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Some effects of lake acidification on Pisidiidae in Southern Ontario, Canada - Tavi acidifikáció hatása a Pisidiumokra Dél-Ontarióban, Kanada

ABSTRACT: The size, weight and calcium content of 14 Pisidiidae species collected along a naturally occurring calcium gradient in Ontario were measured. The analysis revealed both intraspecific and interspecific variations in relation to pH, alkalinity, and total and calcium hardness of water.

INTRODUCTION AND OVERVIEW

Acidification of lakes and rivers is a major international environmental concern. Oxidation and hydrolysis of atmospherically borne sulfur dioxide SO_2 and nitrous oxide NO_2 produces atmospheric sulfuric acid H_2SO_4 and nitric acid HNO_3 which reach lakes and rivers as "Acid Precipitation". Atmospherically induced acidification is a major problem, particularly in dilute waters with limited acid-buffering capabilities. In the Canadian Shield, effects of lake acidification have been documented at various trophic levels including fish BEAMISH, 1974 , zoobenthos CONROY, HAWLEY, KELLER LAFRANCE, 1976 , phytoplankton KWIATKOWSKI ROFF, 1976; CONROY al., 1976 , and zooplankton SPRULES, 1975 as well as on general water quality O.M.E., 1978 . Studies on the impact of acid precipitation on freshwater ecosystems in Norway are particularly well documented see WRIGHT, 1976 for a review of the literature .

The pH in fresh water is governed largely by the buffering reactions of carbonic acid and the amount of bicarbonate and carbonate derived from the weathering of rocks and from annual cycling of carbonates at all trophic levels. The most important carbonate of watersheds is $CaCO_3$, which occurs in natural waters principally as calcite and aragonite. In Canadian fresh waters alkalinity is contributed mainly by bicarbonates. The amount of $Ca\ HCO_3\ _2$ in solution depends on the amount of free CO_2 dissolved in the water. A definite amount of CO_2 known as equilibrium CO_2 will remain free in solution after equilibrium is reached between calcium, bicarbonate, carbonate, and undissociated carbonate. If the amount of free CO_2 is increased above that required to maintain a given amount of $CaCO_3$ in solution at equilibrium as $Ca\ HCO_3\ _2$, this aggressive CO_2 will dissolve more $CaCO_3$. If a solution of $Ca^2\ HCO_3\ ^2$ in eqilibrium with CO_2, H_2CO_3, and $CO_3^=$ loses a portion of the CO_2 required to maintain equilibrium, $CaCO_3$ will precipitate until the equilibrium is reestablished by the formation of CO_2. In lake acidification, carbonates are converted to bicarbonates and bicarbonates to CO_2; this process continues until the carbonate reservoir is depleted and all bicarbonates are converted to CO_2 at which point the acid-neutralizing capability of the lake is lost.

The carbonates involved in the equilibrium process are the bicarbonates in solution and the carbonates in the carbonate reservoir which periodically restores or adds to bicarbonate levels when pH is lowered or CO_2 is added to the system. In this study the carbonate reservoir is considered to include 1 the $CaCO_3$ and $MgCO_3$ that precipitates to the bottom of the lake known here as the equilibrium carbonate pool , for example, during photosynthesis, 2 carbonates in surface runoff and in the inflow influent carbonate pool , and 3 carbonates in organisms biotic carbonate pool , especially molluscs. In hard-water lakes, the most significant carbonate reservoirs are probably the equilibrium and influent carbonate pools. But in soft-water lakes, the biotic carbonate pool is probably the most significant, although this has never been shown. Since acidified lakes are generally soft-water lakes, this study pays particular attention to the biotic carbonate pool, of which the molluscs are hypothesized to be a significant component.

Enormous amounts of $CaCO_3$ are cycled annually by molluscs NEGUS, 1966; STARRETT, 1971; GREEN, 1980 and this must surely have an impact on the acid-neutralizing capability of lakes. Conversely, the availability of $CaCO_3$ in the equilibrium processes of lakes must surely affect production of molluscs. However, the cause and effect relationships are poorly understood. Nevertheless, the rate of lake acidification is probably inversely related to the amount of $CaCo_3$ in the biotic carbonate pool and the greater this amount, the slower the rate of acidification. Implicit in this relationship is that molluscs cannot prevent lake acidification but they may slow the rate of acidification. Indeed, the inability to accurately estimate the time needed to exhaust the watershed's neutralizing capacity LUCAS, 1978 is not only due to lack of detailed information about the buffering capacity of the overburden in a lake's watershed McFEE, KELLY BECK, 1977; DILLON al., 1978 , but probably as well to the lack of consideration of carbonates in the biotic carbonate pool,which may be very significant.

The aims of the studies reported here are 1 to determine the effects of lake acidification as measured by declining alkalinity and pH on calcium carbonate content and morphometrics of pisidiids, a major molluscan group in acidifying lakes in Canada, 2 to determine the source of calcium for pisidiids in lakes with low calcium levels and 3 to determine if the low pH and associated increases in aluminum levels in acidifying lakes are toxic enough to explain the disappearance of some species of pisidiids from the acidifying lakes in southern Ontario. The third objective was established because little or nothing is known about aluminum toxicity in pisidiids, indeed, even in any molluscs. Levels of aluminum in some acidifying lakes in Ontario are considered to be toxic to fish see HARVEY al., 1981 for a review .

The first two studies are part of general molluscan studies reported by MACKIE FLIPPANCE 1938a,b,c . Only brief descriptions of these studies are included here, and only the pisidiid data are described and discussed. Reported for the first time are the significance of the results from these three studies for survival of some pisidiids in acidifying lakes. Also reported for the first time are the total calcium values needed to calculate the potential acid-neutralizing capacity of pisidiids, the carbon values in shells of pisidiids, and the effects of low pH and associated changes in aluminum levels on the survival of sensitive and tolerant species of pisidiids in acidifying lakes of southern Ontario.

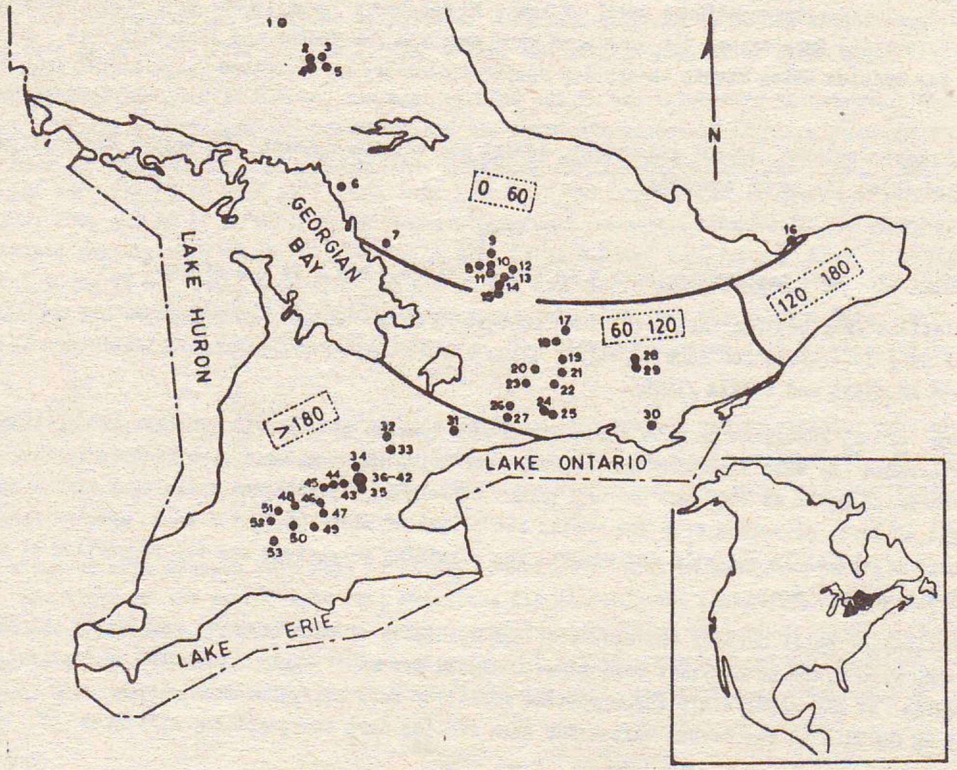

Fig. 1. Locations from which 53 pisidiid samples were collected in southern Ontario. The calcium gradient is indicated by the zones of water hardness /mg $CaCO_3$ L^{-1}, in boxes with dotted lines/ according to Fisheries and Environment Canada /1978/. The inset shows the location of the study area in North America.

STUDY AREA

For the first study, 53 freshwater habitats were sampled within an area bounded by Post Lake of the Vermillion River to the north /81°12'W long., 47°02'N lat./, Britannia Bay of the Ottawa River to the east /75°47'W long., 45°22'N. lat./, Waubuno Creek to the south /81°06'W long., 43°02'N lat./, and the North Thames River to the west /81°14'W long., 43°14'N lat./ in Ontario /Fig. 1/. The study includes the limestone formations in southern Ontario and the granite basement rock in the Sudbury District of Ontario. Thirty-two of the habitats sampled were lentic systems, the remainder were lotic. The pH, alkalinity, total hardness, and calcium hardness of each habitat are depicted in Figs. 2a and 2b. The study area presents a gradient of total alkalinity ranging from 0 to 280 mg $CaCO_3$ L^{-1}, and total hardness, calcium hardness and pH ranging from 5 to 332 mg $CaCO_3$ L^{-1}, 2 to 260 mg $CaCO_3$ L^{-1}, and 5.50 to 8.64, respectively.

MATERIALS AND METHODS

Relationships Between Pisidiid and Environmental Calcium Contents

Water samples from the 53 habitats were collected in 200 ml glass bottles just before the pisidiid samples. These were sampled in the laboratory for pH, total alkalinity, total hardness, and calcium hardness wthin 24 h of sampling, as described in MACKIE and FLIPPANCE /1983a, b/.

Pisidiids were sampled from less than 1 m water depths using a sieve with 1 m handle and mesh openings of 0.32 mm. Sampling continued until at least 10 specimens /usually 25/ of a wide range of size classes of each species were taken. The specimens were measured for lenght and then they were dry-weighed and analyzed for calcium using atomic absorption spectrophotometry as described by MACKIE and FLIPPANCE /1983a, b/.

Relationships between lenght and weight, lenght and calcium content, and weight and calcium content were determined using the power equation,

$$y = Ax^b$$

for each species from each population, were A is the y intercept and b is the slope.

Correlations /r^2/ between mean calcium content /g Ca g^{-1} animal/ of pisidiids and calcium content of the water were determined for each species using a CMS computer program for calculating r^2 according to the methods of STEEL and TORRIE /1980/.

For each of 25 specimens of five the most common species of pisidiids in the 53 habitats, shell $CaCO_3$ was determined by acid digesting preweighed, oven-dried whole animals in hydrochloric acid. The animals were oven-dried again at 100^0 and the dry weight differences between the whole clam and tissue provided the weight of $CaCO_3$ dissolved from the shell. The weight of shell $CaCO_3$ for each species was expressed as a percentage of the whole animal's dry weight. The remaining percentage was the proportion of dry weight of tissue of the whole animal.

For analises of shell carbon, the shells of ten specimens of each of three species of pisidiids with bodies removed, were dried to constant weight and analyzed for shell carbon using the wet oxidation method of RUSSEL-HUNTER et al. /1967/. Att three species /Table 4/ were collected from waters with alkalinities less than 45 mg $CaCO_3$ L^{-1}. The carbon values for each species were expressed per milligram of total shell weight.

For the relationships between total dry weight and calcium content /Table 2, last three columns/, slopes greater than 1.0 indicate that larger individuals contain more calcium per unit weight than do smaller individuals of the same species; slopes = 1.0 indicate that individuals of all weight classes have the same proportion of calcium to dry weight; slopes less than 1.0 indicate smaller individuals have more calcium per unit weight than do larger individuals. Because of these differences in slopes, the potential contribution of $CaCO_3$ by each species /Table 3/ was calculated on the basis of the mean dry weight of the animals used to derive the regression in Table 2 /last three columns/. Since the regressions are based on calcium content, and not on $CaCO_3$ content, the calcium content calculation from the mean dry weights was multiplied by 2.5 /i.e. for every part of calcium, there are 2.5 parts of calcium carbonate/. This value was then divided by the mean dry weight value and multiplied by 100 to express the results as g $CaCO_3$ for 100 g of animals /dry weight/ in each species. The species are arranged in order of decreasing $CaCO_3$ contribution in Table 3.

A canonical correlation analysis /PIMENTAL 1979/ was also performed on all specimens for the three morphological variables, size, weight, and calcium content for each species, and the four environmental variables /herein termed buffer variables/, pH, total alkalinity, total hardness, and calcium hardness. The values for all morphological were log-transformed so that all allometric relationships would be linear. A canonical correlation is the maximum correlation between linear functions of the two sets, with the linear functions chosen so as to maximize the correlation with the restriction that they are independent of previously derived linear combinations. Details of the interpretation of canonical correlations are given in MACKIE and FLIPPANCE /1983b/.

In ordner to determine the source of calcium /in the water/ for the growth of M. securis, newborn clams were grown in ten different treatments, each with a different source of calcium and food. The then treatments were: A, water + algae; B, water + leaves; C, water + sediment; D, water + autoclaved leaves; E, water + autoclaved sediment; F, water + algae + leaves; G, water + algae + leaves + sediment; H, water + algae + autoclaved sediment; I, water + algae + autoclaved leaves; J, water only. The rationale for each treatment and the procedures used are given in MACKIE and FLIPPANCE /1983c/.

Clams were sacrificed at two week intervals and measured for length, dry weight and calcium content using flame spectrophotometry. Food, water, leaves and sediment were also analyzed for calcium content using flame spectrophotometry. A two-way analysis of variance, followed by DUNCAN's test /STEEL and TORRIE 1980/, was used to detect differences in length weight and calcium content of clams among treatments.

A preliminary 96-h static biossay was also carried out in the laboratory to determine the joint and independant toxicity of hidrogen ion concentration and inorganic monomeric aluminum content. Five species of clams /Pisidium casertanum, Pisidium nitidum, Sphaerium rhomboideum, Sphaerium occidentale and Musculium securis/ were tested at four pH's /4.0, 4.5, 5.0, 5.7/ and four levels of inorganic monomeric aluminum /50, 100, 200, 400 µg Al L^{-1}/. In order to keep inorganic monomeric aluminum in solution, 400 µg Al L^{-1} could be tested jointly only at pH 4.0, 200 µg Al L^{-1}, at pH 4.0 and 4.5, 100 µg Al L^{-1}, at pH 4.0, 4.5 and 5.0, and 50 µg Al L^{-1} could be tested jointed at all four pH's. Samples of the test solutions were taken to verify the concentrations of inorganic monomeric aluminum, but the samples are still awaiting analyses. Hence, until the samples have been analyzed, the aluminum content will be referred to as total aluminum.

Reagent grade hydrochloric acid was used to make the pH solutions and to dissolve pure aluminum wire for the stock solution of inorganic monomeric aluminum. The stock solution was kept at pH 2.0 in a plastic container. Appropriate aliquost of the stock sulution were taken to make the four final test concentrations.

Ten clams of each species were kept in plastic containers, wich in turn were placed in plastic dishes containing one liter of the appropriate test solution. All plastic-ware containers were preconditioned to its test solution for 24 h. These solutions were discared and replaced with fresh solution. The clams were then placed in the plastic containers. 500 ml of each test solution was changed daily. Death of clams was determined as cessation of heart beat /seen through the semitransparent shells/ and lack of response to prodding.

RESULTS

Fourteen species of pisidiids were found in the 53 habitats sampled. The most common pisidiids in the study area are Pisidium compressum, Pisidium casertanum, Sphaerium striatinum, Sphaerium simile, Musculium securis and Pisidium variabile. Most of the common species occur over a wide of alkalinities and total and calcium hardnesses /Table 1/. The only exceptions are M. securis, which occurs in waters with alkalinities less than about 170 mg $CaCO_3$ L^{-1}, and S. similis, which occurs in waters with alkalinities greater than about 100 mg $CaCO_3$ L^{-1}.

Some habitats had very low acid-neutralizing capacities and showed a high degree of acidification. The lowest pH of water sampled was 5.50. Only Pisidium casertanum was found at this pH value /Table 1/. The mean lenght-weight, lenght-calcium content and weight-calcium content relationships of each species are given in Table 2.

Of the 13 species of pisidiids examined, S. simile has the greatest potential contribution of $CaCO_3$ to the water /Table 3/. A comparison of data in Tables 3 and 4 indicates that some species /e.g. S. simile/ contain large amounts of free calcium in tissue since the calcium carbonate values from whole animals /Table 3/ exceeds /$P < 0.05$/ the values from shell only /Table 4/. However, the data are not directly comparable since the data in Table 3 are based on populations collected from several localities with different acid-neutralizing capacities and data in Table 4 are based on single populations from waters with low acid-neutralizing capabilities. Table 4 also indicates that the shells of some species, especially P. casertanum, contribute significantly greater /$P < 0.05$/ amounts of carbon than other species.

For some species the variation in calcium content of whole individuals correlates well with the calcium content of their environment /Table 5/. Three species /P. casertanum, P. compressum, and S. striatinum/ show a direct correlation and two species /S. simile and S. rhomboideum/ show an inverse correlation between calcium content of whole individuals and calcium hardness of the environment /Table 5/.

At least four populations were collected for each of six of the thirteen species in the study area to permit canonical correlation analyses. The results of the canonical correlation analyses are shown in Table 6. The first canonical variate /CV/ is significant at the 0.0001 level for all six species. The second CV is significant at $P < 0.002$ for the six species and the third CV is significant at $P < 0.05$ for only two species /Table 6/.

The empirical interpretation of a canonical variate is based on the signs /+ and -/ and magnitudes of the scores. The main trend of CV-I on morphological variables appears to be toward a shortening of the shell with an increase in total weight and calcium content. Since the shell accounts for most of the weight and the calcium is concentrated mainly in the shell, the main trend in CV-I is toward a shorter, heaiver shell. This appears to be related to decreasing alkalinity and pH in relation to calcium and total hardness for P. casertanum and P. variabile, and decreasing alkalinity in relation to total hardness for S. simile and S. striatum.

A second but less common trend of CV-I on morphological variables is toward an increase in shell size and calcium content in relation to total weight. Since the shell accounts for most of the weight, the increase in calcium content relative to weight implies that the calcium might be free calcium /i. e. not monocarbonates/ in tissues. Otherwise an increase in total weight would also be expected. If this is true /and there may be some variation due to dry-weight of fats/, then species with larger shells and lighter tissue calcium appear to be found in waters with high alkalinities, particularly in relation to calcium hardness /e. g. M. securis, Table 6/, and total hardness /e. g. P. compressum, Table 6/. MACKIE and FLIPPANCE /1983b/ describe trends of CV-II and CV-III on the morphological variables and the significance of these in relation to CV-I are discussed later.

The sediment, especially when autoclaved, contributed the greates amounts of calcium to the water. Willow leaves also contributed a significant amount of calcium but algae provided very little /Table 7/.

A large increase in lenght /Fig. 3/ and weight /Fig 4/ of clams occurred after the first two weeks in dishes with algae, leaves and sediment /treatment G/. However, by the sixth week, clams in dishes with algae and leaves /treatment F/ had attained similar /$P > 0.05$/ sizes as those in algae, leaves and sediment. By the tenth week clams in algae and autoclaved leaves /treatment I/ were the same size and weight /$P > 0.05$/ as clams in treatment F /Figs. 3 and 4/. The significant loss in average weight and calcium content of clams that occurred in the eight and tenth weeks in dishes with algae, leaves and sediment /Figs. 3 and 4/ was due to the release of newborn. The only other clams that produced newborn were those in dishes with algae and leaves and algae and autoclaved leaves in the tenth week.

The 96 h static toxicity bioassays indicate that the five species of pisidiids tested are able to tolerate pH down to at least 4.0 and aluminum contents up to at least 400 μg Al L^{-1}. The only species that showed any mortality after 96 h was P. nitidum; there was 10 % mortality at pH 4.0, 0 μg Al L^{-1}, 20% mortality at pH 4.0, 100 μg Al L^{-1}, 40 % mortality at pH 4.0, 200 μg Al L^{-1} and 20 % mortality at pH 4.0, 400 μg Al L^{-1}. Because of the low mortalities, it was not possible to calculate LC50 values for pH and/or aluminum.

DISCUSSION

Responses of Pisidiidae to Low pH and High Aluminum Content.

Acid precipitation is affecting /or already has affected/ many habitats in the Canadian Shield /HARVEY et al. 1981/. Although we did not examine lakes with pH< 4.5 /i.e. acidified lakes/, we did sample pisidiids in lakes with pH 5.5 and no apparent acid-neutralizing capacity /i.e. alkalinity 0/. These lakes still had pisidiids /e.g. P. casertanum, P. ferrugineum, Table 5/. These results compare favourably with those in other studies. Most pisidiids were absent in Norwegian waters with pH less than 5.0 /K. OKLAND, 1979; J. OKLAND and K. OKLAND, 1980; K. OKLAND and KUIPER 1980/. ROFF and KWIATKOWSKI /1977/ found that in the relationship between diversity index for zoobenthos and pH in six lakes southwest of Sudbury, Ontario, the inflection point /i.e. the point at which diversity changed/ occurred at pH 4.8; Pisidium was the only mollusc to be found below pH 5.0 but no molluscs were found below pH 4.8.

If spring pH values are considered, many pisidiids can be found in acidifying lakes with pH as low as 4.4 /i.e. spring depression value/, such as in Chub Lake /No. 10/ and Heeney Lake /No. 8/ /Fig. 1/.

Pisidiids found in these lakes include P. casertanum and P. ferrugineum.

Shells of pisidiids from waters with low acid-neutralizing capacities appear to contain large amounts of carbon /Table 4/. The data for M. securis and S. striatinum are comparable to those of BURKY et al. /1979/ who found that trophic considerations gave the best correlations with shell type at the generic level. There are insufficient data to indicate relationships between shell carbonate content and carbon content but BURKY et al. /1979/ found an inverse relationship in pisidiids. Of the species examined, P. casertanum had the highest amount of carbon present in relation to shell carbonate content. MACKIE /1978/ found that P. casertanum had one of the thickest periostracums of all the pisidiids he examined. The large amount of organic material in the shell supports his observations. These data suggest that the species is able to survive more adverse conditions /e.g. acidifying lakes/ than most other pisidiids because the heavy organic covering and organic matrix would resist shell erosion better than highly carbonaceous shells.

According to Table 5, the calcium content of individuals in five species of pisidiids are also related to pH and/or alkalinity, implying that acid deposition may affect shell formation in these species. However, of the five species, three /P. compressum, S. rhomboideum and S. simile/ have negative correlations indicating that as pH and/or alkalinity is lowered, calcium content of these pisidiids increases. Therefore, these species seem to respond to lake acidification by forming more highly calcified shells, at least down to pH 6.0 and an alkalinity of 20 mg $CaCO_3$ L^{-1}. The toxicity bioassay studies indicate that survival of these species probably is not affected by pH down to 4.0 and/or aluminum up to 400 µg L^{-1}.

The remaining two species /S. striatinum and P. casertanum/ show positive correlations with pH and alkalinity, implying that acid deposition could directly affect shell formation in these species. However, S. striatinum is found only in well-buffered /i.e. pH > 6.00, alkalinity > 20 mg $CaCO_3$ L^{-1}/ water and hence are not likely to be affected by acid deposition. Pisidium casertanum is found in acidifyng water /pH < 5.50/ and seems to be able to concentrate calcium from waters that have little or no acid-neutralizing capacity. Moreover, both species appear able to resist the corrosive effects of hydrogen ions by changes in the morphology of the shell /as well as by forming thick periostracums/. For example, Table 6 indicates that during lake acidification /i.e. decreasing alkalinity/ the calcium contents of both species decrease, but they maintain a high density of $CaCO_3$ in the shell by forming shorter, heavy shells. Hence, the protection offered by the shell in maintained. The canonical correlation analyses also indicate that long, thin shells which presumably offer less protection in acidifying waters than short, thick shells, are formed only in waters with increasing alkalinity relative to calcium hardness, as in M. securis /Table 6/.

MACKIE and FLIPPANCE /1983b/ showed that the only pisidiids that are liable to be affected by acidic deposition are those in waters with poor and decreasing acid-neutralizing capacities. The species to be affected first would probably be those which exhibit decreasing calcium content since calcium is important in shell formation.

The species most likely to be removed by acid deposition is P. compressum /CV-II, Table 6/. However, this species shows at least one other significant canonical variate. These other variates suggest that acidic deposition would not be a factor in the disappearance of any species from waters with pH > 5.50. Indeed, some species show increases in weight and calcium content relative to lenght in waters with low acid-neutralizing capacity relative to hardness /e.g. P. casertanum and P. variabile/ and apparently are not affected by acidic deposition. Of these species, P. casertanum is found in waters with little or no acid-neutralizing capability. The other species is found in waters with alkalinities greater than 20 mg $CaCO_3$ L^{-1} and acid deposition has little effect on pH in such well-buffered waters.

Calcium Sources in Musculium securis

Clearly, algae alone, with its small amounts of calcium /Table 7/ is not sufficient to sustain the growth of M. securis /Figs. 3 and 4/. The greates growth of clams occurs when both food and calcium are provided. Hence, treatments F and I supported the greatest growth of clams /Figs. 3 and 4/. MACKIE and FLIPPANCE /1983c/ and MACKIE and QADRI /1978/ have discussed the significance of sediment, leaves and algae for the growth and reproduction of pisidiids. The most significant result here is that calcium in the leaves appears to be more available to M. securis than calcium from the sediment.

The apparent ability of clams to grow well on algae and leaves together indicates that at least some species of molluscs, such as M. securis, are not dependent upon the calcium from the sediment or bedrock

TABLE 1. Ranges of pH, total alkalinity, total hardness and calcium hardness of waters in which each species of Pisidiidae was found.

Species+	Number of Populations	pH	Alkalinity mg $CaCO_3$ l^{-1}	Total Hardness mg $CaCO_3$ l^{-1}	Ca Hardness mg $CaCO_3$ l^{-1}
Musculium lacustre /MÜLLER/	2	7.34 - 8.64	187 - 220	200 - 330	150 - 200
Musculium securis /PRIME/	7	6.05 - 8.21	18 - 152	21 - 216	15 - 144
Musculium transversum /SAY/	1	6.51	43	60	28
Pisidium adamsi STIMPSON	2	7.56 - 7.93	220 - 275	265 - 302	114 - 156
Pisidium casertanum /POLI/	19	5.50 - 8.34	0 - 280	10 - 332	2 - 260
Pisidium compresse PRIME	20	7.08 - 8.64	58 - 280	60 - 332	50 - 260
Pisidium ferrugineum PRIME	1	5.50	0	10	4
Pisidium nitidum JENYNS	2	6.51 - 7.31	43 - 100	60 - 155	28 - 98
Pisidium variabile PRIME	5	7.72 - 8.64	90 - 280	90 - 332	70 - 260
Sphaerium fabale PRIME	1	7.08	240	280	188
Sphaerium rhomboideum /SAY/	4	7.03 - 7.37	42 - 187	76 - 200	45 - 180
Sphaerium simile /SAY/	8	7.05 - 8.64	115 - 280	115 - 330	98 - 230
Sphaerium striatinum /LAMARCK/	13	6.51 - 8.64	43 - 280	60 - 332	28 - 260

+Pisidium equilaterale PRIME also occurs in the study area /unpublished data/ but it was not found in the present survey.

TABLE 2. Relationships /$y = Ax^b$/ between shell lenght /mm/ and weight /g/, shell length and calcium content /g/, and weight and calcium content for thirteen species of Pisidiidae, where A = y intercept and b = slope. Weights and calcium contents are based on whole animals /see text for explanations/. Standard error /S.E./ of each estimate is given inparentheses. All correlation coefficiens /r^2/ are significant to at least 99.99% level. The number of populations to obtain the degrees of freedom /D.F./ for each species may be found in Table 1.

Species+	D.F.	Shell Size /mm/ vs Weight /g/ Intercept /S.E./	Shell Size /mm/ vs Weight /g/ Slope /S.E./	r^2	Shell Size /mm/ vs Calcium Content /g/ Intercept /S.E./	Shell Size /mm/ vs Calcium Content /g/ Slope /S.E./	r^2	Weight /g/ vs Calcium Content /g/ Intercept /S.E./	Weight /g/ vs Calcium Content /g/ Slope /S.E./	r^2
Musculium lacustre	28	0.138 /0.0844/	2.29 /0.1429/	0.904	0.016 /0.1110/	2.85 /0.1880/	0.895	1.019 /0.0759/	1.24 /0.0289/	0.986
Musculium securis	125	0.087 /0.0552/	2.61 /0.0910/	0.845	0.017 /0.0663/	3.00 /0.1090/	0.833	0.346 /0.1163/	1.01 /0.0457/	0.764
Musculium transversum	23	0.078 /0.1214/	2.35 /0.1832/	0.882	0.007 /0.1746/	3.05 /0.2636/	0.859	1.535 /0.1133/	1.30 /0.0438/	0.976
Pisidium adamsi	39	0.052 /0.0597/	3.61 /0.1146/	0.963	0.009 /0.0627/	4.09 /0.1205/	0.968	0.615 /0.0531/	1.12 /0.0217/	0.986
Pisidium casertanum	312	0.082 /0.0358/	3.24 /0.0840/	0.827	0.007 /0.0710/	4.35 /0.1665/	0.687	2.084 /0.0981/	1.34 /0.0352/	0.823
Pisidium compressum	425	0.117 /0.0203/	3.64 /0.0422/	0.946	0.027 /0.0318/	4.08 /0.0663/	0.899	0.688 /0.0285/	1.12 /0.0127/	0.948
Pisidium ferrugineum	24	0.090 /0.0970/	2.68 /0.3174/	0.757	0.001 /0.4387/	5.59 /1.4360/	0.397	0.008 /1.4153/	1.98 /0.4355/	0.472
Psisidium nitidum	48	0.180 /0.1497/	2.23 /0.4592/	0.335	0.010 /0.2132/	4.25 /0.6544/	0.472	1.896 /0.4144/	1.30 /0.1365/	0.658
Pisidium variabile	61	0.157 /0.0723/	3.29 /0.1583/	0.896	0.035 /0.1338/	3.74 /0.2930/	0.764	0.990 /0.1008/	1.19 /0.0423/	0.941
Sphaerium fabale	24	0.036 /0.0509/	3.47 /0.0544/	0.994	0.010 /0.0519/	3.55 /0.0555/	0.994	0.375 /0.0068/	1.02 /0.0050/	0.999
Sphaerium rhomboideum	72	0.047 /0.0242/	3.20 /0.0276/	0.995	0.001 /0.1242/	4.24 /0.1411/	0.927	0.807 /0.0705/	1.33 /0.0429/	0.931
Sphaerium simile	152	0.121 /0.0353/	2.81 /0.0346/	0.978	0.033 /0.0421/	2.95 /0.0411/	0.971	0.437 /0.0076/	1.05 /0.0066/	0.994
Sphaerium striatinum	283	0.064 /0.0390/	3.27 /0.0470/	0.945	0.019 /0.0422/	3.40 /0.0509/	0.941	0.431 /0.0099/	1.04 /0.0061/	0.990

+Pisidium equilaterale Prime also occurs in the study area /unpublished data/ but morphological data were not taken for the present study.

TABLE 3. Potential contribution of $CaCO_3$ for thirteen species of Pisidiidae. Values are expressed per 100 g of whole animal /shell + tissues/ and are based on regression data in Table 2 using the mean weights below. See text for details.

Species	Mean Dry Weight /mg/	g $CaCO_3$/ 100 g Animal
Sphaerium simile	83.60	96.5
Sphaerium striatinum	30.00	93.6
Pisidium compressum	5.90	92.9
Sphaerium fabale	57.30	88.5
Pisidium variabile	4.47	84.2
Musculium securis	3.00	81.6
Pisidium adamsi	3.70	78.5
Musculium transversum	2.70	65.1
Pisidium ferrugineum	5.70	63.2
Pisidium casertanum	1.80	61.8
Sphaerium rhomboideum	27.50	61.6
Musculium lacustre	2.60	61.6
Pisidium nitidum	0.94	58.6

TABLE 4. Calcium carbonate and carbon content of shells in common species of Pisidiidae in the stady area. The species are arranged in order of decreasing calcium carbonate content.

Species	Shell $CaCO_3$ as % of total dry wt. ± 95% C.I.[1]	µg C mg^{-1} shell ± 95% C.I.
Sphaerium striatinum	92.2 ± 1.69	5.33 ± 0.68
Sphaerium simile	90.7 ± 2.53	ND[2]
Pisidium compressum	90.3 ± 0.89	ND
Musculium securis	80.0 ± 3.21	8.32 ± 1.57
Pisidium casertanum	65.8 ± 1.66	10.18 ± 2.77

[1] C. I. = Confidence Interval
[2] ND = Not determined for species in waters with > 45 mg $CaCO_3$ L^{-1} total alkalinity.

TABLE 5. Correlation coefficients /r^2/ and the significance level of r^2 /in parentheses/ for the relationships between calcium content of the whole animals of Pisidiidae and pH, total alkalinity, total hardness and calcium hardness of the water. The asterisks accentuate the significant correlations.

Species	pH	Alkalinity	Total Hardness	Ca Hardness
Musculium securis	-0.002 /0.983/	0.074 /0.366/	0.087 /0.284/	0.099 /0.226/
Pisidium casertanum	0.113 /0.046/*	0.251 /0.001/*	0.310 /0.001/*	0.271 /0.001/*
Pisidium compressum	-0.160 /0.001/*	0.222 /0.001/*	0.218 /0.001/*	0.240 /0.001/*
Pisidium variabile	0.073 /0.608/	0.192 /0.173/	0.196 /0.164/	0.231 /0.099/
Sphaerium rhomboideum	-0.328 /0.005/*	-0.345 /0.003/*	-0.336 /0.004/*	-0.345 /0.003/*
Sphaerium simile	-0.432 /0.001/*	-0.123 /0.129/	-0.209 /0.009/*	-0.226 /0.005/*
Sphaerium striatinum	0.150 /0.012/*	0.166 /0.005/*	0.125 /0.035/*	0.132 /0.026/*

TABLE 6. Canonical correlation analyses of Pisidiidae on three morphological variables and four buffer variables. The number of observations for each species is given in parentheses after the species' name. Scores are given only for canonical correlations with significance level less than 0.05. See text for further explanations.

Species	Musculium securis /153/			Pisidium casert./313/			Pisidium compr./426/			Pisidium variab./52/			Sphaerium simile/153/			Sphaerium striat./284/		
Canonical Variates	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III	I	II	III
Canonical correlation	0.735	0.459	0.267	0.518	0.204	0.070	0.417	0.257	0.058	0.731	0.624	0.195	0.730	0.289	0.145	0.429	0.237	0.171
Degrees of freedom	12	6	2	12	6	2	12	6	2	12	6	2	12	6	2	12	6	2
F statistic	16.38	8.23	5.67	9.85	2.46	0.75+	9.65	5.09	0.69+	6.29	4.67	0.93+	12.55	2.74	1.59+	7.10	4.16	4.21
Buffer variables																		
Alkalinity	2.874	3.573	-1.281	-0.730	-1.749		3.657	-1.433		-41.857	26.002		-0.686	-0.723		-2.475	3.460	1.596
Ca hardness	-3.610	-2.048	3.728	1.492	-0.215		1.044	0.558		12.132	-2.466		-0.028	0.360		-1.524	-0.749	-3.888
Total hardness	1.505	-1.726	-1.698	0.669	2.542		-4.502	1.708		29.331	-22.324		0.904	1.469		4.374	-2.323	1.402
pH	-0.322	0.730	-0.051	-0.566	-1.022		-0.046	-0.423		-5.526	4.492		0.820	-0.809		0.318	0.458	0.653
Morphological variables																		
Lenght	2.390	-0.868	0.406	-1.258	2.044		3.863	-0.173		-2.526	-1.756		-5.159	1.471		-4.326	-0.203	0.994
Weight	-2.590	-0.760	-0.073	1.116	-1.776		-4.237	1.365		0.996	2.828		4.253	-3.243		3.412	1.439	-2.164
Calcium content	0.127	1.469	0.722	0.874	0.456		0.662	0.423		1.721	-0.693		0.276	2.098		0.941	-0.307	1.645

+ $p > 0.05$

TABLE 7. Mean algal weight /oven-dry basis/ and calcium contents of water and materials /standard deviation in parentheses/ in all dishes of each of ten sediments for growth of Musculium securis. Treatments D and E were kept in the dark to prevent growth of algae.

Treatment	Contents in Dishes /with water/	Algae mg	Calcium of water mg 100 ml^{-1}	Calcium of all materials mg dish^{-1}
A	Algae	31.745 /11.377/	0.057 /0.025/	0.054 /0.017/
B	Leaves	47.162+ /22.332/	1.940 /1.761/	20.310 /3.010/
C	Sediment	665.264+ /741.740/	2.860 /0.775/	22.231 /5.552/
D	Autoclaved leaves	0	1.613 /0.483/	28.442 /3.597/
E	Autoclaved sediment	0	7.420 /2.868/	19.648 /3.867/
F	Algae + leaves	214.540 / 95.623/	1.780 /0.792/	22.581 /3.015/
G	Algae + sediment + leaves	211.190 /121.051/	3.725 /1.597/	43.345 /7.442/
H	Algae + autoclaved sediment	580.516 /713.389/	4.197 /0.698/	26.201 /7.142/
I	Algae + autoclaved leaves	299.766 /212.676/	1.476 /0.316/	29.857 /3.747/
J	Water only	0	0.005 /0.002/	0.003 /0.001/

+Algae had appeared in growth dishes by the fourth week.

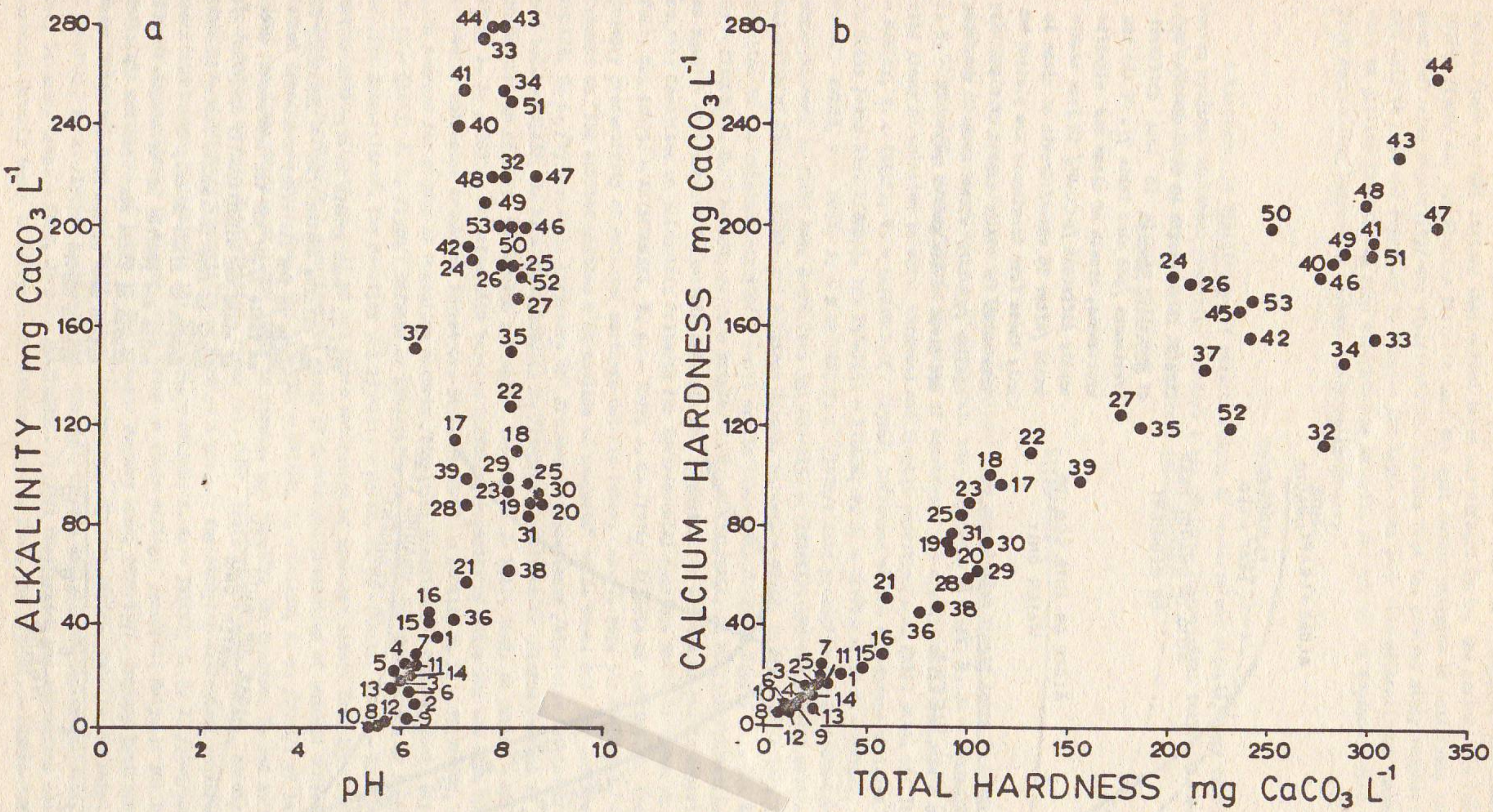

Fig. 2. Some water chemistry characteristics of the 53 habitats showing /a/ pH and alkalinity and /b/ total and calcium hardness. All plots are based on single samples.

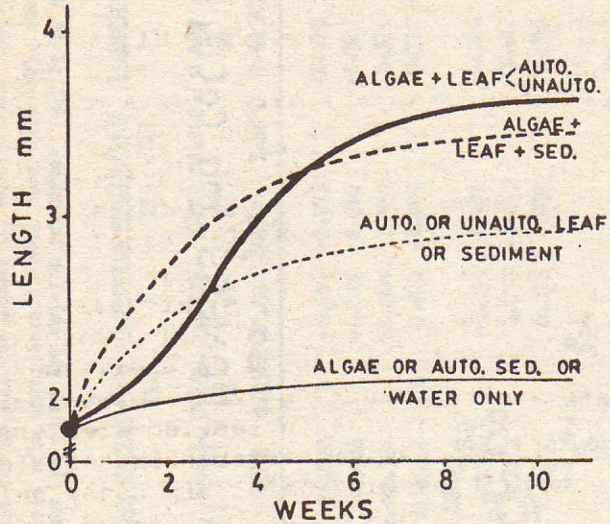

Fig. 3. Mean growth in shell lenght /mm/ of Musculium securis in then different treatments /see also Table 7/. Of the ten treatments, growth of clams was significantly different /$p < 0.05$/ in four treatments /after 10 weeks/. Growth of clams in only these four treatments are plotted but treatments for which growth of clams was similar /$p > 0.05$/ within each of the four are given on the growth curves.

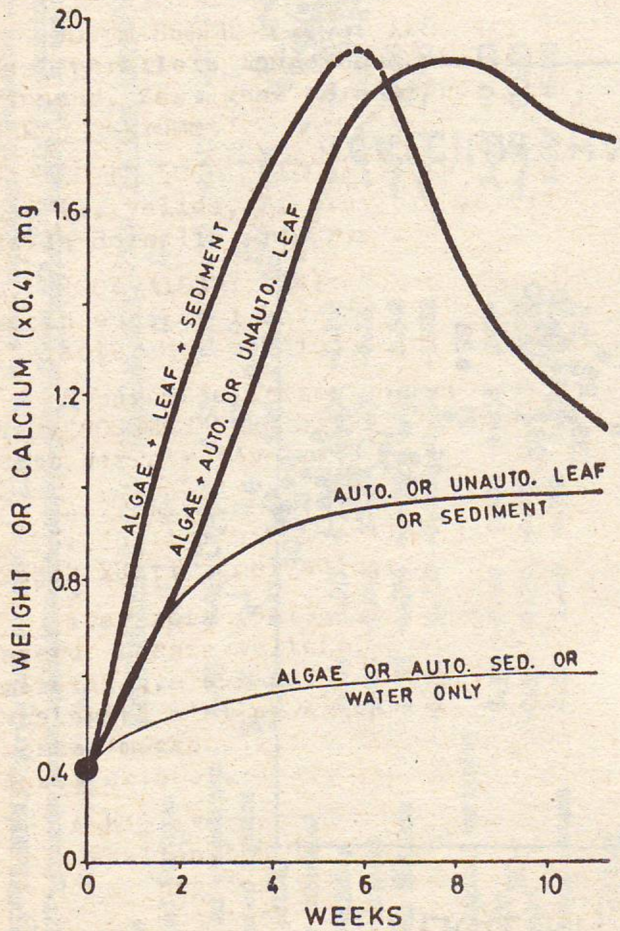

Fig. 4. Mean growth in dry weight /mg/ and calcium content /mg/ of Musculium securis in ten different treatments /see also Table 7/. Of the ten treatments, growth of clams was significantly different /$p < 0.05$/ in four treatments /after 10 weeks/. Growth of clams in only these four treatments are plotted but treatments for which growth of clams was similar /$p > 0.05$/ within each of the four are given on the growth curves.

of lakes and streams for shell growth. Instead, they are able to utilize the calcium from allochthonous material /such as leaf litter/ that enters lakes and streams during the spring. The results of K. OKLAND and KUIPER /1980/ and our studies indicate that the most common molluscs in acidifying lakes /i. e. lakes with poor buffering capability/ are pisidiids. The results from the present study suggest that some pisidiids are able to grow and reproduce in streams and lakes with poor acid-neutralizing capacity because they are able to utilize the calcium from allochthonus material and are not as dependant upon the dissolved calcium from surrounding bedrock as perhaps other molluscs are.

ÖSSZEFOGLALÁS

A tanulmány 14 Pisidiidae-faj méretét súlyút és Ca-tartalmát vizsgálja egy természetes Ca-grádiens mentén gyűjtött mintákban /Ontario, Kanada/. A víz pH-jára, lúgosságára, teljes és Ca-keménységére vonatkozóan fajok közötti és fajon belüli különbségek jelentkeznek.

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