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Acidification of a Dutch moorland pool — a palaeolimnological study

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With 12 figures and 2 tables in the text

Abstract

The Dutch moorland pool Achterste Goorven is undergoing rapid acidification. In the period 1925—1985 sediment core diatom inferred pH has fallen from 5.8 to 4.8. During the same period observed pH fell from 6 to 4.2 and plankton two diatom inferred pH fell from 5.7 to 4.2. To date, this is one of the fastest documented rates of acidification of any pool or lake in temperate regions exposed to acid rain. Our results indicate that useful stratigraphic information can be obtained from an analysis of the organic sediments of even a very shallow (mean depth 0.6 m) pool. Although there is evidence of downward displacement of sediments in such shallow water bodies, this process does not completely homogenize the sediment record. The accuracy of the reconstruction is substantially improved by a multidisciplinary approach.

Introduction

The present study constitutes an attempt to determine whether or not it is possible to reconstruct past events associated with moorland pool development during the last 150 years from an analysis of its submerged sediments. The purpose of the study was to test the application of palaeolimnological techniques in order to determine the rate of acidification in a shallow moorland pool from data assembled by a multidisciplinary team of scientists.

Moorland pools extend over much of western Europe from northestern France to the Baltic and England (Moore & Bellamy 1973). The distribution of approximately 3500 moorland pools referred to as 'ven' (plural: 'vennen') in The Netherlands (not to be confused with fens which are more minerotrophic), is associated with the location of Pleistocene coversands. The moorland pools near Oisterwijk, where our study site is located, have been described by Heimans (1925), Coesel et al. (1978), Van Dam & Kooyman-van Blokland (1978) and Van Dam et al. (1981).

One of the first palaeoecologists to prove that useful stratigraphic information could be obtained from cores removed from shallow waters was Moss (1979, 1980). His study of the palaeoecology of a broad near Norfolk, England, established the validity of stratigraphic analyses for sediments of shallow water habitats.

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The moorland pools of The Netherlands and the adjacent parts of Belgium and Germany present four major problems to the palaeoecologist:

1) They are very shallow, usually less than 2 m deep, with little topographic relief. As a result their entire sediment surface is frequently subjected to wind induced mixing. Wind also plays a major role in determining the morphometry of these pools and in controlling the distribution of their higher aquatic plants (Westhoff et al. 1973). In addition, high winds frequently deposit layers of fine sand at the mud water interface. This sand acts to dilute the authigenic material deposited within the pool.

2) Bioturbation problems are augmented in moorland pools because in addition to the burrowing activities of numerous invertebrates typical of shallow tarns, bioturbation from vertebrate sources must also be considered. During droughts, shorelines encroach toward the center of the pool. As a result trampling by animals (e.g. roe, boar) and tourist often distorts the sediment stratigraphy of the exposed muds.

3) During periods of drought (e.g. 1921, 1959 and 1976, Buishand 1981) moorland pools in northern Belgium and The Netherlands lost a considerable part or even 100 % of their volume due to evaporative losses and lowering of the groundwater table (Sykora 1979, Vangenechten et al. 1981). The exposed shoreline sediments of these pools were subject to desiccation and oxidation. Such conditions results in poor preservation of microfossils (Iversen 1969).

4) Sediment coring is often impeded by a dense aquatic vegetation cover, growing on top of the mud (e.g. mosses). If the vegetation cover is not removed before coring, the uppermost organic layers of sediment will be hopelessly distorted by the action of the core cylinder which forces the vegetation cover down into the flocculant organic material at the mud-water interface. In addition, the dense layers of plant fibres, needles, moss and higher aquatic plant rhizomes in the sediment may impede both coring and sectioning.

We have attempted to determine whether or not downcore changes in the abundances of diatoms could be correlated with known events which occurred in the surroundings of the moorland pool, Achterste Goorven, over the last 150 years. To this end we compared our sediment samples with an extensive series of plankton samples which were collected from this pool by the late Professor Dr. J. Heimans (University of Amsterdam) over the period 1925—1953. After 1975, the second author collected plankton samples from the very same sites visited by Prof. Heimans.

Pollen, fruits and seeds, algae and chironomid head capsules were analysed in order to provide some information about the origin and historical development of the pool. Old topographic maps of the study area were available to provide information about the land use in the surroundings of the pool over the last 150 years.

Site description

Achterste Goorven, located near Oisterwijk in the southeastern portion of The Netherlands, is a shallow moorland pool with low relief, a surface area of approximately 2.3 ha, and a mean depth of 0.6 m (Fig. 1). The pH of its surface waters ranges from 3.4 to 5.5 (median = 3.9), its sulfate content ranges between 12 and 68 mg l^{-1} (mean = 35 mg l^{-1}) and its calcium content between 1 and 11 mg l^{-1} with a mean of 4 mg l^{-1} over the period 1979—1984.

The dominant vegetation surrounding Achterste Goorven consists of *Pinus sylvestris* (the dominant arboreal pollen producer), *Quercus robur*, *Q. rubra* and *Betula pubescens*. The dominant grasses, *Molinia caerulea* and *De-*

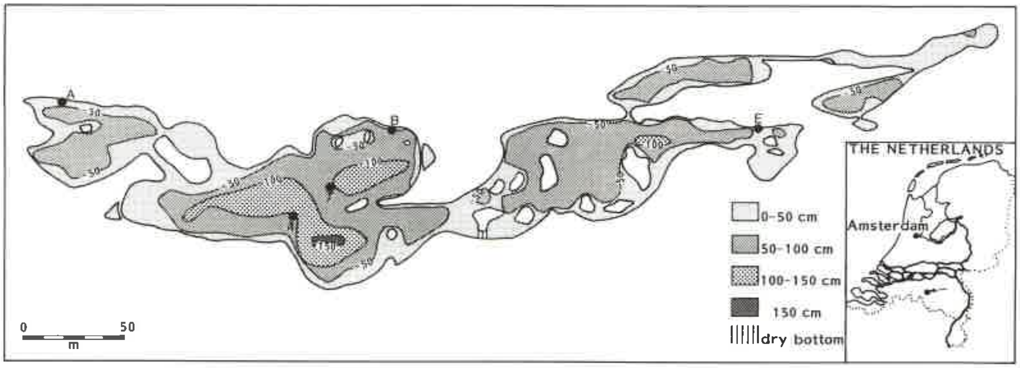

Fig. 1. Bathymetric map of Achterste Goorven (11—13 September 1984) with its location in The Netherlands in the inset. Plankton tow and chemical sampling stations indicated with letters, coring stations with numbers.

schampsia flexuosa, grow in close association with *Calluna vulgaris, Erica tetralix* and *Vaccinium myrtillus.* The pool itself is surrounded by a fringe of *Myrica gale* (Fig. 2). Mosses (e.g. *Drepanocladus* and *Sphagnum* species) play only a minor role in the cover of the shoreline vegetation around the pool. In the

Fig. 2. Looking east across the width of Achterste Goorven near station 7 where the ice was 10 cm thick (30 January 1985). The small island in the foreground has been colonized by *Myrica gale, Molinia caerulea* and *Betula pubescens. Pinus sylvestris* is the dominant species on a sand ridge at the background.

open waters *Nymphaea alba* is the most conspicuous macrophyte but its floating leaves actually cover less than 1% of the total surface area of the pool. Patches of *Juncus bulbosus* are common along the shore.

Methods

Sediment coring

Replicate cores were taken from Achterste Goorven at stations 4 and 7 (Fig. 1) during a period of ice cover on 30 January 1985. Both cores were taken with an Ali corer (Ali 1984). The acrylic coring tube's internal diameter was increased from 3.5 to 7 cm to permit removal of a larger quantity of sediment per core. The 24 cm long core removed from station 4 was extruded and sectioned at 1-cm intervals at the site while the 38 cm long core from station 7 was taken to the laboratory where it was frozen, extruded from its plastic liner and sectioned (also at 1-cm intervals) while frozen. The external stratigraphy of each core was described before sectioning.

Each of the 1-cm thick sections contained 38 ml of sediment. Half of this was used for ^{210}Pb analysis (A. van der Wijk). The remainder was split between B. van Geel (2 ml for pollen analysis), M. Dickman (2 ml for diatom analysis) and A. Klink (c. 15 ml for macroinvertebrate analysis and selection of fruits, seeds and other macrofossils).

The percentage of inorganic material in the core was determined by loss of weight following its oxidation with concentrated HNO_3 and H_2O_2. Microscopic analysis of the inorganic material indicated that it was composed primarily of fine sand along with some diatom frustules and siliceous chrysophyte and poriferan spines.

The replicate cores, AG 4 and AG 7, from Achterste Goorven were analysed at a variety of depths to determine their downcore stratigraphy. However, for the sake of brevity, only those depths that all four researchers analysed together are emphasized in this paper. When not stated otherwise all of the results in this paper refer to core AG 7.

^{210}Pb analysis

^{210}Pb was measured through its alpha emitting granddaughter ^{210}Po using the isotope dilution technique (Flynn 1968, El-Daoushy 1981).

Ten ml of wet sediment was weighed and subsequently dried at 40 °C for about 12 hours. Weight loss was determined and the ratio between wet weight and dry weight volume was established. Approximately 1 g of dry sediment was transferred to a 250-ml Kjehldahl flask. On occasion smaller samples were necessitated for lack of sediment. The material was gently boiled with concentrated HNO_3 to which 30% by volume H_3O_2 was added dropwise until brown fumes no longer emanated from the boiling liquid. The oxidized sediment was separated from the overlying liquid by centrifugation at 3000 rpm for 5 minutes. The residue was repeatedly washed with distilled water until no more color appeared. These washings were retained by transferring them to the beaker containing the original supernatant. The washed residue was then discarded.

After the addition of 100 microlitres of a ^{208}Po spike solution (activity 1 Bq/ml) the solution was evaporated to dryness in a 50-ml Teflon beaker. The remaining salts were chlorinated by dissolving them three times in concentrated HCl and evaporating the reactant until dry. The chlorinated salts were then redissolved in 20 ml of 0.5 N HCl to which 1 mg of ascorbic acid was added. After half an hour the solution was transferred to a Teflon plating cell (Van der Wijk & Mook, in press) and Po was electroplated onto a silver disk by self-deposition at 85 °C for 2 hours. The thinly plated samples were then measured in an alpha spectrometer for ^{208}Po and ^{210}Pb activities. Chemical yields from this procedure varied between 85 and 100%.

Diatoms

The term 'plankton tow diatoms' has a special meaning in this paper. It refers to diatoms collected with a standard plankton net. It does not refer to euplanktonic diatoms as these were never found in Achterste Goorven.

Initially (1925—1953) the plankton tow samples were taken with a 60 μm mesh net (15 cm diameter) by Prof. Heimans (A. van der Werff, pers. comm.). As the plankton net was towed through the water it collected considerable amounts of surficial bottom sediments as well as periphyton which was attached to the aquatic macrophytes which came in contact with the net. These samples were stored in the Hugo de Vries-Laboratory at the University of Amsterdam. After 1975 plankton samples were collected with a 40-μm mesh net of 20 cm diameter.

Both plankton tow and sediment diatoms were cleaned by boiling the raw material for 30 minutes in 30% by volume H_2O_2. To the sediment samples a known amount of polystyrene latex microspheres (mean diameter 8.7 μm, Coulter Counter Electronics Ltd.) was added for calculation of the concentration of each diatom taxon (number per gram sand-free dry weight of sediment) according to the methods of Maher (1981). Plankton diatom counts are expressed only in terms of relative abundance. Slides were prepared by embedding the cleaned diatom valves in either Clearax or Hyrax mounting medium.

Slides were examined under oil immersion using a Zeiss Standard RA microscope equipped with phase contrast optics (NA = 1.30). All diatoms and microspheres within the field of view were counted according to the methods described by Berglund (1979) and Denys & Lodewijckx (1984). Random fields were counted on the slide until a total of 400 diatom valves had been recorded. The keys listed by Van Dam (1984) were used for identification.

The proportion that each diatom taxon comprises in the total assemblage was calculated as a percentage of the total and these results were used to estimate diatom inferred pH (Renberg & Hellberg 1982). The assignment of each diatom to a pH class was described in previous publications (Hustedt 1939, 1957, Renberg 1976, Van Dam et al. 1981, Dickman et al. 1984).

Chironomidae, seeds and fruits

Chironomid head capsules, fruits and seeds were analysed at 5 cm intervals down the length of the core. Using standard wire mesh sieves, each sediment sample was split into two size fractions: (1) > 500 μm and (2) 150—500 μm.

Macro-invertebrates and seeds were sorted using a standard dissecting microscope (× 80 magnification). Subsamples were taken from fraction 2 until a total of 300 chironomid head capsules had been removed. Half head capsules were included as halves in the tabulation of the data. The total chironomid densities were expressed per mg dry weight of organic matter.

Taxonomic keys for the identification of the chironomid head capsules were similar to those used by Moller Pillot (1984 a, b) and Wiederholm (1983).

Pollen

In order to calculate pollen concentrations, *Lycopodium* tablets were added to the samples (Stockmarr 1971). The samples were treated with KOH and subsequently acetolysed (Faegri & Iversen 1975). Clay and sand were removed using a bromoform-alcohol mixture (specific gravity = 2.0). The organic material was embedded in glycerine jelly and sealed with paraffin wax. The samples were searched for pollen, algal remains, Fungi, invertebrates, etc. (cf. Van Geel 1978, Van Geel et al. 1981, 1983). The occurrence (relative abundance) of all palynomorphs is expressed as a percentage of the total tree, shrub and upland herb pollen counts (Σ Pollen). In most samples this total was more than 300 grains. Once this was accomplished, the remaining area of the slide was perused to glean more information about taxa represented in such low numbers that they had not previously been noted. Such taxa are identified by a '+' mark in all pollen diagrams.

Results

Sediment core description

In both replicate cores (AG 4 and AG 7) the surface sediments (0—5 cm) were composed of a flocculant algal gyttja which was intermixed with very fine aeolian sands and coarse plant fibres, leaves, needles and even small twigs. From a depth of 5 to 10 cm the water content of these sediments decreased from 94 % to 89 % and finally to 20 % near the base of the cores. For the sake of brevity, only the data from the AG 7 core are presented here (Table 1).

The percent inorganic content near the base of each core reached 79 % by weight (Table 1). Below a depth of 15 cm the sand became coarser (mean grain diameter was 111 μm, n = 50). This coarser sand was yellow-brown in color and contained only a negligible number of diatom frustules. This is in sharp contrast to the very fine sands (mean grain diameter of 42 μm, n = 50) which

Table 1. The inorganic and organic composition of the 1 cm thick sediment samples. The ^{210}Pb estimated date of each of the sediment sections which were analysed is represented in the far right hand column. The volume/weight ratio is the volume (ml) in which 1 g of dry (organic and inorganic) material was distributed.

Depth (cm)	Water content (%)	Organic matter (%)	Inorganic matter (%)	Volume/Weight (ml g^{-1} dry material)	^{210}Pb (spike eq cm^{-2})	Year AD
0–1	95.4	3.5	1.1	28.1		
1–2					3.66±0.08	1979–1983
3–4	93.7	4.5	1.8	18.4	7.20±0.70	1973–1978
4–5	94.3			20.2		
6–7	93.5	4.4	2.1	18.1	2.34±0.06	1951–1955
9–10	89.1	7.9	3.0	10.1	1.58±0.06	1929–1940
11–12	86.3	5.5	8.2	8.0	0.99±0.04	1914–1925
14–15	81.4	7.4	11.2	6.1	0.66±0.06	1884–1900
16–17	48.8	5.1	46.1	1.7	0.38±0.08	1855–1877
19–20	23.1	2.3	74.6	0.78	0.16±0.13	1836
20–21	35.5	1.4	63.1	0.92		
22–23					0.06±0.06	1816
23–24	20.0	1.5	78.5	0.86		

were observed in the uppermost portions of the core where diatom frustules were relatively abundant.

^{210}Pb analysis

Spectra obtained from Po-sources (Table 1) showed alpha resolution of 25 to 30 KeV. As a result, no corrections for peak overlap were required. Activities were determined in spike equivalents cm^{-2} to prevent the additions of extra inaccuracies resulting from our uncertainty concerning the absolute activity of the spike solution. ^{210}Po was assumed to be in secular equilibrium with ^{210}Pb.

Downcore sediment profile age determinations (Fig. 3) were determined using the constant rate of supply (CRS) model (Goldberg 1963, Oldfield et al. 1978). A problem to this was the apparent low ^{210}Pb activity at 1—2 cm depth, most probably caused by infiltration of freshwater, in which ^{210}Po and ^{210}Pb are not yet in radioactive equilibrium, into the interstitial waters of the surface sediments. This 'mixing layer' may extend to ca 4 cm depth as is indicated by the data obtained from our replicate core AG 4 (Van der Wijk & Mook, in press).

Because of lack of reliable data in the 0—3 cm layer it was assumed that the average rate of deposition of organic matter in the 6—15 cm layer could be extrapolated to this layer (open squares, Fig. 3). Then these extrapolated ages

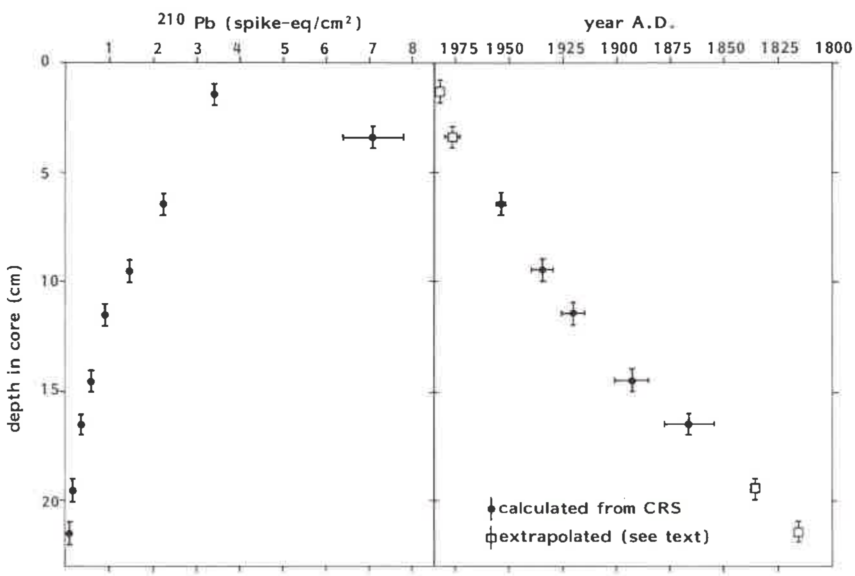

Fig. 3. ^{210}Pb activity and age-depth downcore profile. ^{210}Pb activities expressed as spike-equivalents cm^{-2} (see text).

were used as a reference for further age determination using the CRS model. Integration of the downcore ^{210}Pb activity profile was achieved by interpolation and numerical integration. Open squares (Fig. 3) were also used to denote downcore sediment age extrapolations below 17 cm because below this depth the ^{210}Pb integrated activity approached the total integrated activity which resulted in a large amount of uncertainty in the age determinations.

The average atmospheric ^{210}Pb fall out was estimated from the total integrated ^{210}Pb activity. The obtained value (0.029 pCi $cm^{-2}yr^{-1}$) was considerably lower than the average for the northern hemisphere (0.21 pCi cm^{-2} yr^{-1}, Crozaz et al. 1964). It was also lower than the atmospheric ^{210}Pb activity profiles of other nearby moorland pools (0.17 pCi $cm^{-2}yr^{-1}$, Van der Wijk & Mook, in press).

Diatoms

Diatom nomenclature is in a constant state of flux. Recently, for example, Round & Mann (1981) transferred the small *Anomoeoneis* spp. to the genus *Brachysira*, but did not rename the intraspecific taxa which they transferred from *Anomoeoneis* to *Brachysira*. Ross (in Hartley 1986) renamed and changed the taxonomic ranks of a few infraspecific taxa, with the exception of *A. exilis* forma *lanceolata* Mayer. As we frequently found it in our samples, we were obliged to rename it as *B. vitrea* forma *lanceolata* Van Dam. In this paper, *Eunotia rhomboidea* Hustedt refers to both *Eunotia rhomboidea* and *E. tenella* as interpreted by Van Dam et al. (1981). *Eunotia bilunaris* (Ehrenberg) Nörpel is the correct name for *E. lunaris* (Ehrenberg) Grunow (M. Nörpel pers. comm.).

It was impossible to separate the species *Navicula subtilissima* Cleve and *N. pseudosubtilissima* Manguin using the light microscope. They are combined in this study as *Navicula subtilissima*. Fortunately their ecology is very similar (Germain 1982).

The mean relative abundance of plankton tow diatoms from station B (Fig. 1), calculated for the periods 1925—1929, 1950—1953 and 1984—1985 was based on 5, 3 and 4 samples respectively (Table 2). The data have been organized into pH categories (Hustedt 1939) and the dominant diatoms are given for each of these categories (Table 2). Alkalibiontic taxa were absent from all of our Achterste Goorven sediment samples. Diatom inferred pH based on the formula of Renberg & Hellberg (1982) was also calculated and placed in the table as were species richness and dominance. The latter were used as indicators of biotic diversity as discussed by Van Dam (1982).

The relative abundance of the acidobiontic species increased from the earliest plankton tow sampling dates (1925—1929) until the present when over 80 % of the diatoms in the sample were acidobiontic taxa (Table 2). Initially *Frustulia rhomboides* var. *saxonica* and *Tabellaria quadriseptata* accounted for

Table 2. Relative abundance of the most common diatoms in plankton tow and sediment samples. For the plankton tow samples (station B) the mean relative abundance of a number of samples is represented. The estimates of diatom inferred pH, diatom valve densities, dominance percentage and the number of taxa observed during a count of 400 diatom valves are given at the bottom of the table.

	Sediments										Plankton tows		
core/number of samples	AG7	AG4	AG7	AG4	AG7	AG7	AG7	AG7	AG7	AG7	4	3	5
depth (cm)/period	0–1	1–2	4–5	4–5	6–7	9–10	11–12	14–15	19–20	23–24	1983–'84	1950–'53	1925–'29
Acidobiontic taxa													
Brachysira serians v. *serians*	0.75	5.0	1.0	–	0.75	–	–	–	–	–	–	–	–
Eunotia exigua	36.0	21.0	9.0	10.25	3.0	1.75	1.0	5.25	16.0	–	80.44	0.75	–
Frustulia rhomboides v. *saxonica*	8.75	7.75	10.25	6.75	9.0	8.0	4.0	9.0	10.5	100.0	2.0	13.67	9.45
*Navicula hoefleri**)	2.5	1.0	0.5	0.5	0.5	0.25	0.5	–	–	–	0.13	–	–
Tabellaria quadriseptata	6.25	8.0	3.5	6.5	5.0	6.25	1.75	1.0	6.0	–	1.5	8.75	0.2
others	–	–	–	–	0.75	–	1.25	–	–	–	0.19	0.20	0.04
Subtotals	54.25	42.75	24.25	24.0	19.0	16.25	8.5	15.25	32.75	100.0	84.25	24.42	10.59
Acidophilic taxa													
Brachysira serians brebissonii	0.25	1.5	1.75	0.25	2.75	0.0	0.75	1.0	0.25	–	0.06	5.0	1.4
Cymbella gracilis	0.25	1.25	3.75	3.75	2.25	2.25	2.0	2.75	0.5	–	–	0.83	2.2
Eunotia elegans	3.5	7.75	6.0	6.75	4.25	2.5	1.5	3.25	4.5	–	0.13	0.92	2.25
Eunotia flexuosa	2.0	1.25	1.5	1.75	–	1.5	0.25	0.75	1.25	–	–	–	0.05
Eunotia incisa	7.0	7.75	8.5	6.75	7.0	6.25	2.25	5.5	1.25	–	1.06	26.75	1.4
Eunotia naegelii	1.25	1.0	2.25	2.25	0.5	2.0	0.75	1.5	1.0	–	–	0.25	0.1
Eunotia pectinalis varieties	1.25	4.0	1.75	1.25	2.0	3.25	3.5	2.5	0.25	–	–	–	1.15
Eunotia rhomboidea	6.0	3.25	1.0	6.75	1.75	3.75	2.75	3.75	3.5	–	1.06	4.17	0.5
Navicula leptostriata (=*N. heimansii*)	2.0	3.0	5.25	3.75	5.75	2.25	1.75	1.25	6.0	–	0.31	2.0	20.85
Navicula mediocris	2.5	1.75	0.75	0.75	1.75	0.75	1.5	1.0	1.75	–	0.31	1.25	1.65
Peronia fibula	0.75	–	2.0	0.75	2.25	–	0.25	2.25	8.5	–	–	0.83	1.25
Stauroneis anceps f. *gracilis*	0.75	0.5	0.5	0.75	–	0.75	0.25	2.0	1.75	–	–	–	0.05
Tabellaria flocculosa	0.75	2.25	1.75	1.25	0.5	0.75	1.0	1.5	4.25	–	–	0.58	1.65
others	–	–	–	–	–	0.5	0.5	0.5	0.25	–	0.06	1.67	0.40
Subtotals	28.75	35.25	28.25	36.75	33.5	26.5	19.25	29.5	35.0	–	3.0	44.25	34.9

Table 2. Continued.

	Sediments										Plankton tows		
core/number of samples	AG7	AG4	AG7	AG4	AG7	AG7	AG7	AG7	AG7	AG7	4	3	5
depth (cm)/period	0–1	1–2	4–5	4–5	6–7	9–10	11–12	14–15	19–20	23–24	1983–'84	1950–'53	1925–'29
Circumneutral taxa													
Achnanthes minutissima	0.5	1.5	3.5	7.0	5.0	8.5	19.0	9.0	4.5	–	0.13	0.67	0.9
Brachysira vitrea f. *lanceolata*	4.25	6.25	8.0	9.0	10.0	14.5	24.5	18.5	14.0	–	0.5	5.5	11.35
Eunotia bilunaris	3.5	1.5	4.5	0.5	2.75	5.0	2.5	3.5	0.75	–	8.6	8.08	2.95
Fragilaria virescens	0.75	7.0	14.0	12.75	15.25	14.25	5.75	9.25	2.75	–	2.8	12.5	21.3
Navicula pupula	–	–	–	–	–	–	1.25	–	–	–	–	–	–
Navicula radiosa	–	–	–	–	–	–	1.25	–	–	–	–	–	–
Nitzschia hantzschiana	0.75	0.75	1.0	0.25	–	2.25	–	–	0.25	–	–	0.33	–
Pinnularia abaujensis	0.75	0.5	0.5	2.25	0.75	1.75	0.25	3.5	0.5	–	–	0.17	–
Pinnularia biceps	1.75	0.5	2.75	3.0	2.5	5.50	1.0	5.0	4.75	–	0.13	0.17	0.1
Pinnularia microstauron formae	1.25	1.0	0.5	–	0.75	–	–	–	–	–	–	0.17	–
others	–	–	0.5	0.5	–	0.5	0.5	0.25	–	–	0.06	0.83	0.95
Subtotals	13.5	18.75	35.25	35.25	37.0	52.25	56.0	49.0	27.5	–	12.5	28.42	37.55
Alkaliphilous taxa													
Cymbella microcephala	1.0	0.5	0.75	0.75	2.75	0.25	9.5	2.0	2.0	–	0.13	0.5	1.1
Gomphonema angustatum	–	–	–	–	–	–	1.75	–	–	–	–	–	–
Nitzschia perminuta	3.0	2.75	3.0	3.25	7.75	4.75	3.0	4.25	2.75	–	0.13	1.08	14.55
others	–	–	–	–	–	–	0.5	–	–	–	–	0.12	1.35–
Subtotals	4.0	3.25	3.75	4.0	10.5	5.0	14.75	6.25	4.75	–	0.25	2.5	17.0
Unclassified taxa	–	–	–	–	–	–	1.5	–	–	–	–	0.42	–
Diatom valve concentration (10^7/g dry wt)	3.7	4.9	4.4	0.61	–	5.1	–	0.79	0.43	0.0008	–	–	–
Total number of valves counted	400	400	400	400	400	400	400	400	400	1	1600	1200	2000
Number of taxa in count	30	29	31	29	26	28	37	28	28	1	13.15	24.7	23.0
Dominance percentage	36.0	21.0	14.0	12.75	15.25	14.5	24.5	18.5	14.0	100	80.4	28.0	27.9
Renberg inferred pH	4.8	4.9	5.2	5.2	5.5	5.5	5.8	5.5	5.1	–	4.2	5.1	5.7

*) sensu Ross & Sims (1978).

most of the acidobiontic taxa. After 1955, however, *Eunotia exigua*, which was the most sulfate and acid tolerant species (Van Dam et al. 1981, Descy 1984), completely dominated the plankton tow diatom samples. Acidophilous taxa increased from the 1920s (35%) to the 1950s (44%). During the 1950s *Eunotia incisa* was the dominant diatom.

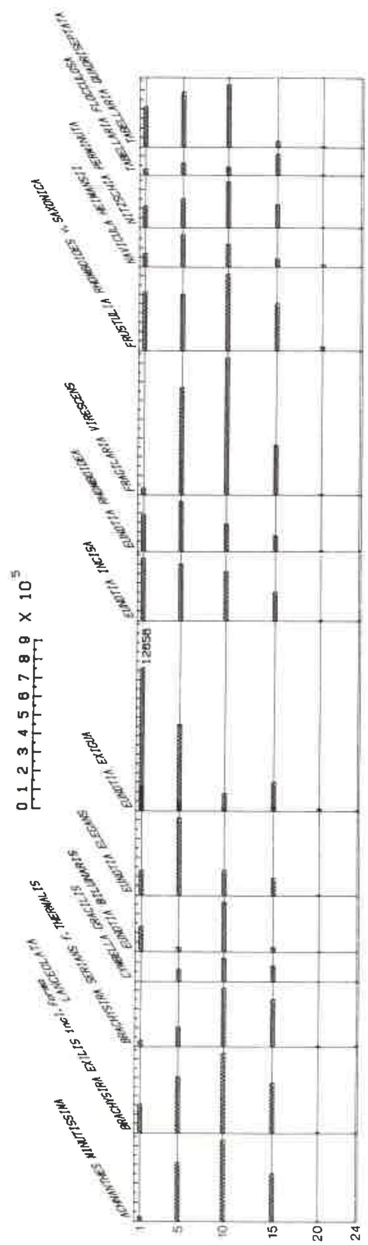

Fig. 4. Downcore distribution of diatoms. Densities are expressed as the number of diatom valves per gram of sand-free dry weight (*Brachysira exilis* should be *B. vitrea*).

The concentration of diatoms per g sand-free dry weight increased downcore in the top 10 cm of the core and then decreased as the sand content of the sediments reached 95 %. Diatom densities in the top 20 cm of sediments ranged between 0.43 and 5.1×10^7 diatom valves per g sand-free dry weight (Table 2). Below 20 cm the diatom density suddenly decreased to 7600 valves per gram sand-free dry weight.

The alkaliphilous diatom *Nitzschia perminuta* declined in absolute as well as relative abundance above a sediment depth of 9 cm (Fig. 4 and Table 2). This was also true for the circumneutral diatoms (e.g. *Fragilaria virescens* and *Brachysira vitrea* forma *lanceolata*) which declined upcore as diatom inferred pH fell from 5.5 to 4.8. The absolute abundance of a number of the acidophilous and acidobiontic taxa, on the other hand, increased upcore (Fig. 4 and Table 2).

The rate of lake acidification was inferred from the shift in downcore diatom species composition and from the inferred pH of the plankton tow diatoms recovered from Achterste Goorven in the 1920s, 1950s and 1970s. The relative abundance of acidobiontic taxa (acidophilic and circumneutral taxa) and alkaliphilic taxa as well as those for which no pH category could be assigned was calculated for both the plankton tow diatoms (open bars) and sediment core diatoms (solid bars). Three time periods are displayed for both the plankton tow and the sediment core diatoms (Fig. 6).

The plankton tow and sediment core diatom inferred pH estimates can be compared with the actual measures of pH for Achterste Goorven (Fig. 6). The downward displacement of *Eunotia exigua* as illustrated in Fig. 7 is discussed in a later section.

During the period 1952 to 1984 the observed pH at station A (Fig. 1) fell from 5.2 (P. van Oije, unpublished data) to 4.0 (Fig. 6). The plankton tow diatom inferred pH calculated from the B Index (Renberg & Hellberg 1976) for the same station (A) fell 1.2 of a pH unit from 1925 to 1955 and 0.8 of a pH unit during the period 1955 to 1984. At station B, which was located near station 4, the pH as measured with colorimetric techniques by J. Heimans (un-

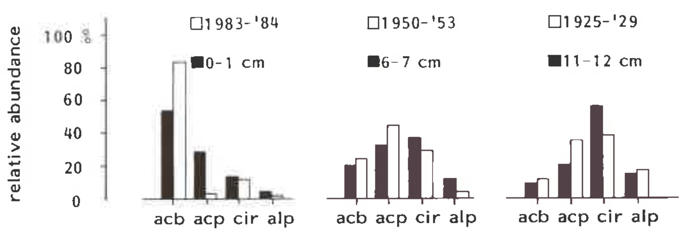

Fig. 5. Histograms of the relative abundance of acidobiontic, acidophilic, circumneutral and alkaliphilons diatoms at 0—1 cm (1983—1984), 6—7 cm (1953—1955) and 11—12 cm (1925—1929).

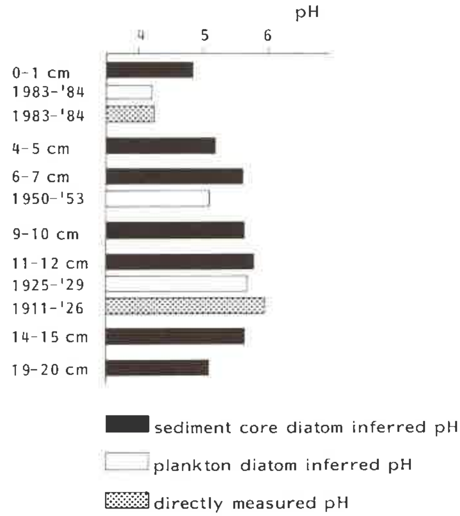

Fig. 6. Comparison of diatom inferred pH and observed pH.

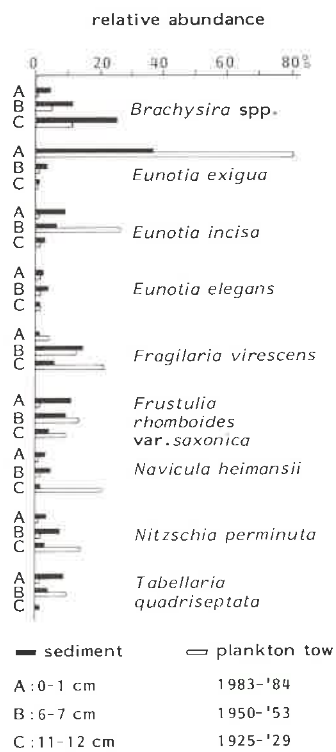

Fig. 7. The relative abundance of the 9 most abundant diatom taxa in the plankton (open bars) and sediments (solid bars) during the period 1925—1985. The relative abundances of diatom taxa at different sediment depths are plotted against the means for the plankton diatoms collected in corresponding periods. Correspondances are based on ^{210}Pb analyses (Fig. 3).

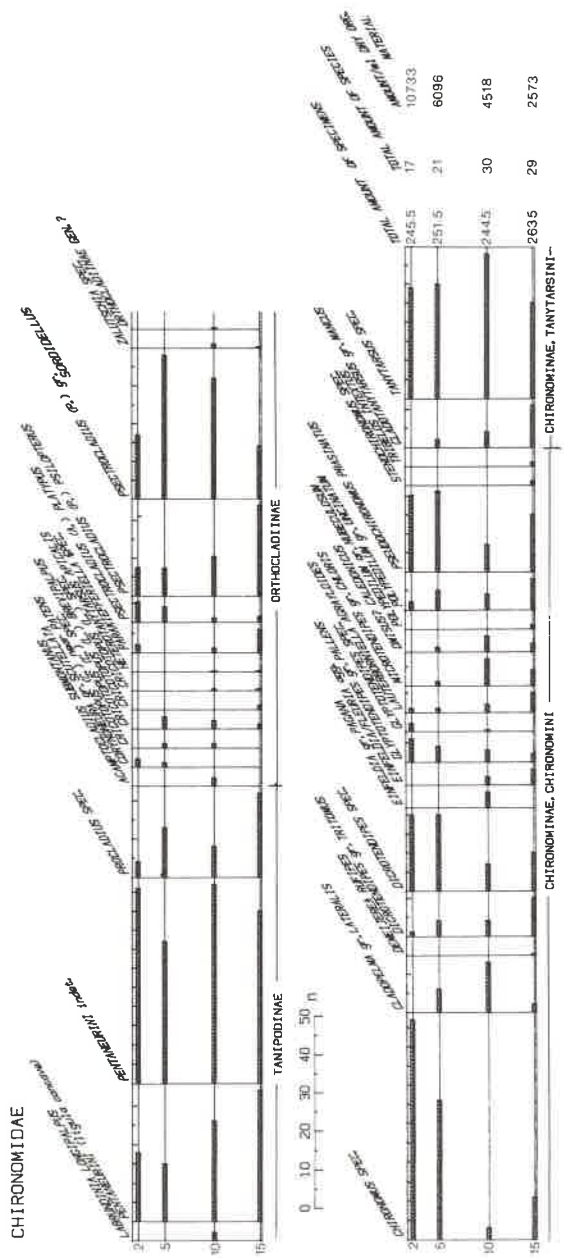

Fig. 8a. Numbers of chironomid head capsules counted at four depths and total amount of species.

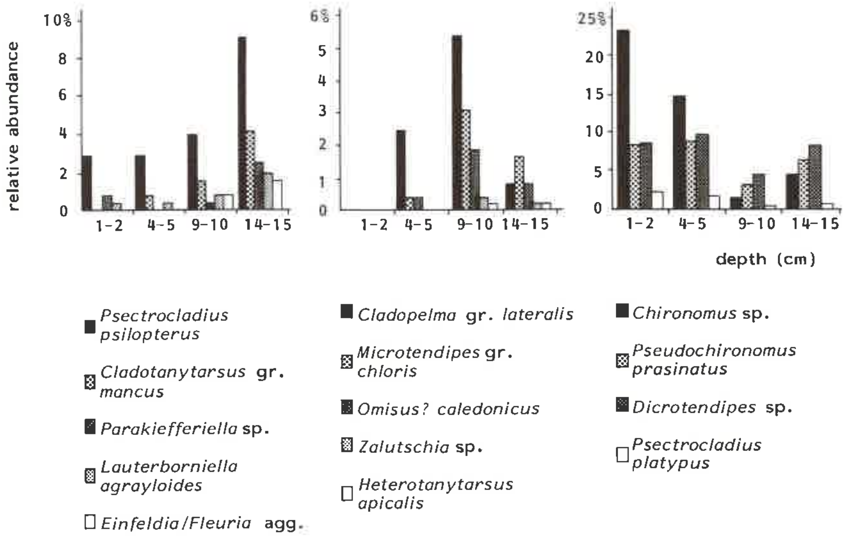

Fig. 8b. Relative abundances of the most prominent chironomid taxa, organized into three assemblages.

published data) fell from 6.0 (mean of 3 measurements during the period 1919—1926) to 4.2 (mean of 4 potentiometric pH measurements during the period 1983—1984). The plankton tow diatom inferred pH at this site fell from 5.8 to 4.2 over the last 60 years. There is excellent agreement between the plankton tow diatom inferred pH data set and the observed changes in pH in Achterste Goorven over the period 1925 to 1984.

Chironomids

Chironomid head capsules were examined at four depths: 15—14 cm, 10—9 cm, 5—4 cm and 1—2 cm. Below 15 cm only negligible quantities of chironomids were found. A survey of all encountered taxa, organized by subfamily, is given in Fig. 8 a.

In Fig. 8 b the most common taxa are organized in three groups: the *Psectrocladius psilopterus* assemblage, the *Cladopelma* assemblage and the *Chironomus* assemblage. These assemblages are named after their most abundant representatives.

The *Psectrocladius* assemblage, which has its optimum in the 14—15-cm layer, is typically found in oligohumic, mesotrophic lakes (Brundin 1949, Saether 1975). The *Cladopelma* assemblage, which was most abundant in the 9—10-cm layer, has never been reported alive from The Netherlands. Brundin (1949) observed this assemblage in three oligotrophic lakes with various con-

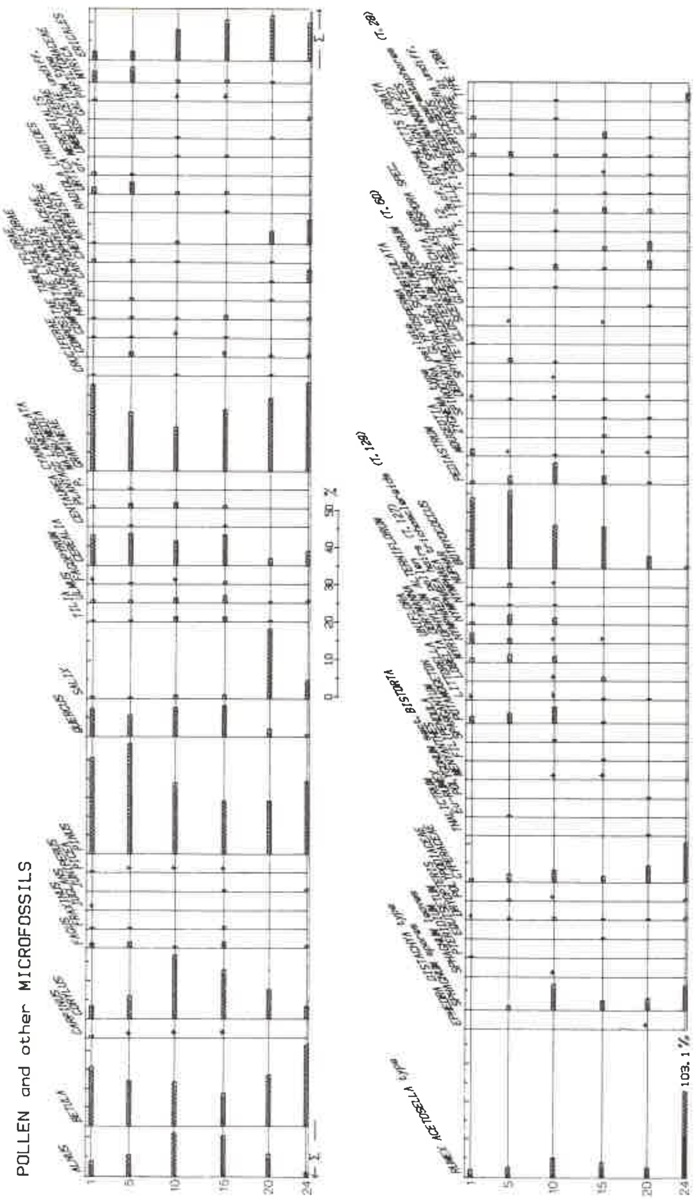

Fig. 9. Downcore percentage pollen and microfossil distributions. For each pollen type the relative abundance is plotted.

centrations of humic acid. The *Chironomus* assemblage has its optimum in the topmost layer of sediment. *Chironomus* may be dominant in very diverse habitats: extremely eutrophic lakes and dystrophic pools (SAETHER 1975, WIE-

DERHOLM 1983). *Psectrocladius platypus* is a definitely acidobiontic species (MOLLER PILLOT 1984b), while *Pseudochironomus* and *Dicrotendipes* can tolerate pH-values as low as 3.4 (LEUVEN et al. in press).

An upcore shift is recorded from a meso- to an oligotrophic environment. Above 5 cm depth acidification is apparent.

Pollen and plant macrofossils

Major changes in the vegetation around Achterste Goorven over the last 150 years are evident from the pollen stratigraphy of its sediment core. Separate pollen profiles for all recorded taxa are provided (Fig. 9) to permit the recognition of downcore pollen patterns. The main trends in the relative abundance (percentage composition) of pollen of upland herbs, cultivated plants and arboreal taxa have been illustrated in an Iversen styled summary diagram (Fig. 10).

Although pollen percentages cannot be directly interpreted in terms of percentage cover, downcore changes in percentage composition can be used to indicate major temporal trends in vegetation types over the last 150 years in this region (e.g. changes in the intensity of land use for agriculture). Specific details of the downcore changes in relative abundance are noted in the discussion section.

In addition to the relative abundance of pollen its downcore concentration (Fig. 11) was calculated to permit us to gain a general impression of pollen and sediment influx.

The seeds, fruits and other botanical macrofossils (Fig. 12) were recorded in order to gain additional information about local changes in species composition in, and near Achterste Goorven.

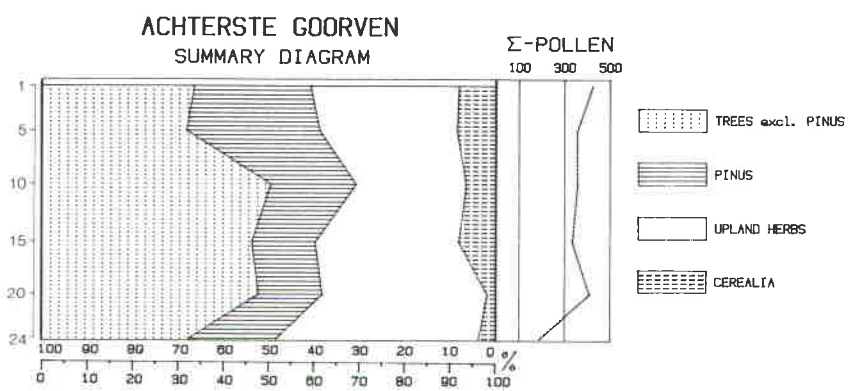

Fig. 10. Iversen styled diagram for pollen of trees, upland herbs and Cerealia.

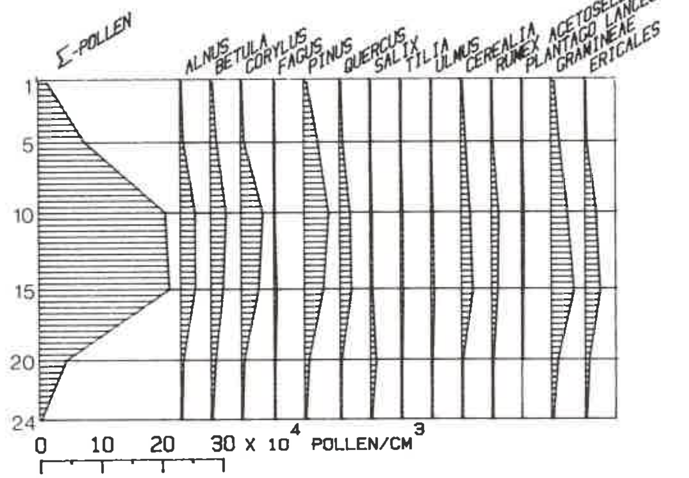

Fig. 11. Pollen concentration diagram (no. of pollen grains ml^{-1}) for 14 taxa.

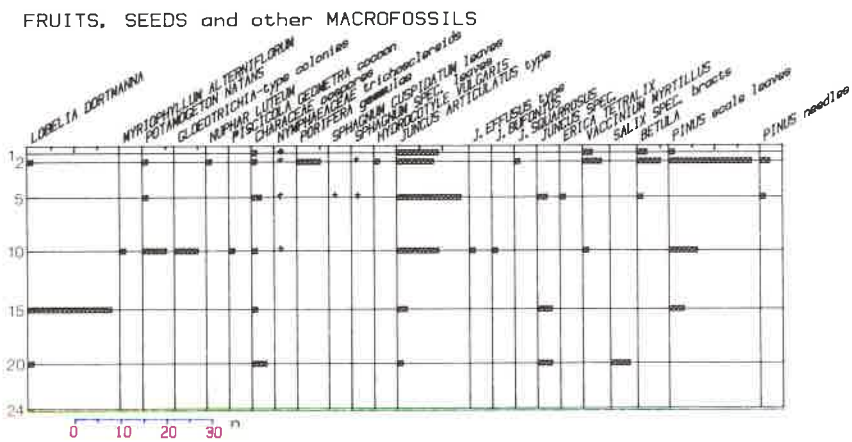

Fig. 12. Diagram of fruits and seeds and other macrofossils from Achterste Goorven.

Discussion

Recent acidification

Belgium and The Netherlands are located in the very centre of the European acid rain region (EMEP/CCC report 1984). Measurements of the pH in the rainwater at the nearest preciptiation monitoring stations, located approximately 20 km from our study area, gave a mean pH for the period 1978—1982 of 4.4 (KNMI-RIV 1983). The mean SO_4^{2-}-S for the same period was 7.1 mg l^{-1} and the mean NH_4^+-N concentration was 1.7 mg l^{-1} (ibid.). Most of the nitrogen is in the form of NH_4^+-N. The mean SO_2-S concentration in the air near Achterste Goorven, according to the Netherlands National Air Pollution Network for the period 1978—1984 was 10.3 $\mu g\ m^{-3}$. This results in the very high deposition rate of about 160 kg S $ha^{-1}y^{-1}$. Accordingly the mean SO_4^{2-} concentration in the pool during the period 1979—1984 was very high with 12 mg l^{-1} as an average of 23 measurements.

Battarbee (1984), reviewing the available studies on diatoms and lake acidification, concludes that the evidence generally indicates that lake acidification is due to an increase in the acidity of precipitation as a result of emissions from fossil fuel combustion. The average decline of the pH, as inferred from diatom data from 34 lakes in Scandinavia and North America was 0.6 units. The onset of acidification was generally between 1920 and 1950, but in one Norwegian lake the acidification already began in 1850.

Berge (1975, 1979), Renberg & Hellberg (1982), Tolonen & Jaakkola (1983), Davis et al. (1983), Flower & Battarbee (1983) and Battarbee et al. (1985) describe the changes in the species composition of diatom assemblages in cores of acidifying lakes in Scandinavia and Scotland. In all cases acidophilous and acidobiontic species are increasing from the bottom to the top of the sediments. Especially in Scandinavia species like *Brachysira serians, Eunotia bactriana, E. denticulata, Navicula subtilissima* and *Semiorbis hemicyclus* are abundant or dominant in the surficial sediments of acidified lakes. *Tabellaria binalis* increases by acidification both in Scandinavia and Scotland, while *T. quadriseptata, Navicula hoefleri* and *Eunotia incisa* seem to be more dominant in the surficial sediments of the Scottish lochs. *E. exigua* generally is of minor importance in the discussed lakes. In contrast this species is the most dominant one in the surficial sediment of Achterste Goorven. The other abundant taxa in the 0—1 cm sediment of Achterste Goorven are very similar to those in Scandinavia and Scotland (e.g. *E. incisa, Tabellaria quadriseptata* and *Navicula hoefleri*). The absence of *Tabellaria binalis* from Achterste Goorven was interpreted as indicative of a preference of *T. binalis* for sandy substrates. Species like *Eunotia bactriana* and *Semiorbis hemicyclus* have never been found in The Netherlands. The absence of the latter species may be associated with its preference for deeper waters, which are rare in The Netherlands. The dominance of *Eunotia exigua*, which is very resistant to acidification (Van Dam et al. 1981) is not matched by lakes in other parts of Europe.

Our data indicate that the rate of acidification is among the highest reported to date. Both plankton tow and sediment diatom inferred pH, as well as direct observations of pH (Fig. 6) demonstrate that the pH declined from about 5.8 to c. 4.2 over the last sixty years. Also the subfossil Chironomid assemblages indicate a recent decrease of pH in this shallow pool. Two major factors are responsible for this high rate of acidification. Firstly the small volume causes large parts of the bottom of the pool to dry up during periods of drought, resulting in oxidation of the reduced sulfur compounds in the sediment. Therefore, sulfate concentrations are high after refilling (Vangenechten et al. 1981). Secondly the atmospheric deposition of acidic substances is very high in this region.

During the early 1900s a large standing crop of macrophytes was present in the pool, as indicated by the seeds and fruits in the sediments and the early records of the pool's vegetation. The abundant vegetation was a good substratum for diatoms, which had a high density in this period (Fig. 4). Also the chironomids attained the maximum density during this period (Fig. 8a). As the pool acidified the macrophyte standing crop declined and with it the chironomid head capsule diversity and the diatom valve density and diversity.

The pH decline in Achterste Goorven is very similar to that in Härsvatten in southern Sweden (Renberg & Hellberg 1982). As far as we are aware only a number of small ($\bar{a} = 59$ ha), but relatively deep ($\bar{z} = 10.3$ m) lakes near Gothenburg is acidifying faster than Achterste Goorven and other moorland pools in The Netherlands. In these lakes pH declined from 6.6 in 1968 to 4.7 in 1979 (average of 18 lakes) and increased slightly afterwards (Morling 1981, 1984).

Before the period of falling pH in Achterste Goorven, the data indicate an increase of pH from the bottom of the core to a depth of ca 12 cm. This, and also the fact that only rather young sediments (age less than 200 years) were found can only be understood after reconstruction of the local history of the moorland pool which will be discussed in the next section.

Historical development

Below 20 cm

The pool Achterste Goorven probably originated during the Late Glacial period as a depression in the landscape and was filled up with peat deposits in the Postglacial (Geenen 1977). The peat was later excavated by man, for use as a fuel. The code for the village of Oisterwijk from the year 1509, which was published by Posthumus (1911) already contained regulations for the excavation of peat from the 'Goer', of which the Achterste Goorven is a part. Documents were found in the archive of the village of Oisterwijk and the National Archive in 's-Hertogenbosch dating from 1724, 1746 and 1823 in which farmers were allowed to excavate peat from the 'Goor'.

The Voorste Goorven (CP I in Fig. 1 of Van Dam & Kooyman-van Blokland 1978) was the other part of the ancient 'Goer', 'Goir' or 'Goor'. Nowadays it is separated from the Achterste Goorven (A I in the same figure) by a narrow dam with a culvert, which allows drainage of water during times of high water levels from the Achterste Goorven to the Voorste Goorven. Counting annual rings of the stubs of cut Scots pines on the dam indicated that this dam is at least hundred years old. According to the code of 1509 the peat-diggers were allowed to construct dams through the moorland pools in order to facilitate the transport of the peat, although it was usual to remove the dams after completion of the peat excavation.

The past connection of Achterste Goorven with Voorste Goorven was important for the determination of the composition of the water in Achterste Goorven. Originally the water of the pools in the very nutrient poor sands near Oisterwijk was oligotrophic and badly suited for any economic purpose, e.g. fish stocking. Therefore, the Voorste Goorven was fertilized with agricultural drainage water, which was supplied through ditches (see Fig. 1 in Van Dam & Kooyman-van Blokland 1978). As early as 1619 the Board of Oisterwijk allowed a citizen to prepare the Witven (CP II in the same figure), which receives the drainage water of Voorste Goorven, for stocking with carps, as appears from an old deed in the State Archive. One may suppose that the trophic state of the Voorste Goorven increased with time, with the intensification of argricultural practice. According to the assemblages of desmids and diatoms in the beginning of this century Voorste Goorven contained mesotrophic water (Heimans 1925, Coesel et al. 1978, Van Dam & Kooyman-van Blokland 1978).

Also important for the interpretation of the present core are the changes of the terrestrial vegetation in the surroundings of Achterste Goorven. The rotational burning of heather coupled with its overgrazing by sheep in the late Middle Ages, the burrowing of rabbits into the hillsides and the hagging of peat were all factors contributing to soil erosion following the felling of the trees in the province of Brabant. The sand so liberated was probably gathered into bare wandering dunes which moved in the direction of the prevailing winds whenever these exceeded a speed of 16 km h^{-1} (Burnett 1964).

The deepest sediments (24—34 cm) in the Achterste Goorven core contained representatives of non-aquatic species (Fig. 9). Terrestrial pollen at 24 cm was associated with large quantities of wind blown sand. All the evidence to date indicates that these sands were deposited over a relatively short period of time (i.e. less than 50 yrs) prior to dune stabilization in the Oisterwijk region. It is hypothesized that these sands partially filled up the peat excavated basin of Achterste Goorven in the early 1800s. The occurrence of a coarse sandy sediment below 20 cm (see sediment core description) reflects erosionary processes in the surroundings of the sample site. The relatively high pollen percentage of the dicot pioneers *Rumex acetosella* and *Artemisia* is typically associated with the regular occurrence of bare soils which are formed as a consequence of these erosionary processes. The very low representation of algae and other water plants in this layer indicates that the sediment and its microfossil contents represents a non-aquatic habitat. We have interpreted this as an indication that the sediments of Achterste Goorven below a depth of 20 cm probably represent a terrestrial or semiaquatic condition, at least at the sample site (station 7) located near the center (Fig. 1). Below a sediment depth of 20 cm diatom valve concentrations dropped three orders of magnitude (from 0.43—5.1 × 10^7 to 7.6 × 10^4 valves per gram sand-free dry weight, Table 2). According to the ^{210}Pb data this sand layer was deposited ca. 1810—1820, which is in agreement with the date of 1823 when the last document found in which farmers were allowed to excavate peat was issued (see above).

Until the past century the Oisterwijk region was poor in forest, although small lots of forest with various tree species and especially Scots pines on the dryest spots have always been present. Stabilization by afforestation of the dunes and heathlands began in the late 1700s and culminated about a century later. In several sites in the sandy Flanders and the province of Brabant, *Pinus* was already planted at the end of the 17th century (Beyens 1984). The dunes on the shores of Achterste Goorven were afforested with pines between 1830 and 1840 (Van Hees & Van den Wijngaard 1976). As a result of the absence of *Pinus* (or at least its very infrequent occurrence) in The Netherlands during the late Holocene a sudden increase in pine pollen in recent sediment core pollen spectra can be used to indicate pine plantations (Janssen 1972). From the *Pinus*-pollen profile for Achterste Goorven (Fig. 10) it is evident that the aquatic sediments of this pool were deposited after the planting of *Pinus sylvestris* in the area. The ^{210}Pb date of ca. 1816 at the bottom of the core in this context seems to be a little too old.

The percentage of herbaceous pollen, especially Ericaceae, grasses, cereals, buckwheat and weeds like *Rumex acetosella* and *Plantago lanceolata* indicate that the forested area near Achterste Goorven was primarily an open forest, i.e. patches of forest intermixed with heathlands and arable fields, which is in accordance with the pattern of land use that is registrated on the topographic maps of 1835 and 1840.

20—15-cm depth

The sample at 20 cm depth, dated with ^{210}Pb at c. 1830—1840 contains *Salix* pollen at its maximum densities in the core (Fig. 9). Also bracts of *Salix* were found, indicating that willows were temporarily present at or near the sample site. The aquatic plants represented at this depth (20—15 cm) were *Lobelia dortmanna*, *Littorella uniflora*, *Characeae*, *Botryococcus*, *Pediastrum*, and spores of Zygnemataceae (*Debarya*, *Mougeotia*, *Spirogyra*, and *Zygnema*, Fig. 12). The pH, inferred from the sediment core diatoms, rose in the period of deposition of the 20—15-cm depth layer from 5.1 to 5.5 (Fig. 6).

15—10-cm depth

Samples from 15 cm to the top of the deposit represent true pool depositions. Some macrofossils from vegetation around the pool were also embedded in the sediments (e.g. *Vaccinium myrtillus, Pinus* and *Juncus* spp.). The seeds of the *Juncus articulatus* type (Körber-Grohne 1964) were probably produced by *J. bulbosus,* which is presently common nearshore. *Myrica gale* and *J. bulbosus* are both examples of plants which were probably common inhabitants along the fringe of the pool in former times, as they are still now.

The presence of the seeds of *Lobelia dortmanna* at 15-cm depth (circa 1890) in Achterste Goorven sediments (Fig. 12) was significant. The habitat of this taxon is characterized by sandy soils, oligotrophic water and fluctuating water level (Schoof-van Pelt 1973). These are precisely the conditions which are associated with a number of taxa from the *Psectrocladius psilopterus* chironomid assemblage which reach peak abundance at 14—15 cm (Fig. 8 b). *Lobelia dortmanna* was not found above 15 cm with the exception of a single seed recorded at 2 cm. Characeae oospores were frequently associated with *Lobelia dortmanna* but the Characean species were found at all depths that we examined (Fig. 12). The upcore disappearance of *Lobelia* may be related to the development of an organic mud layer which is inimical to the growth of this species (Westhoff et al. 1973).

The samples from above the 15-cm level display relatively high pollen percentages of *Potamogeton* (seeds of *P. natans*). *Nymphaea, Nuphar luteum* and *Myriophyllum alterniflorum* were also found (Fig. 13). The species that were recorded from these levels were also recorded by naturalists, who visited Achterste Goorven during the first decennia of this century (e.g. Thijsse 1912, 1916, 1927, Geijskes 1929). None of these authors mentions the presence of *Lobelia dortmanna,* which was a rare plant in The Netherlands and certainly would have been noticed if present. Bergmans (1926) recorded *Lobelia* in small quantities in the Voorste Goorven. Thus the presence of *Lobelia* in the 15-cm level may indicate that the sediments at this depth were deposited well before ca. 1910. This is in good agreement with the time of deposition as obtained from the ^{210}Pb results (approximately 1884—1900).

Between a sediment depth of 10 to 15 cm an upcore increase in the number of chironomid taxa associated with meso- to polyhumic waters was noted (e.g. *Acamptocladius submontanus, Labrundinia longipalpus, Zalutschia* sp. and *Heterotanytarus apicalis*). This combination of chironomids has never been reported as a living assemblage from The Netherlands. In Sweden this essemblage has been reported for the lakes Östra Vontjärn (polyhumic), Stråken (mesohumic) and Skärhultsjön (oligohumic) by Brundin (1949). All three of these lakes are oligotrophic with a pH between 5.8 and 6.8. The diatom inferred pH for the 11—12-cm depth layer (^{210}Pb dated at ca. 1914—1925) in Achterste Goorven was 5.8 (Fig. 6), in good agreement with the plankton tow inferred pH for the period 1925—1929 (5.7) and the observed pH for the period 1919—1926 (6.0).

Thus the diatoms and chironomid data for Achterste Goorven indicate that the 10—15-cm depth represents the highest pH levels that this pool reached over the last 150 years. In addition, the blue-green alga *Gloeotrichia* sp. which is typically associated with a pH above 5.5 (Prescott 1962) was found at this depth (Fig. 12).

10-cm to top of core

A substantial increase in the relative number of *Chironomus* head capsules between 0—10 cm (Fig. 8 b) was associated with a concomitant decrease in chironomid species richness. Thus as the pool acidified, its chironomid assemblages species richness declined as taxa associated with disturbed conditions such as *Chironomus* (Moller Pillot 1984 b) replaced many of the pool's previous inhabitants. The dramatic increase in the relative abundance of the acid indicator species *Psectrocladius platypus* (ibid.) supported the contention that Achterste Goorven has been rapidly acidifying.

It is noteworthy that Walker et al. (1985) observed similar upcore changes in subfossil chironomids in a small humic lake in New Brunswick, Canada. This supports Saether's (1975) contention about the resemblance of palaearctic and nearctic chironomid assemblages.

The most recently deposited sediments which were examined for pollen and algal spores (1—2 cm) contained numerous zygospores of the filamentous green alga *Mougeotia* spp. Species of this genus have been found to grow prolifically in acidifying lakes, as soon as pH is below 5.5 (Stokes 1981, Schindler et al. 1985). Many *Mougeotia* species have been reported to exhibit a considerable tolerance to heavy metals (Foster 1982, Francke & Hillebrand 1980). Heavy metal mobilization associated with acid rain is well documented (Tolonen & Jaakkola 1980, Charles 1982, Schindler et al. 1980).

The increase of *Urtica* (nettles) pollen in the upper sediment samples of Achterste Goorven indicates an extension of nitrogen-rich habitats in the agricultural area which is situated at a distance of 1—2 km from this moorland pool.

Sediment compaction and mixing

If sediment sampling intervals are short (i.e. 1—2 cm), the trends in all pollen concentration profiles (Fig. 11) can be explained in terms of sediment accumulation rates (Middeldorp 1982, 1984). In the present study, sediment sample distances of 5 cm were adopted for pollen profiling. Although a detailed time scale analysis was not possible, general trends in pollen accumulation rates are evident. These trends indicate that the high pollen concentrations in the intermediate sediment depth layer (5—20 cm) were associated with a well compacted sediment. This is in sharp contrast to the poorly compacted surficial sediments (0—5 cm) where the water content reached 95% (Table 1). Pollen concentrations were also very low in the deepest portion of the Achterste Goorven core (20—34 cm) and this was associated with large quantities of coarse sand (Table 1) which presumably acted as a 'diluting' factor.

As already noted in the results section the ^{210}Pb activity profile (Fig. 3) indicates some infiltration of surface water into the interstitial waters of the surficial (0—4) sediments. Evidence for vertical mixing of sediments in this layer as well was obtained from the replicate core AG4, which shows constant ^{210}Pb activity in this surficial layer (VAN DER WIJK & MOOK, in press). Also the comparison of plankton tow diatoms and sediment core diatoms (Fig. 7) indicates mixing of sediment. Although *Eunotia exigua*, an acidobiontic diatom, was absent from the plankton tow samples from the period 1925—1929, it is present with a relative abundance of 1% in the 11—12 cm horizon (Table 3), which was dated by ^{210}Pb to the same period. Similarly this species has also a higher abundance in the sediments at 6—7 cm than in the plankton tow samples from 1950—1953. The downcore disappearance is more gradual than its disappearance from the plankton tow samples. Also in the relative abundance of other taxa in the plankton tows and the sediments often a discrepancy is found (Fig. 7), although the trends are often the same.

As a result of the mixing of sediments the relative abundance of *Eunotia exigua* in the surficial sediment layer is lower than expected. Therefore, diatom inferred pH for the surface sediments (4.8) was significantly higher than the observed and plankton tow inferred pH (both 4.2). The sediment core diatom inferred pH at 11—12 cm (5.8) was in accordance with the plankton tow diatom inferred pH for the period 1925—29 (5.7) and the observed pH in the same period (6.0). Thus the decline of the pH, based on sediment diatom inferred pH (1.0 unit) is much lower than the decline of the pH based on plankton tow diatom inferred pH (1.5 unit) or direct observation (1.8 unit). Therefore, estimates of the rate of acidification from sediment core diatoms will consequently underrate the lake acidification where vertical mixing is indicated.

The fact that the organic sediments of Achterste Goorven are much thicker at wind sheltered than at wind exposed locations indicates that horizontal mixing, i.e. lateral transport of sediment e.g. by wind action, may have taken place as well. This is supported by the ^{210}Pb measurements, yielding a total integrated activity that is much lower than the average atmospheric ^{210}Pb fall out in this region (CROZAZ et al. 1964, VAN DER WIJK & MOOK, in press). This, and the fact that the ^{210}Pb activity depth profile shows continuous exponential behaviour may indicate a continuous transport of (suspended) sediment away from the location AG7. This constant transport however does not affect the interpretation of the other data.

Below a depth of 12 cm in a profile the sediment diatom inferred pH is again lower than at 12 cm. As discussed in the section on historical development of the pool there was a connection more than 100 years ago between the originally oligotrophic (low pH) pool Achterste Goorven and the more mesotrophic (higher pH) pool Voorste Goorven. If the high pH at depths below 12 cm is a result of this connection one would expect the sediment horizon with the highest diatom inferred pH to be at least 100 years old. This is in contradiction with the ^{210}Pb date of ca. 1914—1925 for this horizon. Further studies, e.g. on sediment remains of desmids, of which the living assemblages have been studied by Heimans (1925) and Coesel et al. (1978) may shed light on this question.

Summary

Most palaeolimnological studies have been carried out in relatively deep lakes, where perturbation of the sedimentation process by wind action and bioturbation are of minor importance and where sediments are not exposed to the atmosphere in extremely dry years. The purpose of this study was to investigate the applicability of palaeolimnological methods in a shallow soft water pool in order to determine the rate of acidification.

Pollen stratigraphy provided information about the development of the pool Achterste Goorven over the last 150 years. Pollen and diatom analyses all indicated that our Achterste Goorven sampling site existed as a terrestrial environment shortly after reafforestation with Scots pines of the aeolic drift sands which started in the early 1800s.

The acidification of Achterste Goorven was associated with a decrease in both chironomid and diatom diversity. The chironomid assemblage occurring below 15 cm was relatively diverse and has no living counterpart in The Netherlands. It has been described for poorly buffered waters in Scandinavia. The upcore replacement pattern of chironomid assemblages which took place in Achterste Goorven as it acidified was similar to the one described by Walker et al. (1985) for a small acidifying Canadian lake.

The pH inferred from the plankton tow diatoms which were collected from 1925 to 1929 was 5.7. The 11—12 cm deep sediments were dated at 60—70 years of age (Fig. 3). The diatom inferred pH of these 11—12 cm deep sediments was 5.8 (Fig. 6).

Achterste Goorven is undergoing rapid acidification. During the last 60 years, sediment core diatom inferred pH has fallen from 5.8 to 4.8, observed pH has fallen from 6 to 4.2 and plankton tow diatom inferred pH has fallen from 5.7 to 4.2. During this same period there was a concomitant increase in the relative abundance of acid tolerant chironomid and diatom species and a concomitant reduction in the relative abundance of acid intolerant chironomid and diatom taxa (Table 2, Fig. 8b).

These data indicate that the rate of acidification in Achterste Goorven is among the highest reported to date. Two major factors are responsible for this high rate of acidification: the small volume of the pool and the high level of wet and dry deposition of acidifying substances in the area. The only water bodies outside the Netherlands of which we are aware that those are acidifying faster than Achterste Goorven are located near Gothenburg, Sweden. Mean pH in these lakes fell from 6.6 to 4.7 during the period 1968—1979 (Morling 1981).

In conclusion, our results indicate that useful stratigraphic information can be obtained from an analysis of the sediments of moorland pools as long as it is recognized that mixing of microfossils typically occurs to a larger extent in these shallow pools than it does in sediments from deeper bodies of water.

Zusammenfassung

Die meisten palaeolimnologischen Studien beziehen sich auf tiefere Seen, wo Störungen des Sedimentationsprozesses durch Windwirkung und Bioturbation wenig Einfluß haben und Sedimentablagerungen in extremen Trockenjahren nicht an der Luft exponiert werden. Das Ziel unserer Untersuchung war die Anwendbarkeit von palaeolimnologischen Methoden in einem seichten Weichwasserteich nachzuprüfen, um damit die Schnelligkeit des Versauerungsprozesses festzustellen.

Pollenstratigraphie gab Hinweise auf die Entwicklungsgeschichte des Achterste Goorvens in den letzten 150 Jahren. Die Analyse von Pollen und Kieselalgen ergibt, daß unsere Probeentnahmestelle im Achtersten Goorven eine terrestrische Phase erlebte kurz nach dem Anfang der Wiederbewaldung des Flugsandgebietes mit Kiefern im frühen 19. Jahrhundert.

Die Versauerung des Achtersten Goorvens zeigte sich durch einen Rückgang der Diversität der Chironomiden- und Kieselalgengesellschaften. Die Chironomidengesellschaft in den untersten Sedimentablagerungen (mehr als 15 cm tief) war relativ artenreich und kommt rezent nicht mehr in den Niederlanden vor, wohl aber in schwach gepufferten Gewässern in den nordischen Ländern. Die Änderungen in den Chironomiden-nekrozönosen in rezenteren Ablagerungen des Sediments als Folge des Versauerungsprozesses im Achtersten Goorven korrespondieren mit denen, welche WALKER et al. (1985) von einem kleinen versauerten See in Kanada beschrieben haben.

Der pH-Wert, wie dieser aus der Zusammensetzung der Planktonnetzkieselalgengesellschaft von 1925 bis 1929 berechnet werden kann, war 5,7. Die Sedimente von 11—12 cm Tiefe unter dem Teichboden sind 60—70 Jahre alt, wie mit der ^{210}Pb-Methode bestimmt worden ist (Fig. 3). Der aus den Kieselalgen dieser Sedimentschicht berechnete pH-Wert erwies sich als 5,8 (Fig. 6).

Das Achterste Goorven versauert schnell. In den letzten 60 Jahren ist der pH-Wert, berechnet aus den Sedimentkieselalgen, von 5,8 auf 4,8 gesunken, der pH-Wert berechnet aus den Planktonnetzkieselalgen von 5,7 auf 4,2, und die chemisch bestimmten pH-Werte haben sich von 6 auf 4,2 erniedrigt. In derselben Periode hat die relative Abundanz der säuretoleranten Kieselalgen- und Chironomidenarten zugenommen, und die relative Abundanz der säureintoleranten Kieselalgen- und Chironomidentaxa hat abgenommen (Tabelle 2, Fig. 6b).

Diese Fakten indizieren, daß die Schnelligkeit der Versauerung des Achtersten Goorvens zu den höchsten bis jetzt gemessenen gehört. Für diese schnelle Versauerung gibt es zwei Hauptursachen: das kleine Volumen des Gewässers und das hohe Niveau der nassen und trockenen Immission in diesem Gebiet. Die einzigen Gewässer außerhalb der Niederlande, die uns bis jetzt bekannt sind und schneller versauern, liegen unweit von Gothenburg (Schweden). Der mittlere pH-Wert ist dort von 1968 bis 1979 von 6,6 auf 4,7 gesunken (MORLING 1981).

Unsere Ergebnisse zeigen, daß sich wertvolle stratigraphische Erkenntnisse aus der Analyse von Sedimentablagerungen ehemaliger Heidetümpel ergeben, wenn man berücksichtigt, daß die Mengung von Mikrofossilien in höherem Maße in diesen seichten Gewässern wie in Ablagerungen in tieferen Gewässern stattfindet.

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