Effects of Land-Use History on Sedimentation in the Potomac Estuary, Maryland

A Water-Quality Study of the Tidal Potomac River and Estuary

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By RUTH S. DEFRIES

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FOREWORD

Tidal rivers and estuaries are very important features of the Coastal Zone because of their immense biological productivity and their proximity to centers of commerce and population. Most of the shellfish and much of the local finfish consumed by man are harvested from estuaries and tidal rivers. Many of the world's largest shipping ports are located within estuaries. Many estuaries originate as river valleys drowned by rising sea level and are geologically ephemeral features, destined eventually to fill with sediments. Nutrients, heavy metals, and organic chemicals are often associated with the sediments trapped in estuaries. Part of the trapped nutrients may be recycled to the water column, exacerbating nutrient-enrichment problems caused by local sewage treatment plants, and promoting undesirable algae growth. The metals and organics may be concentrated in the food chain, further upsetting the ecology and threatening the shell and finfish harvests. Our knowledge of the processes governing these phenomena is limited and the measurements needed to improve our understanding are scarce.

In response to an increasing awareness of the importance and delicate ecological balance of tidal rivers and estuaries, the U.S. Geological Survey began a 5-year interdisciplinary study of the tidal Potomac River and Estuary in October of 1977. The study encompassed elements of both the Water Resources Divisions's ongoing Research and River Quality Assessment Programs. The Division has been conducting research on various elements of the hydrologic cycle since 1894 and began intense investigation of estuarine processes in San Francisco Bay in 1968. The River Quality Assessment program began in 1973 at the suggestion of the Advisory Committee on Water Data for Public Use which saw a special need to develop suitable information for river-basin planning and water-quality management. The Potomac assessment was the first to focus on a tidal river and estuary. In addition to conducting research into the processes governing water-quality conditions in tidal rivers and estuaries, the ultimate goals of the Potomac Estuary Study were to aid water-quality management decision-making for the Potomac, and to provide other groups with a rational and well-documented general approach for the study of tidal rivers and estuaries.

This interdisciplinary effort emphasized studies of the transport of the major nutrient species and of suspended sediment. The movement of these substances through five major reaches or control volumes of the tidal Potomac River and Estuary was determined during 1980 and 1981. This effort provided a framework on which to assemble a variety of investigations:

1. The generation and deposition of sediments, nutrients, and trace metals from the Holocene to the present was determined by sampling surficial bottom sediments and analyzing their characteristics and distributions.
2. Bottom-sediment geochemistry was studied and the effects of benthic exchange processes on water-column nutrient concentrations ascertained.
3. Current-velocity and water-surface-elevation data were collected to calibrate and verify a series of one- and two-dimensional hydrodynamic flow and transport models.
4. Measurements from typical urban and rural watersheds were extrapolated to provide estimates of the nonpoint sources of sediments, nutrients, and biochemical oxygen demand during 1980 and 1981.
5. Intensive summertime studies were conducted to determine the effects of local sewage-treatment-plant effluents on dissolved-oxygen levels in the tidal Potomac River.
6. Species, numbers, and net productivity of phytoplankton were determined to evaluate their effect on nutrients and dissolved oxygen.
7. Wetland studies were conducted to determine the present-day distribution and abundance of submersed aquatic vegetation, and to ascertain the important water-quality and sediment parameters influencing this distribution.
8. Repetitive samples were collected to document the distribution and abundance of the macrobenthic infaunal species of the tidal river and estuary and to determine the effects of changes in environmental conditions on this distribution and abundance.

The reports in this Water-Supply Paper series document the technical aspects of the above investigations. The series also contains an overall introduction to the study, an integrated technical summary of the results, and an executive summary which links the results with aspects of concern to water-quality managers.

Philip Cohen
Chief Hydrologist

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Potomac Study Coordinator

CONTENTS

FIGURES

TABLES

A WATER-QUALITY STUDY OF THE TIDAL POTOMAC RIVER AND ESTUARY

Effects of Land-Use History on Sedimentation in the Potomac Estuary, Maryland

By Ruth S. DeFries

Abstract

Pollen assemblages preserved in 20 sediment cores collected throughout the Potomac Estuary record the land-use history of the lower Potomac drainage basin. A slight increase in the proportion of ragweed, an agricultural weed, dates the 1634 initial European settlement, and a large increase in the proportion of ragweed dates extensive land clearance accompanying the 1840 agricultural revival. The presence of water-chestnut seeds indicates the water-chestnut infestation around 1930.

Dated horizons in the cores are used to calculate sedimentation rates and sediment fluxes, which vary from 0.21 to 1.72 centimeters per annum and from 0.09 to 1.14 grams per square centimeter per annum. Fairly constant pollen concentrations with depth indicate that European settlement did not affect sedimentation rates in the mouth of the estuary, and that intensive construction activities, beginning in the 1950's, also did not affect sedimentation rates throughout much of the estuary. The effects of human activity in the drainage basin on sedimentation apparently are confined to local areas. Areal distribution of a local pollen type in five cores from the Port Tobacco subestuary indicates that about 75 percent of the fine-grained sediment entering the head of the subestuary is deposited in the upper one-third of the subestuary, and little is transported to the Potomac Estuary. The subestuaries thus are depositional areas for sediment associated with accelerated erosion from land use in the drainage basin.

Sedimentation rates generally are slow in the lower reach of the Potomac Estuary and rapid in the freshwater upper reach as well as in the middle estuary around Kettle Bottom Shoals. Circulation patterns, changes in competence of currents in the estuary, shore erosion, or landward transport of sediment from the Chesapeake Bay may be more important controls on sedimentation patterns in the estuary than land use in the drainage basin.

INTRODUCTION

The Potomac River is the second largest tributary of the Chesapeake Bay Estuary, the largest estuary on the Atlantic Coast of the United States. The bay is a classic example of a drowned-river-valley estuary, formed when the latest rise in sea level, associated with the most recent retreat of the glaciers, inundated the Susquehanna River and its tributaries 8,000 to 10,000 years ago (Wolman, 1968). The estuarine part of the Potomac River is defined as extending to the Fall Line near Washington, D.C., about 170 km upstream from Chesapeake Bay.

The Potomac Estuary (fig. 1), which broadens from 0.6 km at Washington, D.C., to 10 km at the mouth, can be divided into three reaches: the upper reach from Chain Bridge to Indian Head, the middle reach from Indian Head to the U.S. Highway 301 bridge at Morgantown, and the lower reach from Morgantown to Point Lookout. The upper reach is freshwater (limnetic); the middle reach is the transition between fresh- and brackish water (oligohaline); and the lower reach is brackish (mesohaline) (Lippson and others, 1979). Because salinity distributions vary seasonally and daily owing to tidal intrusions and local weather conditions, boundaries of the three reaches do not remain stationary (Mason and Flynn, 1976).

The Potomac Estuary's watershed has undergone substantial changes in land use since it was settled by Europeans in the late 17th century. Gottschalk (1945) relates excessive erosion from agricultural activities in the drainage basin to siltation of navigable waterways and to downstream migration of the head of tidewater. Froomer (1980) notes that siltation from European settlement caused an increase of flood plain and marsh areas in the heads of several estuaries on the western shore of the Chesapeake Bay. Williams (1977) relates urbanization to the filling of the Potomac near Washington, D.C.

This study used palynological evidence to assess the effects of European settlement and construction activities in the drainage basin on sedimentation in the Potomac Estuary. Analysis of pollen grains preserved in sediment cores provides a method for dating sediment and calculating sedimentation rates. Pollen grains in sediments reflect vegetation in the surrounding area at the time of deposition of sediment. A change in vegetation, such as major land clearance for agriculture, is recorded in the pollen record by an increase

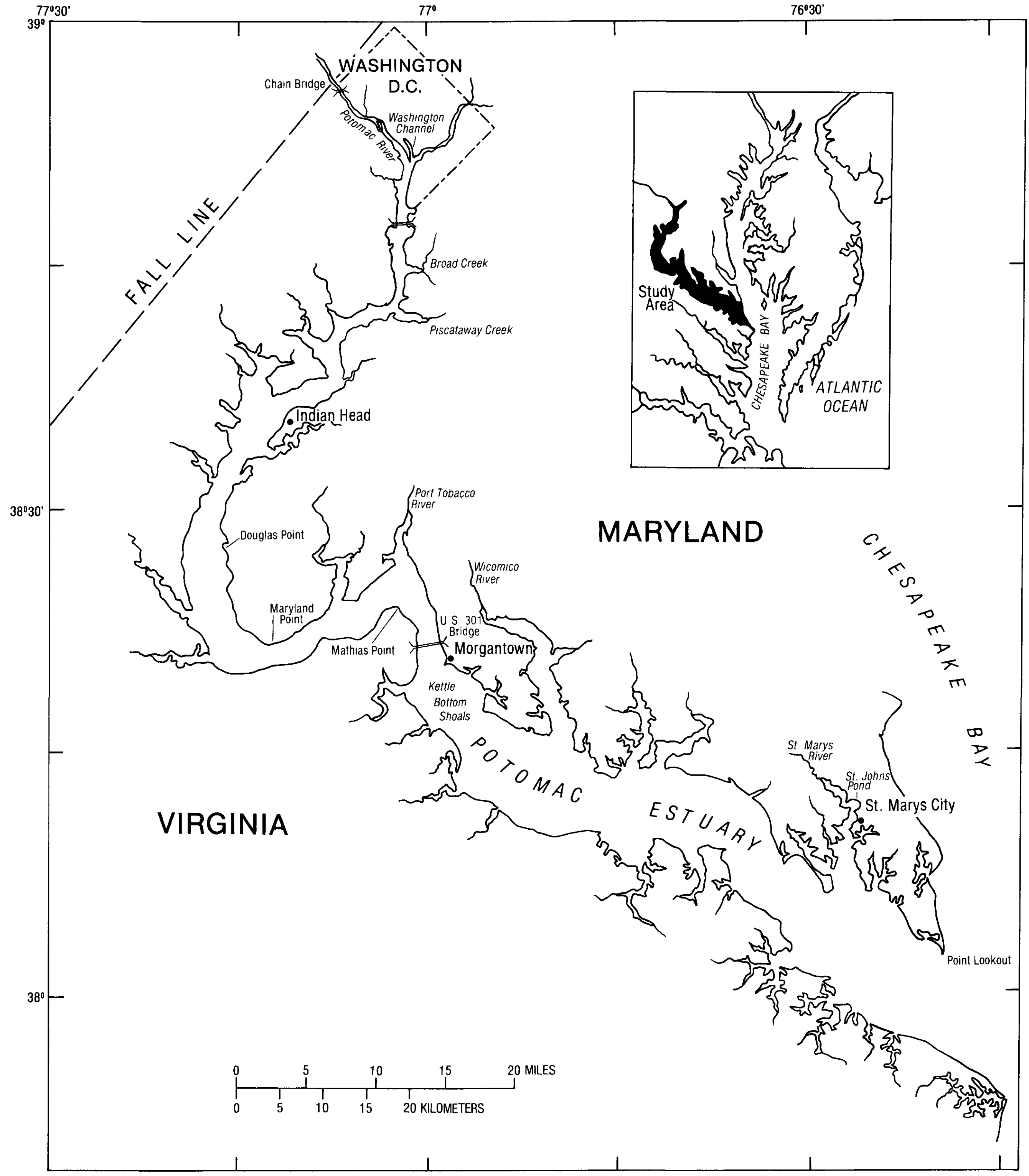

Figure 1. Potomac Estuary

in the proportion of agricultural weeds. Because these agricultural activities are datable by independent historical evidence, the date of the changing pollen assemblage and corresponding sediment can be determined. Sedimentation rates can then be calculated on the basis of successive dated horizons in the cores. Assuming constant pollen input, pollen concentrations indicate changes in sedimentation rates since European settlement. In addition, certain pollen types are equivalent to labeled particles that can be used to trace the path of movement of hydraulically equivalent fine-grained sediment; this path can indicate where excess sediment resulting from land clearance in the drainage basin is deposited. The land-use history of the Potomac drainage basin seaward from the Fall Line (lower Potomac drainage basin), particularly the area of land cleared, is essential to dating pollen assemblages in the sediment cores.

The author thanks G.S. Brush, Johns Hopkins University, for guiding the research, J.L. Glenn for contributing helpful suggestions, and T.C. Winter and J.P. Bradbury for reviewing the paper.

LAND-USE HISTORY OF THE LOWER POTOMAC DRAINAGE BASIN

Prior to European settlement, Indians had been cultivating the land surrounding the Potomac River for, presumably, thousands of years. Because of their agricultural techniques and sparse population, the extent to which they disturbed the forest cover probably was minimal. Semmes (1929) estimates that, when the Europeans first arrived, 1,500 Indians inhabited the area on the Maryland side of the Potomac from the mouth of the estuary to what is now Washington, D.C. Including the Virginia side of the river, there probably were only a few thousand Indians alongside the Potomac Estuary. The Indians employed a slash-and-burn agricultural technique. They cleared the forest and planted crops such as maize, tobacco, beans, peas, and pumpkins, in mounds 30 to 50 cm in diameter and about 1 m apart. When the productivity of the soil decreased, the Indians left it fallow for a period and cleared another field (Herndon, 1967). Because no ground was broken between mounds, minimal soil loss was associated with this planting technique.

The first permanent settlement along the Potomac Estuary was established in 1634 on the east bank of St. Marys River at St. Marys City (fig. 1). Some of the settlers crossed the Potomac to settle along the banks of the Virginia side of the river; in 1639, a Jesuit mission from St. Marys City traveled farther up the Potomac and established a settlement on the Port Tobacco River (fig. 1) (Hayden, 1945). At first, the early colonists cultivated grains by Indian methods. After a few years, the mother country encouraged the production of tobacco, which was to become the most important crop of the colonial times (1634–1776).

Throughout most of the 17th century, Tidewater (Coastal Plain) Virginia and Maryland enjoyed a profitable period of tobacco cultivation. The general practice at this time was to clear fresh land and grow tobacco until the yield decreased enough to make cultivation unprofitable, usually after three or four growing seasons. The farmers paid little attention to soil conservation as long as land was abundant (Bruce, 1896; Craven, 1925). During the last decades of the 17th century, a glutted tobacco market, unfavorable economic conditions, and decreasing areas of fresh land available for expansion ended the previous period of prosperity. Farmers, searching for fertile lands, left the Tidewater area and, in the first quarter of the 18th century, moved across the Fall Line into the Piedmont (Craven, 1925).

The one-crop system of tobacco cultivation required an abundance of land; however, the percentage of total land actually planted at any one time was not large relative to the percentage of total land cleared in the 19th century. The proportion of planted fields on the plantations at any one time was barely one-fifth of the total land cleared, while the remaining fields were lying fallow (Bruce, 1896). Froomer (1978) calculates that the entire tobacco crop from southern Maryland in 1720 was grown on 71 km^2, or 1.4 percent of the total land area in southern Maryland. At the time of the American Revolution (1776), the reported tobacco crop was grown on 3.6 percent of the total land area in southern Maryland.

During the antebellum period (1776–1860), land use in the lower Potomac basin shifted from tobacco monoculture to diversified farming with improved methods of cultivation. The soil-exhausting practices of tobacco cultivation continued into the 19th century, although gentlemen farmers made an effort to upgrade agricultural methods (Craven, 1925). A decrease in the price of tobacco after the War of 1812 and an increase in the price of wheat stimulated farmers to adopt a more diversified agriculture (Eaton, 1949). During the 1830's, most farmers began applying the new techniques developed by the gentlemen farmers. Land values increased, production increased, and emigration slackened (Turner, 1952). Tidewater Virginia abandoned tobacco growing altogether in favor of a scientific cultivation of wheat, whereas Maryland used tobacco in a system of general farming and continued its export (Gray, 1933). In 1840, the Tidewater region of Virginia and Maryland was experiencing an agricultural revival; by the time the Civil War broke out, "Virginia and Maryland were in the best agricultural condition they had ever been" (Craven, 1925, p. 122).

Emigration preceding the agricultural revival in the counties bordering the Potomac Estuary is reflected in the decrease in total population between 1790 (when the U.S. census began) and 1840 (fig. 2). Except in the years immediately after the Civil War (1870's), the population began an upward trend after 1840. In 1850, when the census of agriculture began, the area was in the midst of the agricultural revival, and the percentage of total land area cleared for

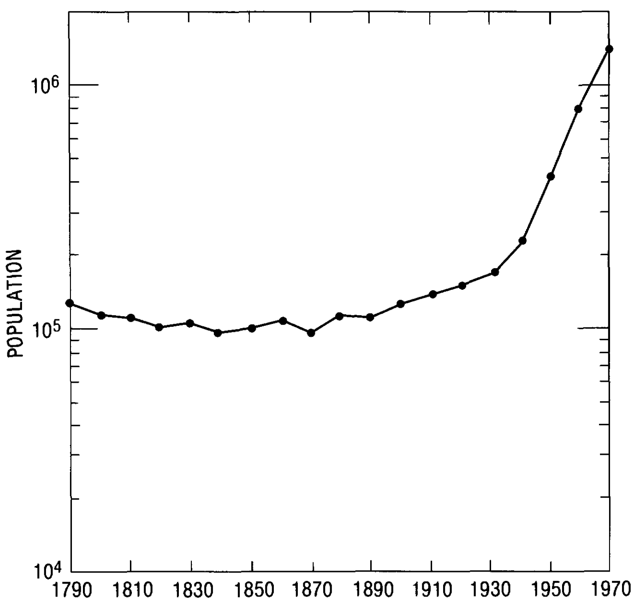

Figure 2. Population change for all Virginia and Maryland counties bordering the Potomac Estuary, 1790–1970. Modified from DeFries (1980, p. 35–41).

farms was about 43 percent (fig. 3). This percentage decreased between 1850 and the time of the Civil War (1865).

During the post-Civil War period [1865–present (1980)], agriculture in the Tidewater area of Maryland and Virginia generally decreased. Although Maryland resumed tobacco cultivation after the Civil War, the State never regained the level of production of the colonial and antebellum periods. The grain products that were cultivated in Tidewater Maryland and Virginia could not compete with products from the Midwest, and agriculture in this area lost its national economic importance (Shannon, 1945; Bruchey, 1974). The percentage of total land area cleared for farms decreased from 43 percent in 1850 to 37 percent in 1870 (fig. 3); it increased to 46 percent by the turn of the century, but followed a downward trend thereafter.

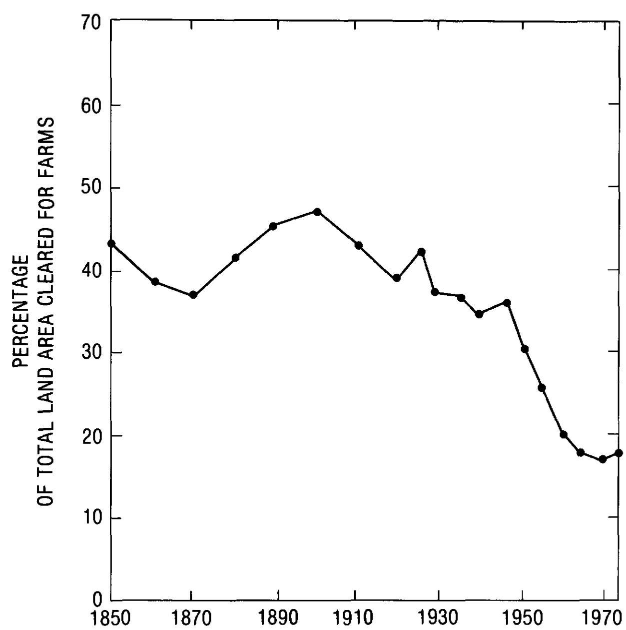

Figure 3. Percentge of total land area cleared for farms for all Virginia and Maryland counties bordering the Potomac Estuary, 1850–1974. Modified from DeFries (1980, p. 35–41).

After 1940, rapid urbanization took place around Washington, D.C. (Allee and others, 1976). Today, the Tidewater counties, which are more sparsely populated than the metropolitan area, support a tobacco, soybean, and general produce truck farming (Mason and Flynn, 1976). The area today is about 40 percent forested (G.S. Brush, Johns Hopkins University, oral commun., 1980).

In summary, soil disturbance probably was minimal during the period of Indian agriculture (?–1634), owing to sparse population and to the Indians' method of cultivation. During the time of the Colonies (1634–1776), a one-crop system of tobacco cultivation dominated the area. Although this system depended on availability of fresh land, only one-fifth of each plantation was cultivated at any one time; therefore, a maximum of 20 percent of the land was cleared. According to estimates based on crop yields, only 1.4 percent to 3.6 percent of the total land area was cleared during this time. Tobacco cultivation continued during the antebellum period (1776–1860). Around 1840, the area experienced an agricultural revival when farmers adopted diversified agriculture and scientific methods of cultivation. During 1850, 43 percent of the land was cleared for farms. In the decades after the Civil War, agricultural production diminished, and the percentage of land area cleared for farms decreased to 37 percent in 1870. This percentage increased from 1870 to around the turn of the century, but decreased thereafter. Industrialization and urbanization occurred during the later part of this period, particularly around the Washington, D.C., metropolitan area.

POLLEN AS A STRATIGRAPHIC TOOL

Pollen grains that settle in a depositional environment are a reflection of parent vegetation. Cutting and clearing of forests by European settlers for agriculture are accompanied by a corresponding change in pollen assemblage, that is, an increase in agricultural weeds (*Ambrosia* spp.) in proportion to arboreal pollen types. Clearing of forests is datable by independent historical evidence presented in the preceding section, so the increase in the percentage of ragweed (*Ambrosia*) pollen provides a dated, stratigraphic horizon.

Pollen analysis in North America has been used mainly for detecting environmental changes as registered by pollen assemblages in Pleistocene and Holocene sediments (Davis, 1967a; Wright, 1972; Davis and others, 1975).

However, some stratigraphic pollen-analysis work has been done in more recent sediments to detect the human effect on vegetational assemblages. Davis (1976), studying the effect of land use on sedimentation rates in a small lake in southeastern Michigan, found that the percentages of ragweed pollen increased abruptly and substantially (from practically 0 to 15–40 percent of total pollen grains) with the change from forest to farmland. She also found an increase in ragweed percentages corresponding to forest clearance in sediments from a lake in Connecticut (Davis, 1967b). In a pond in New Hampshire, Brugam (1978) detected an abrupt increase in ragweed percentages with deforestation in the watershed. Miller and Brush (1979) calculated sedimentation rates in three cores from the upper Potomac Estuary by assigning dates to changes in pollen assemblages at horizons corresponding to the 1840 agricultural expansion and the 1910 agricultural abandonment. However, most work done in estuarine environments has been with pollen in surface sediments and in suspension, rather than in sediment cores (Cross and others, 1966; Groot, 1966).

To use pollen analysis as a stratigraphic tool, one needs to know the source area of vegetation from which the pollen is derived. This consideration is more complicated than it appears; pollen types will be differentially transported (by both eolian and aqueous processes) and differentially intercepted by vegetation. Moreover, the distance pollen is transported by the wind depends on vegetation density (Tauber, 1967). Most researchers agree that 50 to 100 km form a natural limit of eolian pollen dispersal (Faegri and Iversen, 1966; Livingstone, 1968). The distance that pollen is transported in an estuary depends on size and shape of the pollen grain and on hydrodynamics of the estuary. Thus, when land use in the source area is correlated with pollen assemblages in sediments, it is important that the concept of source area remain flexible. Most pollen probably will originate close to the depositional environment, with decreasing contributions from further distances. As land is cleared, pollen can travel farther and the source area may become larger.

A comparison of pollen in surface sediments of the Potomac Estuary with vegetation in the surrounding area indicates that atmospheric and estuarine transport processes serve to erase local patchiness in vegetation (Brush and DeFries, 1981). Pollen in surface sediments mostly represents vegetation from a broad band adjacent to the estuary and dominantly from vegetation seaward from the Fall Line. Moreover, gradients in the percentage of total basal area for common tree species in the vegetation along the course of the estuary also are detectable as gradients in the pollen percentages for corresponding pollen types. Thus, under present-day conditions (1980), when about 40 percent of the land surface is covered by forest, pollen assemblages in surface sediments of the Potomac Estuary accurately portray vegetation in the lower Potomac drainage basin. With past changes in density and type of forest cover, the areal extent of the vegetation that the pollen assemblage represents probably will vary, although it is reasonable to assume that pollen assemblages in sediment cores from the Potomac Estuary generally reflect vegetation of the lower drainage basin.

Field and Laboratory Methods

A total of 20 cores collected throughout the Potomac Estuary were analyzed for pollen. Collection sites are shown in figure 4; descriptions of the collection sites are presented in table 1. Seventeen cores, about 1 m long, were collected by divers from the U.S. Geological Survey, Corpus Christi, Tex., in October 1978. According to x-ray analysis, 13 cores (cores 1, 3–5, 7, 9–15, and 17) were undisturbed and suitable for stratigraphic work. Two cores (cores 18 and 19), several meters long, were collected with a vibra-corer in November 1979 by the University of Delaware for the St. Marys City Commission. Five cores (cores 20–24), approximately 1.5 m long, were collected in June 1979 with a modified piston corer (Livingstone, 1955) by the author.

The cores were sectioned into 1- or 2-cm intervals. Samples were dried and treated with potassium hydroxide, hydrochloric acid, hydrofluoric acid, and an acetolysis mixture (sulfuric acid and acetic anhydride) to isolate the preserved pollen. Processed samples were washed with 95-percent and 100-percent ethyl alcohol, and tertiary butyl alcohol. The complete sample was then placed in a sample bottle with a measured volume of tertiary butyl alcohol, and subsampled. At least two aliquots were examined at 400-times magnification, and a minimum of 100 pollen grains were counted and identified to genus level. Although counting 100 pollen grains is inadequate to calculate reliable relative frequencies of minor components of pollen assemblages, it is adequate for detecting major changes in pollen assemblages on the basis of most abundant pollen types. After scanning the core by counting at least 100 grains at each sample interval, a minimum of 200 grains was counted at intervals where changes in pollen assemblages were apparent. Pollen concentrations (number of grains per gram dry sediment) and relative frequencies of all pollen types were calculated and are reported in DeFries (1980).

Pollen Profiles in Sediment Cores

Stratigraphic distributions of total grains per gram of dry sediment, percentage of ragweed, percentage of oak, and percentage of oak to percentage ragweed (oak to ragweed ratio) in the 20 sediment cores are shown in figures 5 through 24. Stratigraphic horizons (year the pollen was deposited) were established on the basis of the percentage of ragweed pollen and the oak to ragweed ratio. The percentage of ragweed pollen is expected to increase with land

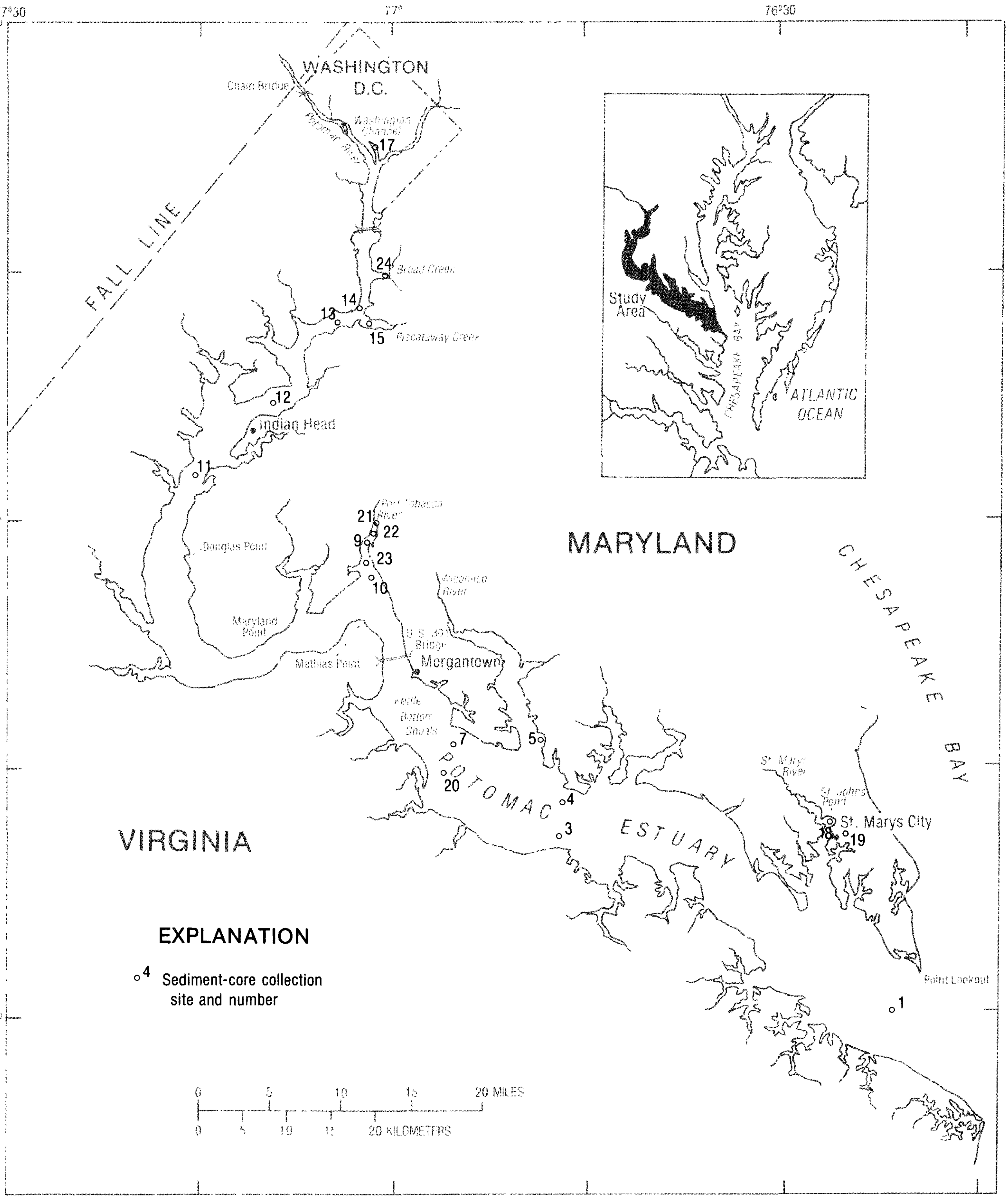

Figure 4. Location of sediment-core collection sites.

Table 1. Description of sediment-core collection sites

Core	Length of core (centimeters)	Approximate mean low water (meters)	Location
1	101	12.8	Main channel, lower reach of Potomac Estuary.
3	87	6.1	Main channel, lower reach of Potomac Estuary.
4	97	11.0	Main channel, lower reach at Potomac Estuary.
5	80	4.9	Wicomico River subestuary, just off center channel, lower reach of Potomac estuary.
7	112	11.0	Main channel, upper end of Kettle Bottom Shoals, lower reach of Potomac Estuary.
9	90	2.4	Port Tobacco River subestuary, channel near upstream limit of navigation, middle reach of Potomac Estuary.
10	96	2.7	Port Tobacco River subestuary, channel at mouth, middle reach of Potomac Estuary.
11	102	8.5	Main channel, middle reach of Potomac Estuary.
12	100	1.5	Shallow-water flat, upper reach of Potomac Estuary.
13	86	9.4	Main channel, upper reach of Potomac Estuary.
14	74	2.7	Shallow-water flat, upper reach of Potomac Estuary.
15	104	2.1	Piscataway Creek subestuary, shallow-water flat, upper reach of Potomac Estuary.
17	124	6.7	Washington Channel subestuary, upper reach of Potomac Estuary.
18	202	1.2	Center, St. Johns Pond, off St. Marys River subestuary.
19	202	0.3	Marsh area, St. Johns Pond, off St. Marys River subestuary.
20	158	6.7	Main channel, upper end of Kettle Bottom Shoals, lower reach of Potomac Estuary.
21	160	0.6	Port Tobacco River subestuary, near marsh area at head of tidal intrusion, middle reach of Potomac Estuary.
22	164	0.9	Port Tobacco River subestuary, channel near upstream limit of navigation, middle reach of Potomac Estuary.
23	144	2.4	Port Tobacco River subestuary, channel in center reach, middle reach of Potomac Estuary.
24	158	0.9	Broad Creek subestuary, shallow-water flat, upper reach of Potomac Estuary.

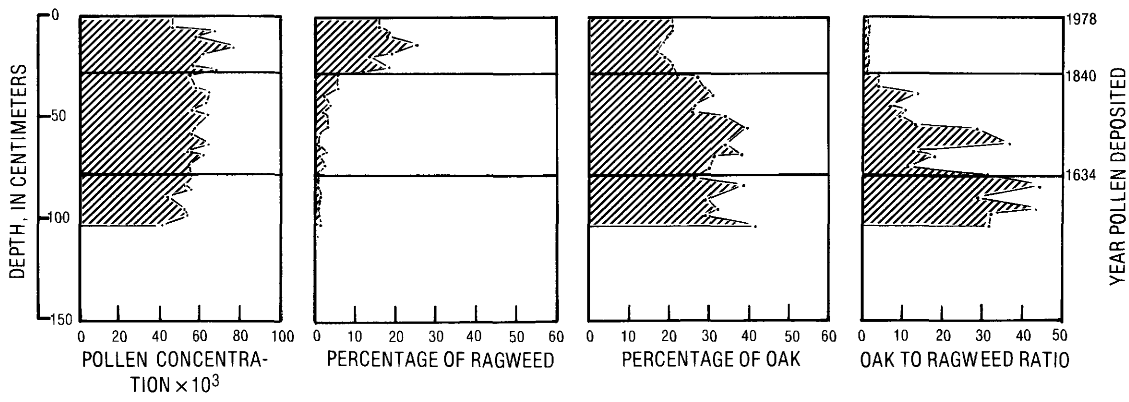

Figure 5. Pollen profile in core 1. Pollen concentration is the total number of pollen grains per gram of dry sediment.

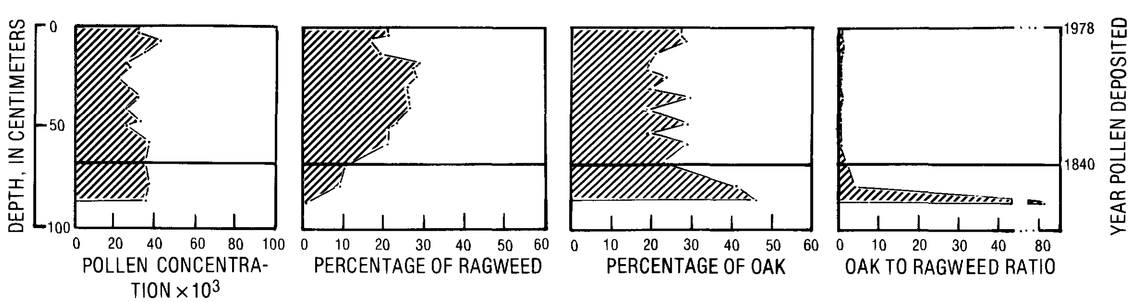

Figure 6. Pollen profile in core 3. Pollen concentration is the total number of pollen grains per gram of dry sediment.

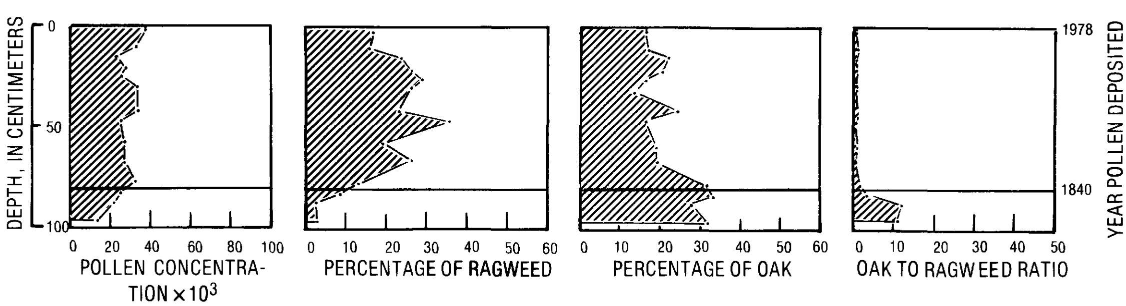

Figure 7. Pollen profile in core 4. Pollen concentration is the total number of pollen grains per gram of dry sediment.

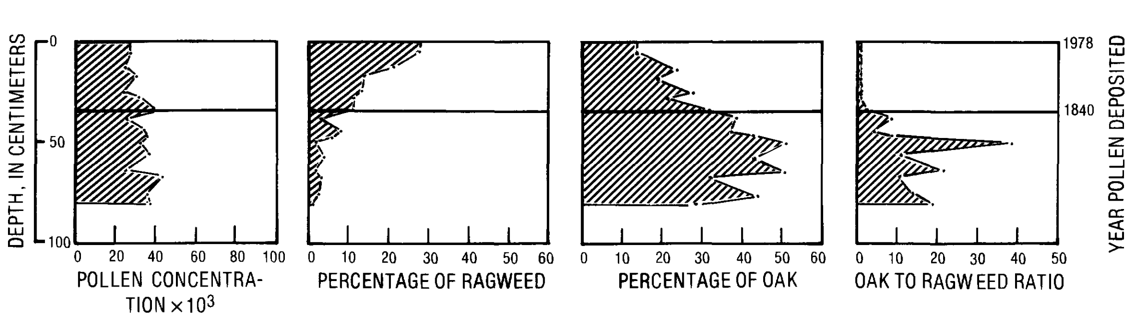

Figure 8. Pollen profile in core 5. Pollen concentration is the total number of pollen grains per gram of dry sediment.

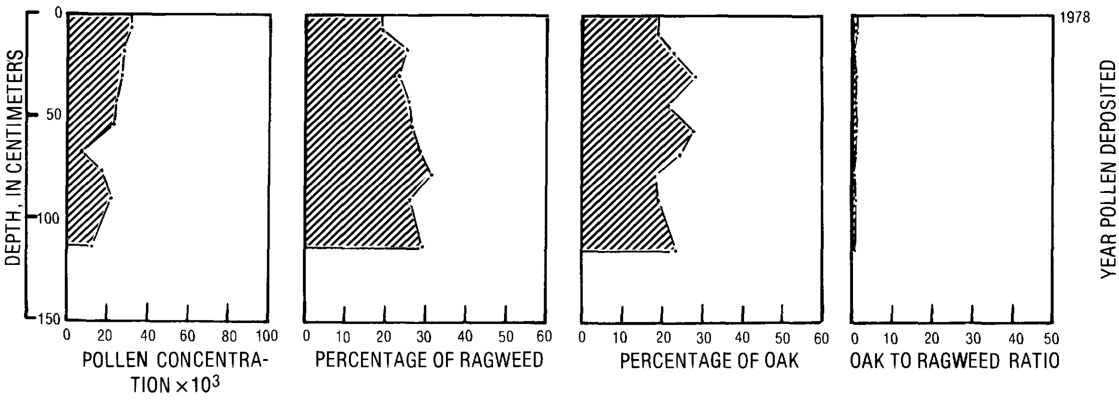

Figure 9. Pollen profile in core 7. Pollen concentration is the total number of pollen grains per gram of dry sediment.

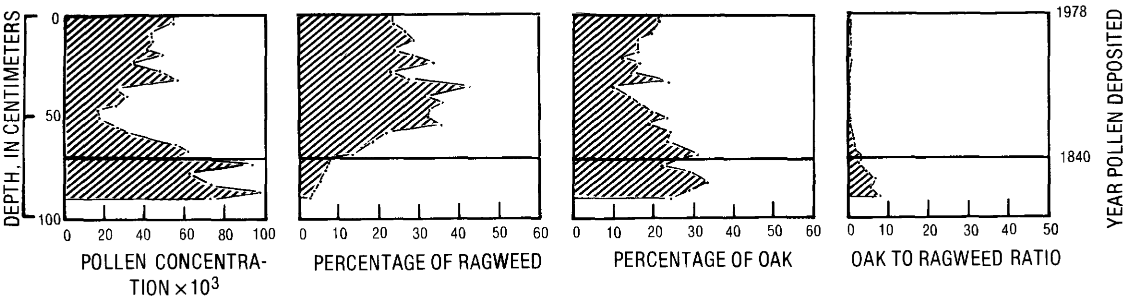

Figure 10. Pollen profile in core 9. Pollen concentration is the total number of pollen grains per gram of dry sediment.

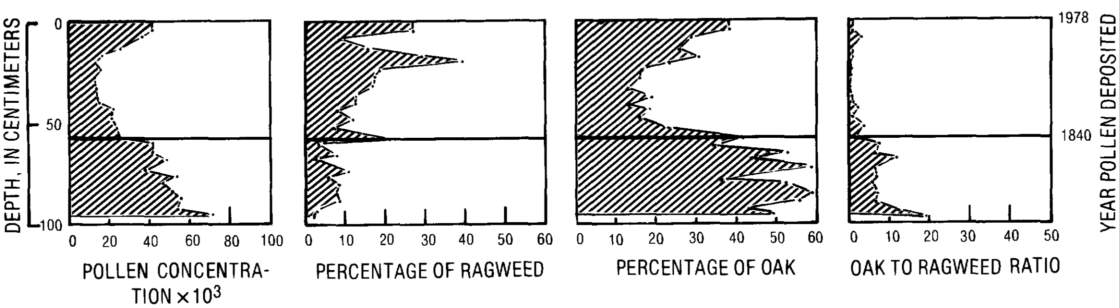

Figure 11. Pollen profile in core 10. Pollen concentration is the total number of pollen grains per gram of dry sediment.

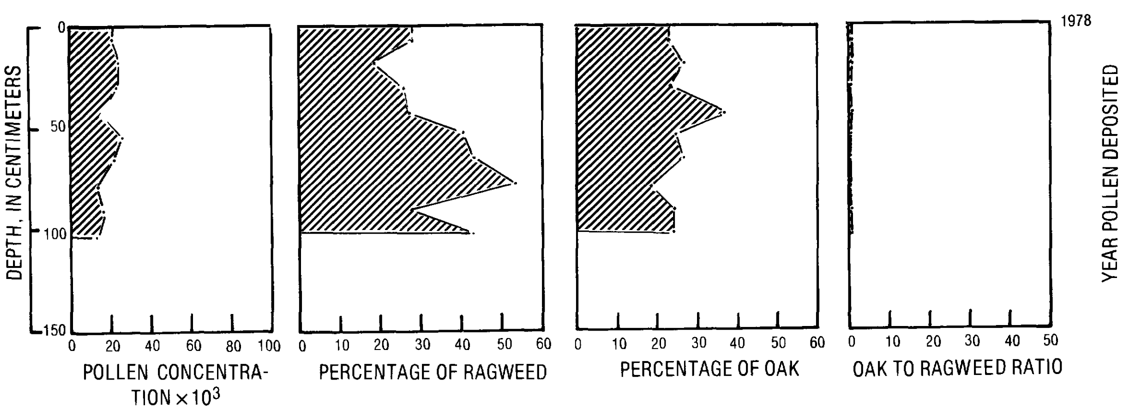

Figure 12. Pollen profile in core 11. Pollen concentration is tht total number of pollen grains per gram of dry sediment.

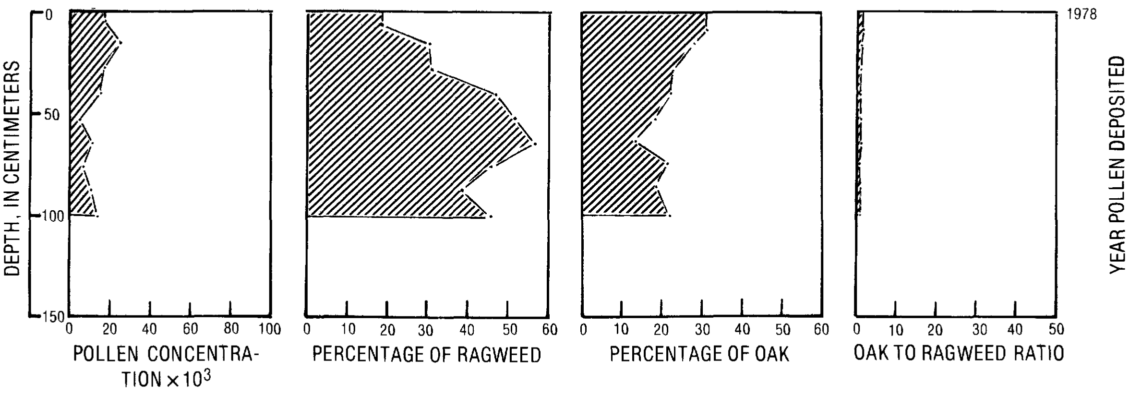

Figure 13. Pollen profile in core 12. Pollen concentration is the total number of pollen grains per gram of dry sediment.

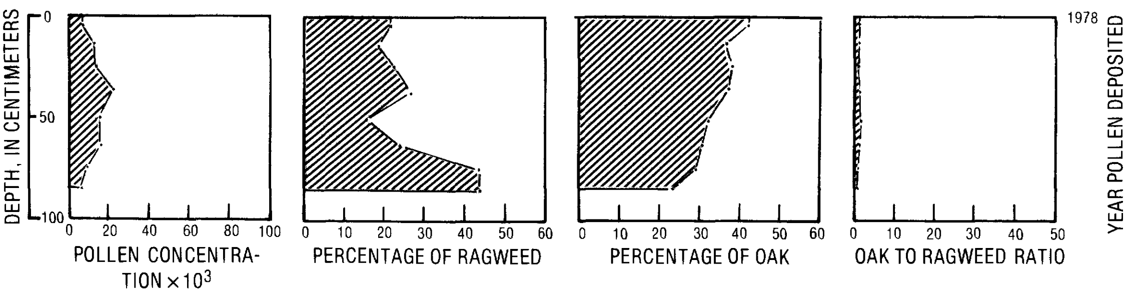

Figure 14. Pollen profile in core 13. Pollen concentration is the total number of pollen grains per gram of dry sediment.

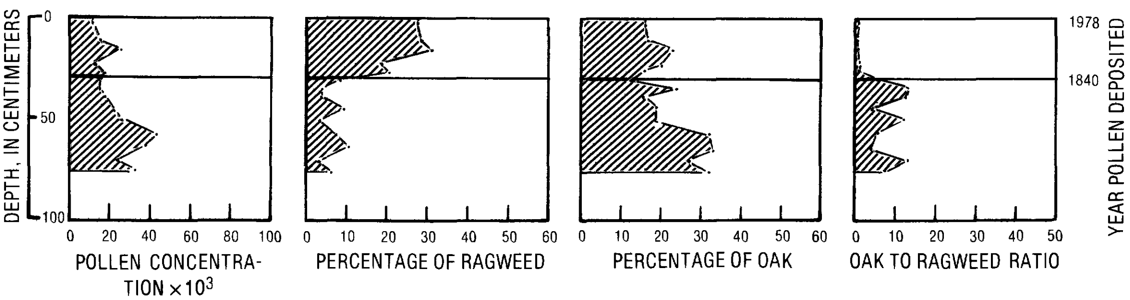

Figure 15. Pollen profile in core 14. Pollen concentration is the total number of pollen grains per gram of dry sediment.

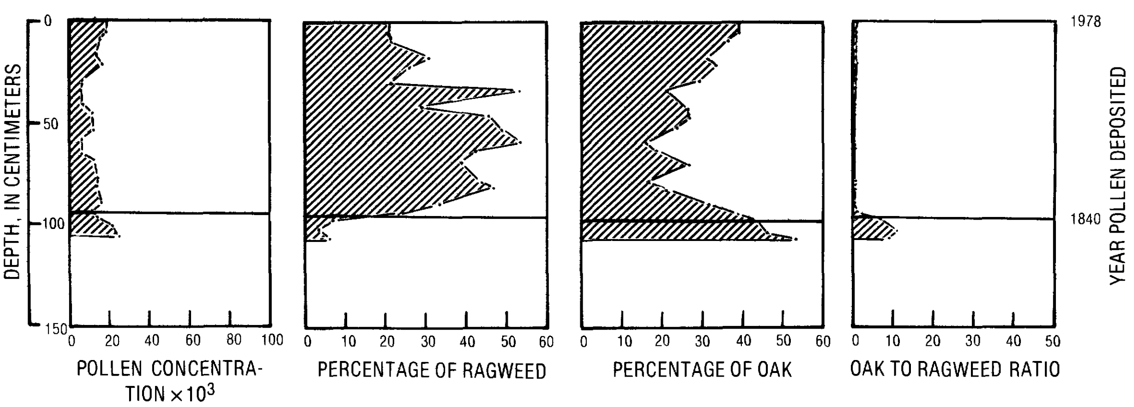

Figure 16. Pollen profile in core 15. Pollen concentration is the total number of pollen grains per gram of dry sediment.

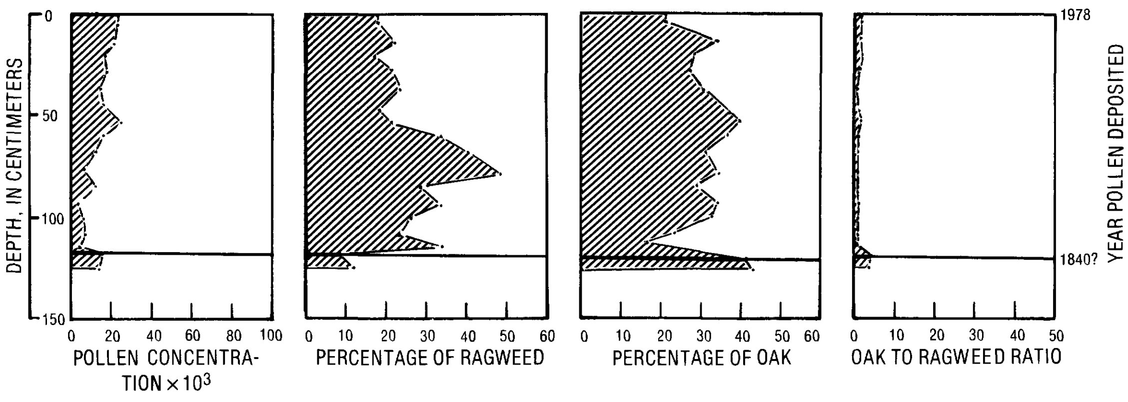

Figure 17. Pollen profile in core 17. Pollen concentration is the total number of pollen grains per gram of dry sediment.

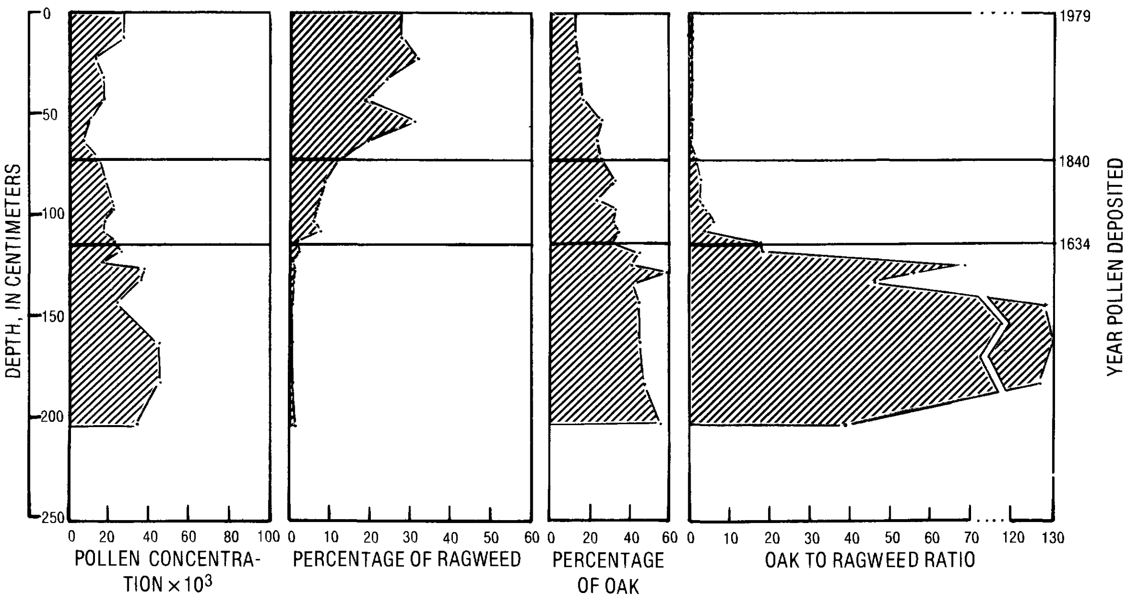

Figure 18. Pollen profile in core 18. Pollen concentration is the total number of pollen grains per gram of dry sediment.

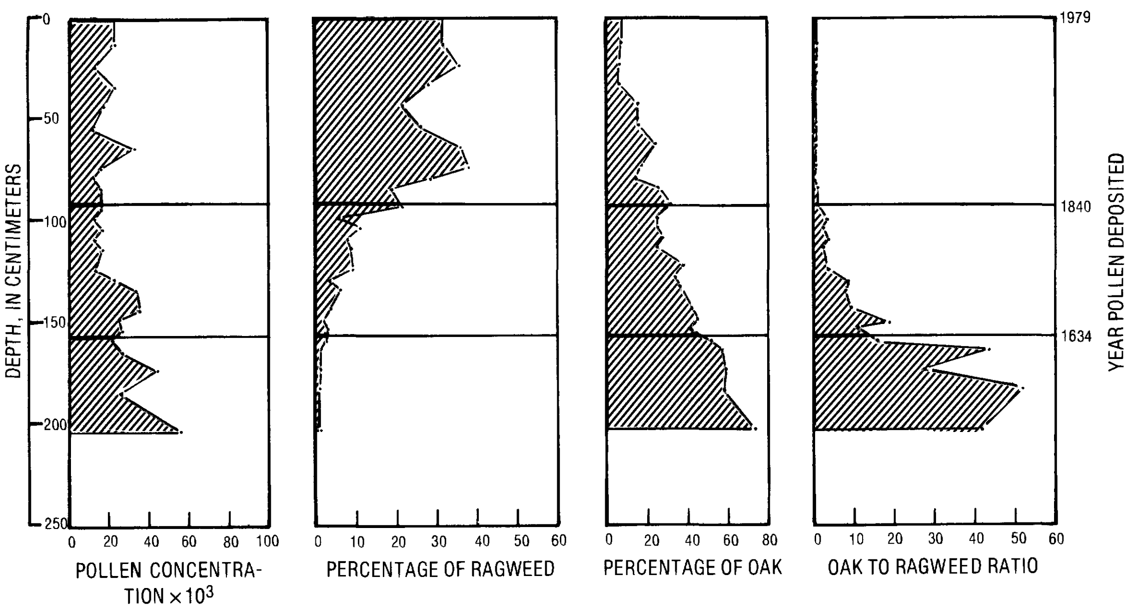

Figure 19. Pollen profile in core 19. Pollen concentration is the total number of pollen grains per gram of dry sediment.

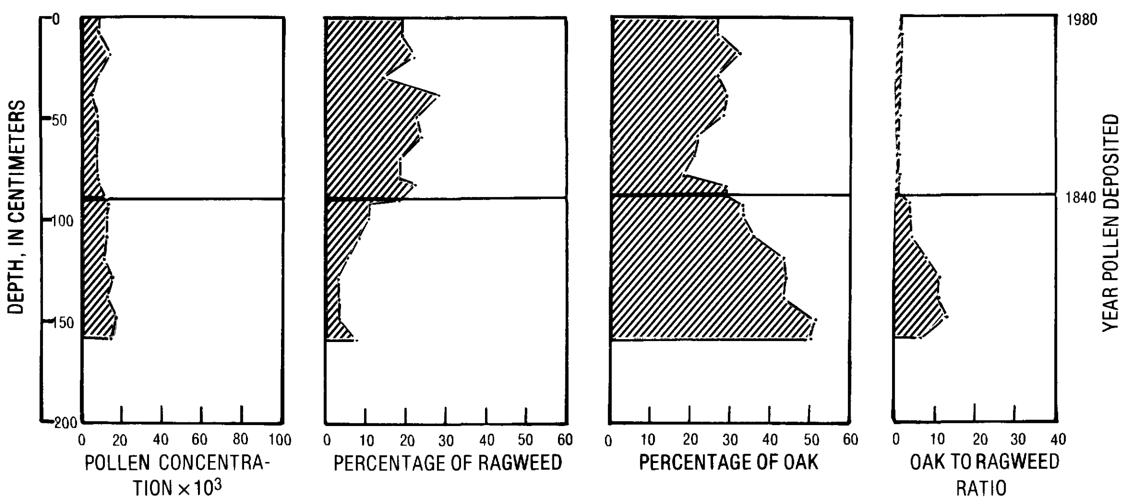

Figure 20. Pollen profile in core 20. Pollen concentration is the total number of pollen grains per gram of dry sediment.

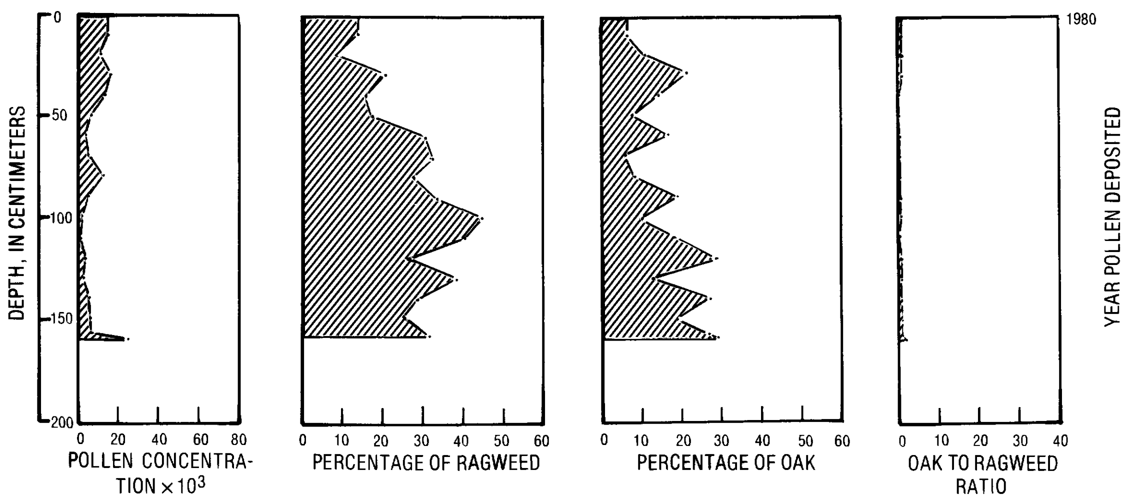

Figure 21. Pollen profile in core 21. Pollen concentration is the total number of pollen grains per gram of dry sediment.

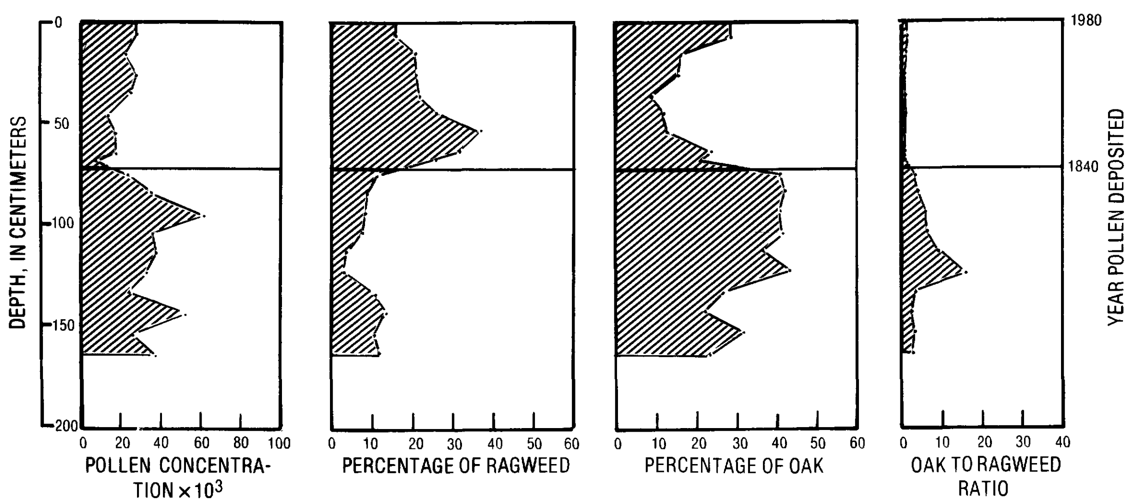

Figure 22. Pollen profile in core 22. Pollen concentration is the total number of pollen grains per gram of dry sediment.

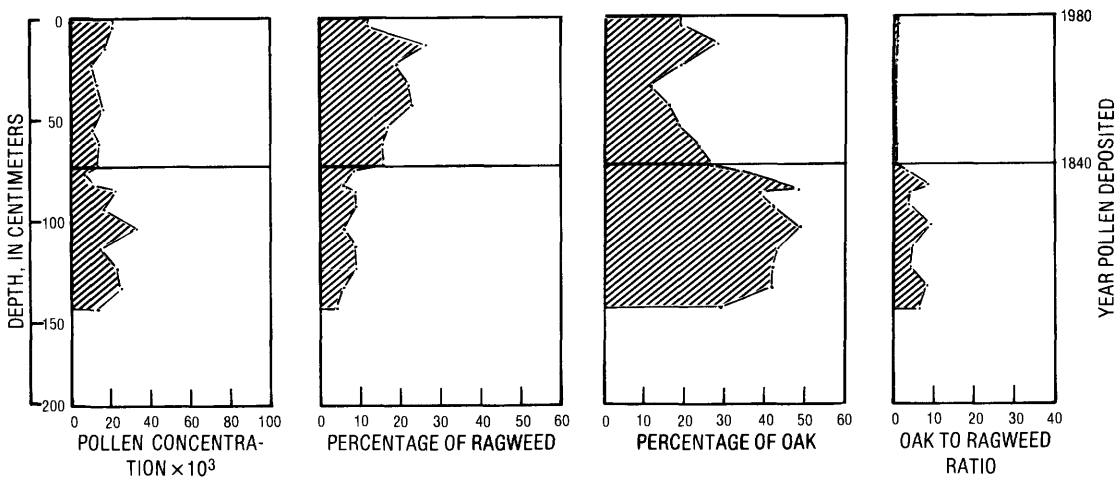

Figure 23. Pollen profile in core 23. Pollen concentration is the total number of pollen grains per gram of dry sediment.

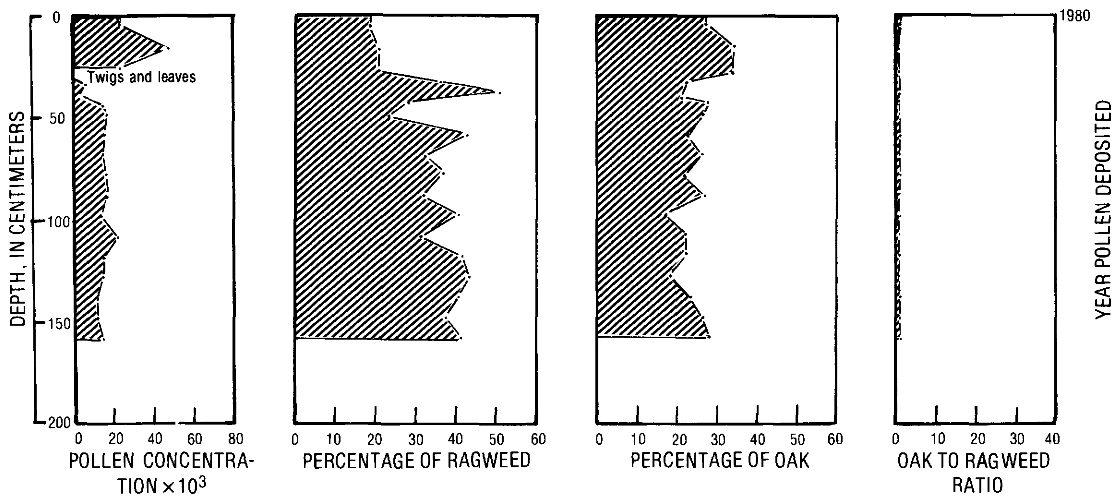

Figure 24. Pollen profile in core 24. Pollen concentration is the total number of pollen grains per gram of dry sediment.

clearance and the oak to ragweed ratio is expected to decrease. Because the proportion of oak pollen characterizes the degree of forest cover in the lower drainage basin, the oak to ragweed ratio may be a better index of land clearance than the percentage of ragweed alone (G.S. Brush, Johns Hopkins University, oral commun., 1980). The winged morphology of pine-pollen grains, the major component of arboreal pollen besides oak (DeFries, 1980), enables the wind to transport pine pollen for long distances. Therefore, the proportion of pine pollen in the assemblages may not necessarily reflect vegetation in the lower drainage basin, especially during times of major forest clearance. Other arboreal pollen types constitute only minor proportions of the pollen assemblages.

The oak to ragweed ratio is a better index of land clearance when percentages of ragweed are small than it is when percentages of ragweed are large. Ratios of percentages can be deceptive; a small change in percentage of ragweed when percentages are small results in a large change in the ratio; a change in percentage of ragweed when percentages are large results in a small change in the ratio. For example, assuming constant values for percentage of oak, a 1-percent increase in percentage of ragweed from 1 to 2 percent results in a 100-percent change in oak to ragweed ratio, whereas a 1-percent increase in ragweed from 10 to 11 percent results in only a 9-percent change in oak to ragweed ratio. Therefore, the oak to ragweed ratio is responsive to changes in land clearance when proportions of ragweed in the pollen assemblages are small, for example, from pre-European settlement until the mid-1800's, when percentage of ragweed was less than 10 percent. The ratio is not sensitive to changes in land clearance in more recent times, when the proportion of ragweed in the pollen assemblages is large, approximately greater than 10 percent.

On the basis of the land-use history of the lower Potomac basin, two horizons are datable: initial European settlement in 1634 and the agricultural revival about 1840. Before European settlement, when Indian agriculture did not disturb the soil to any great extent, percentage of ragweed is very small (less than 1 percent) and oak to ragweed ratio is very large (greater than 30) (table 2). Initial settlement is marked by a slight increase in percentage of ragweed (greater than 1 percent to less than 10 percent) and a corresponding decrease in oak to ragweed ratio (greater than 2 to less than 30). As previously stated, actual land clearance was not very extensive during the time of tobacco cultivation in the Colonies, so percentage of ragweed would be expected to remain small but to increase steadily as population increased, land clearance progressed, and settlement moved across the Fall Line. With the agricultural revival of about 1840, land clearance increased markedly. This is reflected in pollen profiles by an abrupt increase in percentage of ragweed to greater than 10 percent and a decrease in oak to ragweed ratio to less than 2. The trend of the two indices after the Civil War is difficult to determine; as land became fallow, some land was cleared for industrialization and urbanization, and this clearing also provided a habitat for ragweed.

Twenty surface-sediment samples (0–5 cm) were collected throughout the Potomac Estuary, representing sediment deposited in approximately the last 10 years while the lower drainage basin was about 40 percent forested; the mean percentage of ragweed is 16.1 percent, mean percentage of oak is 26.4 percent, and the resulting oak to ragweed ratio is 1.6 (Brush and DeFries, 1981). Using these values, the dating of initial European settlement is based on the

Table 2. Summary of land-use history and characteristic pollen assemblages
[<, approximate percentage or ratio less than the following number; >, approximate percentage or ratio greater than the following number]

Period	Date	Type of agriculture	Land area cleared for farms (percent)	Characteristic pollen assemblage: Ragweed (percent)	Characteristic pollen assemblage: Oak to ragweed ratio
Indian agriculture.	?-1634	Slash and burn	Minimal	< 1	> 30
Colonial	1634-1776	Tobacco	20 maximum, estimated 1.4-3.6.	> 1 - < 10	> 2 - < 30
Antebellum (Early).	1776-1840	Tobacco	20 maximum, estimated 1.4-3.6.		
Antebellum (Late).	1840-60	Diversified, agricultural revival.	38-43	> 10	< 2
Civil War and post-Civil War (Early).	1860-1940	Diversified	35-37		
Post-Civil War (Late).	1940-1974	Diminishing agricultural production; urbanization in Washington, D.C., metropolitan area.	19-35		

slight increase in ragweed to greater than 1 percent and the decrease in oak to ragweed ratio to less than 30, which is apparent in the cores long enough to record this event. The major increase in percentage of ragweed to greater than 10 percent and the corresponding decrease in oak to ragweed ratio to less than 2 are taken to mark 1840, the time of the agricultural revival.

Dated horizons are assigned in the cores according to the criteria in table 2 and according to judgment of the depth at which changes in percentage of ragweed and oak to ragweed ratio occur. These changes usually occur abruptly and are easily distinguished, although the 1840 horizon is more clearly defined in the pollen profiles than is the 1634 horizon.

The initial settlement horizon, marked by the initial increase in percentage of ragweed and decrease in oak to ragweed ratio, is distinguishable in core 1 at a depth of 76 cm, in core 18 at a depth of 118 cm, and in core 19 at a depth of 158 cm. In sediments deposited before 1634, the oak to ragweed ratio varies from 29 to 44 in core 1, from 19 to 130 in core 18, and from 17 to 52 in core 19. The percentage of ragweed averages about 1 percent in sediments deposited before 1634, but varies from 0.7 to 1.3 percent in core 1, from 0.3 to 1.4 percent in core 18, and from 1.3 to 2.2 percent in core 19. Near the 1634 horizon, the oak to ragweed ratio decreases to 12 in core 1, 20 in core 18, and 16 in core 19; at the same horizon, the percentage of ragweed increases to 2.6 in core 1, 2.3 in core 18, and 3.2 in core 19. Statistical tests (DeFries, 1980) confirm that both percentage of ragweed and oak to ragweed ratio are significantly different in the pre-1634 and 1634–1840 periods in core 1 (at p less than 0.001 for both percentage ragweed and oak to ragweed ratio), core 18 (at p less than 0.001 for both percentage ragweed and oak to ragweed ratio), and core 19 (at p less than 0.005 for percentage ragweed and p less than 0.001 for oak to ragweed ratio). The other cores were not long enough, in relation to the sedimentation rate, to extend to presettlement time or to the 1634 horizon.

In most cores, percentages of ragweed vary between about 1 and 10 percent and oak to ragweed ratios fluctuate between about 2 and 30 in sediments deposited between 1634 and 1840. However, in a few cores, such as at about 64 cm in core 1, 85 cm in core 3, and 50 cm in core 5, the ratios increase noticeably, to as much as 81 in core 3. In core 22, the ratios decrease to 2 to 3 in sediments deposited considerably before 1840, which is in contrast to the general pattern in most of the cores (cores 1, 3, 5, 9, 18, and 19), where the ratio progressively decreases from 1634 to 1840.

The increase in percentage of ragweed and the large decrease in oak to ragweed ratio marking the 1840 agricultural revival are easily distinguishable in 70 percent of the cores but are not identifiable in cores 7, 11, 12, 13, 21, and 24. Sedimentation rates in these cores are relatively rapid, and the cores probably are not long enough to extend to 1840. The 1840 horizon assigned in core 17 is questionable because only two data points exist below the designated 1840 horizon. In sediment deposited between 1840 and 1978, percentages of ragweed fluctuate between about 10 and 50 percent and oak to ragweed ratios are less than about 2. Differences in percentages of ragweed and in oak to ragweed ratios between the 1634–1840 and post-1840 periods are so pronounced that no statistical tests are necessary.

Local fluctuations in total pollen concentrations, percentages of ragweed pollen, and oak to ragweed ratios in the cores may result from local variations in land clearance, random fluctuations in pollen output from vegetation, random variations in pollen deposition in the estuary, and sampling and counting techniques. However, these fluctuations do not mask general trends in the two indices, which reflect the area of land clearance in the lower Potomac basin. From these pollen profiles, sedimentation rates in the cores can be calculated.

SEDIMENTATION RATES

Sedimentation rates, in centimeters per annum, based on the pollen profiles, are calculated by dividing depth of the core in the interval between the dated horizons by amount of time between horizons; sediment fluxes, in grams per square centimeter per annum, are determined by dividing cumulative dry weight of the sediment per square centimeter in the interval between the dated horizons by amount of time between horizons (table 3). Actual sedimentation rates and fluxes may vary from calculated rates and fluxes because (1) actual depth of the pollen horizon may differ from the depth to the pollen horizon established according to the criteria above, and (2) actual dates corresponding to the pollen horizon may differ from the dates established by investigation of the land-use records. Uncertainties for the sedimentation rates and fluxes, shown by plus-and-minus values in table 3, were calculated by the first-order propagation of error, as explained in Brush and others (1982). For cores 7, 11, 12, 13, 21, and 24, which did not extend to 1840, only minimum sedimentation rates and fluxes can be calculated (table 3).

Linear regressions of density of sediment, in grams per cubic centimeter (weight of dry sediment divided by volume of wet sediment) against depth in the core, in centimeters, show that slopes of the regression lines are less than 0.0050, indicating that density of sediment changes little with depth in these cores (DeFries, 1980). Therefore, sedimentation rates reported here are not appreciably affected by compaction of the sediment with depth.

Lead-210 dating was independently performed on 13 of the cores dated by the pollen method, and sedimentation rates were calculated by both methods. In the six cores for which a reliable comparison of the two methods could be made, sedimentation rates for 1878 to 1978 calculated by the lead-210 method were in substantial agreement with

Table 3. Sedimentation rates and fluxes for 1634–1840 and 1840–1978 indicated in cores

[cm/a, centimeters per annum; (g/cm²)/a, grams per square centimeter per annum; n.d., no data; cm, centimeters]

Core	Sedimentation rate (cm/a)		Sediment flux ((g/cm²)/a)	
	1634-1840	1840-1978	1634-1840	1840-1978
1	0.23 ± .01	0.21 ± 0.02	0.14 ± 0.01	0.09 ± 0.01
3	n.d.	.56 ± .05	n.d.	.26 ± .02
4	>.10	.56 ± .05	>.07	.27 ± .02
5	>.22	.25 ± .02	>.11	.13 ± .01
7	n.d.	>.81	n.d.	>.42
9	>.12	.48 ± .04	>.06	.23 ± .02
10	>.19	.40 ± .03	>.11	.29 ± .02
11	n.d.	>.72	n.d.	>.44
12	n.d.	>.73	n.d.	>.67
13	n.d.	>.62	n.d.	>.44
14	>0.21	0.22 ± .02	>0.15	0.17 ± .01
15	>.06	[1].67 ± .06	>.05	[1].52 ± .04
17	n.d.	[2].81 ± .07	n.d.	[2].52 ± .04
18	.22 ± .01	.52 ± .05	.15 ± .01	.48 ± .04
19	.31 ± .01	.67 ± .06	.19 ± .01	.51 ± .05
20	>.33	.64 ± .07	>.15	.34 ± .03
21	n.d.	>1.14	n.d.	>1.00
22	>.47	.51 ± .05	>.18	.23 ± .02
23	>.34	.53 ± .05	>.14	.24 ± .02
24	n.d.	[3]>1.14	n.d.	[3]>.83

[1]Two to three water-chestnut seeds at a depth of 30 cm, presumably deposited in approximately 1930 during the water-chestnut infestation of the upper Potomac Estuary, indicate a sedimentation rate of 0.63 cm/a and a sediment flux of 0.34 (g/cm²)/a.

[2]Sedimentation rate and flux are questionable owing to insufficient length of core.

[3]Water-chestnut seeds at a depth of 80-86 cm indicate a sedimentation rate of 1.72 cm/a and a sediment flux of 1.14 (g/cm²)/a.

sedimentation rates for 1840 to 1978 calculated by the pollen method (Brush and others, 1982).

Sedimentation rates are slowest overall in core 1, at the mouth of the Potomac Estuary (table 3); they remained practically unchanged between 1634–1840 and 1840–1978. Sediment fluxes at the site of core 1 were slightly greater from 1634 to 1840 than from 1840 to 1978. Sedimentation rates and fluxes indicated in core 18, from St. Johns Pond near the St. Marys River subestuary, were relatively slow and small during 1634–1840, but increased by a factor of about 2 to 3 during 1840–1978. Similar rates and increases were computed for core 19, also from St. Johns Pond (table 3). G.A. Stone (St. Marys City (Md.) Commission, oral commun., 1979) noted that the pond was formed in about 1823 to 1824, when a public road traversed the lagoon at the mouth of Mill Creek. Thus, increased trap efficiency of the pond or increased sediment input associated with nearby land clearance, or both, could account for this twofold increase in sedimentation.

Most cores (cores 22, 9, 23, and 10) from the Port Tobacco subestuary (fig. 25) indicate similar sedimentation rates and fluxes for 1840–1978 (all less than 0.53 cm/a and less than 0.29 (g/cm²)/a, respectively), but core 21, located far upstream where Port Tobacco Creek enters the subestuary, indicates a sedimentation rate of greater than 1.14 cm/a and a flux of greater than 1.00. The data do not provide rates prior to 1840.

Cores from Kettle Bottom Shoals (fig. 1) indicate rapid sedimentation rates and large sediment fluxes for 1840–1978; the rate and flux for core 7 is greater than 0.81 cm/a and greater than 0.42 (g/cm²)/a, and the rate and flux for core 20 is 0.64 cm/a and 0.34 (g/cm²)/a. In the upper part of the estuary, cores 11–15, 17, and 24 also indicate rapid rates and large fluxes. The pollen profile for core 24 (fig. 24) indicates a sedimentation rate greater than 1.14 cm/a and a sediment flux greater than 0.83 (g/cm²)/a; five water-chestnut seeds at a depth of 80 to 86 cm, presumed to be deposited during the water-chestnut infestation of the upper Potomac Estuary about 1930 (Rawls, 1964), indicate a rate of 1.72 cm/a and a flux of 1.14 (g/cm²)/a). Twigs and leaves at a depth of 26 to 30 cm and extremely small pollen concentrations from a depth of 30 to 40 cm in core 24

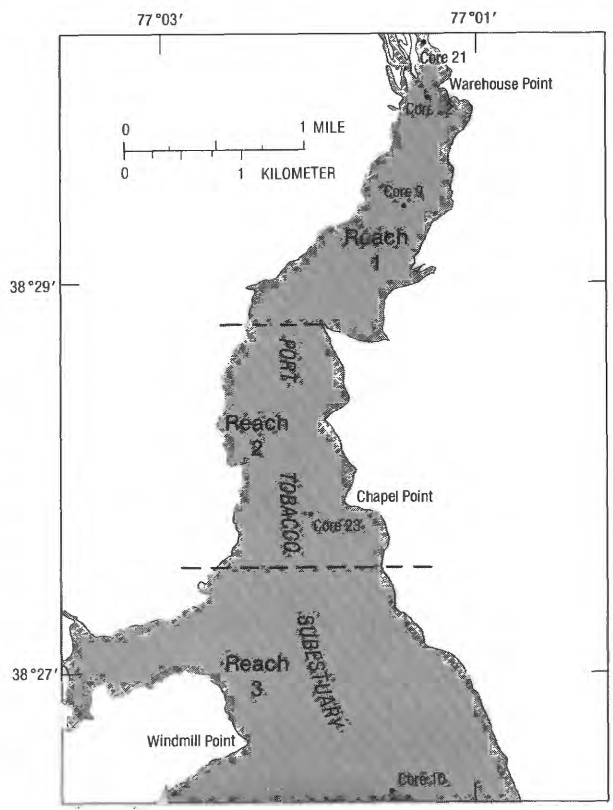

Figure 25. Location of sediment-core collection sites in the Port Tobacco subestuary.

indicate that a storm or other cause of rapid sedimentation deposited these 14 cm of twigs, leaves, and sediment. Two or three water-chestnut seeds at a depth of 30 cm in core 15 indicate a sedimentation rate of 0.63 cm/a and a flux of 0.34 $(g/cm^2)/a$, compared with a rate of 0.67 cm/a and a flux 0.52 $(g/cm^2)/a$ calculated for 1840 to 1978 on the basis of the 1840 horizon, which was based on the increase in ragweed pollen.

LAND USE AND SEDIMENTATION

Pollen concentrations in the cores are the result of both the quantity of pollen input and the sedimentation rate; it is difficult to separate these two effects. Pollen concentrations are statistically related, at the 0.05 significance level, to sedimentation rates ($r = 0.57$, $n = 14$) (DeFries, 1980), indicating that pollen influx is more or less the same throughout the estuary. Moreover, cores 7, 11, 12, 13, 21, and 24, which did not extend to the 1840 horizon and indicate rapid sedimentation rates, have small pollen concentrations. Thus, small pollen concentrations indicate rapid sedimentation rates and large pollen concentrations indicate slow sedimentation rates. Pollen influx has undoubtedly varied with the degree of land clearance, although, when the nearby watershed is deforested, pollen entering the estuary from farther away can compensate for decreased pollen input from vegetation adjacent to the estuary. Fluctuations in the pollen concentrations also may represent fluctuations in the degree of (1) local land clearance, (2) pollen produced from year to year, or (3) sedimentation rate compared with the average rate. Although pollen concentrations vary by as much as 50 percent within the cores (figs. 5–24), the only indication of a large deviation from the average sedimentation rate is the 14 cm of sediment with extremely small pollen concentrations in core 24, indicating deposition by rapid sedimentation. For the most part, pollen concentrations in the cores indicate a process of fairly regular and continuous sedimentation at the sediment-core collection sites used in this study. Rapid and uneven sedimentation, however, may be occurring in the estuary at locations where it is difficult to obtain an undisturbed core that is suitable for stratigraphic analysis.

Pollen concentrations do not decrease above the 1634 horizon in core 1 from the mouth of the estuary (fig. 5), which indicates that the sedimentation rate after European settlement has not been significantly greater than the rate prior to settlement. Because land clearance was not very extensive during the time of the Colonies, pollen input probably remained more or less constant. Therefore, if the sedimentation rate had increased after European settlement, pollen concentrations would be diluted with sediment and would decrease in the core above the horizon representing settlement.

Because the drainage basin has not undergone any large changes in forest cover during the past 50 years, pollen influx probably has remained more or less constant during this period. Therefore, an increase in sedimentation rates from intensive construction activities in the drainage basin during the past 30 years would be reflected in pollen profiles by a decrease in pollen concentrations toward the top of the cores (in the top 21 cm, if the sedimentation rate is 0.7 cm/a). Pollen concentrations do not decrease greatly toward the top of the cores in any of the cores from the lower part of the estuary (cores 1, 3, 4, 5, 7, 9, 10, and 20–23). In most cores from the upper estuary (cores 11–15, 17, and 24), pollen concentrations do not decrease toward the top of the cores; in cores 13 and 14, however, pollen concentrations may decrease slightly toward the top. In core 15, the average sedimentation rate from 1930 to 1978 is practically the same as the average sedimentation rate from 1840 to 1978, although the sediment flux for the former is less than for the latter (table 3).

Cores from the upper estuary near the Washington, D.C., metropolitan area, where construction activities may cause sediment yields as much as 900 Mg/km^2 (Wark and Keller, 1963), are most likely to reflect the effect of construction activities on sedimentation rates. Absence of pollen types whose source vegetation is restricted to the upper Potomac drainage basin, approximately 60 km upstream from the Fall Line, indicates that fine-grained sediment and pollen may not be transported to any great extent by the Potomac River into the estuary (Brush and DeFries, 1981). Thus, land use in the drainage basin upstream from the Fall Line would not affect sedimentation in the estuary. The relationship between locations of the pollen sources and locations of the sediment sources requires further study.

Core 17, collected from the Washington Channel, is representative of the area close to construction activities in Washington, D.C. However, Washington Channel was artificially created and dredged after the Civil War, and core 17 does not adequately represent the estuarine environment. The drainage basins of both Broad Creek, where core 24 was collected, and Piscataway Creek, where core 15 was collected, have been subject to suburban development during about the last 30 years. However, pollen profiles in the cores indicate that sedimentation rates do not increase uniformly through the estuary in response to activities in the drainage basin. Rather, the effect of construction on sedimentation rates probably is confined to local areas.

Pollen profiles in the cores indicate rapid sedimentation rates in the upper estuary, at the head of Port Tobacco subestuary, and in Kettle Bottom Shoals. Because no cores were available between Douglas Point and Mathias Point (fig. 1), sedimentation rates in this area are unknown. According to data in this study, sedimentation rates are not wholly controlled by land use in the drainage basin. Circulation patterns in the estuary may explain accumulation of sediment in Kettle Bottom Shoals. The freshwater–saltwater transition zone, where sediment may accumulate, shifts position throughout the year. During the spring, when sediment discharge is at its annual peak (Wark and Keller, 1963), the freshwater–saltwater transition zone may extend as far downstream as Kettle Bottom Shoals and may result in rapid sedimentation rates at this location.

Because the upper reach of the Potomac Estuary is freshwater at all times of the year, accumulation of sediment in that area cannot be explained by estuarine circulation patterns. A decrease in competence may deposit river sediment, as the Potomac River abruptly drops about 85 ft at Great Falls from the steeper gradient of the Piedmont province to the more gentle gradient of the estuary. A similar process may be operating on a smaller scale at Port Tobacco, where sediment is rapidly accumulating at the head of the subestuary. Morphometry of the Potomac Estuary also may be responsible for accumulation of sediment in the narrow upper reach; if transport conditions are similar, a given volume of sediment will accumulate at a more rapid rate, per unit area, in a narrow section than in a wider section of the Potomac Estuary. Thus, two processes may be controlling sedimentation in the Potomac Estuary: (1) the circulation pattern, which produces an accumulation of sediment in the freshwater–saltwater transition zone, and (2) the deposition of sediment as the river widens and enters the upper estuary. Shoreline erosion and landward transport from Chesapeake Bay also may affect sedimentation patterns in the estuary; these processes are beyond the scope of this study.

Although construction activities do affect sediment loads in the Potomac River (Wark and Keller, 1963; Meade, 1969), the only discernible effect of land use on sedimentation rates is the local effect of increasing sedimentation rates in cores 18 and 19 from St. Johns Pond. European settlement did not alter the sedimentation rate at the mouth of the estuary. Longer cores are needed before the extent to which European settlement affected sedimentation rates in the upper part of the Potomac Estuary can be determined.

MOVEMENT OF SEDIMENT IN PORT TOBACCO SUBESTUARY

Because pollen grains are similar to hydraulically equivalent fine-grained sediment (Brush and Brush, 1972), these grains can be viewed as labeled particles, when the parent vegetation of a specific pollen type is restricted to a known locality. The grains can be used to trace the path and distance that hydraulically equivalent sediment particles are transported in an estuary. *Chenopodium,* a local pollen type abundant in the Port Tobacco subestuary, is found only in very small quantities in other cores from the Potomac Estuary. It represents either a marsh plant or a common pigweed that grows in disturbed areas; these two are not distinguishable on the basis of the pollen grain. The *Chenopodium* pollen grain is 20 to 25 μm in diameter and has a specific gravity of 1.2 (Brush and Brush, 1972). The diameter of a sediment particle with a settling velocity (within Stokes range) equal to a *Chenopodium* pollen grain is given by the following equation:

$$d_s = d_p \left[\frac{(SG_p - 1)K_p}{SG_s - 1} \right]^{1/2} , \qquad (1)$$

where

d_s = diameter of the sediment particle;
d_p = diameter of the pollen grain;
SG_p = specific gravity of the pollen grain;
SG_s = specific gravity of the sediment particles; and
K_p = form coefficient of the pollen grain.

Assuming that K_p equals 1.0 (i.e., the pollen grain is spherical) and SG_s is 2.5, the diameter of a sediment particle with a settling velocity equal to that of a *Chenopodium* pollen grain is approximately 7 to 9 μm. Therefore, the *Chenopodium* pollen grain will be transported like a fine-grained sediment particle.

Transport of sediment, however, may be affected by flocculation to a greater extent than transport of pollen grains. The effect of flocculation in transport of estuarine sediment is unclear, as is the extent to which pollen grains react in flocculation processes. Pollen grains would not react as a charged clay particle, but it is possible that pollen grains would form aggregates along with the sediment. Although pollen grains may not react precisely like fine-grained sediment in the subestuary, the distribution of *Chenopodium* pollen grains in the sediment does provide clues about the movement of fine-grained sediment.

The concentration of *Chenopodium* pollen grains (fig. 26) decreases with distance seaward from core 9, which is located near the head of the Port Tobacco subestuary (fig. 25). Because the pollen grains are hydraulically equivalent to fine sediments, the grains, in effect, label the sediment and indicate that its source is the Port Tobacco drainage basin. The seaward decrease in concentration indicates that the Port Tobacco sediment is diluted by sediment from sources where the *Chenopodium* is not present. Assuming that (1) sediment at core 9 comes solely from the Port Tobacco drainage basin and not from the Potomac Estuary (core 9 is used here instead of core 21 or 22 because core 21 does not have a dated horizon and the time of deposition is unknown, and core 22 is from an area adjacent to marsh vegetation and may not adequately represent the open-water depositional sites), and (2) all *Chenopodium* pollen grains originated from a local source at the head of the Port Tobacco subestuary (a reasonable assumption, because there are few *Chenopodium* pollen grains in the other cores from the Potomac) (DeFries, 1980), then the concentration of *Chenopodium* pollen grains in the cores seaward from core 9 (cores 23 and 10), relative to the concentration at core 9, reflects the degree of dilution by sediment from the Potomac Estuary, from shore erosion between collection sites of the cores or from internal sources. If, for example,

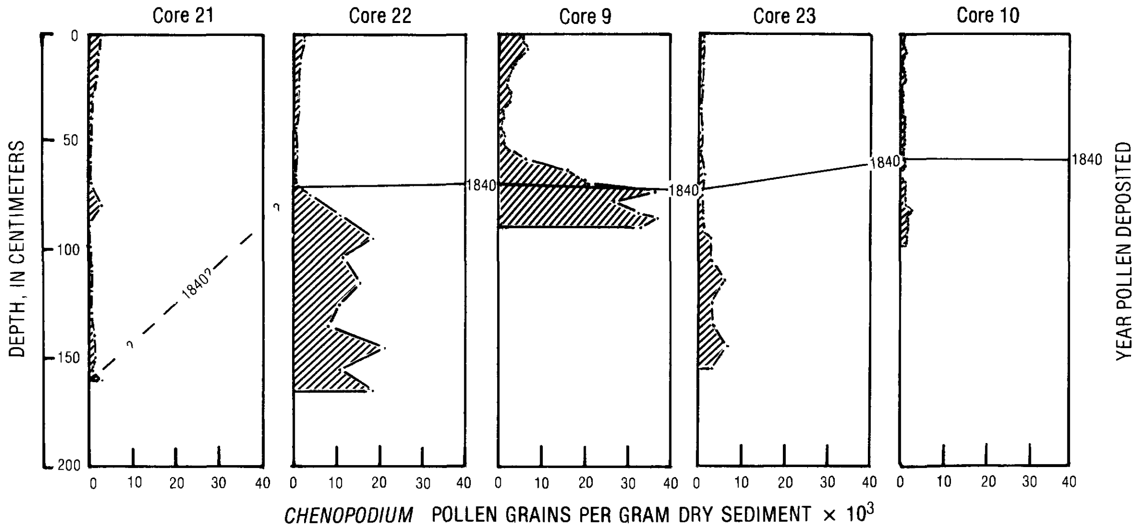

Figure 26. Number of *Chenopodium* pollen grains per gram of dry sediment in cores from the Port Tobacco subestuary.

the concentrations of *Chenopodium* pollen grains at core 9 and at core 10 are equal, the sediment from core 10 is from the Port Tobacco drainage basin; if the *Chenopodium* concentration in core 10 is very small, very little of the sediment comes from the Port Tobacco drainage basin. The proportion of the sediment that is from the same source as the sediment at core 9, then, is given by

$$X_i = \frac{C_i}{C_9}, \qquad (2)$$

where

X_i = the fraction of total sediment from the Port Tobacco drainage basin for a given period of deposition at the collection site of core *i*, in percent;

C_i = the concentration of *Chenopodium* pollen grains at the collection site of core *i* for the given period, in number of grains per gram of dry sediment; and

C_9 = the concentration of *Chenopodium* pollen grains at location of core 9 for the same period, in number of grains per gram of dry sediment.

The average pollen concentrations for samples from each decade between 1840 and 1978 and the ratios of concentrations in cores 23 and 10 to concentrations in core 9 are given in table 4. The ratio in core 9 is assumed (see preceding discussion) to be 1.00; that is, all the sediment at core 9 is assumed to come from the Port Tobacco drainage basin. The average ratio for decades between 1840 and 1978 at core 23 is 0.163; this ratio indicates that about 16 percent, by weight, of the sediment deposited at the collection site of core 23 between 1840 and 1978 came from the Port Tobacco drainage basin and the remaining 84 percent of the deposited sediment came from the Potomac Estuary or other sources. Likewise, about 4 percent of the sediment at the collection site of core 10 came from the Port Tobacco drainage basin and 96 percent is from other sources.

The total quantity of Port Tobacco sediment deposited at each collection site can be obtained by multiplying total grams of dry sediment per square centimeter (DeFries, 1980; Brush and others, 1982) deposited from 1840 to 1978 by the ratios in table 4; 32.6 g/cm^2 of Port Tobacco dry sediment were deposited at the collection site of core 9 between 1840 and 1978, 5.4 g/cm^2 were deposited at the collection site of core 23 between 1840 and 1978, 1.3 g/cm^2 were deposited at the collection site of core 10.

The proportion of total sediment from the Port Tobacco drainage basin that is deposited in different locations can be approximated by dividing the subestuary into three reaches (fig. 25), each about 2.2 km long, but with average widths of 0.9 km in the first reach, 1.1 km in the second reach, and 2.5 km in the third reach, moving seaward from the head of the subestuary. Assuming that sediment deposition within each reach is uniform and that the ratios obtained before for cores 9, 23, and 10 represent the average values for the first, second, and third reach, the quantities of Port Tobacco sediment deposited in each reach between 1840 and 1978 were about 6.9×10^8 kg (first reach), 1.3×10^8 kg (second reach), and 0.9×10^8 kg (third reach). Of the total 9.1×10^8 kg of sediment entering the Port Tobacco subestuary through the head between 1840 and 1978, 75 percent was deposited in the upper one-third of the subestuary, 15 percent in the middle one-third, and 10 percent in the lower one-third. These estimates assume no eolian

Table 4. Concentrations and ratios of *Chenopodium* pollen grains in cores 9, 23, and 10

[C_9, core 9; C_{23}, core 23; C_{10}, core 10; n.d., no data]

Period sediment deposited	Concentration (number of grains per gram of dry sediment)			Ratio	
	C_9	C_{23}	C_{10}	$\frac{C_{23}}{C_9}$	$\frac{C_{10}}{C_9}$
1840-1850-------	21,861	633	674	0.029	0.031
1850-1860-------	16,985	1,270	448	.075	.026
1860-1870-------	6,744	n.d.	105	n.d.	.016
1870-1880-------	6,932	260	302	.038	.044
1880-1890-------	1,866	303	102	.162	.055
1890-1900-------	999	346	89	.346	.089
1900-1910-------	1,077	n.d.	0	n.d.	0
1910-1920-------	2,642	367	0	.139	0
1920-1930-------	2,923	n.d.	0	n.d.	0
1930-1940-------	2,611	707	112	.271	.043
1940-1950-------	3,708	n.d.	344	n.d.	.093
1950-1960-------	4,522	748	0	.165	0
1960-1970-------	6,543	n.d.	687	n.d.	.105
1970-1978-------	5,057	1,240	276	.245	.055
	Average-------------------------			.163	.040

transport of *Chenopodium* pollen grains; therefore, they provide a maximum estimate of the percentage of sediment transported seaward in the subestuary.

Although these estimates are approximate, they indicate that most fine-grained sediment in the Port Tobacco subestuary remains in the upper reach and little enters the main part of the Potomac Estuary. Therefore, sediment resulting from accelerated erosion associated with European settlement or construction activities in the Port Tobacco drainage basin has not greatly affected sedimentation in the main channel of the Potomac Estuary. This result is in agreement with data from the sediment cores collected in the Potomac Estuary; the effect of land use on sedimentation rates is confined to local areas.

SUMMARY

Major changes in land-use history of the lower Potomac drainage basin are reflected in pollen assemblages preserved in 20 sediment cores from the Potomac Estuary. The proportion of ragweed in the pollen assemblage, an agricultural weed that grows in disturbed areas, was very small before European settlement, when soil disturbance was minimal. Initial European settlement in 1634 is marked by a slight increase in the proportion of ragweed in the pollen assemblages. From 1634 to 1840, tobacco farming was the main agricultural practice in the area. The area of land actually planted in tobacco at any one time was not great, and the proportion of ragweed in the pollen assemblages deposited during this time generally is less than 10 percent. The agricultural revival of 1840, when approximately 43 percent of the land area was cleared for farms, is marked by a large increase in the proportion of ragweed. The 1634 initial European settlement horizon is present in three of the cores; the other cores were not long enough to extend to 1634, although 70 percent of the cores were long enough to reach the 1840 horizon. In two cores the presence of water-chestnut seeds, which were presumably deposited during the water-chestnut infestation of the upper Potomac Estuary

about 1930, provides stratigraphic horizons. These two cores were collected from subestuaries, Broad Creek and Piscataway Creek, in the upper Potomac Estuary, which probably provided the most favorable environment for water chestnut during the infestation.

On the basis of these dated horizons, sedimentation rates, in centimeters per annum, and fluxes, in grams per square centimeter per annum, were calculated. The sedimentation rates and fluxes ranged from 0.21 cm/a and 0.09 $(g/cm^2)/a$ at the mouth of the estuary to 1.72 cm/a and 1.14 $(g/cm^2)/a$ in the Broad Creek subestuary near Washington, D.C. The rates generally were slow and the fluxes small in the lower part of the estuary [0.21 cm/a and 0.09 $(g/cm^2)/a$], and rapid and large in the upper part of the estuary [0.22 to 1.72 cm/a and 0.17 to 1.14 $(g/cm^2)/a$] and in Kettle Bottom Shoals [0.64 to greater than 0.81 cm/a and 0.34 to greater than 0.42 $(g/cm^2)/a$]. Several cores in which only minimum sedimentation rates could be determined also indicate rapid sedimentation rates in the upper estuary. Fairly constant pollen concentrations in the cores indicate even and continuous sedimentation, except in a storm deposit 14 cm thick in the core from Broad Creek.

Five cores were collected along the length of the Port Tobacco subestuary. The sedimentation rate and flux from 1840 to 1978 indicated in the core from the head of the subestuary were very rapid and large [greater than 1.14 cm/a and greater than 1.00 $(g/cm^2)/a$]; in the other cores, the indicated sedimentation rates were 0.51, 0.48, 0.53, and 0.40 cm/a and the sediment fluxes were 0.23, 0.23, 0.24, and 0.29 $(g/cm^2)/a$. Two cores from St. Johns Pond near the St. Marys River subestuary indicate slow average sedimentation rates and small sediment fluxes from 1634 to 1840, 0.22 and 0.31 cm/a and 0.15 and 0.19 $(g/cm^2)/a$, but faster sedimentation rates and greater sediment fluxes from 1840 to 1978, 0.52 and 0.67 cm/a and 0.48 and 0.51 $(g/cm^2)/a$. This increase may result from increased sediment input from land clearance in the drainage basin or from increased trap efficiency in the pond.

The sedimentation rate and the flux indicated in the core from the mouth of the estuary remained virtually unchanged between 1634 and 1840 [0.23 cm/a and 0.14 $(g/cm^2)/a$] and 1840 to 1978 [0.21 cm/a and 0.09 $(g/cm^2)/a$]. The pollen concentrations, which should decrease if sedimentation rates increase, did not change, indicating that European settlement did not affect sedimentation in this location. In spite of the observation that construction activities in the drainage basin substantially increase sediment yields, there is no indication that construction in the Washington, D.C., metropolitan area during the last 30 years substantially increased sedimentation rates where the cores were collected. Pollen concentrations generally do not decrease toward the top of the cores, which would be the case if sedimentation rates had increased. In addition, the average sedimentation rate in a core from Piscataway Creek subestuary is practically the same from 1930 to 1978 (0.63 cm/a), as from 1840 to 1978 (0.67 cm/a). Longer cores are needed before pollen analysis can be used to indicate whether European settlement affected sedimentation rates in the upper estuary. From available evidence, the effect of European settlement on construction activities in the drainage basin appears to be confined to localized areas.

Rapid sediment accumulation in two areas of the estuary, the upper freshwater area and the Kettle Bottom Shoals area, may be controlled by two separate processes. In the upper reach of the Potomac Estuary and in the head of the Port Tobacco subestuary, decreased competence as the streams enter the estuaries may deposit the sediment. In these areas, sedimentation rates may appear rapid because of morphometry of each estuary. In Kettle Bottom Shoals, estuarine circulation may control accumulation of sediment. During the spring, at the time of greatest annual sediment discharge, the turbidity maximum may extend as far downstream as Kettle Bottom Shoals. Accumulation of sediment may be associated with the circulation pattern at the turbidity maximum. Thus, the Potomac Estuary is filling at the head of the estuary and at the head of at least one subestuary, as well as in the middle part of the estuary.

A local source of *Chenopodium* pollen is present in the Port Tobacco subestuary, but the pollen grains from this source do not travel into the main part of the Potomac Estuary. About 75 percent of the fine-grained sediment entering Port Tobacco through the head of the subestuary is deposited in the upper one-third of the subestuary; about 15 percent is deposited in the middle one-third, and about 10 percent is deposited in the lower one-third. Thus, much of the sediment entering the subestuaries of the Potomac Estuary from accelerated erosion associated with European settlement remains in the subestuaries and does not significantly affect sedimentation in the main part of the estuary. The effect of human activities in the Potomac drainage basin on sedimentation in the lower Potomac Estuary probably is confined to marsh building, as described by Froomer (1978), to local increases in sedimentation rates, and to downstream migration of the heads of navigation, as described by Gottschalk (1945) and Williams (1977). Although results from this study indicate that the effect of construction on sedimentation rates is confined to localized areas in the upper part of the estuary, further research is needed to fully understand the effects of human activities on the upper part of the estuary.

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CONVERSION FACTORS

Multiply	By	To obtain
centimeter per annum (cm/a)	0.3937	inch per year
gram per square centimeter per annum [$(g/cm^2)/a$]	0.0142	pound per square inch per year
kilometer (km)	0.6214	mile
centimeter (cm)	0.3937	inch
meter (m)	3.281	foot
square kilometer (km^2)	0.3861	square mile
square centimeter (cm^2)	0.1550	square inch
gram per cubic centimeter (g/cm^3)	0.0361	pound per cubic inch
metric ton per square kilometer (Mg/km^2)	2.855	ton per square mile
micrometer (um)	$3.281x10^{-6}$	foot
kilogram (kg)	2.205	pound
gram (g)	0.035	ounce

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