SOME EFFECTS OF SMELTER POLLUTION UPON AQUATIC VEGETATION NEAR SUDBURY, ONTARIO

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Abstract

The numbers of submerged and floating macrophyte species present in 29 ponds and lakes are inversely related to dissolved sulphates, concentrations of which rise sharply within about 4 to 5 miles of the smelters. Although pollution often leads to strong acidification, numbers of species are low even where sulphuric acid is almost wholly neutralized, and waters are above pH 6. Because sulphate ions are unlikely to be toxic at the levels encountered, and since pollution also increases the concentration of heavy metals in the waters, it is suggested that these may reach toxic levels near the smelters.

Leptodictyum riparium and *Eleocharis acicularis* v. *submersa* seem to be most tolerant of smelter pollution, while *Utricularia vulgaris* and *Potamogeton epiphydrus* v. *nuttallii* appear rather sensitive to it.

Introduction

In the course of studies upon smelter pollution and its ecological significance near Sudbury, Ontario (Gorham and Gordon 1960a, 1960b), a sharp rise in sulphate concentration of lake and pond waters was observed within about 4 to 5 miles of the smelter chimneys, owing to oxidation and fallout of sulphur dioxide emitted during the smelting process. In order to examine the effect of smelter pollution upon aquatic vegetation, a floristic survey of 29 lakes and ponds was undertaken.

Methods

During the summer of 1959, 102 lakes and ponds were visited by car or helicopter, and water samples were collected for analysis of pH, calcium, and sulphate (Gorham and Gordon 1960b). In a representative selection of 14 waters the aquatic vegetation was surveyed, between September 5 and 9, by collecting and pressing material of every species of floating or submerged macrophyte (including bryophytes and Characeae) observed in 20 minutes swimming by two men equipped with fins, face masks, and schnorkel breathing tubes. Between August 16 and 19, 1960, a further 15 waters were examined, including 3 not visited in 1959. Species with emergent leaves were not included, unless growing wholly submerged, as was frequently the case with *Lysimachia terrestris*, and once with *Juncus militaris*, which has very characteristic submerged leaves.

The locations of the lakes and ponds are given in Table I.

TABLE I
Numbers of aquatic macrophytes and chemical composition of Sudbury waters

Lake No.	Miles to smelter	Direction from smelter	Smelter*	SO ₄ , meq/l.	Ca, meq/l.	pH aerated	Damage to terrestrial vegetation†	No. species aquatic macrophytes
8	0.9	S.	F	2.75	0.70	3.3	S	1
12	1.2	N.	F	1.48	0.55	3.6	C	0
53	1.2	NW.	CC	1.56	0.58	4.1	VS	3
11	1.5	N.	F	1.36	0.39	3.5	S	4
54	1.8	NW.	CC	1.16	0.50	4.2	S	3
65	1.8	SSW.	C	1.88	1.04	6.1	S	2
14	2.3	N.	F	0.58	0.21	3.9	C	2
56	2.5	NW.	CC	0.77	0.49	6.3	C	4
4	2.8	WSW.	F	1.01	0.64	4.3	S	4
15	3.1	NNE.	F	0.63	0.27	4.1	C	4
69	3.2	NE.	C	1.80	0.97	6.4	S	5
21	3.5	SSE.	CC	1.11	0.56	4.2	C	8
17	4.0	NNE.	F	0.60	0.98	7.9	M	7
22	4.2	S.	CC	0.71	0.34	4.3	C	5
75	6.9	SSE.	C	0.49	0.27	5.6	N	4
23	7.0	SSW.	CC	0.63	0.48	7.0	N	11
33	7.4	SW.	C	0.46	0.28	6.6	N	8
24	10.6	SW.	CC	0.51	0.31	6.3	N	7
25	13.3	SW.	CC	0.47	0.37	7.0	N	17
96	15.6	NNE.	F	0.47	0.26	5.6	N	10
29	16.4	S.	CC	0.36	0.21	4.6	N	6
26	19.2	SW.	CC	0.24	0.27	7.2	N	11
95	19.4	NNE.	F	0.37	0.17	4.4	N	10
94	19.8	WNW.	CC	0.24	0.18	6.0	N	17
27	23.4	SW.	CC	0.29	0.34	7.4	N	10
28	24.2	SW.	CC	0.39	0.41	7.4	N	24
103	31	WNW.	CC	0.25	0.25	6.8	N	18
105	33	WNW.	CC	0.27	0.28	6.9	N	1
104	34	WNW.	CC	0.29	0.25	6.4	N	18

*F = Falconbridge, CC = Copper Cliff, C = Coniston smelter.

†VS = very severe, S = severe, C = considerable, M = moderate, N = not obvious (Gorham and Gordon 1961b).

TABLE II
Submerged and floating macrophytes identified in five or more lakes and ponds

Lake number	8	12	53	11	54	65	14	56	4	15	69	21	17	22	75	23	33	24	25	96	29	26	95	94	27	28	103	105	104
Total no. species per lake	1	0	3	4	3	2	2	4	4	4	5	8	7	5	4	11	8	7	17	10	6	11	10	17	10	24	18	1	18
<i>Leptodictyum riparium</i> *	+		+		+	+	+		+			+				+		+				+							
<i>Eleocharis acicularis</i> v. <i>submersa</i>			+		+					+		+	+	+	?	+		+	+	+		+	+	+		+	+		
<i>Juncus pelocarpus</i> f. <i>submersus</i>								+			+					+		+	+	+	+		+	+		+	+		
<i>Sagittaria</i> (sp. or spp.)								+				+				+		+	+	+	+		+	+	+	+	+		
<i>Eriocaulon septangulare</i>								+				+		+	+	+	+	+	+	+	+	+	+	+	+	+	+		+
<i>Isoetes muricata</i>										+		+				+		+	+	+	+	+	+	+	+	+	+		+
<i>Nymphaea odorata</i>													+	+	+	+	+	+	+	+	+	+	+	+	+	+	+		+
<i>Lobelia dortmanna</i>															+	+	+	+	+	+	+	+	+	+	+	+	+		+
<i>Isoetes riparia</i>																+		+	+	+	+	+	+	+	+	+	+		+
<i>Myriophyllum tenellum</i>																		+	+	+	+		+	+	+	+	+		+
<i>Nuphar</i> (sp. or spp.)																		+	+	+	+	+	+	+	+	+	+		+
<i>Utricularia vulgaris</i>																			+	+	+	+	+	+	+	+	+		+
<i>Potamogeton epihydrus</i> v. <i>nuttallii</i>																				+	+	+		+	+	+	+		+
Miles from nearest smelter	0	1				2			3				4	5			10	15						20	30			35	

*Might be in 11, 22, 25, 95, and 96, from which mosses were recorded in 1959. These moss samples have been mislaid, and might represent either *Leptodictyum riparium* or *Drepanocladus fluitans*.

TABLE III
Submerged or floating macrophytes identified in fewer than five lakes and ponds

Higher plants	Lakes	Bryophytes	Lakes
<i>Brasenia schreberi</i>	27, 28, 104	<i>Cladopodiella fluitans</i>	4, 21
<i>Elatine minima</i>	25	<i>Drepanocladus fluitans</i> *	23, 29, 94
<i>Eleocharis robbinsii</i>	29	<i>Fontinalis novae-angliae</i> †	26, 94, 104
<i>Glyceria borealis</i>	69	<i>Polytrichum commune</i> ‡	54
<i>Hippuris vulgaris</i>	104		
<i>Juncus militaris</i>	103		
<i>Lysimachia terrestris</i>	23, 26, 28, 103		
<i>Myriophyllum farwelli</i>	28, 103		
<i>Najas flexilis</i>	28		
<i>Polygonum amphibium</i>	17, 69		
<i>Potamogeton amplifolius</i>	28		
<i>P. gramineus</i>	17, 27, 28		
<i>P. pectinatus</i>	95		
<i>P. pusillus</i>	23, 25, 104		
<i>P. robbinsii</i>	27		
<i>P. spirillus</i>	28, 94, 103		
<i>Sparganium fluctuans</i>	25, 26, 33, 104		
<i>Utricularia gibba</i>	23		
<i>U. intermedia</i>	96, 103		
<i>U. minor</i>	95		
<i>U. purpurea</i>	94, 96		

*Might also be in 11, 22, 25, 95, and 96; mosses from 1959 mislaid.

†Probably also in 25, 96; mosses from 1959 mislaid.

‡Appearing healthy and naturalized in several feet of water.

Results

Table I also gives the total number of species recorded for each body of water, together with data on water chemistry and a visual estimate of damage to nearby terrestrial vegetation, included from the earlier study.

Within 2 miles of the smelters, the total number of species observed ranged from 0 to 4; between 2 and 5 miles this range increased to between 2 and 8 species; while outside 15 miles the range was from 6 to 24, except for a single lake (No. 105) where only 1 species was recorded. Ranges for dissolved sulphate were 1.16 to 2.75 meq/l. within 2 miles and 0.24 to 0.47 meq/l. outside 15 miles. For pH, these same ranges were 3.3 to 6.1 and 4.4 to 7.4; and for calcium 0.4 to 1.0 meq/l. and 0.2 to 0.4 meq/l. Where Table I records damage to terrestrial vegetation, the maximum number of species recorded was 8, as against 24 where such damage was not obvious.

Table II shows the distribution of all the species identified in five or more sites, and thus gives an idea of the aquatic flora typical of this area. (Some species may have occurred elsewhere as well, but not in identifiable form or in the area traversed by swimming; and the records for *Nuphar* and *Sagittaria* may refer to more than one species, since flowers and fruits were seldom available.) Both *Eleocharis acicularis* v. *submersa* and *Juncus pelocarpus* f. *submersus* were difficult to identify conclusively from keys, but finally compared well with material of the submerged forms of these species in the herbarium at Toronto. Table III rounds out the floristic picture by giving species identified in fewer than five waters. Characeae were not identified to species.

Some species appeared relatively tolerant of pollution; for example *Leptodictyum riparium* (a moss) and *Eleocharis acicularis* v. *submersa* were found within 2 miles of the smelters. *Leptodictyum* sp. has been recorded by Yoshimura (1935) as usually covering the bottom of inorganic acid lakes in Japan, where volcanic waters rich in sulphuric acid are common. *Polytrichum* has also been recorded as a natural inhabitant of an acid Japanese lake, bearing out the apparent naturalization of *Polytrichum commune* in one of the Sudbury lakes (No. 54, pH 4.2, SO_4 1.16 meq/l.). It should also be noted that wefts of algae covered much of the littoral zone in several of the most highly polluted waters, which were thus by no means devoid of vegetation. On the other hand, *Utricularia vulgaris* and *Potamogeton epihydrus* v. *nuttallii* were only observed beyond 15 miles from the smelters, where, however, they occurred in 5 of the 10 waters investigated.

Discussion

It is apparent from Table I that smelter pollution drastically reduces the aquatic flora in the immediate vicinity of Sudbury. And while the present study was concerned with only floristic diversity, it was also evident that heavy pollution greatly reduces productivity, so that in lakes with few species the standing crops of macrophytes are commonly very low. The area subject to severe pollution lies within about 4 to 5 miles of the three smelters, as shown in Fig. 1, where sulphate concentration (x) is plotted versus distance from the nearest smelter (z). The regression is adequately expressed by the equation $x = 1.73 z^{-0.555}$, with the standard error of estimate ± 0.13 meq/l., and the correlation coefficient $r = -0.92$, although the log/log plot inset in Fig. 1 shows a slight tendency to be curvilinear.

FIG. 1. The relation between sulphate concentration in pond and lake waters and distance from smelters (point + represents lake No. 105, see text).

FIG. 2. The relation between the number of species in a pond or lake and its sulphate concentration (the solid line includes all lakes, while the broken line excludes lake No. 105, represented by point +).

The relationship between floristic abundance and pollution is well shown by plotting species number (y) versus sulphate concentration (x), as in Fig. 2. In this case the regression equation is $y = 4.13 x^{-0.728}$, as indicated by the solid line in Fig. 2, with the standard error of estimate 2.0 species, and the correlation coefficient $r = -0.60$. If lake No. 105, with its unusually low species number (see "+" in Fig. 2), is omitted, the correlation coefficient $r = -0.79$, and the regression equation becomes $y = 4.15 x^{-0.905}$, as shown by the broken line in Fig. 2, with the standard error of estimate 1.6 species.

The divergence of lake No. 105 from the general group is evident from the log/log plot inset in Fig. 2, but this lake is in no way unusual in its level of sulphate, calcium, or acidity (see Table I). It differs physically from the others in having a bottom composed largely of boulders, but a few sand patches were observed which might have been expected to support a rather greater variety of flora. Unfortunately its inaccessibility prevents further investigation.

Whether lake No. 105 is included in the regression makes little difference to the relationship illustrated in Fig. 2, from which it is clear that sites subject to heavy sulphur pollution exhibit a marked degree of floristic impoverishment. This seems unlikely to be caused by abundance of sulphate ion, which has been analyzed merely as a good pollution index, and may be due in part to the high levels of acidity in many such waters (e.g. Nos. 8, 11, 12, 14, all below pH 4). Strong acidity is not accompanied by low calcium levels, as is so often the case in acid bog lakes (Gorham 1957), but rather by higher concentrations, owing to increased weathering of calcium from the soils by sulphuric acid. Moreover, three waters with high sulphate levels are not very acid (Nos. 56, 65, 69, all above pH 6), and yet are floristically poor, the number of species ranging from two to five per lake. Since it is difficult to imagine that sulphate itself is toxic at the levels observed (0.8 to 1.9 meq/l.), the cause of floristic poverty must be sought elsewhere. In the course of chemical analysis it was found that heavy metals were abundant in waters collected near the smelters, and had to be complexed by cyanide before satisfactory calcium titrations could be carried out. These heavy metals might be presumed to consist mainly of the copper and nickel smelted at Sudbury, but others (e.g. iron, manganese) might also be leached from rocks and soils under the influence of sulphuric acid produced by oxidation of sulphur dioxide from the smelter chimneys. In addition, preliminary investigations have revealed a strong positive correlation between copper and sulphate in melted snow collected at varying distances NNW. from the Falconbridge smelter, with high concentrations of both near the chimneys, as shown in Table IV. It therefore seems likely that heavy metals such as copper, and perhaps other elements (nickel has not so far been investigated), may reach toxic levels in waters subject to severe aerial pollution, and so account for species impoverishment even where the waters are not strongly acid. Indeed, it is quite conceivable that high acidity is of minor importance, and that heavy metal toxicity is the major factor limiting floristic variety in waters receiving much fallout from the Sudbury smelters. In this connection studies of the relative tolerance of species such as *Eleocharis acicularis* and *Potamogeton epiphydrus* v. *nuttallii* for high levels of both acidity and copper might prove informative.

TABLE IV
Chemical analyses of snow samples collected on the ground
near Falconbridge, February 12-15, 1960

Distance NNW. of smelter, mi	pH	SO ₄ , meq/l.	Ca, meq/l.	Cu* acid-sol. µg/l.
0.8	3.8	0.39	0.045	2300
1.0	4.3	0.09	0.015	300
1.4	3.7	0.47	0.040	2000
2.5	4.5	0.12	—	650
3.2	4.3	0.10	0.018	100
3.3	4.6	0.03	0.010	Ca. 5
5.3	4.4	0.05	0.015	< 5
7.4	4.5	0.03	0.013	< 5

*Biquinoline method in Beckman DU spectrophotometer.

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