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ABSTRACT — Physical and chemical characteristics of four dimictic eutrophic lakes of north-central Minnesota with marl deposits are discussed in relation to production of invertebrate animals (benthos and plankton) that are the basic food of fish. Two of the lakes have a history as "productive" fish lakes and the other two as "problem" fish lakes. The "productive" lakes, as a type, have a larger surface area, a longer shallow-water littoral shelf, and a lower proportion of marly soils in the littoral zone than do the "problem" lakes. The standing crop of invertebrates was about twice as great per habitat unit in the "productive" as in the "problem" lakes. Surface waters of the "productive" lakes were somewhat higher in total phosphorus, total nitrogen and total iron than in the "problem" lakes. Since the "productive" lakes have brownish or greenish water as opposed to clear water in the "problem" lakes, chelation of iron and other trace metals by organic compounds also may be involved in productivity.

In the glaciated area of eastern United States, which includes much of Minnesota, marl has been and is being deposited in many lakes. Marl, which is mostly calcium carbonate and which forms a whitish friable soil upon drying, is deposited by chemical and biological processes whereby carbon dioxide is removed from calcium bicarbonate dissolved in the water (Thiel, 1933). Deposition occurs under somewhat alkaline conditions (pH above 8.0) and is most common in lakes receiving ground water from seepage and springs that is high in calcium bicarbonate. Marl lakes frequently pose problems in management for production of sport-fish. Angling yield is often low and the panfish (sunfishes and largemouth black bass) taken from most marl lakes tend to be small. There are some marl lakes, however, that are quite satisfactory fish lakes.

Several studies concerning marl lakes have been made in other states (Hooper, 1956); Merna, 1964; Wetzel, 1966a, 1966b; Eggleton, 1956). In Minnesota Thiel (1933), who was interested in marl as a source of agricultural lime, found marl lakes and deposits to be most common in the porous soils of the "Red" glacial drift of north-central Minnesota. Here marl is usually deposited along shore, in quite shallow water above the thermocline. It often forms benches, shelves, or "bioherms" that drop off rapidly into deep water. On marl deposits and marly soils there is often a dense growth of low-growing submerged aquatic plants, especially muskgrass (*Chara* spp.) and bushy pondweed (*Najas flexilis*). Such plants usually have shell-like deposits of calcium carbonate on leaves and stems. This material eventually becomes part of the bottom along with calcium carbonate that has been precipitated from the water. Typically, the more infertile marl lakes have quite transparent and colorless water and, from a distance, may appear quite blue. This is probably a physical color caused by splitting of white light by finely suspended material and selective absorption and reflection, the phenomenon (Tyndall effect) also causes the sky and peat smoke to appear blue.

This study compares the physical characteristics, water chemistry, and production of invertebrate animals (benthos and zooplankton) of two lakes each of the "productive" and "problem" types. Field work was done in the summer of 1963. Field and laboratory methods are those described by Dobie and Moyle (1962). Some of the data have been obtained from lake survey files of the Minnesota Division of Game and Fish. Bottom soil types were determined in the field from samples obtained with a 6-inch Petersen dredge. All samples were taken during daylight hours, a condition which may influnce the distribution of microcrustacea.

Description of the Lakes

All four lakes studied are in the vicinity of Brainerd, Crow Wing County, in north-central Minnesota. They lie in a forested area of sandy soils. Two of the lakes, Nokay and Upper Cullen, have a "productive" fishing history, especially for sunfishes, largemouth black bass and northern pike. Clear lake and Nelson lake, the other two, have been "problem" fishing lakes. Panfish taken from them have generally been small, and northern pike scarce. The principal physical and general limnological characteristics of these lakes are shown in Table 1. It will be noted that the two "productive" lakes are larger than the two "problem" lakes, are shallower, have water that is more colored and less transparent, and in summer have warmer water at depths below the thermocline.

The nature of the bottom soils in the four lakes is summarized in Table 2, and it will be observed that there

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TABLE 1. Some physical and general limnological characteristics.

Item	"Productive" marl lakes		"Problem" marl lakes	
	Nokay	Upper Cullen	Clear	Nelson
Area — acres	654.2	416.5	222.4	84.1
Maximum depth — feet	43	40	63	65
Littoral area [1] — percent [1]	31.2	55.0	28.4	34.2
Mean width — feet	310	615	150	300
Inlets	From lake and swamps	Brook	From swamp	From swamp
Outlet	Present	Present	Present	None
Thermocline depth range feet [2]	19–30	14–28	16–32	14–31
Water temperature F°[2]				
Surface — range	66–75	68–76	68–76	68–76
Below thermocline — range	52–56	50–56	42–43	42–43
Secchi disk visibility — feet [2]	12	13	18	20
Water color [2]	Greenish	Brownish	Clear	Clear
pH range [2]				
Surface	8.1–8.5	8.1–8.3	8.3	8.3–8.5
Below thermocline	7.5	7.3–7.4	7.3	7.1–7.2

[1] Percentage of total lake area shallower than 15 feet.
[2] In midsummer, 1963.

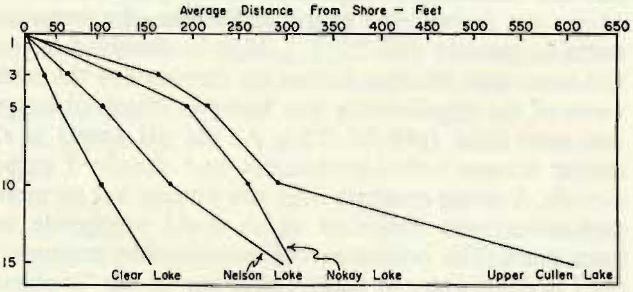

FIGURE 1. Depth gradients in the littoral areas of four Minnesota marl lakes.

is considerably more marl in the littoral zone (water shallower than 15 feet) of the "problem" lakes than the "productive" lakes, although soils with an admixture of marl occur in both types. In the deeper water, marl and soils containing marl are less abundant in the "productive" than in the "problem" lakes. The "productive" lakes have proportionately larger and wider littoral zones, with more loamy organic soils. Pure marl is low in organic matter (Merna, 1964) and, as shown by Dobie (1956) for walleye rearing ponds, best biological productivity is associated with soils of 4 to 8 per cent organic matter. If conditions in the two lakes of each type are averaged, the two types can be compared as follows:

	Productive	Problem
Size: acres	500	150
Maximum depth — feet	42	64
Littoral area — percent of lake area	43	32
Mean width of littoral zone — feet	460	225
Percentage of littoral zone of:		
marl and marl mixtures	11	28
loam and loam mixtures	31	9

Invertebrate Productivity

Since the lakes were selected on the basis of fishing history and past fish-management problems — both qualitative considerations — it is necessary to know whether they differ in productivity of the invertebrate animals that are the basic food of fishes. To obtain this information measured tow net samples were taken of the zooplankton; and samples of the bottom soil containing benthos (bottom fauna)) were taken with a 6-inch Petersen dredge. These data are summarized in Table 3. Zooplankton, mostly microcrustacea, was more abundant in the "productive" than in the "problem" lakes, both in the littoral zone and in surface waters at the center of the lakes. No consistent difference was found for tows made in the center of the

TABLE 2. Percentage of marl, marl mixtures and other soils.

Soil types	"Productive" marl lakes				"Problem" marl lakes			
	Nokay		Upper Cullen		Clear		Nelson	
	T[1]	L[2]	T[1]	L[2]	T[1]	L[2]	T[1]	L[2]
Marl	1.8	5.5	0.05	0.1	16.9	34.5	7.0	15.8
Mixed with other soils	8.6	26.4	6.4	11.7	68.1	54.3	8.2	6.2
Sand	6.3	19.1	4.3	6.6	1.2	4.2	16.4	25.7
Mixed with other soils	20.5	28.4	21.5	35.0	3.1	6.5	16.2	35.3
Loam	53.5	4.0	62.4	37.0	1.0	0.5	48.0	12.0
Mixed with other soils	7.8	11.9	5.3	9.6	9.7	—	4.2	5.1
Clay	0.1	0.2	—	—	—	—	—	—
Mixed with other soils	—	—	—	—	—	—	—	—
Gravel and rubble	1.5	4.7	—	—	—	—	—	—

[1] Percentage of *total* bottom of lake made up of the soil type.
[2] Percentage of *littoral* area (shallower than 15 feet) made up of the soil type.

TABLE 3. Standing crop of zooplankton, mostly microcrustacea, and benthos. (Figures given are means based on the number of samples shown in parentheses)

Item	"Productive" marl lakes		"Problem" marl lakes	
	Nokay	Upper Cullen	Clear	Nelson
Zooplankton lbs./acre foot [1]				
Surface, littoral zone	2.10 (13)	3.07 (14)	0.50 (13)	0.54 (13)
Surface, center of lake	7.62 (13)	1.46 (15)	0.59 (13)	0.49 (14)
10-15 feet, center of lake	13.02 (14)	16.05 (15)	5.71 (13)	15.61 (14)
All	7.6 (40)	6.9 (44)	2.6 (39)	5.6 (41)
Benthos — lbs./acre [2]				
0-5 feet depth	144 (18)	259 (17)	172 (43)	72 (40)
5-15 feet depth	109 (14)	109 (13)	18 (12)	33 (14)
Entire littoral area	127 (32)	184 (30)	95 (55)	53 (54)

[1] Taken in a tow net of 25XX mesh that has been measured for flow through it.
[2] Taken with a 6-inch Peterson dredge.

lakes at depths of 10 to 15 feet, near the upper limit of the thermocline. However, the lowest standing crop of zooplankton, 5.71 pounds per acre-foot, was found in Clear lake, one of the "problem" lakes. As for the zooplankton, the standing crop of benthos, mostly immature aquatic insects, was greater, when the entire littoral zone is considered, in the "productive" lakes. It is of special interest to note that the most productive area for benthos in all four lakes was in the shallower portion of the littoral zone — water 1 to 5 feet deep. Here there was a dense growth of submerged aquatic vegetation, especially *Chara*, *Najas flexilis*, *Elodea canadensis*, and *Potamogeton gramineus*, as well as scattered aquatic plants of other kinds. Because of this depth relationship it could be expected that the lakes with the greatest proportion of water shallower than five feet would have the largest total crop of benthos. As shown in Figure 1, the two "productive" lakes have such a physical configuration.

Averages for invertebrate standing crops in the two lakes of each type (as shown in Table 3) are:

	Productive	*Problem*
Zooplankton, lbs./acre-foot		
surface and littoral waters	3.56	0.53
deep water (10-15 feet)	14.5	10.6
Benthos, lbs./acre		
littoral zone	155	74

It appears, therefore, that the production of larger invertebrate animals that are the food of fish was considerably greater, probably about twice as great, in the "productive" than in the "problem" lakes. An interesting point concerning the zooplankton is that the standing crop was considerably higher in all lakes at a depth of 10 to 15 feet than in the surface waters, indicating favorable conditions and possibly more food available for zooplankton near the upper limit of the thermocline (metalimnion) than at the surface. Wetzel (1967) noted in his study of two marl lakes in Indiana that during thermal stratification levels of glucose, galactose, and acetate increased markedly in or slightly below the metalimnion and that the velocity of bacterial uptake of glucose and acetate increased here. It should be noted, however, that much of the crustacean crop produced in this area would be unavailable to fishes of the kinds found in the Minnesota marl lakes, since they inhabit principally the littoral zone.

Water Quality

All four lakes are of the thermally stratified eutrophic type and have thermoclines (temperature transition zones) in mid-summer beginning at depths from 14 to 19 feet and extending to depths of 28 to 32 feet (table 1). Above the thermocline in the epilimnion, the water was warm in summer (68-75° F.), high in dissolved oxygen, and somewhat alkaline. Below the thermocline the colder water of the hypolimnion was lower in dissolved oxygen and more acid (pH 7.1-7.5). At the pH found in the deeper waters both bicarbonates and dissolved carbon dioxide, forming carbonic acid, are present but no monocarbonates were indicated which could precipitate and form marl. The occurrence of considerable amounts of marl in deep water in Clear Lake, one of the "problem" lakes, may well indicate a shortage of organic matter to provide carbon dioxide to dissolve calcium carbonate precipitated from the upper waters or deposition when the lake was at a lower level. In the "productive" lakes the surface water was greenish or brownish but in the "problem" lakes it was clear. Transparency, as indicated by Secchi disk visibility, was greatest in the "problem" lakes. Characteristics of the two lakes or the two types are shown in Table 1).

As is usual in dimictic eutrophic lakes such as these, following overturn and mixing of the water in spring and fall, concentrations of dissolved oxygen were quite high from top to bottom (Table 4).

In addition to determinations of dissolved oxygen and pH made in the field, water samples were collected and analyzed in the St. Paul chemistry laboratory of the Division of Game and Fish for some other substances, especially those related to the fertility of waters. The results, which are presented in Table 4, show all four lakes to be fairly high in dissolved bicarbonates (as indicated by total alkalinity) and to be of the hard-water type. During the summer stratification period phosphorus (as total phosphorus) in the surface waters was fairly low, as compared to many other Minnesota lakes (Moyle, 1956). Nitrogen (as total nitrogen) fairly high and iron (as total iron) present in amounts about usual for surface waters of Minnesota lakes, and in some cases higher. In general, a somewhat lower chemical fertility is indicated for the "problem" than for the "productive" lakes as indicated in the following comparison of means (as p.p.m.) for surface samples taken in summer:

	Productive	Problem
Total alkalinity	120	102
Total phosphorus	0.020	0.016
Nitrate nitrogen	0.050	0.040
Ammonia nitrogen	0.028	0.028
Nitrite nitrogen	0.001	0.001
Organic nitrogen	0.56	0.44
Total nitrogen	0.60	0.50
Total iron	0.059	0.039

During the summer stratification period there were higher concentrations of bicarbonates, total phosphorus, total nitrogen and total iron below than above the thermocline, indicating both accumulation of these substances in the lower waters from the "fallout" of plankton and other material from the upper waters and reducing conditions in the deeper waters which aid both in keeping salts, including plant nutrients, in solution and in dissolving such materials from the bottom soils. Comparisons of average concentrations (as p.p.m.) found in surface and deep waters during the summer stagnation period are:

	Productive		Problem	
	Surface	Deep	Surface	Deep
Total alkalinity	120	148	102	136
Total phosphorus	0.020	0.095	0.016	0.047
Nitrate nitrogen	0.05	0.15	0.04	0.06
Ammonia nitrogen	0.03	0.60	0.03	0.91
Total nitrogen	0.62	1.055	0.500	1.416
Total iron	0.059	0.799	0.039	0.928

Concentrations of both iron and ammonia indicate conditions favoring chemical reduction to be greater in the depths of the "problem" than in the "productive" lakes. In summer this is also borne out by low concentrations of dissolved oxygen in the deep waters.

During the spring and fall, when the thermocline was absent or poorly differentiated, there was less difference between concentrations of chemical plant nutrients in surface and deep waters.

The usual (average) ratio of total phosphorus to total nitrogen in surface waters of Minnesota lakes is about 1:11 (Moyle, 1956) and that for protoplasm about 1:8, suggesting that phosphorus is a limiting factor in the productivity of some Minnesota lakes. In the four marl lakes the ratio found was even wider, being 1:29 for the "productive" lakes and about 1:31 for "problem" lakes, indicating unused combined nitrogen, and suggesting that greater productivity might be achieved if more phosphorus (and possibly trace elements such as iron) were available.

There are two chemical routes whereby the amount of available inorganic (ortho) phosphate dissolved in the water can be and probably is being eliminated from the water of these marl lakes. First, it is likely, as pointed out by Deevey and Bishop (1942) and Moyle (1965), that the precipitation of calcium monocarbonate as marl may also result in the precipitation and deposition of some insoluble calcium phosphate. This would occur only in the upper waters in summer when the pH is above

TABLE 4. Water chemistry, in parts per million. (The figures presented are means [4])

	"Productive" marl lakes						"Problem" marl lakes					
	Nokay			Upper Cullen			Clear			Nelson		
	Sampling period[1]			Sampling period[1]			Sampling period[1]			Sampling period[1]		
Item	A	B	C	A	B	C	A	B	C	A	B	C
Total alkalinity												
Surface	127.1	118.5	113.0	135.1	120.8	125.0	129.3	113.8	115.0	104.0	90.0	102.5
At thermocline [2]	128.1	124.7	119.0	134.3	130.1	124.0	133.7	127.5	125.0	105.7	103.5	105.0
Below thermocline [3]	128.2	145.9	118.0	135.6	150.3	126.0	134.7	150.5	137.0	108.9	121.2	100.0
Dissolved oxygen												
Surface	11.4	10.3	10.4	12.1	10.5	10.6	12.9	11.2	9.1	13.0	10.6	9.1
At thermocline [2]	11.6	2.2	—	10.7	3.6	—	—	4.7	—	—	4.1	—
Below thermocline [3]	10.1	0.6	8.0	10.2	2.0	10.5	9.4	0.5	6.6	9.1	0.1	6.6
Total phosphorus												
Surface	.017	.019	.044	.017	.022	.043	.018	.018	.018	0.14	.014	.042
At thermocline [2]	.019	.025	.042	.027	.032	.021	.024	.027	.039	.022	.026	.025
Below thermocline [3]	.032	.087	.083	.025	.103	.029	.030	.055	.058	.020	.039	.035
Total nitrogen												
Surface	.668	.570	.772	.509	.660	.823	.572	.474	3.940	.649	.527	1.021
At thermocline [2]	.652	.582	.788	.889	.623	.541	.463	.621	3.630	.591	.663	1.201
Below thermocline [3]	.545	.867	.996	.562	1.244	.520	.625	1.328	1.971	.746	1.503	1.511
Total iron												
Surface	.049	.041	.068	.091	.078	.090	.031	.016	.050	.120	.062	.370
At thermocline [2]	.065	.056	.067	.090	.106	.270	.042	.033	.020.	.104	.076	.240
Below thermocline [3]	.346	.327	.380	.221	1.271	.220	.038	.106	.080	.373	1.749	.085

[1] "A" — after spring overturn and before summer stratification: Nokay, 4/16-6/3; Upper Cullen, 4/16-5/27; Clear 4/17-5/29; Nelson, 4/17-5/29. "B"—during summer stratification: Nokay, 6/13-9/16; Upper Cullen, 6/3-10/28; Clear, 6/5-11/5; Nelson,6/5-11/5. "C"—after fall overturn: Nokay, 9/23-9/30; Upper Cullen, 11/4;Clear, 11/13; Nelson, 11/13.

[2] At a depth of 20 feet for Nokay and Upper Cullen lakes and 25 feet for Clear and Nelson lakes. Midwater dissolved oxygen taken in 35 feet in Clear Lake and 30 feet in Nelson Lake. Thermocline was absent or poorly defined at "A" and "C" sampling periods.

[3] At a depth of 30 feet for Nokay Lake, 35 feet for Upper Cullen Lake and 50 feet for Clear and Nelson lakes. Thermocline was absent or poorly defined in "A" and "C" sample periods.

[4] Means for spring period is based mostly on 5-8 samples; for summer period (B) on 14-21 samples and for fall (C) on 1 or 2 samples. (—) indicates no sample taken.

8.0. Secondly, it is likely that ferrous iron in the bottom waters, especially those next to bottom soils, during the spring and fall overturn when the water is oxygenated, is changed to ferric iron and this combines with phosphate to form insoluble iron phosphate. This process, which was originally proposed by Ohle, is summarized and discussed by Hutchinson (1957).

The two "productive" lakes have either brownish or greenish water in contrast to the colorless and more transparent water of the "problem" lakes. It has been shown for water from a marl lake in Michigan (Schelske, 1962) that chelation of iron by organic compounds may increase biological productivity. This may be a factor here. Merna (1964), found an increase in growth rates of fish in a Michigan marl lake following elevation of water levels and flooding of previously aerated soils that had a higher organic content than the lake bottom. Schelske (1962) added the organic chelating agent HEDTA to water from a marl lake and increased the primary productivity of the water. He attributes this to the greater availability of iron with chelation. Addition of chelated iron and commercial ferilizers to a 14-acre marl lake in Michigan increased primary productivity 4-fold, as indicated by C^{14} uptake. However, use of fertilizer alone to another marl lake did not bring about an increase (Shelske. Hooper and Haertl, 1962). Possibly amines in water may be involved in the chelation process (Kent and Hooper, 1965). Wetzel (1967) notes that *Chara* and *Najas* excrete moderate amounts of simple organic compounds, especially amine acids. From the viewpoint of practical fish management, it seems likely that addition of sufficient amounts of organic material, such as organic matter from bog drainage, could be expected to increase the productivity of marl lakes, replicating the effect obtained by temporary elevation of water levels, as suggested by Merna (1964).

Complexity of the problem of basic fertility of marl lakes is well summed up by D. S. Rawson (1958) in his considerations on Canadian lakes: "There are very many factors influencing the biological production in waters"; and "the individual factors are not expressed independently but are linked together in complex ways."

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High Initial Earnings For Minnesota I. T. Grads

Bachelor degree graduates from the University of Minnesota's Institute of Technology in 1968 received starting salaries which averaged $778 per month ($9,336 per year, a class compilation shows. Those employed within the state of Minnesota received an average of $781 per month ($9,372 per year).

The national average starting salary for graduates in similar technical fields was $736 per month ($9,072 per year) or about 3 percent less than the Minnesota figure.