004).

By integrating land-use reconstructions derived from historical imagery with pollen assemblages from four sediment records across the Lake Simcoe region, this study provides an empirical assessment of how twentieth-century landscape transformation is recorded in pollen assemblages. The results demonstrate that agricultural indicators show the strongest and most consistent relationships with mapped land use, whereas forest and wetland signals are more site-specific and influenced by local landscape structure. Together, these findings illustrate how pollen–land-use relationships vary across different landscape contexts and provide a framework for interpreting anthropogenic signals in recent palaeoecological records.

### *3.15.1 Historical Landscape Transformation in the Lake Simcoe Region*

The landscapes surrounding Lake Simcoe reflect the broader trajectory of land-use transformation that has occurred across southern Ontario since European settlement. The arrival of European settlers in the late eighteenth and early nineteenth centuries initiated a period of widespread forest clearing, wetland drainage, and agricultural expansion that progressively converted the landscape into an agricultural mosaic (Kelly, 1974; McAndrews, 1988). During the twentieth century, continued agricultural intensification and the expansion of urban centres further altered land cover patterns, particularly along the southern margins of the Lake Simcoe watershed, where the northward expansion of the Greater Toronto Area has been one of the fastest rates of suburban growth in Canada (Bourne *et al.*, 2003; Statistics Canada, 2021).

The land-use reconstructions presented here capture the late stages of this transformation. The most dramatic change occurred at Baileys Ecopark, where the expansion of Newmarket converted agricultural land into residential and commercial uses — a pattern consistent with the well-documented urban sprawl of York Region municipalities since the 1970s (Bourne *et al.*, 2003). The relative stability of Beaver River aligns with the persistence of a rural agricultural economy in the northern portions of the Lake Simcoe watershed, where physiographic constraints and lower development pressure have slowed suburban expansion (Palmer *et al.*, 2011). Intermediate trajectories at Bass Lake (Langman) and Rogers Reservoir reflect the moderating influence of conservation designations and wetland protection initiatives, including the Lake Simcoe Protection Plan (LSRCA, 2009) and provincial wetland evaluation processes (Ontario Ministry of Natural Resources, 2010).

Despite differences in local trajectories, several consistent regional patterns emerge. Agricultural land-use remained dominant at all sites throughout the twentieth century, consistent with agricultural census data showing that farmland occupied over 60% of Simcoe County throughout much of the century (Statistics Canada, 2021). Forest cover showed localized increases at some sites, consistent with the broader pattern of forest transition — secondary regrowth on abandoned marginal agricultural land — documented across parts of northeastern North America since the early twentieth century (Ramankutty and Foley, 1999; Foster *et al.*, 2003; Drummond and Loveland, 2010).

### *3.15.2 Pollen Responses to Documented Land-use Change*

The clear separation of sites in PCA ordination space (Fig. 14) confirms that pollen assemblages record compositionally distinct vegetation signals corresponding to the contrasting landscape contexts documented in the GIS reconstruction. This separation is consistent with the principle that pollen assemblages from small-to-medium basins in heterogeneous landscapes integrate vegetation signals from a relevant source area (RSAP) extending hundreds of meters to several kilometers from the sampling point (Bunting *et al*., 2004; Sugita, 2007a; Hellman *et al*., 2009).

The strong association of Baileys Ecopark samples with Cerealia-type pollen and coprophilous fungal spores is particularly noteworthy. Coprophilous fungi are widely recognized as indicators of herbivore presence and pastoral agriculture in palaeoecological records (van Geel *et al*., 2003; Baker *et al*., 2013; Perrotti and van Asperen, 2019). Their prominence at Baileys, together with elevated Glomus (an indicator of soil erosion; van Geel *et al*., 1989) and high Cerealia-type pollen, provides an independent palaeoecological fingerprint of the intensive agricultural landscape documented in the GIS reconstruction. Notably, these agricultural indicators appear to record the farming phase more strongly than the subsequent urban transition — suggesting that the pollen signal of urbanization is an absence of agricultural indicators rather than the appearance of a distinctive urban pollen type (cf. Mack, 2003).

The charcoal-Poaceae association at Rogers Reservoir may reflect a combination of local management burning in the wetland margin and open grassland maintenance, consistent with historical fire as a wetland management tool in northeastern North American settings (Middleton, 2002).

### *3.15.3 Coupling between Pollen Indicators and Mapped Land Use*

The correlation analyses reveal that agricultural indicators — particularly AG3 (pasture) and AG1 (crop) — exhibit the strongest and most consistent relationships with mapped land-use classes across sites (Table 7; Fig. 15). This is consistent with the well-established role of anthropogenic pollen indicators (APIs) as markers of human land use in palaeoecological records, first systematized by Behre (1981) for European landscapes and subsequently applied in North American contexts by McAndrews (1988) and Fuller et al. (1998). The present results extend this framework by providing direct empirical validation against independently mapped land-use data — something rarely available in palaeoecological studies.

The strong Spearman correlation of $\rho = 1.0$ between pasture pollen indicators and mapped pasture at Bass Lake (Langman) is striking, especially because this site failed the multivariate tests (§3.14). This indicates that specific univariate pollen–land-use relationships can be preserved even where the full multivariate signal is decorrelated — an observation with practical implications for palaeoecological interpretation at complex sites.

The negative correlation between AG1 (crop pollen) and mapped cropland at Baileys Ecopark ($r = -0.835$) deserves careful interpretation. This does not indicate that crop pollen behaves contrary to expectation. Rather, it reflects the temporal trajectory of landscape replacement: as cropland was progressively converted to urban land use in the late twentieth century, both the mapped cropland area and the crop-associated pollen signal declined together through time. The negative correlation thus represents a positive ecological relationship (less cropland → less crop pollen) expressed as a mathematically negative correlation when plotted against the declining land-use variable. This is an important interpretive point that should be recognized in any correlative analysis where land-use classes are being replaced rather than simply expanding or contracting (cf. Foster et al., 2003).

The Forest_all variable showed strong positive correlations with mapped forest cover at Beaver River (Pearson $r = 0.889$) and Baileys Ecopark (Spearman $\rho = 0.952$), but weaker relationships at other sites. This pattern is consistent with pollen source-area theory, which predicts that the strength of the local pollen–vegetation relationship depends on the size and configuration of vegetation patches relative to the relevant source area of the basin (Sugita, 2007a; Hellman et al., 2009; Calcote, 1995). At Beaver River, where forest is the dominant landscape element, the pollen source area is largely encompassed within forested terrain, producing strong local correspondence. At more fragmented sites, regional pollen rain from distant forested areas may dilute the local signal.

The bootstrap analysis provides a more nuanced picture of correlation reliability than parametric p-values alone. At Baileys Ecopark, where the largest sample size ($n = 8$) and the most pronounced landscape transformation was available, all reported correlations proved robust to resampling — confirming that pollen indicators of cropland, pasture, and forest cover track mapped land-use change reliably at this site. The robustness of the Bass Lake (Langman) AG3 correlation ($n = 5$) is particularly notable, demonstrating that the pasture pollen signal tracks mapped pasture even at the site where multivariate tests failed.

At Beaver River and Rogers Reservoir, the fragility of individual-group correlations under bootstrapping (Forest_all and AG3+AG4, respectively) highlights the inherent limitation of evaluating univariate relationships at $n = 6–7$. Importantly, the significant Mantel and Procrustes results at both sites (Table 8) demonstrate that the overall multivariate relationship between pollen assemblage composition and landscape structure is robust, even where individual indicator-group correlations are sample-size-limited. This underscores the value of the multi-method analytical framework adopted here: univariate correlations identify specific pollen–land-use linkages, while multivariate tests assess the overall coherence of the two datasets. Where both lines of evidence converge — as at Baileys Ecopark — confidence in the pollen–landscape relationship is highest. Where they diverge — as at Beaver River and Rogers Reservoir — the multivariate concordance provides the more reliable assessment.

The multivariate analyses (Mantel and Procrustes) provide a complementary assessment that transcends the limitations of individual indicator-group comparisons. The strong concordance at three of four sites (Mantel r = 0.66–0.77; Procrustes correlation = 0.76–0.85) demonstrates that overall pollen assemblage turnover parallels mapped landscape change. These values are comparable to or exceed the pollen–landscape correspondences reported in Scandinavian calibration studies using the REVEALS/LOVE framework (Broström et al., 2008; Mazier et al., 2012), suggesting that the hybrid air-photo/pollen approach can yield quantitatively robust pollen–landscape linkages even without formal pollen productivity estimates.

### *3.15.4 The Bass Lake (Langman) problem: Landscape complexity and the limits of pollen–geospatial coupling*

The failure of multivariate tests at Bass Lake (Langman) (Mantel r = −0.54; Procrustes correlation = 0.48; both non-significant) warrants careful examination rather than dismissal. A negative Mantel r does not simply indicate absence of signal; it indicates that the two datasets are organized in opposing directions in multivariate distance space. Several factors, individually or in combination, likely contribute to this pattern.

First, the pollen source area at Bass Lake (Langman) may extend substantially beyond the mapped air-photo extent. Wind-pollinated arboreal taxa such as *Pinus*, *Betula*, and *Quercus* can contribute significant regional pollen from sources several kilometers distant (Sugita, 2007b; Calcote, 1995). If a substantial fraction of the pollen signal originates outside the mapped landscape, the correlation between local land-use composition and pollen composition is expected to weaken or even reverse where local and regional vegetation trajectories diverge.

Second, the wetland-to-upland transitions at Bass Lake (Langman) are spatially complex and do not lend themselves easily to broad polygon classification. Small, interdigitated patches of swamp forest, emergent marsh, and upland deciduous forest may be classified as discrete polygons in the GIS, but their ecological boundaries are gradational, and pollen from these mapped categories is likely thoroughly mixed within the depositional basin. This classification-resolution mismatch is a recognized source of error in pollen–landscape comparisons (Bunting et al., 2004; Gaillard et al., 2008).

Third, chronological uncertainty and temporal resolution differences between datasets further contribute to the observed mismatch. Although the Bass Lake (Langman) rbacon median chronology is independently corroborated by Ambrosia biostratigraphic cross-validation, with the Ambrosia rise at Bass Lake (Langman) (rbacon: ~1909 CE) agreeing within approximately six years with the same event at Beaver River ($^{210}$Pb: ~1915 CE), the formal 95% confidence envelopes remain wide, on the order of 80–150 years per sample. Median ages are therefore used as point estimates for interpolating GIS land-use values, introducing uncertainty in the alignment between individual pollen samples and specific aerial photograph dates. At a sample size of $n = 5$, even modest misalignment of one or two samples could substantially affect the Mantel and Procrustes statistics. In addition, low sedimentation rates at Bass Lake (Langman) result in standard 1 cm sediment intervals integrating longer periods of pollen deposition, producing temporal averaging that does not correspond directly to discrete cartographic snapshots.

Fourth, short-term, non-linear disturbance events that pre-date the aerial photograph record may also contribute to the decorrelation between pollen assemblages and mapped land-use patterns. In southern Ontario, conflict-driven land-use disruption during the Beaver Wars has been associated with population displacement, settlement reorganization, and localized land abandonment (Trigger, 1987; Warrick, 2000; Birch, 2015). Such events fall outside the temporal range of the GIS reconstruction, which is limited to the twentieth century onward, and therefore cannot be directly captured in mapped land-use datasets. However, they may still be recorded in sedimentary archives as short-lived ecological responses. At Bass Lake (Langman), such processes may contribute to the co-occurrence of disturbance indicators reflective of fire events and soil erosion such as charcoal, Glomus and shifts in late-successional taxa such as *Fagus grandifolia*. These signals reflect episodic disturbance and landscape instability that are not directly comparable to the longer-term, spatially aggregated land-use patterns derived from aerial imagery.

We interpret the Bass Lake (Langman) result not as a failure of the hybrid method but as an informative finding about its boundary conditions. Of the contributing factors identified, including pollen source-area mismatch, classification-resolution mismatch in heterogeneous wetlands, chronological uncertainty, and short-term non-linear disturbance, the first two are likely the primary drivers. The Ambrosia cross-validation supports the overall reliability of the Bass Lake (Langman) median chronology, indicating that chronological uncertainty is a contributing but not dominant factor. Non-linear disturbance events likely introduce additional variability in the pollen record, but operate at temporal and spatial scales that are not directly comparable to aerial photo-derived land-use patterns.

Complex wetland landscapes characterized by high spatial heterogeneity, extensive ecotonal gradients, and limited sample sizes may therefore require more spatially explicit approaches, such as pollen source-area modelling using REVEALS/LOVE (Sugita, 2007a, 2007b) or high-resolution vegetation mapping within defined catchment buffers, to achieve meaningful multivariate pollen–landscape comparisons. Notably, individual pollen–land-use relationships can still be preserved at such sites, as demonstrated by the bootstrap-robust AG3 (pasture) correlation at Bass Lake (Langman), even where the full multivariate signal is decorrelated.

### *3.15.5 Implications for interpreting anthropogenic signals in pollen records*

The strong correspondence between agricultural land-use classes and pollen indicators confirms that anthropogenic signals associated with agriculture can be reliably detected in sediment records, even over relatively short twentieth-century timescales. This extends the classical European API framework (Behre, 1981) to a North American setting and demonstrates that it holds at decadal resolution when tested against independently mapped land-use data. The present study thus provides a rare empirical validation of palynological land-use indicators in a region where such calibrations are scarce.

It is important to recognize that the pollen–land-use crosswalk used here does not guarantee positive correlations. The crosswalk defines an expected ecological correspondence between pollen taxa and mapped land-use classes, but whether that correspondence is actually expressed in the data depends on multiple independent factors: the fidelity of the pollen signal, the accuracy of the GIS classification, the temporal alignment between the two datasets, the pollen source area relative to the mapped extent, and the degree to which the mapped land-use class actually supports the expected vegetation. The fact that predicted associations were confirmed at some sites but not others — and that bootstrap analysis identified several reported correlations as fragile — demonstrates that the crosswalk functions as a genuine hypothesis-testing framework rather than a self-confirming assignment scheme. The most informative results are arguably the negative ones: the failure of forest pollen to track mapped forest cover reliably at sites with fragmented canopy, and the failure of fallow-disturbance indicators at Rogers Reservoir, reveal the ecological and methodological limits of the indicator-group approach and identify conditions under which pollen records cannot be straightforwardly linked to land-use maps.

Forest and wetland signals show more complex and site-dependent relationships with mapped land use. In landscapes where forest cover is fragmented and arboreal pollen is contributed by both local and regional sources, quantitative reconstructions based on forest pollen alone may misrepresent local forest-cover dynamics (Jacobson and Bradshaw, 1981; Prentice, 1985). The broad Forest_all metric used here partially mitigates this issue by collapsing forest subclasses, but more sophisticated approaches — such as the Landscape Reconstruction Algorithm (LRA; Sugita, 2007a) — may be necessary where precise quantitative forest-cover estimates are required.

These findings underscore the value of integrating palaeoecological data with spatially explicit landscape reconstructions. GIS-based reconstructions from historical air photographs provide an independent framework against which pollen signals can be tested, calibrated, and interpreted — transforming pollen records from qualitative narratives of change into quantitatively anchored records of documented landscape transformation. The hybrid approach applied here could be extended to other regions where historical air-photo archives are available — particularly in rapidly changing peri-urban landscapes of the Great Lakes region, where the pace of twentieth-century transformation has been exceptionally rapid (Drummond and Loveland, 2010).

### *3.15.6 Implications for management*

Across the study sites, palaeoecological signals, when interpreted alongside aerial photograph derived land-use reconstructions, indicate that protection, through conservation designation and limits on direct land-use disturbance, can support relative ecological stability and partial recovery, but does not fully isolate ecosystems from external pressures. For example, at

Beaver River, which is managed as a conservation area within a predominantly rural agricultural landscape, both pollen assemblages and geospatial-based land-use data reflect a relatively stable system, with a strong forest signal alongside continued agricultural influence. This suggests that the site has undergone partial ecological recovery following historical disturbance, while remaining functionally connected to broader catchment-scale processes. As a result, recovery in such systems should be understood as context-dependent, occurring within, rather than independent of, ongoing land use.

In contrast, sites influenced by urbanization and active management, such as Baileys Ecopark, show clear ecological responses to land-use transitions, particularly from agriculture to urban environments, as documented in the aerial photograph record. However, the continued presence of disturbance-related indicators in the pollen data demonstrates that these systems do not return to pre-disturbance conditions, but instead represent novel ecosystems shaped by legacy effects and ongoing inputs. This highlights that restoration in highly modified landscapes often results in new ecological states rather than full recovery of historical conditions.

More broadly, results of this chapter show that agricultural indicators provide the most consistent and sensitive signal of land-use change across sites, while forest and wetland signals are more variable and influenced by local conditions and spatial scale. This has important implications for monitoring, as it suggests that some aspects of ecological change are more readily detectable and comparable than others across both ecological and geospatial datasets.

These findings emphasize that effective land management requires a landscape-scale perspective, where conservation outcomes depend not only on site-level protection, but also on hydrological connectivity, surrounding land-use intensity, and system-specific dynamics.

## 3.16 Conclusions

This Chapter demonstrates the value of integrating historical aerial photography and GIS reconstructions with palaeoecological analysis to investigate twentieth-century landscape change across the Lake Simcoe region. The key findings are:

a) GIS reconstruction from historical air photographs reveals distinct land-use trajectories along an urban–rural gradient, from pronounced urban expansion at Baileys Ecopark to stable rural agriculture at Beaver River, with intermediate conditions at Bass Lake (Langman) and Rogers Reservoir.

b) Pollen assemblages capture compositional differences among sites consistent with their contrasting landscape contexts, as demonstrated by clear site separation in PCA ordination.

c) Agricultural pollen indicators — particularly those associated with pasture (AG3), cropland (AG1), and combined pasture-fallow disturbance (AG3+AG4) — show the strongest and most consistent correlations with mapped land-use classes, confirmed as robust by bootstrap analysis at Baileys Ecopark and for the pasture signal at Bass Lake (Langman).

d) Forest indicators perform well where forest is the dominant landscape element (Beaver River) but show weaker or bootstrap-fragile correspondence at more fragmented or heterogeneous sites, consistent with pollen source-area effects.

e) Multivariate concordance between pollen and GIS datasets is significant at three of four sites (Mantel r = 0.66–0.77; Procrustes correlation = 0.76–0.85), confirming that overall pollen assemblage turnover tracks documented landscape change.

f) The non-significant result at Bass Lake (Langman) identifies landscape complexity, spatial heterogeneity, and small sample size as the primary boundary conditions for pollen–GIS coupling at complex wetland sites. Although the radiocarbon-based chronology carries wider formal age uncertainties than the radionuclide-dated cores, independent biostratigraphic cross-validation with the *Ambrosia* rise at Beaver River (~6 years agreement) supports the reliability of the median chronology. Individual indicator-group relationships (AG3 pasture) can be preserved even where multivariate tests fail.

Several limitations should be considered when interpreting these results. First, the sample sizes available for site-level correlation analyses are small (n = 5–8), reflecting the number of air-photo dates available for comparison. While the multi-method analytical framework (correlations + Mantel + Procrustes + bootstrap CIs) provides mutual reinforcement, the statistical power of individual correlations at low n is limited. It is important to note that at Beaver River (n = 6) and Rogers Reservoir (n = 7), the non-significant Spearman results for Forest_all and AG3+AG4, respectively, reflect the limited statistical power of rank correlation at small sample sizes rather than the absence of a pollen–land-use relationship. At n = 6, Spearman's test requires $|\rho| > 0.886$ for significance at $\alpha = 0.05$ — a threshold that excludes all but near-perfect monotonic associations. Future studies could increase temporal density by incorporating satellite imagery, cadastral records, or agricultural census data. Second, pollen assemblages integrate vegetation signals across a source area that may extend well beyond the mapped landscape. Discrepancies between pollen signals and mapped land-use classes may reflect this scale mismatch. Explicit pollen source-area modelling (Sugita, 2007a, 2007b) could quantify this effect and refine pollen–landscape comparisons.

Third, the temporal resolution of historical air photographs and palynological "time slices" are uneven — intervals between mapped years and individual palynological assemblages vary from a few years to over a decade — and may miss shorter-term land-use transitions.

Fourth, no formal classification accuracy assessment was conducted for the air-photo interpretation. While interpretation was based on high-resolution imagery and standardized visual classification criteria, uncertainty associated with edge delineation and feature interpretation remains unquantified. However, positional accuracy of the georeferenced imagery was evaluated during processing, with RMSE values reported for each image (Appendix Table 1). Because land-cover features were manually delineated through visual interpretation rather than automated classification, no fixed minimum mapping unit (MMU) was applied.

Fifth, the 0.5 weighting applied to residential subclasses R2 and R3 was estimated from visual inspection of air photographs and represents an approximate correction for the pollen-silent impervious fraction of residential parcels. Alternative weightings (e.g., 0.3 or 0.7) would shift the magnitude of the residential contribution to the forest and open-land metrics but are unlikely to alter the principal conclusions, given that residential classes represent a relatively small proportion of the total mapped landscape at most sites and time periods.

Despite these limitations, the integration of historical GIS reconstruction with palaeoecological data provides a powerful framework for examining recent landscape change. Future research could expand this approach to additional sites, incorporate formal pollen source-area models, and extend the temporal baseline using pre-photographic documentary sources. Together, these results provide methodological guidance for future pollen–landscape studies and a regionally specific reconstruction of landscape change that informs conservation and environmental management in the Lake Simcoe watershed. The hybrid approach demonstrated here — combining the spatial precision of historical GIS with the temporal continuity of palaeoecological records — offers a transferable framework for linking sedimentary archives with documented landscape change across rapidly transforming temperate landscapes.

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# *Chapter 4 – Thesis Conclusions*

This thesis demonstrates that land-use change in the Lake Simcoe watershed has left distinct and persistent ecological signatures in sedimentary archives, and that these signatures can be meaningfully linked to independently documented landscape transformation.

Chapter 2 establishes the long-term palaeoecological context for the watershed, revealing that Indigenous land use produced detectable but spatially focused ecological signals including cultigen pollen and disturbance indicators embedded within a resilient forested landscape that did not undergo sustained structural transformation. In contrast, Euro-Canadian settlement initiated multi-proxy, basin-wide ecological reorganization that persists to the present. The nested design further demonstrates that the expression of these land-use signals varies systematically with basin type, hydrological connectivity, and position along a north–south settlement gradient, establishing that palaeoecological baselines are not directly transferable across contrasting depositional environments.

Chapter 3 extends this framework by providing the first systematic, quantitative comparison of pollen assemblages with independently reconstructed land-use trajectories across multiple sites within the Lake Simcoe region. GIS reconstruction from historical air photographs reveals distinct land-use trajectories along an urban–rural gradient, and the hybrid pollen–GIS analysis demonstrates that agricultural pollen indicators, particularly pasture, cropland, and fallow-disturbance indicators show robust correspondence with mapped land-use classes, confirmed by bootstrap analysis. The significant multivariate concordance at three of four sites (Mantel r = 0.66–0.77; Procrustes correlation = 0.76–0.85) confirms that overall pollen assemblage turnover tracks documented landscape change. The non-significant result at Bass Lake (Langman) identifies landscape complexity, spatial heterogeneity, and small sample size as boundary conditions for pollen–GIS coupling, while demonstrating that individual indicator-group relationships can be preserved even where multivariate tests fail.

Taken together, these findings make three contributions:

First, they provide empirical validation of anthropogenic pollen indicators against independently mapped land-use data in a North American temperate setting — something rarely available in the palaeoecological literature.

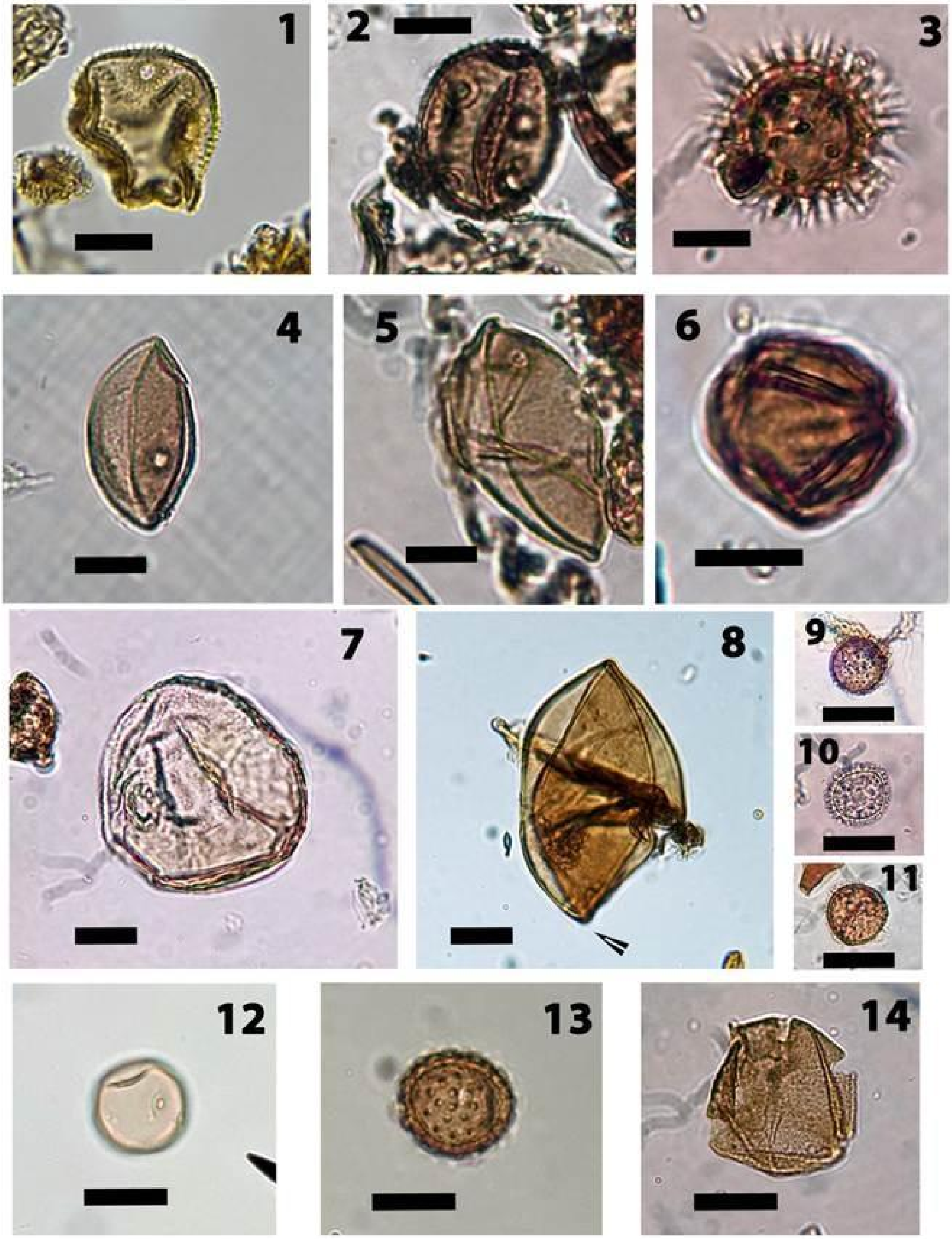
Second, they demonstrate that ecological baselines are not fixed pre-disturbance states but are structured by land-use regime and archive sensitivity and cannot be transferred across sites without accounting for depositional context.

Third, they advance a transferable, two-part framework, combining the temporal depth of nested palaeoecological analysis with the spatial precision of historical aerial imagery and GIS reconstruction, that can be applied to other rapidly transforming temperate landscapes where both sedimentary archives and historical aerial photography are available. These results reinforce the importance of considering historical land-use legacies in contemporary conservation and management, as present-day ecosystem structure and function in the Lake Simcoe watershed remain strongly conditioned by past landscape transformations whose magnitude, timing, and persistence this thesis has documented.

# *Appendices*

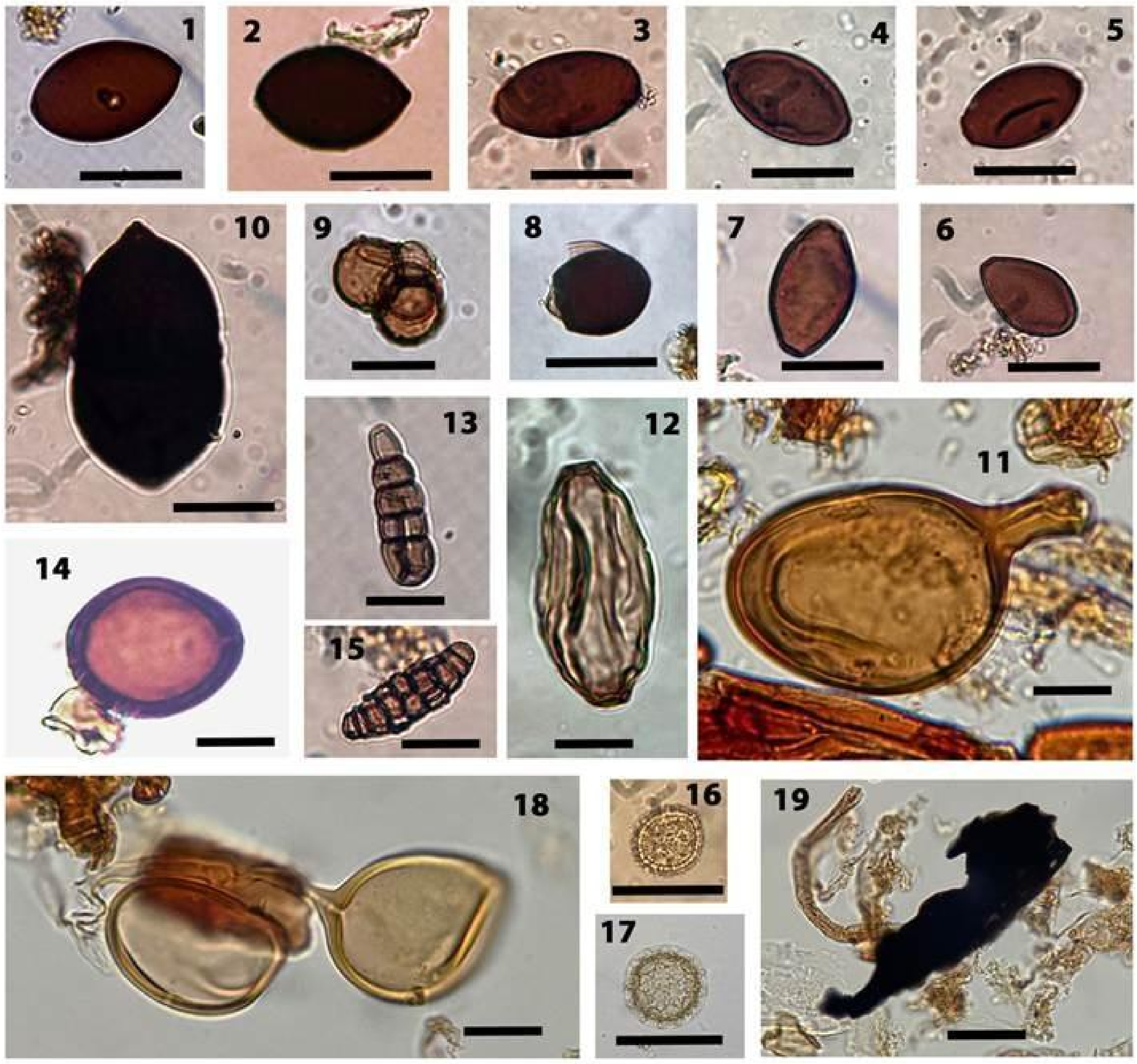
## *Appendix 1 - Palaeoecological Plates*

### *Plate 1*



*Appendix Plate 1. Pollen and spores associated with the Iroquoian and European periods (900 cal years BP to present. 1-2: Cucurbita pepo-type; 3: Helianthus annuus-type, 4-5: Cerealia-type pollen; 6: Nicotiana cf. rustica; 7-8: Zea mays-type; 9-11: Ustilago maydis (corn smut) spores; 12: Poaceae (wild grass); 13 Ambrosia (ragweed); 14: Portulaca oleracea-type (purslane). 1-3, 6, 9-11, and 14 appear exclusively in the Iroquoian period (900–350 cal years BP), 4-5 appear exclusively in the Euro-Canadian Period (350 cal years BP to present).*

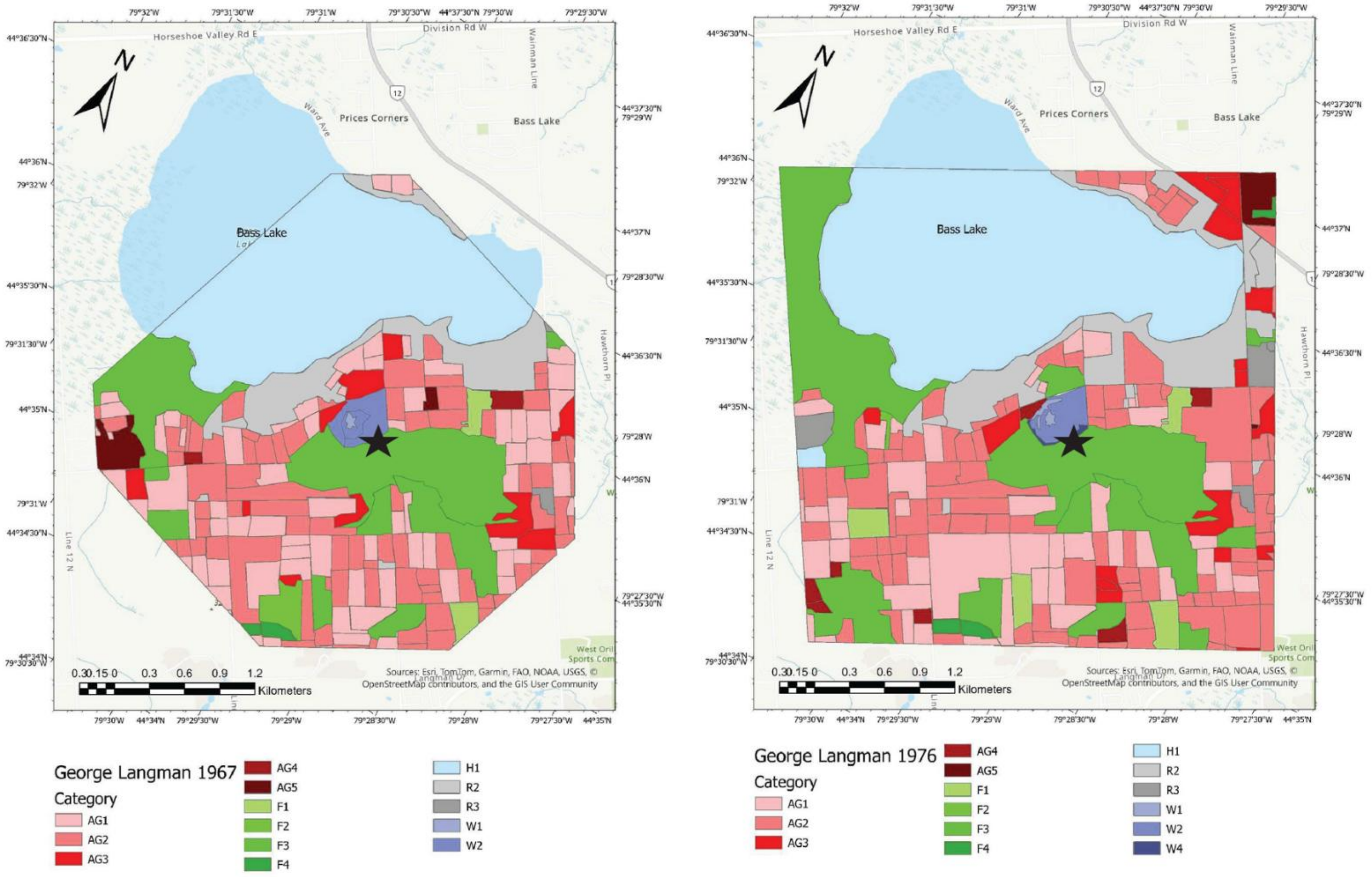
Plate 2



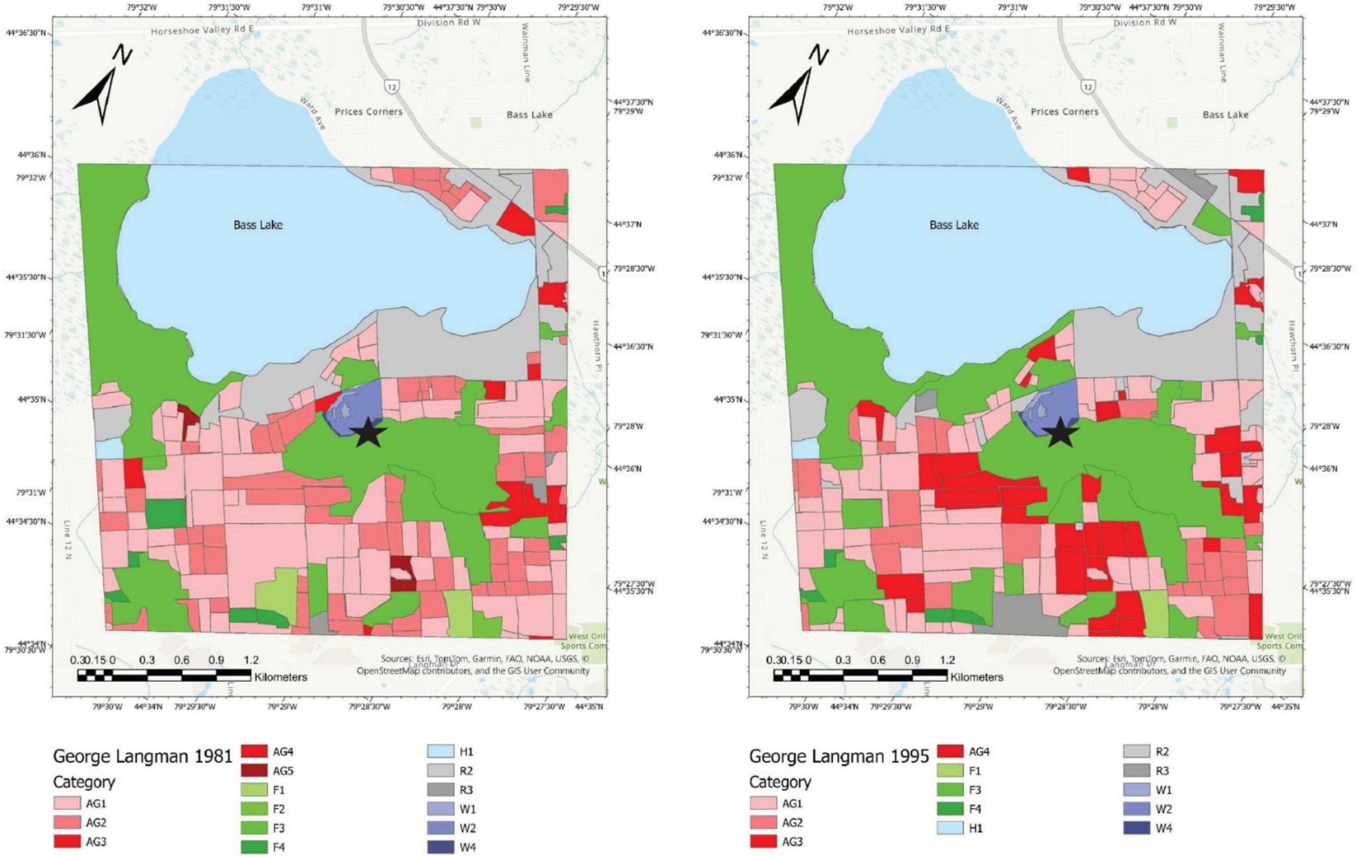
*Appendix Plate 2. Non-pollen palynomorphs (NPP) associated with the Iroquoian and European periods (900 cal years BP to present). Coprophilous fungi: 1-2 - Sordaria-type; 3-5 – Podospora-type; 6-7 – Cercophora-type; 8 - Tripterospora-type (Type 169); 10 – Delitschia-type. Soil erosion indicators: 9- Type UAB-30B; 11 and 18 – Glomus. Plant parasites: 13 – Alternaria cf. helianthi-type; 14 – Pseudoperonospora cubensis-type; 15 – Alternaria spp.; 16 – Ustilago maydis-type. 17 – unknown palynomorph.*

# *Appendix 2 - Land use Classification Maps*

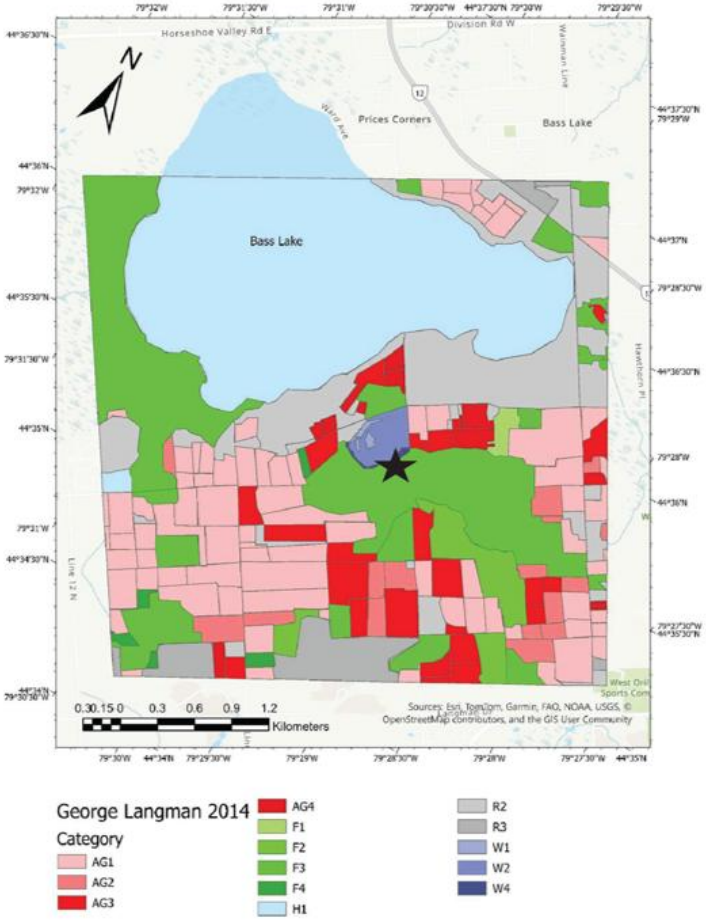
## *Bass Lake (Langman) Land use Classification Maps*



*Appendix Figure 1. Land-use classification map for the Bass Lake (Langman) study area in 1967 and 1976 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1-F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). These maps depict land-use change surrounding the core site (black star) for the 1967-1976 period.*

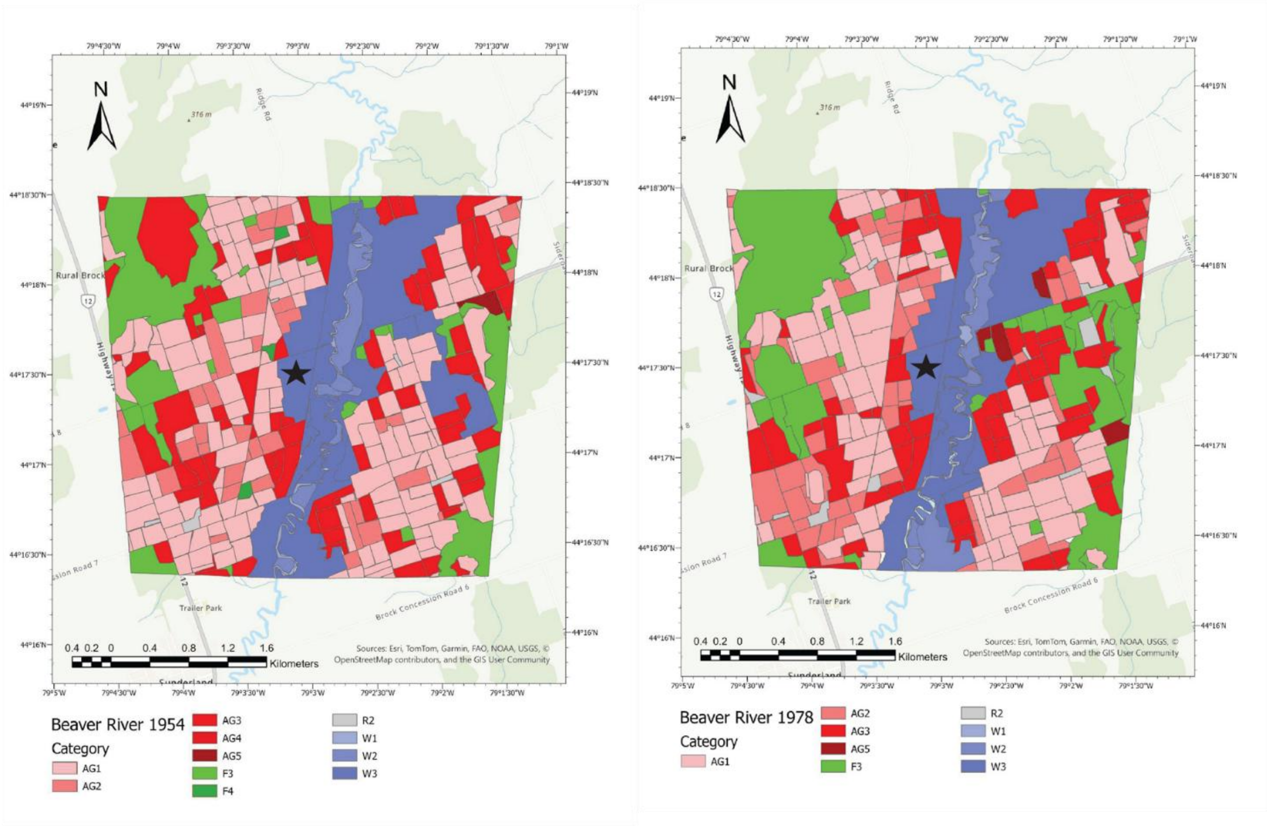


*Appendix Figure 2. Land-use classification map for the Bass Lake (Langman) study area in 1981 and 1995 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1-F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). These maps depict land-use change surrounding the core site (black star) for the 1981-1995 period.*

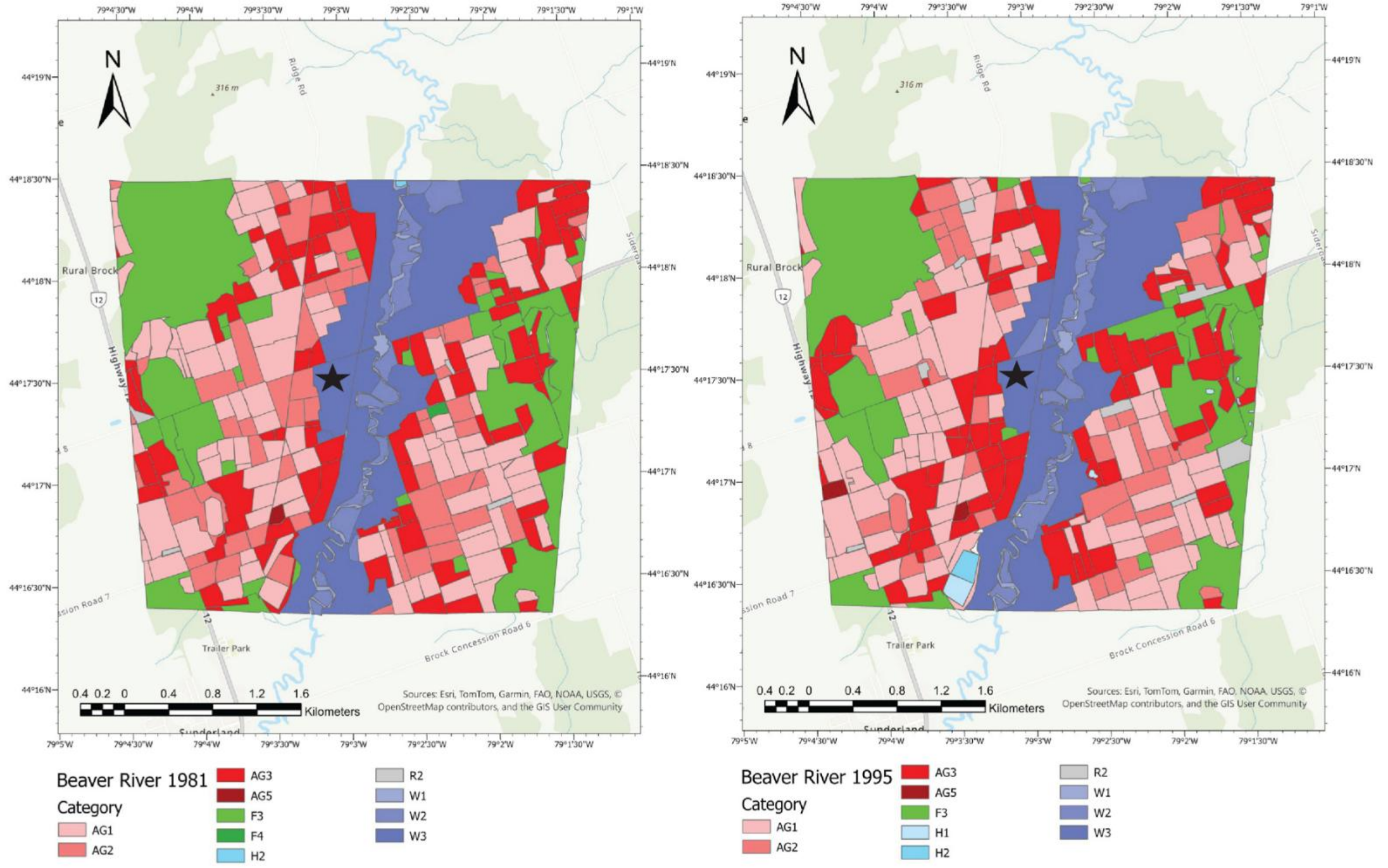


*Appendix Figure 3. Land-use classification map for the Bass Lake (Langman) study area in 2014 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1–F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). This map depicts land-use change surrounding the core site (black star) in the year 2014.*

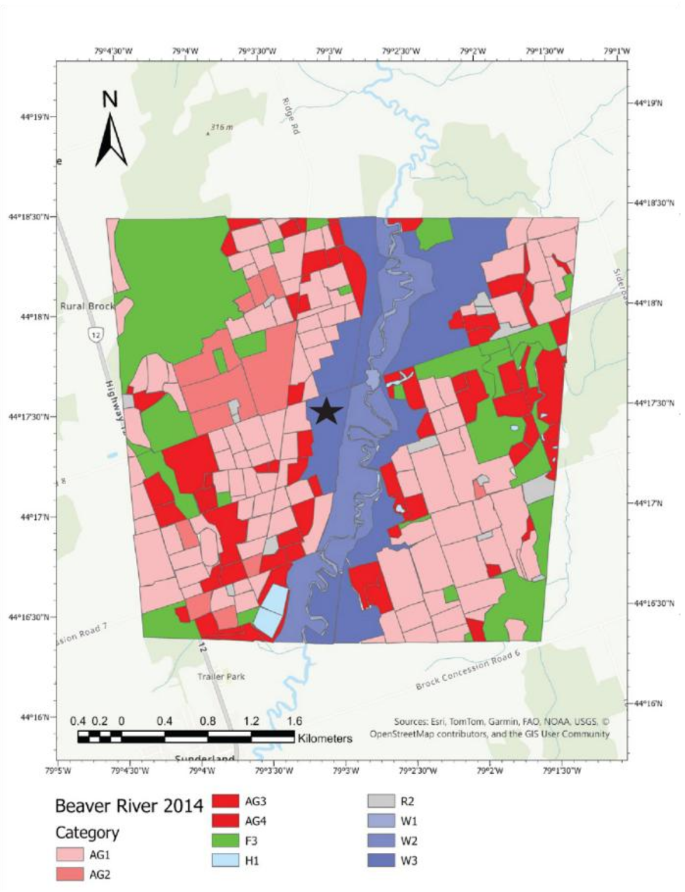
*Beaver River Land use Classification Maps*



*Appendix Figure 4. Land-use classification map for the Beaver River study area in 1954 and 1978 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1-F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). These maps depict land-use change surrounding the core site (black star) for the 1954-1978 period.*

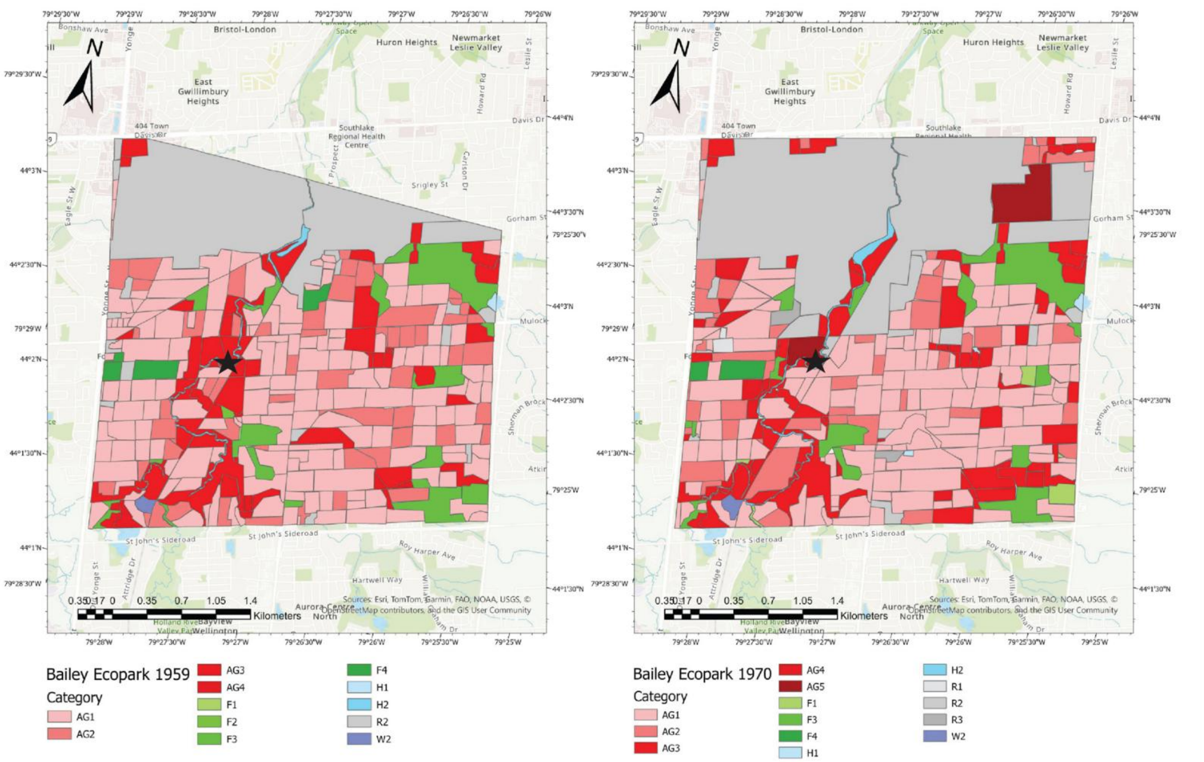


*Appendix Figure 5. Land-use classification map for the Beaver River study area in 1981 and 1995 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1-F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). These maps depict land-use change surrounding the core site (black star) for the 1981-1995 period.*

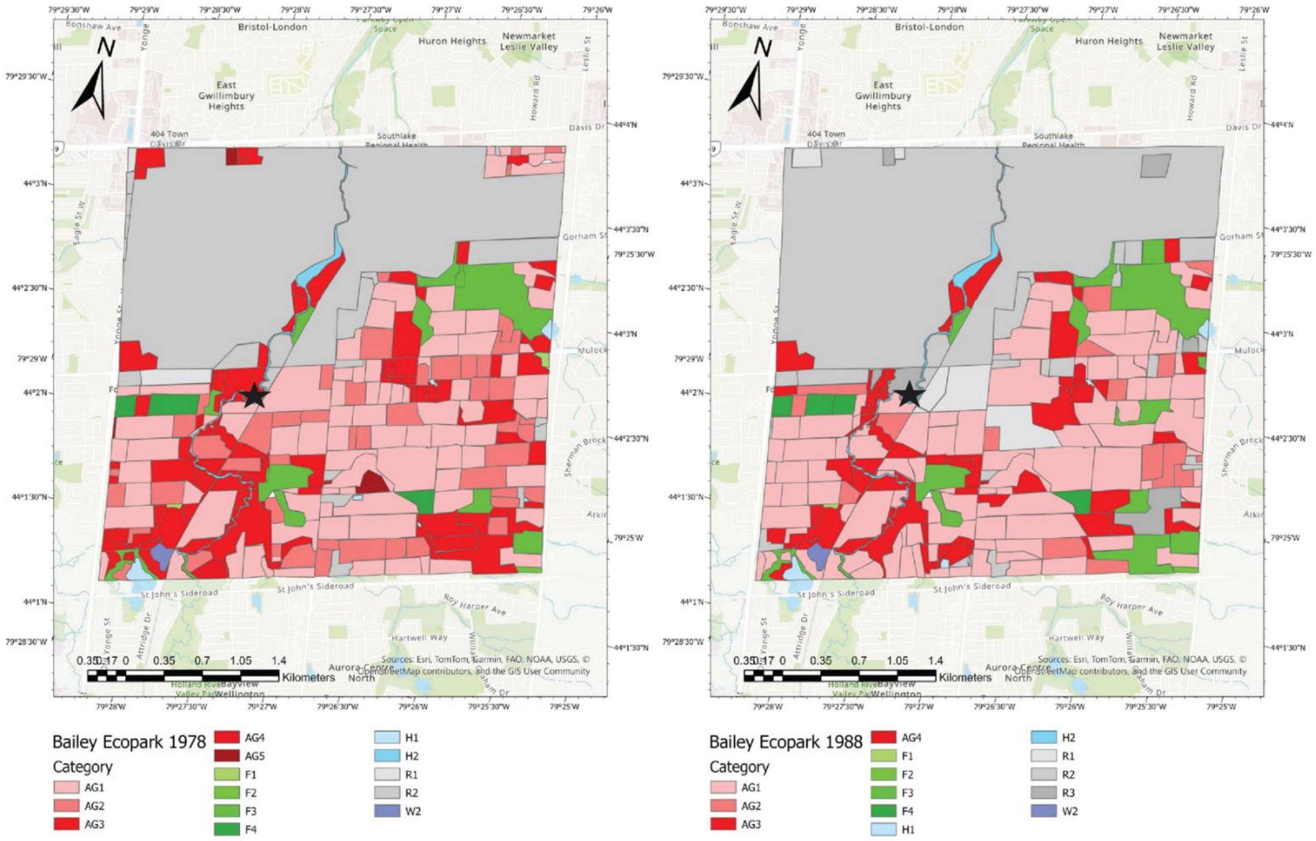


*Appendix Figure 6. Land-use classification map for the Beaver River study area in 2014 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1–F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). This map depicts land-use change surrounding the core site (black star) in the year 2014.*

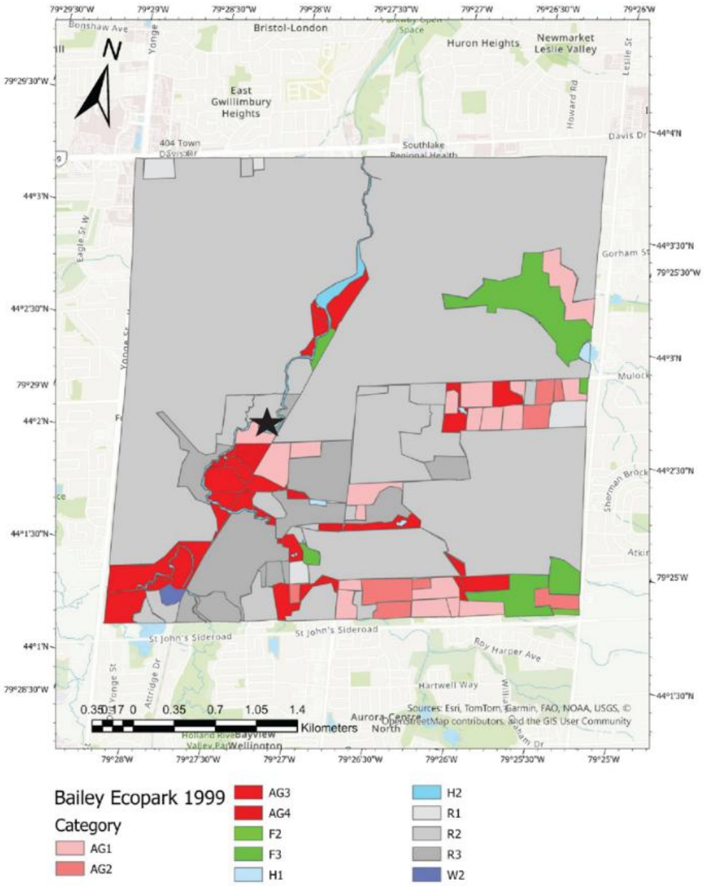
## *Baileys Ecopark Land Use Classification Maps*



*Appendix Figure 7. Land-use classification map for the Baileys Ecopark study area in 1959 and 1970 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1-F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). These maps depict land-use change surrounding the core site (black star) for the 1959-1970 period.*

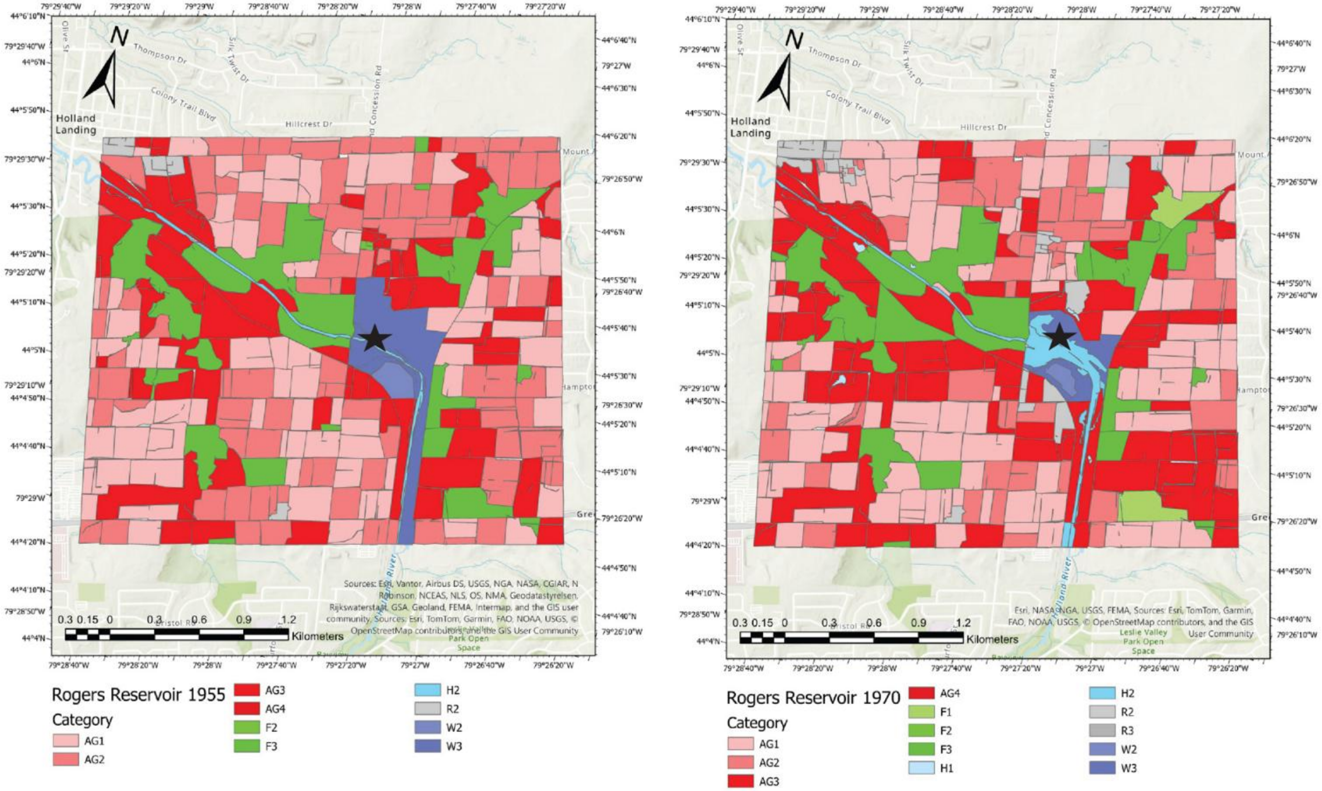


*Appendix Figure 8. Land-use classification map for the Baileys Ecopark study area in 1978 and 1988 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1-F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). These maps depict land-use change surrounding the core sites (black star) for the 1978-1988 period.*

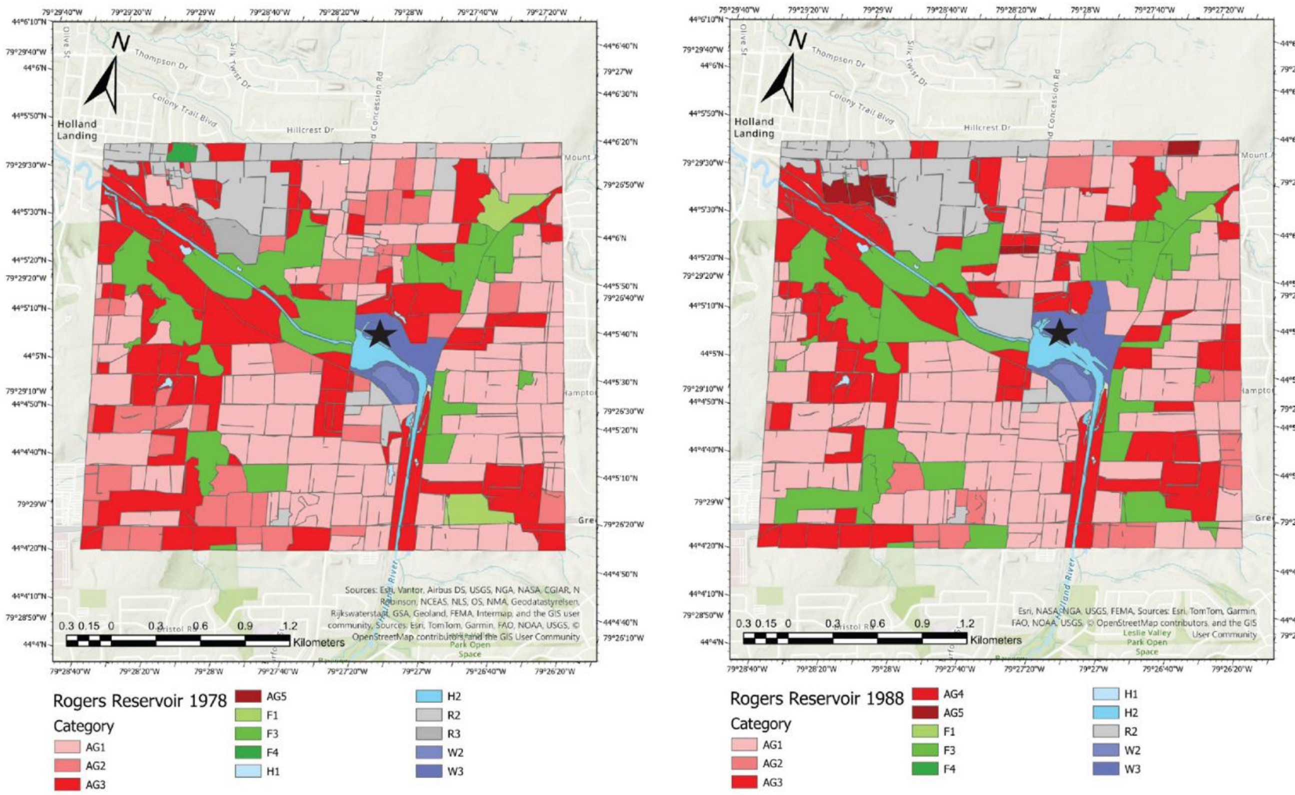


*Appendix Figure 9. Land-use classification map for the Baileys Ecopark study area in 1999 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1–F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). This map depicts land-use change surrounding the core site (black star) in the year of 1999.*

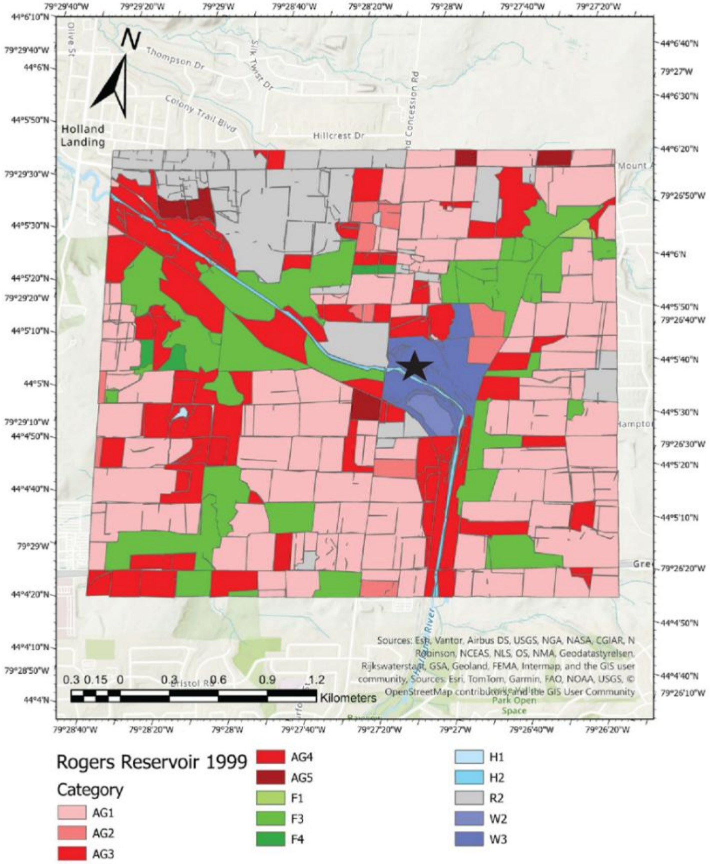
## *Rogers Reservoir Land Use Classification Maps*



*Appendix Figure 10. Land-use classification map for the Rogers Reservoir study area in 1955 and 1970 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1-F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). These maps depict land-use change surrounding the core site (black star) for the 1955-1970 period.*



*Appendix Figure 11. Land-use classification map for the Rogers Reservoir study area in 1978 and 1988 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1-F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). These maps depict land-use change surrounding the core site (black star) for the 1978-1988 period.*



Sources: Esri, Vantor, Airbus DS, USGS, NGA, NASA, CGIAR, N Robinson, NCEAS, NLS, OS, NMA, Geodatastyrelsen, Rijkswaterstaat, GSA, Geoland, FEMA, Intermap, and the GIS user community, Sources: Esri, TomTom, Garmin, FAO, NOAA, USGS, © OpenStreetMap contributors, and the GIS User Community

*Appendix Figure 12. Land-use classification map for the Rogers Reservoir study area in 1999 CE, derived from orthorectified and georeferenced historical aerial imagery. Polygons were digitized in ArcGIS Pro and classified into agricultural classes (AG1–AG5), forest types (F1-F4), wetlands (W1-W4), hydrology (H1-H2), residentials (R1-R3), and infrastructure (I1). This map depicts land-use change surrounding the core site (black star) in the year 1999.*

# *Appendix 3 - Summary of georeferencing and spatial characteristics for all imagery used across study sites*

*Appendix Table 1. Summary of georeferencing and spatial characteristics for all imagery used across study sites (Bass Lake (Langman), Beaver River, Rogers Reservoir, and Baileys Ecopark), including image source, pixel size, total mapped area, transformation method, number of control points, and root mean square error (RMSE), where applicable.*

| Site | Image / Year | Source | Pixel Size (m) | Total Mapped Area (km²) | Transformation | Control Points | RMSE (m) |
|---|---|---|---|---|---|---|---|
| Beaver River | 1927 (1 of 2) | EODMS | 0.5m | 11.8km² | 2nd Order Polynomial | 15 | 3.3 |
| | 1927 (2 of 2) | EODMS | 0.5m | 11.8km² | 2nd Order Polynomial | 10 | 4.1 |
| | 1954 | Lake Simcoe Region Conservation Authority | 1.4m | 15.7km² | 2nd Order Polynomial | 25 | 10.92 |
| | 1978 | Lake Simcoe Region Conservation Authority | 1.3m | 15.7km² | 2nd Order Polynomial | 19 | 15.28 |
| | 1981 | EODMS | 2.04m | 15.7km² | 2nd Order Polynomial | 21 | 7.4 |
| | 1995 | EODMS | 3m | 15.7km² | 2nd Order Polynomial | 21 | 7.04 |
| | 2014 | Esri World Imagery Wayback | 0.04–0.15 m | 15.7km² | N/A | N/A | N/A |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 2024 | Esri World Imagery Wayback | 0.04–0.15 m | 15.7km² | N/A | N/A | N/A |
| Rogers Reservoir | 1927 | EODMS | 0.5m | 8.5km² | 2nd Order Polynomial | 11 | 5.33 |
| | 1954 | EODMS | 0.8m | 14.8km² | 2nd Order Polynomial | 10 | 13.8 |
| | 1970 | York Region WMS | 1.52m | 15.8km² | N/A | N/A | N/A |
| | 1978 | York Region WMS | 1.52m | 15.8km² | N/A | N/A | N/A |
| | 1988 | York Region WMS | 1.52m | 15.8km² | N/A | N/A | N/A |
| | 1999 | York Region WMS | 1.52m | 15.8km² | N/A | N/A | N/A |
| | 2011 | York Region WMS | 1.52m | 15.8km² | N/A | N/A | N/A |
| | 2025 | York Region WMS | 1.52m | 15.8km² | N/A | N/A | N/A |
| Bass Lake (Langman) | 1927 (1 of 2) | EODMS | 3m | 8.4km² | 1st Order Polynomial | 8 | 6.83 |
| | 1927 (2 of 2) | EODMS | 4m | 8.4km² | 2nd Order Polynomial | 10 | 6.68 |
| | 1967 | EODMS | 0.8m | 12.1km² | 2nd Order Polynomial | 14 | 2.54 |
| | 1976 | EODMS | 1.6m | 16km² | 2nd Order Polynomial | 24 | 8.51 |
| | 1981 | EODMS | 1.54m | 16km² | 2nd Order Polynomial | 21 | 11.49 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | 1987 | EODMS | 1.6m | 16km$^2$ | 2nd Order Polynomial | 19 | 11.51 |
| | 1995 | EODMS | 1m | 16km$^2$ | 2nd Order Polynomial | 19 | 8.69 |
| | 2014 | Esri World Imagery Wayback | 0.04–0.15 m | 16km$^2$ | N/A | N/A | N/A |
| | 2024 | Esri World Imagery Wayback | 0.04–0.15 m | 16km$^2$ | N/A | N/A | N/A |
| Baileys Ecopark | 1927 | EODMS | 0.5m | 3.9km$^2$ | 1st Order Polynomial | 14 | 5.2 |
| | 1959 | EODMS | 0.8m | 13.8km$^2$ | 2nd Order Polynomial | 10 | 3.77 |
| | 1970 | York Region WMS | 1.52m | 15.6km$^2$ | N/A | N/A | N/A |
| | 1978 | York Region WMS | 1.52m | 15.6km$^2$ | N/A | N/A | N/A |
| | 1988 | York Region WMS | 1.52m | 15.6km$^2$ | N/A | N/A | N/A |
| | 1999 | York Region WMS | 1.52m | 15.6km$^2$ | N/A | N/A | N/A |
| | 2011 | York Region WMS | 1.52m | 15.6km$^2$ | N/A | N/A | N/A |
| | 2025 | York Region WMS | 1.52m | 15.6km$^2$ | N/A | N/A | N/A |

# *Appendix 4 – Bass Lake (Langman) rbacon age–model output for the twentieth-century interval*

*Appendix Table 2. Bass Lake (Langman) rbacon age–model output for the twentieth-century interval, including depth (cm), median calibrated age (CE), 95% confidence interval bounds, and age uncertainty (spread, years).*

| Depth (cm) | Median Age (CE) | 95% CI Lower | 95% CI Upper | Spread (years) |
|---|---|---|---|---|
| 0 | 2022 | -75 | -68 | 7 |
| 1 | 2010 | -71 | -41 | 30 |
| 2 | 1998 | -70 | -11 | 59 |
| 3 | 1987 | -68 | 20 | 88 |
| 4 | 1975 | -67 | 50 | 117 |
| 5 | 1964 | -66 | 81 | 147 |
| 6 | 1953 | -53 | 87 | 140 |
| 7 | 1942 | -44 | 91 | 135 |
| 8 | 1930 | -38 | 100 | 138 |

## *Appendix 5 - Complete taxon-to-land-use-group crosswalk*

*Appendix Table 3. Complete taxon-to-land-use-group crosswalk: pollen taxa, broad vegetation types, assigned land-use categories, and notes. Taxon assignments to land-use classes were established a priori based on known autecology, field observations at the study sites, and established palynological indicator frameworks (Behre, 1981; McAndrews, 1988; Fuller et al., 1998). Pollen identification follows Moore et al. (1991).*

| Taxon | Vegetation Type | Land-Use Categories | Notes |
|---|---|---|---|
| *Pinus* | Conifer | F2 + F4 | Common in managed and natural conifer stands |
| *Picea* | Conifer | F2 | Boreal/mesic conifer indicator |
| *Abies balsamea* | Conifer | F2 | Moist conifer forests |
| *Tsuga canadensis* | Conifer | F2 | Shade-tolerant late-successional species |
| *Larix* | Conifer | F2 | Often associated with wet soils |
| *Thuja* | Conifer | F2 | Wetland/lowland conifer indicator |
| *Acer* | Deciduous | F1 | Mixed hardwood forests |

| | | | |
|---|---|---|---|
| *Betula* | Deciduous | F1 | Early successional/disturbance-tolerant |
| *Populus* | Deciduous | F1 | Pioneer species, disturbance indicator |
| *Quercus* | Deciduous | F1 | Upland hardwood forests |
| *Ulmus* | Deciduous | F1 | Floodplain/riparian environments |
| *Fagus grandifolia* | Deciduous | F1 | Late-successional hardwood |
| *Carya ovata* | Deciduous | F1 | Mature deciduous forests |
| *Juglans cinerea* | Deciduous | F1 | Disturbance-associated hardwood |
| *Carpinus/Ostrya* | Deciduous | F1 | Understory hardwood species |
| *Fraxinus* | Deciduous | F1 | Often in moist or riparian zones |
| *Tilia* | Deciduous | F1 | Rich mesic forests |
| *Prunus serotina* | Deciduous | F1 | Secondary growth/disturbance |

| | | | |
|---|---|---|---|
| *Alnus viridis* | Deciduous | F1 | Nitrogen-fixing, disturbed or wet sites |
| *Salix* | Deciduous | F1 | Riparian/wetland margins |
| *Poaceae* | Herb | AG2 | Grasslands and hayfields |
| Cerealia | Herb | AG1 | Cultivated crops |
| *Zea mays* | Herb | AG1 | Intensive agriculture indicator |
| *Ambrosia* | Herb | AG3 + AG4 | Strong disturbance/agriculture indicator |
| *Aster* | Herb | AG3 + AG4 | Open/disturbed land |
| *Artemisia* | Herb | AG3 + AG4 | Dry/disturbed environments |
| Cheno-Am | Herb | AG3 + AG4 | Agricultural/disturbed soils |
| *Rumex* | Herb | AG3 + AG4 | Grazed/disturbed land |
| *Fabaceae* | Herb | AG3 + AG4 | Nitrogen-fixing in disturbed soils |
| *Ranunculus* | Herb | AG3 + AG4 | Moist disturbed habitats |
| *Taraxacum* | Herb | AG3 + AG4 + R3 | General disturbance indicator |

| | | | |
|---|---|---|---|
| *Cyperaceae* | Herb | W2 | Wetland/sedge communities |
| *Juncaceae* | Herb | W2 | Wet or saturated soils |
| Aquatics | Herb | W1 + W2 | Open water and aquatic margins |
| Ferns | Herb | AG4 + AG5 | Shaded or recovering/disturbed areas |
| *Glomus* | NPP | AG4 + AG5 | Soil disturbance indicator |
| Fungi (Dung) | NPP | AG3 | Grazing/pasture indicator |
| Charcoal | NPP | AG4 + AG5 | Fire/disturbance signal |

# *Appendix 6 - Principal Component Analysis (PCA) axis loadings*

*Appendix Table 4. Principal Component Analysis (PCA) axis loadings for all pollen taxa included in the ordination (Fig. 14). Loadings represent the contribution of each taxon to the primary axes of variation (PC1 and PC2), with higher absolute values indicating stronger influence on axis structure. Positive and negative loadings reflect opposing ecological or land-use gradients captured by the ordination.*

| Taxon | PC1 | PC2 |
|---|---|---|
| Charcoal | -0.4037 | 0.36746 |
| Dung Fungi | -0.1152 | -0.3808 |
| *Pinus* | 0.34363 | -0.1804 |
| *Glomus* | -0.2407 | -0.2661 |
| Poaceae | -0.3042 | 0.16581 |
| *Quercus* | 0.24835 | 0.10328 |
| Ferns | -0.2561 | -0.048 |
| Aquatics | 0.24244 | 0.08268 |
| *Taraxacum* | -0.2429 | -0.0774 |
| *Picea* | 0.23673 | 0.0596 |
| Cerealia | -0.1662 | -0.154 |
| *Acer* | 0.18902 | 0.05396 |
| Cyperaceae | -0.0704 | -0.177 |

| | | |
|---|---|---|
| *Betula* | 0.08221 | -0.1324 |
| *Ambrosia* | 0.14426 | 0.00596 |
| *Aster* | 0.00945 | -0.1376 |
| *Tsuga canadensis* | -0.1036 | -0.0721 |
| *Ulmus* | 0.10436 | 0.05291 |
| *Juglans cinerea* | -0.0226 | -0.1022 |
| *Larix* | 0.10194 | -0.0219 |
| *Fagus grandifolia* | 0.02562 | 0.07044 |
| *Zea mays* | 0.02508 | -0.0705 |
| *Alnus viridis* | 0.07037 | -0.0077 |
| Cheno Am | 0.0072 | -0.0625 |
| *Carya ovata* | 0.05203 | 0.01285 |
| *Tilia* | -0.0311 | 0.0389 |
| *Abies balsamea* | -0.0342 | -0.0353 |
| *Fraxinus* | 0.04277 | -0.0193 |
| *Salix* | 0.01059 | -0.0397 |
| *Thuja* | -0.0312 | -0.0219 |
| *Carpinus Ostrya* | 0.0234 | -0.0216 |

| | | |
|---|---|---|
| *Prunus serotina* | 0.02343 | 0.00345 |
| *Populus* | -0.0171 | 0.01461 |
| *Artemisia* | 0.01979 | -0.0024 |
| Juncaceae | 0.01844 | -0.0049 |
| Fabaceae | 0.0122 | 0.00414 |
| *Rumex* | 0.00447 | -0.0004 |
| *Ranunculus* | 0.00115 | 0.00318 |

# *Appendix 7 - Pearson (r) and Spearman (ρ) correlation coefficients and associated p-values between pollen-derived land-use groups and mapped land-use classes for each study site.*

*Appendix Table 5. Pearson (r) and Spearman (ρ) correlation coefficients and associated p-values between pollen-derived land-use groups and mapped land-use classes for each study site. Sample size (n) reflects the number of time intervals included in each site-specific analysis (Bass Lake (Langman) n = 5; Beaver River n = 6; Rogers Reservoir n = 7; Baileys Ecopark n = 8).*

| Site | Pollen Group | Land Use Class | n | Pearson_r | Pearson_p | Spearman_rho | Spearman_p |
|---|---|---|---|---|---|---|---|
| Bass Lake (Langman) | AG1 | Cropland | 5 | 0.248504 | 0.686883 | 0.4 | 0.516667 |
| | AG2 | Hay | 5 | 0.417832 | 0.483912 | 0.9 | 0.083333 |
| | AG3 | Pasture | 5 | 0.955919 | 0.011036 | 1.0 | 0.016667 |
| | AG3_AG4 | Pasture + Fallow | 5 | -0.3372 | 0.57895 | -0.1 | 0.950000 |
| | AG4_AG5 | Pasture + Mixed use | 5 | 0.46686 | 0.427936 | 0.5 | 0.450000 |
| | F1 | Coniferous Forest | 5 | 0.427502 | 0.472754 | 0.3 | 0.683333 |
| | F2 | Deciduous Forest | 5 | 0.667281 | 0.218519 | 0.62 | 0.268998 |
| | F2_F4 | Deciduous + Plantation | 5 | -0.12051 | 0.846929 | -0.1 | 0.950000 |
| | W1_W2 | Open water + Marsh | 5 | 0.077383 | 0.901572 | 0 | 1 |
| | W2 | Marsh | 5 | 0.554343 | 0.332219 | 0.6 | 0.35 |
| | Forest_all | All Forest Cover | 5 | 0.58975 | 0.295248 | 0.3 | 0.683333 |
| Beaver River | AG2 | Hay | 6 | 0.074839 | 0.887951 | 0.371429 | 0.497222 |
| | AG3 | Pasture | 6 | -0.5158 | 0.294913 | -0.5409 | 0.267778 |
| | AG3_AG4 | Pasture + Fallow | 6 | 0.353033 | 0.492451 | 0.428571 | 0.419444 |
| | AG4_AG5 | Fallow + Mixed Use | 6 | 0.250304 | 0.632385 | 0.085714 | 0.919444 |
| | W1_W2 | Open Water + Marsh | 6 | 0.282306 | 0.58779 | 0.371429 | 0.497222 |
| | Forest_all | All Forest Cover | 6 | 0.889079 | 0.017773 | 0.6 | 0.241667 |

|  |  |  |  |  |  |  |  |
|---|---|---|---|---|---|---|---|
| Rogers Reservoir | AG1 | Cropland | 7 | 0.652797 | 0.111933 | 0.642857 | 0.138889 |
|  | AG2 | Hay | 7 | -0.45521 | 0.304726 | -0.25 | 0.594841 |
|  | AG3 | Pasture | 7 | 0.239736 | 0.604606 | 0.285714 | 0.555952 |
|  | AG3_AG4 | Pasture + Fallow | 7 | -0.82791 | 0.021458 | -0.60714 | 0.166667 |
|  | AG3_AG4_R3 | Pasture +Fallow + Buildings with turf | 7 | 0.162325 | 0.728045 | 0.035714 | 0.963492 |
|  | AG4_AG5 | Fallow + Mixed Use | 7 | -0.69594 | 0.082446 | -0.37062 | 0.413116 |
|  | F1 | Coniferous Forest | 7 | 0.26936 | 0.559126 | 0.396412 | 0.378635 |
|  | F2 | Deciduous Forest | 7 | 0.132613 | 0.776844 | -0.11822 | 0.800709 |
|  | F2_F4 | Deciduous + Plantation | 7 | 0.44373 | 0.318617 | 0.378394 | 0.402602 |
|  | W2 | Marsh | 7 | 0.596294 | 0.157616 | 0.571429 | 0.200000 |
|  | Forest_all | All Forest Cover | 7 | -0.10139 | 0.828752 | -0.42857 | 0.353571 |
| Baileys Ecopark | AG1 | Cropland | 8 | -0.83509 | 0.009871 | -0.88095 | 0.007242 |
|  | AG2 | Hay | 8 | -0.29075 | 0.484783 | -0.45238 | 0.26746 |
|  | AG3 | Pasture | 8 | 0.893792 | 0.002762 | 0.904762 | 0.004563 |
|  | AG3_AG4 | Pasture + Fallow | 8 | 0.811284 | 0.014514 | 0.833333 | 0.015377 |
|  | AG3_AG4_R3 | Pasture + Fallow + Buildings with turf | 8 | 0.466489 | 0.243941 | 0.428571 | 0.299206 |
|  | AG4_AG5 | Fallow + Mixed Use | 8 | -0.06566 | 0.877241 | 0.268373 | 0.520441 |
|  | F1 | Coniferous Forest | 8 | 0.199086 | 0.636461 | 0.179644 | 0.670344 |
|  | F2 | Deciduous Forest | 8 | -0.32416 | 0.433432 | -0.45202 | 0.26083 |
|  | F2_F4 | Deciduous + Plantation | 8 | -0.48905 | 0.21875 | -0.41856 | 0.302042 |
|  | W2 | Marsh | 8 | 0.720811 | 0.043649 | 0.547619 | 0.170982 |
|  | Forest_all | All Forest Cover | 8 | 0.833783 | 0.010097 | 0.952381 | 0.001141 |

## *Appendix 8 - Full land-use proportional composition for each site at every mapped year (raw data underlying Figure 7).*

*Appendix Table 6. Full land-use proportional composition for Bass Lake (Langman).*

| Land Use Category | Frequency | Surface % | Year |
|---|---|---|---|
| AG1 | 77 | 21.62 | 1930 |
| AG2 | 77 | 22.92 | 1930 |
| AG3 | 13 | 6.21 | 1930 |
| AG4 | 1 | 0.23 | 1930 |
| AG5 | 1 | 1.37 | 1930 |
| F1 | 1 | 0.77 | 1930 |
| F3 | 11 | 29.10 | 1930 |
| F4 | 5 | 0.50 | 1930 |
| H1 | 1 | 15.76 | 1930 |
| R2 | 1 | 0.03 | 1930 |
| W1 | 1 | 0.05 | 1930 |
| W2 | 1 | 1.43 | 1930 |
| AG1 | 55 | 19.83 | 1967 |
| AG2 | 73 | 22.37 | 1967 |
| AG3 | 8 | 3.83 | 1967 |
| AG4 | 2 | 0.72 | 1967 |
| AG5 | 2 | 1.86 | 1967 |
| F1 | 3 | 2.39 | 1967 |
| F2 | 1 | 0.07 | 1967 |
| F3 | 9 | 24.74 | 1967 |
| H1 | 1 | 15.66 | 1967 |

| | | | |
|---|---|---|---|
| R2 | 6 | 6.24 | 1967 |
| R3 | 2 | 0.37 | 1967 |
| W1 | 1 | 0.05 | 1967 |
| W2 | 1 | 1.86 | 1967 |
| AG1 | 31 | 15.07 | 1976 |
| AG2 | 66 | 24.18 | 1976 |
| AG3 | 8 | 3.04 | 1976 |
| AG4 | 2 | 0.75 | 1976 |
| AG5 | 1 | 0.03 | 1976 |
| F1 | 5 | 4.12 | 1976 |
| F2 | 1 | 0.17 | 1976 |
| F3 | 11 | 25.55 | 1976 |
| H1 | 2 | 16.12 | 1976 |
| R2 | 8 | 7.19 | 1976 |
| R3 | 4 | 2.31 | 1976 |
| W1 | 1 | 0.05 | 1976 |
| W2 | 1 | 1.27 | 1976 |
| W4 | 1 | 0.16 | 1976 |
| AG1 | 53 | 24.58 | 1981 |
| AG2 | 48 | 13.54 | 1981 |
| AG3 | 7 | 2.90 | 1981 |
| AG4 | 2 | 0.34 | 1981 |
| AG5 | 2 | 0.85 | 1981 |
| F1 | 2 | 1.56 | 1981 |
| F2 | 11 | 0.91 | 1981 |
| F3 | 2 | 25.75 | 1981 |
| F4 | 2 | 0.94 | 1981 |
| H1 | 7 | 16.07 | 1981 |
| R2 | 3 | 10.54 | 1981 |
| R3 | 1 | 0.54 | 1981 |
| W1 | 1 | 0.04 | 1981 |

| | | | |
|---|---|---|---|
| W2 | 1 | 1.29 | 1981 |
| W4 | 1 | 0.17 | 1981 |
| AG1 | 33 | 14.00 | 1987 |
| AG2 | 49 | 17.12 | 1987 |
| AG3 | 24 | 7.52 | 1987 |
| F3 | 18 | 30.82 | 1987 |
| H1 | 2 | 15.87 | 1987 |
| R2 | 11 | 12.03 | 1987 |
| R3 | 1 | 1.18 | 1987 |
| W1 | 1 | 0.05 | 1987 |
| W2 | 1 | 1.29 | 1987 |
| W4 | 1 | 0.13 | 1987 |
| AG1 | 51 | 18.34 | 1995 |
| AG2 | 21 | 6.70 | 1995 |
| AG3 | 28 | 11.25 | 1995 |
| AG4 | 1 | 0.38 | 1995 |
| F1 | 1 | 0.74 | 1995 |
| F3 | 17 | 30.54 | 1995 |
| F4 | 1 | 0.04 | 1995 |
| H1 | 2 | 16.05 | 1995 |
| R2 | 15 | 12.55 | 1995 |
| R3 | 2 | 1.92 | 1995 |
| W1 | 1 | 0.05 | 1995 |
| W2 | 1 | 1.32 | 1995 |
| W4 | 1 | 0.13 | 1995 |
| AG1 | 49 | 20.11 | 2014 |
| AG2 | 15 | 4.29 | 2014 |
| AG3 | 21 | 9.33 | 2014 |
| AG4 | 4 | 1.20 | 2014 |
| F1 | 1 | 0.72 | 2014 |
| F2 | 3 | 4.74 | 2014 |

|  |  |  |  |
|---|---|---|---|
| F3 | 14 | 24.94 | 2014 |
| H1 | 4 | 16.11 | 2014 |
| R2 | 18 | 14.04 | 2014 |
| R3 | 1 | 2.80 | 2014 |
| W1 | 1 | 0.05 | 2014 |
| W2 | 1 | 1.30 | 2014 |
| W4 | 1 | 0.37 | 2014 |
| AG1 | 28 | 11.41 | 2024 |
| AG2 | 46 | 16.85 | 2024 |
| AG3 | 10 | 3.12 | 2024 |
| AG4 | 1 | 0.74 | 2024 |
| F1 | 3 | 1.59 | 2024 |
| F3 | 14 | 27.73 | 2024 |
| F4 | 1 | 0.01 | 2024 |
| H1 | 2 | 15.80 | 2024 |
| I1 | 3 | 5.16 | 2024 |
| R2 | 12 | 12.40 | 2024 |
| R3 | 5 | 3.69 | 2024 |
| W1 | 1 | 0.05 | 2024 |
| W2 | 1 | 1.31 | 2024 |
| W4 | 1 | 0.15 | 2024 |

*Appendix Table 7. Full land-use proportional composition for Beaver River.*

| Land Use Category | Frequency | Surface % | Year |
|---|---|---|---|
| AG1 | 99 | 22.29 | 1927 |
| AG2 | 63 | 16.31 | 1927 |
| AG3 | 83 | 23.19 | 1927 |
| AG4 | 1 | 0.04 | 1927 |
| AG5 | 1 | 0.48 | 1927 |
| F3 | 16 | 13.65 | 1927 |
| F4 | 3 | 0.29 | 1927 |
| R2 | 8 | 0.83 | 1927 |
| W1 | 2 | 0.80 | 1927 |
| W2 | 3 | 2.79 | 1927 |
| W3 | 5 | 19.33 | 1927 |
| AG1 | 124 | 33.25 | 1950 |
| AG2 | 31 | 8.04 | 1950 |
| AG3 | 64 | 21.09 | 1950 |
| AG4 | 2 | 0.35 | 1950 |
| F3 | 23 | 10.02 | 1950 |
| F4 | 4 | 0.43 | 1950 |
| R2 | 5 | 0.46 | 1950 |
| W1 | 2 | 0.80 | 1950 |
| W2 | 9 | 2.96 | 1950 |
| W3 | 13 | 22.59 | 1950 |
| AG1 | 77 | 25.60 | 1978 |
| AG2 | 48 | 12.45 | 1978 |
| AG3 | 60 | 17.78 | 1978 |
| AG5 | 4 | 1.19 | 1978 |
| F3 | 25 | 16.59 | 1978 |

| | | | |
|---|---|---|---|
| R2 | 8 | 1.10 | 1978 |
| W1 | 2 | 1.21 | 1978 |
| W2 | 9 | 3.73 | 1978 |
| W3 | 13 | 20.34 | 1978 |
| AG1 | 81 | 24.09 | 1981 |
| AG2 | 54 | 16.19 | 1981 |
| AG3 | 63 | 16.67 | 1981 |
| AG5 | 1 | 0.17 | 1981 |
| F3 | 24 | 16.72 | 1981 |
| F4 | 1 | 0.15 | 1981 |
| H2 | 1 | 0.04 | 1981 |
| R2 | 2 | 0.15 | 1981 |
| W1 | 2 | 1.30 | 1981 |
| W2 | 20 | 4.29 | 1981 |
| W3 | 8 | 20.22 | 1981 |
| AG1 | 78 | 25.57 | 1995 |
| AG2 | 36 | 10.48 | 1995 |
| AG3 | 73 | 19.63 | 1995 |
| AG5 | 1 | 0.17 | 1995 |
| F3 | 18 | 16.44 | 1995 |
| H1 | 3 | 0.46 | 1995 |
| H2 | 1 | 0.40 | 1995 |
| R2 | 7 | 0.95 | 1995 |
| W1 | 2 | 1.31 | 1995 |
| W2 | 20 | 5.17 | 1995 |
| W3 | 7 | 19.42 | 1995 |
| AG1 | 86 | 31.56 | 2014 |
| AG2 | 12 | 8.13 | 2014 |
| AG3 | 53 | 15.13 | 2014 |
| AG4 | 5 | 0.65 | 2014 |
| F3 | 19 | 16.26 | 2014 |

| | | | |
|---|---|---|---|
| H1 | 5 | 0.95 | 2014 |
| R2 | 12 | 1.30 | 2014 |
| W1 | 2 | 1.31 | 2014 |
| W2 | 4 | 9.50 | 2014 |
| W3 | 6 | 15.22 | 2014 |
| AG1 | 75 | 28.70 | 2024 |
| AG2 | 10 | 3.54 | 2024 |
| AG3 | 62 | 18.10 | 2024 |
| F3 | 25 | 17.80 | 2024 |
| H1 | 5 | 0.95 | 2024 |
| H2 | 1 | 1.53 | 2024 |
| R2 | 12 | 1.37 | 2024 |
| I1 | 1 | 1.99 | 2024 |
| W1 | 2 | 1.33 | 2024 |
| W2 | 7 | 12.36 | 2024 |
| W3 | 5 | 12.33 | 2024 |

*Appendix Table 8. Full land-use proportional composition for Baileys Ecopark.*

| Land Use Category | Frequency | Surface % | Year |
|---|---|---|---|
| AG1 | 105 | 47.83 | 1927 |
| AG2 | 36 | 17.78 | 1927 |
| AG3 | 31 | 30.77 | 1927 |
| F1 | 3 | 0.47 | 1927 |
| F3 | 3 | 2.51 | 1927 |
| W2 | 1 | 0.64 | 1927 |
| AG1 | 84 | 54.68 | 1959 |
| AG2 | 25 | 12.23 | 1959 |
| AG3 | 32 | 21.15 | 1959 |
| AG4 | 4 | 1.11 | 1959 |
| F1 | 1 | 0.05 | 1959 |
| F2 | 1 | 0.23 | 1959 |
| F3 | 7 | 4.58 | 1959 |
| F4 | 4 | 2.74 | 1959 |
| H2 | 3 | 1.02 | 1959 |
| R2 | 6 | 1.70 | 1959 |
| W2 | 1 | 0.52 | 1959 |
| AG1 | 55 | 39.69 | 1970 |
| AG2 | 27 | 17.97 | 1970 |
| AG3 | 31 | 16.41 | 1970 |
| AG4 | 9 | 3.66 | 1970 |
| AG5 | 1 | 2.08 | 1970 |
| F1 | 2 | 0.23 | 1970 |
| F3 | 8 | 4.89 | 1970 |
| F4 | 2 | 2.53 | 1970 |
| H1 | 1 | 0.04 | 1970 |

| | | | |
|---|---|---|---|
| H2 | 2 | 0.99 | 1970 |
| R1 | 2 | 0.74 | 1970 |
| R2 | 9 | 8.94 | 1970 |
| R3 | 2 | 1.17 | 1970 |
| W2 | 1 | 0.65 | 1970 |
| AG1 | 27 | 30.15 | 1978 |
| AG2 | 18 | 11.74 | 1978 |
| AG3 | 42 | 24.74 | 1978 |
| AG4 | 2 | 1.10 | 1978 |
| AG5 | 1 | 0.07 | 1978 |
| F1 | 1 | 0.10 | 1978 |
| F3 | 8 | 4.40 | 1978 |
| F4 | 2 | 2.55 | 1978 |
| H1 | 1 | 0.29 | 1978 |
| H2 | 2 | 0.99 | 1978 |
| R1 | 1 | 0.22 | 1978 |
| R2 | 7 | 22.98 | 1978 |
| W2 | 1 | 0.65 | 1978 |
| AG1 | 47 | 38.30 | 1988 |
| AG2 | 4 | 3.38 | 1988 |
| AG3 | 30 | 17.53 | 1988 |
| AG4 | 1 | 0.23 | 1988 |
| F1 | 1 | 0.10 | 1988 |
| F3 | 6 | 3.94 | 1988 |
| F4 | 3 | 2.54 | 1988 |
| H1 | 1 | 0.40 | 1988 |
| H2 | 3 | 0.99 | 1988 |
| R1 | 2 | 4.56 | 1988 |
| R2 | 10 | 25.66 | 1988 |
| R3 | 2 | 1.73 | 1988 |
| W2 | 1 | 0.65 | 1988 |

| | | | |
|---|---|---|---|
| AG1 | 3 | 3.38 | 1999 |
| AG2 | 1 | 0.31 | 1999 |
| AG3 | 17 | 12.32 | 1999 |
| AG4 | 4 | 1.58 | 1999 |
| F3 | 2 | 0.87 | 1999 |
| H1 | 9 | 0.58 | 1999 |
| H2 | 2 | 1.21 | 1999 |
| R1 | 1 | 0.65 | 1999 |
| R2 | 13 | 58.62 | 1999 |
| R3 | 11 | 19.94 | 1999 |
| W2 | 1 | 0.54 | 1999 |
| AG1 | 1 | 0.07 | 2011 |
| AG2 | 1 | 0.02 | 2011 |
| AG3 | 7 | 9.93 | 2011 |
| F1 | 1 | 0.92 | 2011 |
| F3 | 7 | 6.15 | 2011 |
| H1 | 8 | 0.82 | 2011 |
| H2 | 2 | 1.22 | 2011 |
| R2 | 16 | 67.20 | 2011 |
| R3 | 5 | 13.37 | 2011 |
| W2 | 1 | 0.32 | 2011 |
| AG1 | 1 | 0.07 | 2024 |
| AG3 | 6 | 6.46 | 2024 |
| F3 | 10 | 11.69 | 2024 |
| H1 | 10 | 1.83 | 2024 |
| H2 | 2 | 0.30 | 2024 |
| R2 | 19 | 69.82 | 2024 |
| R3 | 2 | 9.53 | 2024 |
| W2 | 1 | 0.31 | 2024 |

*Appendix Table 9. Full land-use proportional composition for Rogers Reservoir.*

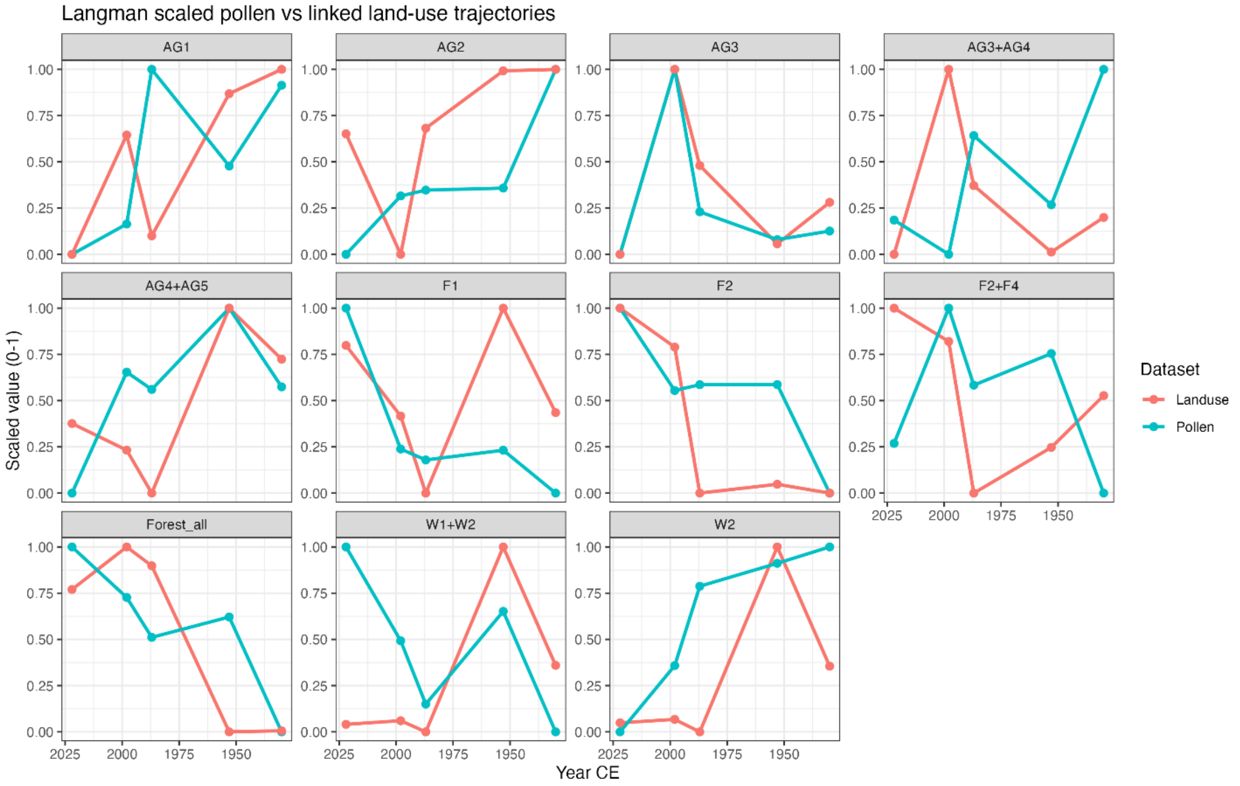
| Land Use Category | Frequency | Surface % | Year |
|---|---|---|---|
| AG1 | 104 | 25.79 | 1930 |
| AG2 | 96 | 29.50 | 1930 |
| AG3 | 71 | 28.49 | 1930 |
| AG4 | 2 | 0.64 | 1930 |
| F1 | 2 | 0.23 | 1930 |
| F2 | 1 | 0.33 | 1930 |
| F3 | 10 | 9.50 | 1930 |
| F4 | 1 | 0.09 | 1930 |
| H2 | 4 | 1.81 | 1930 |
| R2 | 1 | 0.17 | 1930 |
| W2 | 1 | 0.71 | 1930 |
| W3 | 2 | 2.72 | 1930 |
| AG1 | 80 | 26.75 | 1955 |
| AG2 | 92 | 29.10 | 1955 |
| AG3 | 58 | 24.13 | 1955 |
| F2 | 1 | 0.05 | 1955 |
| F3 | 21 | 13.75 | 1955 |
| H2 | 2 | 0.74 | 1955 |
| R2 | 4 | 0.83 | 1955 |
| W2 | 1 | 0.55 | 1955 |
| W3 | 2 | 4.09 | 1955 |
| AG1 | 99 | 32.22 | 1970 |
| AG2 | 47 | 14.29 | 1970 |
| AG3 | 86 | 31.32 | 1970 |
| F1 | 2 | 1.65 | 1970 |
| F3 | 22 | 13.43 | 1970 |

|  |  |  |  |
|---|---|---|---|
| H1 | 5 | 0.13 | 1970 |
| H2 | 5 | 0.09 | 1970 |
| H3 | 3 | 2.13 | 1970 |
| R2 | 18 | 3.01 | 1970 |
| W2 | 1 | 0.28 | 1970 |
| W3 | 2 | 1.45 | 1970 |
| AG1 | 107 | 37.78 | 1978 |
| AG2 | 41 | 11.37 | 1978 |
| AG3 | 76 | 25.45 | 1978 |
| F1 | 2 | 1.65 | 1978 |
| F3 | 18 | 11.83 | 1978 |
| F4 | 1 | 0.25 | 1978 |
| H1 | 6 | 0.18 | 1978 |
| H2 | 2 | 1.62 | 1978 |
| R2 | 24 | 6.88 | 1978 |
| R3 | 1 | 0.82 | 1978 |
| W2 | 1 | 0.47 | 1978 |
| W3 | 2 | 1.70 | 1978 |
| AG1 | 104 | 40.08 | 1988 |
| AG2 | 16 | 5.15 | 1988 |
| AG3 | 71 | 22.87 | 1988 |
| AG5 | 4 | 1.24 | 1988 |
| F1 | 1 | 0.17 | 1988 |
| F3 | 30 | 16.14 | 1988 |
| H1 | 4 | 0.10 | 1988 |
| H2 | 2 | 1.82 | 1988 |
| R2 | 16 | 9.22 | 1988 |
| W2 | 1 | 0.48 | 1988 |
| W3 | 2 | 2.74 | 1988 |
| AG1 | 94 | 43.61 | 1999 |
| AG2 | 10 | 2.45 | 1999 |

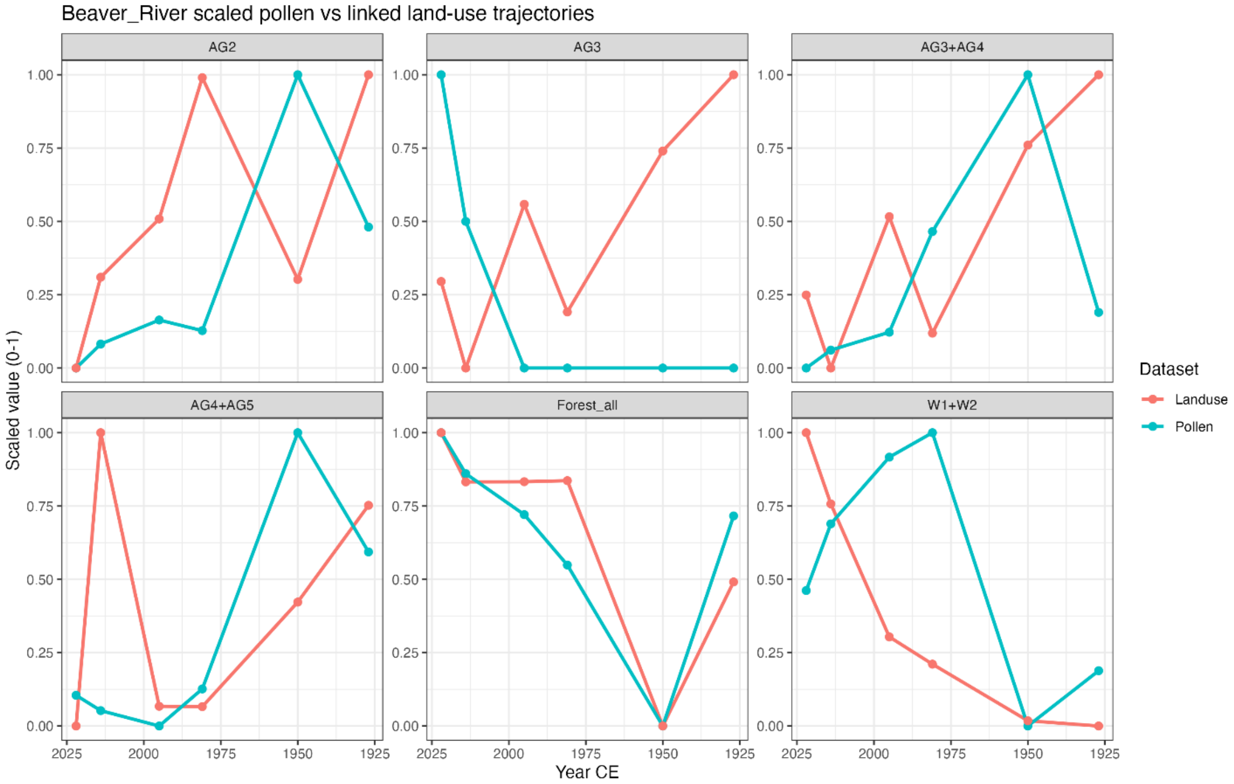
| | | | |
|---|---|---|---|
| AG3 | 65 | 20.27 | 1999 |
| AG4 | 2 | 0.52 | 1999 |
| AG5 | 4 | 1.29 | 1999 |
| F1 | 1 | 0.17 | 1999 |
| F3 | 29 | 17.18 | 1999 |
| F4 | 3 | 0.53 | 1999 |
| H1 | 1 | 0.04 | 1999 |
| H2 | 3 | 0.79 | 1999 |
| R2 | 21 | 12.17 | 1999 |
| W2 | 1 | 0.97 | 1999 |
| W3 | 2 | 3.06 | 1999 |
| AG1 | 78 | 39.64 | 2011 |
| AG2 | 4 | 1.41 | 2011 |
| AG3 | 45 | 13.60 | 2011 |
| AG4 | 10 | 3.19 | 2011 |
| AG5 | 3 | 0.91 | 2011 |
| F3 | 25 | 20.59 | 2011 |
| F4 | 5 | 0.89 | 2011 |
| H1 | 3 | 0.24 | 2011 |
| H2 | 3 | 1.23 | 2011 |
| R1 | 1 | 0.18 | 2011 |
| R2 | 28 | 14.17 | 2011 |
| W2 | 1 | 1.07 | 2011 |
| W3 | 2 | 2.88 | 2011 |
| AG1 | 65 | 35.00 | 2024 |
| AG2 | 1 | 0.46 | 2024 |
| AG3 | 19 | 7.68 | 2024 |
| AG4 | 7 | 1.76 | 2024 |
| AG5 | 3 | 0.73 | 2024 |
| F2 | 1 | 0.24 | 2024 |
| F3 | 33 | 24.24 | 2024 |

|  |  |  |  |
|---|---|---|---|
| F4 | 3 | 0.48 | 2024 |
| H1 | 3 | 0.24 | 2024 |
| H2 | 3 | 1.19 | 2024 |
| R1 | 1 | 0.51 | 2024 |
| R2 | 30 | 23.75 | 2024 |
| W2 | 1 | 1.07 | 2024 |
| W3 | 2 | 2.65 | 2024 |

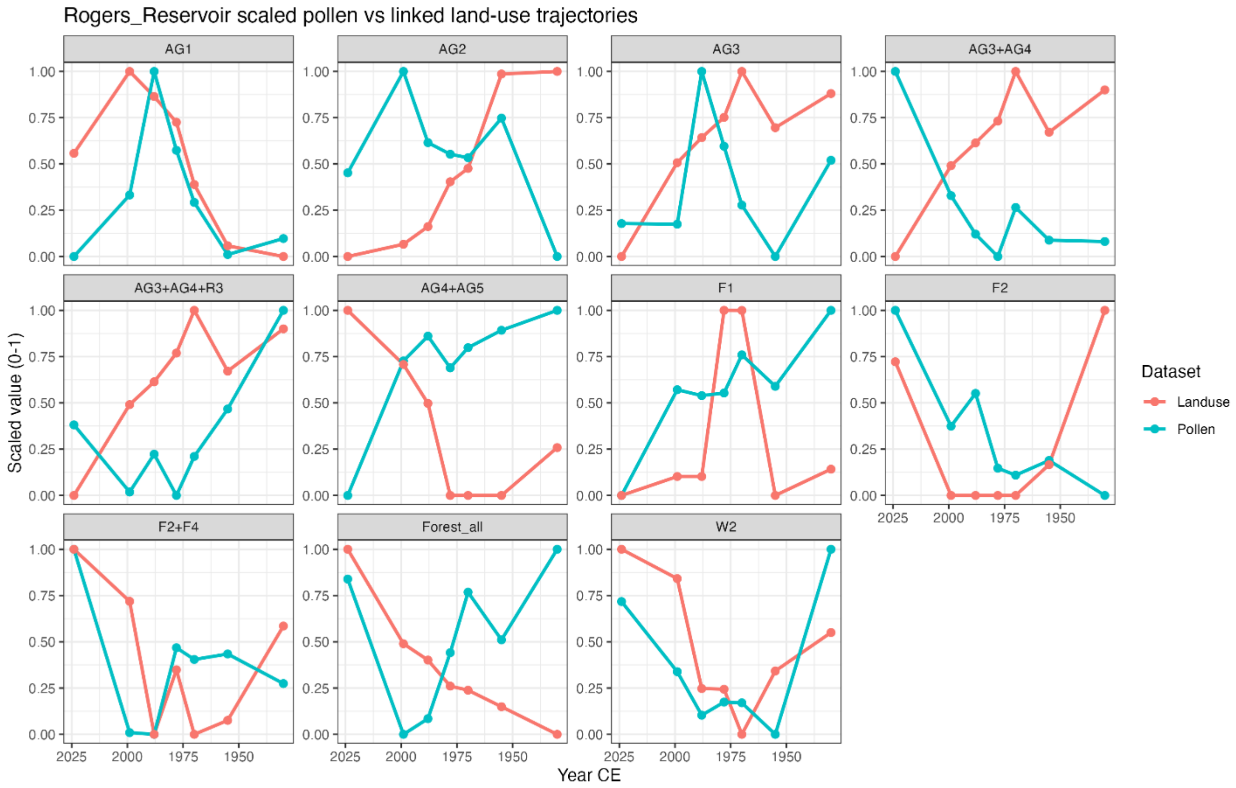
# *Appendix 9 - Time-series comparison of scaled pollen indicator groups and corresponding aerial photo-derived land-use proportions*



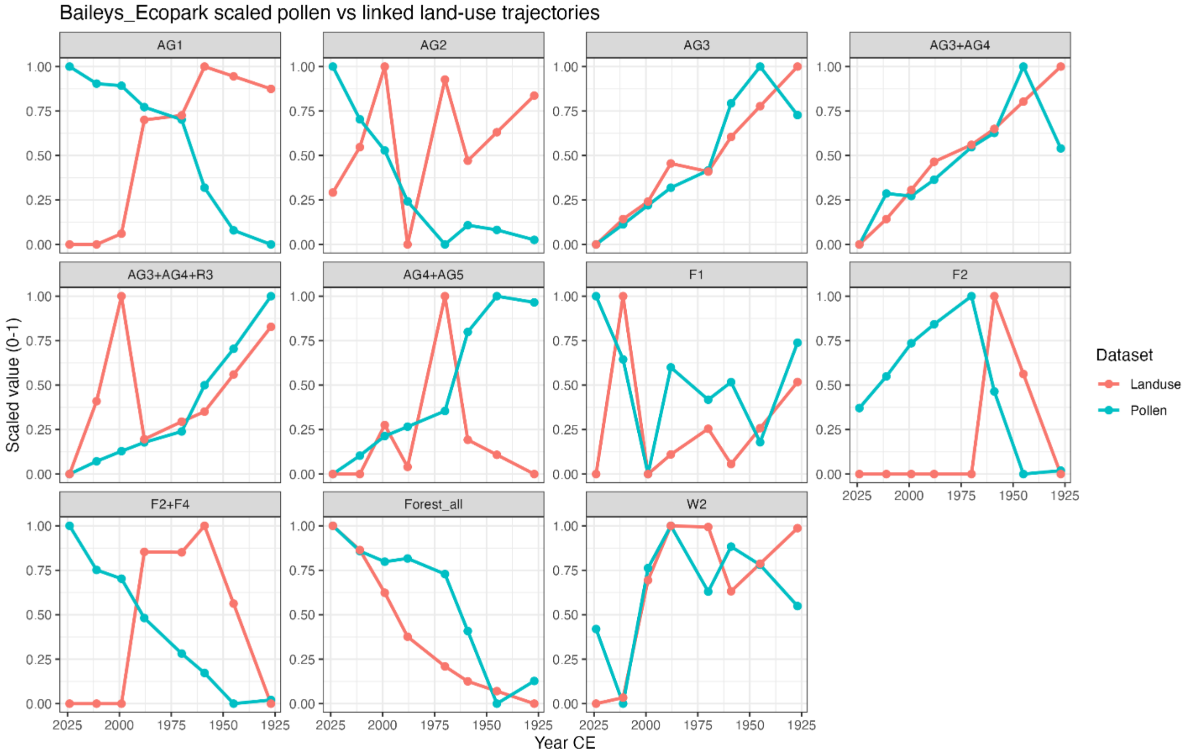
*Appendix Figure 13. Time-series comparison of scaled pollen indicator groups and corresponding aerial photo-derived land-use proportions at Bass Lake (Langman). Values are normalized (0–1) to facilitate comparison of relative trends through time. Panels represent individual land-use classes and aggregated groups, with pollen-derived indicators compared directly to mapped land-use trajectories (CE).*



*Appendix Figure 14. Time-series comparison of scaled pollen indicator groups and corresponding aerial photo-derived land-use proportions at Beaver River. Values are normalized (0–1) to facilitate comparison of relative trends through time. Panels represent individual land-use classes and aggregated groups, with pollen-derived indicators compared directly to mapped land-use trajectories (CE).*

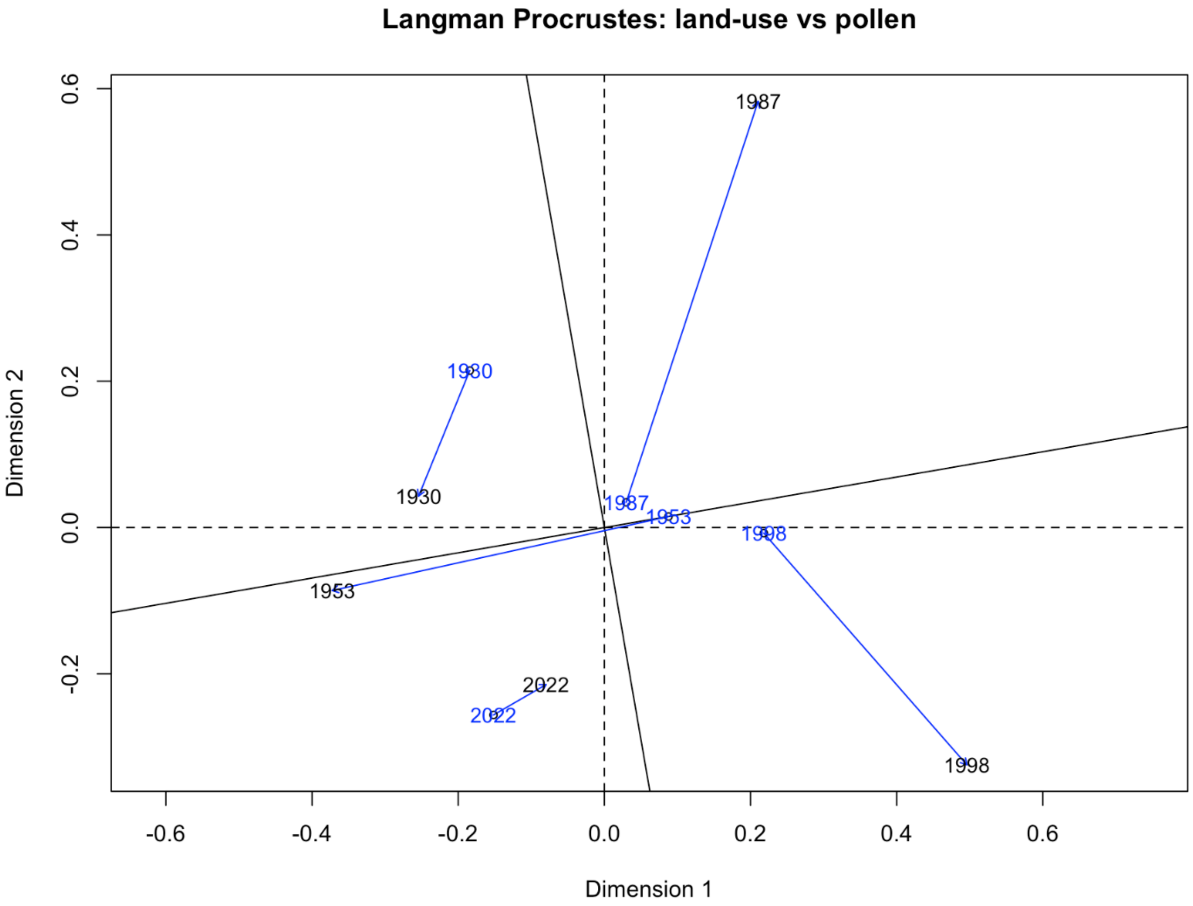


*Appendix Figure 15. Time-series comparison of scaled pollen indicator groups and corresponding aerial photo-derived land-use proportions at Rogers Reservoir. Values are normalized (0–1) to facilitate comparison of relative trends through time. Panels represent individual land-use classes and aggregated groups, with pollen-derived indicators compared directly to mapped land-use trajectories (CE).*

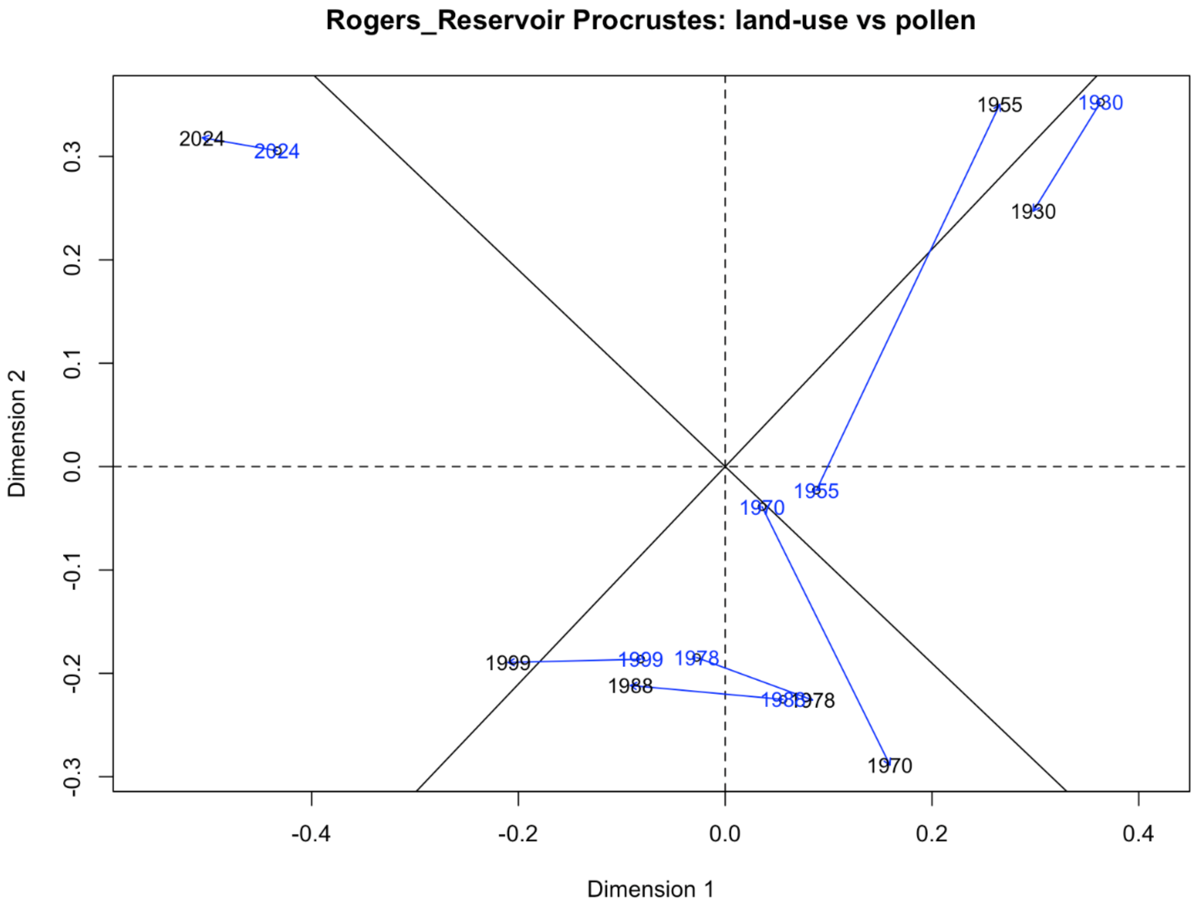


*Appendix Figure 16. Time-series comparison of scaled pollen indicator groups and corresponding aerial photo-derived land-use proportions at Baileys Ecopark. Values are normalized (0–1) to facilitate comparison of relative trends through time. Panels represent individual land-use classes and aggregated groups, with pollen-derived indicators compared directly to mapped land-use trajectories (CE).*

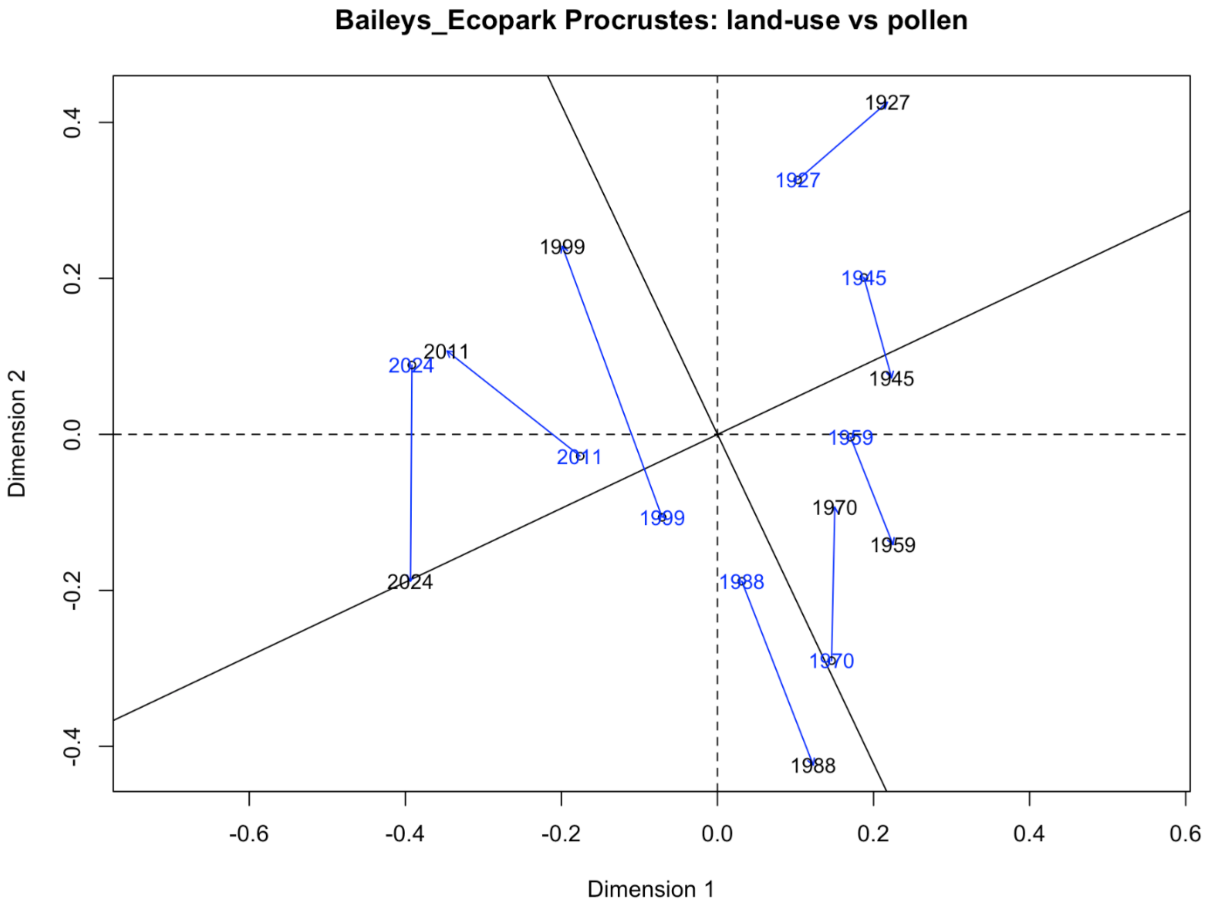
# *Appendix 10 - Procrustes rotation comparing pollen and land-use ordinations*



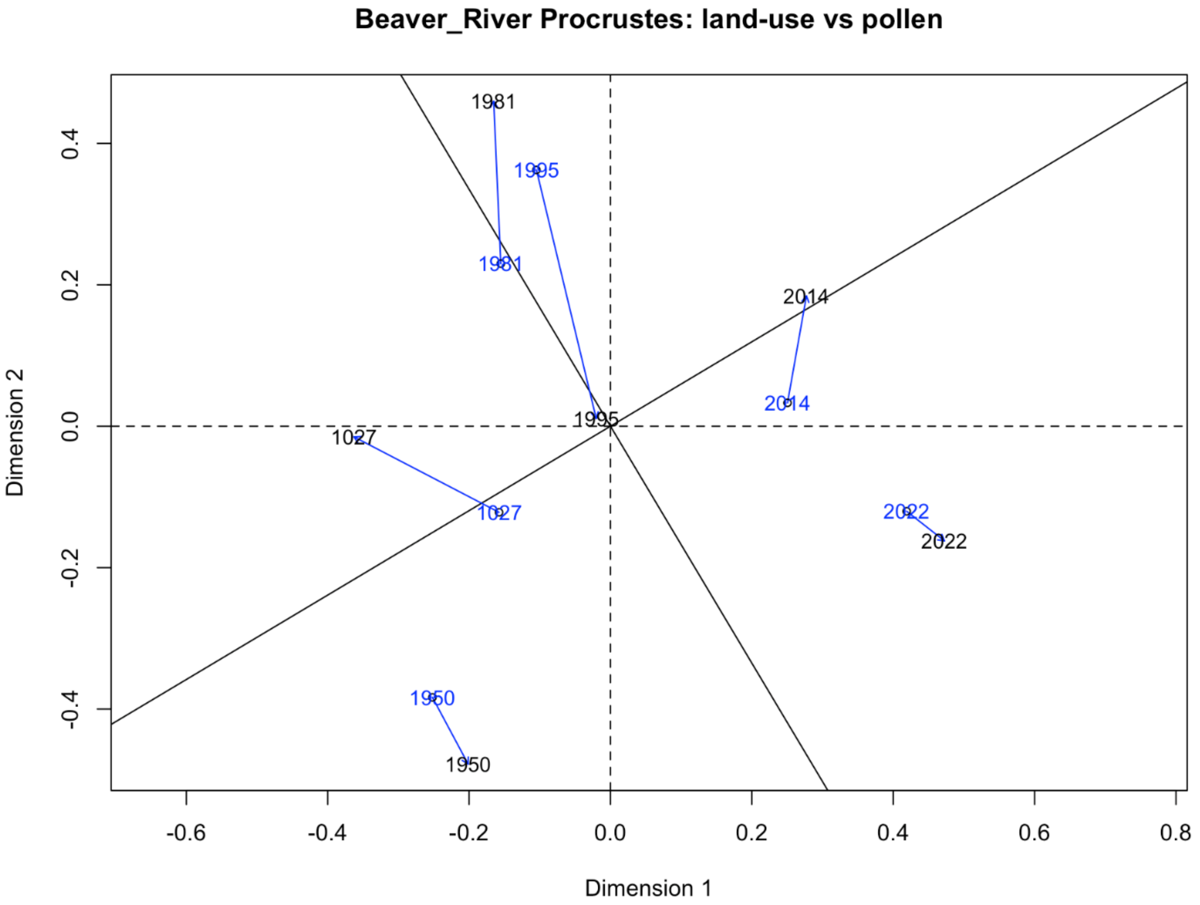
*Appendix Figure 17. Procrustes rotation comparing pollen and land-use ordinations at Bass Lake (Langman). Points represent individual time intervals (CE), with lines connecting corresponding pollen and aerial photo-derived land-use positions.*



*Appendix Figure 18. Procrustes rotation comparing pollen and land-use ordinations at Rogers Reservoir. Points represent individual time intervals (CE), with lines connecting corresponding pollen and aerial photo-derived land-use positions.*



*Appendix Figure 19. Procrustes rotation comparing pollen and land-use ordinations at Baileys Ecopark. Points represent individual time intervals (CE), with lines connecting corresponding pollen and aerial photo-derived land-use positions.*



*Appendix Figure 20. Procrustes rotation comparing pollen and land-use ordinations at Beaver River. Points represent individual time intervals (CE), with lines connecting corresponding pollen and aerial photo-derived land-use positions.*