

3040

CENTER FOR CLIMATIC RESEARCH

Institute for Environmental Studies
University of Wisconsin-Madison

1225 West Dayton Street
Madison, Wisconsin 53706

608-262-2839

26 February 1990

Supt. Andrew Ringgold
U.S. Dept. of the Interior, NPS
Cape Cod National Seashore
Marconi Station Headquarters
Route 6
South Wellfleet, Mass. 02663

Dear Supt. Ringgold:

This is the final report of the study of the Provincetown Ponds entitled Recent Changes in Trophic Status of Duck and Bennett Ponds Relative to Possible Landfill Enrichment. It is an amended and edited version of the Provincetown Ponds report sent to NPS and the CCNS in September, 1989, and replaces that report with new information, new radiocarbon dates, and revised data interpretation. In addition, there is further evidence for the evolution of the interdunal ponds in the Provincelands. The wetlands at the Duck and Bennett sites were initiated on eolian sand about a millenium ago and became ponds more recently.

Sincerely,

Marjorie A. Winkler

Marjorie Green Winkler
Associate Scientist

xc: Dr. M. Foley
Dr. M. Soukup
J. Portnoy
D. Manski

3904e

Provincetown Ponds, Final Report

I. Recent Changes in Trophic Status of Duck and Bennett Ponds
Relative to Possible Landfill Enrichment

II. Evolution of Interdunal Ponds in the Provincelands
Cape Cod National Seashore

Marjorie Green Winkler

Center for Climatic Research
Institute for Environmental Studies
University of Wisconsin-Madison
1225 West Dayton Street
Madison, Wisconsin 53706

February 23, 1990

North Atlantic Regional Office, National Park Service
Order No. PX-1600-6-0004

EXECUTIVE SUMMARY

1. Recent eutrophication of Duck and Bennett ponds is evident from:

- a. the changes in diatom species in the top sediments,
- b. an increase in carbonates and organics in the top centimeters of the sediments,
- c. the increased phosphorus, total dissolved solids, alkalinity, specific conductance, pH, chlorides, and coliform counts in the pondwater chemistry measured since 1986, and
- d. the greatly increased sedimentation rate, stimulated by the increased nutrients, in both ponds during the past 30 years.

All of these changes can be directly traced to the proximity of the Provincetown Municipal Landfill, especially for Bennett Pond. Duck Pond, located adjacent to a main highway, may have impacts from additional anthropogenic factors. The ponds receive excess nutrients and contaminants from the landfill through windborne dust and detritus and waterborne leachate.

2. As a consequence of eutrophication, sedimentation rates in both ponds have increased dramatically in the past about 30 years. The sedimentation rate for Duck Pond increased 4-fold--from 0.5 mm/yr to 2 mm/yr, while the Bennett Pond sedimentation rate increased 5-fold--from 0.19 mm/yr to 1.0 mm/yr.

3. In Duck Pond, recent increases in the accumulation rates of both pelagic and littoral cladocera and in harpacticoid copepods which inhabit surface sediments, point to increased productivity in zooplankton and zoobenthic systems. This evidence correlates well with the diatom and sediment changes and the pondwater chemistry, all of which indicate eutrophication of the pond. However, as of 1986, increased productivity had not yet reduced the diversity of the aquatic micro-fauna. It is possible that cladoceran analysis of a surface sediment sample taken from Duck Pond today,

would reveal a more monotypic fauna. Further sampling and analysis should be done to test this hypothesis.

4. Neutron activation analysis of insect chitin picked from the sediments of the surface sample from Bennett Pond has shown increased vanadium and potassium over pond sediment levels. This kind of trace element analysis of the benthic invertebrates and possibly of some of the zooplankton could provide an indication of the kind and amount of elements--some of them harmful--which come from the landfill and are being concentrated by organisms. Although pondwater and groundwater analysis may at times not show large concentrations of pollutants, the concentration of these elements and compounds in pond organisms will be much higher than those in ambient water or sediment.

5. Both Duck Pond and Bennett Pond in the Provincelands evolved within the last millenium (960 ± 60 and 910 ± 70 yr B. P., respectively). $\delta^{13}\text{C}$ isotope values show that there was no influence of marine carbon at initiation of these wetlands. The radiocarbon dates are close to the one obtained from basal organics for nearby Clapp's Pond ($1,155 \pm 200$, Zeigler et al., 1965). All of these ponds are interdunal (see Winkler, 1990), and at least Duck and Bennett were bogs at the beginning of their development. Both Duck and Bennett subsequently changed from Sphagnum bogs to shallow ponds. Duck Pond made this transition at European settlement of the Provincelands about 330 years ago as land use changes modified drainage patterns, while Bennett Pond had become a pond at least 200 years before that time. Dune building took place before about 1100 years ago in this region of the Provincelands Hook (both ponds overlies eolian sands). Dune movement did not occur again in the pond region although parabolic dunes farther to the northeast in the Provincelands were active episodically during the past thousand years (see

Winkler [1990] for expanded discussion of these changes).

Recommendations

Based on the above study of the sediments and limnology of Bennett and Duck ponds in the Provincelands, and evaluation of the recent pondwater chemistry, I make the following recommendations:

- a. Close observation of the chemistry of the water in the landfill monitoring wells should continue.
- b. More adequate mapping of the landfill site, the positions of the monitor wells, and the morphometry of the ponds, should be done.
- c. Establishment of additional wells is necessary in light of elevated elements and compounds found at the present monitoring sites.
- d. Close interval (seasonal) observation of the chemical changes in the pondwater and monitoring of the changes in pond biota should be done. Although the landfill site is going to be closed, seepage from the present facility will continue to impact the groundwater and the ponds. It will be interesting to monitor the changes as conditions improve in the next years.
- e. A systematic study of trace elements in pond organisms should be initiated.
- f. A study of the evolution of other ponds in the Provincelands would provide additional chronostratigraphic data and enable comparison of the wetland changes with those found in Bennett and Duck ponds.

INTRODUCTION

The proximity of the Provincetown Municipal Landfill to some of the interdunal ponds within the Cape Cod National Seashore prompted this study. There was the possibility of both groundwater and surface water changes due to windblown pollutants and waterborne leachate coming from the sanitary landfill facility. Additions of excess nutrients and toxic elements and chemicals could cause unwanted changes in the pond biota and lead to eutrophication and increased sedimentation in the ponds. The origin and evolution of these interdunal ponds is also of interest since the Provincelands Hook is a relatively young addition to the glaciated remainder of Cape Cod and is derived from waterborne and wind-sculpted crystalline outwash sands. Sediment and aquatic pollen changes in the cores trace wetland development and/or adjacent dune movement over millenia. There is controversy about the chronology and the morphometry of the evolution of the Provincelands (see Leatherman, 1979; Zeigler *et al.*, 1965; Winkler, 1990). The chronostratigraphy from Duck and Bennett Ponds in Provincetown would illuminate aspects of this problem.

Sediment cores were obtained on October 3, 1986 from Duck Pond and Bennett Pond in Provincetown, Massachusetts (Fig. 1). The core from Duck Pond was 55 cm long and the core from Bennett Pond was 45 cm long. Both cores were taken with a modified Livingstone corer in polycarbonate tubes and showed an undisturbed sediment/water interface. Subsampling of the cores has been completed as has the analysis of the % H_2O , % loss-on-ignition (LOI) - a measure of the % of organic matter in the sediments, and % loss-on-high temperature ignition (HLOI), an estimate of the % carbonate in the sediments.

Pollen, charcoal, zooplankton, and diatoms in the sediments were also analyzed. Methods for these analyses are described or referenced in Winkler,

1989. Pondwater and wellwater chemistry, measured by others, was evaluated. The basal organic sediments from each pond were radiocarbon-dated (Table 1) and $\delta^{13}\text{C}$ was analyzed by mass spectrometer (Table 1) to identify marine carbon contribution to the pond sediments, if any.

RESULTS

Duck Pond, Provincetown

Pre-European-settlement

The ^{14}C date for the basal organic sediments of this pond shows that wetland growth was initiated by 960 ± 60 yr B. P. (Table 1). The $\delta^{13}\text{C}$ value is -28.4 , well within the stable carbon isotope range of freshwater and upland plant carbon. There is no indication of a marine carbon contribution at initiation of this bog. The wetland pollen and spore stratigraphy (Fig. 2a) indicates that this site was a Sphagnum bog dominated by a groundcover of Sphagnum mosses, Osmunda ferns, and Lycopodium club mosses, surrounded by Ilex (holly) for the first 600 years of its development. This occurred before European settlement of the Provincelands. The regional forest was dominated by pitch pine (Pinus rigida) and oak (Quercus spp.) (Fig. 2b and see Winkler, 1985a). Charcoal abundances were high during this time suggesting that the peatland burned periodically. Sarcodines (testate amoebae, see Winkler, 1990) were abundant below 15 cm in the core. These organisms are found frequently in acid, Sphagnum bogs where their resistant tests withstand periodic water level changes.

At settlement (about 330 years ago)

There was a regional decrease in pines, an increase in birch (Betula) and bracken fern (Pteridium)- possibly in response to post-settlement logging fires and forest clearance. Charcoal abundances decrease in the sediment at the bog/pond transition (at about 15 cm) and increase after that time.

Post-European settlement

Ambrosia (ragweed) and other herb and grass pollen increase (Figs. 2b, 3F) indicating European settlement. There is a decrease in the pollen from all trees except scrub oak (Fig. 2b).

The wetland changes are concurrent with the rise in Ambrosia pollen and show that there was an increase in water levels in the pond at about the time of European settlement. Sphagnum spores decrease and pollen from aquatic macrophytes (waterlilies, Potamogeton, and sedges) increase (Fig. 2a). Sarcodines become infrequent and cysts of chrysophyte algae increase in number. The wetland change, a transition from Sphagnum bog to deep water marsh, is concurrent with settlement changes and suggests that recent wetland changes at Duck Pond may be anthropogenic, rather than natural (climatic, edaphic, or morphometric). Disruption of water flow by roadbuilding results in ponding and causes changes in wetland development. On the other hand, increased pumping of groundwater for domestic or industrial use could lower freshwater tables in the region.

The changes in percent organic matter (Fig. 3D), decreasing from over 70% when Duck Pond was a bog to less than 50% as the water level increased at settlement, also documents the wetland changes. The sharp decrease in organic matter after settlement (Fig. 3D), as well as an increase in carbonates (Fig. 3E), indicates erosion from road building and other construction and land clearance changes. An increase in organic matter most recently is evident as more nutrients enrich the pondwater. The sedimentation rate for Duck Pond increased 4-fold--rising from 0.5 mm/yr for 930 years to 2 mm/yr in the past 30 years.

Diatom stratigraphy

The diatom changes upcore (Fig. 4) are consistent with the wetland

vegetation changes (Fig. 2a). There are high percentages of Pinnularia diatoms which are found in acid Sphagnum bogs. There are also aerophilic (wind-borne) diatoms and other diatom species which live on mosses. During the high Sphagnum stage there is a transition to high percentages of Eunotia diatoms (acid periphytic species) and as the water level increases even more there is a higher abundance of planktonic diatoms, primarily Tabellaria and Fragilaria species. The top 6 cm of the core shows evidence of recent disturbance and changes in diatom taxa. Diatoms which respond to more eutrophic conditions--Melosira ambigua, Nitzschia, Gomphonema, and Synedra--increase. The change in Fragilaria species is exemplified by the decrease of almost 50% of the acidophilic Fragilaria virescens var exigua, and an increase in Fragilaria stricta and its varieties. Zooplankton analysis (discussed below) also suggests a change to a species assemblage indicative of increased productivity in the top sediments. There is a doubling of both Chydorus sp. and Eubosmina in the surface sample.

The pH during the life of the bog/pond has been reconstructed from the diatom stratigraphy (Tables 2, 3, Fig. 5). The theory and methods for this analysis are presented in Winkler, 1985b; 1988; and 1989. Duck Pond, Provincetown, has been an acid wetland for 960 years. Over that time, it has had a mean diatom-inferred pH of 4.92 ± 0.34 (range: 3.9 - 5.2). The pond increased in pH above about 16.5 cm in the core (slightly below European settlement), going from a mean pH of 4.82 ± 0.4 before European settlement to a mean pH of 5.07 ± 0.09 after European settlement. However, the most dramatic increase in pH has been found in the past few years (1985 through 1989) (Table 4) as the monthly measured pH (Acid Rain Monitoring Project, ARM data) has ranged from 5.1 to 6.49. Measurements taken at the beginning of May, 1989 also show pH values ranging from 6.39-6.44 (Lepore et al., 1990).

Cladoceran Analysis (by Dr. P. Sanford)

Cladocera from the 53 cm core representing the complete sedimentary record of this 960 ± 60 yr B. P. shallow interdunal pond were analyzed. Samples for analysis were taken contiguously in the top 4.5 cm, at 3-4 cm intervals down through 18 cm, and at approximately 10 cm intervals thereafter. Methods of processing and identification are discussed by P. Sanford in Winkler (1989). Littoral Chydorid Cladocerans.

Littoral chydorid cladocerans dominate the sediments (Fig. 6a). This was the expected finding for a shallow pond which evolved from a Sphagnum bog as regional water levels increased or as highway and other construction modified drainage patterns. Chydorids comprise 90-100% of the cladoceran sum for the samples from the bottom 2/3 of the core (16.5-53 cm) (Fig. 6a) which pollen analytical and diatom evidence show to represent Sphagnum bog. The major chydorid genera throughout bog formation are Chydorus and Alonella which occur in roughly equal proportions. Alonella is most frequently found in unpolluted ponds and bogs. Chydorids decline to 55% of the cladoceran sum at 12-13.3 cm (Fig. 6a) when pollen and diatom evidence indicate pond formation. Pelagic (open water) forms of cladocera (Bosminidae, Daphnidae, and Sididae) comprise the remaining 45% of the sample (Fig. 6a). Early in the development of the pond (12-13.5 cm in the core) the accumulation rate of Chydorids is very slightly less than that of pelagic cladocera (Fig. 6b)---the only time this situation occurs in the Duck Pond sedimentary record. Coincident with the change in the cladoceran record between 16.5 and 13.5 cm is a decline in both concentration and accumulation rates of harpacticoid copepod spermatophores (Figs. 7a, b). These structures are frequently found as microfossils in Sphagnum peats (Frey, 1964). Their decline is yet another indicator of the change from bog to pond.

In the first half of the 20th century (6-7.5 cm) the littoral chydorid concentrations and accumulation rates once again exceed those of pelagic cladocera (Fig. 6b). This trend continues upcore in the most recent sediments and is probably the result of development of macrophyte beds over the pond bottom. Alonella, co-dominant with Chydorus during bog formation, declines in importance and Alona takes its place. Both Chydorus and Alona inhabit macrophyte vegetation and at times are found in open water where they use planktonic algae as a feeding substrate (Whiteside, 1970). In the most recent sample, approximating the period 1978 - 1986, chydorid concentrations and accumulation rates increase by 40% over those of immediately underlying sediments (Fig. 6b). This is due chiefly to an increase in Chydorus spp. This Chydorus is the same cladoceran which has been previously identified by many investigators as C. sphaericus, an indicator of eutrophic environments (the species designation in North America has been questioned by D. Frey, pers. comm.). Slight increases in Alona, Acroperus, and Alonella also occur (Figs. 8a,b). These increases do not occur at the expense of species diversity which remains unchanged in the three most recent samples. Increased abundances of chydorids in the most recent sediments suggest increased productivity in response to increased nutrients, but no essential change in the structure of the littoral cladoceran community occurs.

Pelagic Cladocerans

Pelagic cladocerans, Eubosmina longispina and Daphnia sp., occur in low numbers in both middle and late periods of bog development (Fig. 6a) indicating intermittent periods of standing water in the bog. Significant increases in percent, concentration, and accumulation rate of pelagic cladocerans occur at 12-13.5 cm (approximately 330 years ago) (Figs. 6a,b) when pollen (Fig. 2a) and diatom (Fig. 4) evidence indicate pond formation.

Pelagic forms outnumber littoral forms for only a short period in the early development of the pond. Eubosmina longispina is the principle pelagic species. The explosive increase in pelagic cladoceran abundances following initial colonization of a new habitat subsides as plant macrophyte communities cover the pond bottom (Fig. 2a) and provide new habitat for littoral chydorids. However, pelagic cladoceran numbers never fall to pre-pond levels and a more diverse species assemblage develops (Fig. 9a). In the most recent sediment (Figs. 9a,b,c) pelagic cladoceran concentrations equal those of the early pond period, while their accumulation rates are the highest in the history of the pond. The increased accumulation rate is due primarily to a doubling in numbers of E. longispina, E. tubicen, and Bosmina longirostris (Fig. 9b).

Recent large accumulation rate increases in both pelagic and littoral cladocera and in harpacticoid copepods (Fig. 7b) which inhabit surface sediments, point to increased productivity in zooplankton and zoobenthic systems within Duck Pond. These changes reflect increased nutrients in the pondwater. As of 1986 increased productivity had not reduced the diversity of aquatic micro-fauna.

Bennett Pond

The evolution of the wetland at Bennett Pond is the same as that at Duck Pond with Sphagnum bog changing to pond, although the time of transition is different at each site (Fig. 10). This change at Bennett Pond is evident from a decrease in organic matter (Fig. 3A)--peats have more than 60% organic matter and gyttja (lake sediment) has less--as well as a dramatic decrease in Sphagnum spores, a concurrent increase in pollen from sedges and aquatic macrophytes (Fig. 11a), a decrease in the number of bog-dwelling sarcodines

(testate amoebae) in the sediments, and an increase in the number of algal chrysophyte cysts (abundant at times in deeper water). The initiation of the interdunal bog at this site was radiocarbon-dated at 910 ± 70 yrs B. P. (Table 1). The $\delta^{13}\text{C}$ value of the basal organics at Bennett Pond was -27.7 (Table 1), indicating no contribution of marine carbon at initiation of the interdunal bog, similar to the findings from Duck Pond, Provincetown. Unlike Duck Pond, however, the transition from a bog to a deeper pond (Fig. 11a) occurred well before European settlement.

The settlement horizon at about 12 cm is indicated by an increase in pollen from Ambrosia (ragweed), Rumex, other herbs, and grass and a decrease in pine pollen (Fig. 11b). The pollen from the 13-14 cm subsample was counted but has not yet been plotted on Fig. 11b. This sample contains 0.3 % Ambrosia pollen, less than 1% pollen from other non-arboreal taxa, high pine pollen percentages, and no other indication that settlement changes had begun. High charcoal abundances are found in the bog peats and also at European settlement. The change in organic matter at about 12 cm in the core (Fig. 3A) is probably associated with erosion from land use changes. As at Duck Pond, there are high carbonates in the most recent sediments of Bennett Pond (the topmost 3 cm, Fig. 3B) which probably indicate the windblown dust and silt from the landfill. Organic enrichment in these top sediments is also evident (Fig. 3A) as are diatom changes in response to nutrient loading (discussed below) and sedimentation rate changes--a three-fold increase in the last 30 years (to 1 mm/yr) as compared to the sedimentation rate calculated for the preceding 300 years of settlement (0.3 mm/yr) and a five-fold increase compared to the sedimentation rate calculated for the preceding 880 years (0.19 mm/yr).

Diatom changes (Fig. 12) as well as wetland vegetation changes (Fig. 11a)

document several water level changes at this site. There was an early pre-bog-forming stage with dominant Pinnularia diatoms (similar to that at Duck Pond) and then a transition to acid periphytic Eunotia and Frustulia species. As the water levels further increased, the diatoms that dominated the pond were Fragilaria virescens var exigua, an acid, planktonic species. An increase in nutrient inputs to the pond occurred documented by diatom changes in the top 3 cm of the sediment which probably was caused by creation of the adjacent sanitary landfill. Very acid Eunotia species of diatoms become dominant again as well as more eutrophic diatoms such as Nitzschia, Gomphonema, and Synedra. Fragilaria (F. lapponica) also increase.

The reconstructed pH of Bennett Pond shows changes that are similar to those found in Duck Pond (Tables 2 and 3, Fig. 5). Both Duck and Bennett Ponds in Provincetown had the most acid pH-distribution over millenia compared to the ponds in the Truro and Wellfleet outwash plains (Winkler, 1989). The soils of the Provincelands, which are derived from the outwash sands of the glaciated portion of the Outer Cape (Winkler, 1990), are very low in carbonate. This is because the original glacial deposits are crystalline, coarse sands, already low in carbonate, and the mechanics of redeposition further removed nutrients from the soil.

Bennett Pond has been an acid wetland for 910 years (Fig. 5). It has had a mean diatom-inferred pH of 4.91 ± 0.12 (range: 4.67 - 5.1). The pond increased in pH in the top levels in the core, going from a mean pH of 4.84 ± 0.12 before European settlement to a mean pH of 4.95 ± 0.11 after European settlement. However, the most dramatic increase in pH has been found in the past few years (1985 through 1989) (Table 4) as the monthly measured pH (Acid Rain Monitoring Project, ARM data) has fluctuated between 4.7 and 6.3. Measurements taken at the beginning of May, 1989 also show pH values ranging

from 6.38-6.44 (Lepore et al., 1990). It is interesting to note that the high HLOI values (% carbonates) in the top centimeters of the Bennett Pond sediments (Fig. 3B) and the increase in more eutrophic diatoms, foreshadow the finding that groundwater in monitoring well #6 (between Bennett Pond and the landfill site, Fig. 1) has become more contaminated and is the drainageway for leachate from Phase II of the operation at the landfill (Lepore et al. 1990). Windblown detritus coming from the landfill litters the surface of Bennett Pond (pers. obs.), and lime, used in the septage lagoons (Lepore et al., 1990), may also be entrained by the wind and enter the pond as dust, increasing the pH of the pondwater dramatically.

Neutron Activation Analyses

In an attempt to test a new technique for determining the concentration of toxic elements and compounds in organisms in Bennett Pond, samples of whole sediment and arthropod parts within the sediments were separated at several levels. Ephippia (the egg cases of cladocerans) were also separated from the sediment in hopes that element analysis of this homogenous zooplankton sample could be done. Organisms concentrate elements from their environment. Toxic elements or metals are concentrated as they are transferred through the foodchain (Nehring, 1976; Weiss et al., 1981; Colborn, 1982). These facts suggest that although normal levels of substances may be measured in pondwater or pond sediment, organisms within the lake may still be receiving damaging or toxic levels of some materials.

Neutron activation analysis is a sensitive technique by which concentrations of trace elements and heavy metals can be measured in biological as well as inorganic materials (Tölgyessy and Klehr, 1987). This was to be a preliminary study with the cooperation of Dr. R. Cashwell of the Neutron Activation Laboratory at U. W.-Madison. We were not charged for the

analyses. We found that we would need a much larger sediment sample than was available because the insect and cladoceran parts, although relatively abundant in the sediments, were very light in weight. In order to contrast concentrations of elements from various samples, the dry weight of the samples had to be known. The only sample that could be analyzed was arthropod parts picked from the surface centimeter of Bennett Pond. This sample was found to be enriched in vanadium and potassium over background sediment levels. These findings may indicate excessive (possibly toxic) levels of these elements in pond insects, but may merely be within the range of normal concentrations of vanadium and potassium in insect chitin. We are continuing to analyze samples and are planning a more systematic temporal and spatial study of element concentrations in pond organisms. Picking insect chitin and cladoceran ephippia is very laborious and time-consuming, so we will also experiment with flotation and freeze-drying techniques of separation.

Wellwater and Pondwater Chemistry

Wellwater chemistry from samples collected from monitoring wells (Fig. 1) in November, 1986, and from the wells and the ponds in January, March, June, and September, 1987 (Table 5), was analyzed by GHR Analytical, Inc., 26 Main Street, Lakeville, Massachusetts. The observations show that groundwater flows in the direction of Duck Pond from the landfill site with monitoring well #4 (Fig. 1) being consistently most contaminated. However, there is seepage from the landfill site in all directions. Evidence for this can be seen in high nitrate values in well #9 near the septage lagoons, high alkalinity, specific conductance, and chlorides in wells 2, 3, and 4, high values of total dissolved solids in well #4, and instances of elevated coliform counts in many of the wells and also in each of the ponds (Fig. 1, Table 5). Chloride and sodium are high in the ponds (43.2-39.2 for Cl^- and

25.2-20.4 for Na^+) but part of the abundance of these elements may be a function of the proximity of the sea. Values from other bogs from the northeast through the midwest, however, show maximum values of 26 mg/l for chloride and 13 mg/l for sodium (Gorham et al., 1985). Phosphorus is also high in the ponds (as it is in wells #5 through #9), especially in June, 1987, in Bennett (0.23) and in Duck (0.26), but also in September, 1987. These phosphorus values indicate enrichment of the groundwater as well as the pondwater. For comparison (Gorham et al., 1985; Charles, 1985; Lillie and Mason, 1983; Dunne and Leopold, 1978; Clausen and Brooks, 1980; Groundwater Contamination, 1984), mean total phosphorus values in Wisconsin bogs are 0.031 mg/l, Michigan 0.014, Connecticut 0.031, Maine 0.008, and the range of values for Minnesota lakes and bogs are 0.024-0.176, for Poconos 0.015-0.732 (latter value from a peat mining site), Adirondacks 0.0027-0.0628, "uncontaminated water" 0.03-0.1. Total Solids (TDS) are elevated in most of the monitoring wells and are also increasingly elevated in the ponds (Table 5).

Uncontaminated water has less than 50 mg/l or a range of 50-90 mg/l TDS (depending on the reference, see sources above) while the values of TDS in the two ponds are from 73 to 182 mg/l and in the monitoring wells range between 90 and 1200 mg/l showing contamination in both the ponds and the wells.

Measureable toxic organic compounds have been found in wells 1, 2, 3, 4, and 9. The concentrations of organic compounds should be closely watched since monitoring wells # 3, 4, and 9 had high levels of chlorobenzene, ethylbenzene, and methylene chloride on or before March 17, 1987 (Table 5), and high levels of the above mentioned compounds plus additional toxic organic compounds (benzene, trichloroethane, and xylene--all volatile carcinogens) were also found in monitoring wells #1, 2, 3, and 4 in June and September of 1987 (Table 5). Organic compound values higher than 50 ug/L are defined as

the point where wells should be closed (Groundwater Contamination, 1984). Chlorobenzene levels in well #4 have reached to over 30 and should be closely watched. PCBs and other polycyclic hydrocarbons have been found in open seeps within the landfill in May, 1988 (Lepore et al., 1990). Little is known about the cycling, residence time, and hazardous effects of these substances in ground and surface waters, but there is evidence of mobility of organic compounds after deposition (Tan and Heit, 1981). Because organic sediments such as those found in ponds are natural sinks of these toxic compounds (Winkler and DeWitt, 1985), further monitoring of these seeps is crucial.

The pH of the water in the monitoring wells has increased to between 5.8 and 6.8 in the September 1987 measurements, but had been between 5.3 and 6.5 in November 1986 analyses. The pondwater pH, as discussed above, has also increased dramatically (Tables 2,3,4,5). Bennett Pond has fluctuated between pH 4.7 and 6.4 and Duck Pond has increased from pH 5.1 to 6.49. pH of the pondwater has been consistently above 6 in the past 3 years, while pre-landfill and pre-European settlement pH values of both ponds were below pH 5.

While it is evident that contamination of both groundwater and surface waters has occurred in Bennett and Duck ponds due to proximity of the landfill, continued monitoring of these wells and ponds is needed to further define and clarify the effects of the landfill on the groundwater in the area and the movement of the plume of contaminated water from the landfill to the pond aquifer.

Conclusions

1. Recent eutrophication of Duck and Bennett ponds is evident from:
 - a. the changes in diatom species in the top sediments,
 - b. an increase in carbonates and organics in the top centimeters of the sediments,

c. the increased phosphorus, total dissolved solids, alkalinity, specific conductance, pH, chlorides, and coliform counts in the pondwater chemistry measured since 1986, and

d. the greatly increased sedimentation rate, stimulated by the increased nutrients, in both ponds during the past 30 years.

All of these changes can be directly traced to the proximity of the Provincetown Municipal Landfill, especially for Bennett Pond. Duck Pond, located adjacent to a main highway, may have impacts from additional anthropogenic factors. The ponds receive excess nutrients and contaminants from the landfill through windborne dust and detritus and waterborne leachate.

2. As a consequence of eutrophication, sedimentation rates in both ponds have increased dramatically in the past about 30 years. The sedimentation rate for Duck Pond increased 4-fold--from 0.5 mm/yr to 2 mm/yr, while the Bennett Pond sedimentation rate increased 5-fold--from 0.19 mm/yr to 1.0 mm/yr.

3. In Duck Pond, recent increases in the accumulation rates of both pelagic and littoral cladocera and in harpacticoid copepods which inhabit surface sediments, point to increased productivity in zooplankton and zoobenthic systems. This evidence correlates well with the diatom and sediment changes and the pondwater chemistry, all of which indicate eutrophication of the pond. However, as of 1986, increased productivity had not yet reduced the diversity of the aquatic micro-fauna. It is possible that cladoceran analysis of a surface sediment sample taken from Duck Pond today, would reveal a more monotypic fauna. Further sampling and analysis should be done to test this hypothesis.

4. Neutron activation analysis of insect chitin picked from the sediments of the surface sample from Bennett Pond has shown increased vanadium and potassium over pond sediment levels. This kind of trace element analysis of

the benthic invertebrates and possibly of some of the zooplankton could provide an indication of the kind and amount of elements--some of them harmful--which come from the landfill and are being concentrated by organisms. Although pondwater and groundwater analysis may at times not show large concentrations of pollutants, the concentration of these elements and compounds in pond organisms will be much higher than those in ambient water or sediment.

5. Both Duck Pond and Bennett Pond in the Provincelands evolved within the last millenium (960 ± 60 and 910 ± 70 yr B. P., respectively). $\delta^{13}\text{C}$ isotope values show that there was no influence of marine carbon at initiation of these wetlands. The radiocarbon dates are close to the one obtained from basal organics for nearby Clapp's Pond ($1,155 \pm 200$, Zeigler *et al.*, 1965). All of these ponds are interdunal (see Winkler, 1990), and at least Duck and Bennett were bogs at the beginning of their development. Both Duck and Bennett subsequently changed from Sphagnum bogs to shallow ponds. Duck Pond made this transition at European settlement of the Provincelands about 330 years ago as land use changes modified drainage patterns, while Bennett Pond had become a pond at least 200 years before that time. Dune building took place before about 1100 years ago in this region of the Provincelands Hook (both ponds overlies eolian sands). Dune movement did not occur again in the pond region although parabolic dunes farther to the northeast in the Provincelands were active episodically during the past thousand years (see Winkler [1990] for expanded discussion of these changes).

Recommendations

Based on the above study of the sediments and limnology of Bennett and Duck ponds in the Provincelands, and evaluation of the recent pondwater chemistry, I make the following recommendations:

- a. Close observation of the chemistry of the water in the landfill monitoring wells should continue.
- b. More adequate mapping of the landfill site, the positions of the monitor wells, and the morphometry of the ponds, should be done.
- c. Establishment of additional wells is necessary in light of elevated elements and compounds found at the present monitoring sites.
- d. Close interval (seasonal) observation of the chemical changes in the pondwater and monitoring of the changes in pond biota should be done. Although the landfill site is going to be closed, seepage from the present facility will continue to impact the groundwater and the ponds. It will be interesting to monitor the changes as conditions improve in the next years.
- e. A systematic study of trace elements in pond organisms should be initiated.
- f. A study of the evolution of other ponds in the Provincelands would provide additional chronostratigraphic data and enable comparison of the wetland changes with those found in Bennett and Duck ponds.

ACKNOWLEDGEMENTS

I thank J. Portnoy, J. Overpeck, and K. Gajewski for field assistance and P. Sanford for laboratory help and for the cladoceran analysis. P. Behling prepared some of the figures. M. Kennedy, M. Woodworth, and A. Anderle at CCR helped in many ways. J. Portnoy and D. Manski at CCNS facilitated this study by providing chemical data and local maps. Dr. M. A. Soukup, who was Chief Scientist at NARO-NPS when this research was initiated, provided financial as well as scientific support.

This research was funded by the Office of Scientific Studies, North Atlantic Regional Office, National Park Service, Order No. PX-1600-6-0004, and by NSF grant ATM87-13227 to J. E. Kutzbach, Center for Climatic Research, University of Wisconsin-Madison.

Literature Cited

- Charles, D. F. (1985). Relationship between surface sediment diatom assemblages and lakewater characteristics in Adirondack Lakes. Ecology 66: 994-1011.
- Clausen, J. C. and Brooks, K. N. (1980). The water resources of peatlands: A literature review. Minnesota Dept. of Natural Resources. Minnesota Peat Program. 143 pp.
- Colborn, T. (1982). Aquatic insects as measures of trace-element presence in water: cadmium and molybdenum. pp. 316-325 In Aquatic Toxicology and Hazard Assessment: Fifth Conference. J. G. Pearson, R. B. Foster & W. E. Bishop, eds. Amer. Soc. for Testing and Materials.
- Dunne, T. and Leopold, L. B. (1978). Water in Environmental Planning. W. H. Freeman and Co., San Francisco. 818 pp.
- Frey, D. G. (1964). Remains of animals in Quaternary lake and bog sediments and their interpretation. Ergebnisse der Limnologie. Archiv f. Hydrobiologie 2:1-114.
- Gorham, E. et al. (1985). The chemistry of bog waters. pp. 339-363 In Chemical Processes in Lakes. W. Stumm, ed. J. Wiley and Sons, New York.
- Groundwater Contamination (1984). Studies in Geophysics Series. National Research Council. National Academy Press. Washington, D. C. 179 pp.
- Leatherman, S. P. (1979). Evolution of the Province Lands. pp. 193-206 In Leatherman, S. P. (ed.) Environmental Geologic Guide to Cape Cod National Seashore. Field Trip Guide Book for the ESPM. NPS-CRU, Univ. of Massachusetts-Amherst.
- Lepore, J. V., Ruge, C. D. and Ahlert, R. C. (1990). Provincetown Municipal Landfill containment assessment. Final Report to the National Park Service, Cape Cod National Seashore. 28 pp.
- Lillie, R. A. and Mason, J. W. (1983). Limnological characteristics of Wisconsin lakes. Dept. of Natural Resources Technical Bulletin No. 138, P. O. Box 7921, Madison, Wisconsin 53707.
- Nehring, R. B. (1976). Aquatic insects as biological monitors of heavy-metal pollution. Bulletin of Environmental Contamination and Toxicology 15:147-154.
- Tan, Y. L. and Heit, M. (1981). Biogenic and abiogenic polynuclear aromatic hydrocarbons in sediments from two remote Adirondack lakes. Geochimica et Cosmochimica Acta 45:2267-2279.
- Tölgyessy, J. and Klehr, E. H. (1987). Nuclear Environmental Chemical Analysis. Ellis Horwood Limited, Publ., Chichester, England. 185 pp.

Weiss, C. M., Maas, R. P. and Dressing, S. A. (1981). Stream monitoring for heavy-metals. Water Resource Research Institute Report 162. University of North Carolina, Raleigh, N. C. 140 pp.

Whiteside, M. C. (1970). Danish Chydorid Cladocera: Modern ecology and core studies. Ecological Monographs 40(1):79-188.

Winkler, M. G. (1985a). A 12,000-year history of vegetation and climate for Cape Cod, Massachusetts. Quaternary Research 23, 301-312.

Winkler, M. G. (1985b). Diatom evidence of environmental changes in wetlands: Cape Cod National Seashore. Technical Report to the North Atlantic Regional Office of the National Park Service. Part I. Prehistoric and Historic Trends in Acidity of the Outer Cape Ponds. 97 pp.

Winkler, M. G. (1988). Paleolimnology of a Cape Cod kettle pond: diatoms and reconstructed pH. Ecological Monographs 58(3):197-214.

Winkler, M. G. (1989). Geologic, Chronologic, Biologic, and Chemical Evolution of the Acid Kettle Ponds within the Cape Cod National Seashore. Report to the National Park Service, North Atlantic Region. 145 pp.

Winkler, M. G. (1990). The evolution of modern and ancient interdunal bogs in the Provincelands of the Cape Cod National Seashore. Report to the National Park Service, North Atlantic Region. 38 pp.

Winkler, M. G. and C. B. DeWitt (1985). Environmental impacts of peat mining: Documentation for wetland conservation. Environmental Conservation 12:317-330.

Zeigler, J. M., Tuttle, S. D., Tasha, H. J., and Giese, G. S. (1965). The age and the development of the Provincelands Hook, Outer Cape Cod, Massachusetts. Limnology and Oceanography 10 (Supplement), R298-R311.

Table 1. RADIOCARBON DATES FROM THE PROVINCELANDS

960 ± 60

WIS-2005. Duck Pond, Provincetown

$\delta^{13}\text{C} = -28.4 \text{ o/oo}$

Core coll Oct 1986 from Duck Pond, Barnstable Co (42°03'00"N, 70°11'30"W)
and subm by M Winkler, University of Wisconsin-Madison. Peaty gyttja from 103
to 103.5cm below water surface, water depth 50cm. Acid treatment only.

910 ± 70

WIS-2006. Bennett Pond, Provincetown

$\delta^{13}\text{C} = -27.7 \text{ o/oo}$

Core coll Oct 1986 from Bennett Pond, Barnstable Co (42°03'30"N,
70°12'00"W) and subm by M Winkler. Gyttja from 90cm below water surface,
water depth 70cm. Acid treatment only.

Duck Pond Provincetown							
Depth(cm)	Date	%Acb	%acp	%Ind	%alk	%Akb	recpH
1.5	33	7	61	18	9	0	5.192
3	66	5	61	18	8	0	5.078
6	132	6	63	19	4	0	4.748
13.5	297	3	64	7	14	0	5.066
16.5	357	7	78	4	7	0.25	5.05
21	438	7	77	4	5	0	4.884
27	546	6	67	3	13	0	5.006
36	708	0	84	4	5	0	4.954
45	870	1	66	0	1	0	3.934
53	960	5	80	12	2	0	5.076

Bennett Pond Provincetown							
Depth(cm)	Date	%Acb	%acp	%Ind	%alk	%Akb	recpH
1	21	3	60	25	5	0	5.092
2	42	4	58	27	3	0	5
3	63	5	61	24	3	0	5
5	105	4	70	17	1	0	4.856
7	147	1	78	6	4	0	4.792
8	168	5	69	9	4	0	4.674
10	210	4	64	21	2	0	4.986
12	252	4	69	17	3	1	4.954

Southeast Pond Wellfleet							
Depth(cm)	Date	%Acb	%acp	%Ind	%alk	%Akb	recpH
1		10	54	16	7	0	4.81

Table 2. Diatom-inferred pH for the Provincetown Ponds. Percentage of diatom taxa distributed in pH groups (see Winkler, 1989).

	<u>Mean Geom pH</u>	<u>Standard Deviation</u>	<u>Pop. Variance</u>
Duck Pond Wellfleet	5.2	± 0.3	
Great Pond Wellfleet	5.3	± 0.25	$= \pm 0.063$
Dyer	5.19	± 0.27	$= \pm 0.07$
Great Pond Truro	5.84	± 0.7	$= \pm 0.48$
Ryder	5.55	± 0.26	$= \pm 0.07$
→ Duck Pond (Prov)	4.92	± 0.34	$= \pm 0.11$ pre 1986
→ Bennett Pond (Prov)	4.91	± 0.12	$= \pm 0.02$ pre 1986

Mean Geom pH

	<u>Pre Eur Sett</u>	<u>Post Sett</u>	<u>Post Indust</u>	<u>Post Lim</u>
Great Pond Wellfleet	5.34 $\pm$ 0.2			
Dyer	5.24 $\pm$ 0.17	5.07 $\pm$.39	4.96 $\pm$.37	
Great Pond Truro	6.04 $\pm$ 0.76	5.46 $\pm$ 0.27	5.41 $\pm$ 0.25	5.35 $\pm$ 0.24
→ Duck Pond (Prov)	4.82 $\pm$ 0.4	5.07 $\pm$ 0.09		
→ Bennett Pond (Prov)	4.84 $\pm$ 0.12	4.95 $\pm$ 0.11		

Great Pond Truro

Before 13000	7.4 $\pm$ 0.4
0 to 12,999 yr B.P.	5.6 $\pm$ 0.3

Pollen zones

Great Pond Truro			Duck Pond Wellfleet		
1a	14100 - 13790	7.6 $\pm$ 0.3	1a	before 12000	4.83
1b	13790 - 11000	6.3 $\pm$ 0.6	1bc	11800 - 10500	5.41 $\pm$ 0.42
1c,2	11000 - 9900	5.7 $\pm$ 0.14	2	10500 - 9000	4.97 $\pm$ 0.08
3a	9000 - 8200	6.15	3a	9000 - 8000	5.46 $\pm$ 0.12
3b	8200 - 5000	5.4 $\pm$ 0.35	3b	8000 - 5000	5.1 $\pm$ 0.12
3c	5000 - 2200	5.5 $\pm$ 0.2	3c	5000 - 2200	5.6 $\pm$ 0.09
3d	2200 - 330	5.8 $\pm$ 0.2	3d	2200 - 330	5.02 $\pm$ 0.23
3e	330 - 0	5.46 $\pm$ 0.27	3e	330 - 0	5.1 $\pm$ 0.2
3e1	330 - 150	5.81 $\pm$ 0.03	3e1	330 - 150	5.23 $\pm$ 0.2
3e2	150 - 0	5.41 $\pm$ 0.25	3e2	150 - 0	4.95 $\pm$ 0.08

Table 3. Mean pH for Duck Pond (Provincetown) and Bennett Pond (Provincetown) (from Winkler, 1989).

MoYr	HorSpH	HorAlkE	↓ DProvPH	↓ DProvAlkE	DPrvCond	LBenPvPH	LBenAlkE	LBeAlkSM	LBenCond	↓ BenPrPH	BenAlkE	BenCorrd
1	9.75									4.89		80.30
2	1.76											
3	4.82					5.10	-6.30	-5.40	88.70			
4	2.83											
5	3.83											
6	4.83											
7	5.83											
8	6.83											
9	6.83											
10	7.83											
11	8.83											
12	9.83											
13	10.83											
14	11.83											
15	12.83											
16	1.84											
17	2.84											
18	3.84											
19	4.84											
20	5.84											
21	11.84											
22	12.84											
23	1.85											
24	3.85											
25	4.85	5.72	0.60	6.49	6.10	6.03	1.70					
26	5.85											
27	7.85											
28	7.85											
29	7.85											
30	8.85											
31	9.85											
32	10.85											
33	10.85											
34	11.85											
35	12.85											
36	1.86											
37	1.86											
38	4.86	5.85	-0.10	6.18	3.00	5.29	0.30					
39	7.86	6.44	2.80	5.97	5.80	4.94	0.40					
40	10.86	6.28	1.20	5.22	0.30	4.57	-1.50					
41	1.87			5.10		110.00				4.70		120.00
42	1.87	5.65	0.20	5.34	0.80	4.83	-0.90					
43	3.87			6.00	32.00	205.00				4.90		113.00
44	4.87	5.69	0.60	5.93	3.40	4.73	-1.10					
45	6.87			6.20	38.00	208.00				6.30	37.00	131.00
46	7.87	6.19	1.60	6.10	14.40	16.90	4.35					
47	9.87			6.10	12.00	180.00				5.10		145.00
48	10.87	6.07	0.50	6.14	6.90	9.40	4.70	-1.10	0.90			
49	1.88	5.45	0.00	5.81	3.90	5.80	5.79	6.10	8.40			
50	4.88	5.42	-0.10	6.33	4.00	6.30	5.90	2.70	4.60			
51	7.88	6.05	1.30	5.60	1.40		4.60	-1.00				
52	10.88	6.26	1.40	5.79	2.40		4.44	0.00				
53	1.89	5.42	0.30	5.74	3.40		4.95	0.80				
54	4.89	5.20	-0.90	5.75	2.10		5.06	-0.10				
55	7.89	6.01		5.90			4.59					

Table 4. Pondwater chemistry from 4/85 to 7/89. Dprov=Duck Pond Provincetown. BenPr=Bennett Pond Provincetown.

Provincetown Landfill Site, Wellwater Chemistry

																				collected 11/13/86	
Well #	pH	Alkal	Sp. Cond	NH3	NO3	BOD5	COD	Chloride	P-Total	Sulfate	MBAS	TDS	TVols	TCol	Iron	Lead	Mn	Na	Zinc	TorgHal	OrgCompds
2	6.3	788	1425	55.8	bdl	14	104	88.1	0.33	bdl	bdl	699	251	bdl	97.4	bdl	1.41	45.6	0.12		
3	6.2	119	500	9.51	0.25	27	71.4	61.4	0.12	24	0.01	207	108	24000	15.3	bdl	0.3	33.9	0.2		
4	6.5	1320	2700	89.2	0.3	30	195	110	0.15	5	0.08	1070	374	bdl	79.8	bdl	1.36	87.8	0.088		33 chlorobenzene
5	6	88	350	3.27	bdl	25	86	37.8	0.17	17	bdl	181	136	5400	7.15	bdl	0.19	25.8	0.054		
6	5.4	16	118	0.14	bdl	16	bdl	24.4	0.66	bdl	bdl	90	122	45	7.8	bdl	0.04	16.6	0.074		
7	5.7	28	235	0.7	bdl	46	132	49	0.87	9	bdl	159	82	bdl	9.95	bdl	0.1	26.6	0.098		
8	5.3	14	100	0.13	bdl	28	109	22	0.14	bdl	bdl	73	107	bdl	7.33	bdl	0.08	13.7	0.106		
9	5.7	98	450	0.8	4.62	26	62	36.6	0.08	34	0.01	321	84	bdl	0.32	bdl	0.69	26.1	0.13		6 methylene chloride
																				11/15/87	
1	6.4	150	400	7.21	0.45	54	108	40.8	0.13	19	bdl	210	106	9200	10.4	bdl	0.32	32.4	0.06	0.044	
2	6.5	710	1200	44.2	0.26	27	118	69	0.34	bdl	0.01	612	132	bdl	106	0.043	1.5	49.8	0.07	0.12	
3	6.4	300	590	15.5	bdl	17	45	50.5	0.06	10	bdl	283	143	1100	35.9	0.022	0.6	28.9	0.51	0.074	7 chlorobenzene
4	6.3	1000	1500	48.8	bdl	22	136	58.3	0.12	19	0.03	788	138	na	92.2	0.007	1.22	39.4	0.05		30/5 = and ethylbenzene
4	6.5	1000	1500	45	0.22	37	144	60.2	0.09	18	0.02	814	187	78	96.5	0.007	1.29	44.8	0.05	0.21	
5	5.7	200	331	3.73	bdl	24	66.9	42.7	0.06	24	bdl	258	108	20	4.12	bdl	0.2	26.9	0.02	0.067	
6	5.5	22	128	0.38	bdl	44	124	25.2	0.49	5	bdl	99	84	bdl	9.6	bdl	0.06	15.5	0.02	0.05	
7	5.3	11	293	3.6	0.65	44	105	53.4	0.28	38	bdl	183	62	bdl	1.14	0.003	0.24	28	0.22	0.106	
8	5.4	13	96	0.14	bdl	24	75.5	22.7	0.12	bdl	bdl	95	57	bdl	7.58	bdl	0.08	12.9	0.08	0.072	
9	5.9	160	400	0.1	9.69	14	47.7	21.8	0.04	35	0.02	277	59	61	0.36	0.002	0.38	15.8	0.02	0.064	
uck ennett	5.1	bdl	110	0.07	0.28	bdl	bdl	28.5	0.04	7	0.01	94	26	40	1	bdl	0.06	15.6	0.06	0.072	
	4.7	bdl	120	0.12	bdl	bdl	bdl	28.5	0.18	8	0.01	73	48	900	0.46	bdl	0.05	17	bdl	0.114	
																				3/17/87	
1	6.6	160	300	8	bdl	58	171	40.2	0.02	16	0.04	238	48	bdl	8.3	bdl	0.24	23.7	0.05		
2	6.6	656	1230	42.6	0.84	25	127	61.6	0.5	bdl	0.07	479	96	bdl	91.2	0.002	1.18	23.8	0.07		
3	6.7	886	1650	50.4	bdl	49	151	70.2	0.03	6	0.09	723	125	bdl	81.6	0.002	1	52.8	0.14		25 chlorobenzene
4	6.6	993	1740	66.2	bdl	9	108	81.3	0.09	19	0.09	805	135	bdl	81.2	bdl	0.99	59.1	0.06		28 chlorobenzene
5	6.2	78	300	2.76	bdl	19	50.7	36.9	0.03	17	0.02	209	50	bdl	4.02	bdl	0.22	24	0.06		
6	5.8	18	163	0.31	0.21	33	96.6	31.6	0.45	11	0.02	130	54	bdl	9.48	bdl	0.06	18.4	0.05		
7	5.8	20	266	bdl	0.26	38	154	62.4	0.27	12	bdl	197	87	20	16	bdl	0.06	33.5	0.15		
8	5.8	14	76	bdl	bdl	35	123	21.7	0.04	bdl	bdl	126	42	140	6.58	bdl	0.07	12.3	0.04		
9	6.2	120	320	bdl	26.6	46	106	26.6	bdl	40	0.04	280	82	490	0.22	bdl	0.58	18.1	0.05		
uck ennett	6	32	205	0.33	bdl	4	94.8	34.4	0.18	bdl	0.01	182	91	310	6.18	0.011	0.19	18.4	0.06		
	4.9	bdl	113	bdl	bdl	4	30.8	20.5	0.09	bdl	0.01	90	32	45	0.64	bdl	0.04	11.5	0.05		
																				6/24/87	
1	6.5	110	370	7.59	bdl	63	114	44.9	0.03	16	0.02	220	82	20	10.3	bdl	0.26	25.6	0.11		2.8 trichloroethene
2	6.6	760	1220	43.6	0.61	31	140	74.9	0.03	9	0.06	660	140	45	158	0.003	1.74	47.6	0.23		3.3 xylenes
3	6.6	780	1440	47.3	0.46	29	124	68	0.03	13	0.06	780	280	20	72.9	bdl	1.01	49.2	0.23		4.4 trichloroethene
4	6.6	1200	2310	114	0.46	15	165	140	0.02	4	0.07	1100	270	bdl	84.5	bdl	1.02	100	0.08		2.6 chlorobenzene
4	6.6	1300	2350	113	0.43	12	165	142	0.03	bdl	0.09	1100	270	bdl	77.6	0.002	1	104	0.31		32 chlorobenzene
5	6.3	59	250	2.08	bdl	48	117	37.8	0.13	6	0.01	160	68	bdl	3.59	0.004	0.13	18.9	0.07		3.1 benzene
6	5.7	27	180	0.49	0.28	28	127	38.3	5.88	8	bdl	160	120	bdl	9.25	0.004	0.06	21.8	0.05		33 chlorobenzene
7	5.7	29	164	0.41	0.3	33	200	34.6	1.24	5	bdl	200	120	bdl	16.5	0.004	0.06	16.8	0.05		
8	5.7	15	133	0.22	0.3	34	92	31.8	0.08	3	0.01	110	110	bdl	8.47	bdl	0.08	14.1	bdl		
9	6	110	480	0.17	4.98	3	36.3	35.5	0.06	27	0.06	300	89	78	0.22	0.002	0.9	24.4	0.07		
uck ennett	6.2	38	208	1.34	0.3	6	102	41.2	0.26	4	0.01	180	150	5400	7.49	0.002	0.16	20.8	bdl		
	6.3	37	131	0.18	bdl	3	75.1	32.2	0.23	6	0.01	120	44	490	1.51	0.002	0.07	14.6	bdl		
																				9/15/87	
1	6.6	139	370	7.19	bdl	17	53.2	36.7	0.03	9	0.02	210	50	bdl	11.2	bdl	0.34	26.6	0.07		
2	6.7	835	1500	59.4	bdl	26	131	84.4	0.08	46	0.05	750	250	bdl	102	0.002	1.46	60.9	0.33		
3	6.5	43	245	2.25	bdl	4	bdl	43.2	0.07	16	0.01	150	41	1700	10.2	0.008	0.2	26.8	0.06		
4	6.8	1440	2400	122	bdl	11	174	141	0.09	bdl	0.09	1200	270	bdl	69.8	bdl	1.2	111	0.02		12 benzene
4	6.8	1450	2400	119	bdl	20	172	141	0.06	bdl	0.1	1200	240	bdl	72.6	bdl	1.18	106	0.03		6 benzene
5	6.5	74	259	2.52	bdl	bdl	47.2	34.7	0.11	bdl	0.02	160	70	140	4.23	bdl	0.17	22	0.02		2.4 ethylbenz
6	5.9	31	175	0.76	bdl	44	242	40.6	0.55	6	bdl	180	170	bdl	10.5	0.006	0.1	21.7	0.1		4.3 chlorobenzene
7	6.2	46	155	1.1	bdl	30	214	34.9	1.09	bdl	bdl	250	200	bdl	16.8	0.003	0.11	19.3	0.03		16 chlorobenzene
8	5.8	15	120	0.2	bdl	bdl	56.3	29.8	0.11	6	bdl	120	56	bdl	8.37	0.002	0.12	17.6	0.03		
9	6.3	99	410	10.2	bdl	9	47.2	50.4	0.14	34	0.14	240	43	24000	0.57	bdl	1.06	35	0.08		
uck ennett	6.1	12	180	0.08	bdl	bdl	67.3	43.2	0.07	bdl	0.02	140	80	170	0.81	0.002	0.12	25.2	0.12		
	5.1	bdl	145	0.15	0.27	bdl	59.3	39.2	0.09	bdl	0.01	110	86	5400	0.57	0.004	0.08	20.4	0.19		5.3 xyl.

Table 5. Wellwater and pondwater chemistry. Provincetown Municipal Landfill site monitoring wells and Duck and Bennett Ponds, Provincetown. (Chemical analyses done by GHR Analytical, Inc., Lakeville, MA).

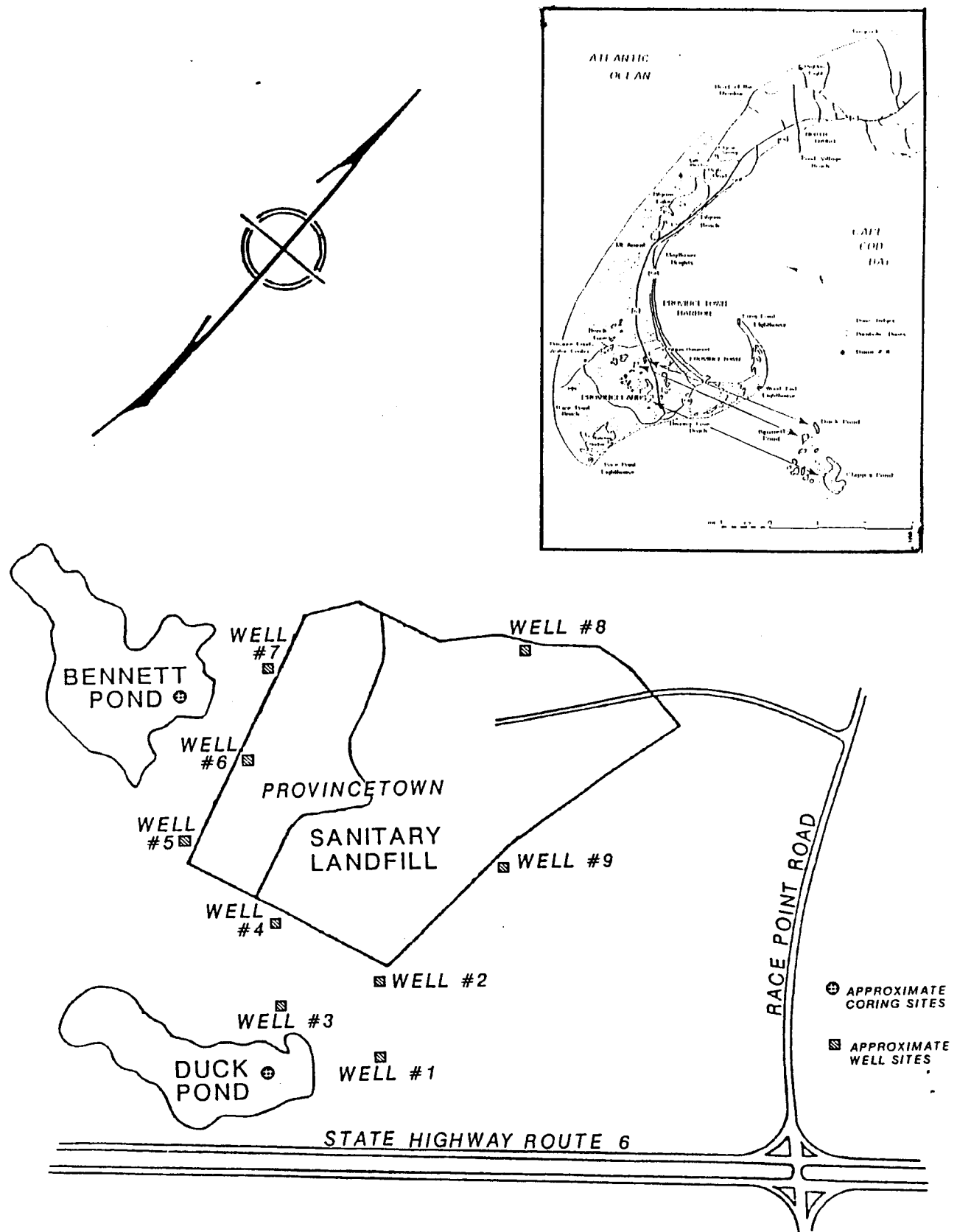
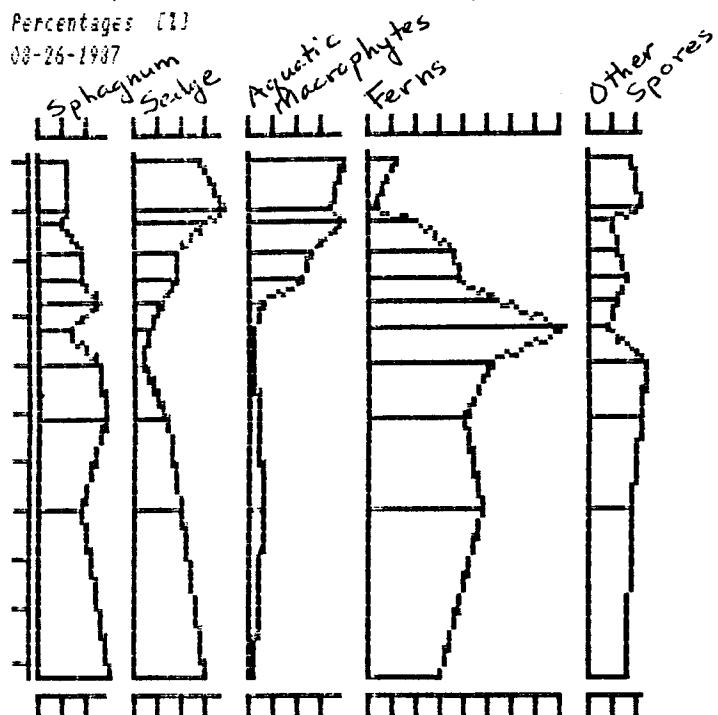


Fig. 1. Map of Bennett and Duck Ponds and the Provincetown, Massachusetts Sanitary Landfill. Landfill monitoring wells are designated. Inset map shows Provincelands region of Outer Cape Cod.

Duck Pond, Provincetown, Massachusetts (Aquatics)

Percentages [1]

08-26-1987



Duck Pond, Provincetown, Massachusetts (Aquatics)

Percentages [1]

Page 1 of 1

08-26-1987

D(cm)	Spha	Sedg	Macr	Fern	OSpr	COUNT
1	9.5	26.2	38.1	9.5	16.7	84
6	10.9	35.9	32.8	0.0	20.3	64
7	3.8	27.5	37.4	18.7	7.7	91
10	15.4	15.4	24.6	33.8	10.8	65
13	16.4	15.1	19.2	35.6	13.7	73
15	23.9	10.1	3.7	52.3	10.1	109
18	9.9	3.9	0.5	79.8	5.9	203
21	23.5	2.5	0.7	50.3	22.9	153
27	26.9	11.9	2.2	38.8	20.1	134
36	15.9	18.2	4.5	45.5	15.9	44
53	28.6	28.6	0.0	28.6	14.3	14

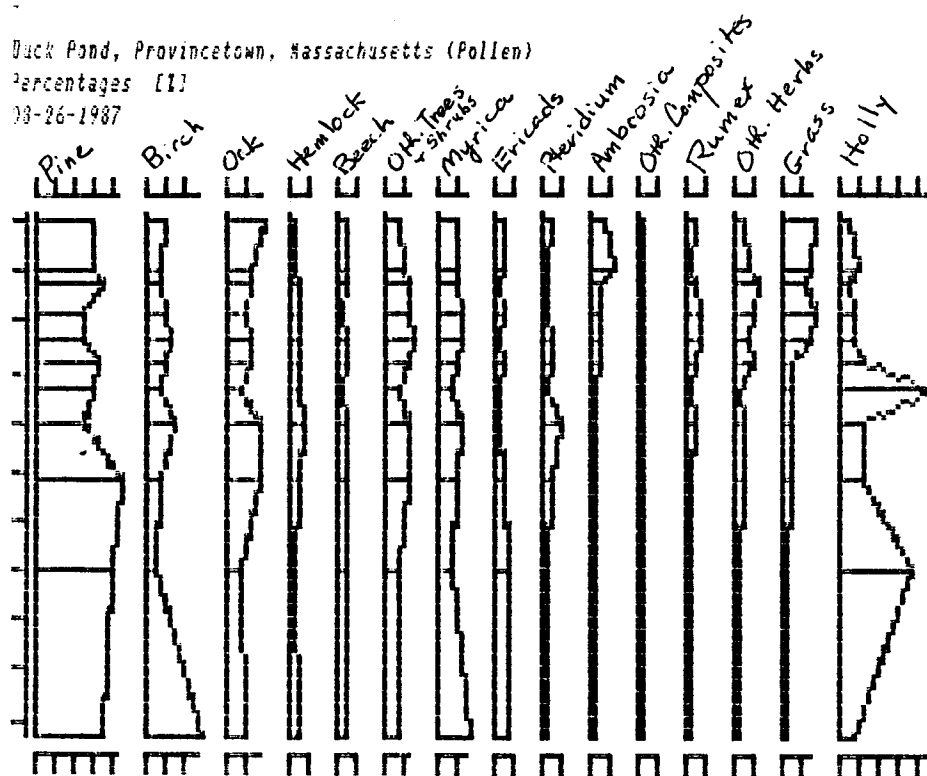
pond/
bog
transition

Fig. 2a. Percentage diagram of aquatic pollen and spores from Duck Pond, Provincetown

Duck Pond, Provincetown, Massachusetts (Pollen)

Percentages [1]

08-26-1987



Duck Pond, Provincetown, Massachusetts (Pollen)

Percentages [1]

Page 1 of 1

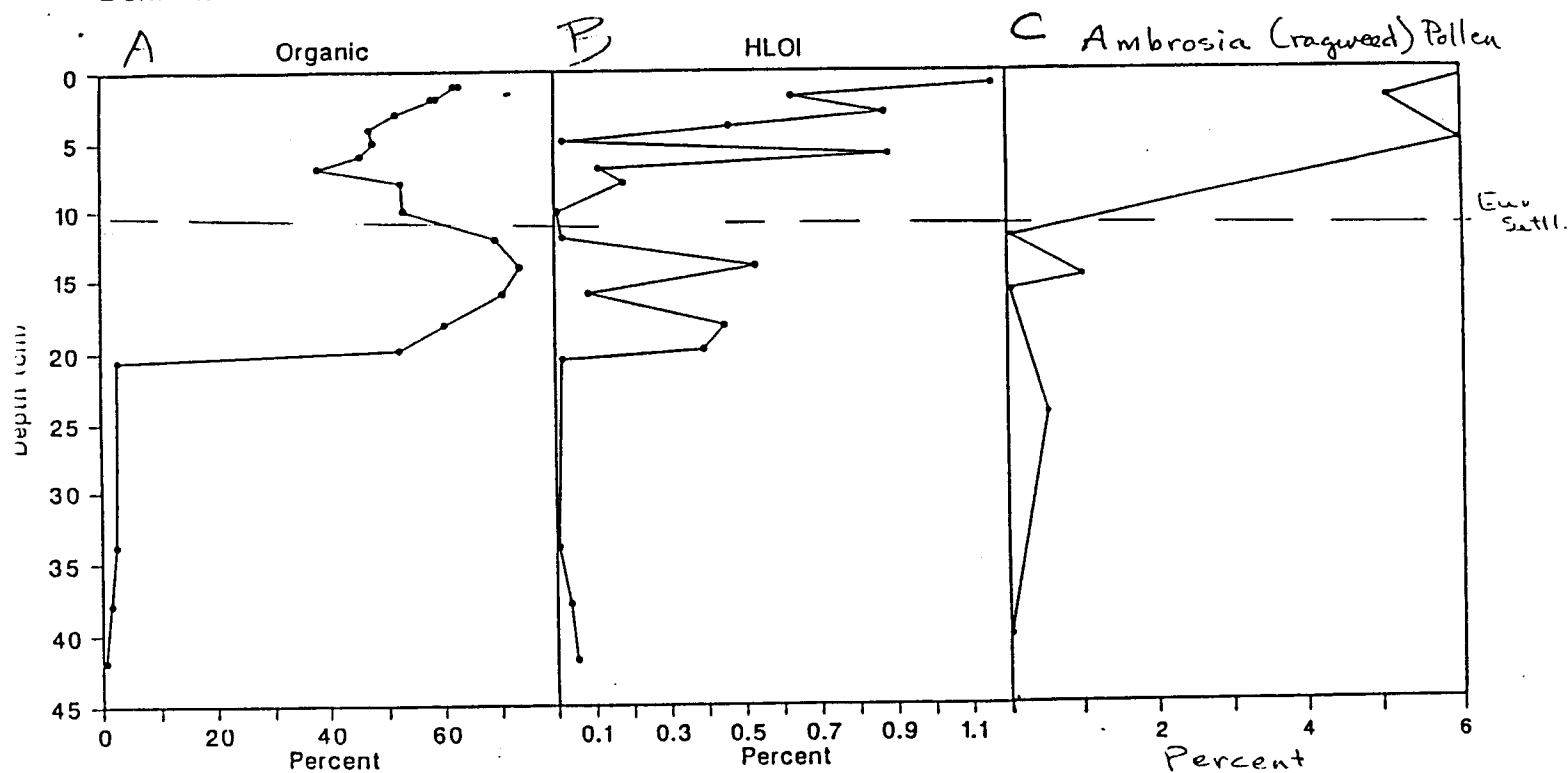
08-26-1987

D(cm)	Pine	Betu	Quer	Tsug	Fagu	OTre	Myri	Eric	Pter	Amb	Comp	Rum	OHer	Grass	Ilex	COUNT	
1	28.1	6.7	18.0	0.4	1.9	6.0	6.4	1.5	3.4	4.1	0.7	2.6	2.6	14.2	3.4	267	
6	26.8	4.5	10.9	1.1	3.0	8.3	7.2	1.9	0.4	10.9	0.0	1.1	5.7	11.7	6.4	265	
7	32.6	5.2	10.7	1.6	1.6	10.7	7.1	0.8	0.8	3.3	0.3	1.9	9.9	11.0	2.5	365	
10	23.6	7.2	8.7	1.4	1.1	10.1	10.1	1.8	0.4	2.9	1.1	4.0	8.0	14.9	4.7	276	
13	21.6	10.6	9.6	1.7	2.3	11.6	9.6	0.7	1.3	3.7	1.0	4.0	4.0	13.6	4.7	301	Eur. Settlement
15	30.2	6.8	9.5	2.4	2.4	10.5	7.5	3.2	2.4	2.2	0.7	1.9	8.0	3.4	8.8	411	
18	26.9	3.9	5.8	1.9	1.2	4.1	4.6	1.0	0.9	0.7	0.3	0.5	1.2	2.4	41.5	584	
21	22.3	12.5	14.3	4.0	2.4	9.5	10.1	0.6	7.9	0.6	0.3	1.5	2.7	2.4	8.8	328	
27	41.7	5.5	13.8	2.0	2.8	9.4	6.3	2.8	1.6	0.0	0.8	0.0	2.0	2.0	9.4	254	
36	36.8	3.3	5.8	0.8	2.8	4.0	4.3	4.3	1.0	0.5	0.0	0.0	0.3	0.8	35.8	400	
53	32.5	27.2	7.0	1.7	2.2	5.9	14.0	3.9	0.3	0.0	0.0	0.0	0.3	0.0	5.0	357	960 ± 60 yr B.P.

Fig. 2b. Percentage diagram of upland pollen from Duck Pond, Provincetown.

Provincetown Ponds

Bennett



Duck

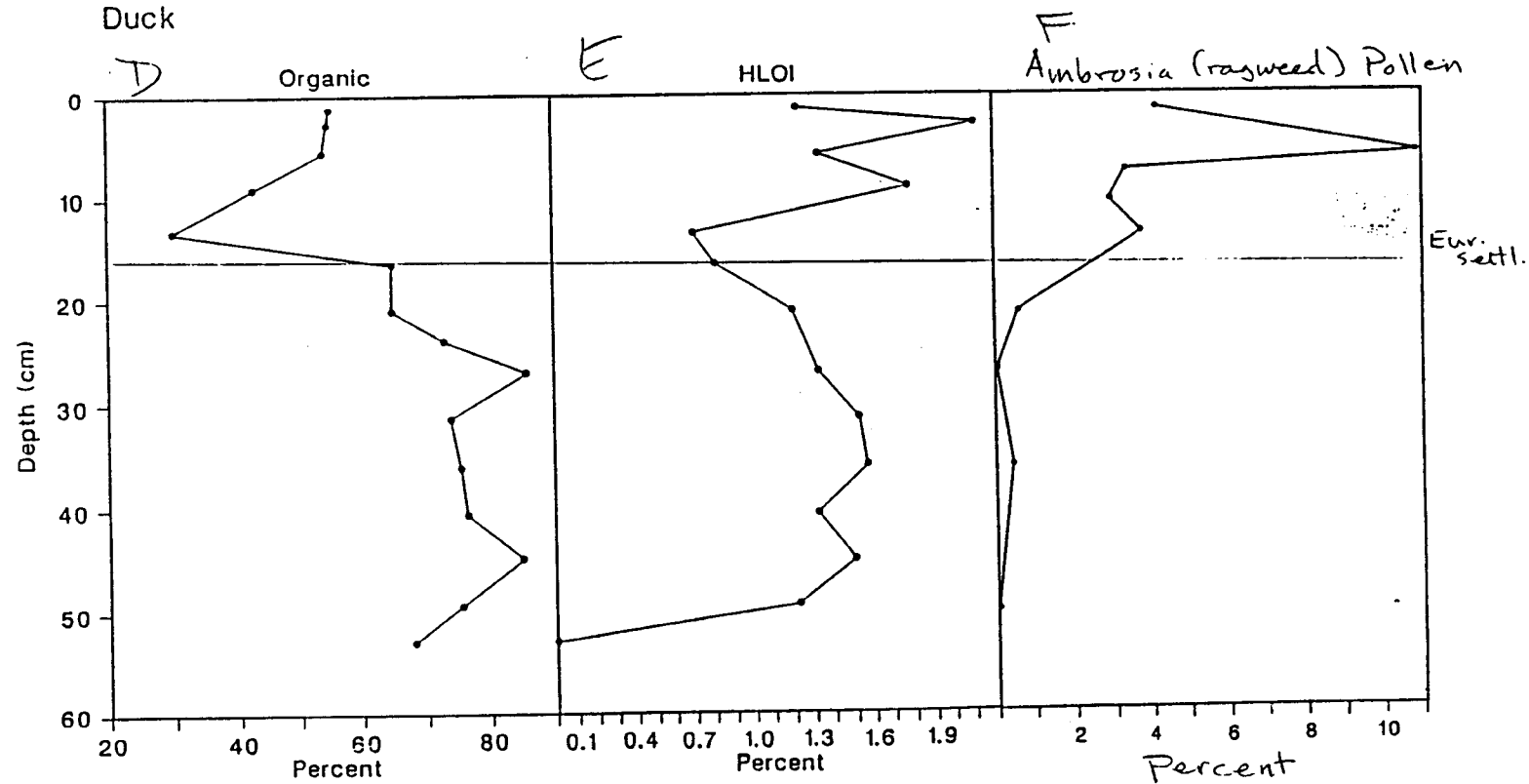
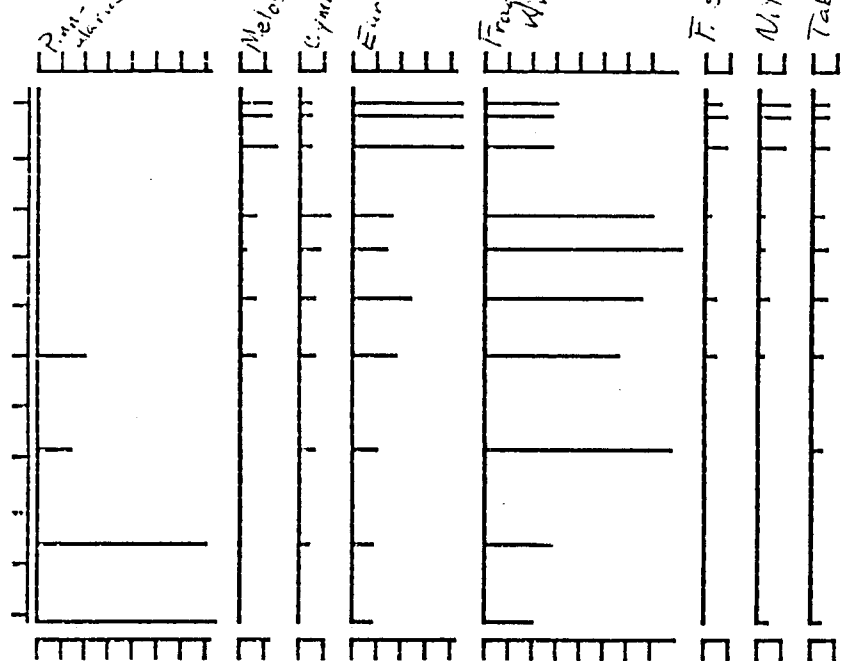


Fig. 3 (A-F). Percent organic matter from loss-on-ignition analyses, percent carbonate from high temperature ignition, and percent Ambrosia (ragweed pollen) defining European settlement in Duck and Bennett Ponds, Provincetown.

Duck Pond, Provincetown (Diatoms)

Percentages [1]

06-01-1987



Duck Pond, Provincetown (Diatoms)

Percentages [1]

D(cm)	Pinn	Melo	Cymb	Eunl	Frag	Fstr	Hitz	Ttot	COUNT
2	0.0	9.3	1.9	41.6	27.9	4.7	9.9	4.7	365
3	0.0	9.5	1.5	41.0	26.2	5.8	10.5	4.8	400
6	0.0	12.2	1.5	42.9	25.7	5.2	7.3	4.3	329
13	0.0	4.2	9.9	13.4	39.7	0.7	0.4	2.3	264
16	0.0	0.3	5.5	11.6	72.2	0.0	0.3	3.1	327
21	0.0	3.2	4.6	22.1	64.9	1.1	1.1	3.2	291
27	18.2	3.7	3.3	19.7	53.7	2.1	0.8	2.5	242
36	11.3	0.0	4.9	7.4	75.0	0.0	0.0	1.5	204
45	57.1	0.0	1.3	6.6	25.0	0.0	0.0	0.0	76
53	72.3	0.0	0.0	6.2	17.5	0.0	1.2	1.2	152

Duck Pond, Provincetown (Diatoms)

percentages [1]

D(cm)	Anon	Melo	Cymb	Eunl	Ftot	Fras	Gomp	Hitz	Pinn	Ttot	Syne	10th	COUNT
2	0.9	7.4	1.5	33.0	33.6	0.9	3.7	7.3	4.8	3.7	1.1	1.7	461
3	0.4	7.5	1.2	32.9	32.5	0.3	2.3	8.3	3.9	3.7	0.6	0.4	507
6	0.5	9.7	1.2	34.3	28.7	1.0	3.2	5.3	8.0	3.4	1.9	2.2	411
13	0.5	3.2	7.5	10.2	67.5	1.1	0.5	0.3	7.0	2.2	0.0	0.0	372
16	0.0	0.3	4.5	9.6	73.5	1.5	0.3	0.3	6.3	2.5	0.0	0.3	396
21	0.5	2.5	3.5	16.9	55.9	4.1	0.5	0.8	12.3	2.5	0.0	0.5	367
27	0.7	3.0	2.6	12.5	54.3	0.3	1.0	0.7	19.1	2.0	2.0	2.0	304
36	0.0	0.0	4.5	6.7	73.2	1.3	0.0	0.0	12.9	1.3	0.0	0.0	224
45	0.0	0.0	1.1	5.7	23.0	3.4	0.0	0.0	61.4	0.0	0.0	2.3	87
53	0.0	0.0	0.0	5.7	17.3	1.1	0.0	1.1	72.4	1.1	0.0	0.6	174

Fig. 4 Diatom stratigraphy and diatom percentages.
Duck Pond, Provincetown.

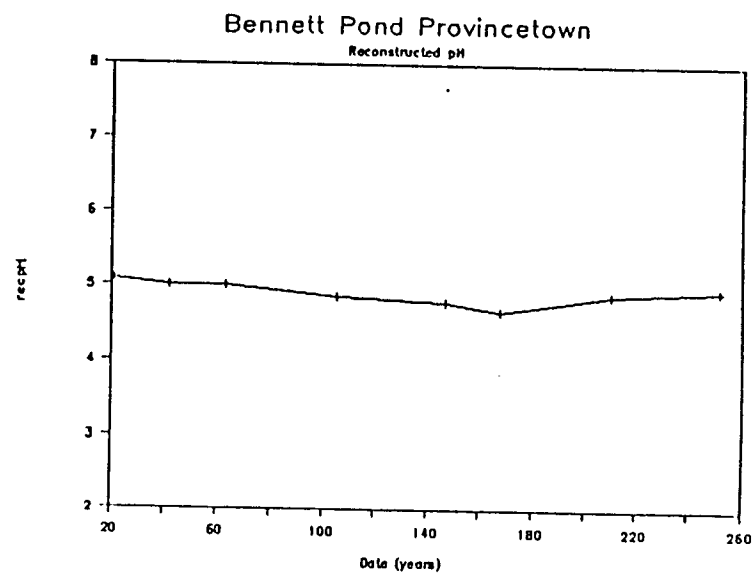
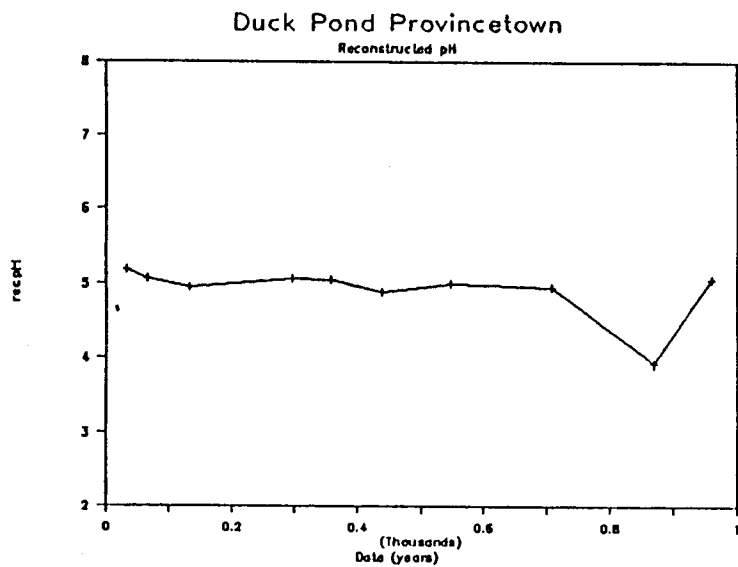
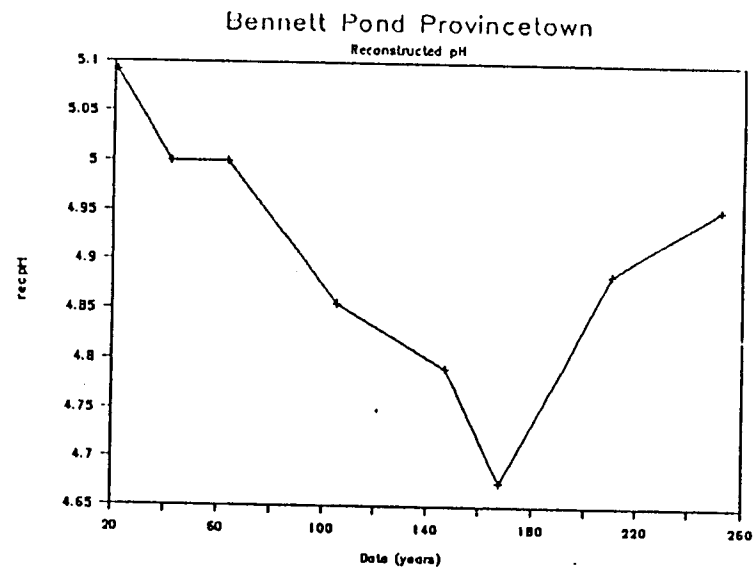
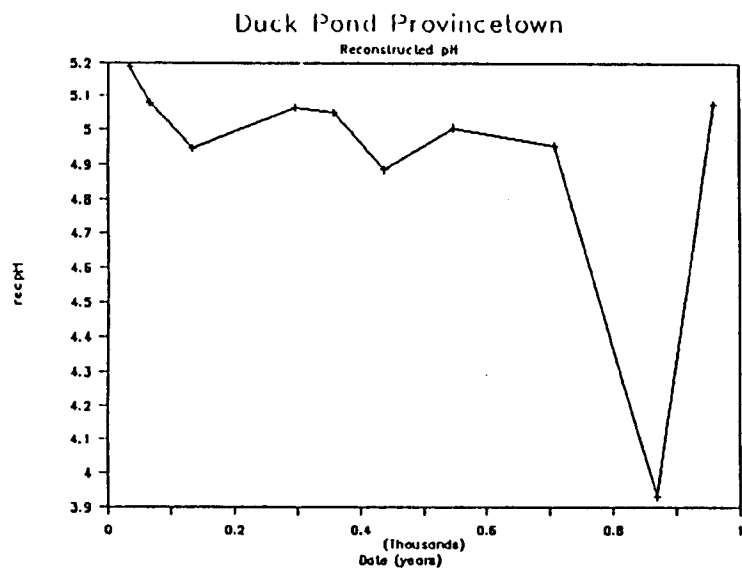


Fig. 5. Provincetown Ponds. Reconstructed pH of Duck Pond and Bennett Ponds since their development.

Cladocera

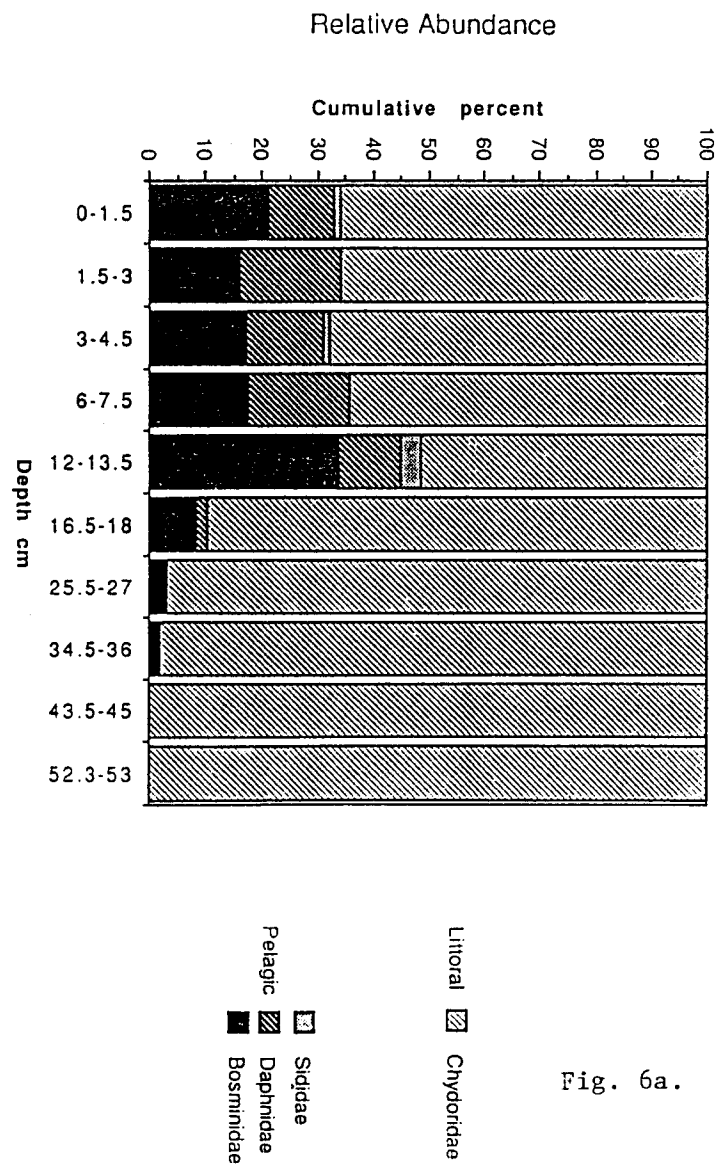


Fig. 6a.

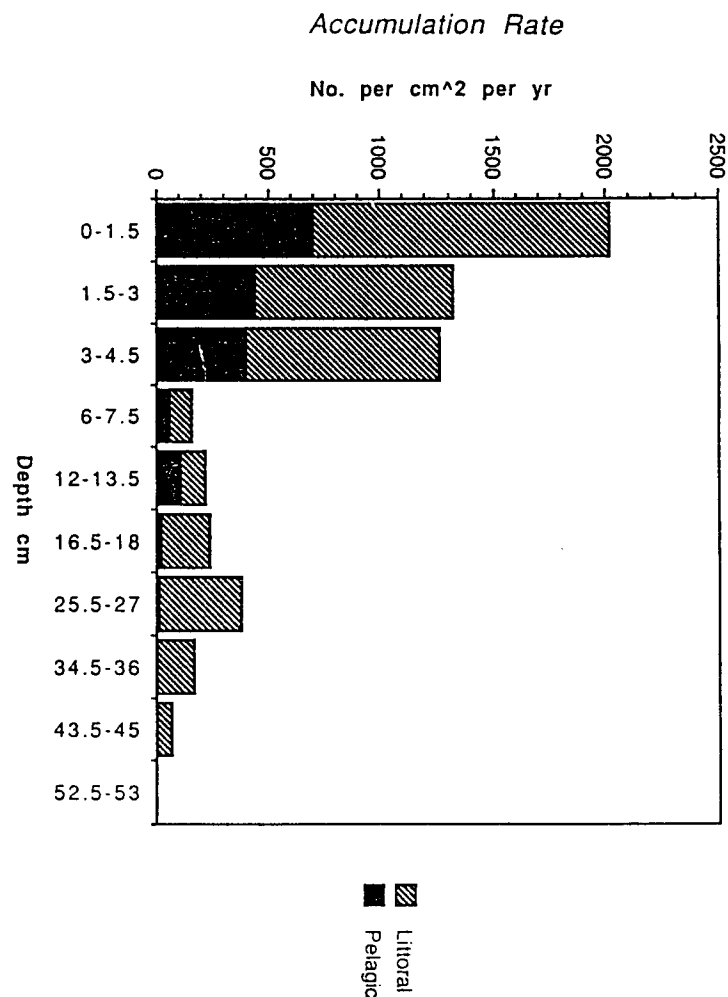


Fig. 6b.

Fig. 6 a and b. Relative abundance and accumulation rates of Total cladocera.

Duck Pond Provincetown MA

Copepod (cf. Harpacticoid) Spermatophore

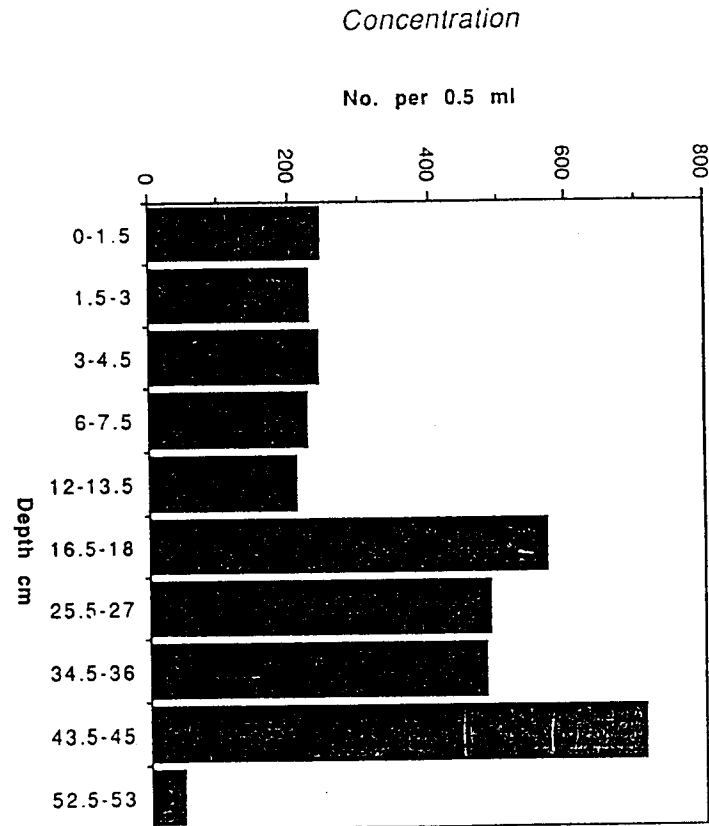


Fig. 7a.

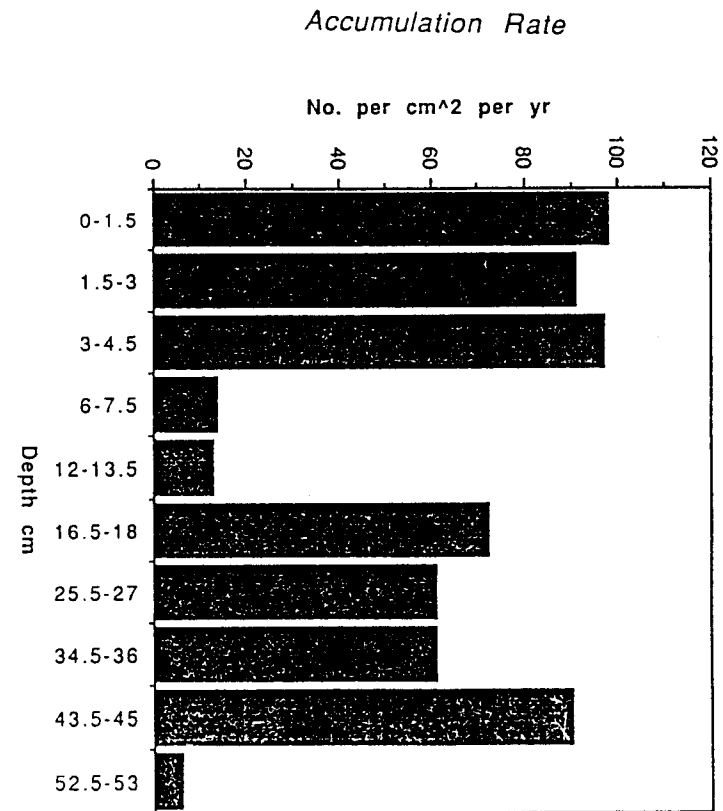


Fig. 7b.

Fig. 7 a and b. Copepod spermatophores. Abundant during bog formation, spermatophores decrease sharply with onset of pond formation, but increase again in more recent deposits probably as a result of increased nutrients.

Littoral Cladocera

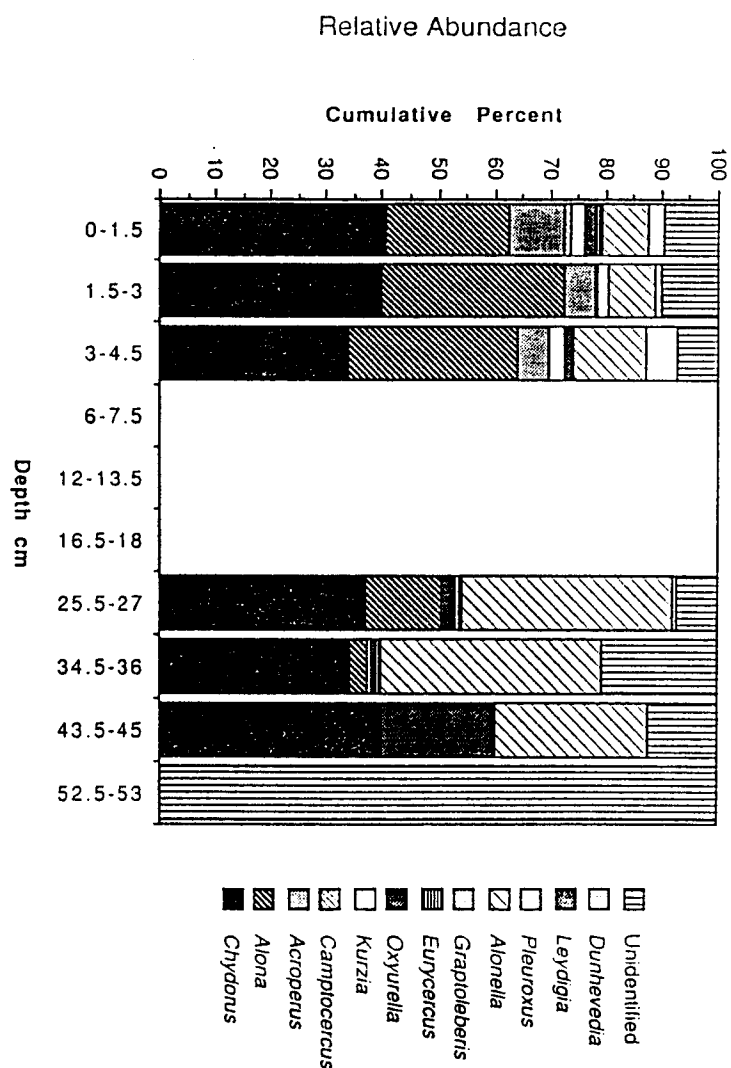


Fig. 8a.

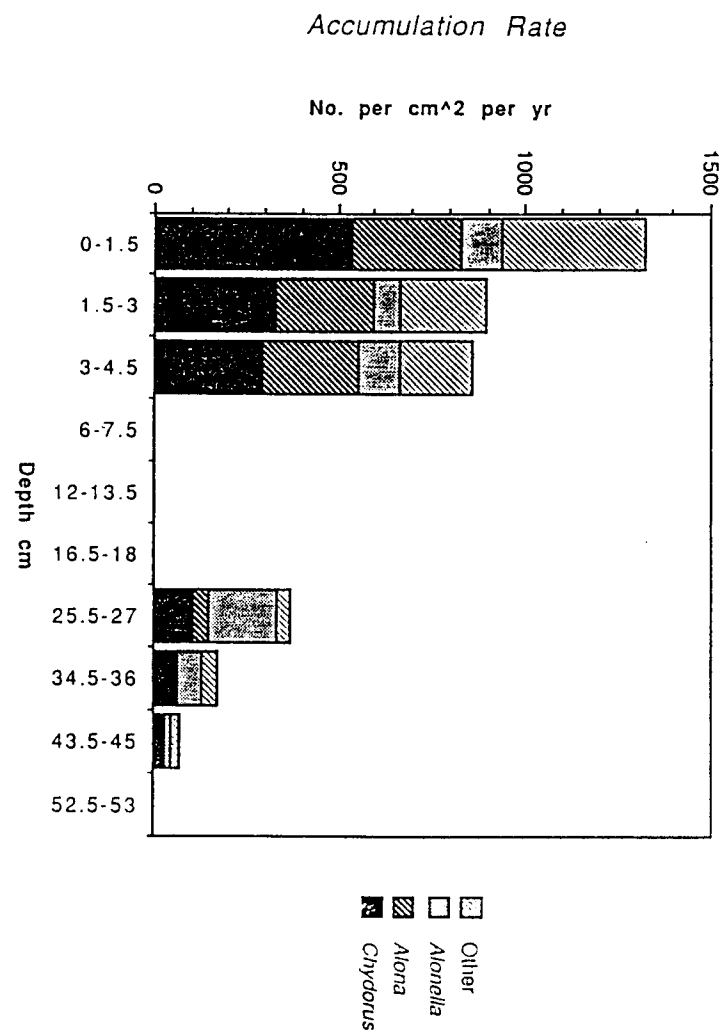


Fig. 8b.

Fig. 8 a and 8b. Littoral cladocera. Generic diversity is low at the onset of bog formation, but increases through time. Increased abundances in recent sediments may be a response to increased nutrient supply.

Pelagic Cladocera

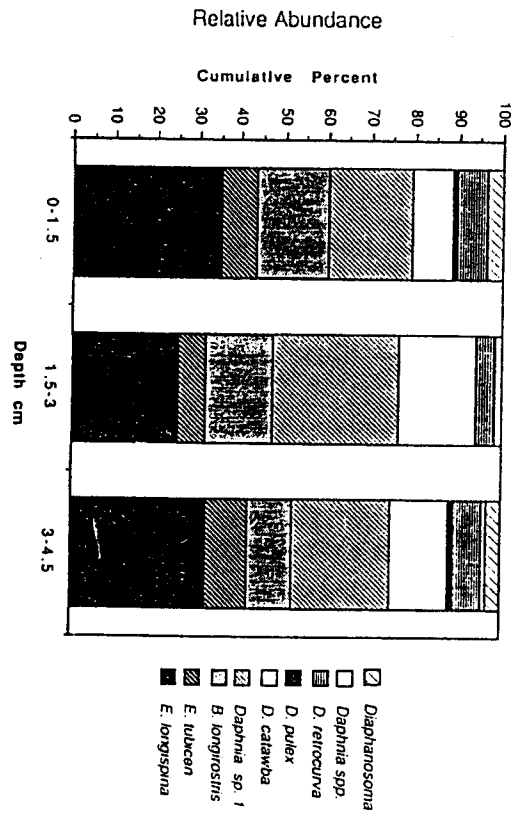


Fig. 9a.

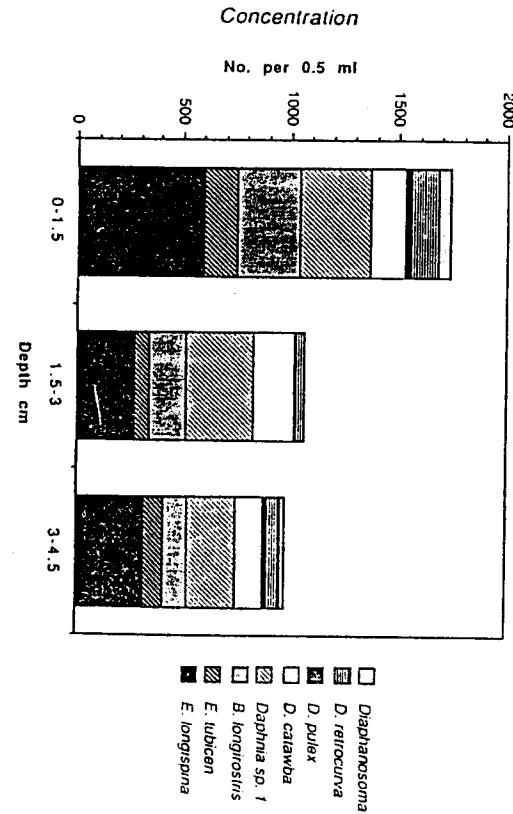


Fig. 9b.

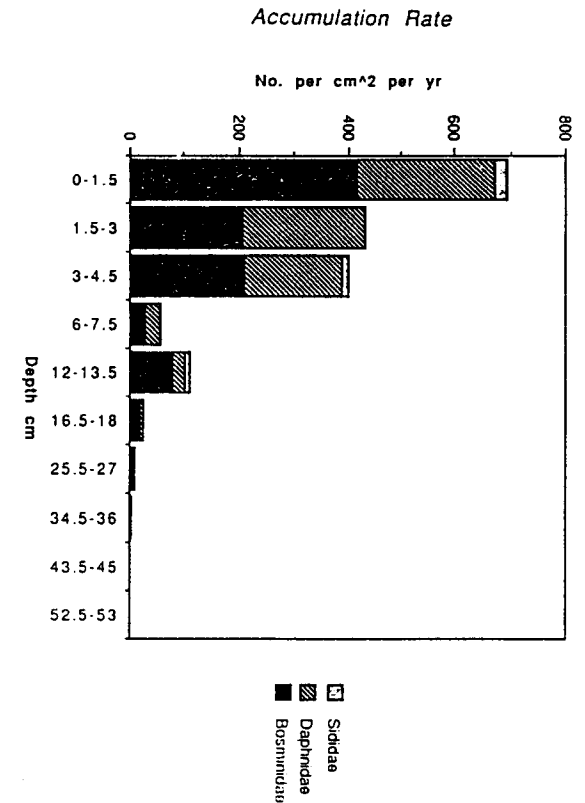


Fig. 9c.

Figs. a, b, and c. Pelagic cladocera. A diverse suite of pelagic forms respond to increased nutrients, especially in the most recent sample.

PROVINCETOWN PONDS: SEDIMENT STRATIGRAPHY

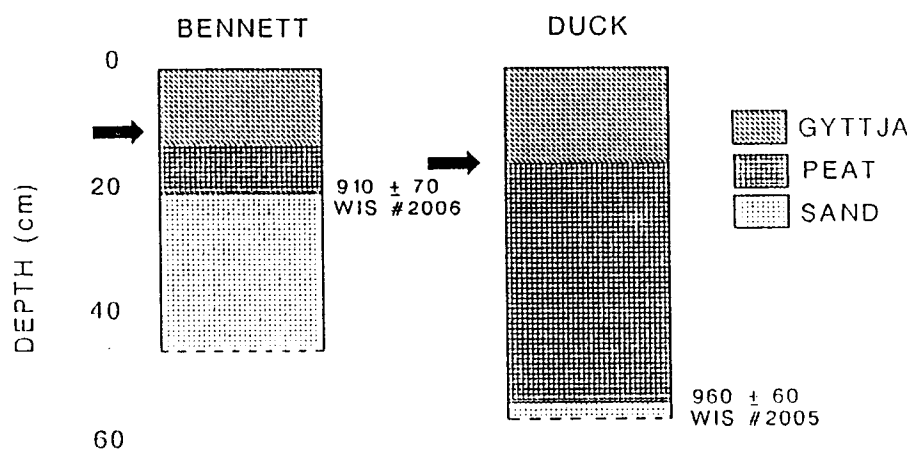
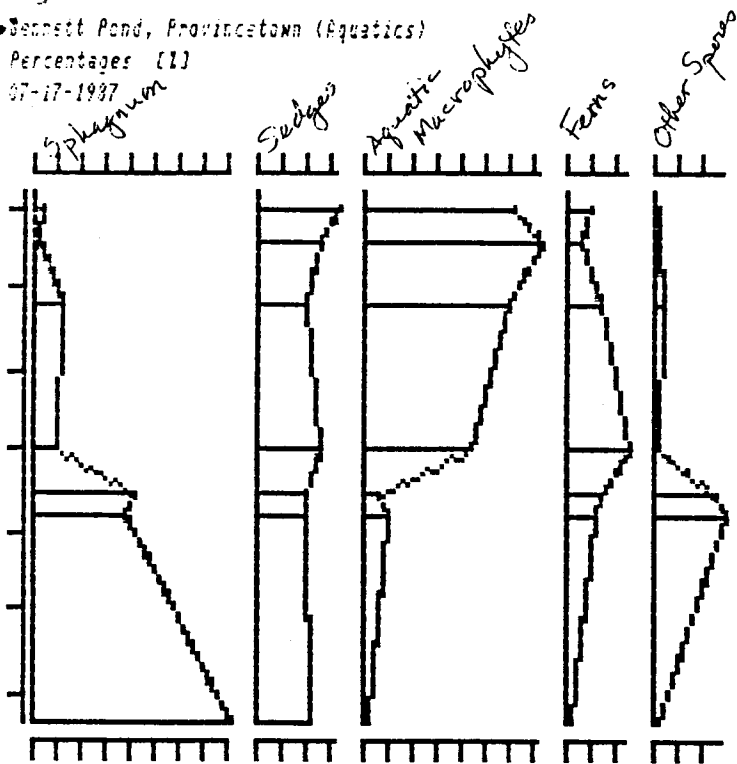


Fig. 10. Sediment stratigraphy of cores from Provincetown ponds: Bennett and Duck. Arrow designates European settlement horizon (app. 330 years ago).

Bennett Pond, Provincetown (Aquatics)

Percentages [1]

07-17-1987



Bennett Pond, Provincetown (Aquatics)

Percentages [1]

Page 1 of 1

07-17-1987

D(cm) Spha Sedg Macr Fern OSpr COUNT

1 1.9 31.5 58.3 8.3 0.0 108

3 0.9 23.3 72.4 3.4 0.0 116

7 9.8 17.1 58.5 12.2 2.4 41

16 8.4 24.3 43.0 24.3 0.0 107

19 40.8 18.4 4.1 12.2 24.5 49

20 35.7 17.9 7.1 10.7 28.6 28

33 30.0 20.0 0.0 0.0 0.0 20

14 1.4 28 78 13 8 71

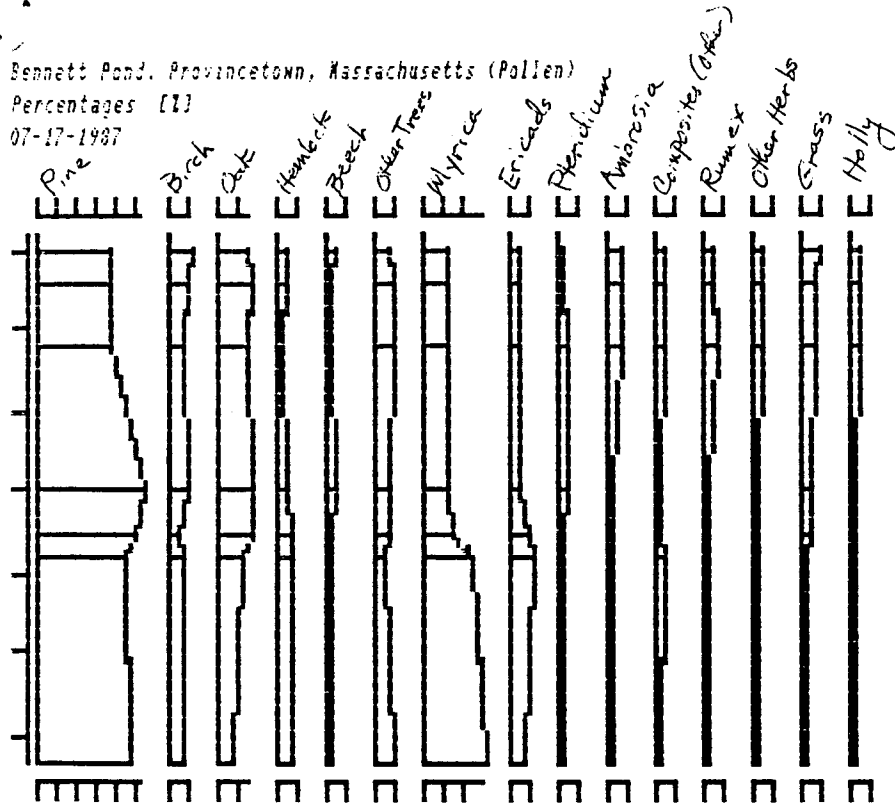
bog/pond
transition

Fig. 11a. Percentage diagram of aquatic pollen and spores from Bennett Pond, Provincetown.

Bennett Pond, Provincetown, Massachusetts (Pollen)

Percentages [1]

07-17-1987



Bennett Pond, Provincetown, Massachusetts (Pollen)

Percentages [1]

Page 1 of 1

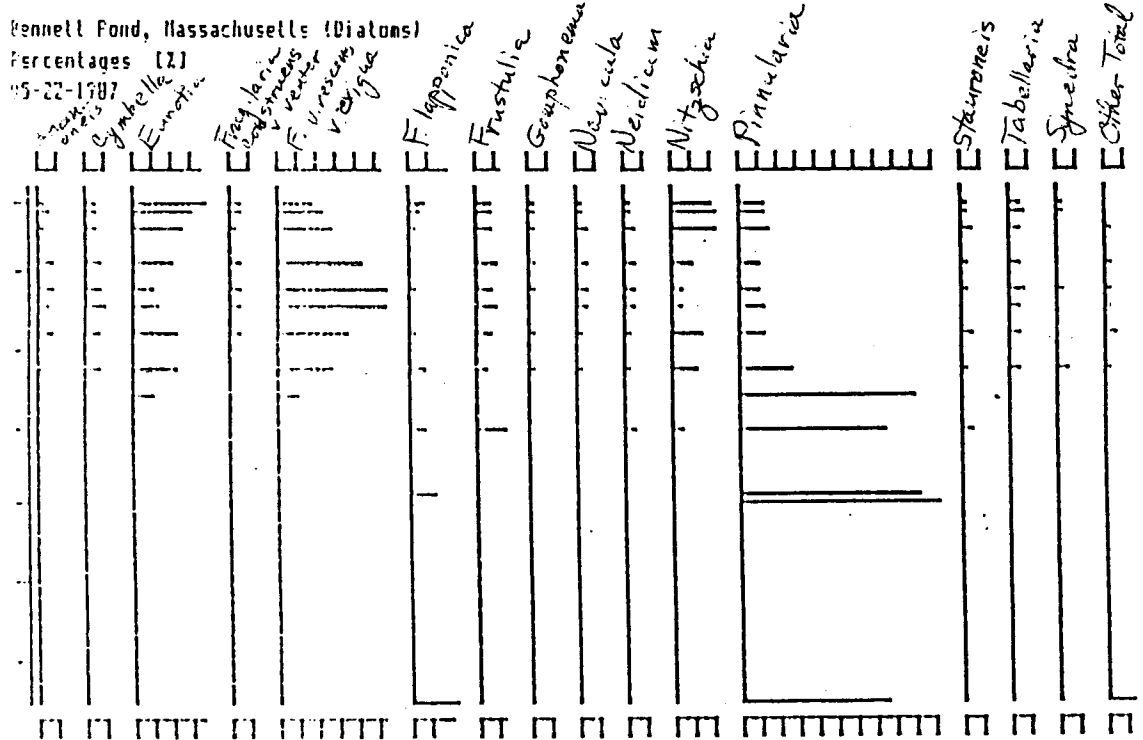
07-17-1987

D(cm)	Pine	Betu	Guer	Isug	Fagu	OTre	Myri	Eric	Pter	Ambr	Comp	Rumex	Other	Gram	Ilex	COUNT
1	35.6	9.7	11.5	1.4	1.4	5.0	11.2	1.4	0.7	5.4	2.5	2.9	2.5	6.5	2.2	273
3	35.9	9.2	14.3	1.4	1.2	7.3	10.6	1.6	0.5	5.9	2.6	2.3	1.6	3.8	2.8	426
7	35.4	5.1	13.3	1.0	0.5	7.7	9.7	1.5	2.1	5.6	2.6	4.6	2.1	5.1	3.6	195
16	52.2	7.1	15.3	1.9	1.9	5.2	9.0	2.5	1.6	0.5	0.0	0.3	0.3	1.6	0.0	366
19	48.4	2.4	13.9	4.5	0.7	3.8	12.9	8.0	1.0	0.3	0.0	0.0	0.3	3.5	0.0	287
20	42.5	3.9	9.1	4.9	0.4	3.5	22.5	9.1	0.7	0.0	2.8	0.0	0.0	0.7	0.0	285
33	44.5	5.7	4.5	4.5	0.0	6.4	29.1	3.8	0.4	0.4	0.0	0.4	0.0	0.4	0.0	265
111	48	4	12	2	4	12	12	0.3	3	0.3	0.6	0	0.3	1.0	0.3	320

Fig. 11b. Percentage diagram of upland pollen from Bennett Pond, Provincetown.

[illegible]

Bennett Pond, Massachusetts (Diatoms)
Percentages (%)
05-22-1987

Jennett Pond, Massachusetts (Diatoms)
Percentages (1)

Decn	Ance	Cyab	EunT	Ferr	Fvve	Flap	Fras	Gasp	Havi	Heid	Kitz	Pinn	Stau	Itot	Syne	10th	COUNT
1	1.0	1.7	33.0	2.5	14.3	4.9	5.2	0.7	0.7	0.5	16.3	10.3	1.0	3.7	1.2	0.0	406
2	1.1	2.3	28.0	2.8	12.1	5.3	5.6	0.2	0.7	0.9	20.5	9.2	1.2	4.0	0.2	0.0	425
3	1.1	2.0	21.3	0.2	24.7	0.2	5.4	0.2	1.7	1.7	20.7	11.6	1.4	3.4	0.0	0.3	352
5	1.1	4.6	12.3	1.3	38.3	0.0	7.2	0.4	2.4	1.7	7.3	9.3	0.9	3.7	0.0	0.4	459
7	5.1	4.7	7.5	2.3	53.1	0.3	5.5	0.4	3.2	1.3	2.6	6.5	0.6	4.9	0.2	0.4	507
8	3.2	6.6	10.3	2.2	53.3	0.0	6.6	0.0	1.5	1.7	1.7	9.5	0.0	3.2	0.0	0.2	409
10	4.0	4.2	15.0	1.7	32.0	0.3	6.1	0.6	0.9	0.6	13.0	11.0	1.4	2.9	0.0	1.7	347
12	1.0	3.3	19.5	0.0	23.9	6.1	3.1	0.7	1.0	0.7	9.6	24.2	0.3	3.4	2.4	0.3	293
14	0.0	0.0	6.3	0.0	6.3	0.0	0.0	0.0	0.0	0.0	0.0	37.5	0.0	0.0	0.0	0.0	16
16	0.0	0.0	0.0	0.0	0.0	1.2	11.3	0.0	0.0	2.9	2.9	73.5	2.9	0.0	0.0	0.0	34
20	0.0	0.0	0.0	0.0	0.0	10.7	0.0	0.0	0.0	0.0	9.0	89.3	0.0	0.0	0.0	0.0	28
21	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	0.0	25
34	0.0	0.0	0.0	0.0	0.0	12.0	0.0	0.0	0.0	0.0	0.0	71.4	0.0	0.0	0.0	9.5	21

Fig. 12. Diatom stratigraphy and diatom percentages. Bennett Pond, Provincetown.