PALYNOLOGIC DETERMINATION OF HISTORICAL SEDIMENT ACCUMULATION RATES AND PALEOECOLOGICAL VARIATION IN MARSHES ON THE ST. JONES RIVER, DELAWARE, USA

by

Susanne M. Moskalski

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Susanne M. Moskalski

Approved: _____
Ronald E. Martin, Ph.D.
Professor in charge of thesis on behalf of the Advisory Committee

Approved: _____
James E. Pizzuto, Ph.D.
Chair of the Department of Geology

Approved: _____
Thomas M. Apple, Ph.D.
Dean of the College of Arts and Sciences

Approved: _____
Conrado M. Gempesaw II, Ph.D.
Vice Provost for Academic and International Programs

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ABSTRACT

The analysis of pollen assemblage zones in three cores from salt marshes on the St. Jones River in central Delaware shows major shifts in vegetation over the last 1000 years. Variations in pollen assemblages reveal both natural changes in the plant community and anthropogenic changes related to European settlement. This interdisciplinary study combines pollen analytic biostratigraphy with lithostratigraphy and well-documented local history to develop a more comprehensive understanding of the recent history of the study area. Age estimates derived from changes in the plant community combined with a well-documented physical stratigraphy of the study area allow assessment of the impact of post-European-settlement land-use practices on sedimentation and ecological conditions in the St. Jones estuarine system. The area surrounding the St. Jones River has been continuously inhabited since 1650, when the English established the settlement of St. Jones Neck, while other portions of Delaware were settled as early as 1631. Prior to the advent of European agricultural practices, Delaware was thickly forested with mixed conifers and hardwoods. Clear-cutting for agriculture and fuel wood supply, beginning in the late 1600's, quickly denuded the area, which did not begin to recover until late in the twentieth century. Analysis of the pollen record of three cores reflects a shift from this forested setting to one with a significant proportion of open areas. The lower, pre-settlement parts of the cores are dominated by *Quercus*, with abundant *Pinus* and *Carya* and common Graminae and Cyperaceae, indicating highly forested conditions. The upper, post-settlement

intervals are rich in *Quercus*, with common *Pinus* and *Carya*, but the abundances of Compositae are conspicuously higher, indicating increased amounts of open spaces, and decreased forest cover. These shifts place the European agricultural horizon at a depth between 2.10 m and 2.20 m in the supratidal cores and 3.45 m in an intertidal core. Age estimates based on this palynologically derived horizon and independent radiocarbon dates indicate that sediment accumulation rates increased by approximately 4.5 times following European settlement. The paleoenvironmental history of the St. Jones River basin over the past 1000 years as seen in the pollen record is one of increasing disturbance of natural systems with increasing population growth. Additional results of pollen analysis indicate that the pollen record can provide general patterns of river salinity as well as the degree of forest clearance, leading to the possibility of more detailed studies comparing pollen analysis to other paleosalinity techniques. Micropaleontological analysis of pollen assemblages yields considerably greater temporal and paleoenvironmental resolution than lithostratigraphy alone.

Chapter 1

INTRODUCTION AND BACKGROUND

This study uses pollen analysis to compare sediment accumulation rates before and after European settlement in a central Delaware tidal marsh, and to clarify vegetational and environmental changes over the past 1000 years. A multidisciplinary approach is used, and integrates pollen analytic biostratigraphy, lithostratigraphy, and a well-documented local history in the development of a recent paleoecologic understanding of the study area and in the determination of linear sediment accumulation rates. Sediment accumulation rates are used instead of bulk sedimentation rates because the differences in autocompaction of different sediment types puts the calculations necessary for such correction outside the scope of the present study. The hypothesis for this study is that over the past few hundred years, environmental changes linked to European settlement had a more significant impact on the sediment accumulation rate of marshes flanking the St. Jones River than natural environmental changes, and that these changes can be detected by pollen assemblage zones that are used as a proxy for vegetational and environmental change.

In Delaware, tidal marshes tend to form in the flood plains of tidal rivers fringing the section of river that is subject to salt wedge intrusion at high tides. The river water in the downstream section is a mixture of fresh water from upstream and saline water from the ocean or bay. Upstream of the tidal limit the fringing marshes are fresh water in nature. Marshes serve important functions in local ecology (Teal

and Howes, 2000; Valiela et al., 2000). They provide habitat to both native and migrating fauna and act as storage areas for fresh water. They provide a buffer zone around rivers, filtering out water impurities garnered from overland runoff and pollution. Marshes also reduce river turbidity, and hence biochemical oxygen demand, by storage of sediment, thus increasing the oxygen content of the water column. Marshes also play an important role in the cycling of carbon and nitrogen (Teal and Howes, 2000; Valiela et al., 2000).

Although they filter impurities and pollutants, tidal marshes are sensitive to environmental change, and can be greatly affected by a variety of causative factors (Adam, 1990). Natural environmental changes such as sea level rise, droughts, and long-term temperature changes can affect the types and abundances of plants and animals that inhabit wetlands. Non-natural environmental changes involve human activities, and encompass a wide variety of causes. Common anthropogenic causes of ecological change in marshes include alteration of the marsh or surrounding landscape or native plant communities by activities such as lumbering, agriculture, or construction, infilling or reclamation of marsh land, chemical and biological pollution, introduction of foreign plant and animal species, and manipulation of species abundances and other management practices (Adam, 1990).

As tidal marshes are located at sea level, the extent of marshes in any one area is partly dependent on the rate of sea level rise or fall. On the east coast of North America, the areal extent of tidal marshes is declining due to several interacting factors (Kraft et al., 1992). Sea level in Delaware has been rising since the last glacial maximum due to ice melt and isostatic rebound. Under natural conditions, the marshes would move inland as sea level rose, with the regular soils adjacent to the

marshes slowly becoming wetland soils. Because of the popularity of East Coast beach towns, however, it is not uncommon to see residential and commercial properties constructed directly adjacent to tidal marshes. Putting buildings, roads, and parking lots on top of the ground makes it impervious to water. As a result, the marshes cannot expand inland. Further, vertical accretion of the marsh surface keeps pace with sea level rise under natural conditions, but human activities tend to cause increased erosion, and subsequent sedimentation, into the marshes. Increased vertical accretion, in turn, will eventually raise the marsh surface above mean higher high water (MHHW), at which point it can no longer be considered a marsh.

It has become an accepted practice in the United States to create artificial tidal marshes in an attempt to preserve the coastal wetland ecosystem and its benefits. In creating a wetland, one must ask what plants should be included. What was the natural, undisturbed state of marshes in the area, as pertains to both plant communities and sedimentation patterns? These questions can be answered in part by paleoecological studies designed to discover the pre-European-settlement state of the marsh. Such an approach assumes that the pre-settlement marsh was, in fact, undisturbed, with no significant impact by the indigenous peoples.

Many marsh studies investigate changes in sediment accumulation rate through ^{210}Pb or ^{137}Cs dating, or measure current sediment accumulation rates with a sediment elevation table (SET) (e.g., Sommerfield, 2005; Chmura and Hung, 2004; Kearney at al, 1994; Zwolman et al., 1993; Orson et al., 1990). This study uses pollen analysis as the primary method of estimating ages of sediments in the cores, with ^{14}C and ^{210}Pb data from other researchers used as secondary methods (Wilson, 2005; Sommerfield, 2005). Pollen analysis allows the identification of well-dated events

that correspond to anthropogenic activity, such as the clear-cutting associated with the advent of European agricultural practices.

Ambrosia (ragweed) is a natural component of forests in Delaware, but the plant is an opportunistic colonizer of disturbed areas, so forest clearance events will provoke a spike in ragweed growth (Bazazz, 1974). Since European settlers used clear-cutting techniques for agricultural purposes and to provide firewood and lumber, the beginning of this activity shows up in the pollen record as a decrease in pollen from old-growth tree species like *Quercus* (oak), and an increase in *Ambrosia* pollen. Brush (1989) used the ratio of *Quercus* to *Ambrosia* (oak-to-ragweed ratio) to locate the agricultural horizon, the depth at which greater than 50% of forest land in the watershed had been cleared. Dividing the amount of *Quercus* by the amount of *Ambrosia* amplifies the signal, making the delineation of this agricultural horizon much easier. The pollen horizons as used in the Chesapeake Bay area by Brush (1989) are shown in Table 1.1.

Table 1.1 Pollen horizons used by Brush for dating Chesapeake Bay sediments.

Date of Horizon	Change in vegetation	Pollen representation
1930 (1923-1937)	Demise of American chestnut	Decrease in chestnut pollen to <1%
1780 (1760-1800)	40-50% of land cleared for agriculture	% ragweed pollen >10 oak:ragweed ratio <5
1730 (1720-1740)	<20% of land cleared for agriculture	% ragweed pollen >1 to <10 oak:ragweed >5

(Brush and Davis, 1984; Brush, 1989)

The actual dates used will be different in the St. Jones River basin, but the values of the oak-to-ragweed ratio should remain approximately the same due to the similarities in plant communities between the Chesapeake Bay area and Delaware. The oak-to-ragweed ratio may show additional forest disturbance horizons other than the agricultural horizon. The advent of suburbanization in the early twentieth century, for example, would generate the same signature in any area where land was cleared for new construction. Forest fires and Native American activities also may result in a lower oak:ragweed ratio. Once the date of European settlement is established in a core, pre- and post-settlement sediment accumulation rates can be compared, and ecological changes evident from the pollen record can be analyzed for possible causes. The use of radiometric dating as an additional method provides dates for deeper parts of the cores.

Additionally, the pollen analytical conclusions in this study are further constrained by the well-documented Holocene lithostratigraphy of the study area (Wilson, 2005). Most pollen analytical studies are not able to include a detailed examination of the physical stratigraphy. The opportunity to do so here facilitates the interpretation of the pollen biostratigraphy in light of indicated depositional environments and unconformities. At the same time, micropaleontological analysis of pollen assemblages yields considerably greater temporal and paleoenvironmental resolution than lithostratigraphy alone, thus increasing the level of detail available for consideration.

Pollen Analysis

Pollen Production and Dispersal

It is helpful to understand the mechanics of pollination, since this process directly impacts the types and amounts of pollen deposited. Plants are pollinated by wind, animals, or water. The method of pollination determines the amount of pollen released and how widely it will disperse. Pollen from aquatic plants that release their pollen underwater are limited by water transport, and can be expected to be found only in sediments of marine, lacustrine, or possibly marsh origin. Animal- or insect-pollinated plants tend to produce grains that will in some way stick to the organism that carries their pollen. These will not be widely dispersed uniformly over a region, but may be found near the location of the mother plant. In contrast to the other two types, wind-pollinated plants produce large quantities of pollen and rely only on the wind to transfer grains between flowers. The pollen from these plants is dispersed widely over the area. Forest trees can produce literally hundreds of thousands of pollen grains per tree per year (Faegri et al., 1989).

As pollen grains from wind-pollinated plants are released from each flower, some fall immediately, and some become airborne. The grains may fall onto the ground or may be intercepted by leaves of other plants. The airborne pollen can in turn be deposited on plants or water surfaces with which the airmass carrying the pollen comes into contact, or may continue airborne until forced to settle. Cooling and subsequent sinking of the airmass at night causes most pollen to settle, as does rain,

but if grains are carried high enough into the atmosphere by updrafts they may be carried greater distances. The distance covered in one day of transport tends to be limited to 50 to 100 km, but pollen has been found up to 3,500 km away from any possible source (Faegri et al., 1989). These long distance transport events are not typical, but atmospheric conditions sometimes permit them. Pollen in any given area usually comes from plants in the surrounding several kilometers. Pollen from a lone tree can be identified up to 300 m away, after which it can no longer be traced to that one tree (Faegri et al., 1989). In a lake, and presumably in a marsh as well, there is a greater prevalence, relative to upland sediments, of pollen from farther away due to water transport. Any grains that fall into a stream will be washed downstream and deposited in the streambed, swept into a lake, or deposited in a marsh at its inundation period. Water and wind may also rework previously deposited pollen, and rain may wash pollen to the ground from other surfaces.

Other possibilities for deposition of pollen exist, although they do not contribute to regional pollen rain. Fecal transport and human transport produce local anomalies. These include activities such as tracking pollen from elsewhere on shoes or clothing, and grazing animals carrying pollen with them to locations foreign to that plant species and depositing it in their feces (Faegri et al., 1989).

The implications of pollen transport on my study area are contingent on the distance of the tidal marsh field location from the forest. The highest concentrations of arboreal pollen should be found in old forest sediments, corresponding to the pollen that fell to the ground immediately (Faegri et al., 1989). Concentrations of pollen that became airborne and was transported locally into the marsh should drop off about 300 m away from the forest edge, but pollen should still

be present even in sediments from the areas of the marsh that were farthest away from the forest (Faegri et al., 1989). Pollen assemblages from the interior of the marsh should therefore represent the average wind-pollinated plant community of the surrounding 50 to 100 kilometers (Faegri et al., 1989). Since the study area is in a tidal marsh on a tidal river, there may have been some deposition of pollen that was transported by the river over longer distances. The sediment may contain non-aeolian pollen, such as those from insect-pollinated plants, but these will not have traveled far from the source plant, and may be considered to represent plants from the immediate study area, not the surrounding area. All these factors contribute to the types of pollen and the amounts of pollen that are deposited at any one site in a marsh. Natural and man-made variations in factors such as wind patterns, stream flow, and plant cover will affect the pollen counts somewhat, even in the absence of major ecological change.

Pollen Morphology

Pollen analysis depends upon the ability of the researcher to accurately identify pollen grains from individual taxa. This requires a full understanding of the morphology of pollen grains. Pollen morphology as presented here is summarized from Faegri et al. (1989) and Kapp et al. (2000). The part of a pollen grain that survives as a sub-fossil is called the exine (Figure 1.1). This is the outer layer of the grain, and is made of a very resistant organic substance called sporopollenin, a lipid-like material formed from oxidized carotene polymers (Faegri et al., 1989). The exine

can be further subdivided into two layers, the outer ektexine and the inner endexine. The endexine is a homogenous continuous membrane that may be intersected by apertures if they are present in the particular species. The outer ektexine, however, is structured radially and varies in form with species (Faegri et al., 1989). Small columns (columellae or baculae) sit atop the basal foot layer and support the tectum. This tectum is actually the fused tips of the columellae, and comprises the structural elements that enable one to distinguish between pollen genera. The simplest type of ektexine has no internal structure and is said to be atectate. When the tips of columellae are not fused together, the ektexine type is called intectate. Tectate types that do have the tips of the columellae fused can be perforate, where some of the columellae are not fused, or imperforate, where all are fused.

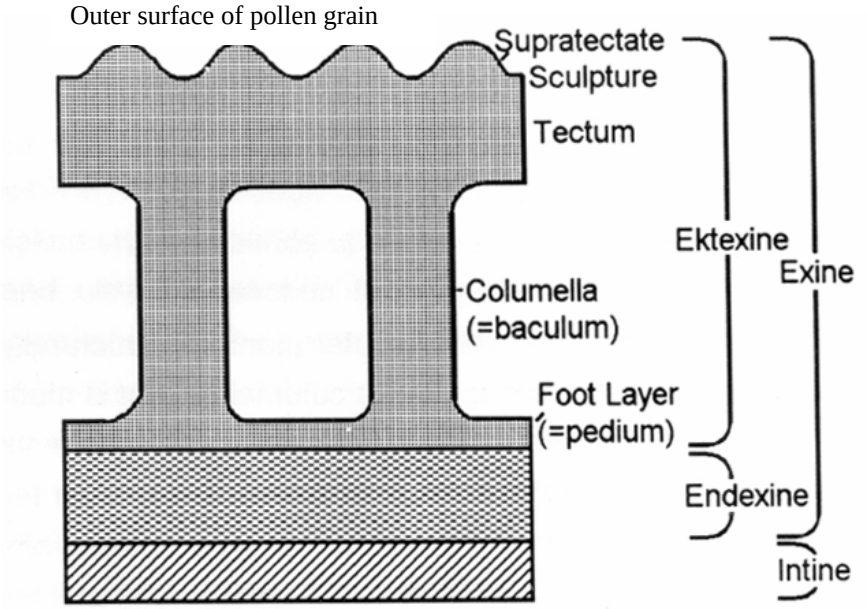

Figure 1.1 The wall structure of a pollen grain (Kapp et al., 2000).

The structure of an ektexine, also referred to as the texture, describes all the characteristics of the ektexine that are inside the tectum (Faegri et al., 1989). Sculpturing refers to form on top of the tectum and is strictly external. Examples of common textures are illustrated in Figure 1.2. Both structure and sculpturing are diagnostic of pollen genera (Kapp et al., 2000; Faegri et al., 1989). A completely smooth surface is called psilate. This is basically no sculpture. Small rounded protrusions are called scabrate, verrucate, or gemmate sculpture, in increasing size. Sculpture that looks like little clubs thicker at the outside are clavate while clubs of uniform thickness throughout the entire length are baculate sculpture. All sizes of spikes are referred to as echinate sculpture. Reticulate sculpture looks like netting or a honeycomb while a pattern of parallel lines is striate. The term rugulate refers to shorter lines that are not parallel but more wiggly. These last three patterns can be caused by both positive and negative relief, but the opposite of rugulate is called fossulate. Other possibilities are fenestrate (windows), and foveolate, or pitted. Structures can also be described as micropitted, microscabrate, microreticulate, and so forth, if the structure is less than 1μm in size.

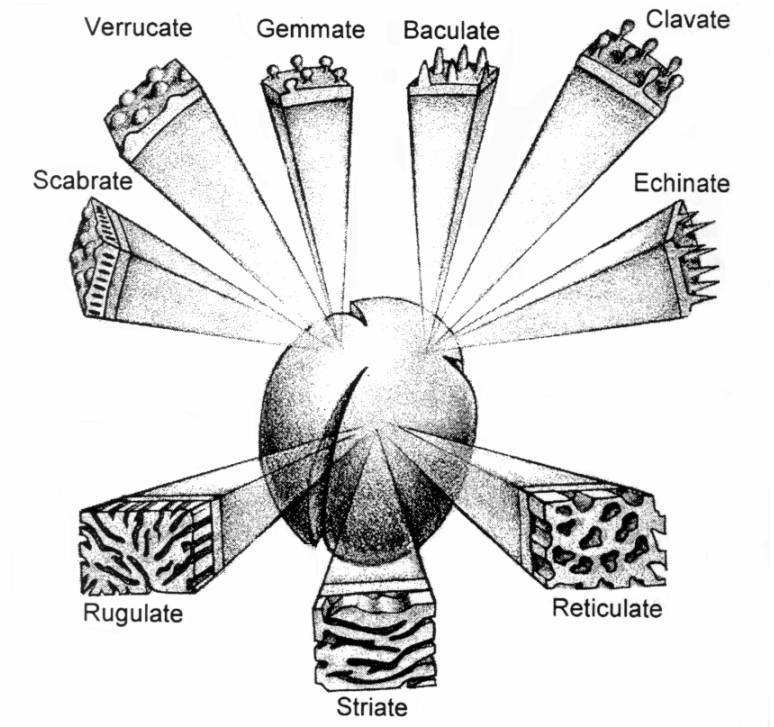

Figure 1.2 Types of pollen texture (Kapp et al., 2000).

Pollen grains also have openings called apertures. The two basic types are pores and furrows (colpi) (Kapp et al., 2000; Faegri et al., 1989). Pores are more or less round and colpi are elongated. Pollen grains are described by the number of each type of aperture. Figures 1.3 and 1.4 illustrate morphological types of pollen grains. A grain with one pore is called monoporate, while a grain with three pores is called triporate. A grain with more than three pores is stephanoporate. The same terminology applies to colpate grains: monocolpate for one colpus, tricolpate for three colpi, and stephanocolpate for more than three. More specific distinctions can be

made based on thickened apertural edges, differences in sculpture inside and outside the colpi, and distribution pattern of apertures around the grain. Spores, as opposed to pollen, do not have pores and colpi, but they do have apertures called laesurae, or slits.

The morphology of pollen grains serves practical purposes other than identification. The laesurae, colpi, and pores are the apertures from which a pollen grain extrudes its genetic material during the process of reproduction, and are also thought to assist in volume regulation (Faegri at al., 1989). The various patterns of sculpturing affect the aerodynamics of windborne grains and affect the degree to which grains will adhere to each other or other surfaces (Faegri et al., 1989).

Other diagnostic factors for pollen include the size, shape, and scarring of the grain (Kapp et al., 2000, Faegri et al., 1989). The size of pollen grains can vary within the same species, but they generally fall within a certain range for each genus. Shape is less variable, and usually ranges from spherical to oblate or prolate (Figure 1.5). If a spherical pollen grain is thought of as a globe, flattened spheres are prolate if the long axis is polar and oblate if the long axis is equatorial. Other forms include pear-shaped, triangular, square, or bean-shaped.

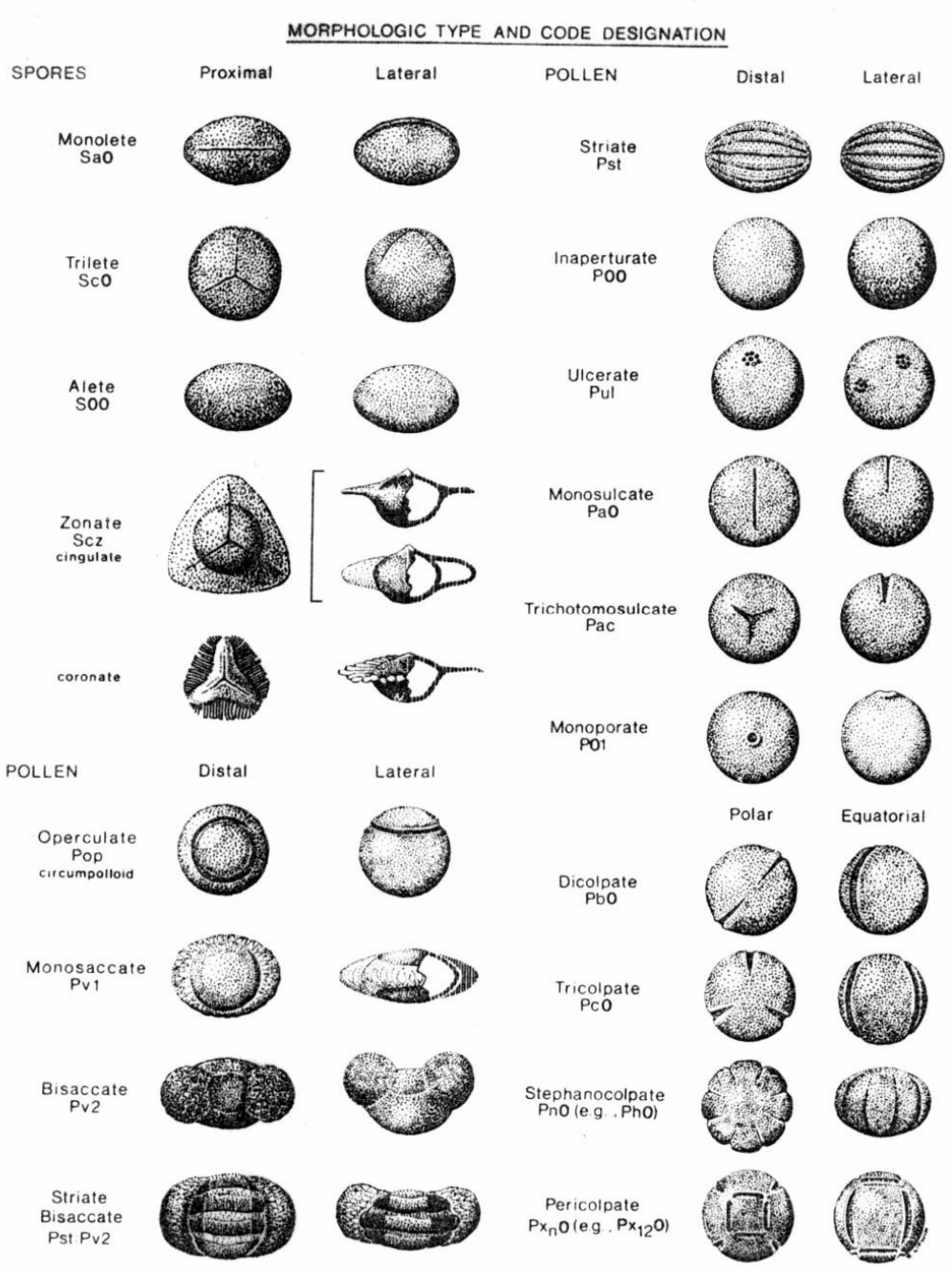

Figure 1.3 Pollen morphological types (Traverse, 1988).

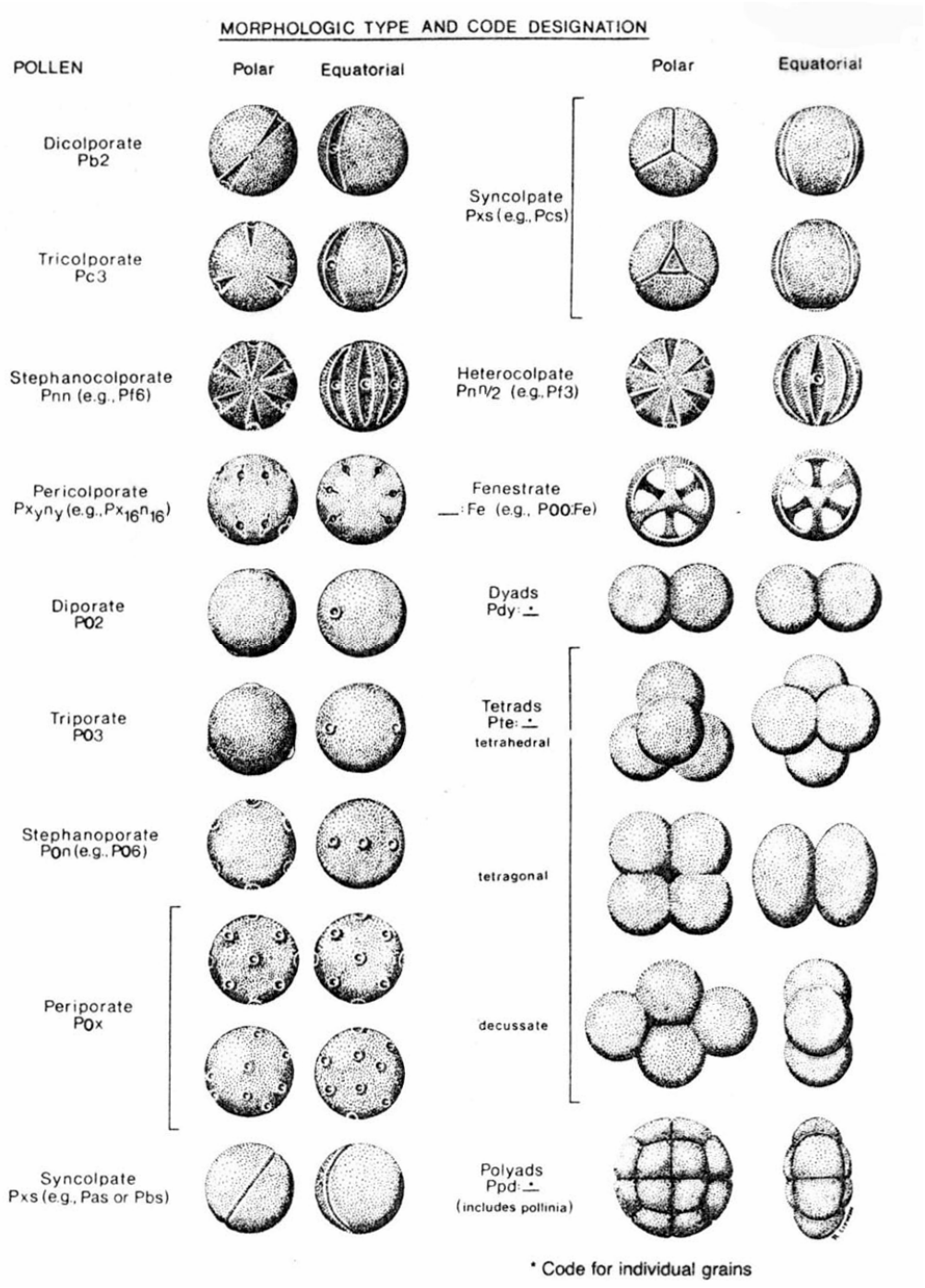

Figure 1.4 More pollen morphological types (Traverse, 1988).

Scars may indicate where each pollen grain was attached to others in its original tetrad group (Faegri et al., 1989). Pollen commonly grows in groups of four, or tetrads, which vary in arrangement. Most of the time these break up upon dispersal, but the scar remains where the grain was attached to its neighbors.

When taken together, all the characteristics of the exine of a pollen grain or spore enable identification. Identification is usually possible only to the genus level, but occasionally only to the family, as in grasses (family Poaceae), since the characteristics that define species are carried by the part of the pollen that degrades.

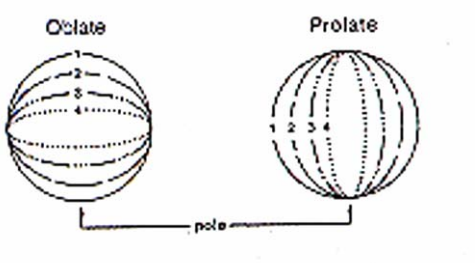

Figure 1.5 Oblate versus prolate (Traverse, 1988).

Interpretation of Pollen-Stratigraphic Data

The main tool used to assist with interpretation of pollen-stratigraphic data is the pollen diagram. The primary objective of the pollen diagram is to give a visual presentation of the numerical data (Faegri et al., 1989). It is usually easier to gain an understanding of data presented in charts than by examining raw numbers. Interpretation of these diagrams involves reconstruction of local plant populations from the data and inference of climate or land use history (Faegri et al., 1989). Because pollen diagrams show abundances of pollen present throughout the depth of the core, they do not directly reflect the local plant population at the time of deposition. Only those pollen grains that were deposited at the core site, preserved in the sediment, and ultimately recovered comprise the pollen data (Faegri et al., 1989).

Other biological factors must be considered when interpreting as well. Pollen deposited on a marsh surface comes mostly from the rain of wind-dispersed pollen produced by plants living both locally and regionally, but also includes water-dispersed pollen and some insect-dispersed pollen (Faegri et al., 1989). Only flowering and spore-producing plants are represented, however. Plants that were not able to flower are not represented. Factors that prevent plants from flowering, such as critical environmental conditions, will prevent their pollen from being deposited even if the species in question is very prominent (Faegri et al., 1989). Differences in pollen production between species can also skew data. *Pinus*, for example, produces very large quantities of pollen whereas some other trees, like *Fagus*, do not (Faegri et al., 1989). It is even possible to find *Pinus* pollen present at sites that have no local pine trees. The composition of the plant community will affect relative abundances, too, and this together with different pollen production rates can greatly affect how data are

interpreted. The percentages or proportions of individual species relative to the whole pollen signal do not directly reflect the percentages of those species in the plant community (Faegri et al., 1989). An additional problem is the difficulty of identifying some pollen to the species level. Certain types can only be identified to genus or family (Faegri et al., 1989).

Calculating percentages requires a clear understanding of the question to be answered. Relative percentages are figured as fractions of the pollen sum, which is the total of all grains counted that relate to the question being investigated. Therefore, the choice of which taxa to include in the pollen sum is very important. One might, for example, study the evolution of the terrestrial plants in an area over time, and thus include all pollen and spores except those of aquatic plants. One might study forest succession, and therefore include only tree pollen. The taxa included in this sum can vary according to the study, so careful consideration must be made about which taxa to include or reject (Faegri et al., 1989).

Other sources of difficulty in reconstructing vegetation are reworked pollen, stratigraphic problems, local overrepresentation, long-distance transport, and poor preservation or degradation (Faegri et al., 1989). Pollen will accumulate in sediment in which the grains have the same hydrodynamic properties as the pollen, so some sediments may contain less pollen, or less of certain types (Faegri et al., 1989). Older pollen may be reworked into younger sediment or transported from sediment eroded elsewhere, and this may not necessarily be obvious from the stratigraphy of the core. Unconformities also may not be obvious, so a good understanding of the stratigraphy of the study area is beneficial. Overrepresentation of species like *Pinus* is to be expected, but other species may be overrepresented due to local conditions, like

preferential logging or local cultivation of some species. Long-distance transport may bring in pollen from outside the study area. In a tidal marsh flanking a river, for example, the river may bring in pollen from the headwaters, which could then be deposited in the marsh at high tide. Pollen of species foreign to the marsh and surrounding forest could thus be introduced. Pollen grains may degrade over time due to oxic conditions in the sediment, or be damaged accidentally during chemical processing. Features crucial to positive identification may be rendered indistinct, making identification difficult or impossible. These types of difficulties cannot be protected against, but their overall impact on the pollen record is minor (Faegri et al., 1989).

The pollen spectrum directly records information about the plants present in the area and how the composition of the plant community might have changed over time. Any information about what caused the plant community to change is indirectly recorded (Faegri et al., 1989), impeding interpretation of the causes of changes in species abundances. For example, pollen data may show that a certain tree species declined dramatically. This could have been caused by disease, climate change, increased competition, or human activities, none of which can be proven based solely on the pollen record (Faegri et al., 1989).

Climate change can be indicated by the movement of plant assemblages from those that thrive under one set of climatic conditions to those that thrive at another. Resolving conclusions about absolute paleoclimatic conditions, however, is more difficult, and involves defining ecologic niches of various plants involved until the range of climate parameters can be narrowed to meaningful values or by using transfer functions (Faegri et al., 1989). It is more common to confine interpretations

to general climate conditions, like cooler or moister based on the types of plants present in the pollen record. For example, *Pinus* grows in warmer conditions than *Picea*, so a change from *Pinus* species to *Picea* would indicate a cooler climate. More specific conclusions are usually not supportable due to the large number of agents that can change the composition of plant communities and the possibility that more than one agent of ecological change may act concurrently (Faegri et al., 1989). Determining human impact on plant communities is more straightforward, however, and depends somewhat on knowledge of the habitation history of an area. Clearing a forest for farming, for example, will be recorded in the pollen record as a drop in tree pollen and a rise in certain weeds, although this pattern could also be caused by non-anthropogenic forest clearance, like a fire. Examples of major pollen groups useful for paleoecological conclusions in the study area and the conditions they usually indicate are given in Table 1.2.

Age estimation is another common application of pollen analysis. Pollen "dating" is purely relative, so it is not appropriate to use the term dating in this context. Age estimating is a more accurate phrase. Pollen analysis identifies plant events of stratigraphic significance, and these are then dated by other means, like comparison with historical records or geochemical techniques (Faegri et al., 1989). To estimate ages based on pollen data, one needs to have a more absolute method to provide anchor points for reference. Radiocarbon is usually used to provide these anchors because of the prevalence of peat in marsh sediments, but bioturbation and contamination can cause radiocarbon dates to be younger or older than the actual age of the sediment, and can mix pollen from different time periods. Even so, use of a secondary method of dating provides a check on the accuracy of the dates generated

with pollen analysis. Pollen analytic age estimation also relies upon known dates of plant events, like the American chestnut (*Castanea dentata*) blight, which reached Delaware in 1930, or the beginning of forest clearance for agriculture and industry by European settlers.

Table 1.2 Paleoecological significance of some major pollen groups.

Scientific name	Common name	Significance
Pinus	Pine	upland soils, common to Mid-Atlantic forests, moderate temperatures
Picea	Spruce	upland soils, colder temperatures
Quercus	Oak	upland soils, common to Mid-Atlantic forests
Carya	Hickory	upland soils, common to Mid-Atlantic forests
Salix	Willow	wet soils
Alnus	Alder	wet soils
Ambrosia	Ragweed	thrives in open areas
Cheno-Ams	Sea Blite, e.g.	open areas, tolerates saline conditions
Cyperaceae	Sedges	live in wet areas, most species in study area prefer fresh water
Poaceae	Grasses	live in open areas, most species in study area are salt-tolerant

Study Area

Local History

The Delaware River was discovered by Henry Hudson, working for the Dutch East India Company, in 1609 (Delaware Division of Historical and Cultural Affairs (DHCA), 1976). The first settlement in the future state of Delaware was a Dutch whaling colony on Cape Henlopen in 1631 (Heite and Heite, 1985). Zwaanendael, as it was called, lasted only one year before being destroyed by the local Native Americans. The site was not resettled until 1661 (DHCA, 1976). Sweden also wanted to claim Delaware for itself, and so established its own colony. Fort Christina, the first permanent settlement in Delaware, was established by the Swedes in 1638, at present-day Wilmington (DHCA, 1976). The Dutch quickly established their own rival colony nearby in 1651 (DHCA, 1976): Fort Casimir was located near the modern town of New Castle. Competition between the two colonies was intense, resulting in military conflicts.

The arrival of the English in the middle seventeenth century, however, eventually calmed the hostilities. They began settling areas south of Fort Christina and Fort Casimir, including the St. Jones River, which was first settled by the English in 1650 with a town called St. Jones Neck (Heite and Heite, 1985). Ownership of Delaware fluctuated between the Swedes, Dutch, and English, but the English gained permanent control in 1674 (DHCA, 1976) and managed to make a lengthy but successful transition to English government while peacefully integrating the rival

communities (Custer et al., 1986). Under the English system of law, two legal jurisdictions were established to serve the people of Delaware, one in New Castle and one in Lewes. In 1680, however, population growth reached the point that a third court jurisdiction was established in the Dover area, with the town of Dover built in the 1720s (Heite and Heite, 1985).

Early settlement in Delaware was mainly on well-drained land along creeks and rivers, as these were the primary means of transportation (Custer et al., 1986). Settlers tended to follow the long-lot system, which had narrow but lengthy lots along waterways. The house was built at the front and the land behind farmed. The interior areas were settled only as roads were built and towns established at crossings (Custer et al., 1986).

Agriculture has dominated Delaware throughout its history. Grain was the first dominant commodity, and was exported to larger cities like Wilmington and Philadelphia (Matlack, 1997a). Poor farming practices depleted the soil throughout the eighteenth century, resulting in lower fertility (Custer et al., 1986). The introduction of fertilizers in 1836, however, revived agriculture in the state (Custer et al., 1986). Most East Coast states saw a regrowth of forest after the Midwest opened for agriculture in the early 1800s, but Delaware farms switched to vegetables, milk, and chickens, thus preventing large-scale forest regeneration (Matlack, 1997a).

An agriculture depression in the early 1900s followed by the Great Depression in the 1930s, compounded by increased competition from non-local farms, resulted in farm abandonment and a general decline in farm area (Matlack, 1997a). Most of the abandoned farms were converted to housing, either suburban or estate, with forest regeneration confined to plots within large estates and along borders of

farms and housing developments (Matlack, 1997a; Matlack, 1997b). A phase of increased development took place starting around World War II, with the advent of suburbanization and the accompanying construction boom. It was also about this time that Dover Air Force Base was constructed, in 1942. Since then, the state of Delaware has become very popular for both residences and businesses. Large tracts of farmland were converted to housing or industrial complexes instead of being abandoned long enough to regrow forest, as in other states (Matlack, 1997a).

The end result is a state with large tracts of agricultural, industrial, and residential land and very few forested areas. Figure 1.6 shows an aerial photo of the study area in 1937, with the location of core RPC2 marked. In 1937, there were large amounts of farmland and relatively few forested tracts. Figure 1.7 shows the same area in 1954. The large black box is the Dover Air Force Base. Outside of the base, the land is still mostly agricultural. Figure 1.8 is from 1981. By this time, the agricultural land has been converted to housing developments, and that the forested areas are still in the minority and largely confined to the river. By 1990 (Figure 1.9), the amount of forested land is still very small, and more farms have been converted to housing and industrial development.

Figure 1.6 Aerial photo of the study area in 1937.

Figure 1.7 Aerial photo of the study area in 1954.

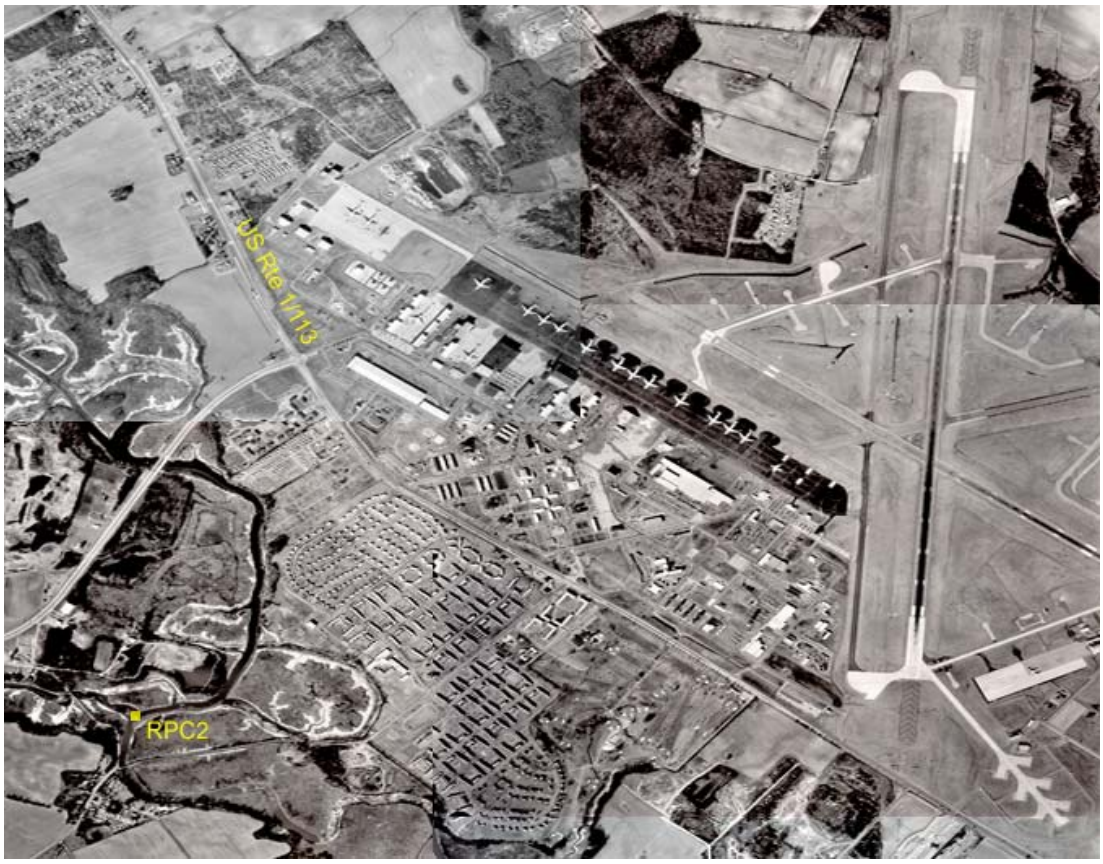

Figure 1.8 Aerial photo of the study area in 1981.

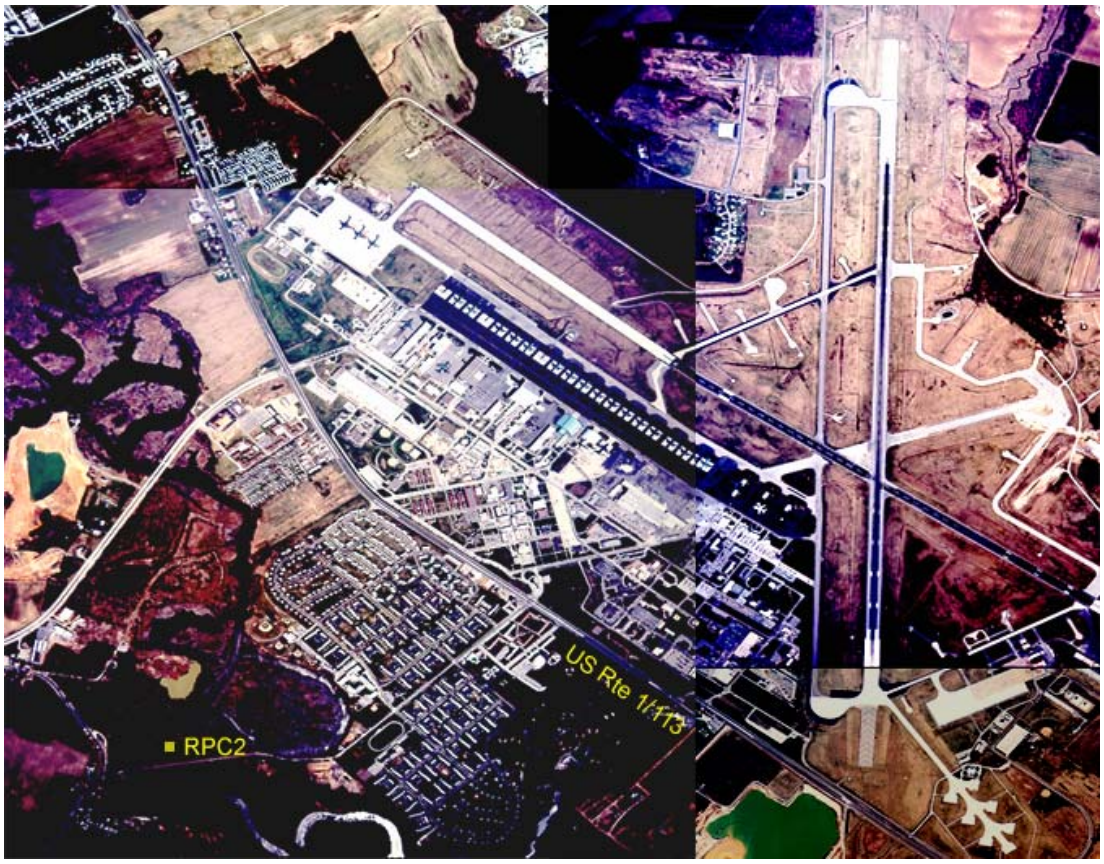

Figure 1.9 Aerial photo of the study area in 1990.

Geology

The St. Jones River is a sub-estuary of the larger Delaware Bay estuarine complex. The total length of the Delaware River is about 215 km, with 60 km belonging to the upper river, 80 km in the middle, partially mixed section of river, and the lower 75 km comprising the saline section (Fletcher et al., 1992). Numerous streams, creeks, and smaller rivers discharge into Delaware Bay, and an extensive system of fringing tidal marshes surrounds the bay and its tributaries.

The ancestral Delaware River was incised into Pleistocene fluvial and aeolian sediments during the Late Wisconsinan deglaciation (Fletcher et al., 1992; Kraft, 1971). The mouth of the river at that sea-level lowstand extended to the edge of the continental shelf, and the ancestral river valley slowly filled during the Holocene transgression (Kraft, 1971). The Delaware River and Bay and its tributaries presently sit atop Holocene sediments deposited in the ancestral channel during this transgression (Wilson, 2005). Because the Mid-Atlantic region is subsiding due to post-glacial isostatic adjustments, the Holocene transgression is still occurring. The landward limit of the transgression is marked by the boundary between marsh sediments and upland sediments, with the marsh sediments moving inland as sea-level rises.

There are four factors that control tidal marsh accretion rates: sediment supply, plant productivity, subsidence of the marsh surface due to autocompaction, and sea-level change (Chmura et al., 2001). Marsh sediment comes from both allochthonous and autochthonous sources. Allochthonous sediment, or sediment from elsewhere, can come in with the tides, be washed down river from upland areas, or brought overland with erosion. In the case of water-borne sediment, the inundation

period controls the amount of sediment that can be deposited. Low marsh areas and intertidal mudflats, which are inundated most of the time, tend to have higher sediment accumulation rates than less-often inundated high marsh areas (Fletcher et al., 1992; Stumpf, 1981, 1983; Pethick, 1981). Autochthonous sediments are those that develop in place. In a marsh these are organic in nature, like peat. Autochthonous sediments are derived from the plants growing in the marsh, and are thus dependent on plant productivity. Organic sediments like peats will compact over time as they are buried, and this autocompaction tends to lower the marsh surface. Changes in sea level will also affect the height of the marsh surface. High marsh elevation is controlled by the height of the maximum spring high tide (MHHW) (Fletcher et al., 1992; Stumpf, 1981, 1983; Pethick, 1981). If the marsh surface should become any higher than this, it will cease to be a wetland and develop into an upland area as the surface is no longer able to be inundated. Likewise, a rise in sea level will cause the fringing marshes to expand landward.

As with the Delaware River, the bed of the St. Jones River was incised into Pleistocene sediments during the Late Wisconsinan deglaciation (Wilson, 2005). Holocene sediments in the ancestral St. Jones River incised valley are characterized by a shallowing-upward sequence of deposition. Subtidal sediments such as inorganic clays and silts were overlain by intertidal sediments (organic clays), followed by tidal marsh sediments (Wilson, 2005). The depositional environments in the river valley became progressively more supratidal throughout the Holocene. Additionally, the course of the river changed frequently, resulting in many paleochannels under the modern marsh surface (Wilson, 2005). The lithostratigraphy under the marsh is thus quite complicated and not a simple layer-cake configuration.

Ecology

The St. Jones River is a mesohaline, microtidal river that discharges into Delaware Bay (Figure 1.10) (DNREC, 1999). The river runs through the town of Dover and is adjacent to Dover Air Force Base. About half of the watershed area is used for agriculture. Of the other half, 25% of the watershed is developed, 14% is wetlands, and 10% is forested (Figure 1.11) (DNREC, 1999). Mean tidal range of the St. Jones River is about 1.5 m. Maximum tidal velocities in the seaward end of the river range between 20 and 40 cm/sec. Salinity in the lower St. Jones River ranges between 1 and 20 ppt (DNREC, 1999).

The wetlands adjacent to the river are dominated by *Spartina alterniflora* in the low marsh, where the land is flooded daily at high tides (DNREC, 1999). In the high marsh, where flooding frequency is less than once per day, the vegetation is more diverse, and not dominated by *S. alterniflora*. Other important plants present in the marsh include common reed (*Phragmites australis*), marsh elder (*Iva frutescens*), groundselbush (*Baccharis halimifolia*), saltmeadow cordgrass (*Spartina patens*), saltgrass (*Distichlis spicata*), and big cordgrass (*Spartina cynosuroides*). Trees in and adjacent to the marsh include smooth alder (*Alnus serrulata*), dogwoods (*Cornus* spp.), red cedar (*Juniperus virginiana*), willows, (*Salix* spp.), red maple (*Acer rubrum*), green ash (*Fraxinus pennsylvanicus*), black or sour gum (*Nyssa sylvatica*), and sweet gum (*Liquidambar styraciflua*). Upland vegetation apart from agriculture includes mixed deciduous hardwood forest. Forests in the area had been clear cut for lumber, and are neither old-growth or very continuous in extent. Dominant species include tulip poplar (*Liriodendron tulipifera*), American beech (*Fagus grandifolia*), white oak (*Quercus alba*), southern red oak (*Q. falcata*), black cherry (*Prunus*

serotina), American holly (*Ilex opaca*), sassafras (*Sassafras albidum*), and various hickory species (*Carya* spp.) and pines (*Pinus* spp.).

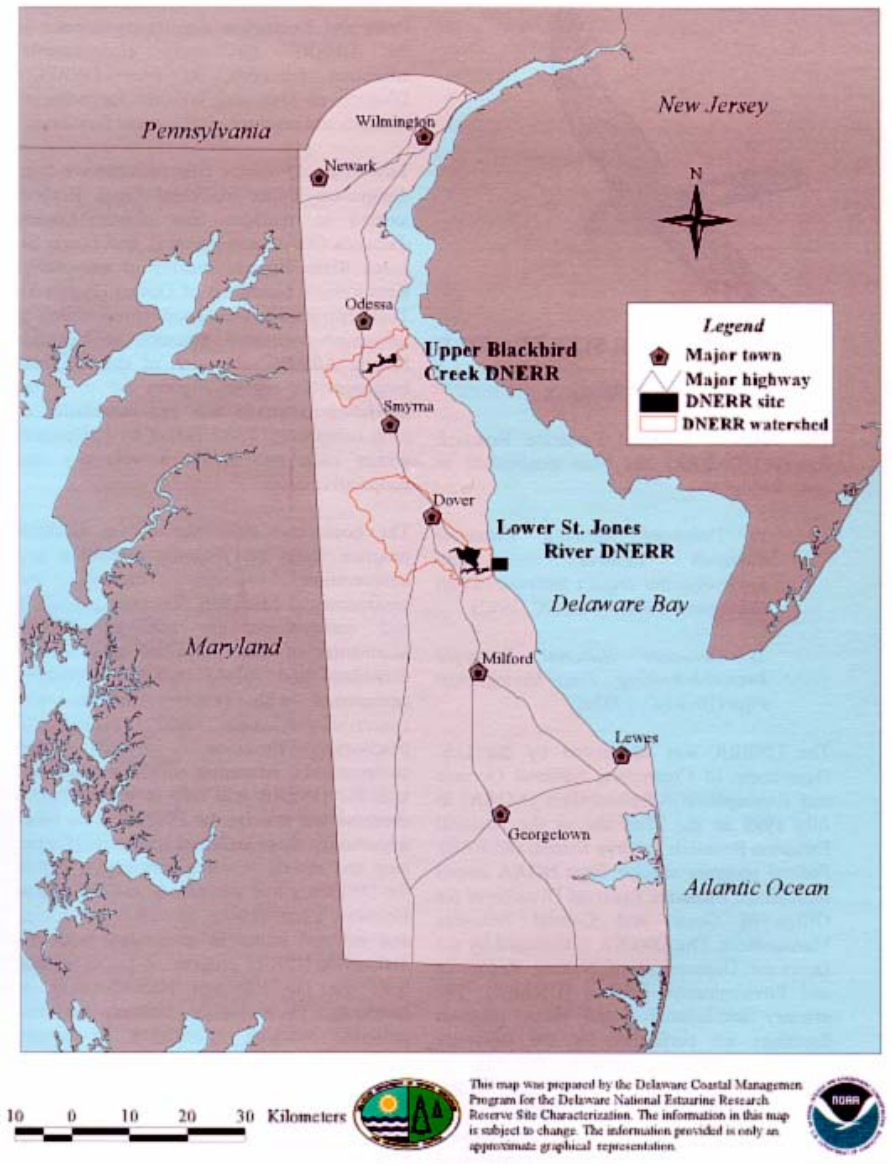

Figure 1.10 Map of Delaware showing the location of the St. Jones River and Delaware's National Estuarine Research Reserve (DNREC, 1999).

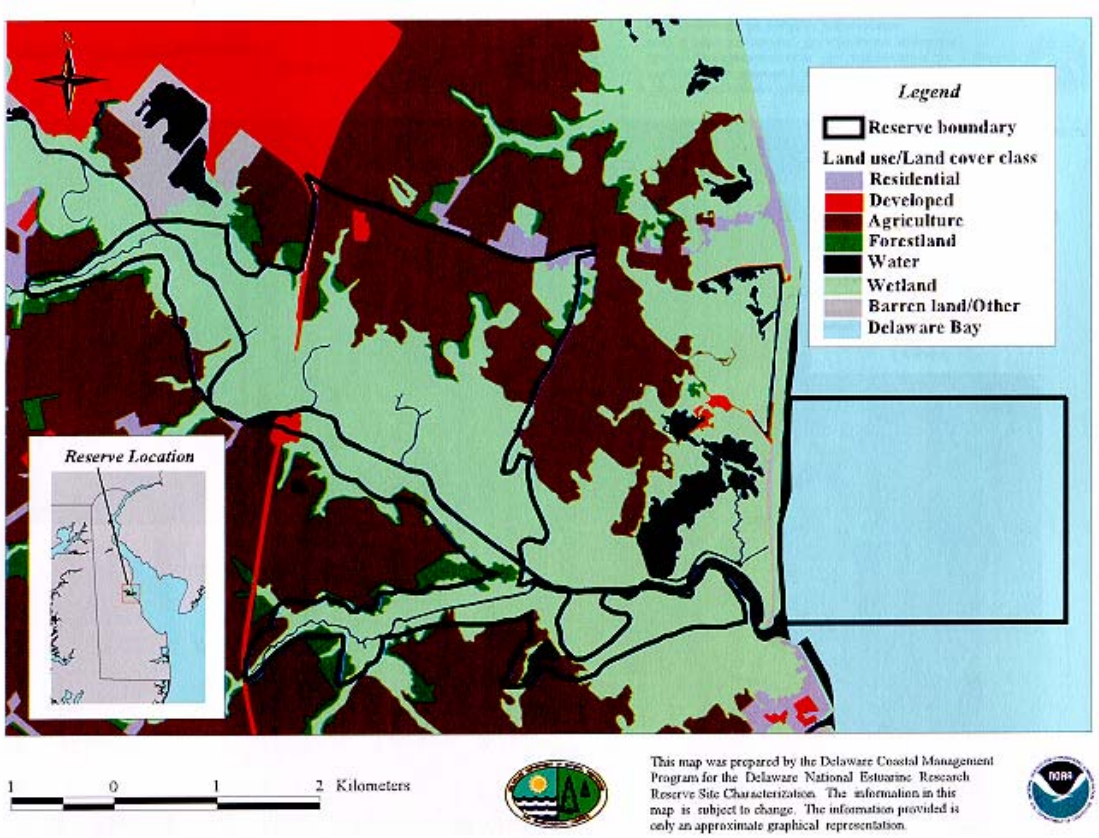

Figure 1.11 Dominant land uses in the study area (DNREC, 1999).

Previous Work

In the study area

The geology of the St. Jones River marshes was investigated by Wilson (2005) in an effort to describe the response of an estuarine ecosystem to natural and anthropogenic environmental changes. Sub-bottom sonar profiles, vibracores, and Dutch auger cores were used to describe marsh sediments and develop a model of marsh deposits and changes in river-valley geometry over time. Sediments from 32 auger cores and 14 vibracores were collected along five transects across the lower St. Jones River. Sediment types were examined and classified according to depositional environment. Plant remains were also identified and used to help determine both depositional environments and degree of marsh salinity. Sub-bottom sonar was used on the river to identify paleochannels and other relict structures in the sediments under the riverbed. Wilson found that the course of the river changed frequently, resulting in many paleochannels under the marshes.

Sea-level was not the only major factor in the development of the St. Jones River estuary. Halophyte distribution, organic and inorganic sediment supply, antecedent topography, and the degree of channelization of river flow all contributed significantly to the evolution of the St. Jones River (Wilson, 2005). Prior to 2000 years before present (YBP), the river valley was dominated by intertidal and subtidal environments with thin fringing marshes containing few halophytes (Wilson, 2005).

Additionally, the river valley was very narrow at that point in time, resulting in faster velocities and a greater tidal prism than at present. After 2000 YBP, however, halophytic plants were able to successfully colonize the region, increasing inorganic sediment deposition by trapping (Wilson, 2005). From 1500 YBP to 1000 YBP, the river valley became dominated by emergent marshes and a widespread supratidal environment (Wilson, 2005). The rate of sea-level rise remained the same as in the past, but it was the increased presence of halophytes along the fringes that enabled sedimentation to increase (Wilson, 2005). Natural levees built up around the banks of the river, causing river flow to become more channelized, and increasing river salinity (Wilson, 2005). By 300 YBP, the rate of sea-level rise had slowed a bit and sediment deposition had decreased, resulting in a loss of marsh area. The decrease in sediment supply to the marshes was the result of both a period of lower plant productivity and the channelized river flow carrying sediments past the marshes (Wilson, 2005).

European settlers arrived in the area starting about 350 YBP. Their land-use practices increased sediment and nutrient supply into the rivers and caused the marsh surface to once again become more emergent, and the river to incise further and become even more channelized (Wilson, 2005). The St. Jones River estuary today is becoming unstable, with large scale erosion on riverbanks, increased ponding and inundation periods, development of salt pans, vegetation diebacks, and changes in plant distributions (Wilson, 2005). According to Wilson, collapse of the entire system seems inevitable, as the natural dynamics of the ecosystem have been irreversibly altered.

Most studies involving fossil pollen in Delaware have been conducted by the Delaware Geological Survey as part of its work on the local aquifers (e.g.

McLaughlin and Benson, 2002). As the aquifers in Delaware are all of Pleistocene age and older, these studies are of limited benefit to Holocene investigations. Archaeological studies related to the construction of State Route 1 and studies of several historical sites near Dover by the Delaware Department of Transportation (DelDOT) have also included pollen analysis as part of the investigation. The purpose of these studies was primarily to ascertain the cultural resources in areas intended for major construction projects, and palynological conclusions are usually limited to the presence or absence of cultivated grains.

Daniels (1993) studied the Quaternary history of an archaeological site three miles northwest of Dover in the St. Jones River's floodplain as part of an archaeological study for DelDOT. Although the study area was far beyond the tidal influence of the river, the results show general climatic trends for central Delaware. Pollen analysis, radiocarbon dating, and subsurface investigations yielded a 20,000 year paleoenvironmental reconstruction. The environment prior to 21,000 YBP consisted primarily of sand dunes. Many of the interdune areas became increasingly flooded and eroded up to 15,000 YBP. There were thick sections of sand and gravel deposited by the St. Jones River between 15,000 and 10,300 YBP, indicating an increase in large storms and related erosional events. By 10,300 YBP, the floodplains were dominated by vertically accreting sediments, indicating drier conditions had developed. These persisted until 2,800 YBP, with an interval of severe drought between 8,800 YBP and 5,680 YBP. After 2,800 YBP the climate became wetter and more like the current conditions in the St. Jones River basin.

Brush (1994) studied the pollen, seed, and charcoal record in three cores from tidal streams along the proposed extension route for State Route 1, one of which

was from the St. Jones River. Cores were dated with ^{14}C, ^{210}Pb, and pollen events. The charcoal record indicated a dry period with many fires between 2000 and 1000 YBP. The amounts of charcoal in the core decreased dramatically after 1000 YBP. Fossil seeds showed large numbers of sedges and aquatic and emergent plants between 1200 and 650 YBP and an increasing number of plants that grow exclusively on dry ground, such as *Cephalanthus occidentalis* (buttonbush) and *Rumex verticillata* (dock) starting 400 YBP. The pollen record showed abundant ferns between 2000 and 1000 YBP, and smaller but omnipresent numbers afterwards. *Pinus* and *Tsuga* were present in large numbers prior to 1000 YPB. The *Pinus* species is inferred to have been *Pinus rigida* (pitch pine), a species that relies on fire to germinate. There was a large decrease in all arboreal pollen 1000 years ago, but "wet" species like *Fraxinus*, *Juglans*, and *Nyssa* were less affected. At the same time, Nymphaceae (water lilies) disappear and Chenopodaceae (flowering weeds) declined dramatically. The presence of *Zizania* (wild rice) and submerged aquatics after 1200 YPB marked a return to wetter conditions. After 400 YBP, however, conditions in the St. Jones River valley became drier, as indicated by analysis of fossil seeds.

In the region

Most Holocene pollen work in the Mid-Atlantic region has been done in the Chesapeake Bay by Brush and colleagues (Brush et al., 1982; Brush and Davis, 1984; Brush, 1989; Ward et al., 1998). Brush and Davis (1984) used pollen dating and diatom analyses to study human impacts on Chesapeake Bay. They found that human

land-use changes such as clearing forests for agriculture, increased use of fertilizers, sewage discharge into the bay, and toxic pollution from herbicides affected both the diatom population and the macrophytes of the area. Changes in such practices since the seventeenth century are recorded in the sediment as changes in diatom population and macrophyte seeds. Brush (1989) used pollen analysis in cores from the Chesapeake Bay to establish dates, which were then used to calculate sediment accumulation rates. She found that the highest rates of sediment influx coincided with both large storms and periods when large amounts of land have been cleared for cultivation. Ward et al. (1998) and Kearney et al. (1994), in related studies, used pollen chronology, along with ^{210}Pb and ^{137}Cs, to calculate sediment accumulation rates in Chesapeake Bay tributaries. They found that sediment accumulation rates, not accounting for autocompaction, differ spatially according to depositional environments. Interior marsh areas tend to have lower sediment accumulation rates than sections of marsh directly bordering streams, and upstream areas tend to have higher marsh accretion rates than downstream areas, although accretion rates do not vary systematically.

Brush and colleagues use the oak-to-ragweed ratio to find the agricultural horizon in Mid-Atlantic sediments (Brush, 1989; Brush and Davis, 1984). The basal area of oak trees in a watershed correlates closely with the amount of oak pollen deposited (Brush and DeFries, 1981), making it a good indicator of the degree of forest cover. Ragweed (*Ambrosia*), although a native plant and natural part of the ecosystem, is an opportunistic colonizer of disturbed areas, such as agricultural fields and the perimeters of parking lots (Bazzaz, 1974). Any forest clearance event may prompt a spike in ragweed growth. Dividing the amount of oak pollen by the amount

of ragweed pollen in a sample highlights the difference between the two abundances. The oak-to-ragweed ratio was estimated by Brush to be below 10 in sediments deposited under mildly deforested conditions (20% of land cleared), and under 5 for severely deforested conditions (over 40% of land cleared). The amounts of land cleared and the corresponding oak-to-ragweed ratios used by Brush in the Chesapeake Bay area are given in Table 1.1.

Colman and Bratton (2003) used pollen stratigraphy along with ^{14}C, ^{210}Pb, and ^{137}Cs to reconstruct diatom history and sediment accumulation rates in a high-sedimentation-rate section of the Chesapeake Bay for the past 1500 years. Over the past 400 years, biogenic silica fluxes, indicative of diatom productivity, increased 4 to 5 times over pre-settlement rates. Total sediment accumulation rates at the study sites has also increased steadily to the present. These results indicate a very high magnitude of anthropogenically-induced changes to the Chesapeake Bay ecosystem.

Fletcher et al. (1993) used pollen analysis, geochemical studies, and sedimentological characteristics of cores from the southeast coast of Delaware Bay to determine the extent of marine and non-marine environments in the Holocene depositional history of a tidal wetland. Pollen analysis was used to determine paleoenvironments and local climate fluctuations. Results showed five episodes of rapid, short-term sea- level rise, with climate varying between warm with variable humidity and cooler with higher humidity.

Orson et al. (1990) used pollen analysis and radiocarbon dating to determine sediment accumulation rates on cores from a tidal freshwater marsh near Philadelphia, PA. Radiocarbon dating was used to provide ages in cores and pollen analysis was used as confirmation. Results showed marsh accretion rates increasing

steadily from about 0.04 cm/yr prior to European settlement to a peak in 1965 of 1.67 cm/yr.

Russell (1980) examined the pollen record from three lakes in northern New Jersey to determine the evolution of the local plant population from pre-colonial times to the present. Three pollen zones were defined, corresponding to pre-European settlement, a period of deforestation, and a period of forest recovery.

Willard et al. (2000; 2003) used analysis of pollen, foraminifera, and dinoflagellate cysts along with radioisotope analysis to reconstruct paleoecological variations over the past 2300 years. Benthic foraminifera data indicate 14 wet-dry cycles over the past 500 years, with "mega-droughts" indicated in the sixteenth and early seventeenth centuries. These and less severe dry periods caused increased salinity in the bay, while wet periods increased fresh water influx into the bay. The regional climate became wetter in the nineteenth century, interrupted by dry periods in the 1930s and 1960s. The pollen record shows a sharp increase in *Ambrosia* and concomitant decrease in *Quercus* in the late nineteenth century, reflecting a time when 80 % of the Chesapeake Bay watershed, including the area drained by the tributary Susquehanna River, was deforested due to a high degree of lumbering activity. Tree pollen increases in early twentieth-century sediments, reflecting forest recovery. This recovery is followed by another *Ambrosia* and *Quercus* event, indicating a return to deforestation in the 1950s and 1960s. Sediment influx into the Chesapeake Bay was greatest during periods of intense land clearance, such as in the nineteenth and late twentieth centuries (Willard et al., 2000, 2003).

Non-local studies of interest

Several studies located outside the study area have used pollen analysis as a method for studying sediment accumulation rates in ways similar to the present study. Time intervals range from the past 200 years to over 6000 YBP. These other studies illustrate the acceptance of pollen analysis as a valid investigational tool in marsh accretion research.

Chmura et al. (2001) used ^{137}Cs, ^{210}Pb, and pollen analysis to determine tidal marsh accumulation rates for three marshes on the outer Bay of Fundy in Canada. These dating methods yield three time periods of 30, 100, and 170 years, across which the sediment accumulation rates were estimated. Results indicated that marsh accumulation rates generally kept pace with sea-level rise, but were higher during the eighteenth and nineteenth centuries.

Similarly, Gehrels et al. (2003) reconstructed changes in sea level on the northern coast of Maine for the past 1200 years from foraminifera, pollen analysis, and isotopic dating methods. Pollen analysis was used to provide historical time markers, while peats were dated by ^{137}Cs, ^{210}Pb, $^{206}Pb/^{207}Pb$, and ^{14}C methods. Regression analysis provided relationships between modern foraminifera and marsh surface elevation relative to tides, which were used to infer marsh surface elevation relative to tides from fossil foraminifera data. Results showed increased rates of relative sea level rise in the 20th century.

Long et al. (1996) used radiocarbon, pollen, diatom, and sedimentary evidence to trace the Holocene development of coastal sedimentation in the Romney Marsh region of southern England. Sea level fluctuations over the past 7000 years are evident in the types of sediments deposited. The development of a gravel barrier in

the study area around 6000 YBP enabled sedimentation in the marsh to increase and provided protection against erosion. Marine conditions returned to the area between 3000 and 2000 YBP, and the barrier destabilized, moving landward.

Pollen analysis is an accepted tool for studying wetland sediment accumulation rates and paleoecological trends. In the Mid-Atlantic region, sediment accumulation rates in marshes have increased throughout the Holocene and since European settlement, although specific rates vary between watersheds. Outside of the Mid-Atlantic region, pollen analysis of marsh sediments yields different conclusions, but the techniques used are the same.

Chapter 2

METHODS

Field Methods

Three cores were used in this study. Figure 2.1 shows the locations of each core. SJB6 and SJC6 were collected in 2000 by Wilson (2005) from high marsh locations using a Vibracorer, while RPC2 was collected in 2004 by my field group from an intertidal mudflat via Russian Peat Corer.

SJB6 and SJC6 were taken from the lower St. Jones River marshes via vibracore using aluminum irrigation pipe 7.62 cm in diameter and approximately 6 m long. The vibracorer is an end-filling sampler that uses a vibrating motor to help drive the sampling tube into the sediment. After the pipe was driven into the ground, the distance between the top of the marsh surface in the pipe and the top of the actual marsh surface adjacent to the pipe was measured to determine the degree of compaction that developed during the coring process. The pipe was filled with water and capped to prevent the core from slipping out of the pipe. The pipe was then raised with the help of a chain winch on a tripod, and the bottom was capped. The cores were cut into 1.5 m lengths, each capped at both ends, to facilitate transport back to the lab. The core was transported in the irrigation pipe to be cut and sampled in more controlled conditions at the lab, thus minimizing chances of contamination with modern pollen. At the lab, the aluminum pipe was first cut with a circular saw on two opposite sides, being careful to cut only the pipe and not mar the core inside. The

cores were then sliced in half lengthwise with a wire to minimize smearing and contamination. One half of the core was saved for future use and the other half was sampled.

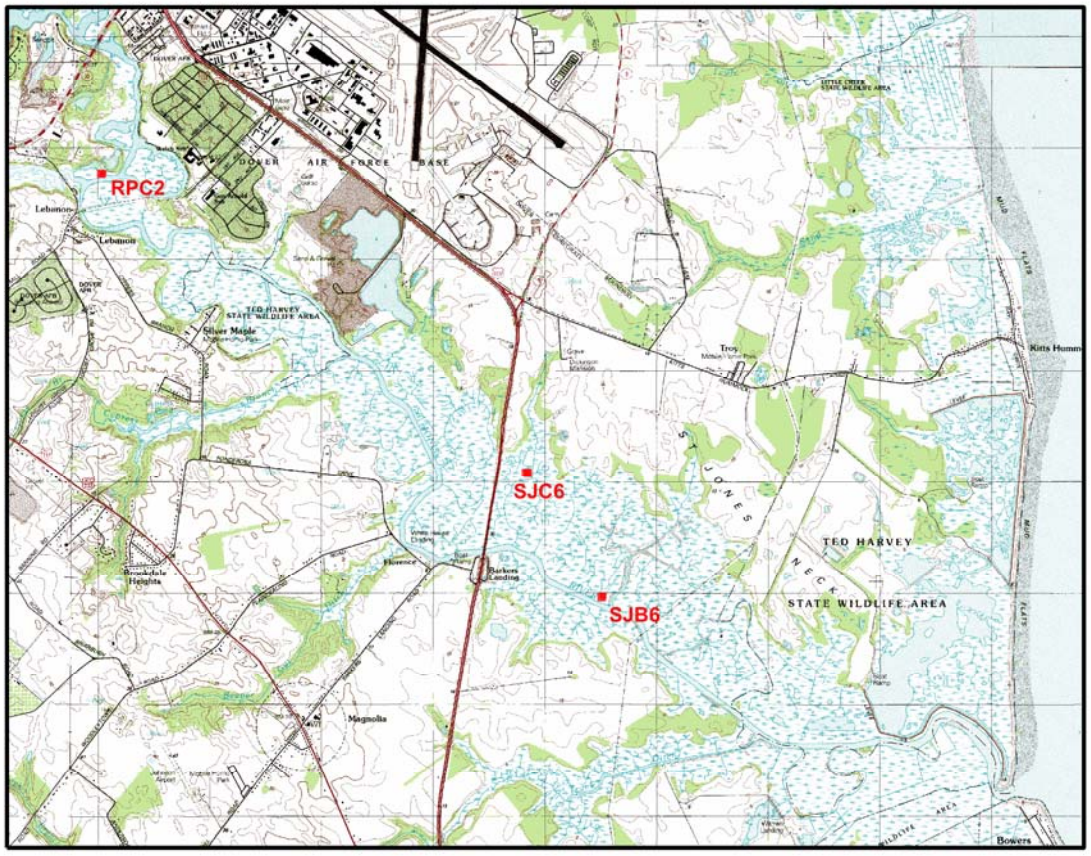

Figure 2.1 Locations of cores in study area.

The University of Delaware Geology Department's vibracoring equipment has been shown to be capable of producing continuous cores up to 12 m in length

(Wilson, 2005). The diameter of the irrigation pipe makes a large amount of material available for sampling, and provides a significant area of distortion-free sediment between the edges of the pipe. Vibracores are thus favorable for sampling, because of the large sample size available and the minimal contamination possible with careful handling. Additionally, the large barrel size, minimal distortion, and potential for drawing long cores make this equipment favorable for detailed stratigraphic and lithologic study. The major weaknesses inherent in the use of this sampler are compaction and rodding. Rodding occurs when sediment plugs the pipe, and a section of sediment is squished out to the side instead of entering the pipe. Compaction is the result of friction between the sediment and the pipe, and results in layers of sediment being thinner in the core than they are in the ground. These weaknesses were minimized by use of an end plug stopper while driving the pipe to create suction antithetical to the direction of the pipe movement.

RPC2 was collected via Russian Peat Corer from an intertidal mudflat upstream from the other two cores. The Russian Peat Corer is a side-cutting sampler consisting of a semicircular chamber 5.08 cm in diameter and 50 cm long with a heavy tapered weight at the bottom. The corer is driven into the sediment just to the top of the chamber and rotated. The leading edge of the semicircular chamber is sharp, and cuts into the sediment. The chamber is closed by turning it against a leaf-shaped blade. The blade keeps the corer in place and holds the core in the chamber during extraction. To retrieve more than 50 cm of sediment, further cores must be taken. This may be accomplished by inserting the device into the same hole, but it is likely that the head of the corer will compact the sediments in the next section on the way down. In this study, in order to prevent such a problem, the sampler was driven into

two holes alternately, with the depth into the sediment carefully measured to allow for a 5 cm overlap between core sections. Ideally, the two holes should be no more than about 30 cm apart to minimize chances that major stratigraphic changes might occur between holes (Peter McLaughlin, oral communication). In the case of an intertidal mudflat, however, the spacing between holes must be estimated. Additionally, there could not be two set holes in this case, because the tide was rising and the surface of the mudflat was obscured by water and by fluidized mud. The corer was therefore lowered alternately off the port and starboard corners of the stern platform of the boat. Intervals of 45 cm were marked on the handle of the corer and used to drive the device to the desired depth. The marks started 15 cm from the top of the core barrel, which was the water depth when coring began. In this way, 4.5 m of core were recovered in 10 sections. Each section overlapped the adjacent ones by about 5 cm. After recovering each segment, the chamber was gently rotated back to expose the core on the blade. The core segments were covered with kitchen plastic wrap, and then covered with a split section of 2-inch PVC pipe. The pipe and corer were overturned, leaving the core contained in the pipe. The edges of the plastic wrap were moved to cover the surface of the core for transport back to the lab for sampling.

The advantages of using the Russian Peat Corer are its small size and light weight, minimal necessary equipment, and the side-cutting nature of the tool. There is no chance of compaction or rodding when using this device. On the other hand, this device recovers smaller-diameter cores, and can only recover 50 cm at a time, although a 1 m version is available. This short sample interval makes it necessary to recover piecemeal a length of core that can be retrieved at one time by a vibracorer.

Additionally, small changes in stratigraphy between core holes may make it difficult to reconstruct the composite core for sampling.

The cores were brought back to the lab and stored at room temperature until sampling could begin. RPC2 was sampled within the week after it was collected in June 2004, but SJB6 was sampled almost 4 years after collection, in January 2004. SJC6 was sampled in 2000, but the samples remained refrigerated until use in this study. The composite sections of the Russian Peat Core were matched together with a 2.5 cm overlap at each end of each section to account for the 5 cm sampling overlap. The mudflat was sampled during a rising to slack tide, and the water depth reached a maximum of 30 cm on the mudflat by the time sampling had finished. The sections were not taken at precise time intervals so the overlap was not precisely 5 cm throughout the entirety of the core. Therefore, the overlap spacing between each section had to be estimated. It was decided that the difference in water depth and the resulting difference in core section depth were small enough that the same amount of overlap could be used between each core section. The range of error in the amount of overlap is estimated to be up to 1.5 cm in each overlap section.

Samples for pollen analysis were taken from all three cores every 10 cm using disposable 10 cc medical syringes that had been cut off at the 0 mark. Samples were taken from the cut surface of the core, which was cleaned directly before sampling to remove possible contaminants. The syringes were pushed into the core at designated sample depths, filled to just past the 1 cc mark, and then extruded back to the 1 cc mark. The excess sediment was discarded. The samples were then pushed out into the 50 ml centrifuge tubes used for processing. Every other sample was

processed, for a sample interval of 20 cm. The intervening samples were saved for possible future processing in the event that finer pollen analytical detail was desired.

Because the action of the vibracore equipment causes some compaction during coring, it was necessary to decompact both vibracores. Both the depth in core of each sediment layer and the depth in core of the sample depths were adjusted to account for compaction. The depth of sediment layers in core SJB6 was adjusted by Wilson (2005) by taking a Dutch auger core directly adjacent to the vibracore and using the depths from the Dutch auger as the decompacted depths in the vibracore. Core SJC6, on the other hand, was not decompacted by Wilson because the compaction was only 0.875 m over a 9 m core. SJB6, by comparison, had 2.07 m of compaction over an 11 m core. To make the cores more comparable, the differences between compacted and decompacted depths in SJB6 were used to determine the relative proportion of total compaction seen in each type of sediment layer in that core, and the results applied to core SJC6. It was seen that compaction occurred in SJB6 only from the top down to the first non-organic layer. Peats were reduced by 40% of the total amount of compaction, clayey peats by 40%, and peaty clay or organic clay by 20%. Core SJC6 was decompacted by applying this same system in reverse. The total decompacted length for core SJC6 was 9.875 m. Additionally, sample depths for SJB6 and SJC6 were converted to decompacted depth in core by spreading out evenly the amount of total decompaction assigned to each layer and adjusting layers down as each layer's thickness was expanded.

Laboratory Methods

Laboratory technique for isolating pollen grains for analysis from sediment involves many steps, but the process can be changed to suit the condition of the sediment as needed. This study followed a modified version of procedures recommended by Faegri et al. (1989). Sediment was first deflocculated. This was accomplished by soaking in distilled water. A known quantity of 15μm polystyrene beads was introduced to the sample to assist with counting and calculation of statistics, but an exotic pollen or spore may also be used. The next several steps involved removal of minerals. Removal of calcium carbonate was accomplished by adding cold 37% hydrochloric acid (HCl) and mixing, after which the sample was centrifuged and poured off, then rinsed with distilled water and centrifuged for 5 minutes; repeat iterations of adding distilled water, mixing, centrifuging, and pouring supernatant continued until the solution was neutral. Silicate minerals were removed with cold 48% hydrofluoric acid (HF). The acid was added to the sample and left to react for at least 24 hours. The liquid was poured off and 20% HCl was added to remove the hydrous silicates that may form during HF treatment, then rinsed until neutral as above.

With demineralization complete, the sample was ready for removal of organics. Oxidation with nitric acid (HNO_3) may be used to remove extraneous organic matter, but this step is not recommended for Holocene samples, as some recent pollen types are delicate, and may be damaged. Humic acid removal was accomplished next via treatment with cold 5% ammonium hydroxide (NH_4OH); hot 10% potassium or sodium hydroxide (KOH and NaOH) are sometimes used in other labs. After rinsing until neutral with distilled water, the samples must be dehydrated

before acetolysis, which will remove cellulose. Failure to dehydrate will result in extremely violent reactions upon addition of the acetolysis mixture. Care was taken to pour off as much water as possible without losing any of the sample. Acetic acid ($C_2H_4O_2$), the dehydrating agent, was added, the sample was centrifuged, and the acid was decanted. The acetolysis solution was made by mixing one part sulfuric acid (H_2SO_4) to 9 parts acetic anhydride ($(CH_3CO)_2O$). This mixture was added to the sample, which was then immersed in a boiling water bath for 5 minutes. The supernatant was decanted and the sample was rinsed with acetic acid again, and then rinsed with distilled water until neutral.

With acetolysis finished, the sample may be subjected to several treatments to further isolate the pollen: heavy liquid flotation, filtering, and sieving. Choice of technique depends on the condition of the sample after the chemical steps are complete, so the sample should be examined under the microscope to help decide which approach to use. All samples were coarse sieved, and some that had large amounts of very fine detritus were filtered. Two drops of trisodium phosphate detergent was added to the samples to prevent particles from sticking together. They were then put through a 250µm sieve to trap large debris. The samples that had large amounts of very fine material were filtered through a 7µm fabric mesh using light suction to remove very fine mineral particles.

None of the samples were subjected to heavy liquid flotation due to the preponderance of large pieces of organic detritus in the samples and absence of large amounts of non-organic minerals. This technique is used to separate the pollen from non-organic minerals. Heavy liquid flotation involves zinc chloride ($ZnCl_2$) in this lab, but other chemicals with a specific gravity of about 2 may be used, such as

Bromoform. The chemical is added to the sample, which is mixed and left overnight or centrifuged. Organic matter floats to the top and mineral matter sinks. If the sample has large amounts of organic detritus left in it, this step will not separate all the non-pollen matter, as some of it may become trapped on larger organic particles and float to the top.

With isolation of pollen grains complete, the samples were ready to be stained. This lab uses safranin, but most red and black stains give good results (Faegri et al., 1989). Two drops of Safranin were added and the samples were left for 5 to 10 minutes. They were centrifuged and the stain poured off. The samples were then rinsed with about 10 ml of water and 2 drops of ethanol and spun, and the supernatant poured off again. Following staining, the samples were ready to be mounted on slides. If needed, any of the processing steps may be repeated. Pollen processing procedures can be tailored to suit the condition of the sediment, and it is expected that procedures will be so adjusted.

Samples can be mounted with a liquid mount or a solid one. The liquid, such as glycerine jelly or silicone oils, allows pollen to be manipulated on the slide, but are less permanent. This lab uses a solid double mount technique, wherein pollen is affixed to the cover slip, which is then affixed to the slide. Pollen cannot be turned, but the slide will last longer, and coordinates of any particular grain can be noted for future reference. Furthermore, the slides can take rougher handling than liquid mounted ones, and can be stored vertically.

Safety is of primary importance when processing pollen. Most of the chemicals involved can damage human skin, and the hydrofluoric acid used in silicate removal is deadly. Gloves and goggles must be worn, and long sleeves with a lab coat

are also recommended. All steps involving chemicals must be done under a fume hood. HF requires extra precautions due to the toxic nature of its effects on humans (Traverse 1988). Special gloves and apron are worn, and a face shield is used in addition to the above-mentioned precautions. HF must be stored in plastic containers, and any residue from lab procedures must be likewise stored, labeled, and disposed of by approved authorities. Sodium carbonate should be kept on hand to neutralize any small spills within the hood. Gloves and equipment should be decontaminated and washed thoroughly after use. An HF safety kit containing emergence exposure materials must be kept in the lab, and kept up-to-date, at all times. In case of contact with HF, the victim must immediately shower and remove contaminated clothes, which must be carefully bagged and labeled by an assistant. The victim must be taken to the emergency room by ambulance, accompanied by the assistant and the Materials Safety Data Sheet for HF and proper HF exposure treatment information. Care must be taken not to contaminate anyone else in the process. Finally, and most importantly, no one must be allowed to use HF without proper training.

Analytical Methods

Analytical methods involve data capture, creation of pollen stratigraphic diagrams (assemblage zones), and statistical analysis. Data capture began with the examination of each slide with a Leitz microscope under 400X magnification. Oil immersion with magnification of 1000X was used for difficult-to-identify palynomorphs. For each sample, 300 to 500 pollen grains were identified and

counted, with most counts between 480 and 520. Each sample had two coverslips per slide. Starting at the top of one coverslip, pollen grains and polystyrene beads were found by scanning back and forth until 300 to 500 grains were counted. In most cases the whole coverslip was examined. If the requisite number of pollen grains had not been reached, the second coverslip was counted using the same technique until at least 480 grains were tallied. A second slide was prepared if necessary, although third slides were not. Identifications were made down to the genus level for all trees, and down to the family level for grasses and some herbaceous taxa. Taxa were tallied via a computer program as counting took place. Final counts for each core were transferred to other programs for the production of pollen diagrams and statistical analysis. The raw counts were converted to percent of pollen sum, expressed as proportions. Since this study is concerned with the pollen record of human use of the local forests and the changes in plant communities caused by such use, the pollen sum includes all land and aqueous plants.

The number of beads counted per slide was used to compute the number of palynomorphs per cubic centimeter (cc) of sediment. The solution containing the beads originally had a concentration of 100,000 beads per milliliter (beads/ml) of solution, and 0.1 ml of solution was added to each sample. The actual concentration of the solution decreases over time through accidental spillage and dehydration, so the solution was calibrated by counting the number of beads per 0.01 ml 12 times using a hemacytometer. The counts were averaged, the concentration of beads/ml was calculated, and the standard deviation was computed. After counting pollen and beads in each sample, the number of total pollen and spores, including unidentifiable ones, were divided by the number of beads in that sample. This “palynomorphs per bead”

figure was multiplied by the number of beads per 0.1 ml of solution. Since each 1 cc sediment sample received 0.1 ml, the resulting figure was palynomorphs/cc of sediment.

Many different software programs are available to assist with data capture, production of pollen stratigraphic diagrams, and statistical analysis. BugWin software was chosen for data capture. BugWin is designed for rapid input of biostratigraphic data, like pollen counts, and can generate abundance charts and spreadsheets compatible with other programs. Entering pollen counts in BugWin involves a simple point-and-click approach. The user interface is a spreadsheet with taxa listed according to user preference and counts tallied in the adjacent space. One simply points to the taxon and left-clicks the mouse to add one, while right-clicking the mouse subtracts one from the count. The program tallies individual taxon counts and total counts automatically. New taxa can be easily added to the counting interface, and space is available to enter other related data, such as sample lithology or depth in core. Charts can be produced in BugWin or BugCAD, or the data can be exported to a variety of other software programs for charting or statistical analysis. All available options produce publication quality charts.

A program called C2 was chosen for producing pollen diagrams (Juggins, 2003). It is Windows-based and was designed for ecological and paleoecological data. The program produces high-quality abundance charts which can be adjusted to suit the user's preference, and can be exported to other graphing programs for further manipulation. For statistical analysis, a program called PAST, or Paleontological Statistics version 1.32 (Hammer et al., 2001), was used. This program performs most of the statistical functions that are used in various branches of paleontology. It is

Windows-based, and can import data from common spreadsheet programs like Excel. Both PAST and C2 data and charts can be exported to other programs for further analysis or refinement.

The first component of the statistical analysis is derivation of a pollen stratigraphic zonation of each core via cluster analysis. PAST was originally used to create cluster dendograms, but using the stratigraphically constrained function generated confusing diagrams with many overlapping lines. For this reason, a program called CLUSTER was used instead. CLUSTER functions similarly to PAST's cluster analysis algorithm, and the most of the same distance measures and clustering methods are available. Percent of pollen sum data, expressed as proportions, was imported into the statistical program. Stratigraphically constrained cluster analysis was used to limit the program to combining adjacent samples only, as the goal was to make a stratigraphic zonation. The program allows two choices of algorithm for constrained clustering: minimum variance (Ward's method) and furthest neighbor. Minimum variance groups samples together in such a way as to minimize the increase in total within-group distance (Birks and Gordon, 1985). Distance refers to the amount of space between samples as plotted on multidimensional axes, with each taxon present in a sample making a different axis. Furthest neighbor, the other available algorithm, uses the distance between farthest-apart members of a group to determine linking order (Birks and Gordon, 1985). This method links groups or objects that will result in the smallest increase in the farthest-apart distance. Minimum variance was chosen for this study because its clustering method tends to produce tight groups, and this effect would be more likely to highlight differences in the pollen spectra of different samples within each core (Birks and Gordon, 1985). The distance

matrix was computed with the Euclidean distance measure. This distance measure uses a multidimensional version of the Pythagorean theorem to compute distances between samples, and gives the actual distance in multidimensional space. Euclidean distances are not affected by the presence of outliers, so such anomalous data points need not be removed; however, Euclidean distances are affected by differences in scale between variables (Birks and Gordon, 1985). Care must be taken to assure all data is in the same measurement scale. For this study, all percent of pollen sum data were expressed as proportions, so scale was not a problem.

The second component of the statistical analysis is to ascertain possible causes of paleoecological variation between samples. To this end, Principal Components Analysis, within the PAST program, was used, as it highlights associations of similar samples. The object of PCA analysis is to attempt to simplify the data without losing meaning, by finding the components that explain the most variation between samples (Birks and Gordon, 1985). Data must be normally distributed, so the percent of pollen sum data, expressed as proportions, was log transformed. The PCA program gives the option of using either a correlation matrix, which is used if the data is not measured in the same units, or a variance-covariance matrix, which is for data measured in the same units (Hammer et al., 2001). The variance-covariance matrix was used for this study. The PCA algorithm finds the components that explain the most variation between samples by plotting the data in imaginary multidimensional space and choosing axes through the data points to minimize the distance from the data points and the new axis (Birks and Gordon, 1985). Axes are generated until all the variation between samples is explained. The first several axes usually explain most of the variation. The program then generates a

list of “loadings” for each sample and component. The sample loadings indicate the position of each data point on each new axis (the aforementioned components). The component loadings indicate what environmental factors might have caused each component. For example, Component 1 might have high positive loadings for *Quercus*, *Pinus*, and *Carya*, and strong negative loadings for *Ambrosia*, Poaceae, and Cheno-Ams. Based on these loadings, Component 1 could represent forest vs. cleared land. The data can be plotted, usually on the first two axes. The investigator can then examine these plots for patterns. Used this way, PCA is more of an exploratory method, whereby one looks to see if there is any useful information hidden in the data.

Non-metric Multidimensional Scaling (NMDS) is sometimes used in paleoenvironmental studies for the same objectives as PCA (e.g. Morabito et al., 2003; Pryor and Gastaldo, 2000), although there have not been many palynological studies using this method (e.g. Cupper et al., 2000; Flakne, 2003). NMDS uses a distance matrix to place data points in a two-dimensional space in such a manner that the ranked differences are preserved (Hammer et al., 2001). The effectiveness of NMDS in revealing useful data patterns for this study was evaluated by comparison of NMDS plots with PCA plots. For this study, the Euclidean distance measure was used since it was also used in PCA and cluster analysis.

Chapter 3

RESULTS

The results comprise two sections: physical results and analytical results. Lithology and pollen stratigraphic data, the physical results, are given for each core. Analytical results include cluster analysis, principal components analysis, and non-metric multidimensional scaling. Cluster analysis enabled biostratigraphic assemblage zones to be delineated for each core. Principal components analysis (PCA) of data from all three cores together led to the definition of associations of similar samples and the determination of the dominant agents of ecological change. Non-metric multidimensional scaling (NMDS) of data from all three cores was compared to the PCA results to ascertain the relative usefulness of NMDS for this study.

Lithological descriptions for SJB6 and SJC6 are taken from Wilson (2005), while the descriptions for RPC2 use the same criteria. Lithology categories include inorganic clay, organic clay or mud, peaty clay, clayey peat, and peat. Depositional environments are inferred from both the sediment type present and the type and species of plant remains in each interval. According to Wilson (2005), the inorganic clays comprise the subtidal sediments. Intertidal sediments include the organic clays and the peaty clays. Mudflat sediments, although intertidal, are given their own category by Wilson. This designation is based on the presence of fine, in-

place stems in the organic clays. Supratidal sediments contain plant materials larger than fine stems, and include peats and clayey peats.

Core SJB6

Core SJB6 is located at 39.0814° N and 75.4444° W in the lower-middle end of the St. Jones River estuary (Figure 2.1). The site is in a high-marsh environment near the confluence of the river with one of its tributary creeks. Samples for pollen analysis were taken every 20 cm to 6.2 m depth.

Lithology

Core SJB6 was collected and described by Wilson (2005) in 2000. The lithology and inferred depositional environments are illustrated in Figure 3.1. For the purposes of this study, I simplified Wilson's (2005) detailed descriptions of lithology and plant remains. The core is 11 meters long. The bottom 1.7 meters consists of light gray inorganic clay with some woody fragments and plant pieces. From 9.3 m to 8.6 m there is a layer of peaty clay, overlain by inorganic clay with plant fragments up to 6.8 m. From 6.8 m to 5.7 m, the clay is organic, with a layer of inorganic clay between 5.7 m and 5.6 m. A peat layer from 5.6 m to 4.75 m is overlain by organic clay from 4.75 m to 4.4 m. Clayey peat with various plant fragments completes the

core. From 4.4 m to 2.0 m, the clayey peat contains black organic laminations every 3 to 4 cm. At 2.0 m, there is a layer of black humus, above which the clayey peat continues without laminations until 1.0 m. A layer of peaty clay from 1.0 m to 0.4 m is overlain by 0.4 m of clayey peat.

The presence of inorganic clay from 11 m to 6.8 m led Wilson (2005) to a paleoenvironmental interpretation of fluvial deposition. He indicated intertidal deposits from 6.8 m to 4.4 m because of the organic nature of the clay. The peaty clay and clayey peat above 4.4 m depth were determined to be from a supratidal emergent depositional environment.

Wilson (2005) reported two AMS radiocarbon dates in this core. At 9.3 m depth, the radiocarbon date range is 4,560 to 4,840 Cal YBP. The ^{14}C date at 1.9 m gives a range of 250 to 330 Cal YBP.

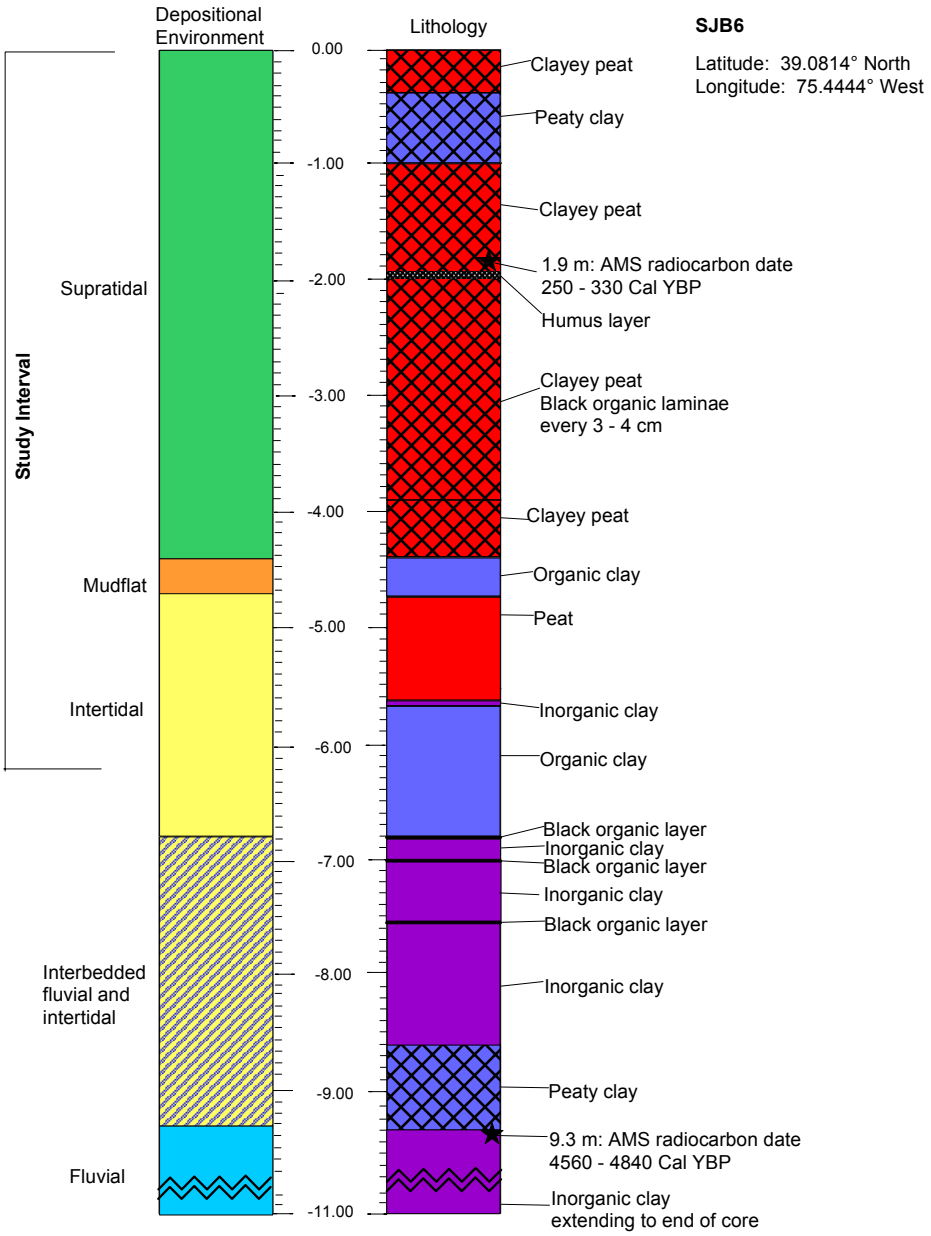

Figure 3.1 Lithology and depositional environments for core SJB6 (after Wilson 2005).

Palynology

The raw data from the pollen analysis of core SJB6 are shown in Appendix A, and the pollen diagram is shown in Figure 3.2. Abundant taxa are *Pinus*, *Quercus*, and Poaceae, which each have percents of pollen sum above 10% for most or all of the samples. Common taxa, with percents of pollen sum between 1% and 10% in most of the samples, are *Alnus*, *Ambrosia*, *Carya*, and Cyperaceae. The percent of arboreal pollen (AP) ranges from 40% to 74% of the pollen sum, with an interval of lower values between 5.75 m and 4.00 m, followed by a section of increasing values until 2.75 m, above which it declines dramatically. AP reaches its nadir at 1.40 m, and rises to a plateau at the top of the core, with a value of 57.4% at 0.10 m. Non-arboreal pollen (NAP) varies between 26% and 60%, and remains high throughout the core except for two intervals of values below 40%: between 2.09 m and 3.17 m, and below 6.00 m. Of the non-arboreal pollen, the vast majority (≥75%) is from herbaceous plants.

Quercus pollen varies between 25% and 41% for the bottom half of the core, but above 2.10 m it drops below 25% and only surpasses that percent again at 0.10 m. *Pinus* declines from 32% at 6.00 m to 3.7% at 4.56 m. Above 4.56 m, it gradually rises again to vary a bit around 20% for the top half of the core. Poaceae has two intervals of high abundance: between 6.00 m and 4.50 m, and between 3.70 m and 2.90 m. Between 4.50 m and 3.70 m, and above 2.90 m, Poaceae pollen stays below 27%. Interestingly, Cyperaceae pollen abundances follow the exact opposite pattern

from Poaceae, with high abundances when Poaceae is weak, and low abundances when Poaceae is strong.

The oak:ragweed ratio, an indicator of the agricultural horizon, varies between 26 and 225 from 6.20 m at the bottom of the core until 2.36 m, at which point it drops to 10.19. At 2.09 m, the oak:ragweed ratio is 4.686, well within the limits set by Brush for the agricultural horizon (Brush and Davis 1984, Brush 1989). The agricultural horizon in core SJB6 is therefore determined to be just above 2.36 m depth. For the purposes of calculating sediment accumulation rates, the depth used for the agricultural horizon will be 2.20 m.

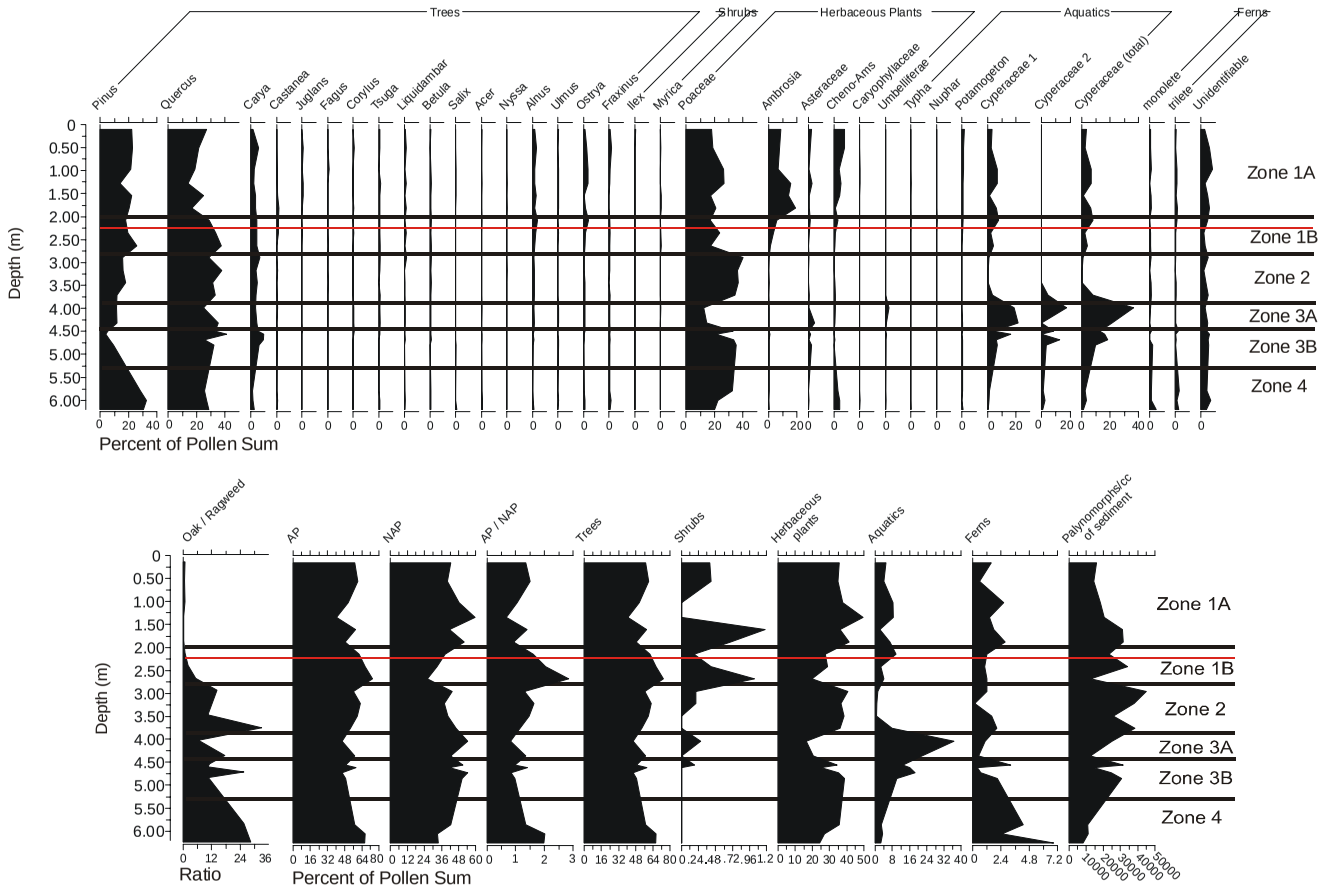

Figure 3.2 Pollen assemblage zones and stratigraphic diagram for core SJB6. The depth of the agricultural horizon is marked in red. Pollen zones are derived from stratigraphically constrained cluster analysis of data in this core.

Core SJC6

Core SJC6 is located at 39.0906° N and 75.4543° W in the lower-middle end of the St. Jones River estuary (Figure 2.1). The site is in a high-marsh environment, and is near State Route 1/113. Samples for pollen analysis were taken every 20 cm to 5.4 m depth.

Lithology

Core SJC6 was collected and described by Wilson (2005). The lithology and inferred depositional environments, simplified for this study, are illustrated in Figure 3.3. This core was 9.875 meters long. Dark gray peaty clay with in-place stems persists from 9.8 m to 7.33 m, with a 0.05 m layer of peat covered by a film of organic clay at 7.33 m. A 0.15 m layer of clayey sand lies atop the peat, from 7.38 m to 7.28 m. From 7.28 m to 2.28 m there is gray organic clay with plant fragments, black laminations, and lighter gray layers. A dark grayish brown peaty clay layer from 2.28 m to 1.75 m is overlain by a dark gray layer of clayey peat from 1.75 m to 0.6 m. The core is topped by 0.6 m of dark brown peat.

Wilson's (2005) paleoenvironmental interpretation, based on lithology and plant fragments, is slightly different from that of SJB6. He considered the peaty clay from 9.8 m to 7.33 m to be indicative of supratidal deposition, and the organic clay

above that as indicative of an intertidal environment. Above 2.28 m depth, the depositional environment was described as supratidal.

The sharp changes in lithology at 7.33 m depth, coupled with the AMS radiocarbon dates, indicates a possible unconformity. The upper AMS ^{14}C date is located at 7.13 m, in the 0.05 m peat layer that lies under the 0.1 m clayey sand layer. The range of dates for this radiocarbon date is 760 to 940 Cal YBP. Only 2 m down, however, the second AMS ^{14}C date gives a range of 4,010 to 4,280 Cal YBP at 9.1 m depth.

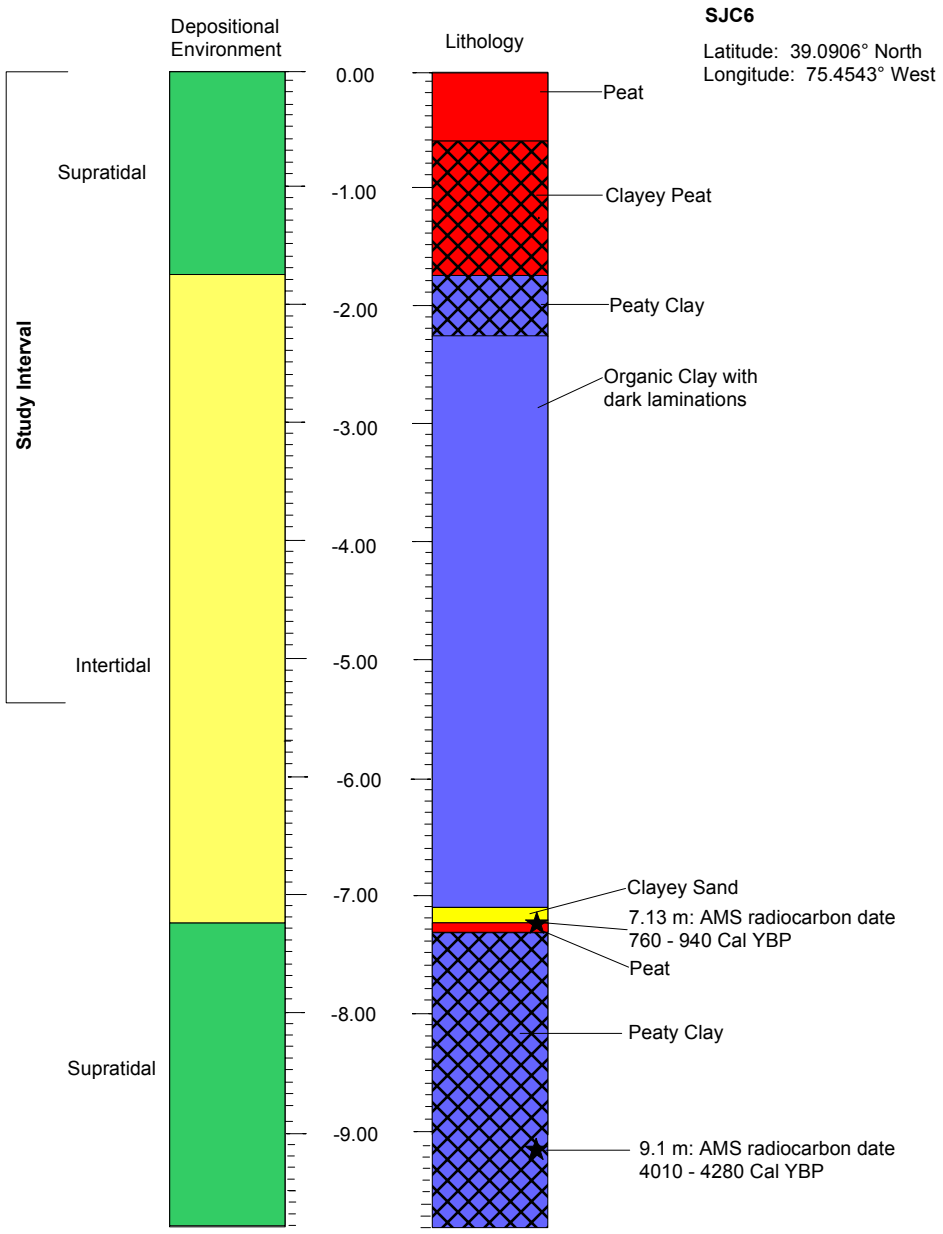

Figure 3.3 Lithology and depositional environments for core SJC6 (after Wilson 2005).

Palynology

The raw data from the pollen analysis of core SJC6 are shown in Appendix B, and the pollen diagram is shown in Figure 3.4. Abundant taxa include *Pinus*, *Quercus*, and Poaceae. Common taxa include *Betula*, *Alnus*, *Ambrosia*, *Carya*, Chenopodiaceae-Amaranthaceae (Cheno-Ams), and all fern spores. Arboreal pollen ranges between 84% and 73% of the pollen sum from the bottom of the core until 2.60 m. Above this point, AP declines to a nadir at 1.50 m, after which it rises again to a value of 62.8% in the top sample (0.63 m). Non-arboreal pollen varies between 16% and 58%, with values consistently below 25% from the bottom sample until 3.00 m. NAP reaches its highest point at 1.50 m and declines a bit to a value of 37.2% at 0.63 m. As in core SJB6, herbaceous plants make up 75% or more of the NAP.

Quercus pollen decreases very gradually throughout the entire core, but experiences a sudden decrease above the agricultural horizon before recovering some of its former abundance above 1.20 m. *Pinus* abundances remain steady, varying little until 2.40 m. Above 2.40 m there is a decline, followed by an increase starting at 1.00 m. Poaceae pollen increases very gradually through most of the core, remaining below 20% until 2.78 m. Above this point, it increases to a high of 48% at 1.50 m before declining gradually again to 25% at 0.63 m.

The oak:ragweed ratio varies between 21.1 and 61.33 from 5.38 m until 2.38 m. At 2.38 m, it is 22.25, but at 2.08 m, the ratio drops to 3.194, and stays below 5 until the top of the core, placing the agricultural horizon just below 2.08 m depth.

For the purposes of calculating sediment accumulation rates, the depth used for the agricultural horizon is 2.15 m.

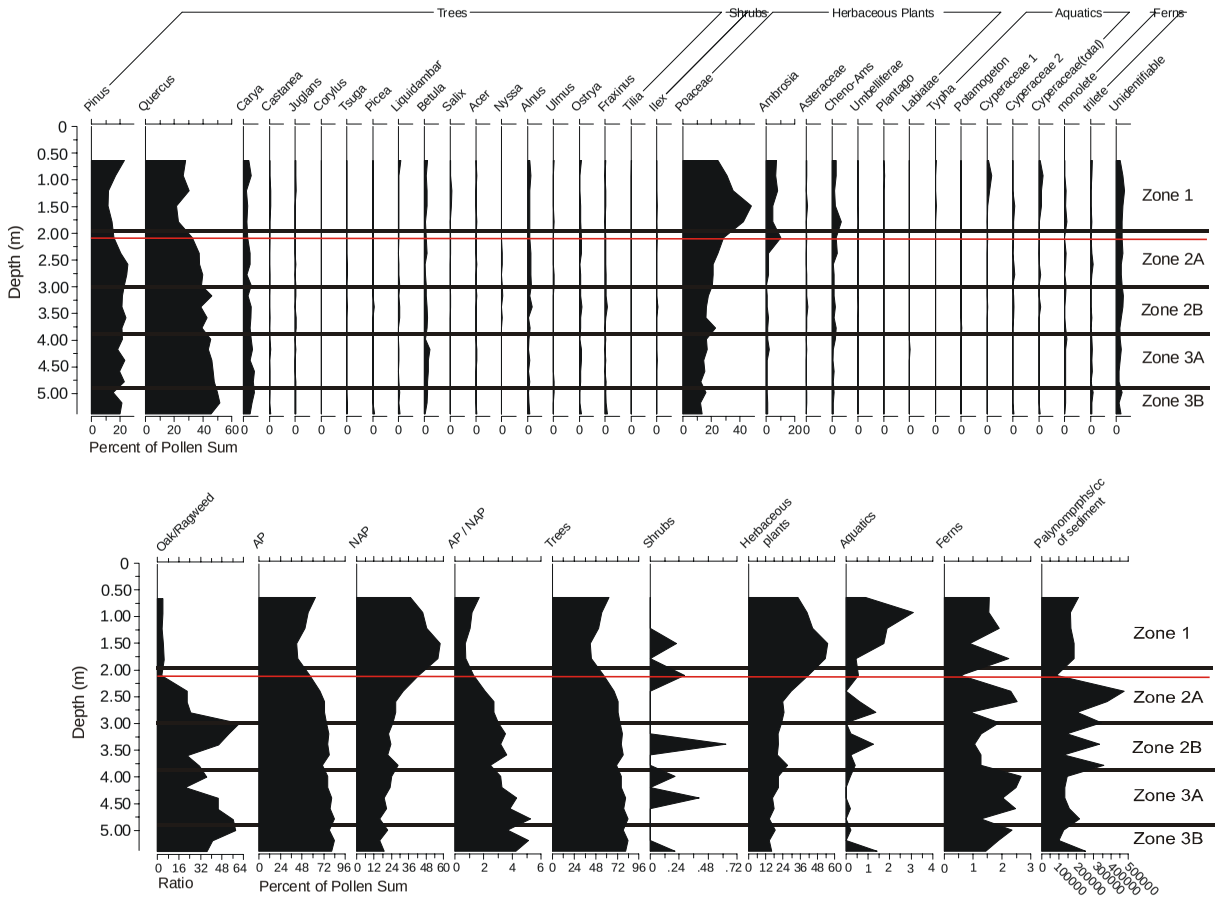

Figure 3.4 Pollen assemblage zones and stratigraphic diagram for core SJC6. The depth of the agricultural horizon is in red. Pollen zones are derived from stratigraphically constrained cluster analysis of data in this core.

Core RPC2

Core RPC2 is located at 39.0116° N and 75.4969° W close to Dover Air Force Base (Figure 2.1). This core was taken from an intertidal mudflat located in the area of confluence of the river with one of its tributary streams. The river is more brackish than at the other two core sites. There is currently a tidal marsh on one bank of the stream and a small forested plot on the other bank. There is also a defunct gravel quarry-turned-landfill on the other side of the forest. Samples for pollen analysis were taken every 20 cm to 4.2 m depth.

Lithology

Core RPC2 was collected independently of the other two cores. Figure 3.5 shows the lithology, which was described as part of this study. Core RPC2 is 4.41 m long. From 4.41 m to 3.5 m there is greenish gray mud with fine plant stems and some plant fragments. Brown peaty mud grading to brown organic mud, from 3.5 m to 2.8 m, lies under a layer of peat with plant fragments and woody pieces between 2.8 m and 2.6 m. From 2.6 m to 1.35 m, muddy peat transitions to peaty mud, with fine stems, plant fragments, and several more pieces of wood interspersed throughout this layer. At 2.47 m, there is a thin black layer of decomposed grass fragments. From 1.35 m to 1.33 m there is a layer of clean white coarse sand, topped by 5 cm of tan coarse sand and gravel between 1.33 m and 1.28 m. Fine tan mineral mud completes

the anomalous layer, from 1.28 m to 1.26 m. From 1.26 m to the top of the core, organic mud with ultrafine stems grades from brown to greenish gray to brown.

Using the same depositional environment criteria from Wilson (2005), the paleoenvironmental reconstruction begins with intertidal deposits from 4.41 m to 2.8 m. Deposition becomes supratidal starting 2.8 m, but returns to intertidal at 1.25 m.

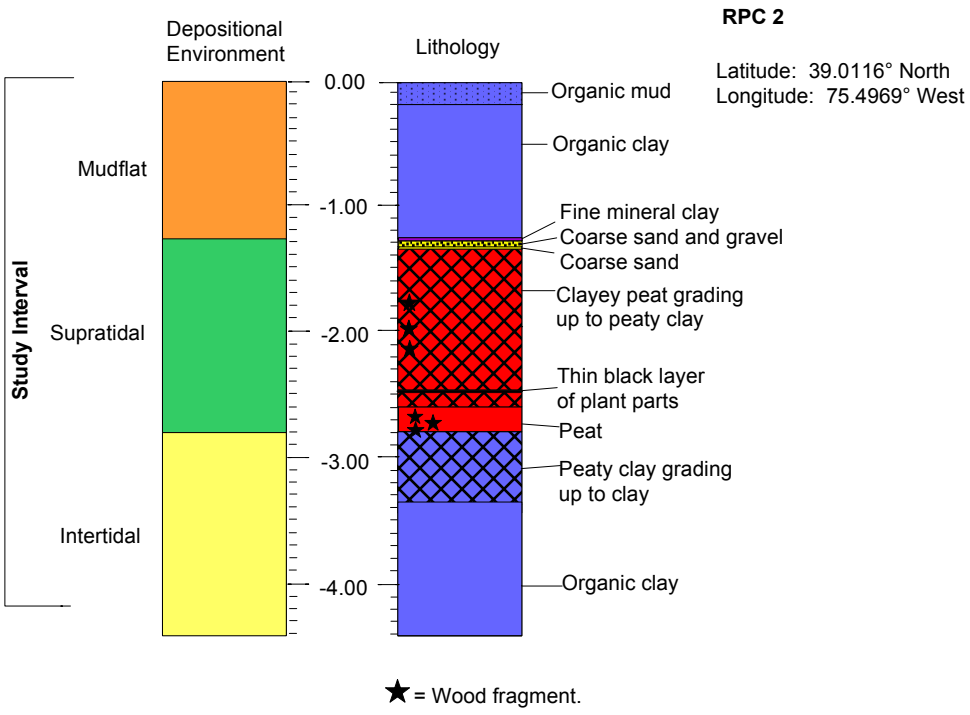

Figure 3.5 Lithology for core RPC2, composite of all 10 sections.

Palynology

The raw data from the pollen analysis of core RPC2 are shown in Appendix C, and the pollen diagram is shown in Figure 3.6. Abundant taxa are *Pinus*, *Quercus*, and Poaceae, although *Pinus* and Poaceae are much less abundant throughout this core than the other two cores. Common taxa are *Alnus*, *Betula*, *Ambrosia*, *Carya*, *Ostrya*, Cyperaceae, Asteraceae, Cheno-Ams, and all fern spores. Core RPC2 also had the greatest variety of taxa represented, with 39 total, as opposed to 32 in the other two cores. The additional taxa were of the herbaceous varieties, like *Amaryllidaceae*, *Plantago*, *Impatiens*, and *Labiatae*. The percent of arboreal pollen (AP) ranges from 46% to 74% of the pollen sum, while non-arboreal pollen (NAP) varies between 26% and 54%, with 75% or more being due to herbaceous plants. The difference in pollen assemblages between core RPC2 and the other two cores is expected, as RPC2 was much farther upstream, about 4.5 km in a straight line from SJC6.

Quercus pollen has its highest abundance, 41% of pollen sum, at 4.25 m, after which it declines to 21% at 3.05 m. Its abundance then varies between 25% and 36% until 1.25 m, when it drops below 22%. *Quercus* abundance rises to plateau around 29% at 0.45 m. *Pinus* starts at 18% at 4.25 m, but drops below 20% by 3.45 m. *Pinus* abundance remains below 20% until 2.05 m, and varies between 20% and 22% until 1.45 m. From there to the top of the core, *Pinus* remains below 20% except for samples between 0.45 and 0.25 m. Poaceae pollen abundances are steadily below 22% throughout the core, with the exception of a spike to 44% at 2.65 m and a spike to 29% at 1.25 m. *Ambrosia* pollen is present throughout the core, but varies in abundance. It is present in low amounts, below 10%, from the bottom of the core to

3.45 m, between 2.85m and 1.25 m, and from 0.45 m to the top of the core. Between 3.25 m and 3.05 m, and between 1.05 m and 0.65 m, *Ambrosia* is present above 10% of the pollen sum. Cheno-Ams are present in amounts above 2 % of the pollen sum only in the top 1.5 m of core. Cyperaceae are consistently below 6.5 % throughout the core, but are most abundant, with amounts between 4% and 6.5 %, between 2.45 m and 1.05 m.

The oak:ragweed ratio displays a much different pattern in this core than in cores SJB6 and SJC6. The oak:ragweed ratio is 29.43 at 4.25 m, drops a little, then rises to 44.25 at 3.65 m. At 3.45 m, the oak:ragweed ratio drops to 3.9, and stays below 5 until 2.05 m except for a small rise to 15 at 2.65 m. Above 2.05 m the ratio again rises above 10, varying between 34 and 151. At 1.25 m, the ratio again drops, to 2.857. The oak:ragweed ratio stays below 5 until the top two samples, at which point the ratio rises to 6.364 and 5.185 respectively. According to this pattern in the oak:ragweed ratio, the agricultural horizon is placed at 3.45 m. A second oak:ragweed horizon occurs at 1.25 m, when the ration again decreases.

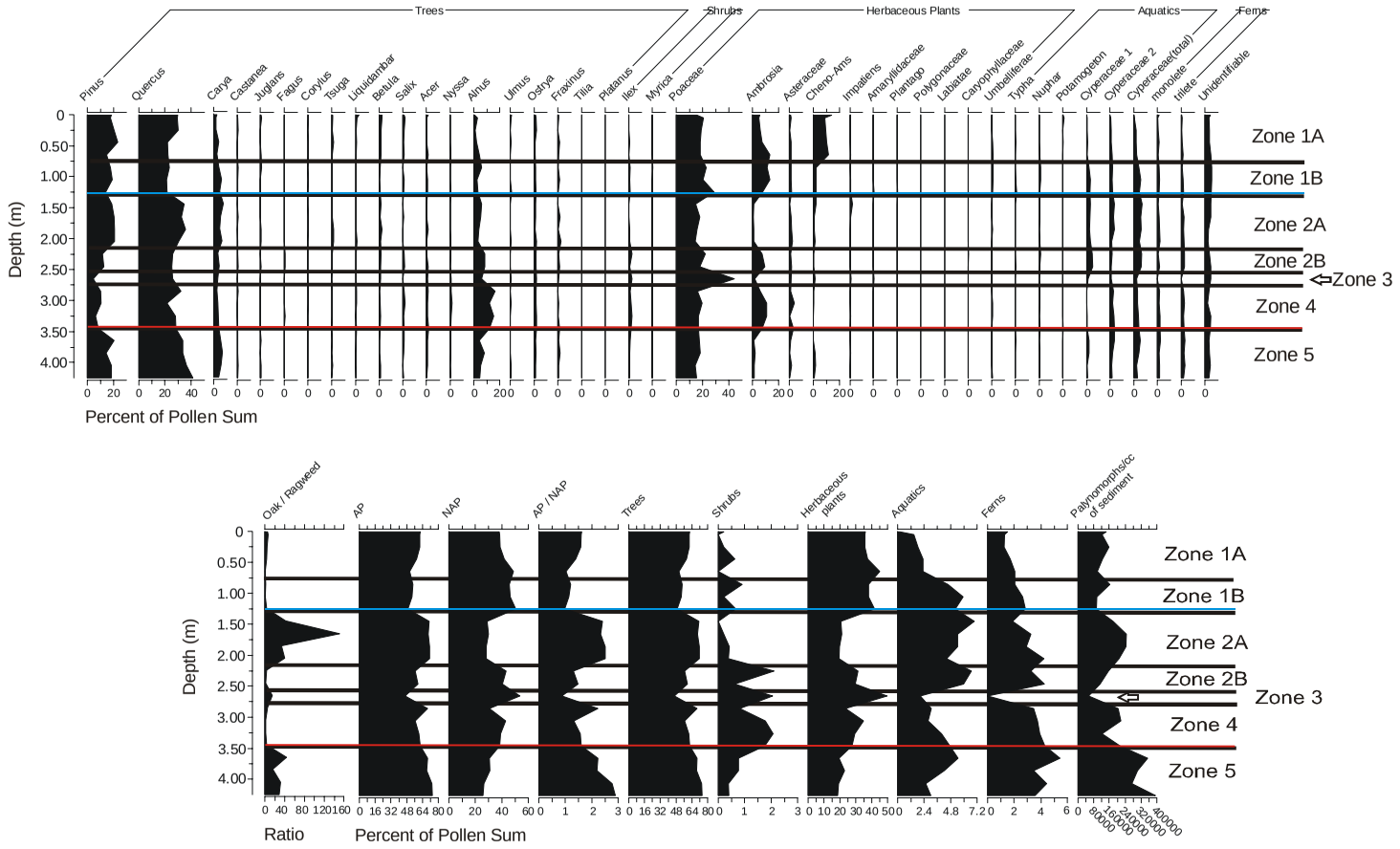

Figure 3.6 **Pollen assemblage zones and stratigraphic diagram for core RPC2. The depth of the agricultural horizon is in red, and the upper horizon is in blue. Pollen zones are derived from stratigraphically constrained cluster analysis of data in this core.**

Analytical Results

Pollen Zonations

Stratigraphically constrained cluster analysis, with a minimum variance algorithm (Ward's method), was used to create pollen stratigraphic zonations, using assemblage zones, for each core. The dendograms for each core, with zonations superimposed, are shown in Figures 3.7 through 3.9. The zonations are also superimposed on the pollen diagrams in Figures 3.2, 3.4, and 3.6 above. The partitions suggested by the clustering algorithm matched, or came close to, partitions made on the basis of oak:ragweed ratios.

Core SJB6 is broken into four zones, two of which could be further subdivided. Zone 1A contains samples from 0.10 m through 1.82 m. Zone 1B contains samples at 2.09 m through 2.63 m. The agricultural horizon falls in the middle of this zone, instead of at a zone boundary. The pollen diagram for SJB6 (Figure 3.2) shows that the oak:ragweed ratio declines gradually through this interval, indicating that Zone 1B is a transitional zone. Zone 2 comprises samples from 2.90 m to 3.71 m, and is clustered down with lower samples before being joined to the Zone 1 samples at the last step of the dendogram. Zone 3A contains samples from 3.98 m to 4.31 m, while zone 3B contains samples from 4.50 m to 4.80 m. Zone 4 contains the last three samples, from 5.80 m to 6.20 m.

Core SJC6 contains three zones, two of which are subdivided. Zone 1 contains samples from 0.63 m to 0.92 m. The subsequent zones all cluster together

before joining Zone 1 in the last step of the dendogram. Zone 2A begins above 2.08 m although the pollen-derived agricultural horizon sits between 2.08 m and 2.38 m. Zone 2A continues until 2.98 m. Zone 2B contains samples from 3.18 m to 3.78 m. Zone 3A comprises samples from 3.98 m to 4.78 m, and Zone 3B contains the last three samples, from 4.98 m to 5.38 m.

RPC2 contains five zones, of which two are subdivided. Zone 1A contains samples from 0.00 m – 0.65 m, and Zone 1B contains samples from 0.85 m to 1.25 m. At this boundary falls the upper pollen-derived horizon. Zone 2A contains samples from 1.45 m to 2.05 m, and Zone 2B contains two samples, 2.25 m and 2.45 m. Zone 3 comprises one anomalous sample, at 2.65 m. This sample clusters down with the rest of the samples below. Zone 4 contains samples from 2.85 m to 3.45 m, and Zone 5 contains samples from 3.65 m to 4.25 m. The pollen-derived agricultural horizon sits at the boundary between Zones 4 and 5.

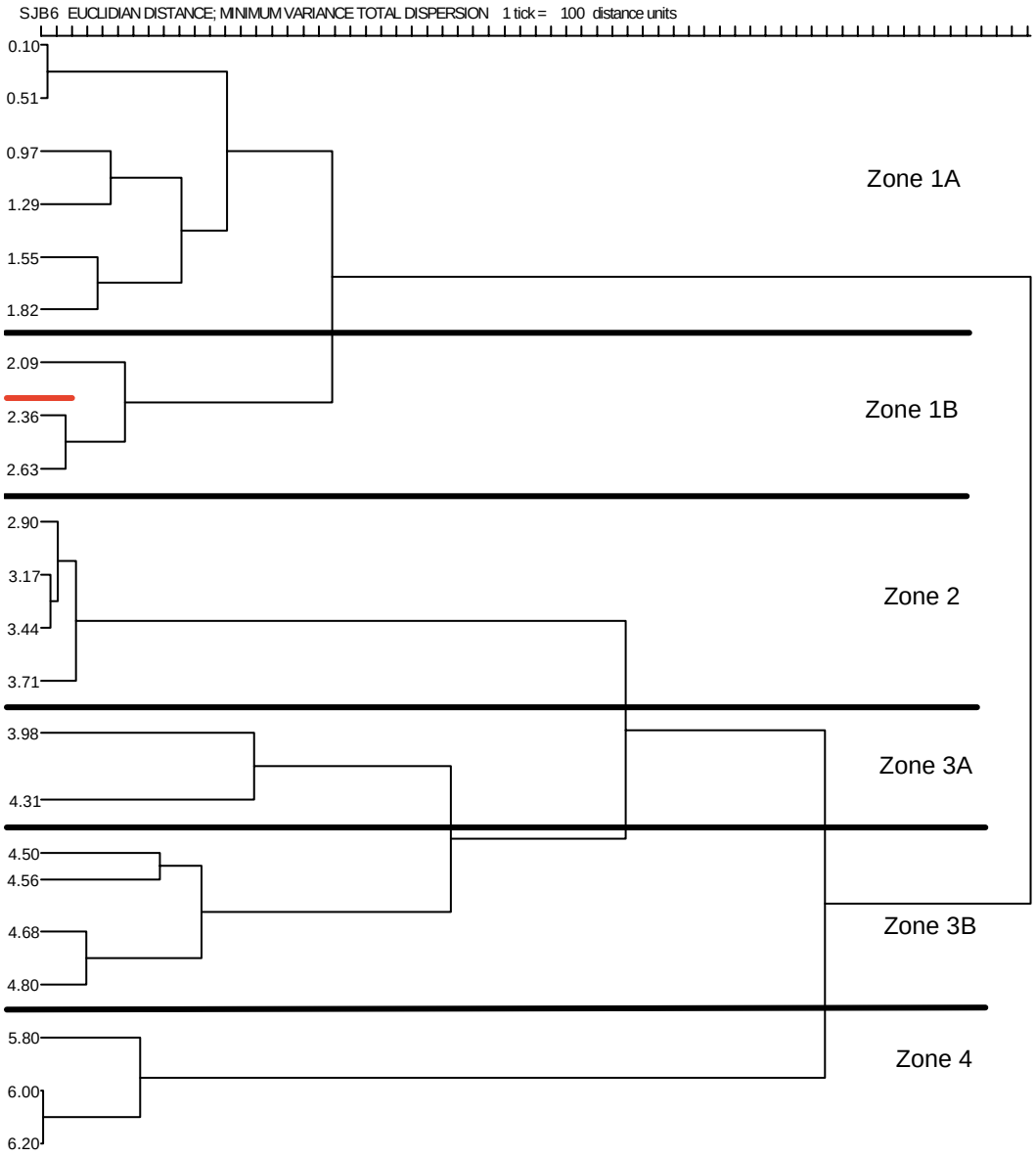

Figure 3.7 Cluster analysis dendogram of core SJB6 with zones superimposed. The red line indicates the depth of the agricultural horizon.

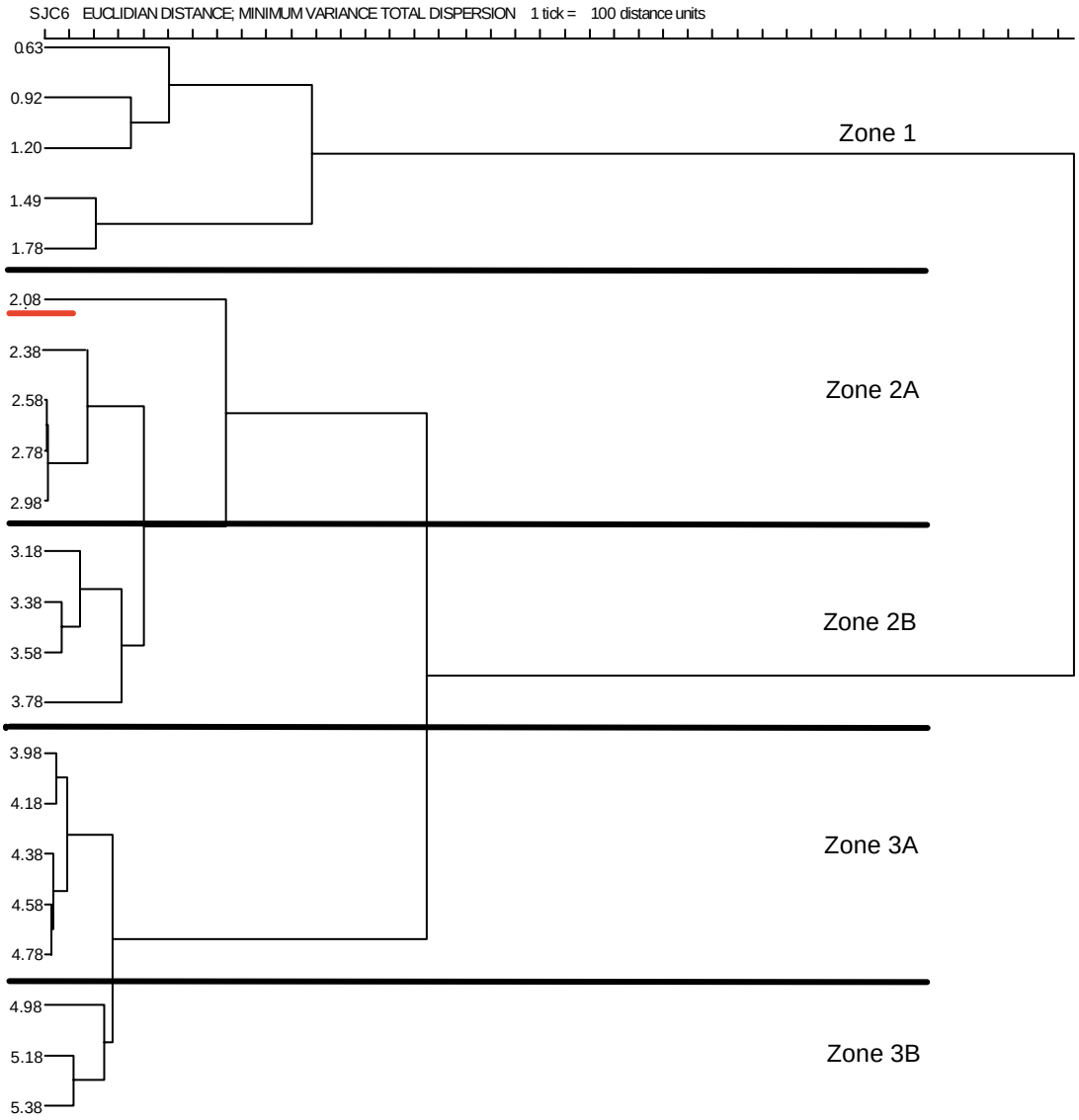

Figure 3.8 Cluster analysis dendogram of core SJC6 with zones superimposed. The red line indicates the depth of the agricultural horizon.

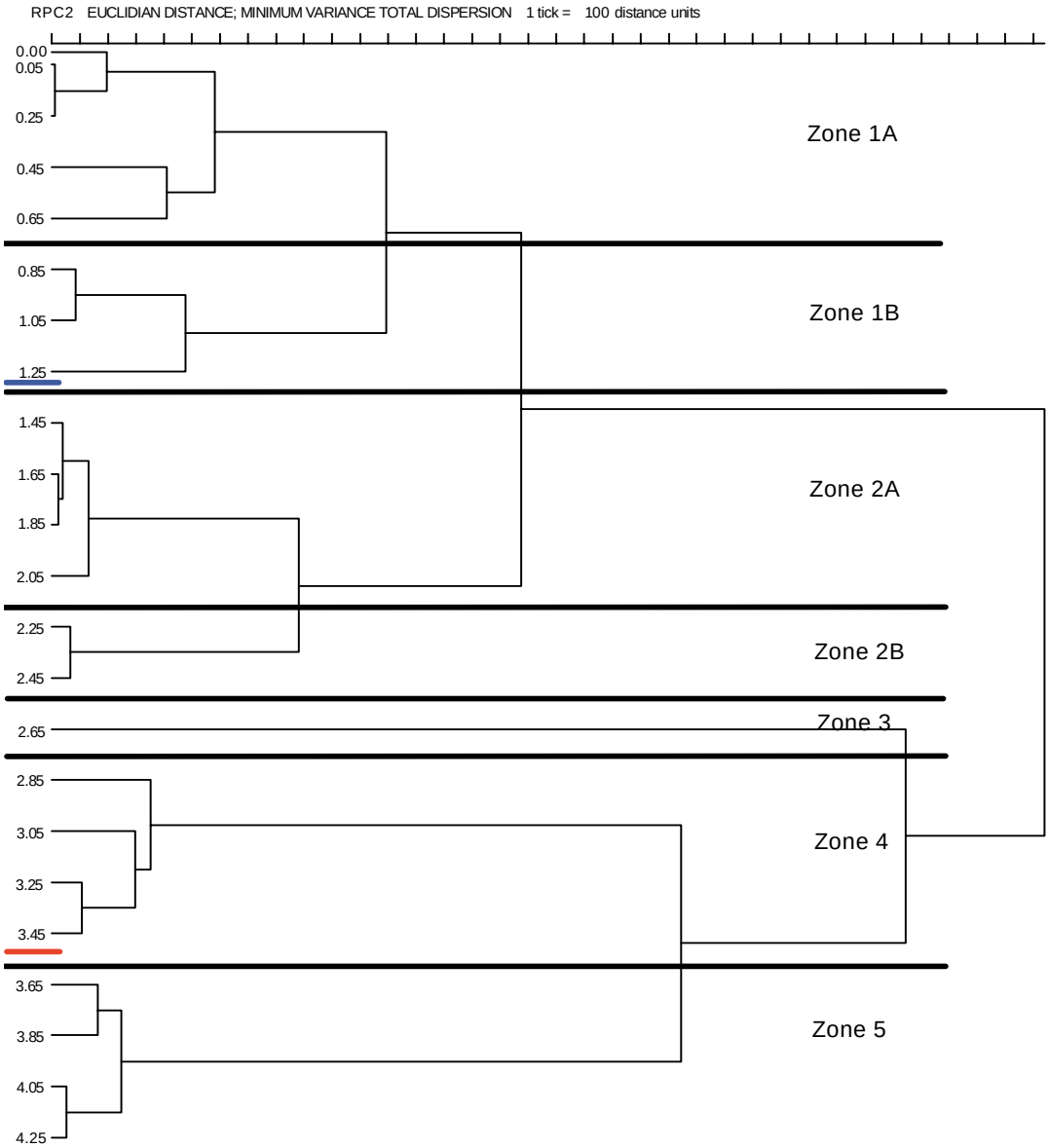

Figure 3.9 Cluster analysis dendogram of core RPC2 with zones superimposed. The red line indicates the depth of the agricultural horizon, and the blue line the depth of the upper horizon.

Principal Components Analysis

Principal Components Analysis was undertaken primarily as a method to simplify the data and to elucidate similarities between samples and associations between taxa. Evaluation of the constituents of the component axes allows interpretation of the possible causative factors for the variation between samples. The data was entered into the PCA program as log-transformed proportions of the pollen sum. Because the pollen sum includes all taxa, it is likely that there are two distinct but overlapping causes of variation in the pollen assemblages: a local signal based on flora in the St. Jones River basin and a regional signal based on upland flora in most of central Delaware. It is therefore possible that any one component axis may indicate more than one cause of variation. Table 3.1 lists the eigenvalues and percent variances for the top six components, and Table 3.2 lists the loadings for each taxon and each component considered. Figure 3.13 shows the scree plot of eigenvalues for all principal components. Analysis is confined to the top three components because of the minimal change in percent variance after Component 3.

Component 1 (Figure 3.10) has high positive loadings for *Ambrosia*, *Alnus*, Cyperaceae, and Asteraceae. *Alnus* and Cyperaceae are common to wetland environments in Delaware, and *Ambrosia* and Asteraceae live in open areas like fields or forest clearings (USDA and NRCS, 2004). Component 1 also has several lower positive loadings: *Salix*, *Acer*, *Ilex*, and *Ostrya*. *Salix*, *Acer*, and *Ostrya* all have species that prefer to live around streams and other wet areas, and three *Ilex* species are found in the lower St. Jones River area (DNREC, 1999). Negative loadings for

Component 1 are all rather small, but they include *Pinus*, *Quercus*, *Betula*, and *Carya*. These trees are common to forests in the Mid-Atlantic region (USDA and NRCS, 2004; Peattie, 1948). Component 1, therefore, reflects the amount of wetland surface area, with positive numbers corresponding to greater area of wetlands and negative numbers corresponding to lower areas of wetlands.

Component 2 (Figure 3.11) has high positive loadings for Cheno-Ams and *Ambrosia*. Cheno-Ams present in the St. Jones marshes include *Salsola kali*, *Suaeda* spp., and *Atriplex patula* (DNREC 1999). Cheno-Ams inhabit seashore areas like dunes, and the edges of saline and brackish wetlands (Duncan and Duncan, 1987), while *Ambrosia* lives in disturbed area, like parking lots and forest clearings (Bazzaz, 1974). There is only one palynomorph with a strong negative loading, the Cyperaceae family. Cyperaceae inhabit wetland areas (USDA and NRCS, 2004; Duncan and Duncan, 1987). Species in the study area marshes include three *Scirpus* species, each of which has a different salinity tolerance, ranging from high to low, and six *Carex* species, all of which have no salinity tolerance (USDA and NRCS, 2004). Because of the predominance of *Carex* spp. in the local Cyperaceae community, and the high positive loadings for *Ambrosia* and Cheno-Ams, Component 2 could be interpreted to indicate saline water, in the positive direction, versus fresh water in the negative direction. It is more likely, however, that the component reflects the type of open areas, with wet open land, like wetlands, in the negative direction (Cyperaceae) versus dry open land like forest clearings in the positive direction (Cheno-Ams and *Ambrosia*), with the implication that dry open areas are likely to indicate anthropogenic disturbance.

Component 3 (Figure 3.12) has strong positive loadings for Cyperaceae and Cheno-Ams. *Ambrosia*, *Potamogeton*, and Poaceae all have minor positive loadings, but these are inconsequential compared to the strong positive loadings. Cyperaceae and Cheno-Ams species in the study area, including *Carex* spp., *Eleocharis* spp., *Atriplex patula*, *Salsola kali*, and *Suaeda* spp., all can live in fresh to brackish marshes (USDA and NRCS, 2004). *Alnus* has the only strong negative loading, but taxa with minor negative loadings include *Betula*, *Salix*, *Acer*, *Nyssa*, *Quercus*, *Carya*, *Fraxinus*, *Ilex*, *Nuphar*, and ferns. *Alnus* prefers to live in wet soils such as those found in emergent areas adjacent to marshes, but will not live in the marsh itself (Peattie, 1948). Component 3 is therefore interpreted to refer to greater amounts of emergent areas in the negative direction versus greater amounts of marsh area in the positive direction.

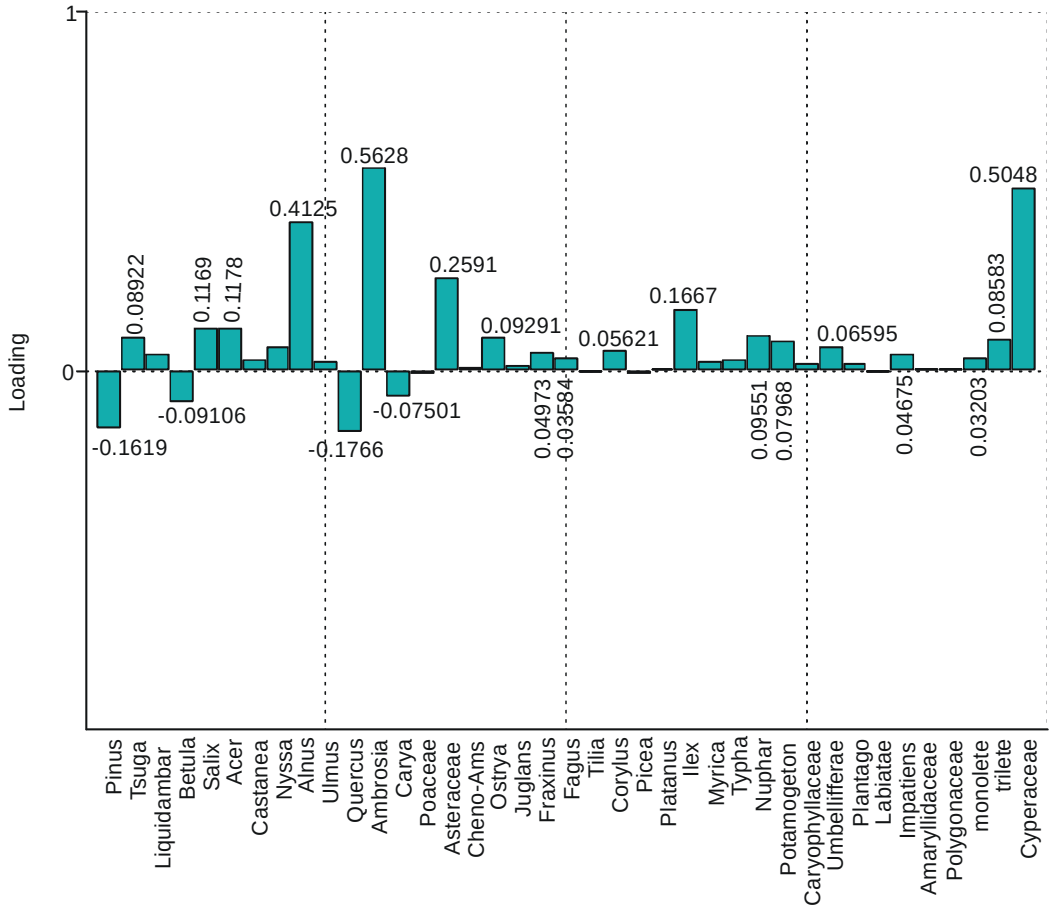

Figure 3.10 Loadings for Component 1, amount of wetland surface area. Loadings above 0.1 and below –0.1 were considered. Positive loadings are marsh species, and negative loadings are forest species.

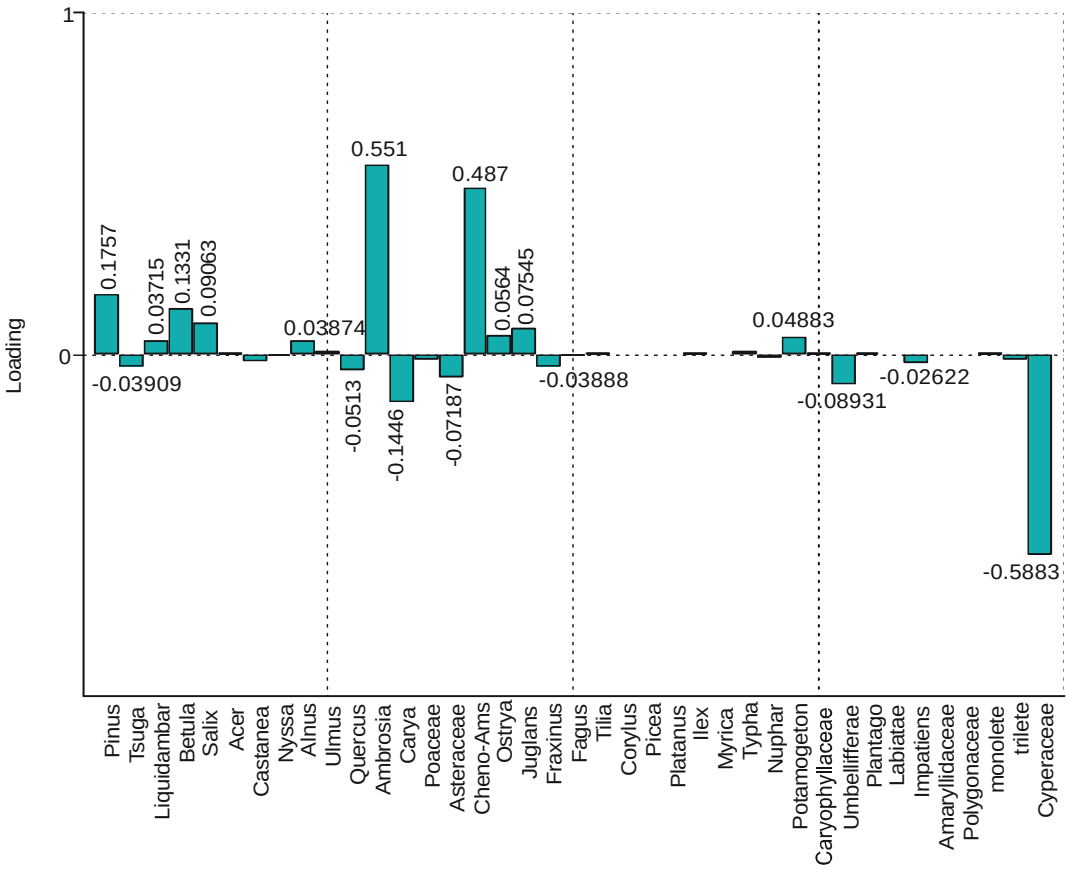

Figure 3.11 Loadings for Component 2, type of open area. Loadings above 0.1 and below –0.1 were considered. Positive loadings are species that live in wet open areas, and negative loadings are species that live in dry open areas.

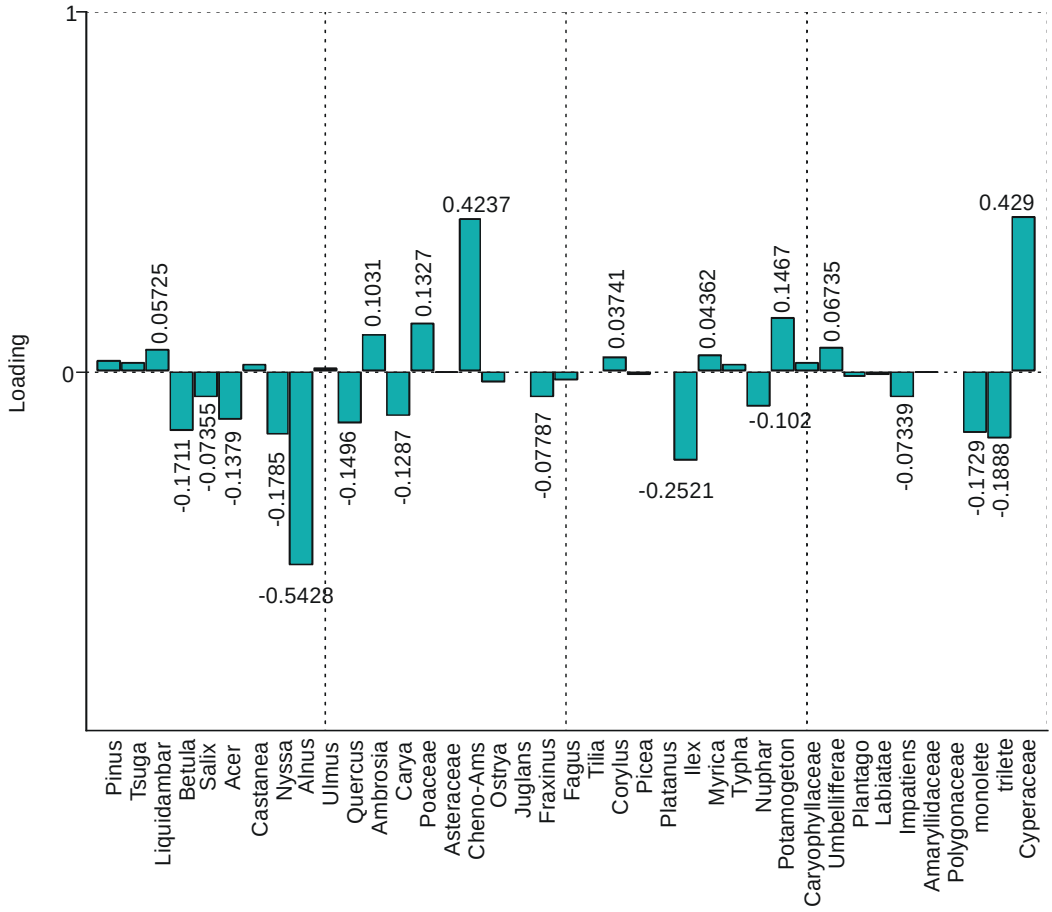

Figure 3.12 Loadings for Component 3, amount of emergent versus marsh area. Loadings above 0.1 and below –0.1 were considered. Positive loadings are species that live in emergent wet soils, and negative loadings are species that live in marshy wet soils.

Table 3.1 Eigenvalues and percent variances for the top six principal components.

Component	Eigenvalue	Percent Variance	Sum Percent Variance
1	1.12488	26.83	26.83
2	0.98603	23.518	50.348
3	0.54867	13.087	63.435
4	0.27706	6.6083	70.0433
5	0.18519	4.417	74.4603
6	0.16693	3.9816	78.4419

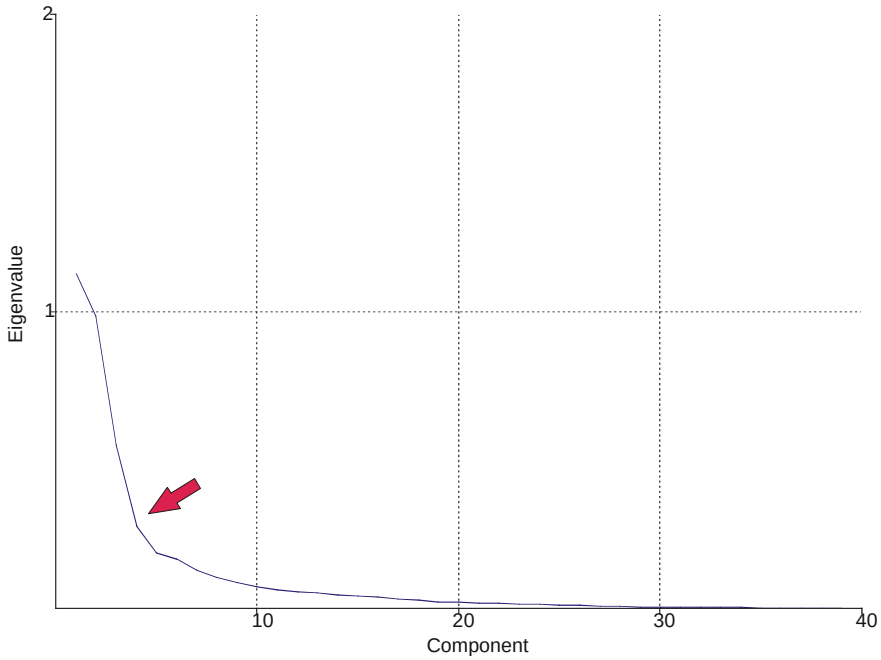

Figure 3.13 Scree plot of eigenvalues and loadings for principal components. The red arrow shows the location of the break between the third and fourth components.

Table 3.2 Loadings for top three components. Loadings above 0.1 and below -0.1 are highlighted in bold type.

Taxon	Component 1	Component 2	Component 3
Pinus	**-0.1619**	**0.1757**	0.02956
Tsuga	0.08922	-0.03909	0.02328
Liquidambar	0.04445	0.03715	0.05725
Betula	-0.09106	**0.1331**	**-0.171**1
Salix	**0.1169**	0.09063	-0.07355
Acer	**0.1178**	0.002001	**-0.1379**
Castanea	0.03047	-0.02528	0.01604
Nyssa	0.06577	-0.00871	**-0.1785**
Alnus	**0.4125**	0.03874	**-0.5428**
Ulmus	0.02568	0.008174	0.007508
Quercus	**-0.1766**	-0.0513	**-0.1496**
Ambrosia	**0.5628**	**0.551**	**0.1031**
Carya	-0.07501	**-0.1446**	**-0.1287**
Poaceae	-0.01158	-0.01731	**0.1327**
Asteraceae	**0.2591**	-0.07187	-0.00842
Cheno-Ams	0.006463	**0.487**	**0.4237**
Ostrya	0.09291	0.0564	-0.035
Juglans	0.01202	0.07545	-0.00178
Fraxinus	0.04973	-0.03888	-0.07787
Fagus	0.03584	-0.00744	-0.03075
Tilia	-0.00731	0.005062	-0.00319
Corylus	0.05621	-0.00363	0.03741
Picea	-0.01226	-0.00278	-0.01342
Platanus	0.000654	-0.00206	-0.00261
Ilex	**0.1667**	0.003861	**-0.2521**
Myrica	0.02144	-0.00062	0.04362
Typha	0.02854	0.0102	0.01653
Nuphar	0.09551	-0.01048	**-0.102**
Potamogeton	0.07968	0.04883	**0.1467**
Caryophyllaceae	0.01742	0.003397	0.02263
Umbellifferae	0.06595	-0.08931	0.06735
Plantago	0.02055	0.003274	-0.01863
Labiatae	-0.00899	-0.00149	-0.01223
Impatiens	0.04675	-0.02622	-0.07339
Amaryllidaceae	0.005155	-0.00086	-0.00521
Polygonacaea	0.000485	-0.00232	-0.00145
monolete spores	0.03203	0.001229	**-0.1729**
trilete spores	0.08583	-0.019	**-0.1888**
Cyperace	**0.5048**	**-0.5883**	**0.429**

Associations of similar samples were able to be defined from the PCA plots. The combined data group into reasonably well-defined associations upon plotting on the first and second component axes (Figure 3.14). A plot of the data onto the second and third component axes is shown in Figure 3.15, and a plot of the first and third component axes is shown in Figure 3.16. In all three figures, sample numbers correspond to depth in core, and are preceded by a letter that indicates the specific core: "R" samples are from RPC2, "C" samples are from SJC6, and "B" samples are from SJB6.

Samples were assigned to associations based primarily on their positions in the plot of components 1 and 2, but with additional consideration of the other two PCA plots. In the case of non-adjacent samples plotting in the same PCA groupings, further weight was given to stratigraphic position. Association I A and I B comprise samples above the agricultural horizon, and Association I C is just below it, representing the historical period of exploration and early settlement. Core RPC2 only has these three associations, while SJB6 and SJC6 have two or more further divisions, Associations II A, II B, III A, and III B. The paleoecological associations determined from the PCA results are given names that reflect the amount of wetland surface area and the type of open land indicated. Names are summarized in Table 3.3.

Association I A contains all the uppermost samples in each core, and represents the past 30 or so years. On the PCA plot of Components 1 and 2, this group is located in the uppermost center of the graph, which indicates that this association represents the driest type of open areas, such as those found outside of wetlands, and has wetland surface areas ranging from medium-low to medium high (Figure 3.14) depending on core site. The samples in this association also plot reasonably close

together in Figures 3.15 and 3.16, although there is a little more scatter. Association I A therefore is named "medium marshy, most-dry open." Association I B plots in the center right of Figure 3.14. It represents the highest amount of wetland area of all associations, but shows a lower amount of dry open areas than Association I A. Association I B is therefore "most marshy, medium-dry open." Samples in Association I C are located in the middle of the plot of Components 1 and 2, indicating open areas dominated by neither dry types or wet types, and medium wetland surface areas, or "medium marshy, medium open." These samples were deposited before the agricultural horizon, but after European settlers arrived, and are somewhat transitional in nature.

Table 3.3 Summary of paleoecological associations.

Association number	Descriptive name
I A	medium marshy, most-dry open
I B	most marshy, medium-dry open
I C	medium marshy, medium open
II A	medium-low marshy, medium open
II B	least marshy, medium-dry open
III A	medium marshy, wet open
III B	medium-low marshy, medium-dry open

All samples in Associations II and III come from cores SJB6 and SJC6, and represent the time before European exploration and settlement. Association II A samples group together near the center left of Figure 3.14. This position indicates low

wetland surface area and lack of dominance of dry open areas over wet open areas. It is therefore called "medium-low marshy, medium open". Samples from Association II B are found only in core SJC6, and have the lowest amount of wetland surface area of all associations, but have medium-dry types of open areas. Association II B is called "least marshy, medium-dry open."

Association III is found only in core SJB6. Samples in Association III A group together near the center bottom of Figure 3.14, indicating wet types of open areas, and a medium amount of wetland surface area. Association III A therefore is called "medium marshy, wet open." Association III B, however, is located in the same group as Association II A, with low wetland surface area and medium-dry types of open areas, and is called "medium-low marshy, medium-dry open."

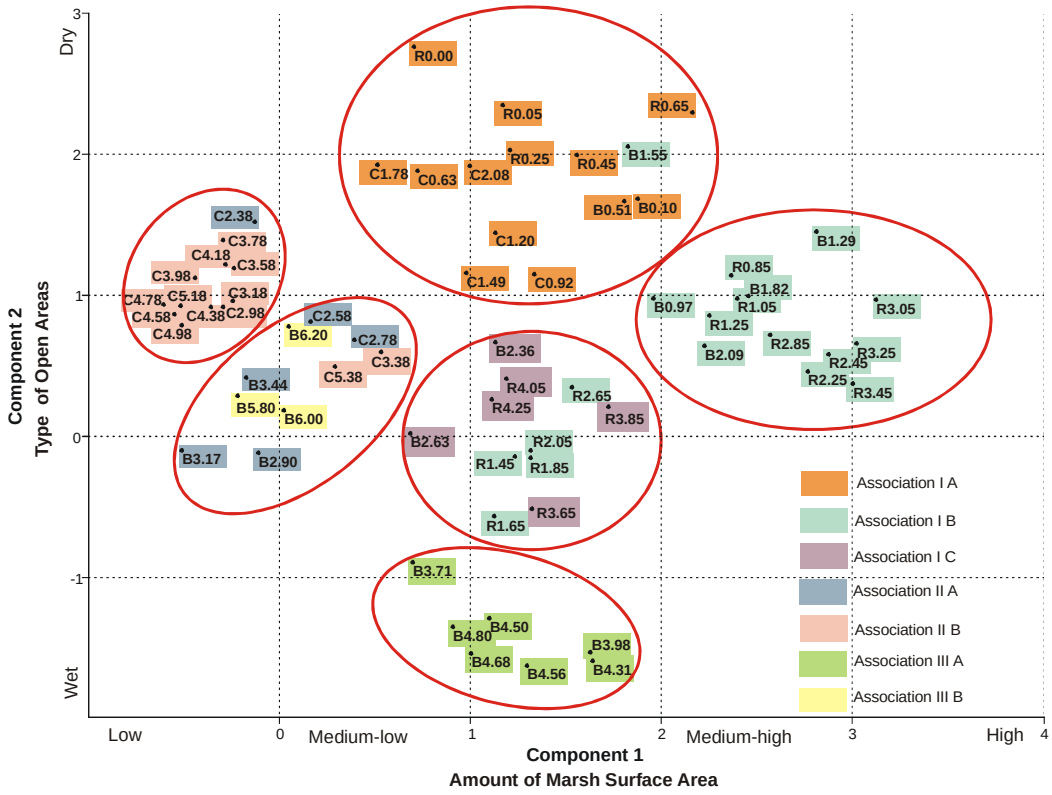

Figure 3.14 PCA plot of Components 1 and 2. Groups of similar samples are circled in red and environmental associations are color-coded. Samples in Associations I A and I B are above the agricultural horizon.

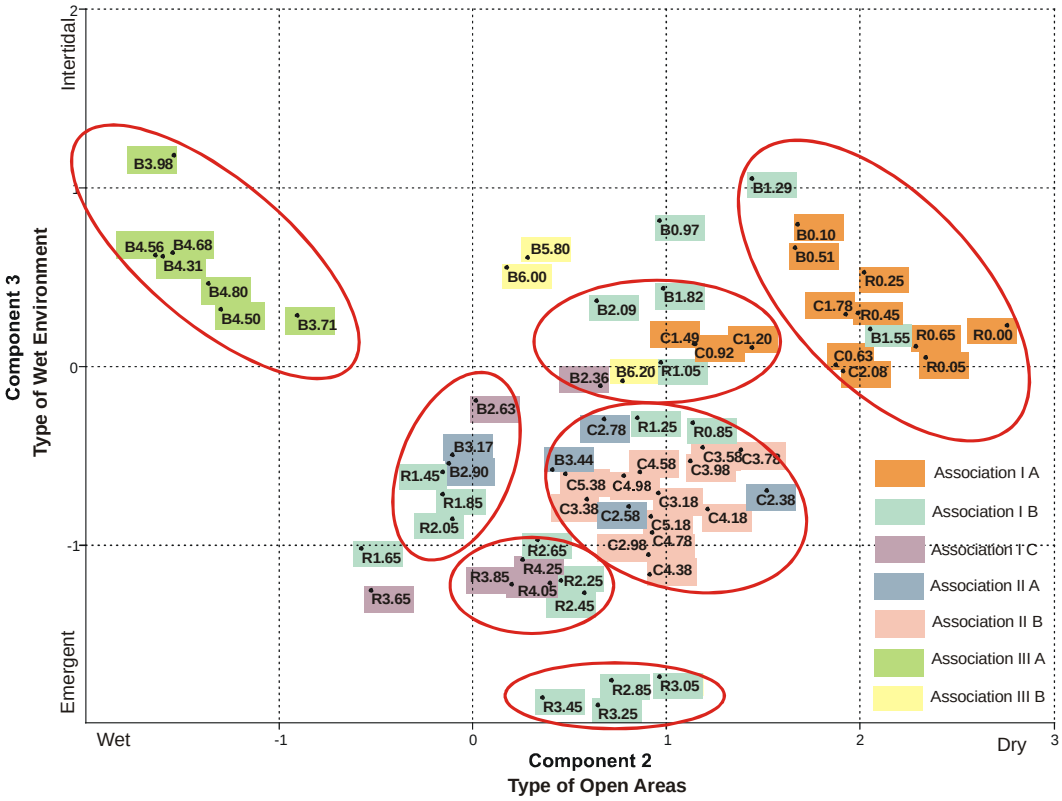

Figure 3.15 **PCA plot of Components 2 and 3. Groups of similar samples are circled in red and environmental associations are color-coded. Samples from Associations I A and I B are above the agricultural horizon.**

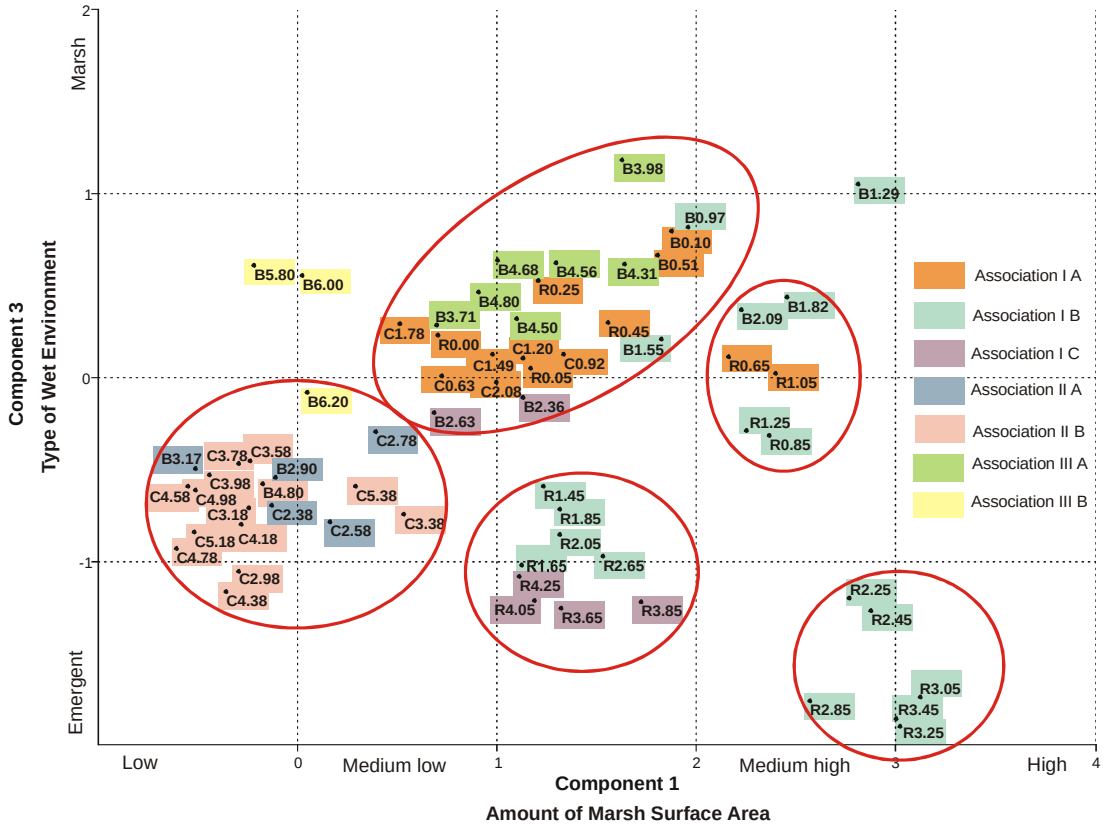

Figure 3.16 PCA plot of Components 1 and 3. Groups of similar samples are circled in red and environmental associations are color-coded. Samples from Associations I A and I B are above the agricultural horizon.

Non-metric Multidimensional Scaling (NMDS)

This study used NMDS to gauge the difference, if any, in results between it and PCA. Like PCA, NMDS is an ordination method that helps to reduce the complexity of the data set without losing meaning (Birks and Gordon, 1985). Whereas PCA preserves distances between samples, NMDS preserves rankings present in the input data. Additionally, NMDS coordinate axes are not placed so as to explain the maximum amount of variability in the data set as in PCA. Instead, they are placed arbitrarily. The NMDS plot of Coordinates 1 and 2 is shown in Figure 3.17. There are some differences, but overall, the data points make groups of samples very similar to the groupings seen on the PCA plot of Component 1 and Component 2 (Figure 3.14). There are seven groups, which are named numerically and from left to right on Figure 3.17. Groups 1 and 2 contain samples that are in PCA Association I B in cores RPC2 and SJB6. Group 3 contains all of the samples from Association I A and I B in core SJB6, Association I in core SJC6, and Association I A in core RPC2. Group 4 contains samples from PCA Association I B and I C from core RPC2, and Association I C in core SJB6. Group 5 contains all samples from core SJC6 except those of PCA Association I. Group 6 contains samples from Associations II and III B in core SJB6. Group 7 contains samples from Association III A in core SJB6. Three samples could not be assigned to groups, as they plotted well away from other samples. Although the sample groupings are similar to those given by PCA, the placement of each group along each axis differs from the PCA plot of Components 1 and 2. The amount of paleoecological information that can be gleaned from the two

methods is similar, but the PCA method of preserving distances between data points is preferable to the NMDS method of preserving the rankings of data for this study. Therefore, this study will focus on PCA for paleoecological analysis.

Figure 3.17 NMDS plot with groups circled in red and labeled. Highlighted samples are above the agricultural horizon.

Chapter 4

DISCUSSION AND INTERPRETATION

Discussion and interpretation of results are herein presented in three parts. Sediment accumulation rates are calculated and discussed and the results of the cluster analysis are interpreted together in the Time section. Environment-related results are discussed and interpreted next, including the results of pollen counts and Principal Components Analysis. Finally, time and environment are integrated to create a paleoenvironmental interpretation of the recent history of the study area.

Time

Analysis of sediment accumulation rates within and between cores shows some important trends and correlations with core lithologies. The biostratigraphic zonations derived from cluster analysis highlight the degree of differences between zones and samples within each core.

Sediment accumulation rates

Sediment accumulation rates were calculated based on radiocarbon dates and the agricultural horizon. This study used sediment accumulation rates, as opposed to sedimentation rates, because the problem of correcting for autocompaction of salt marsh sediments is outside of the scope of this study. Accumulation rates are sufficient to answer the question presented (the null hypothesis), and are a common tool for studying recent changes in marsh sedimentation (Orson et al., 1990; Kearney et al., 1994; Ward et al., 1998; Chmura et al., 2001; Colman and Bratton, 2003). The tables that follow summarize sediment accumulation rate calculations. For each interval, the depth range and interval thickness are given in meters and millimeters respectively. The ages and amount of elapsed time for each interval are expressed as variations around the mean. Finally, sediment accumulation rates are also expressed as variation around the mean.

In core SJB6, there are two ^{14}C dates: 4560 to 4840 Cal YBP at 9.3 m, and 250 to 330 Cal YBP at 1.9 m depth. The agricultural horizon, which corresponds to the years 1680 to 1710, or 290 to 320 YBP, falls just above 2.36 m depth, with the practical depth for calculation purposes set at 2.20 m. All three of these age ranges are calculated as of the year 2000, when core SJB6 was collected. Sediment accumulation rates are calculated for two intervals: Interval A, from year 2000 to the agricultural horizon; and Interval B, between the agricultural horizon and the lower radiocarbon date. The upper radiocarbon date is not used in sediment accumulation rate

calculations because, although it is consistent with the depth of the agricultural horizon, it is only 3 cm above it.

Table 4.1 shows the ranges of calculated sediment accumulation rates for each interval. Interval B contains sediments from 2.2 m to 9.3 m, and is bounded by the agricultural horizon and the lower radiocarbon date. Because both dates are given as ranges of years, maximum and minimum sediment accumulation rates can be calculated and then averaged. The average sediment accumulation rate for pre-settlement Interval B is 1.7 ± 0.6 mm/yr. Interval A, which is post-settlement, contains 1.9 m of sediment, and is bounded by the agricultural horizon and the top of the core. The average sediment accumulation rate for Interval A is 7.2 ± 0.3 mm/yr. Therefore, sediment accumulation rates increased by about 4.3 times in the vicinity of core SJB6 after European settlement.

Although autocompaction was not taken into account when calculating sediment accumulation rates, the rate increase seen here is similar to that seen in other similar studies. Brush et al. (1982) compared pre- and post-settlement sediment accumulation rates in marshes along Chesapeake Bay tributaries, and found pre-settlement rates to vary between 0.5 and 1.8 mm/yr, while post-settlement rates varied between 3.4 and 5.1 mm/yr. Orson et al. (1990) studied a freshwater tidal marsh near Philadelphia, PA, and found pre-settlement sediment accumulation rates of 0.4 mm/yr. Post-settlement accumulation rates were found to be 1.2 mm/yr prior to 1940 when tidal influence of the marsh became regular, and ranged between 10.4 and 13.8 mm/yr between 1940 and 1988. Zaprowski (1998), in an investigation of the history of a New Hampshire salt marsh, found sediment accumulation rates tripled after European settlement, from 0.7 mm/yr to 2.3 mm/yr.

Table 4.1 Sediment accumulation rates for core SJB6.

Interval	Depth Range (m)	Thickness (mm)	Age Range (YBP)	Elapsed Time (yr)	Average Sediment accumulation rate (mm/yr)
A	0–2.2	2200	290-320	305±15	7.2 ± 0.3
B	2.2–9.3	7100	4550-4240	4395±155	1.7 ± 0.6

Core SJC6 also has two ^{14}C dates, one at 7.1 m of 760 to 940 Cal YBP, and one at 9.1 m with a range of 4010 to 4280 Cal YBP. Because of the unconformity inferred below 7.1 m, the sediment accumulation rate will not be calculated below that depth. The agricultural horizon, corresponding to 290 to 320 YBP (as of 2000), falls just below 2.08 m, with the practical depth for calculations being 2.15 m. Sediment accumulation rates can be calculated for two intervals: Interval A, from the top of the core to the agricultural horizon and Interval B, from the agricultural horizon to the upper ^{14}C date. Table 4.2 lists the factors involved in calculating the rates.

Table 4.2 Sediment accumulation rates for core SJC6.

Interval	Depth Range (m)	Thickness (mm)	Short Age Range (YBP)	Maximum Elapsed time (yr)	Average Sediment accumulation rate (mm/yr)
A	0-2.15	2150	290-320	305±15	7.1 ± 0.3
B	2.15-7.1	4950	320-760	545±105	9.6 ± 1.9

Interval B contains sediments between 2.15 m and 7.1 m, and is bounded by the radiocarbon date and the agricultural horizon. As in core SJB6, the two bounding dates are given as ranges. Therefore, maximum and minimum sediment accumulation rates are calculated and then averaged. Interval B has an average sediment accumulation rate of 9.6 ± 1.9 mm/yr. This pre-settlement sediment accumulation rate is higher than that of SJB6 because this core site experienced intertidal deposition for a longer period of time than did SJB6 (Wilson, 2005). The post-settlement Interval A contains sediment from the top of the core to 2.15 m, and is bounded by the top of the core and the agricultural horizon. Calculating maximum and minimum sediment accumulation rates gives an average post-settlement sediment accumulation rate of 7.1 ± 0.3 mm/yr. The post-settlement sediment accumulation rate in core SJC6 is higher than the pre-settlement rate because the depositional environment at the site of SJC6 was intertidal for most of its history. The intertidal setting that dominated the pre-settlement history of this site is the cause of the high pre-settlement sediment accumulation rates. Intertidal areas have the potential for

longer periods of sediment deposition because they are inundated for longer periods of time than supratidal areas.

Sediment accumulation rates for RPC2 are calculated from pollen analytical horizons alone. Core RPC2 can be divided into two sections: Interval A, which goes from the top of the core to the upper oak:ragweed horizon, and Interval B, which is between the upper horizon and the agricultural horizon. Pre-settlement sediment accumulation rates cannot be calculated for this core due to the lack of a date at the bottom of the core. The agricultural horizon occurred between 1680 and 1710, which is 294-324 YBP, calculated as of the year 2004 when core RPC2 was collected. The upper horizon is inferred to be related to suburbanization or to the construction of Dover Air Force Base in 1942, so the range of dates used for this horizon could be as early as 1940 and as late as 1960 (44-64 YBP as of 2004). Figures 1.6 through 1.10 illustrate the amount of construction projects that took place in the study area after World War II.

Although construction related to World War II is the most obvious cause of both the upper pollen horizon and the sand layer seen at the same depth, it is by no means conclusive. It would explain the sand layer, but the base was built on agricultural land, not forest, so this date does not fully explain the pollen horizon. Other possible candidates for the date of the upper horizon include several local road and bridge construction projects between 1900 and 1950, and the initial straightening of the St. Jones River in 1913, which altered the hydrologic regime of the river and would have allowed sediment from Delaware Bay to move farther upstream than before. The exact date of the upper pollen horizon is somewhat ambiguous and difficult to establish based on the information available. It is necessary, however, to

calculate sediment accumulation rates above this horizon, so 1940 to 1960 will be used as dates. Table 4.3 summarizes the sediment accumulation rates.

Table 4.3 Sediment accumulation rates for core RPC2.

Interval	Depth Range (m)	Thickness (mm)	Short Age Range (YBP)	Maximum Elapsed time (yr)	Average Sediment accumulation rate (mm/yr)
A	0-1.25	1250	44-64	54±10	23.9 ± 4.4
B	1.25-3.45	2200	230-280	255±25	8.7 ± 0.8
A+B	0-3.45	3450	294-324	309±15	11.1 ± 0.5

Both intervals in this core are above the agricultural horizon, so only limited comparisons to the other two cores are possible. Interval B, which includes sediment between 1.25 m and 3.45 m, has an average sediment accumulation rate of 8.7 ± 0.8 mm/yr. Interval A, with sediment from the top of the core to 1.25 m, corresponds approximately to the last half of the twentieth century. This section has an average sediment accumulation rate of 23.9 ± 4.4 mm/yr. The sediment accumulation rate from the top of the core to the agricultural horizon (from the top of the core to 3.45 m) is 11.1 ± 0.5 mm/yr.

Independent ^{210}Pb and ^{137}Cs dating of the upper 1 m of sediment at this site (Sommerfield, 2005) showed two important results (Figure 4.1). First,

bioturbation has not greatly affected the mudflat, as both profiles are smooth, and the concentrations do not fluctuate much with depth. Second, the sediment accumulation rates for the uppermost 1 m as calculated from the ^{210}Pb and ^{137}Cs dates alone are 9.5 mm/yr and 11 mm/yr respectively. This is less than half of the pollen-derived sediment accumulation rates for the upper 1.25 m. One possible explanation is that the date picked for the upper oak:ragweed horizon is too recent. If the date for this upper horizon was around 1900 instead of 1950, then the pollen-derived sediment accumulation rate for the upper 1.25 m of core RPC2 would more closely match the ^{210}Pb and ^{137}Cs sediment accumulation rates, with a value of 12.5 mm/yr. The other possible explanation is that the date picked and the calculated accumulation rate are correct. The sediment accumulation rate in interval A could have increased due to the straightening of the river channel, as sediment from Delaware Bay would be able to be transported farther upstream after such a construction project. Sediment input from land also would have increased during all of the housing and industrial construction projects as soil was exposed. Either possibility could be correct. Accurate determination is not possible with the current data.

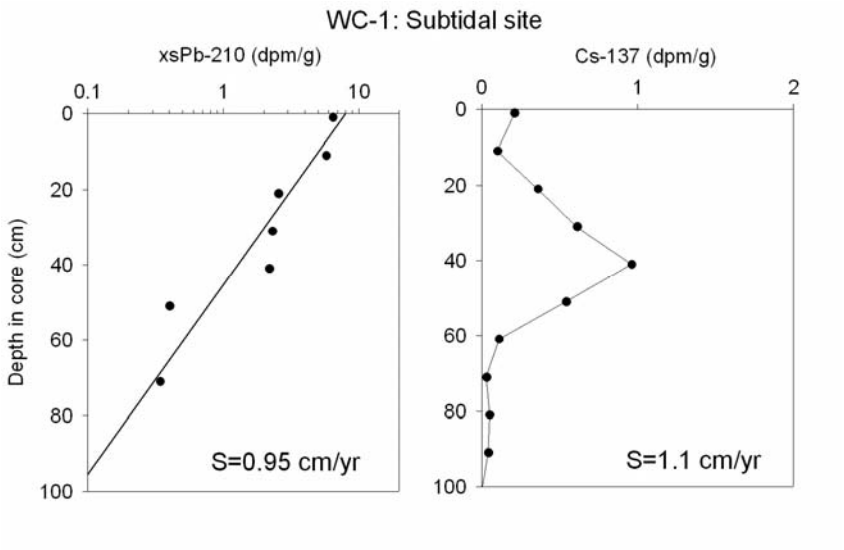

Figure 4.1 **^{210}Pb and ^{137}Cs data for site of core RPC2 (Sommerfield, written communication).**

Pollen Zonations

Cluster analysis was used to assess the similarity of stratigraphically adjacent samples, and to use that information to make biostratigraphic zonations for each core. Partitioning samples with cluster analysis takes into account all taxa represented, so some differences are expected between cluster analysis boundaries and boundaries derived from simpler methods, such as the oak:ragweed horizon. In core RPC2, the clustering algorithm agrees well with the pollen analytical horizons, making major divisions at both the agricultural horizon and the upper horizon.

In cores SJB6 and SJC6, however, the clusters do not match as well. In core SJB6 the clustering algorithm placed a major division one sample higher than the agricultural horizon, above 2.09 m instead of above 2.36 m (Figure 4.2), clustering 2.09 m, 2.36 m, and 2.63 m (Zone 1B). The reason for this can be ascertained by examination of the pollen diagram for SJB6 (Figure 3.2). The oak:ragweed ratio declines gradually in Zone 1B, making this zone transitional in nature between pre-settlement and post-settlement assemblages. The arboreal pollen (AP) gradually declines while non-arboreal pollen (NAP) gradually increases throughout this zone. Additionally, the clustering program uses all taxa when determining similarity, whereas the oak:ragweed ratio takes only two taxa into account. Although Zone 1B is a transitional zone, the clustering program indicates greater similarity to the samples above it than to the samples beneath it, as the clustering algorithm links Zone 1B upward, with Zone 1A.

In core SJC6, the clustering algorithm also makes a major division one sample higher than the agricultural horizon, above 2.08 m instead of above 2.38 m (Figure 4.2). The sample at 2.08 m is linked downward to join a larger cluster of samples, but it is the last sample to be included before the entire lower portion of the core is linked with the top five samples, indicating that the similarity with the lower portion of the core is somewhat weak. This discrepancy between the clustering program and the pollen analytical horizon can be easily explained, as in SJB6, by the difference in the amount of data used by each method to determine partitions. The agricultural horizon was placed between the samples at 2.08 m and 2.38 m because of the oak:ragweed ratio. The clustering algorithm, however, takes into account all taxa when grouping samples. So despite the oak:ragweed ratio, the sample at 2.08 m is

more like the underlying samples then the overlying ones when all taxa are considered.

Cluster analysis was accomplished using Ward's Method in stratigraphically constrained mode, which groups depth-adjacent samples in such a way as to minimize the variation in the within-group sum-of-squares distance (Birks and Gordon, 1985). An alternative method available in the cluster analysis program used is the furthest-neighbor algorithm, which uses the distance between farthest-apart group members. Furthest-neighbor clustering links objects or groups that have the smallest farthest-neighbor distance. Overall, the differences between the two clustering algorithms were minor, leading to the conclusion that the stratigraphic zonation based on Ward's method is sound.

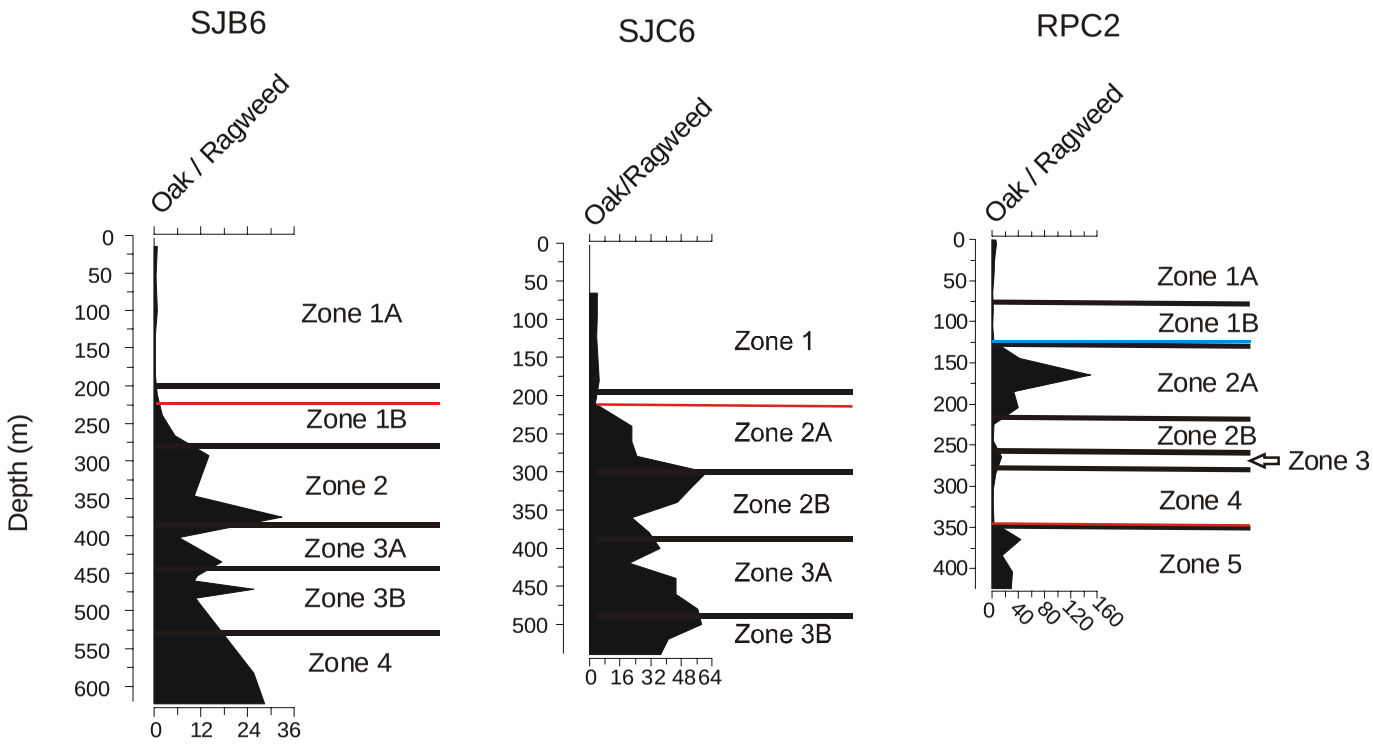

Figure 4.2 Oak-to-ragweed ratios and pollen assemblage zones.

Environment

Paleoenvironmental conditions can be ascertained by careful examination of the results of Principal Components Analysis and pollen analysis. The associations of similar samples generated from PCA and the causes of ecological variation inferred from the taxon loadings for each component axis show how the amounts of wetland surface area and open area have changed throughout the past ~1000 years. The results of pollen analysis yield trends in salinity and amount of forest coverage.

Paleoecological Associations

Paleoecological associations of samples with similar pollen assemblages were derived from Principal Components Analysis. Associations yielded information about changes in surface area of marshes and dominant type of open areas. Here the Associations will be evaluated based on their occurrences in stratigraphic order and in linear space.

Although most of the paleoenvironmental associations occur in more than one core, they do not always occur in samples from the same depositional environments. Associations III A and III B are found only in core SJB6. Association III B, medium-low marshy and medium-dry open, falls within the intertidal section of core SJB6 (Figure 4.3). The sediment in this interval is organic clay overlain by peat (Wilson, 2005). The areal extent of marshes during this interval was rather low, according to the PCA results. According to Wilson (2005), the St. Jones River basin

at this time was characterized by narrow fringing marshes and large tracts of intertidal areas. He explains the presence of a peat deposit in this interval by postulating that it was either a localized patch of well-developed peat or a slump block transported from its original location. The "medium-dry open" label refers to a greater prevalence of open areas outside of wetlands, such as forest clearings. These upland-type clearings would have been caused by natural forest clearance events, like fires, or by the small-scale forest agricultural plots favored by the Native Americans.

Association III A, medium marshy and wet open, begins in the intertidal section of core SJB6, in the peat deposit. The depositional environment is supratidal, however, with the sediment being clayey peat from 4.4 m up to 1 m. The depositional environment became supratidal after the radiation of halophyte plants in the river basin around 2000 YBP (Wilson, 2005). The increased number of these plants allowed for increased trapping of allochthonous sediment and increased production of autochthonous sediment, thus raising the intertidal surfaces to supratidal elevations. The lithology and the PCA results both indicate that marsh surface area increased during this time period. Accordingly, the dominant type of open areas switched from dry upland clearings to wet marshy areas.

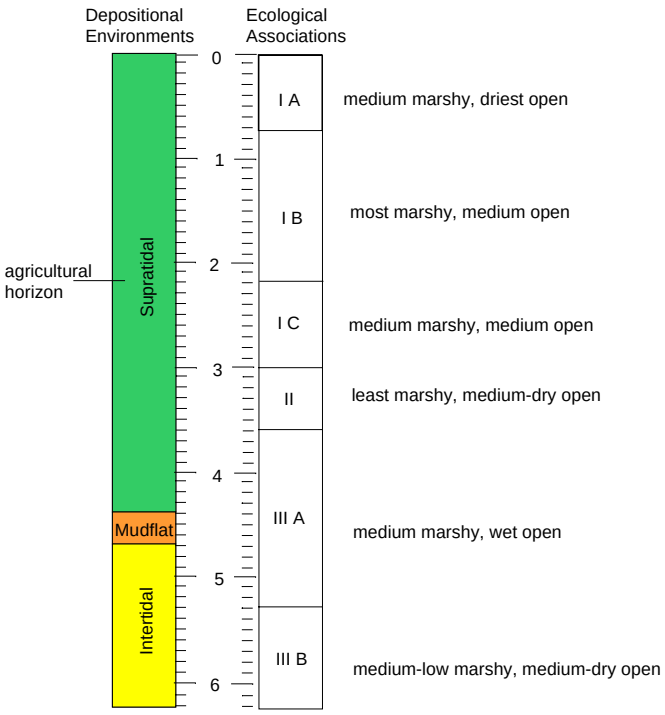

Figure 4.3 Depositional environments and ecological associations for core SJB6.

Association II, with low amounts of marsh surface area and medium-dry types of open land, occurs in the supratidal clayey peat section of core SJB6 (Figure 4.2). In core SJC6, Associations II B and II A are in intertidal sediments of organic clay from 5.5 m to 2.15 m (Figure 4.4). Association II B has low amounts of marsh surface area and medium-dry types of open land while Association II A has medium-low amounts of marsh surface area and medium types of open land, indicating a decrease in marsh surface area during Association II. Wilson (2005) indicates that there were some die-backs of certain halophyte species as the river flow became more

channelized and river salinity changed after 2000 YBP. SJC6 has a much greater length of core in Association II than does SJB6 because the site of SJC6 during this time interval was still intertidal (Wilson, 2005). This section of SJC6 represents infilling of a river channel that had cut into older sediments. The highly forested nature of both these Associations is due to the lack of European settlers and their tendency to use clear cutting techniques. The greater amount of cleared upland areas in Association II B could have been caused by forest fires, Native American activities, or natural expansion of fringing marsh.

Association I is seen in all three cores, and in subdivided into three sections in SJB6 and RPC2. Association I C, medium marshy and medium open, is in supratidal clayey peat sediments in SJB6 (Figure 4.3) (Wilson, 2005) and intertidal organic clay sediments in RPC2 (Figure 4.5). This association represents the time between European discovery of the area and the agricultural horizon, when forest clearing was limited in extent. Individual settlers would have clear cut forest plots for their agricultural fields and for fuel wood, but the population density would not have been sufficient to make as significant an impact on the paleoecological record as it would in later times.

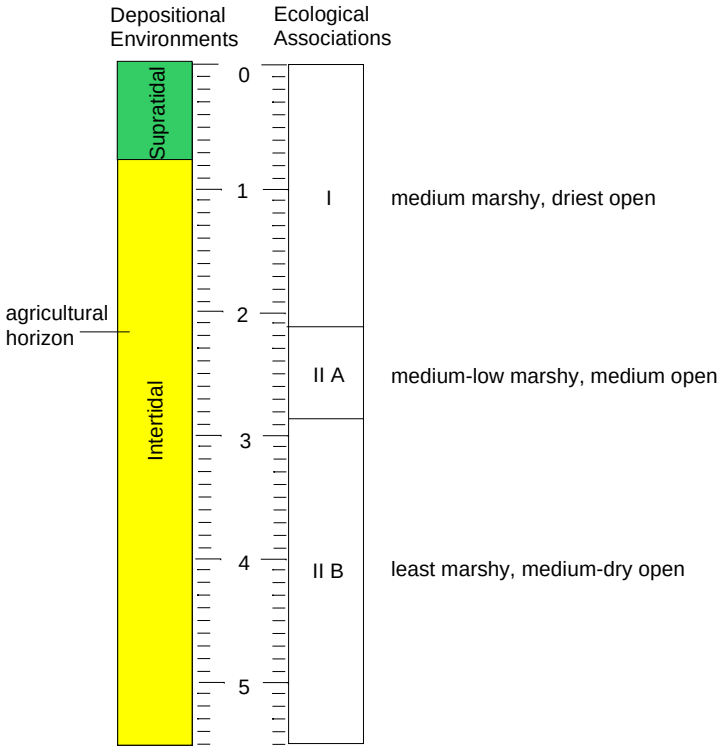

Figure 4.4 Depositional environments and ecological associations for core SJC6.

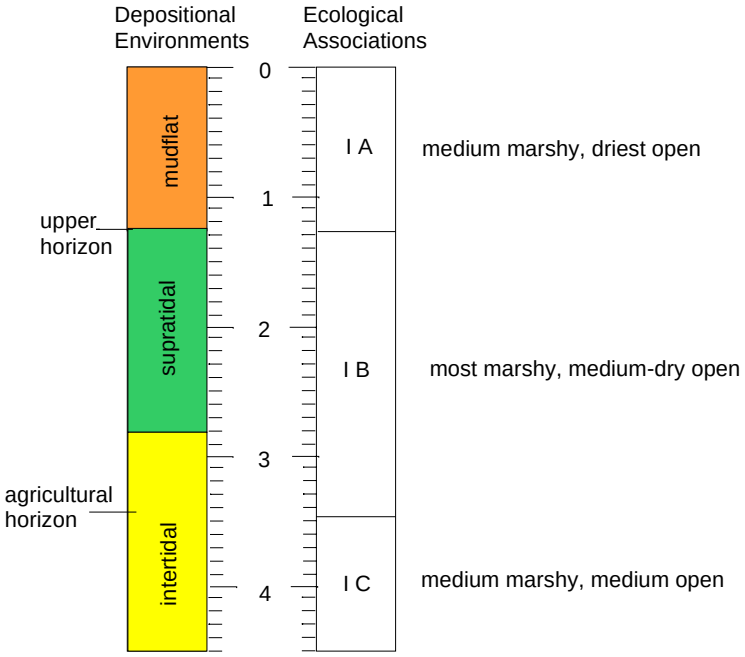

Figure 4.5 Depositional environments and ecological associations for core RPC2.

Association I B, with the highest extent of marsh surface area and medium types of open area, is entirely supratidal in core SJB6, with clayey peat sediments overlain by peaty clay above 1 m (Wilson, 2005). In RPC2, Association I B starts in intertidal peaty clay grading up to clay, but the depositional environment becomes supratidal at 2.8 m, with peat and clayey peat sediments. Association I B was deposited after the agricultural horizon, when anthropogenic land clearance surpassed approximately 40 % of the total forest surface area (Brush, 1989; Brush and Davis, 1984), thus increasing the dominance of dry upland types of open areas.

Association I A, with medium amounts of marsh surface area and the driest types of open areas, occurs in supratidal sediments in core SJB6 (Wilson, 2005) and in intertidal mudflat sediments in RPC2. In SJC6, Association I was not able to be subdivided, but the samples plotted in the same group as Association I A on the PCA plots. The depositional environment for Association I in SJC6 began as intertidal and became supratidal at 0.75 m (Wilson, 2005). This uppermost association represents the past 30 to 50 years, a time characterized by suburbanization and expansion of "sprawl" in Delaware. During this time, dry open areas include environments such as parking lots, roadsides, and residential lawns as well as natural ones like forest clearings. The imposition of impervious surfaces like asphalt roads and concrete foundations atop natural soils prevents infiltration of precipitation, thus increasing runoff and sediment transport into rivers and streams. The increased sediment supply increases vertical accretion in the fringing marshes, making some marsh areas accrete faster than the local rate of sea level rise. With some impervious surfaces currently located very near the boundary between wetland and upland soils, the marsh expansion that naturally keeps pace with sea level rise will eventually become impeded. The end result is decreasing marsh surface area, as the PCA results indicate.

The PCA plots also indicate that the pollen assemblages in each core are slightly different from each other. Core RPC2 is markedly different from the other two cores below 0.65 m (Figure 4.6). The lower samples in RPC2 mostly form groups by themselves, with some SJB6 samples intermixed. This result makes sense, however, considering the results of the sediment accumulation rate calculations. RPC2 has a much higher sediment accumulation rate than cores SJB6 and SJC6, so

that the agricultural horizon occurs much lower in RPC2 than in the other two cores. For this reason, all the samples in RPC2 are more similar to samples in the top 2 m of SJB6 and SJC6. Additionally, the site of RPC2 is currently an intertidal mudflat, and has been for most of the past 350 years. The different depositional environment will affect the relative amounts of airborne and waterborne pollen deposited at the site, making the pollen assemblages different from those at the supratidal sites. Core SJC6 samples also tend to group together without much mixing with samples from SJB6 below the agricultural horizon, but this core has had a different sequence of depositional environments than SJB6. As with core RPC2, this would have affected the relative amounts of airborne and waterborne pollen deposited at the site, thus creating a pollen record subtly different from that of core SJB6.

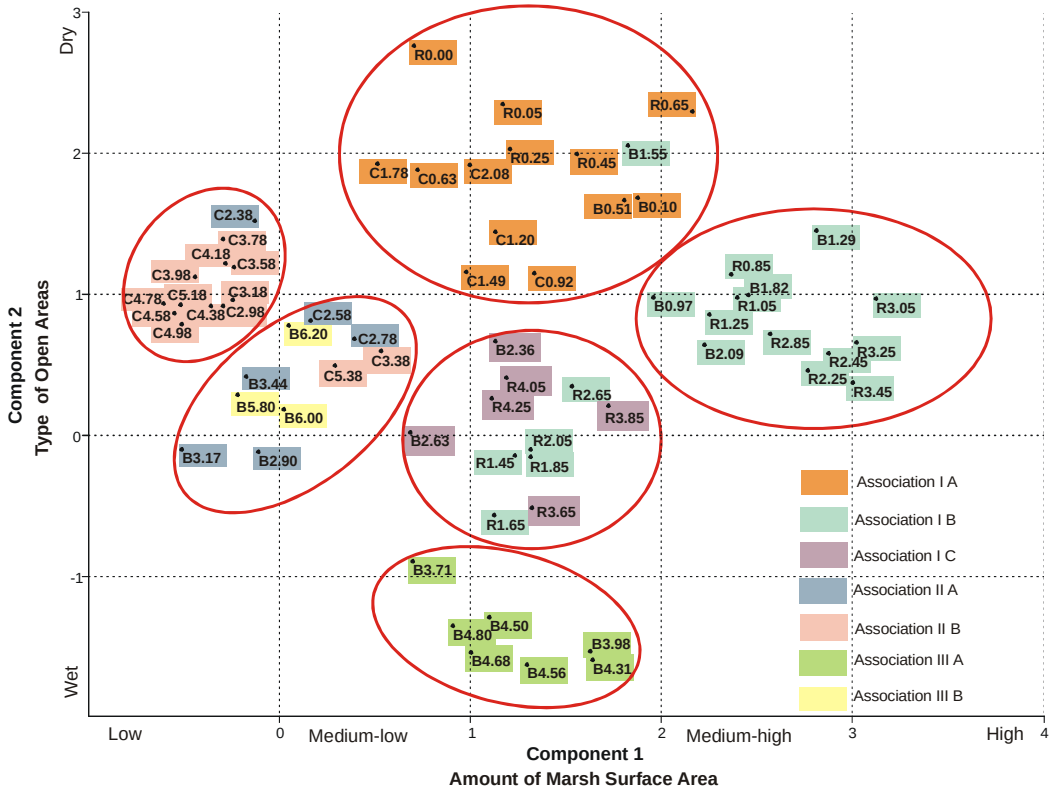

Figure 4.6 PCA plot of Components 1 and 2. Groups are circled in red and paleoecological associations are color-coded.

Palynology

Pollen analytical results for each core are given in Appendices A, B, and C, as both raw counts and as percent of pollen sum. Due to the proximity of the cores, there are some shared characteristics between pollen assemblages at the three sites. All three cores are dominated by *Quercus, Pinus,* and Poaceae throughout each core, and in places have high amounts of *Ambrosia* and Cyperaceae. *Pinus* dominates the pollen assemblages because these species are prominent in the upland forests and tend to overproduce pollen relative to their population. Similarly, *Quercus* species are well represented in both the upland vegetation and in the vicinity of the marshes. Poaceae include everything from marsh grasses to lawn grass and tend to live in a wide variety of environments. The periodically high incidence of *Ambrosia* and Cyperaceae are due to environmental factors. *Ambrosia* is common after European settlement, as it grows best in any cleared area, from forest clearings to parking lots (Bazazz, 1974). Cyperaceae, predominantly fresh water species in the study area (USDA and NRCS, 2004), will tend to vary in abundance with river salinity. All three cores also have very clear oak:ragweed horizons, supported by concomitant decreases in arboreal pollen.

Paleoecological patterns of river salinity and arboreal cover can be seen in the pollen diagrams for individual cores. Core SJB6 shows an interval of increased Cyperaceae, decreased Poaceae, and decreased *Pinus* between 3.98 m and 4.80 m depth. This interval corresponds to biostratigraphic Zones 3A and 3B, and to ecological Association III A. Seven out of nine local Cyperaceae species in the St. Jones River area do not tolerate salinity, and the marsh Poaceae species are all halophytic (USDA and NRCS, 2004). *Pinus* species in the area are mostly upland

species, so this may be a coincidental association (DNREC, 1999; Peattie, 1948). Other recent studies have also used pollen analysis to determine changes in paleosalinity using Poaceae, Cyperaceae, and Cheno-Ams (Byrne et al., 2001; Stutz and Prieto, 2003; Prabhu et al., 2004)

Figure 4.7 shows the pollen diagrams for Poaceae and Cyperaceae, with intervals of more saline river water and fresher river water highlighted. The dates to the left include the agricultural horizon and those calculated based on sediment accumulation rates. The reciprocal relationship seen between Cyperaceae and Poaceae abundances reflect four intervals of paleosalinity conditions. A high-salinity interval indicated by Poaceae dominance at the bottom of the core is followed by a period of decreased river salinity in Association III A. This corresponds roughly to the years 500 to 1300 A.D. Conditions became more saline again, as indicated by a return of Poaceae plants and the near disappearance of Cyperaceae in Association II. This interval corresponds to the period between 1300 and 1650 A.D. The pollen record also indicates that river salinity freshened just before the agricultural horizon, when Cyperaceae reappear and Poaceae abundances decrease above 3.00 m depth. The paleosalinity signal in the top 1.5 m of the core is rather ambiguous, so more recent changes cannot be determined.

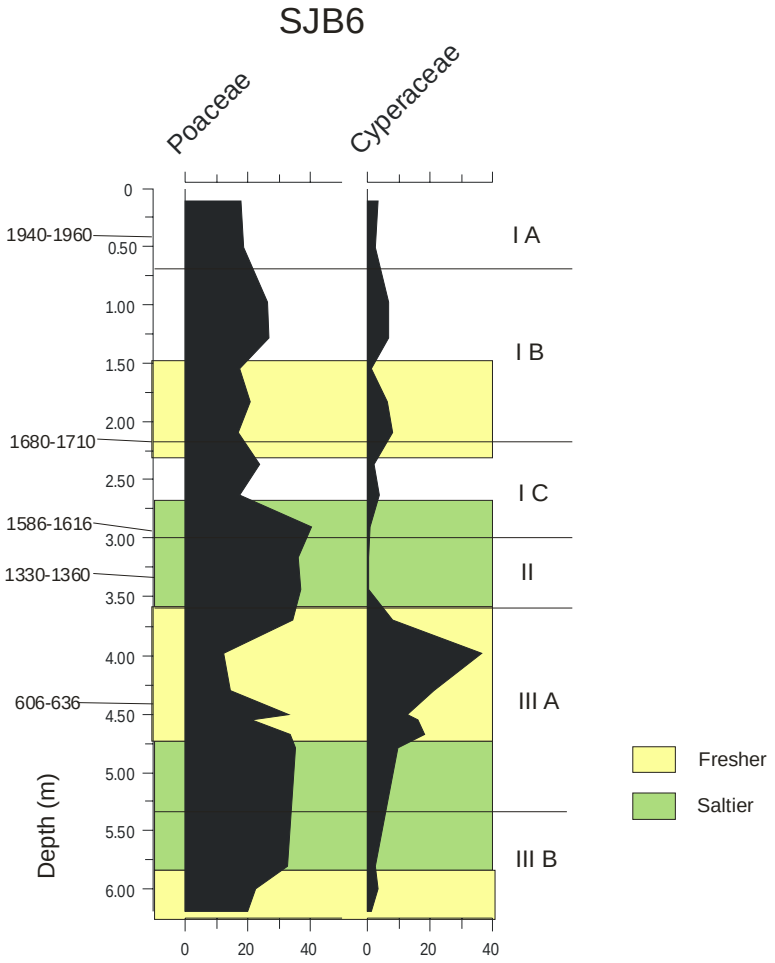

Figure 4.7 Poaceae and Cyperaceae abundances for core SJB6.

These results correspond to those of another recent area study. Willard et al. (2000, 2003), in a multiproxy study of Chesapeake Bay paleoenvironmental conditions, used foraminifera to generate paleosalinity patterns (Figure 4.8). Changes in Chesapeake Bay salinity was inferred to have been caused by changes in the amount of precipitation, with wetter periods generating less-saline conditions than

drought periods. They found an interval of more saline conditions between 1450 and 1675 A.D. followed by an interval of less saline conditions between 1675 and 1750 A.D. Another period of increased salinity persisted from 1750 to 1850 A.D.

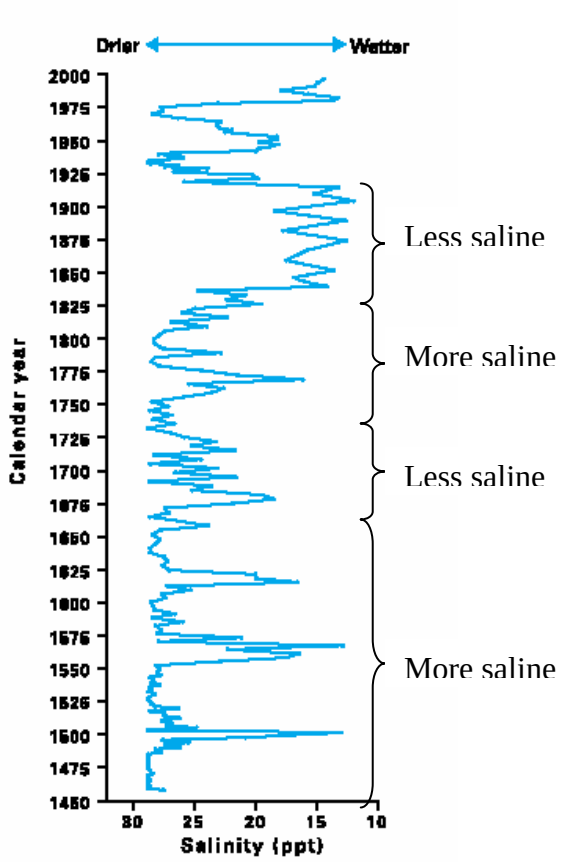

Figure 4.8 Paleosalinity results from Chesapeake Bay (Willard et al., 2000).

Core SJB6 also shows a decrease in aquatic plants partway through Association III A, at 3.98 m depth, coinciding with the increased Cyperaceae and decreased Poaceae. The decrease in aquatic plants in this interval of fresher water could be explained by increased river flow, as most aquatic plants in the study area tend to prefer quiet water (USDA and NRCS, 2004). Trees also increase above this depth until the agricultural horizon, at which point everything except herbaceous plants decreases temporarily. The marsh surface area decreases to its lowest point in Association II, so the decreasing tree pollen in the uppermost section of Association III A reflects the beginning of this decrease in marshy areas. The ratio of arboreal pollen to non-arboreal pollen (AP:NAP) fluctuates throughout the core, but reaches its maximum just before the agricultural horizon, around which point it declines sharply, and only just begins to recover in the top 90 cm of the core before leveling out in the top 30 cm.

Core SJC6 shows a slight increase in Cyperaceae above 1.50 m depth, but does not show the dramatic variations between Cyperaceae and Poaceae seen in core SJB6. The lack of large fluctuations between salt tolerant and salt intolerant plants in the pre-settlement section of core can be explained by two facts about the site. First, SJC6 is located on a tributary creek instead of on the main branch and is located much closer to trees than SJB6, making it more likely that this site would receive greater amounts of tree pollen, obscuring any salinity signal from the grasses and sedges. This effect can be seen by dividing Cyperaceae pollen abundances by Poaceae pollen abundances to generate a "sedge-to-grass ratio" that magnifies the differences between salt-tolerant Poaceae and freshwater Cyperaceae. The resulting plots are shown in

Figure 4.9. The ratios in core SJB6 are much greater than those of cores SJC6 and RPC2, which both have trees in close proximity to the core location.

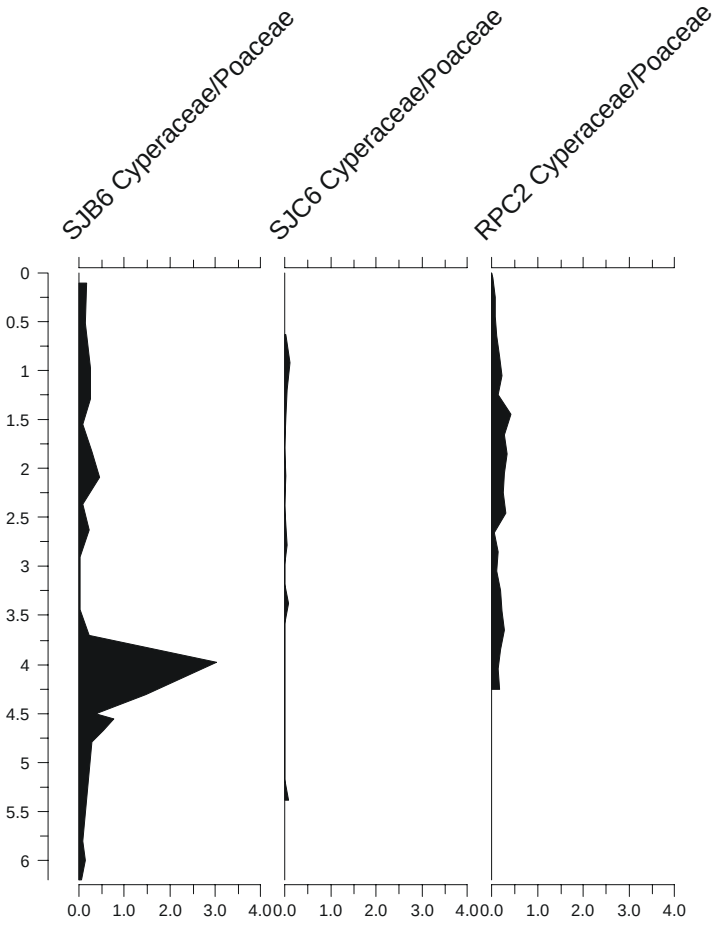

Figure 4.9 Cyperaceae-to-Poaceae ratios.

The second salient fact explaining the lower magnitude of variations in Poaceae and Cyperaceae involves the depositional history of the sites. The location for core SJC6 was intertidal for most of the past 3000 years (Wilson, 2005), so the relative amounts of airborne and waterborne pollen deposited at the site of SJC6 would have differed from that of mostly-supratidal core SJB6. This difference in pollen assemblage caused by different depositional environments is reflected in the placement of SJC6 samples almost exclusively by themselves on the PCA plots (Figure 4.6).

Arboreal pollen decreases dramatically after the agricultural horizon in core SJC6. Likewise, AP:NAP drops gradually throughout the whole sampled section of core, and only begins to rise again in the top 1 m. Poaceae reaches its highest amounts after the agricultural horizon, indicating higher salinity, which could have been caused by the channelization of the river that began in 1913. Channelization involved dredging a new straighter channel that cuts across meanders. This allows the tidal prism to penetrate farther upstream than before the operation, increasing salinity in upstream areas. Likewise, Cyperaceae have their zenith after the agricultural horizon. SJC6 is presently located away from the main branch of the river, allowing for more of the quiet water that aquatic plants tend to prefer (USDA and NRCS, 2004). The pollen record from core SJC6 shows much less salinity variation than in core SJB6 farther downstream, although this could be caused by the greater influx of arboreal pollen at the site.

Core RPC2 does not go back as far in time as SJB6 and SJC6, but it provides much more detail for the past 350 years. As mentioned above, there are two maxima, and two associated minima, in the oak:ragweed ratio in core RPC2. The

bottom one would correspond to the agricultural horizon, but the timing for the upper horizon is less clear. Suburbanization, according to state archaeology resources, began in Delaware as early as 1880, but it was not prevalent around the Dover area until the 1940s, when returning World War II veterans sought affordable housing, and Dover Air Force Base was built (Frucht, 1994). Arboreal pollen decreased slightly after the agricultural horizon, and decreased dramatically around the same time as a small blip on the oak:ragweed profile, at 2.65 m depth. AP increased steadily until it reached a post-settlement maximum between 2.10 m and 1.3 m depth, corresponding to Zone 2A. NAP has its lowest values after the agricultural horizon in this interval, as do the constituent herbaceous plants. Salinity variations are not in evidence at this site, even though it is the farthest upstream and currently located near the limit of saline influence. Like SJC6, core RPC2 is very close to a patch of woods, making it likely that any salinity signal is obscured by arboreal pollen influx. On the PCA plot of Components 1 and 2 (Figure 4.6), this interval plots in the same group as Association I C, medium-marshy with few open areas, indicating a temporary return to less-disturbed conditions in the vicinity of this core between 2.10 m and 1.3 m.

Paleoenvironmental Interpretation

Taken together, the results of pollen analysis, principal components analysis, cluster analysis, and sediment accumulation rate calculations enable formulation of a historical-era paleoecological reconstruction of the St. Jones River

area. Table 4.4 and Figure 4.10 summarize the ecological changes in the St. Jones River area through time.

Prior to 1600 AD, ecological change in the St. Jones River area was limited to natural causes and possibly occasional Native American activity. Sediment accumulation rates were generally low, on the order of 1-2 mm/yr. This time period, comprising Associations III A and III B, was marked by mostly continuous tracts of forest outside of the fringing marshes. Pollen diagrams for this interval show the highest amounts of arboreal pollen, including the greatest amounts of *Pinus*, *Quercus*, and *Carya*. Cleared areas were infrequent and occurred mostly in drier upland areas. They were caused by natural processes such as fires or tree falls, or by Native American tribes practicing their small-scale agricultural techniques.

Table 4.4 Summary of paleoecological changes in the St. Jones River area.

Time period (AD)	Extent of forest	Degree of clearance	Causes of clearance	River salinity
1900-2004	patchy	heavy	housing and industry	brackish early to saline late
1720-1900	almost nonexistent	heavy	agriculture and fuel wood	brackish
1600-1720	mostly continuous	occasional but increasing	agriculture and fuel wood	saline
prior to 1600	mostly continuous	minimal	fires, Native Americans	saline early to brackish late

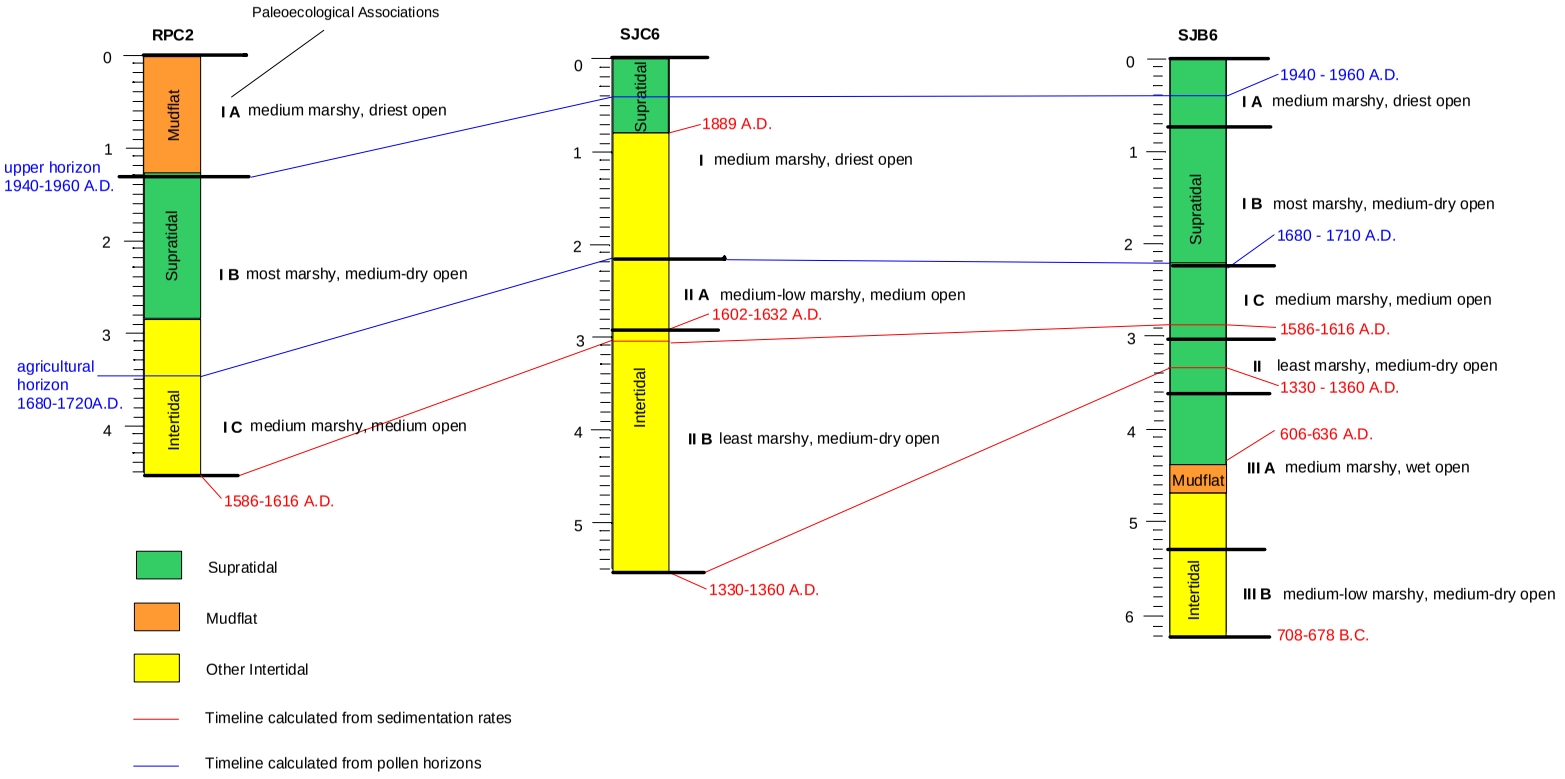

Figure 4.10 Summary diagram of paleoenvironmental interpretation. Dates in red are calculated from sediment accumulation rates, and dates in blue are from pollen horizons.

There was some variation in the extent of the fringing marshes, with a slight expansion during Association III A, as indicated by the PCA plots (Figure 4.6). This expansion roughly coincides with the halophyte radiation indicated by Wilson (2005) around 2000 YBP, when the depositional environment changed from intertidal to supratidal at a depth of 4.4 m in SJB6. Salinity of the St. Jones River freshened somewhat between 2000 and 1600 YBP, as evidenced by the increase in salt-intolerant Cyperaceae and concomitant decrease in halophytic Poaceae. The period from 1300 to 1600 is marked by a drastic difference in sediment thickness between cores SJB6 and SJC6. This period is represented by about 2.5 m of sediment in SJC6, whereas in SJB6 there is only 0.5 m of sediment for this period of time. The reason for this can be found in Wilson (2005). He reports an unconformity toward the bottom of core SJC6, which is shown to have been caused by migration of the river channel. The channel scoured through older sediments, and this channel later was filled in. The sediment in Association II B in core SJC6 represents the infilling of the paleochannel. Core SJB6 was not subject to these conditions at the same time, and therefore maintained a much lower sediment accumulation rate.

These results correspond well with other research done in the study area. Brush (1994) found varying intervals of wet periods and dry periods in a core from the St. Jones River. The period between 1000 and 2000 YBP was generally dry with frequent fires. Brush's pollen profiles show decreased arboreal pollen during this time period, which corresponds roughly with the upper part of Association III A, or Zone 3A in core SJB6. This zone has steadily decreasing amounts of arboreal pollen, and very low amounts of herbaceous plants. Cyperaceae abundances, however, rise to a sharp peak during this interval, whereas Cyperaceae do not change much in Brush's

work. Brush reports evidence of a very wet interval between 1200 and 650 YBP, as indicated by fossil seeds. Sedges, submerged aquatics, and emergent species are particularly abundant in the seed record after 1200 YBP, but they gradually decreased in occurrence upcore. The pollen profiles from SJB6 and SJC6 also show a decrease in the amount of sedges above Association III A, during an interval that roughly corresponds to Brush's wet interval. Association II in SJB6 and II B in SJC6 both have decreasing Cyperaceae abundance followed by none at all. Daniels (1993) focused his research in the St. Jones River area on much earlier time periods, but he does report wetter conditions in the area starting 2,800 YBP.

The period from 1600 to 1720, corresponding to Associations II and I C, was marked by European exploration and early settlement. Sediment accumulation rates in supratidal areas like the site of core SJB6 remained about 1.6 mm/yr, but the site of core SJC6 was intertidal at this time, with a sediment accumulation rate around 9.5 mm/yr. Primeval forests dominated the landscape early in this interval, but European settlers began to clear small plots toward the latter part of the seventeenth century. The earliest settlers in the area practiced small-scale agriculture based on slash-and-burn methods, with farm plots being moved as fertility decreased (Matlack, 1997a). The humus layer at 1.95 m in core SJB6 (Figure 3.1) may be related to this. By 1700, however, wheat had become a local specialty, and it was exported through Wilmington and Philadelphia, thus increasing pressure to create more agricultural fields (Matlack, 1997a). During this period, forests were also cut for fuelwood both for local inhabitants and to supply the larger cities (Matlack, 1997a). The PCA plot of Components 1 and 2 (Figure 4.6) shows different degrees of clearance in different cores, but the overall trend is of increasing clearance in relation to older samples.

Additionally, the oak:ragweed ratio begins to decrease slightly during this time period, another indicator of increasing forest clearance. Salinity increased in the downstream portion of the river during this time, as seen in a great increase in Poaceae abundance and concomitant decrease in Cyperaceae in core SJB6 during this interval. This same pattern was not observed in cores SJC6 and RPC2. It is possible that salinity remained steady in upstream areas, but a likelier explanation is that the greater amounts of tree pollen in SJC6 and RPC2 obscured any signal that could otherwise have been gleaned from the Poaceae and Cyperaceae abundances. Brush (1994) determined that conditions in the St. Jones River basin became drier after about 400 YBP, based on increased prevalence of seeds of plants that grow exclusively on dry ground, such as *Cephalanthus occidentalis* and *Rumex verticillata*. Although fossil seeds were not examined for this study, all three cores show less Cyperaceae and more Cheno-Ams after the agricultural horizon, giving potential support to Brush's findings of drier conditions. Willard et al. (2000;2003), in research in the Chesapeake Bay, infer a drier period punctuated by occasional wetter years starting prior to 450 YBP and ending around 200 YBP. These results were based on changes in benthic foraminiferal assemblages, with more salt-tolerant assemblages inferred to indicate higher bay salinity caused by lower precipitation influx into the bay.

From 1720 to 1900, ecological change in the study area was dominated by human influence. Matlack (1997a) reports that forest clearance had reached such a degree that wood shortages became a serious problem. There were actually restrictions against cutting any live trees, and it became more economical to import coal from Britain than to continue using wood for fuel (Matlack, 1997a). Eventually, wheat production shifted to the Mid-West, and most East Coast states saw forest

regeneration beginning in the late 1800s (Matlack, 1997a). Delaware farmers, however, switched to growing vegetables and chickens, thus postponing forest regrowth (Matlack, 1997a). This interval corresponds to Association I B. Sediment accumulation rates after the agricultural horizon were about 7.2 mm/yr in core SJB6, which was supratidal at the time, and 7.0 mm/yr in core SJC6, which was intertidal at the beginning of this time interval but became supratidal later. Core RPC2 has an overall sediment accumulation rate from the agricultural horizon to the present of about 11.2 mm/yr, but the sediment accumulation rate is only 8.7 mm/yr if the twentieth century sediment is excluded from the calculations. The PCA plot (Figure 4.6) shows that this interval was marked by great amounts of open area, and the highest amount of marsh surface area. The oak:ragweed ratio also indicates large amounts of open area, with extremely low values throughout this interval. AP:NAP remains low as well. Other regional studies (Willard et al., 2000; Brush and Davis, 1984) note high *Ambrosia* abundances and decreased *Quercus* abundances in sediments deposited after European settlement. River salinity decreased slightly at SJB6, as indicated by increased amounts of Cyperaceae with little change in Poaceae. Interestingly, Willard et al. (2000, 2003) found a period of decreased salinity, inferred to have been caused by increased precipitation, between 1800 and 1925 A.D.

The final period, 1900 to present, corresponds to Association I A. Sediment accumulation rates in cores SJB6 and SJC6, both supratidal by this point in time, are around 6 – 7 mm/yr. Core RPC2, an intertidal mudflat at this time, has a sediment accumulation rate between 19 and 28 mm/yr. Ecological change in the study area is again dominated by human activities. Some of the agricultural land was converted to estates earlier in the century, but large-scale development of previously

rural areas became increasingly prevalent after World War II (Matlack, 1997a). The oak:ragweed ratio stays low throughout this interval, but AP:NAP begins to rise again in the top few samples of each core. The increasing amounts of arboreal pollen indicate that forest regeneration began only in the last 30 years or so. Modern forests in Delaware tend to be limited to relatively small and narrow linear tracts of 30 to 60 hectares separated by agricultural land or commercial and residential development (Matlack, 1997a; Matlack, 1997b). Additionally, most of the current forests are dominated by successionally young species, with a concomitant lack of old regrowth and understory species, resulting in species impoverishment (Matlack, 1997b). River salinity as gauged by Cyperaceae and Poaceae increased slightly in downstream areas early in this period, but decreased again in very recent times. This last pulse of increased salinity was probably caused by channelization of the St. Jones River. In 1913 the river was dredged and straightened, allowing the tidal salt wedge to penetrate farther upstream. Maintenance dredging was performed every few years, with the last episode in 1931 (Wilson, oral communication). The results of this activity can be seen today in large stands of dead trees between the sites of core SJC6 and RPC2. Alternatively, Willard et al. (2000; 2003) report a dry period between 1920 and 1940, followed by a wetter period until about 1965. A short drought ended around 1980, after which conditions became much wetter into the present. These recent fluctuations in precipitation would have been at least regional in extent, and could have been sufficient to have caused the salinity changes seen in the St. Jones River as well.

The ecological changes seen in the St. Jones River cores after the time of European occupation have most likely been caused by human activities, and not by natural causes. The magnitude of changes in the relative abundances of *Ambrosia* and

Cheno-Ams before the agricultural horizon is much smaller than that seen after the agricultural horizon. *Pinus* and *Quercus* abundances clearly vary in different ways after the agricultural horizon than before. Additionally, the magnitude of the increases in sediment accumulation rates before and after the agricultural horizon are similar to those seen in other regional studies (Brush et al., 1982; Orson et al., 1990; Zaprowski, 1998). The biostratigraphic zonations derived from cluster analysis also indicate changes in the composition of the local plant community that coincide with the agricultural horizon. In all three cores, the dendograms link the samples above the agricultural horizon with the samples below it at the last step in the clustering process, indicating a dramatic difference between the two groups of samples. All these lines of evidence together indicate that the changes in sediment accumulation rates and the composition of the plant community that seem to be linked to European occupation were in fact caused by human activities, and cannot be adequately explained by natural variation.

Chapter 5

CONCLUSIONS

This study of the historical-era paleoecology of the St. Jones River area has yielded several important conclusions. First, the general agreement between pollen derived sediment accumulation rates and those derived from ^{14}C, ^{210}Pb, and ^{137}Cs indicates that pollen analysis is a valid means to determine datable horizons in recent sediments. The second conclusion is that sediment accumulation rates in the St. Jones River's fringing salt marshes have increased by a factor of about 4.5 since the arrival of European settlers, with variations based on depositional environments. Third, the pollen record provided general patterns of river salinity as well as the degree of forest clearance, leading to the possibility of more detailed studies comparing pollen analysis to other paleosalinity techniques.

Additionally, combining pollen analysis with a well established physical stratigraphy has led to a detailed ecological history of the study area, as micropaleontological analysis of pollen assemblages yields considerably greater temporal and paleoenvironmental resolution than lithostratigraphy alone. The paleoenvironmental history of the St. Jones River basin over the past 1000 years as seen in the pollen record is one of increasing disturbance of natural systems with increasing population growth. Prior to 1600 AD, ecological change in the St. Jones River area was limited to natural causes and occasional Native American activity.

Sediment accumulation rates were generally low, on the order of 1-2 mm/yr. This time period was marked by mostly continuous tracts of forest outside of the fringing marshes. Cleared areas were small and infrequent, being caused by natural processes such as fires or tree falls or by Native American tribes practicing small-scale agricultural techniques. There was some variation in the extent of the fringing marshes, with a slight expansion after 2000 YBP. Salinity of the St. Jones River freshened somewhat toward the end of this period.

The period from 1600 to 1720 was marked by European exploration and early settlement. Sediment accumulation rates in supratidal areas like the site of core SJB6 remained about 1.6 mm/yr, but the site of core SJC6 was intertidal at this time, with a sediment accumulation rate around 9.5 mm/yr. Primeval forests dominated the landscape early in this interval, but European settlers began to clear small plots toward the latter part of the seventeenth century. Salinity increased in the downstream portion of the river, but remained steady in the upstream areas.

From 1720 to 1900, ecological change in the study area is dominated by human influence, mostly extreme forest clearance. Sediment accumulation rates after the agricultural horizon were about 7.0 mm/yr in supratidal areas, and about 11 mm/yr in intertidal areas. This interval was marked by great amounts of open area, and the highest amount of marsh surface area. River salinity decreased slightly in downstream areas during this time period.

During the final period, from 1900 to present, sediment accumulation rates in supratidal areas were around 6 to 7 mm/yr, while intertidal sediment accumulation rates were between 19 and 28 mm/yr. Ecological change in the study area was still dominated by human activities. The increasing amounts of arboreal pollen indicate

that forest regrowth began only in the last 30 years or so. River salinity increased slightly in downstream areas early in this period, but has recently decreased again.

Appendix A

POLLEN COUNTS FOR CORE SJB6

Table A.1. Raw pollen counts for core SJB6.

Sample number	Depth (m)	Pinus	Quercus	Carya	Castanea	Juglans	Fagus	Corylus	Tsuga	Liquidambar	Betula	Salix	Acer	Nyssa	Alnus	Ulmus	Ostrya	Fraxinus	Ilex	Myrica	Poaceae	Ambrosia
0.10	0.10	222	134	9	1	1	0	1	2	4	2	0	2	0	8	2	5	4	2	0	89	42
0.51	0.51	218	104	25	1	3	0	4	2	5	1	0	1	0	14	0	11	7	0	2	89	37
0.97	0.97	162	70	10	1	1	4	0	0	2	1	1	0	0	6	1	11	3	0	0	99	26
1.29	1.29	116	58	9	1	3	0	0	5	5	3	1	1	1	8	1	13	1	0	0	110	65
1.55	1.55	226	126	16	5	5	0	1	3	2	2	3	1	0	13	2	3	1	1	5	88	71
1.82	1.82	180	73	14	8	1	0	1	1	6	2	0	0	1	8	1	5	0	0	3	91	83
2.09	2.09	202	164	23	7	0	1	1	3	2	5	0	2	0	20	0	20	2	0	1	97	35
2.36	2.36	188	163	20	7	2	0	2	2	7	2	1	1	0	11	3	6	4	0	2	114	16
2.63	2.63	254	182	21	1	0	2	0	4	3	4	1	0	0	9	0	4	2	1	4	85	7
2.90	2.90	154	140	30	1	0	0	0	4	8	5	1	1	1	5	1	3	2	0	1	198	2
3.17	3.17	162	187	18	4	0	0	0	3	0	2	1	0	2	6	1	2	2	0	1	179	0
3.44	3.44	174	152	22	0	1	3	0	1	3	5	1	1	1	6	0	4	1	0	0	178	3
3.71	3.71	162	225	26	2	0	0	0	5	4	3	0	0	0	8	0	6	5	0	0	233	1
3.98	3.98	174	186	24	5	1	0	2	4	5	4	1	2	0	6	2	6	3	0	2	90	4
4.31	4.31	144	209	24	1	0	0	2	6	5	2	1	1	0	9	2	6	2	0	0	87	2
4.50	4.50	60	176	26	2	2	0	4	2	2	3	0	0	0	4	0	5	4	0	1	176	3
4.56	4.56	36	199	45	2	0	0	2	2	2	2	0	3	0	2	1	2	2	0	0	102	4
4.68	4.68	54	104	35	2	0	0	0	0	3	4	0	1	0	4	1	2	3	0	0	137	1
4.80	4.80	88	153	28	3	0	0	0	1	0	0	1	0	0	2	1	0	2	0	0	169	3
5.80	5.80	228	102	5	0	0	0	0	0	2	1	0	1	0	0	0	2	2	0	0	130	1
6.00	6.00	258	107	7	3	0	0	0	1	3	1	0	3	0	2	1	3	5	0	0	89	0
6.20	6.20	178	83	7	1	0	0	0	1	1	1	2	2	0	3	0	2	2	0	0	58	1

Table A.1 continued

Sample number	Asteraceae	Cheno-Ams	Caryophyllaceae	Umbelliferae	Typha	Nuphar	Potamogeton	Cyperaceae 1	Cyperaceae 2	Cyperaceae (total)	Monolete ferns	Trilete ferns	Unidentifiable	beads	Pollen Sum	Total Palonomorphs	Palys / # of beads	beads / cc of sediment	Palys / cc of sediment
0.10	10	36	0	0	1	0	8	16	0	16	3	5	12	442	498	510	1.15	13759	15875.77
0.51	6	35	0	0	0	0	6	13	0	13	2	1	28	486	478	506	1.04	13759	14325.21
0.97	2	13	1	0	0	0	5	26	0	26	5	5	30	305	374	404	1.32	13759	18225.04
1.29	11	19	1	0	2	0	4	29	0	29	0	6	12	286	415	427	1.49	13759	20542.28
1.55	5	20	1	0	0	0	5	7	0	7	5	4	24	235	508	532	2.26	13759	31148.03
1.82	4	3	0	0	0	0	3	27	0	27	5	7	25	200	437	462	2.31	13759	31783.29
2.09	7	16	1	1	2	3	5	45	0	45	1	6	25	355	571	596	1.68	13759	23099.62
2.36	5	5	0	0	0	0	2	10	0	10	2	3	10	198	484	494	2.49	13759	34328.01
2.63	1	3	0	0	0	0	0	19	0	19	3	3	14	542	486	500	0.92	13759	12692.80
2.90	2	0	0	0	0	0	0	5	0	5	4	2	25	158	493	518	3.28	13759	45108.62
3.17	1	1	0	0	1	0	0	3	0	3	1	0	11	184	496	507	2.76	13759	37912.03
3.44	1	3	0	0	0	0	0	3	0	3	4	4	17	269	484	501	1.86	13759	25625.50
3.71	7	6	1	0	0	0	0	23	31	54	9	5	34	256	681	715	2.79	13759	38428.46
3.98	4	8	0	18	0	0	1	141	131	272	4	4	22	423	745	767	1.81	13759	24948.35
4.31	25	2	0	5	0	0	2	128	0	128	1	2	28	698	596	624	0.89	13759	12300.31
4.50	3	1	0	0	0	0	2	22	45	67	7	10	23	241	530	553	2.29	13759	31571.48
4.56	9	1	0	4	0	0	0	78	0	78	0	2	28	484	482	510	1.05	13759	14498.12
4.68	1	2	0	2	0	0	1	24	51	75	0	3	20	240	408	428	1.78	13759	24536.88
4.80	10	0	0	3	0	0	1	32	15	47	9	1	25	226	478	503	2.23	13759	30622.91
5.80	0	10	0	0	0	0	1	5	5	10	5	12	17	528	398	415	0.79	13759	10814.37
6.00	1	16	1	1	0	0	0	3	10	13	5	5	26	516	396	422	0.82	13759	11252.52
6.20	0	12	0	0	1	0	2	1	3	4	13	7	11	518	292	303	0.58	13759	8048.22

Table A.2 Proportion of pollen sum data for core SJB6.

Sample number	Depth (m)	Pinus	Quercus	Carya	Castanea	Juglans	Fagus	Corylus	Tsuga	Liquidambar	Betula	Salix	Acer	Nyssa	Alnus	Ulmus	Ostrya	Fraxinus	Ilex	Myrica	Poaceae	Ambrosia
0.10	0.10	22.29	26.91	1.81	0.20	0.20	0.00	0.20	0.40	0.80	0.40	0.00	0.40	0.00	1.61	0.40	1.00	0.80	0.40	0.00	17.87	8.43
0.51	0.51	22.80	21.76	5.23	0.21	0.63	0.00	0.84	0.42	1.05	0.21	0.00	0.21	0.00	2.93	0.00	2.30	1.46	0.00	0.42	18.62	7.74
0.97	0.97	21.66	18.72	2.67	0.27	0.27	1.07	0.00	0.00	0.53	0.27	0.27	0.00	0.00	1.60	0.27	2.94	0.80	0.00	0.00	26.47	6.95
1.29	1.29	13.98	13.98	2.17	0.24	0.72	0.00	0.00	1.20	1.20	0.72	0.24	0.24	0.24	1.93	0.24	3.13	0.24	0.00	0.00	26.51	15.66
1.55	1.55	22.24	24.80	3.15	0.98	0.98	0.00	0.20	0.59	0.39	0.39	0.59	0.20	0.00	2.56	0.39	0.59	0.20	0.20	0.98	17.32	13.98
1.82	1.82	20.59	16.70	3.20	1.83	0.23	0.00	0.23	0.23	1.37	0.46	0.00	0.00	0.23	1.83	0.23	1.14	0.00	0.00	0.69	20.82	18.99
2.09	2.09	17.69	28.72	4.03	1.23	0.00	0.18	0.18	0.53	0.35	0.88	0.00	0.35	0.00	3.50	0.00	3.50	0.35	0.00	0.18	16.99	6.13
2.36	2.36	19.42	33.68	4.13	1.45	0.41	0.00	0.41	0.41	1.45	0.41	0.21	0.21	0.00	2.27	0.62	1.24	0.83	0.00	0.41	23.55	3.31
2.63	2.63	26.13	37.45	4.32	0.21	0.00	0.41	0.00	0.82	0.62	0.82	0.21	0.00	0.00	1.85	0.00	0.82	0.41	0.21	0.82	17.49	1.44
2.90	2.90	15.62	28.40	6.09	0.20	0.00	0.00	0.00	0.81	1.62	1.01	0.20	0.20	0.20	1.01	0.20	0.61	0.41	0.00	0.20	40.16	0.41
3.17	3.17	16.33	37.70	3.63	0.81	0.00	0.00	0.00	0.60	0.00	0.40	0.20	0.00	0.40	1.21	0.20	0.40	0.40	0.00	0.20	36.09	0.00
3.44	3.44	17.98	31.40	4.55	0.00	0.21	0.62	0.00	0.21	0.62	1.03	0.21	0.21	0.21	1.24	0.00	0.83	0.21	0.00	0.00	36.78	0.62
3.71	3.71	11.89	33.04	3.82	0.29	0.00	0.00	0.00	0.73	0.59	0.44	0.00	0.00	0.00	1.17	0.00	0.88	0.73	0.00	0.00	34.21	0.15
3.98	3.98	11.68	24.97	3.22	0.67	0.13	0.00	0.27	0.54	0.67	0.54	0.13	0.27	0.00	0.81	0.27	0.81	0.40	0.00	0.27	12.08	0.54
4.31	4.31	12.08	35.07	4.03	0.17	0.00	0.00	0.34	1.01	0.84	0.34	0.17	0.17	0.00	1.51	0.34	1.01	0.34	0.00	0.00	14.60	0.34
4.50	4.50	5.66	33.21	4.91	0.38	0.38	0.00	0.75	0.38	0.38	0.57	0.00	0.00	0.00	0.75	0.00	0.94	0.75	0.00	0.19	33.21	0.57
4.56	4.56	3.73	41.29	9.34	0.41	0.00	0.00	0.41	0.41	0.41	0.41	0.00	0.62	0.00	0.41	0.21	0.41	0.41	0.00	0.00	21.16	0.83
4.68	4.68	6.62	25.49	8.58	0.49	0.00	0.00	0.00	0.00	0.74	0.98	0.00	0.25	0.00	0.98	0.25	0.49	0.74	0.00	0.00	33.58	0.25
4.80	4.80	9.21	32.01	5.86	0.63	0.00	0.00	0.00	0.21	0.00	0.00	0.21	0.00	0.00	0.42	0.21	0.00	0.42	0.00	0.00	35.36	0.63
5.80	5.80	28.64	25.63	1.26	0.00	0.00	0.00	0.00	0.00	0.50	0.25	0.00	0.25	0.00	0.00	0.00	0.50	0.50	0.00	0.00	32.66	0.25
6.00	6.00	32.58	27.02	1.77	0.76	0.00	0.00	0.00	0.25	0.76	0.25	0.00	0.76	0.00	0.51	0.25	0.76	1.26	0.00	0.00	22.47	0.00
6.20	6.20	30.48	28.42	2.40	0.34	0.00	0.00	0.00	0.34	0.34	0.34	0.68	0.68	0.00	1.03	0.00	0.68	0.68	0.00	0.00	19.86	0.34

Table A.2 continued

Sample number	Asteraceae	Cheno-Ams	Caryophyllaceae	Umbelliferae	Typha	Nuphar	Potamogeton	Cyperaceae 1	Cyperaceae 2	Cyperaceae (total)	Monolete ferns	Trilete ferns	Unidentifiable	Oak / Ragweed	AP	NAP	AP / NAP	Trees	Shrubs	Herbaceous plants	Aquatics	Ferns
0.10	2.01	7.23	0.00	0.00	0.20	0.00	1.61	3.21	0.00	3.21	0.60	1.00	2.41	3.19	57.43	42.57	1.35	57.43	0.40	35.54	5.02	1.61
0.51	1.26	7.32	0.00	0.00	0.00	0.00	1.26	2.72	0.00	2.72	0.42	0.21	5.86	2.811	60.04	39.96	1.50	60.04	0.42	34.94	3.97	0.63
0.97	0.53	3.48	0.27	0.00	0.00	0.00	1.34	6.95	0.00	6.95	1.34	1.34	8.02	2.692	51.34	48.66	1.05	51.34	0.00	37.70	8.29	2.67
1.29	2.65	4.58	0.24	0.00	0.48	0.00	0.96	6.99	0.00	6.99	0.00	1.45	2.89	0.892	40.48	59.52	0.68	40.48	0.00	49.64	8.43	1.45
1.55	0.98	3.94	0.20	0.00	0.00	0.00	0.98	1.38	0.00	1.38	0.98	0.79	4.72	1.775	58.27	41.73	1.40	58.27	1.18	36.42	2.36	1.77
1.82	0.92	0.69	0.00	0.00	0.00	0.00	0.69	6.18	0.00	6.18	1.14	1.60	5.72	0.88	48.28	51.72	0.93	48.28	0.69	41.42	6.86	2.75
2.09	1.23	2.80	0.18	0.18	0.35	0.53	0.88	7.88	0.00	7.88	0.18	1.05	4.38	4.686	61.47	38.53	1.60	61.47	0.18	27.50	9.63	1.23
2.36	1.03	1.03	0.00	0.00	0.00	0.00	0.41	2.07	0.00	2.07	0.41	0.62	2.07	10.19	67.15	32.85	2.04	67.15	0.41	28.93	2.48	1.03
2.63	0.21	0.62	0.00	0.00	0.00	0.00	0.00	3.91	0.00	3.91	0.62	0.62	2.88	26	74.07	25.93	2.86	74.07	1.03	19.75	3.91	1.23
2.90	0.41	0.00	0.00	0.00	0.00	0.00	0.00	1.01	0.00	1.01	0.81	0.41	5.07	70	56.59	43.41	1.30	56.59	0.20	40.97	1.01	1.22
3.17	0.20	0.20	0.00	0.00	0.20	0.00	0.00	0.60	0.00	0.60	0.20	0.00	2.22	#####	62.30	37.70	1.65	62.30	0.20	36.49	0.81	0.20
3.44	0.21	0.62	0.00	0.00	0.00	0.00	0.00	0.62	0.00	0.62	0.83	0.83	3.51	50.67	59.50	40.50	1.47	59.50	0.00	38.22	0.62	1.65
3.71	1.03	0.88	0.15	0.00	0.00	0.00	0.00	3.38	4.55	7.93	1.32	0.73	4.99	225	53.60	46.40	1.16	53.60	0.00	36.42	7.93	2.06
3.98	0.54	1.07	0.00	2.42	0.00	0.00	0.13	18.93	17.58	36.51	0.54	0.54	2.95	46.5	45.37	54.63	0.83	45.37	0.27	16.64	36.64	1.07
4.31	4.19	0.34	0.00	0.84	0.00	0.00	0.34	21.48	0.00	21.48	0.17	0.34	4.70	104.5	57.38	42.62	1.35	57.38	0.00	20.30	21.81	0.50
4.50	0.57	0.19	0.00	0.00	0.00	0.00	0.38	4.15	8.49	12.64	1.32	1.89	4.34	58.67	49.06	50.94	0.96	49.06	0.19	34.53	13.02	3.21
4.56	1.87	0.21	0.00	0.83	0.00	0.00	0.00	16.18	0.00	16.18	0.00	0.41	5.81	49.75	58.51	41.49	1.41	58.51	0.00	24.90	16.18	0.41
4.68	0.25	0.49	0.00	0.49	0.00	0.00	0.25	5.88	12.50	18.38	0.00	0.74	4.90	104	45.59	54.41	0.84	45.59	0.00	35.05	18.63	0.74
4.80	2.09	0.00	0.00	0.63	0.00	0.00	0.21	6.69	3.14	9.83	1.88	0.21	5.23	51	49.16	50.84	0.97	49.16	0.00	38.70	10.04	2.09
5.80	0.00	2.51	0.00	0.00	0.00	0.00	0.25	1.26	1.26	2.51	1.26	3.02	4.27	102	57.54	42.46	1.36	57.54	0.00	35.43	2.76	4.27
6.00	0.25	4.04	0.25	0.25	0.00	0.00	0.00	0.76	2.53	3.28	1.26	1.26	6.57	#####	66.92	33.08	2.02	66.92	0.00	27.27	3.28	2.53
6.20	0.00	4.11	0.00	0.00	0.34	0.00	0.68	0.34	1.03	1.37	4.45	2.40	3.77	83	66.44	33.56	1.98	66.44	0.00	24.32	2.40	6.85

Appendix B

POLLEN COUNTS FOR SJC6

Table B.1 Raw pollen counts for core SJC6.

Sample number	Depth (m)	Pinus	Quercus	Carya	Castanea	Juglans	Corylus	Tsuga	Picea	Liquidambar	Betula	Salix	Acer	Nyssa	Alnus	Ulmus	Ostrya	Fraxinus	Tilia	Ilex	Poaceae	Ambrosia
0.63	0.63	208	125	16	1	1	0	0	0	8	9	2	0	0	5	2	6	1	1	0	110	32
0.92	0.92	110	85	17	1	2	0	0	0	1	4	2	1	0	7	0	1	0	0	0	100	22
1.20	1.20	76	96	6	3	2	0	0	0	1	6	4	0	0	4	0	2	1	0	0	111	25
1.49	1.49	106	98	13	3	0	0	0	0	1	7	4	0	0	6	0	4	2	0	1	218	21
1.78	1.78	128	102	11	1	0	0	0	0	1	4	0	1	0	6	1	3	0	0	0	188	21
2.08	2.08	112	115	10	1	0	0	0	0	1	5	1	0	0	5	0	4	2	0	1	100	36
2.38	2.38	196	178	21	0	0	0	0	0	0	8	1	1	1	10	0	6	2	0	0	118	8
2.58	2.58	242	178	22	1	1	0	1	0	1	3	0	2	2	11	0	2	1	0	0	100	8
2.78	2.78	216	174	11	2	0	0	2	0	1	4	0	0	0	10	1	4	3	0	0	93	7
2.98	2.98	216	184	25	3	2	0	0	0	3	7	0	0	1	13	1	4	3	0	0	97	3
3.18	3.18	204	214	15	0	2	0	0	0	2	6	1	2	3	6	0	5	3	0	0	82	4
3.38	3.38	202	184	26	1	0	1	1	4	4	8	1	1	0	15	0	8	8	0	3	78	4
3.58	3.58	232	201	24	2	3	0	0	0	3	10	0	1	1	3	0	5	2	0	0	77	9
3.78	3.78	206	188	22	1	4	0	0	0	0	8	0	0	0	8	0	5	0	0	0	108	6
3.98	3.98	214	221	27	3	0	0	0	0	1	4	0	0	0	4	1	3	2	0	1	82	6
4.18	4.18	176	211	31	4	2	0	0	0	3	18	0	2	0	3	1	7	0	0	0	82	10
4.38	4.38	230	227	23	0	1	0	0	0	2	12	1	2	1	6	1	6	2	0	2	71	5
4.58	4.58	190	227	36	2	1	0	1	0	1	12	0	0	1	2	0	5	1	0	0	73	5
4.78	4.78	222	227	32	2	1	0	0	0	2	11	0	0	0	7	1	4	3	0	0	61	4
4.98	4.98	146	235	36	2	1	0	0	0	3	11	0	0	0	3	1	3	1	1	0	76	4
5.18	5.18	206	247	27	1	2	0	1	0	1	8	0	0	0	4	0	3	4	1	0	58	6
5.38	5.38	198	222	22	5	2	0	3	6	7	3	1	3	0	7	0	7	8	0	1	66	6

Table B.1 continued

Sample number	Asteraceae	Cheno-Ams	Umbelliferae	Plantago	Labiatae	Typha	Potamogeton	Cyperaceae 1	Cyperaceae 2	Cyperaceae(total)	Monolete ferns	Trilete ferns	Unidentifiable	beads	PollenSum	Total Palynomorphs	Palys / # of beads	beads / cc of sediment	Palys / cc of sediment
0.63	1	12	0	0	0	1	0	3	0	3	2	5	13	35	447	460	13.14	16139	212112.57
0.92	1	8	0	1	0	0	0	10	0	10	2	3	15	33	323	338	10.24	16139	165302.48
1.20	0	6	0	0	0	0	0	6	0	6	4	2	18	32	317	335	10.47	16139	168955.16
1.49	3	9	0	0	0	1	0	2	5	7	3	1	20	41	455	475	11.59	16139	186976.22
1.78	0	29	1	0	0	0	0	0	2	2	7	3	18	40	445	463	11.58	16139	186808.93
2.08	2	9	0	0	0	0	0	1	1	2	0	2	14	71	352	366	5.15	16139	83195.41
2.38	0	16	0	0	0	0	0	0	0	0	6	5	21	17	479	500	29.41	16139	474676.47
2.58	0	5	0	0	0	0	0	0	3	3	4	8	17	21	474	491	23.38	16139	377345.19
2.78	2	6	0	0	0	0	0	0	6	6	1	3	17	36	438	455	12.64	16139	203979.03
2.98	2	6	0	0	0	0	0	0	0	0	6	3	20	23	471	491	21.35	16139	344532.57
3.18	2	7	0	0	0	0	0	0	1	1	3	3	23	54	463	486	9.00	16139	145251.00
3.38	6	10	1	0	0	0	0	2	4	6	2	3	21	24	476	497	20.71	16139	334211.79
3.58	2	7	0	0	0	0	0	0	1	1	1	5	18	63	473	491	7.79	16139	125781.73
3.78	2	13	0	0	0	0	2	0	0	0	4	2	12	22	476	488	22.18	16139	357992.36
3.98	1	11	1	0	1	1	0	0	0	0	9	4	15	55	490	505	9.18	16139	148185.36
4.18	2	5	0	0	2	0	0	0	0	0	5	7	19	60	483	502	8.37	16139	135029.63
4.38	1	3	1	0	0	0	0	0	0	0	5	5	14	61	492	506	8.30	16139	133874.33
4.58	1	7	1	0	0	0	0	1	0	1	5	7	10	50	484	494	9.88	16139	159453.32
4.78	0	5	0	0	0	0	0	0	0	0	3	3	9	36	477	486	13.50	16139	217876.50
4.98	2	7	0	0	0	0	0	1	0	1	3	8	20	62	471	491	7.92	16139	127810.47
5.18	1	4	0	0	0	0	0	0	0	0	4	5	10	80	480	490	6.13	16139	98851.38
5.38	1	4	1	0	0	1	1	0	5	5	2	5	16	32	488	504	15.75	16139	254189.25

Table B.2 Proportion of pollen sum data for core SJC6.

Sample number	Depth (m)	Pinus	Quercus	Carya	Castanea	Juglans	Corylus	Tsuga	Picea	Liquidambar	Betula	Salix	Acer	Nyssa	Alnus	Ulmus	Ostrya	Fraxinus	Tilia	Ilex	Poaceae	Ambrosia	Asteraceae	Cheno-Ams
0.63	0.63	23.27	27.96	3.58	0.22	0.22	0.00	0.00	0.00	1.79	2.01	0.45	0.00	0.00	1.12	0.45	1.34	0.22	0.22	0.00	24.61	7.16	0.22	2.68
0.92	0.92	17.03	26.32	5.26	0.31	0.62	0.00	0.00	0.00	0.31	1.24	0.62	0.31	0.00	2.17	0.00	0.31	0.00	0.00	0.00	30.96	6.81	0.31	2.48
1.20	1.20	11.99	30.28	1.89	0.95	0.63	0.00	0.00	0.00	0.32	1.89	1.26	0.00	0.00	1.26	0.00	0.63	0.32	0.00	0.00	35.02	7.89	0.00	1.89
1.49	1.49	11.65	21.54	2.86	0.66	0.00	0.00	0.00	0.00	0.22	1.54	0.88	0.00	0.00	1.32	0.00	0.88	0.44	0.00	0.22	47.91	4.62	0.66	1.98
1.78	1.78	14.38	22.92	2.47	0.22	0.00	0.00	0.00	0.00	0.22	0.90	0.00	0.22	0.00	1.35	0.22	0.67	0.00	0.00	0.00	42.25	4.72	0.00	6.52
2.08	2.08	15.91	32.67	2.84	0.28	0.00	0.00	0.00	0.00	0.28	1.42	0.28	0.00	0.00	1.42	0.00	1.14	0.57	0.00	0.28	28.41	10.23	0.57	2.56
2.38	2.38	20.46	37.16	4.38	0.00	0.00	0.00	0.00	0.00	0.00	1.67	0.21	0.21	0.21	2.09	0.00	1.25	0.42	0.00	0.00	24.63	1.67	0.00	3.34
2.58	2.58	25.53	37.55	4.64	0.21	0.21	0.00	0.21	0.00	0.21	0.63	0.00	0.42	0.42	2.32	0.00	0.42	0.21	0.00	0.00	21.10	1.69	0.00	1.05
2.78	2.78	24.66	39.73	2.51	0.46	0.00	0.00	0.46	0.00	0.23	0.91	0.00	0.00	0.00	2.28	0.23	0.91	0.68	0.00	0.00	21.23	1.60	0.46	1.37
2.98	2.98	22.93	39.07	5.31	0.64	0.42	0.00	0.00	0.00	0.64	1.49	0.00	0.00	0.21	2.76	0.21	0.85	0.64	0.00	0.00	20.59	0.64	0.42	1.27
3.18	3.18	22.03	46.22	3.24	0.00	0.43	0.00	0.00	0.00	0.43	1.30	0.22	0.43	0.65	1.30	0.00	1.08	0.65	0.00	0.00	17.71	0.86	0.43	1.51
3.38	3.38	21.22	38.66	5.46	0.21	0.00	0.21	0.21	0.84	0.84	1.68	0.21	0.21	0.00	3.15	0.00	1.68	1.68	0.00	0.63	16.39	0.84	1.26	2.10
3.58	3.58	24.52	42.49	5.07	0.42	0.63	0.00	0.00	0.00	0.63	2.11	0.00	0.21	0.21	0.63	0.00	1.06	0.42	0.00	0.00	16.28	1.90	0.42	1.48
3.78	3.78	21.64	39.50	4.62	0.21	0.84	0.00	0.00	0.00	0.00	1.68	0.00	0.00	0.00	1.68	0.00	1.05	0.00	0.00	0.00	22.69	1.26	0.42	2.73
3.98	3.98	21.84	45.10	5.51	0.61	0.00	0.00	0.00	0.00	0.20	0.82	0.00	0.00	0.00	0.82	0.20	0.61	0.41	0.00	0.20	16.73	1.22	0.20	2.24
4.18	4.18	18.22	43.69	6.42	0.83	0.41	0.00	0.00	0.00	0.62	3.73	0.00	0.41	0.00	0.62	0.21	1.45	0.00	0.00	0.00	16.98	2.07	0.41	1.04
4.38	4.38	23.37	46.14	4.67	0.00	0.20	0.00	0.00	0.00	0.41	2.44	0.20	0.41	0.20	1.22	0.20	1.22	0.41	0.00	0.41	14.43	1.02	0.20	0.61
4.58	4.58	19.63	46.90	7.44	0.41	0.21	0.00	0.21	0.00	0.21	2.48	0.00	0.00	0.21	0.41	0.00	1.03	0.21	0.00	0.00	15.08	1.03	0.21	1.45
4.78	4.78	23.27	47.59	6.71	0.42	0.21	0.00	0.00	0.00	0.42	2.31	0.00	0.00	0.00	1.47	0.21	0.84	0.63	0.00	0.00	12.79	0.84	0.00	1.05
4.98	4.98	15.50	49.89	7.64	0.42	0.21	0.00	0.00	0.00	0.64	2.34	0.00	0.00	0.00	0.64	0.21	0.64	0.21	0.21	0.00	16.14	0.85	0.42	1.49
5.18	5.18	21.46	51.46	5.63	0.21	0.42	0.00	0.21	0.00	0.21	1.67	0.00	0.00	0.00	0.83	0.00	0.63	0.83	0.21	0.00	12.08	1.25	0.21	0.83
5.38	5.38	20.29	45.49	4.51	1.02	0.41	0.00	0.61	1.23	1.43	0.61	0.20	0.61	0.00	1.43	0.00	1.43	1.64	0.00	0.20	13.52	1.23	0.20	0.82

Table B.2 continued

Sample number	Umbelliferae	Plantago	Labiatae	Typha	Potamogeton	Cyperaceae 1	Cyperaceae 2	Cyperaceae(total)	Monolete ferns	Trilete ferns	Unidentifiable	Oak/Ragweed	AP	NAP	AP / NAP	Trees	Shrubs	Herbaceous plants	Aquatics	Ferns
0.63	0.00	0.00	0.00	0.22	0.00	0.67	0.00	0.67	0.45	1.12	2.91	3.91	62.86	37.14	1.69	62.86	0.00	34.68	0.89	1.57
0.92	0.00	0.31	0.00	0.00	0.00	3.10	0.00	3.10	0.62	0.93	4.64	3.86	54.49	45.51	1.20	54.49	0.00	40.87	3.10	1.55
1.20	0.00	0.00	0.00	0.00	0.00	1.89	0.00	1.89	1.26	0.63	5.68	3.84	51.42	48.58	1.06	51.42	0.00	44.79	1.89	1.89
1.49	0.00	0.00	0.00	0.22	0.00	0.44	1.10	1.54	0.66	0.22	4.40	4.67	41.98	58.02	0.72	41.98	0.22	55.16	1.76	0.88
1.78	0.22	0.00	0.00	0.00	0.00	0.00	0.45	0.45	1.57	0.67	4.04	4.86	43.60	56.40	0.77	43.60	0.00	53.71	0.45	2.25
2.08	0.00	0.00	0.00	0.00	0.00	0.28	0.28	0.57	0.00	0.57	3.98	3.19	56.82	43.18	1.32	56.82	0.28	41.76	0.57	0.57
2.38	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.25	1.04	4.38	22.25	68.06	31.94	2.13	68.06	0.00	29.65	0.00	2.30
2.58	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.63	0.84	1.69	3.59	22.25	73.00	27.00	2.70	73.00	0.00	23.84	0.63	2.53
2.78	0.00	0.00	0.00	0.00	0.00	0.00	1.37	1.37	0.23	0.68	3.88	24.86	73.06	26.94	2.71	73.06	0.00	24.66	1.37	0.91
2.98	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.27	0.64	4.25	61.33	75.16	24.84	3.03	75.16	0.00	22.93	0.00	1.91
3.18	0.00	0.00	0.00	0.00	0.00	0.00	0.22	0.22	0.65	0.65	4.97	53.50	77.97	22.03	3.54	77.97	0.00	20.52	0.22	1.30
3.38	0.21	0.00	0.00	0.00	0.00	0.42	0.84	1.26	0.42	0.63	4.41	46.00	76.26	23.74	3.21	76.26	0.63	20.80	1.26	1.05
3.58	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.21	0.21	1.06	3.81	22.33	78.44	21.56	3.64	78.44	0.00	20.08	0.21	1.27
3.78	0.00	0.00	0.00	0.00	0.42	0.00	0.00	0.00	0.84	0.42	2.52	31.33	71.22	28.78	2.47	71.22	0.00	27.10	0.42	1.26
3.98	0.20	0.00	0.20	0.20	0.00	0.00	0.00	0.00	1.84	0.82	3.06	36.83	76.12	23.88	3.19	76.12	0.20	20.82	0.20	2.65
4.18	0.00	0.00	0.41	0.00	0.00	0.00	0.00	0.00	1.04	1.45	3.93	21.10	76.60	23.40	3.27	76.60	0.00	20.91	0.00	2.48
4.38	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.02	1.02	2.85	45.40	81.10	18.90	4.29	81.10	0.41	16.46	0.00	2.03
4.58	0.21	0.00	0.00	0.00	0.00	0.21	0.00	0.21	1.03	1.45	2.07	45.40	79.34	20.66	3.84	79.34	0.00	17.98	0.21	2.48
4.78	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.63	0.63	1.89	56.75	84.07	15.93	5.28	84.07	0.00	14.68	0.00	1.26
4.98	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.21	0.64	1.70	4.25	58.75	78.56	21.44	3.66	78.56	0.00	18.90	0.21	2.34
5.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.83	1.04	2.08	41.17	83.75	16.25	5.15	83.75	0.00	14.38	0.00	1.88
5.38	0.20	0.00	0.00	0.20	0.20	0.00	1.02	1.02	0.41	1.02	3.28	37.00	80.94	19.06	4.25	80.94	0.20	15.98	1.43	1.43

Appendix C

POLLEN COUNTS FOR CORE RPC2

Table C.1 Raw pollen counts for core RPC2.

Sample number	Depth (m)	Pinus	Quercus	Carya	Castanea	Juglans	Fagus	Corylus	Tsuga	Liquidambar	Betula	Salix	Acer	Nyssa	Alnus	Ulmus	Ostrya	Fraxinus	Tilia	Platanus	Ilex	Myrica	Poaceae	Ambrosia	Asteraceae
0.00	0.00	172	140	12	0	1	0	2	4	12	10	5	5	0	5	4	4	3	0	0	1	0	73	27	3
0.05	0.05	168	140	8	2	4	0	2	3	6	9	8	2	0	14	1	7	3	0	0	0	0	99	22	6
0.25	0.25	202	147	9	4	1	0	1	3	3	8	5	3	1	6	0	8	1	0	0	1	0	94	30	3
0.45	0.45	226	106	17	0	0	0	1	5	5	7	3	1	0	11	1	2	6	1	0	3	0	88	34	6
0.65	0.65	134	99	11	0	2	0	2	1	1	8	3	5	1	19	0	2	4	0	0	0	0	80	59	5
0.85	0.85	154	102	17	3	4	0	0	1	2	3	0	1	0	26	0	3	1	0	0	3	1	100	49	5
1.05	1.05	178	97	26	1	0	0	1	2	1	1	3	3	0	12	0	3	5	0	0	1	0	93	60	6
1.25	1.25	128	100	21	2	0	0	0	1	2	4	1	4	2	15	3	6	2	0	0	3	0	133	35	8
1.45	1.45	184	169	34	0	0	0	0	2	2	8	0	3	1	29	0	5	0	0	0	0	0	73	4	3
1.65	1.65	188	151	23	4	0	0	1	1	2	4	2	2	1	25	0	5	7	1	0	1	0	83	1	5
1.85	1.85	202	170	21	0	1	0	1	5	2	10	1	6	0	19	0	3	2	0	0	2	0	74	5	7
2.05	2.05	218	160	32	2	3	0	1	6	7	6	0	3	2	18	3	9	12	0	1	2	0	75	4	13
2.25	2.25	120	136	15	3	0	2	1	3	3	8	4	2	3	44	1	7	4	0	0	11	0	115	37	5
2.45	2.45	120	117	20	3	2	2	0	2	3	6	6	6	1	40	0	6	5	0	0	3	0	84	43	8
2.65	2.65	28	76	9	0	0	0	0	0	1	4	0	2	3	18	1	5	3	0	0	6	0	130	5	4
2.85	2.85	100	157	13	4	1	1	2	3	4	3	4	6	4	79	1	6	1	0	0	4	0	78	29	5
3.05	3.05	108	109	15	1	1	0	2	3	4	5	9	4	6	61	3	7	5	0	0	9	0	99	53	19
3.25	3.25	62	135	17	0	0	3	0	3	1	6	2	4	4	75	1	9	3	0	0	10	0	81	51	3
3.45	3.45	88	145	20	3	1	0	0	1	5	5	5	8	3	60	0	8	7	0	0	9	0	87	37	15
3.65	3.65	218	177	26	2	2	1	1	2	2	3	4	4	2	22	1	5	4	0	0	4	0	93	4	5
3.85	3.85	152	173	35	2		0	1	1	1	3	2	5	3	41	0	6	8	0	0	3	1	95	11	3
4.05	4.05	192	189	29	5	2	0	1	4	1	7	0	5	1	29	2	5	4	0	0	2	0	74	6	9
4.25	4.25	184	206	19	3	2	1	0	1	2	6	2	2	2	23	2	5	5	0	0	2	0	76	7	3

Table C.1 continued

Sample number	Cheno-Ams	Impatiens	Amaryllidaceae	Plantago	Polygonaceae	Labiatae	Caryophyllaceae	Umbelliferae	Typha	Nuphar	Potamogeton	Cyperaceae 1	Cyperaceae 2	Cyperaceae(total)	Monolete ferns	Trilete ferns	Unidentifiable	beads	Pollen Sum	Total Palynomorphs	Palys / # of beads	beads / cc of sediment	Palys / cc of sediment
0.00	67	0	0	0	0	0	0	0	0	0	1	0	0	0	5	2	20	57	472	492	8.63	16805	145053.68
0.05	43	0	0	0	0	0	0	0	0	0	5	1	1	2	2	4	16	67	476	492	7.34	16805	123403.88
0.25	45	0	0	0	0	0	1	1	0	0	1	3	5	8	4	2	19	54	491	510	9.44	16805	158713.89
0.45	48	0	0	0	0	0	0	2	1	1	1	4	4	8	5	3	18	67	479	497	7.42	16805	124657.99
0.65	51	1	0	0	0	0	0	3	0	1	0	2	7	9	4	5	20	78	443	463	5.94	16805	99752.76
0.85	9	0	0	0	0	0	0	4	0	3	0	8	9	17	6	3	23	48	440	463	9.65	16805	162098.23
1.05	9	1	0	0	0	0	0	4	2	3	0	14	8	22	7	5	24	85	457	481	5.66	16805	95096.53
1.25	10	2	1	2	0	0	0	1	3	1	0	11	9	20	5	8	22	86	459	481	5.59	16805	93990.76
1.45	10	8	0	0	1	0	0	1	1	2	0	14	17	31	5	4	23	48	488	511	10.65	16805	178903.23
1.65	3	3	0	0	0	1	0	1	0	2	0	11	12	23	6	9	22	33	461	483	14.64	16805	245964.09
1.85	5	1	0	0	0	0	0	2	0	0	0	10	16	26	7	7	13	34	478	491	14.44	16805	242683.97
2.05	7	1	0	0	0	1	1	0	0	2	0	15	6	21	11	11	14	43	523	537	12.49	16805	209867.09
2.25	3	1	0	0	0	0	2	1	1	4	0	22	8	30	5	12	19	58	523	542	9.34	16805	157039.83
2.45	2	1	0	0	0	0	0	0	1	2	0	21	4	25	8	12	21	72	468	489	6.79	16805	114133.96
2.65	4	2	1	0	0	0	0	0	0	0	0	4	2	6	0	0	13	98	294	307	3.13	16805	52644.23
2.85	2	0	0	1	0	0	0	0	0	2	1	0	12	12	8	9	17	42	490	507	12.07	16805	202860.36
3.05	2	0	0	1	0	0	0	2	0	2	0	1	11	12	7	12	11	40	507	518	12.95	16805	217624.75
3.25	1	3	0	0	0	0	0	2	0	1	1	2	15	17	10	9	22	69	483	505	7.32	16805	122993.12
3.45	0	0	0	1	0	0	0	1	0	3	2	2	17	19	11	11	21	42	511	532	12.67	16805	212863.33
3.65	0	0	0	0	0	0	0	0	2	1	1	8	17	25	13	16	17	26	531	548	21.08	16805	354197.69
3.85	7	3	0	0	0	0	0	0	0	2	1	8	11	19	7	11	20	30	520	540	18.00	16805	302490.00
4.05	9	1	0	0	0	0	0	0	0	2	1	3	7	10	8	15	21	33	517	538	16.30	16805	273972.42
4.25	5	0	0	0	0	0	0	3	0	2	0	4	9	13	9	9	16	22	502	518	23.55	16805	395681.36

Table C.2 Proportion of pollen sum data for core RPC2.

Sample number	Depth (m)	Pinus	Quercus	Carya	Castanea	Juglans	Fagus	Corylus	Tsuga	Liquidambar	Betula	Salix	Acer	Nyssa	Alnus	Ulmus	Ostrya	Fraxinus	Tilia	Platanus	Ilex	Myrica
0.00	0.00	18.22	29.66	2.54	0.00	0.21	0.00	0.42	0.85	2.54	2.12	1.06	1.06	0.00	1.06	0.85	0.85	0.64	0.00	0.00	0.21	0.00
0.05	0.05	17.65	29.41	1.68	0.42	0.84	0.00	0.42	0.63	1.26	1.89	1.68	0.42	0.00	2.94	0.21	1.47	0.63	0.00	0.00	0.00	0.00
0.25	0.25	20.57	29.94	1.83	0.81	0.20	0.00	0.20	0.61	0.61	1.63	1.02	0.61	0.20	1.22	0.00	1.63	0.20	0.00	0.00	0.20	0.00
0.45	0.45	23.59	22.13	3.55	0.00	0.00	0.00	0.21	1.04	1.04	1.46	0.63	0.21	0.00	2.30	0.21	0.42	1.25	0.21	0.00	0.63	0.00
0.65	0.65	15.12	22.35	2.48	0.00	0.45	0.00	0.45	0.23	0.23	1.81	0.68	1.13	0.23	4.29	0.00	0.45	0.90	0.00	0.00	0.00	0.00
0.85	0.85	17.50	23.18	3.86	0.68	0.91	0.00	0.00	0.23	0.45	0.68	0.00	0.23	0.00	5.91	0.00	0.68	0.23	0.00	0.00	0.68	0.23
1.05	1.05	19.47	21.23	5.69	0.22	0.00	0.00	0.22	0.44	0.22	0.22	0.66	0.66	0.00	2.63	0.00	0.66	1.09	0.00	0.00	0.22	0.00
1.25	1.25	13.94	21.79	4.58	0.44	0.00	0.00	0.00	0.22	0.44	0.87	0.22	0.87	0.44	3.27	0.65	1.31	0.44	0.00	0.00	0.65	0.00
1.45	1.45	18.85	34.63	6.97	0.00	0.00	0.00	0.00	0.41	0.41	1.64	0.00	0.61	0.20	5.94	0.00	1.02	0.00	0.00	0.00	0.00	0.00
1.65	1.65	20.39	32.75	4.99	0.87	0.00	0.00	0.22	0.22	0.43	0.87	0.43	0.43	0.22	5.42	0.00	1.08	1.52	0.22	0.00	0.22	0.00
1.85	1.85	21.13	35.56	4.39	0.00	0.21	0.00	0.21	1.05	0.42	2.09	0.21	1.26	0.00	3.97	0.00	0.63	0.42	0.00	0.00	0.42	0.00
2.05	2.05	20.84	30.59	6.12	0.38	0.57	0.00	0.19	1.15	1.34	1.15	0.00	0.57	0.38	3.44	0.57	1.72	2.29	0.00	0.19	0.38	0.00
2.25	2.25	11.47	26.00	2.87	0.57	0.00	0.38	0.19	0.57	0.57	1.53	0.76	0.38	0.57	8.41	0.19	1.34	0.76	0.00	0.00	2.10	0.00
2.45	2.45	12.82	25.00	4.27	0.64	0.43	0.43	0.00	0.43	0.64	1.28	1.28	1.28	0.21	8.55	0.00	1.28	1.07	0.00	0.00	0.64	0.00
2.65	2.65	4.76	25.85	3.06	0.00	0.00	0.00	0.00	0.00	0.34	1.36	0.00	0.68	1.02	6.12	0.34	1.70	1.02	0.00	0.00	2.04	0.00
2.85	2.85	10.20	32.04	2.65	0.82	0.20	0.20	0.41	0.61	0.82	0.61	0.82	1.22	0.82	16.12	0.20	1.22	0.20	0.00	0.00	0.82	0.00
3.05	3.05	10.65	21.50	2.96	0.20	0.20	0.00	0.39	0.59	0.79	0.99	1.78	0.79	1.18	12.03	0.59	1.38	0.99	0.00	0.00	1.78	0.00
3.25	3.25	6.42	27.95	3.52	0.00	0.00	0.62	0.00	0.62	0.21	1.24	0.41	0.83	0.83	15.53	0.21	1.86	0.62	0.00	0.00	2.07	0.00
3.45	3.45	8.61	28.38	3.91	0.59	0.20	0.00	0.00	0.20	0.98	0.98	0.98	1.57	0.59	11.74	0.00	1.57	1.37	0.00	0.00	1.76	0.00
3.65	3.65	20.53	33.33	4.90	0.38	0.38	0.19	0.19	0.38	0.38	0.56	0.75	0.75	0.38	4.14	0.19	0.94	0.75	0.00	0.00	0.75	0.00
3.85	3.85	14.62	33.27	6.73	0.38	0.00	0.00	0.19	0.19	0.19	0.58	0.38	0.96	0.58	7.88	0.00	1.15	1.54	0.00	0.00	0.58	0.19
4.05	4.05	18.57	36.56	5.61	0.97	0.39	0.00	0.19	0.77	0.19	1.35	0.00	0.97	0.19	5.61	0.39	0.97	0.77	0.00	0.00	0.39	0.00
4.25	4.25	18.33	41.04	3.78	0.60	0.40	0.20	0.00	0.20	0.40	1.20	0.40	0.40	0.40	4.58	0.40	1.00	1.00	0.00	0.00	0.40	0.00

Table C.2 continued

Sample number	Poaceae	Ambrosia	Asteraceae	Cheno-Ams	Impatiens	Amaryllidaceae	Plantago	Polygonaceae	Labiatae	Caryophyllaceae	Umbelliferae	Typha	Nuphar	Potamogeton	Cyperaceae 1	Cyperaceae 2	Cyperaceae(total)	Monolete ferns	Trilete ferns	Unidentifiable
0.00	15.47	5.72	0.64	14.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.00	0.00	0.00	1.06	0.42	4.24
0.05	20.80	4.62	1.26	9.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.05	0.21	0.21	0.42	0.42	0.84	3.36
0.25	19.14	6.11	0.61	9.16	0.00	0.00	0.00	0.00	0.00	0.20	0.20	0.00	0.00	0.20	0.61	1.02	1.63	0.81	0.41	3.87
0.45	18.37	7.10	1.25	10.02	0.00	0.00	0.00	0.00	0.00	0.00	0.42	0.21	0.21	0.21	0.84	0.84	1.67	1.04	0.63	3.76
0.65	18.06	13.32	1.13	11.51	0.23	0.00	0.00	0.00	0.00	0.00	0.68	0.00	0.23	0.00	0.45	1.58	2.03	0.90	1.13	4.51
0.85	22.73	11.14	1.14	2.05	0.00	0.00	0.00	0.00	0.00	0.00	0.91	0.00	0.68	0.00	1.82	2.05	3.86	1.36	0.68	5.23
1.05	20.35	13.13	1.31	1.97	0.22	0.00	0.00	0.00	0.00	0.00	0.88	0.44	0.66	0.00	3.06	1.75	4.81	1.53	1.09	5.25
1.25	28.98	7.63	1.74	2.18	0.44	0.22	0.44	0.00	0.00	0.00	0.22	0.65	0.22	0.00	2.40	1.96	4.36	1.09	1.74	4.79
1.45	14.96	0.82	0.61	2.05	1.64	0.00	0.00	0.20	0.00	0.00	0.20	0.20	0.41	0.00	2.87	3.48	6.35	1.02	0.82	4.71
1.65	18.00	0.22	1.08	0.65	0.65	0.00	0.00	0.00	0.22	0.00	0.22	0.00	0.43	0.00	2.39	2.60	4.99	1.30	1.95	4.77
1.85	15.48	1.05	1.46	1.05	0.21	0.00	0.00	0.00	0.00	0.00	0.42	0.00	0.00	0.00	2.09	3.35	5.44	1.46	1.46	2.72
2.05	14.34	0.76	2.49	1.34	0.19	0.00	0.00	0.00	0.19	0.19	0.00	0.00	0.38	0.00	2.87	1.15	4.02	2.10	2.10	2.68
2.25	21.99	7.07	0.96	0.57	0.19	0.00	0.00	0.00	0.00	0.38	0.19	0.19	0.76	0.00	4.21	1.53	5.74	0.96	2.29	3.63
2.45	17.95	9.19	1.71	0.43	0.21	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.43	0.00	4.49	0.85	5.34	1.71	2.56	4.49
2.65	44.22	1.70	1.36	1.36	0.68	0.34	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	1.36	0.68	2.04	0.00	0.00	4.42
2.85	15.92	5.92	1.02	0.41	0.00	0.00	0.20	0.00	0.00	0.00	0.00	0.00	0.41	0.20	0.00	2.45	2.45	1.63	1.84	3.47
3.05	19.53	10.45	3.75	0.39	0.00	0.00	0.20	0.00	0.00	0.00	0.39	0.00	0.39	0.00	0.20	2.17	2.37	1.38	2.37	2.17
3.25	16.77	10.56	0.62	0.21	0.62	0.00	0.00	0.00	0.00	0.00	0.41	0.00	0.21	0.21	0.41	3.11	3.52	2.07	1.86	4.55
3.45	17.03	7.24	2.94	0.00	0.00	0.00	0.20	0.00	0.00	0.00	0.20	0.00	0.59	0.39	0.39	3.33	3.72	2.15	2.15	4.11
3.65	17.51	0.75	0.94	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.19	0.19	1.51	3.20	4.71	2.45	3.01	3.20
3.85	18.27	2.12	0.58	1.35	0.58	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.38	0.19	1.54	2.12	3.65	1.35	2.12	3.85
4.05	14.31	1.16	1.74	1.74	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.39	0.19	0.58	1.35	1.93	1.55	2.90	4.06
4.25	15.14	1.39	0.60	1.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.00	0.40	0.00	0.80	1.79	2.59	1.79	1.79	3.19

Table C.2 continued

Sample number	Oak/Ragweed	AP	NAP	AP / NAP	Trees	Shrubs	Herbaceous plants	Aquatics	Ferns
0.00	5.19	62.08	37.92	1.64	62.08	0.21	36.02	0.21	1.48
0.05	6.36	61.55	38.45	1.60	61.55	0.00	35.71	1.47	1.26
0.25	4.90	61.30	38.70	1.58	61.30	0.20	35.44	1.83	1.22
0.45	3.12	58.25	41.75	1.40	58.25	0.63	37.16	2.30	1.67
0.65	1.68	50.79	49.21	1.03	50.79	0.00	44.92	2.26	2.03
0.85	2.08	54.55	45.45	1.20	54.55	0.91	37.95	4.55	2.05
1.05	1.62	53.39	46.61	1.15	53.39	0.22	37.86	5.91	2.63
1.25	2.86	49.46	50.54	0.98	49.46	0.65	41.83	5.23	2.83
1.45	42.25	70.70	29.30	2.41	70.70	0.00	20.49	6.97	1.84
1.65	#####	70.07	29.93	2.34	70.07	0.22	21.04	5.42	3.25
1.85	34.00	71.55	28.45	2.51	71.55	0.42	19.67	5.44	2.93
2.05	40.00	71.51	28.49	2.51	71.51	0.38	19.50	4.40	4.21
2.25	3.68	56.60	43.40	1.30	56.60	2.10	31.36	6.69	3.25
2.45	2.72	59.62	40.38	1.48	59.62	0.64	29.49	5.98	4.27
2.65	15.20	46.26	53.74	0.86	46.26	2.04	49.66	2.04	0.00
2.85	5.41	69.18	30.82	2.25	69.18	0.82	23.47	3.06	3.47
3.05	2.06	57.00	43.00	1.33	57.00	1.78	34.71	2.76	3.75
3.25	2.65	60.87	39.13	1.56	60.87	2.07	29.19	3.93	3.93
3.45	3.92	61.64	38.36	1.61	61.64	1.76	27.59	4.70	4.31
3.65	44.25	69.11	30.89	2.24	69.11	0.75	19.21	5.46	5.46
3.85	15.73	68.65	31.35	2.19	68.65	0.77	22.88	4.23	3.46
4.05	31.50	73.50	26.50	2.77	73.50	0.39	19.15	2.51	4.45
4.25	29.43	74.30	25.70	2.89	74.30	0.40	18.73	2.99	3.59

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