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Winter Limnological Conditions in a PRAIRIE Pothole and the Application of Molecular Oxygen

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WINTER LIMNOLOGICAL CONDITIONS IN A PRAIRIE

POTHOLE LAKE AND THE APPLICATION OF MOLECULAR OXYGEN

BY

RICHARD A. FIKE

A thesis submitted
in partial fulfillment of the requirements for the
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1979

WINTER LIMNOLOGICAL CONDITIONS IN A PRAIRIE

POTHOLE LAKE AND THE APPLICATION OF MOLECULAR OXYGEN

This thesis is approved as a creditable and independent investigation by a candidate for the degree, Master of Science, and is acceptable for meeting the thesis requirements for this degree. Acceptance of this thesis does not imply that the conclusions reached by the candidate are necessarily the conclusions of the major department.

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WINTER LIMNOLOGICAL CONDITIONS IN A PRAIRIE
POTHOLE LAKE AND THE APPLICATION OF MOLECULAR OXYGEN

Abstract
RICHARD A. FIKE

The physical, chemical, and biological conditions in
Round Lake, Oakwood Lakes State Park, South Dakota were
monitored during the 1977-1978 winter, and reaeration
utilizing molecular oxygen was evaluated as a practical
method to prevent winterkill.

Ice and snow conditions after 20 December, 1977
allowed little light penetration, and phytoplankton numbers
(6174/ml to 1668/ml) and chlorophyll concentration (46.6
mg/L to 14.1 mg/L) decreased throughout the winter. Aquatic
bacteria and fungi comprised from 87.0% to 93.7% by number
of the total cells identified (phytoplankton, bacteria, and
fungi) in the lake water under ice.

Dissolved oxygen declined to anoxic conditions after
19 January, 1978, and hydrogen sulfide gas reached a mean
maximum (6.0 mg/L) on 12 February. Analysis of chemical
parameters indicated increased chemical concentrations
attributable to the "freezing out" of ions. A mean free
carbon dioxide level increase from 0.95 mg/L to 59 mg/L
was caused by increased respiration not counterbalanced by

photosynthesis.

Community respiration measured by the diel oxygen method (community metabolism) varied from 1.4 mg O_2/L/24 hrs 1-2 December, 1977, to a low (0.2 mg O_2/L/24 hrs) 11-12 January, 1978. Water biochemical oxygen demand (BOD) measurements from samples incubated below the ice indicated that mean lake BOD increased from 0.8 mg O_2/L/24 hrs 12 February, 1978, to 8.5 mg O_2/L/24 hrs 16 March, 1978. Sediment BOD was 10 to 15 times that of the water BOD during the same period.

Liquid oxygen stored in 127,440 L O_2 gas capacity tanks, rubber welders hose, and graphite air stones comprised the molecular oxygenation apparatus. Oxygenation employing 3 different strategies, resulted in 711,400 liters of oxygen gas being expended under the ice with few positive effects noted in reducing anoxic conditions in the lake.

The total lake oxygen demand for the 4 month period was calculated to be 1.05×10^8 L O_2. Depending on molecular oxygen dissolution efficiency, an expenditure of $70,000 to $350,000 for oxygen alone, might have been required to prevent winterkill in Round Lake during 1977-1978.

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RAF

[1]Cooperating agencies: South Dakota Department of Game, Fish and Parks, South Dakota State University, and United States Fish and Wildlife Service.

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INTRODUCTION

The objectives of this study were to document winter limnological conditions in highly eutrophic Round Lake, Oakwood Lakes State Park, South Dakota during the winter of 1977-1978, and evaluate molecular oxygen aeration under ice cover as a practical method to prevent winterkill.

The northeastern South Dakota glacial lakes district abounds in shallow eutrophic pothole lakes. Eutrophication is a result of natural or artificial nutrient additions to a body of water (National Academy of Sciences 1969).

Fertilizer and sediment run-off from agricultural land is the largest problem contributing to water pollution in South Dakota. Pollutants deposited on lake bottoms over a period of years may become a longlasting source of enrichment. An example of this is the Oakwood Lakes near Bruce, South Dakota. The South Dakota Department of Environmental Protection (1978) reports that the major water quality problems in the Oakwood Lakes are high nutrient and unionized ammonia concentrations.

Winters in the northern prairie states are characteristically severe. Ice and snow cover usually lasts from November through March with ice reaching thicknesses up to 100 cm and snow 30 to 40 cm or more. When ice and snow cover prevents sufficient light from reaching the phytoplankton in eutrophic lakes, they die and decay rapidly. Consumption

of dissolved oxygen by catabolic processes can then exceed
augmentation by photosynthesis, and lead to severe reductions
in dissolved oxygen or even to total anoxia (Wetzel, 1975).
This phenomenon is termed "winterkill", and has detrimental
effects on aquatic life.

Oakwood Lakes State Park has a history of winterkills
documented as far back as 1951-1952, and has suffered at
least a partial winterkill the last 3 winters (1976-1979),
(South Dakota Department of Game, Fish, and Parks, lake
survey data, 1951-1979, unpublished). The scope of the
winterkill problem was demonstrated by the extensive winter-
kill of 1977-1978 (Fig. 1). The majority of northeastern
South Dakota lakes, including Lake Poinsett, the largest
natural lake in the state, were affected.

The investigation of molecular oxygen use in reaeration
is relatively recent. Since oxygen comprises approximately
19% of the atmosphere, molecular oxygen has a solubility
in water approximately five times greater than compressed
air. Therefore smaller amounts of molecular oxygen would
be required for reaeration. However, the oxygen must be
manufactured and the advantage of less quantity may be
offset by the disadvantage of higher cost (King 1970, and
LaBounty and King 1977). Speece (1969, 1971) found that
pure oxygen often was economically competitive for artificial
aeration. Proper oxygenation system design can make

Fig. 1. Winterkilled fish piled along the shore of East
Oakwood Lake at a spring area during breakup of the ice,
March, 1978.

molecular oxygen use efficient and advantageous. Various studies have investigated optimum oxygenation system design and methodology with molecular oxygen (Amberg et al. 1969; Speece 1969, 1971; King 1970; Fast et al. 1975; LaBounty and King 1977; Lorenzen and Fast 1977).

There is a paucity of research related to molecular oxygen use under winter ice cover. Seppänen (1974, cited by Lorenzen and Fast 1977) described the design and operation of a liquid oxygen aerator on lakes Hemtrask and Kiteenjarni, Finland during winter ice cover. LaBounty and King (1977) researched a technique utilizing liquid oxygen to prevent winter anoxia with positive results. Molecular oxygen gas produced from liquid oxygen passed through tubing and a series of diffusers mounted approximately 2t) meters below the ice and 1 meter above the bottom.

STUDY AREA

Round Lake is situated in Oakwood Lakes State Park,
4.8 kilometers west of Bruce, South Dakota, in northwestern
Brookings County. It is the smallest (21 ha) lake of a
group of 5 within the park (Fig. 2). These lakes are glacial
in origin and lie on the Coteau des Prairies, a highland
area between the Minnesota-Red River lowland and the James
River lowland in eastern South Dakota.

The Oakwood Lakes are high in dissolved solids and exist
as a closed system except for runoff and ground water seep-
age. Many sloughs and potholes are in the area. Inflow and
drainage streams are small with intermittent flow. Round
Lake is connected at its west side to West Oakwood Lake
(Tetonkaha Lake) during highwater levels. Prior to this
study South Dakota had experienced a drought period, and
although 1977-1978 was a period of normal moisture levels,
the lakes still had not returned to normal levels.

The watershed surrounding the Oakwood Lakes area is
agricultural with several farming and feedlot operations
extending to the lake edges on the park boundaries. Summer
cabins and a resort area line the southern shore of West
Oakwood Lake. Round Lake lies entirely within the park,
with no development on its shores except for a park road-
way along the south and east sides.
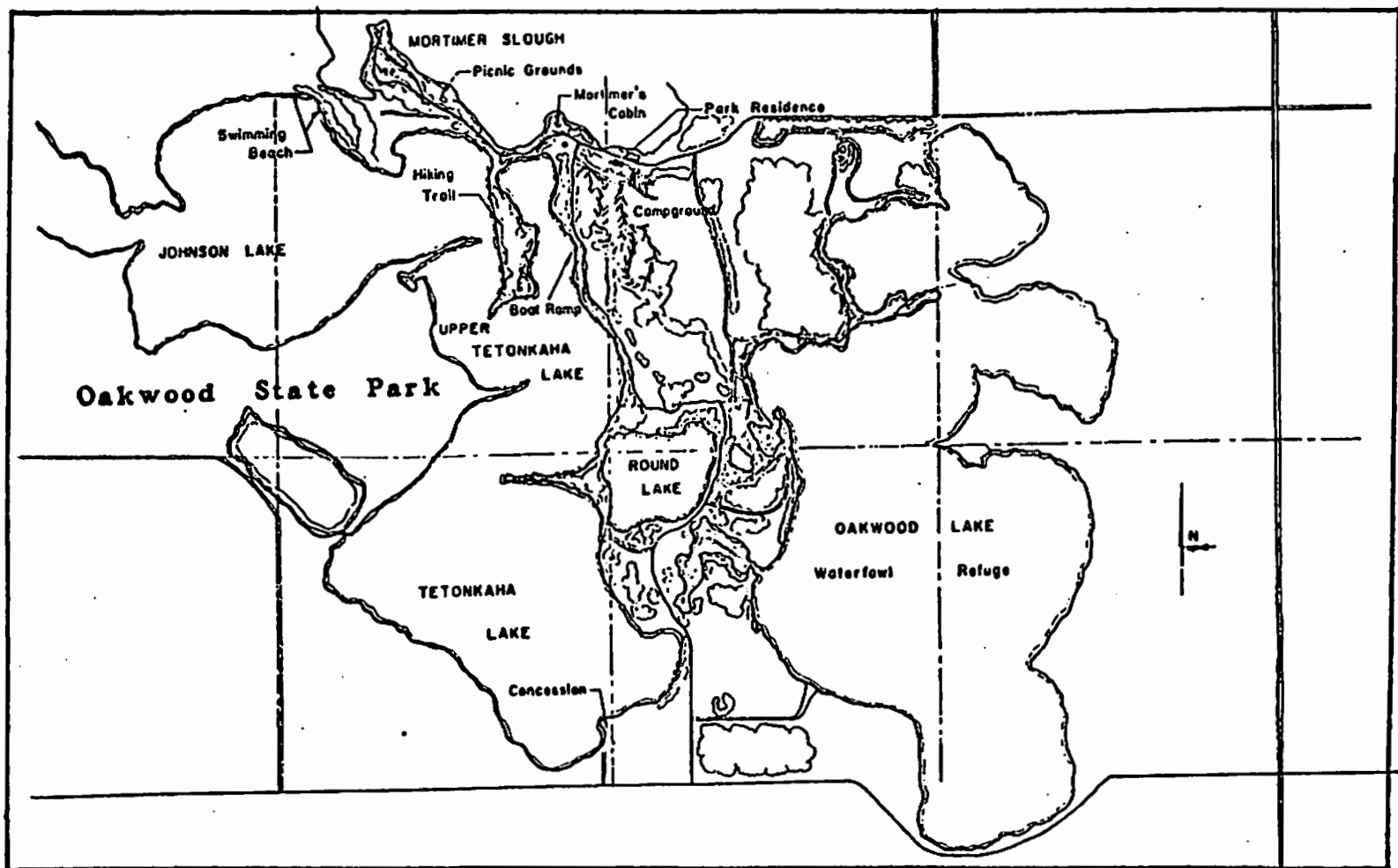
Fig. 2. Map of Oakwood Lakes State Park, Brookings Co., South Dakota, showing the location of Round Lake.

The Oakwood Lakes are all relatively shallow and flat bottomed with maximum depths of 3.0 m in East and West Oakwood Lakes and 1.4 m in Round Lake during the study period (Fig.3).

Blue green algal blooms occur during the summer and fall periods. The water is characteristically greenish brown in color. The lake bottoms are heavily silted with fine grained, organically rich mud. Shorelines subjected to wave action vary from sand and gravel to rubble and boulders. Submerged and emergent vascular aquatic vegetation is limited in the lakes to a few scattered areas due to shifting substrate, limited light penetration, and carp, Cyprinus carpio, activity.

The Oakwood Lakes have historically supported a high density of black bullheads, Ictalurus melas. Prior to 1968 during winterkill free periods, high densities of yellow perch, Perca flavescens, and walleye, Stizostedion vitreum, flourished in the lakes (South Dakota Department of Game, Fish, and Parks, lake survey data, 1951-1979, unpublished). A severe winterkill during 1968-1969 decimated the sport fish population. The lakes have since been stocked with northern pike, Esox lucius, (considered to be more tolerant of lower oxygen conditions), and adult yellow perch. The forage fish population consists primarily of carp, fathead minnows, Pimephales promelas, white suckers,

Lake Morphometry

Shoreline Length=1826m
Shoreline Area=20.9ha
0.5m Depth Area=16.5ha
1.0m Depth Area=12.0ha
1.2m Depth Area=4.8ha
1.4m Depth Area=1.7ha
Lake Volume=186,668m^3

Magnetic

x = Sampling Sites

Scale: 1cm= 36meters
(Submerged contours
in meters)

O_2 site is approximately
to scale
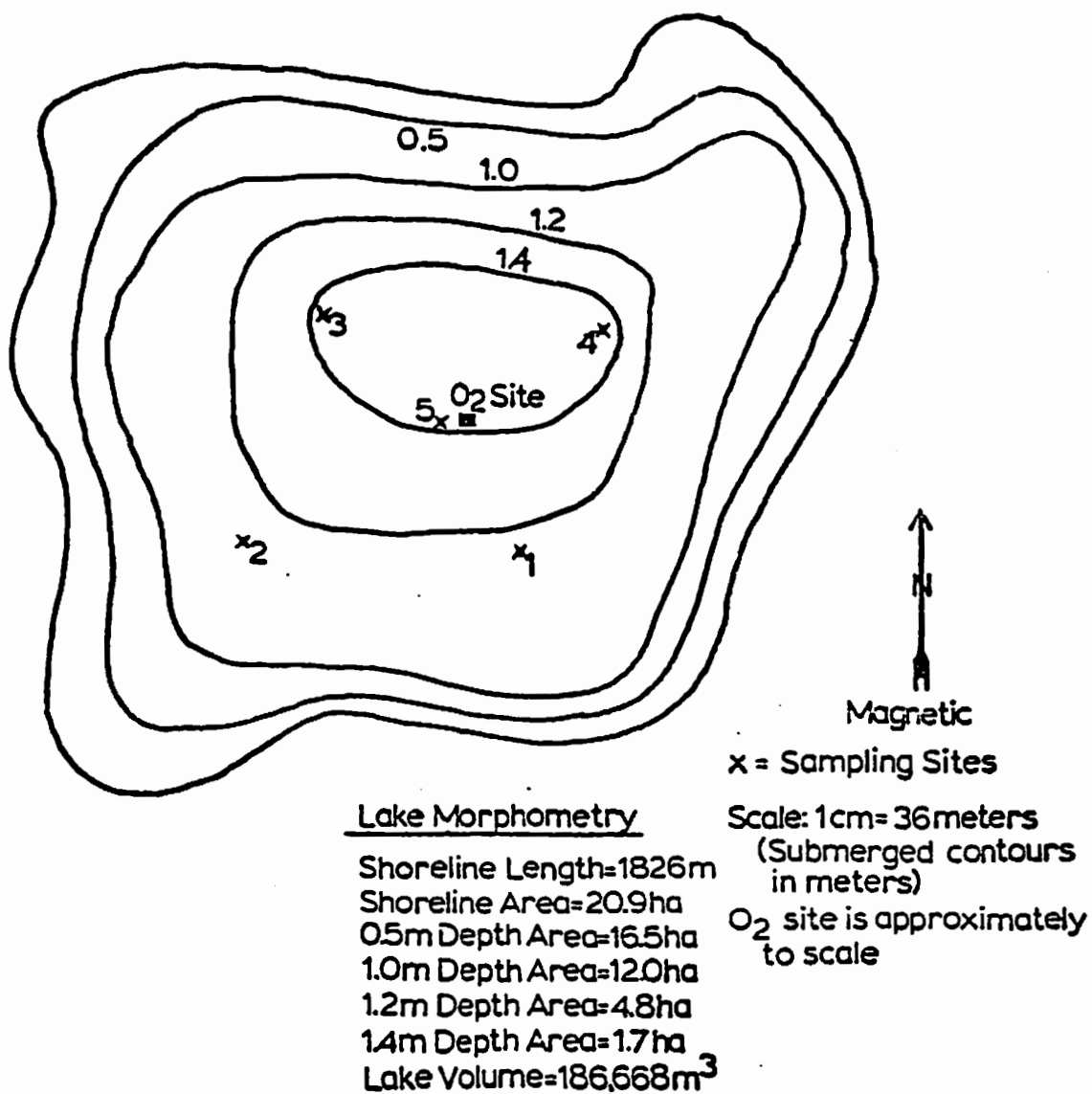
Fig. 3. Contour map of Round Lake, Oakwood Lakes State Park, Brookings Co., South Dakota, 1977.

Catostomus commersoni, and bigmouth buffalo, *Ictiobus cyprinellus*.

MATERIALS AND METHODS

Measurements were first taken December 1, 1977, on
the lake to determine physical characteristics. Water
depth was measured through the ice. The lake was mapped
to scale using the outline from a 1964 South Dakota Depart-
ment of Game, Fish, and Parks map, and the volume calculated.
Water stages in both 1964 and 1977 were similar. Five
permanent sampling stations were established, marked, and
the oxygenation site located (Fig. 3).

On each sampling date ice thickness was measured at
each station and a relative observation made of ice
clarity, snow condition, and percentage snow cover on
the lake. The depth of deepest snow cover was measured
with a meter stick and recorded. Weather conditions, time
of day, and other general observations were also recorded.
All samples were taken one to two hours before sunset.
Light penetration was measured with a secchi disk lowered
into a hole drilled through the ice. Battery failure due
to cold temperatures, prevented the use of a relative
irradiance meter with a submersable photocell.

Water sample collection in subfreezing weather often
required specialized techniques. Glass BOD bottles were
subject to rapid freezing and shattering. The solution
was to place the filled sample bottles in an ice chest
warmed with hot water bottles. After the chest was

transported to the vehicle, the first two Winkler reagents were added. Any error incurred in dissolved oxygen measurement by this technique was unavoidable and constant throughout the sampling period.

Similar problems in collection of water samples for other parameters were nullified by the use of 4 L plastic sample bottles. Problems with the use of any battery powered instrument were related to battery power loss due to the cold, or freezing of electrodes. Any analysis requiring the use of a battery powered instrument was completed in the vehicle or laboratory. The only exception was water temperature, with the sole solution being rapid measurement. All sample collection and measurements on the ice were conducted with the aid of a snowmobile.

All water samples were analyzed according to procedures outlined in the American Public Health Association (1971) unless otherwise indicated. Water samples were collected with a 2 L (PVC) plastic Kemmerer water sampler and stored in 4 L plastic water bottles (filled to the top to avoid aeration), for transportation to the laboratory. Care was taken to avoid agitating the water while drilling holes in the ice and sampling. Due to the shallow nature of the lake and the ice thickness, only temperature was measured at different depths. Samples were taken at a mean point between the ice and bottom sediment. Three replicate

samples were taken and reported as a mean value.

Water temperature was measured just below the ice
and at 0.5 intervals using a battery powered Yellow
Springs Instruments Company resistance thermometer.
Specific conductance was measured in the laboratory at 25 C
using a platinum electrode, temperature compensating
conductivity meter. Dissolved solids samples were filtered
through 0.45um pore size, acid washed Millipore filters.
Three 50 ml portions of the filtrate were dried at 179-181 C
overnight, then placed in a desiccator until weighed.
Samples for the determination of pH were collected in 300 ml
BOD bottles to prevent CO_2 loss from the sample, placed in
an ice chest with hot water bottles to prevent freezing, and
transported to the vehicle. The pH determination was made
immediately in the vehicle using a temperature compensating,
portable pH meter with polyethylene covered glass electrode.
The meter was calibrated daily with standard buffer solutions
prepared by the Hach Chemical Company. Free CO_2 was deter-
mined using the nomographic method. Phenolphthalein
alkalinity and total hardness were analyzed in the labora-
tory. Total alkalinity and total hardness were analyzed
in the laboratory. Total alkalinity was measured by the
mixed bromcresol green-methyl red indicator method and the
appropriate calculations made to obtain the CO_3 and HCO_3
fractions. Hydrogen sulfide was determined in the field

by use of a Hach Chemical Company test kit from samples collected in 300 ml BOD bottles. Samples for dissolved oxygen determination were collected in 300 ml BOD bottles, placed in an ice chest with hot water bottles, and transported to the vehicle. They were then immediately fixed using the azide modification of the Winkler method. The fixed samples were acidified and titrated in the laboratory.

To measure the community production and respiration of oxygen, the diel oxygen method (community metabolism) developed by McConnel (1962) was selected. This method allowed the calculation of gross photosynthesis and community respiration. The ratio of photosynthesis to respiration furnished an indicator by which the progression to winterkill could be plotted. In addition, phytoplankton and bacterial cell counts were made. Three lake water samples were collected from each station and pooled into 4 L plastic bottles. Three 500 ml samples were measured from each mixed sample bottle and concentrated to 10 ml using an ultracentrifuge. The concentrated samples were preserved with Lugol's solution. Cell counts were made using the Edmundson technique (Lackey 1938). A 0.1 ml sample was pipetted onto the counting slide and the 100 most abundant cells, colonies, or filaments counted at 400 x. Phytoplankton was identified to genus according to Prescott

(1962, 1970). The aquatic bacteria and fungi (those
visible at 400 x) were identified according to Cooke
(1963) and Prevot (1966).

Spectrophotometric determinations of chlorophylls and
plant carotenoids were made on Round Lake water according
to the methodology in Strickland and Parsons (1968).
Sample collection was the same as previously described
for cell counts. A Bausch and Lomb Spectronic 70 spectro-
photometer and 1 cm light path cuvettes were used to
measure the sample light extinction (absorbance).

When it was no longer possible to measure dissolved
oxygen, it was necessary to abandon the community metabolism
procedure and measure respiration by the BOD method
(American Public Health Association 1971). Samples of lake
water were collected in 4 L plastic bottles and saturated
with air by shaking them. Four 300 ml BOD bottles were
filled and overflowed several times their volume by
siphoning the aerated water from the plastic bottles.
Three bottles were incubated under the ice for 24 hours.
The first 2 Winkler reagents were added to the fourth
bottle to provide a measure of the initial oxygen
concentration in the bottles. After 1 March, 1978, the
lake water was diluted with standard dilution water
before filling the BOD bottles. Dilutions up to a factor
of 0.8 were required. Concurrently a BOD determination

was made on the lake bottom sediment. A sediment sample
to a 5 cm depth, was obtained with an Ekman dredge. The
sediment was mixed in a bucket to obtain a homogeneous
sample and a portion diluted with aerated standard dilution
water to a factor of 0.99. The mixture was siphoned into
4 500 ml BOD bottles. Three were incubated under the
ice for 24 hours. The fourth was flocculated to remove
sediment interference with the Winkler dissolved oxygen
determination. Then the first two Winkler reagents
were added to measure the initial oxygen level. All
bottles were treated using the alum-flocculation modifica-
tion of the Winkler method.

The sediment volume affecting the lake water oxygen
demand was calculated using the lake surface area and a
5 cm depth. The lake volume was calculated from measure-
ments taken just after ice cover occurred, then corrected
for ice cover throughout the winter. Ice volume was
calculated using the lake surface area divided by the
coefficient of expansion for ice (1.125).

Mean sediment and water oxygen demand values from
community respiration and BOD (water and sediment) measure-
ments throughout the winter were multiplied by the
associated sediment volume and lake volume respectively
during that period then combined. These short time period
totals were then combined to obtain total lake oxygen

demand over the 4 month period from December through March. The amount of molecular oxygen required to increase the dissolved oxygen in the water to 5 mg/l was also calculated. This level is usually considered as the minimum acceptable dissolved oxygen level to sustain most sport fish. Whenever community respiration or BOD measurements were taken, such as the sediment BOD values during the first part of the study, the closest measurement time wise was used in the short time period oxygen demand calculation.

Prior to the initiation of sampling, the molecular oxygenation apparatus was tested in the laboratory. All materials were obtained from the Dakota Welding Supply Company, Sioux Falls, South Dakota. The graphite oxygenation stones, through which molecular oxygen was bubbled into the water (Fig. 4), were obtained from the Union Carbide Corporation, Chicago, Illinois. These stones measured 1.9 m in length with a 5.1 cm diameter. The air stone's center was hollow to a diameter of 1.3 cm permitting gas passage the stone's length. The stones were modified with 1.4 cm diameter welder's hose fittings on one end and threaded plugs on the other. A desirable characteristic of the graphite stone was the extremely small diameter bubbles released, facilitating more efficient molecular oxygen dissolution. A 1.4 cm diameter welder's hose connected each graphite stone to the regulator and

Fig. 4.   Above left: Gas Pack 45 oxygen tank with regulator
and hoses.   Above right: Graphite air stone.   Below: Open water
above the oxygenation site at termination of oxygenation.

oxygen tank (Fig. 4). The Gas Pack 45 oxygen tank had
a 127,440 L molecular oxygen gas capacity at atmospheric
pressure. A smaller K tank, used when it was necessary
to recharge the Gas Pack 45, had a 6910 L capacity. At
a 15 L/min. maximum flow rate, each Gas Pack 45 oxygen
tank had sufficient capacity to last approximately 6 days.

The oxygenation site was located near the lake center
within the deepest contour (Fig. 3). Sampling sites
were selected to allow measurement of dissolved oxygen
dispersal (Fig. 5). During oxygenation experiments 1
and 2, the air stones were suspended 10 cm off the bottom
with ropes anchored in the ice to prevent sediment mixing.
The stones were moved for oxygenation experiment 3. It
was not possible to resuspend the stones from the ice due
to ice thickness, and they rested on the bottom.

Oxygenation Experiment 1

On 14 January, 1978 the mean dissolved oxygen level
on Round Lake was decreasing rapidly. Molecular oxygen
gas at a 5 L/min. rate was released under the ice for 4 hours.
Dissolved oxygen determinations were made before, immedi-
ately following, and 24 hours after oxygenation at sampling
sites within the oxygenation area. When oxygenation
ceased, the stones and hoses were removed from the water
to prevent freezing.
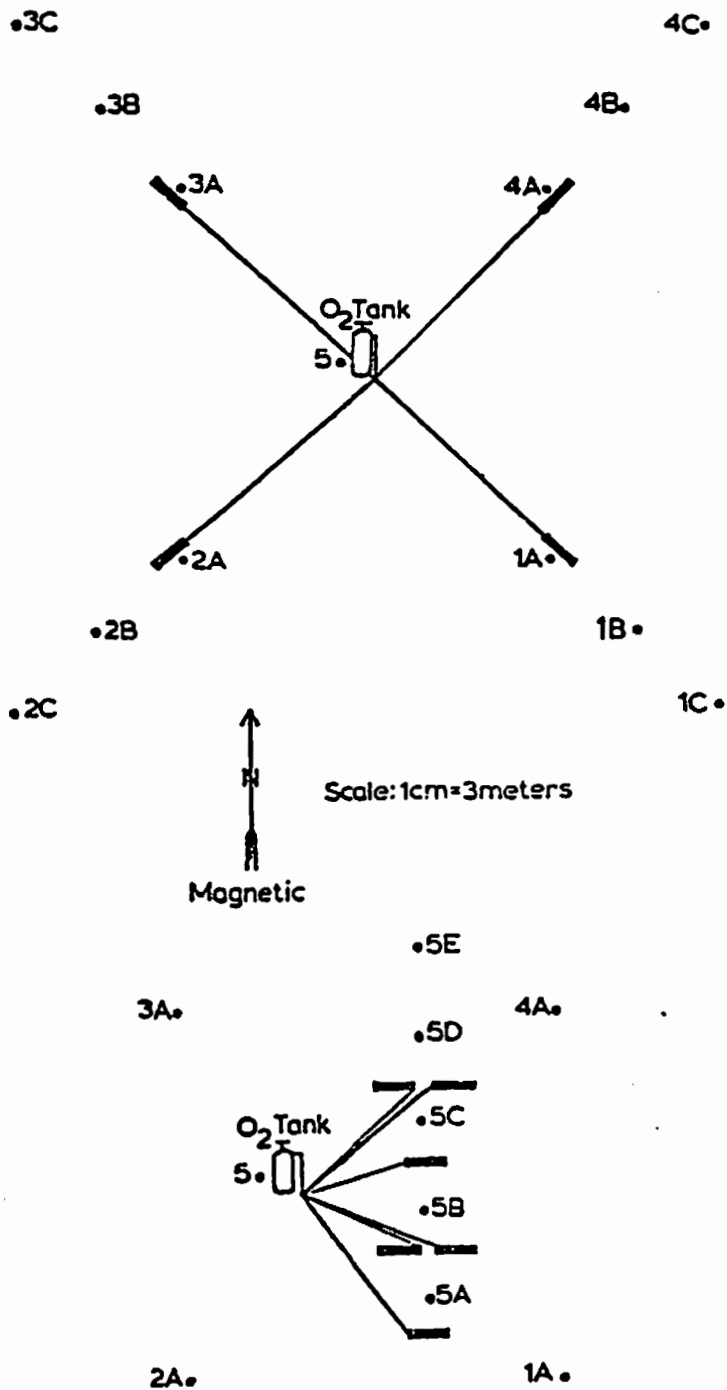
Fig. 5. Placement of the air stones and sampling sites. Above:
Oxygenation experiments 1 and 2. Below: Oxygenation experiment 3.

Oxygenation Experiment 2

Between 21 and 23 January, 1978 molecular oxygen gas was released at a 10 L/min. rate for 48 hours. Dissolved oxygen determinations were made before, after 24 hours, and at completion of oxygenation. Test netting was conducted under the ice during oxygenation using a 30.5 m, 0.6 to 3.8 cm variable mesh experimental gill net to determine if fish were being attracted to the area. The stones and hoses were removed after oxygenation ceased.

Oxygenation Experiment 3

After experiments 1 and 2, the oxygenation stones were placed closer together under the ice to provide a concentrated oxygenation area. Between 1 February and 14 March, 1978, oxygen gas was released under the ice continuously for 42 days (1008 hrs.) at the maximum 15 L/min. rate. To prevent emptying the tank completely and to provide a continuous oxygen gas flow, at 5 day intervals the Gas Pack 45 oxygen tank was replaced by a smaller K tank and recharged. Due to the smaller K tank capacity, molecular oxygen flow under the ice was reduced to 3 to 4 L/min. until the Gas Pack 45 oxygen tank could be recharged and reconnected. Dissolved oxygen determinations were made in the oxygenation site at 3 day intervals.

In an attempt to determine the oxygenation effects other than dissolved oxygen measurements, comparisons

were made utilizing various parameters measured in and ·
outside (sampling sites 1-4) the oxygenation site, both
during and after the oxygenation. These included; BOD
in the lake water and sediment, water temperature, secchi
disk visibility, hydrogen sulfide, free carbon dioxide,
CO_3 and HCO_3 alkalinity, total hardness, dissolved solids,
specific conductance, and pH.

To test the significance of the difference between
sample data group means obtained at stations in and out of
the oxygenation site, the Students t statistic was employed.
Only the sample data group means for dissolved oxygen,
water BOD, and sediment BOD were tested. All means were
tested at the 0.05 probability level.

On 14 March, 1978 at the end of oxygenation 3, a
series of samples was taken on stations 1 through 4, and
5B for analysis by the Water Quality Laboratory, South
Dakota State University, Brookings. Sulfate (SO_4) was
measured by the turbidimetric method; nitrate (N) by the
brucine method; nitrogen (NH_3) by the nesslerization method;
nitrogen (organic) by the kehldahl method; phosphate (ortho)
by the stannous chloride method; and phosphate (total) by
the persulfate digestion and stannous chloride methods.

RESULTS AND DISCUSSION

Physical Conditions

Measurements taken on Round Lake 1 December, 1977, indicated a 0.9 m mean depth and an approximate 186,668 m^3 volume. Ice cover formed on the lake from 1 December, 1977 (20 cm, 17.8% of lake volume), to after 21 March, 1978 (92 cm, 72% of lake volume) (Table 1). From 20 December, 1977, until ice breakup in late March, drifted snow covered Round Lake up to a 60 cm depth. Ice thickness exceeded depth of secchi disk visibility after 20 December, 1977, and until ice breakup, minimal light penetrated the ice and snow cover. Between 19 December, 1977 and 16 February, 1978, 60 consecutive days below freezing occured (a South Dakota record).

Mean temperatures in Round Lake just after freeze-over varied from 1.5 C below the ice to 4.0 C above the sediment (Fig. 6). As winter progressed and ice cover increased, water temperatures gradually decreased. However on 2 March, 1978, measurements indicated that water temperatures had increased slightly, particularly in the area around station 3. Since no thaw had occured prior to this date, the temperature increase could be attributed to sampling error.

Chemical Analysis

In general, the water of Round Lake would be classified

Table 1. Ice and snow conditions and secchi disk visibility on Round Lake during the winter of 1977-1978

| Date	Mean Ice Thickness(cm)	Ice Clarity	%Snow Cover	Snow Depth and Condition	Mean Secchi Disk Visibility(cm)
12/1/77	20	Opaque	60-70%	Drifted up to 30cm, dry and packed.	70
12/7/77	20	Opaque	98%	Drifted up to 30cm, dry and packed.	...
12/14/77	30	Opaque	90%	Drifted up to 15-20cm, dry and packed.	...
12/15/77	...	Opaque	40-50%	Drifted up to 20-30cm, wet and packed.	...
12/20/77	36	Opaque	100%	Drifted up to 30cm, dry and packed.	40
1/12/78	59	Opaque	100%	Drifted up to 45cm, dry and packed.	40
1/14/78	...	Opaque	100%	Drifted up to 45-60cm, dry and packed. 2-3cm dusting of dry, loose snow.	...
1/19/78	61	Opaque	100%	Drifted up to 60cm, dry and packed.	...
1/30/78	75	Opaque	100%	Drifted up to 30-60cm, dry and packed.	...
2/4/78	...	Opaque	100%	Drifted up to 30-45 cm, blowing snow.	...
2/12/78	85	Opaque	100%	Drifted up to 30-45 cm, dry and packed. 5-7cm of dry, loose snow on top.	...
3/2/78	92	Clear to opaque	100%	Drifted up to 30-60cm, 7-10cm new snow.	40
3/9/78	...	Shifting, clear to opaque	100%	Drifted up to 30-45 cm, wet and corny.	...
3/12/78	...	Crust breaking, soft and opaque	100%	Drifted up to 15-30cm, wet and slushy.	50
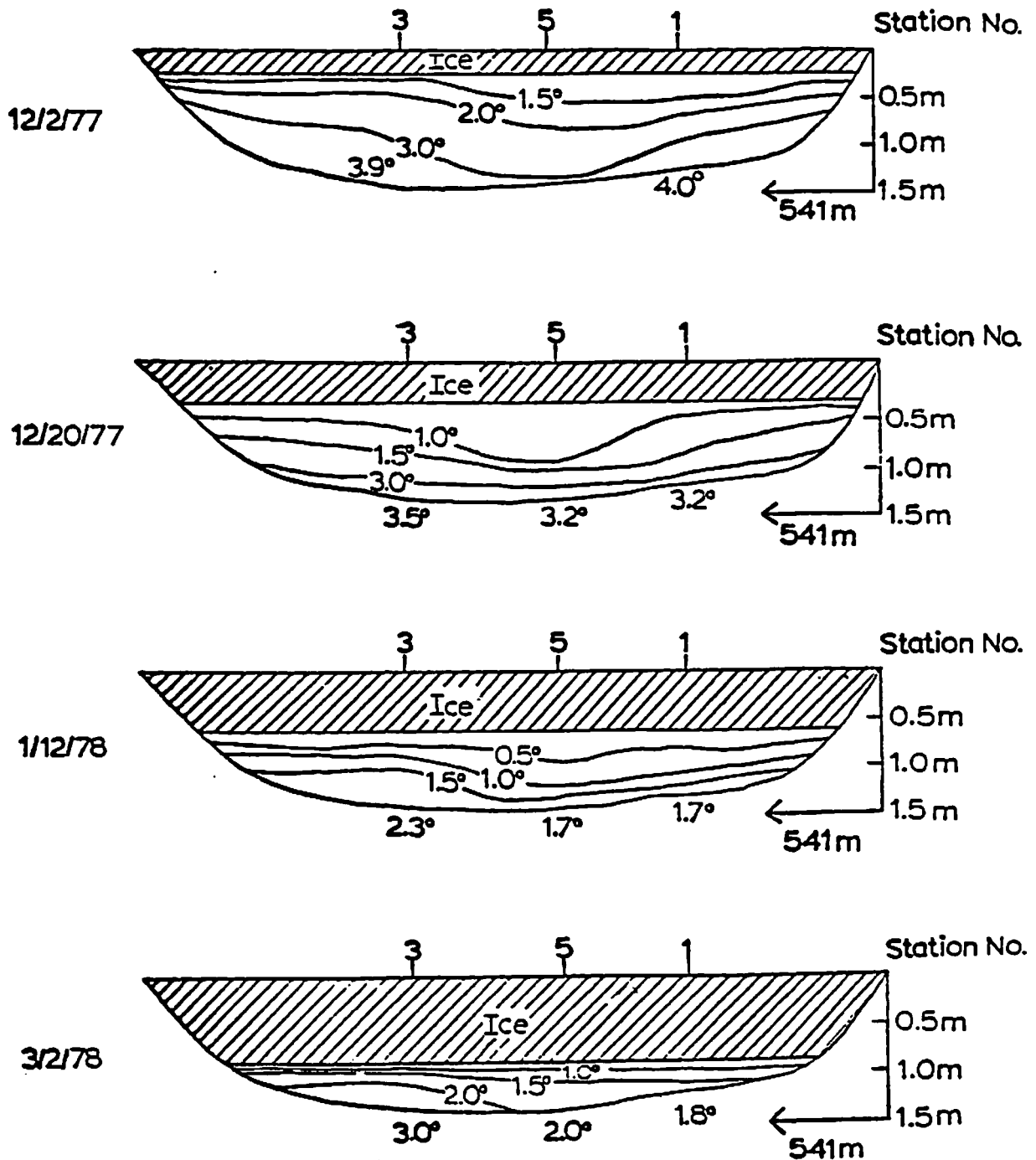
Fig. 6. Profile of Round Lake on a NW to SE axis showing water temperature (C) and ice cover on selected dates, winter of 1977-1978.

as very hard. Dissolved solids, specific conductance, and total hardness all exhibited gradual increases in concentration attributable to the exclusion of ions from ice (Table 2) observed by Gloss (1969). The volume of unfrozen water decreased 81% between 1 December, 1977 and 2 March, 1978. This would explain the maximum percentage increases (based on the initial 2 December sample), in dissolved solids (109%), specific conductance (71%), and total hardness (94%) shown in Fig. 7.

Carbonate alkalinity disappearance after 2 December, 1977 corresponds to the equivalence point (pH 8.3) for the conversion of carbonate ion to bicarbonate ion. The pH decreased from 8.64 to 7.28 as winter progressed (Fig. 8).

The part of the total hardness that is chemically equivalent to the bicarbonate plus carbonate alkalinities present in a water is considered to be carbonate hardness (Sawyer and McCarty 1967). Therefore the increase in carbonate hardness was equal to the bicarbonate alkalinity increase throughout the winter. Carbonate hardness increased from 23% to 33% of the total hardness between 2 December, 1977 and 15 March, 1978. Concurrently the noncarbonate remainder of the total hardness decreased from 77% to 67%. The sulfate ion comprised the majority of this.

In the absence of dissolved oxygen and nitrates,

Table 2. Mean chemical analysis of Round Lake during the winter of 1977-1978 including the corresponding 95% confidence interval

|	12/2/77		12/20/77		1/12/78		1/19/78		2/12/78		3/2/78		3/15/78	
	Mean	C.I.	Mean	C.I.	Mean	C.I.	Mean	C.I.	Mean	C.I.	Mean	C.I.	Mean	C.I.
Dissolved Oxygen (mg/l)	12.0	0.8	10.4	2.4	2.6	0.9	0.5	0.4	0	0	0	0	0	0
Free Carbon Dioxide (mg/l)	0.95	0.5	2.6	0.5	8.4	1.6	11.7	3.2	33	4	56	2	59	3
CO3 Alkalinity (mg/l as CaCO3)	6.1	2.1	0	0	0	0	0	0	0	0	0	0	0	0
HCO3 Alkalinity (mg/l as CaCO3)	159	1	190	2	270	5	295	3	400	16	446	18	443	15
Total Hardness (mg/l as CaCO3)	704	5	771	21	989	24	1021	10	1234	17	1365	13	1330	52
Dissolved Solids (mg/l)	1135	5	1347	22	1703	22	1737	13	2235	151	2369	75	2342	166
Specific Conductance (umhos/cm2)	1460	30	1633	43	1950	57	2067	65	2383	17	2500	60	2470	114
f=Dissolved Solids / Specific Cond.	0.78	0.01	0.82	0.01	0.87	0.01	0.84	0.02	0.94	0.06	0.96	0.02	0.95	0.03
pH (units)	8.64	0.02	8.25	0.1	7.92	0.09	7.79	0.11	7.49	0.02	7.32	0	7.28	0.02
Hydrogen Sulfide (mg/l)	0	0	0	0	0	0	0.2	0.2	6.0	3.2	2.0	0.8	1.9	1.1
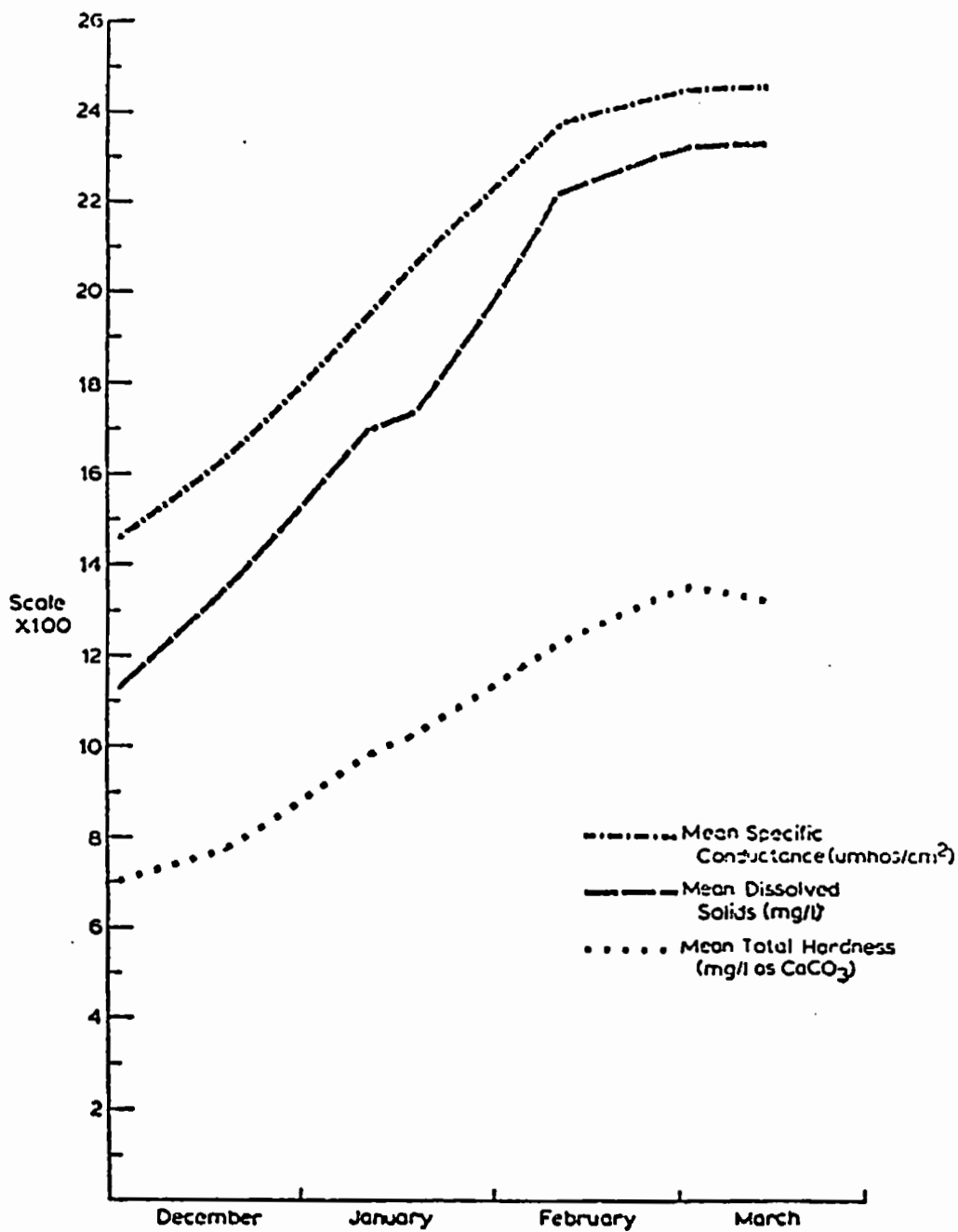
Fig. 7. Comparison of mean specific conductance, dissolved solids, and total hardness concentrations in Round Lake during the winter of 1977-1978.
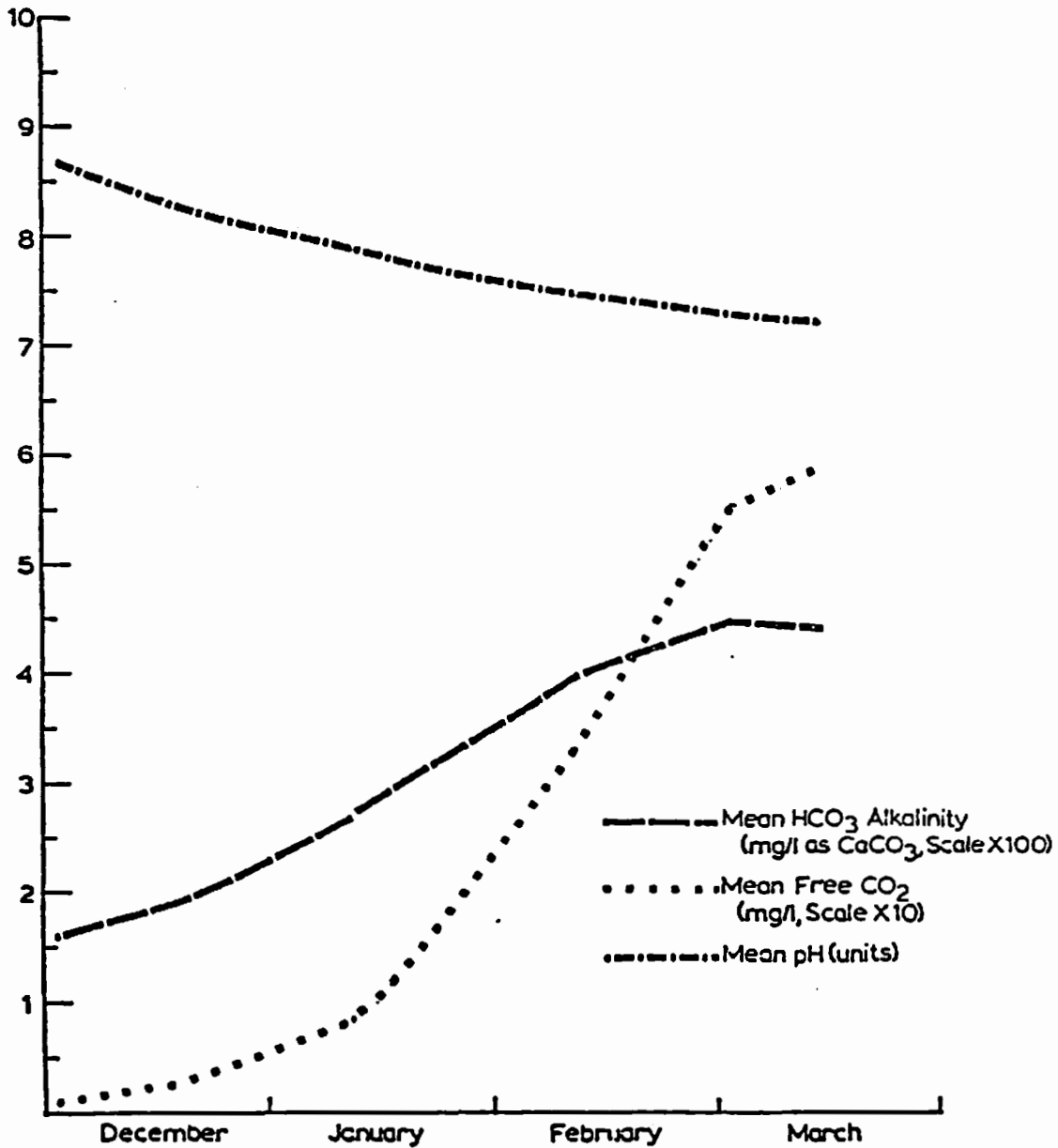
Fig. 8. Comparison of mean HCO$_3$ alkalinity, free CO$_2$, and pH in Round Lake during the winter of 1977-1978.

sulfates serve as an oxygen source for biochemical
oxidations produced by anaerobic bacteria. Under anaerobic
conditions the sulfate ion is reduced to sulfide. At pH
levels below 8.0, the equilibrium shifts toward the forma-
tion of unionized hydrogen sulfide and is about 80% complete
at pH 7 (Sawyer and McCarty 1967). Further, other anaerobic
sulfur oxidizing bacteria oxidize hydrogen sulfide and
deposit sulfur inside the cell.

Another point of interest was the gradual increase
in the factor obtained form the ratio of dissolved solids
to specific conductance (Table 2). This factor which
once determined is usually constant for a given water body,
increased from 0.78 to 0.96 through the winter.

Dissolved oxygen concentrations in Round Lake declined
from a 12.0 mg/L mean after ice formation 2 December, 1977
to nearly anoxic conditions (0.5 mg/L mean) by 19 January,
1978. After 19 January, the lake was anoxic until ice
breakup. In accord with dissolved oxygen decline and
disappearance, hydrogen sulfide gas formation was first
detected 19 January, reached a mean maximum (6.0 mg/L)
12 February, then declined to 1.9 mg/L before ice break-
up (Fig. 9).

A severe winterkill occured in Round Lake during the
1977-1978 winter. Highly reduced anoxic conditions pre-
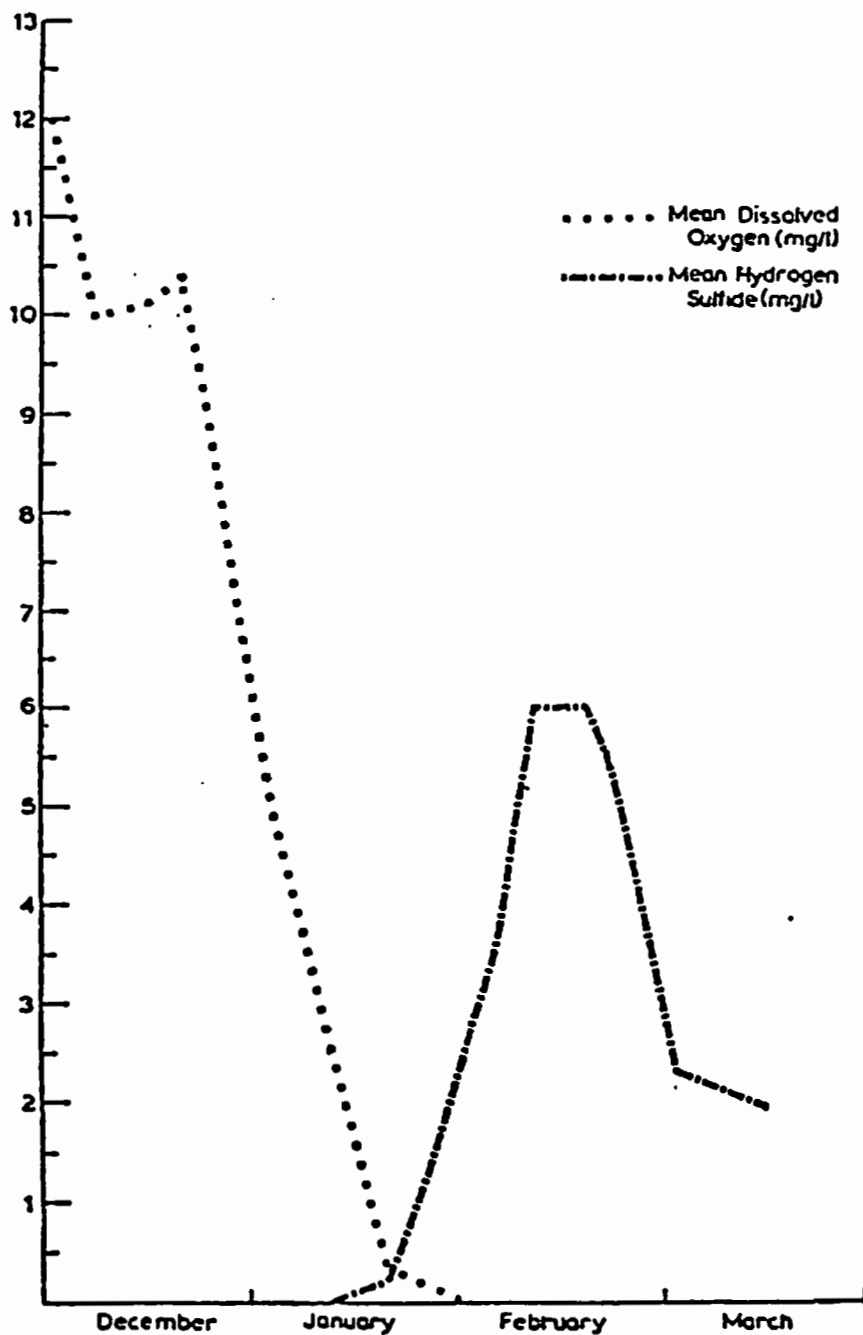dominated in the lake from 12 January to late March, and

Fig. 9. Comparison of mean dissolved oxygen and hydrogen sulfide
levels in Round Lake during the winter of 1977-1978.

concentrations of dissolved gasses toxic to aquatic
organisms (carbon dioxide, hydrogen sulfide, and ammonia)
reached high levels. Mortality to aerobic aquatic organisms
was assumed complete. Even so, sampling on 9 March, 1978
revealed the presence of a live chironomid larva.

Biological Interactions

The results of the diel oxygen method (community
metabolism) are shown in Fig. 10. The results by date
are presented on a lake mean basis in terms of community
respiration (CR), gross photosynthesis (GP), and a ratio
of photosynthesis to respiration (P/R). CR varied during
the study period from an initial high (1.4 mg O_2/L/24 hrs.)
1-2 December, to a low (0.1 mg O_2/L/24 hrs.) 11-12 January
1978. Only 1-2 and 20-21 December, did the P/R ratio exceed
1.0 indicating net increase in dissolved oxygen during the
24 hour period. On other sampling dates the P/R ratio
was below 1.0 and dissolved oxygen decline occured until
after 22 January, 1978 no oxygen was detected.

Oxygenation experiment 1, 14 January, 1978 increased
the indicated rates of CR and GP in the immediate oxygenation
site (Fig. 10). However the P/R ratio was still below 1.0
with a resultant net decline over the 24 hour period in
dissolved oxygen. Because the 4 hour oxygenation period
preceeded the community metabolism determination on this
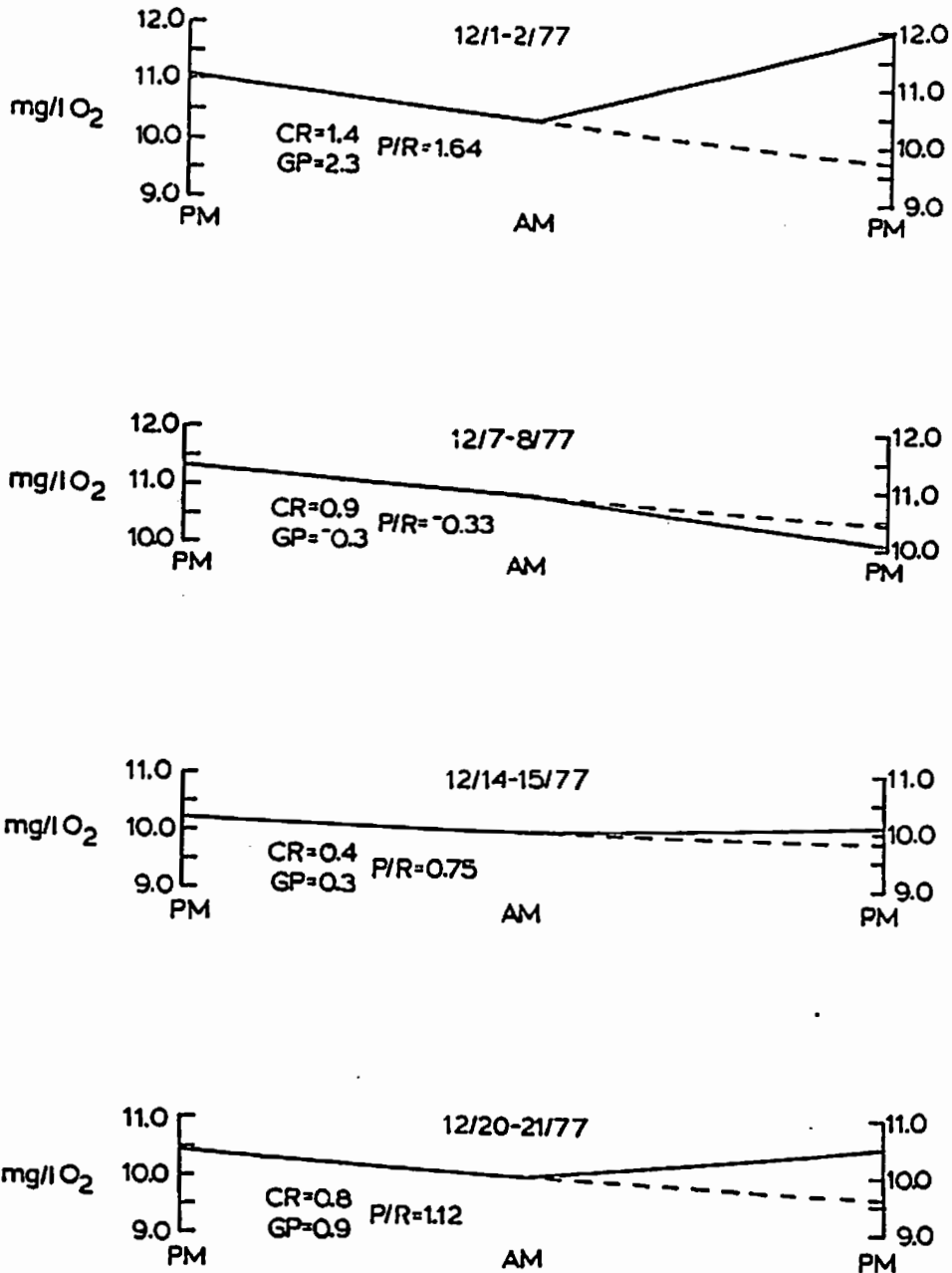date, the values were not indicative of the levels which

Fig. 10. Mean lake community metabolism by date in
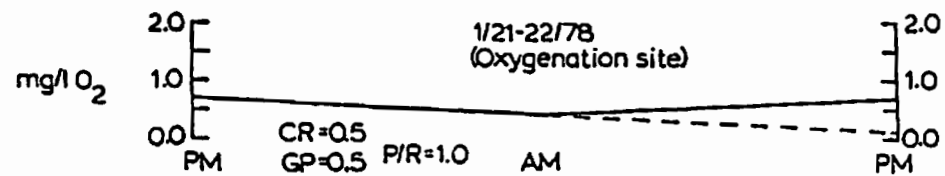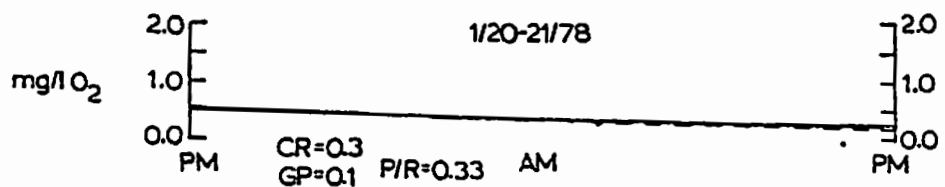Round Lake, winter, 1977-1978.
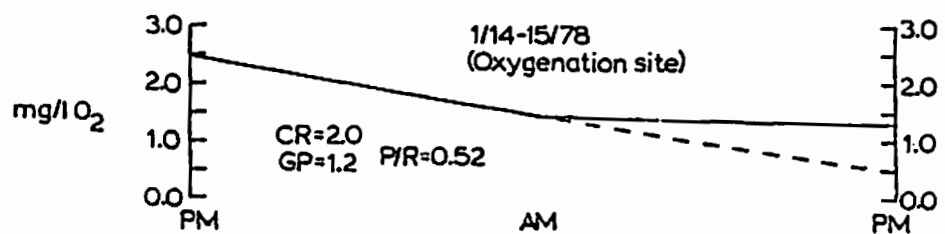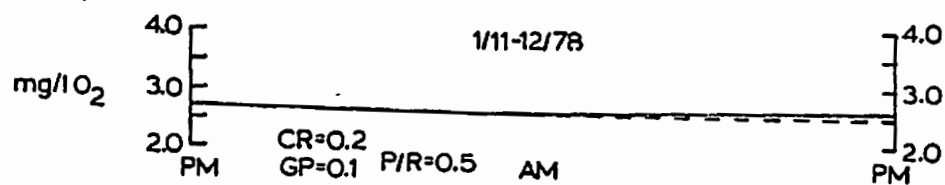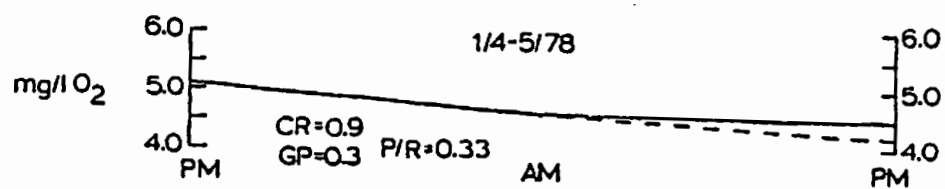
Fig. 10. (continued)

would have been obtained had the oxygenation continued throughout. The community metabolism determination was however a measure of how rapidly oxygen in reaerated water would decline. The P/R ratio after oxygenation was practically unchanged from the mean lake ratio obtained earlier, 11-12 January and would indicate that oxygenation had little effect.

Oxygenation experiment 2, 21-23 January, 1978 slightly increased indicated CR and GP in the immediate oxygenation site (Fig. 10). The 1.0 P/R ratio indicated that GP relative to CR was stable. In experiment 2 oxygenation continued for 48 hours throughout the community metabolism sampling period. No net gain in dissolved oxygen occured after 24 hours. Compared to oxygenation experiment 1, CR and GP rates were reduced. By 21 January, 1978 oxygen demand in the lake water may have been sufficiently high that it was not possible to reaerate enough to effect a meaningful determination of CR. Edberg and Hofsten (1973) found reduction in oxygen consumption with decreasing oxygen concentration. Studies by Hargrave (1969) demonstrated decreased oxygen consumption when dissolved oxygen concentrations fell below 8.6 mg/L. Consequently, during this period measurement of CR by the community metabolism method could have been significantly affected by the low dissolved oxygen values.

Some differences in CR rates between stations (Fig. 11) were noted on each date, but no pattern developed from which inferences could be drawn. The amount of variation could be accounted for by error introduced in the sampling technique. It is also possible that CR at different sample stations was subject to variation. However, the difference between stations shown in Fig. 11 on 20-21 December, 1977, is suspect and probably attributable to sampling error. In general, CR values declined during December, increased slightly during the first week of January, then declined again during the balance of January.

The effect of oxygenation experiment 1 on CR at each sampling station in the oxygenation area is shown 14-15 January (Fig. 11). In addition, little effect by station (within the oxygenation area) on 21-22 January is shown for oxygenation experiment 2.

When dissolved oxygen in Round Lake was depleted, it was necessary to abandon the community metabolism method and obtain water respiratory oxygen demand measurements by the BOD method described in American Public Health Association (1971). The BOD determinations are shown in Figure 12 from 12 February through 22 March, 1978. Initially both light and dark bottles were used to determine if any oxygen production was evident in the water. The results indicated no difference between light and dark bottles. Consequently
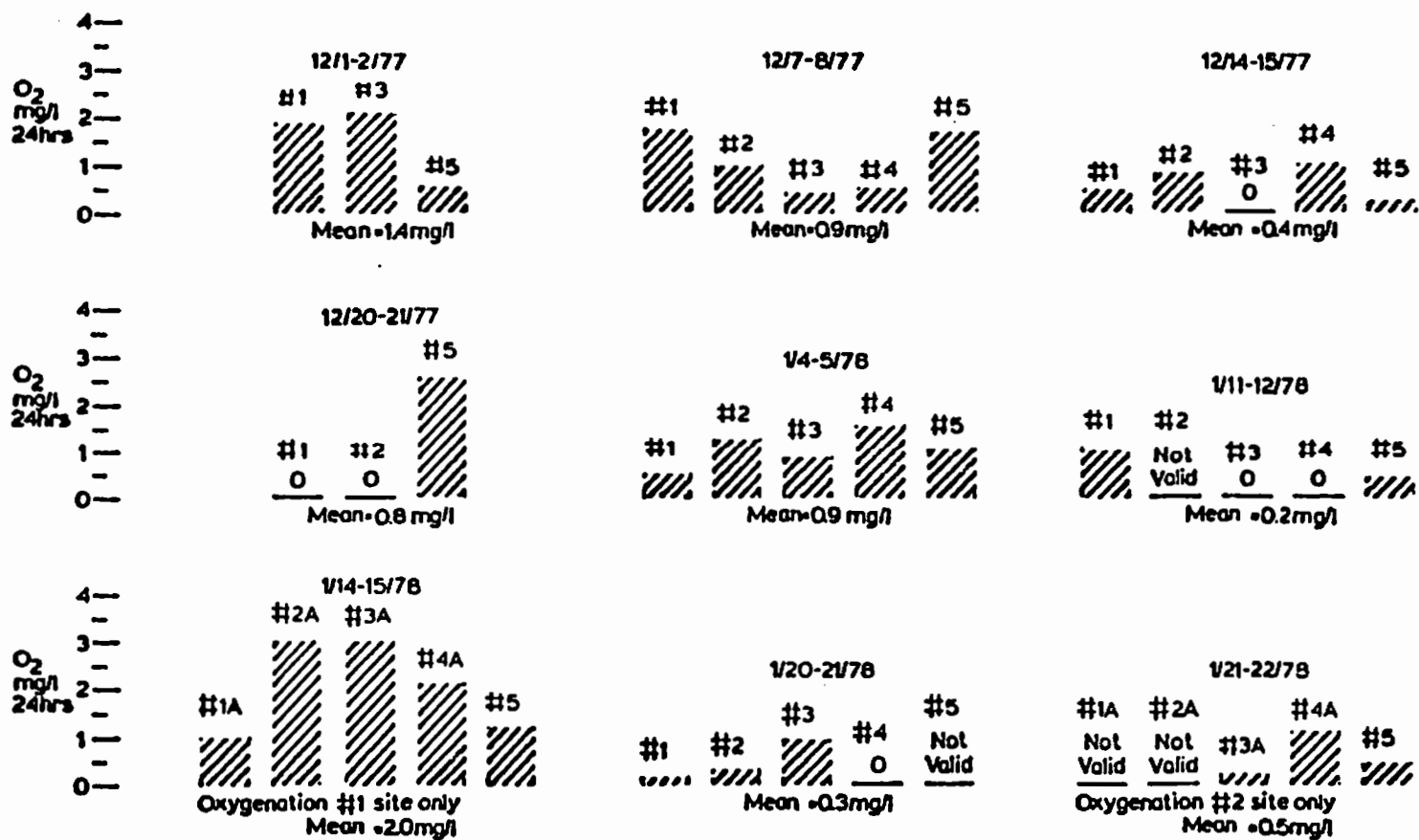
Fig. 11. Total community respiration at each station on Round Lake by the community metabolism method.
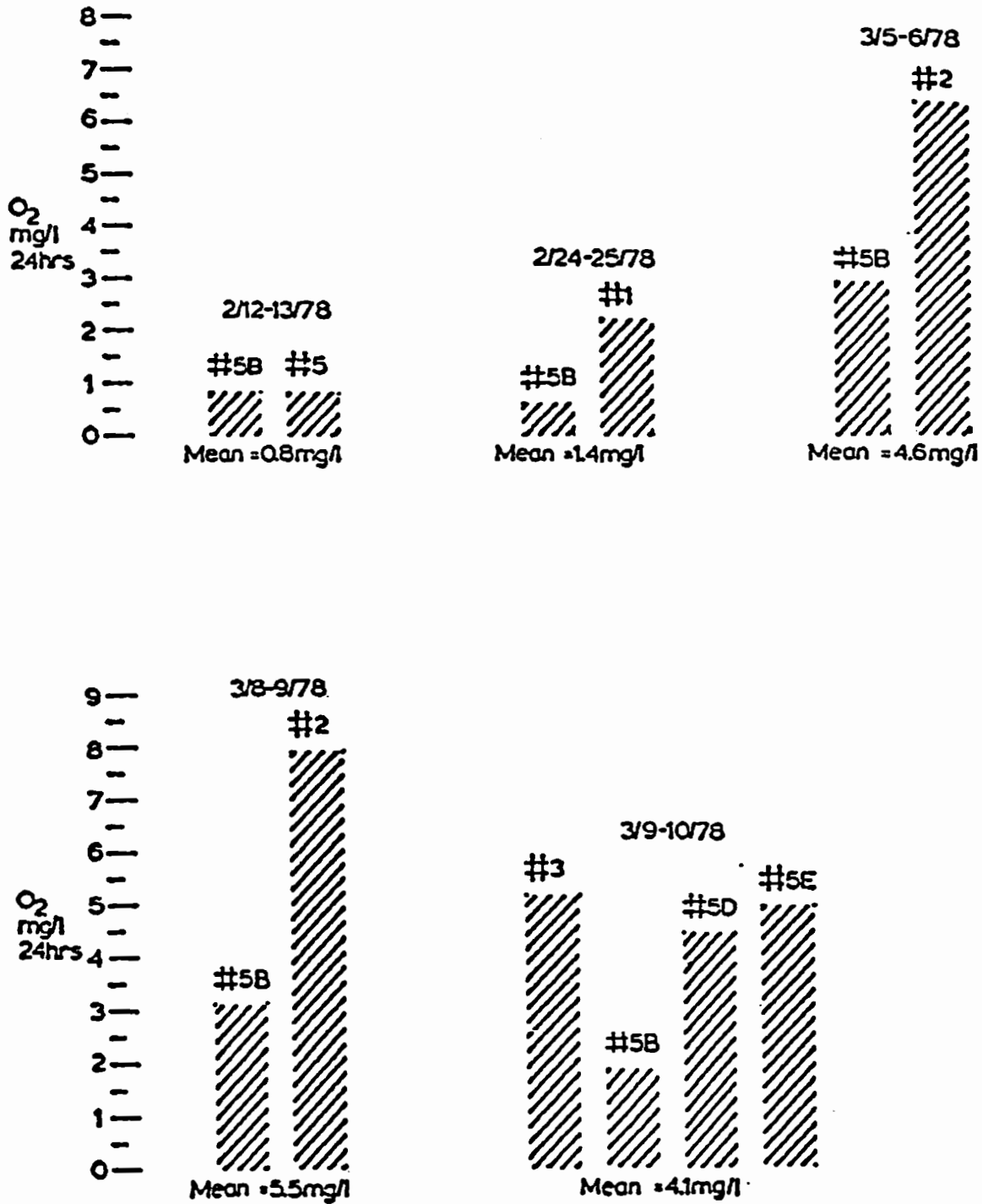
Fig. 12. 24 hour lake water BOD by date at selected stations on Round Lake, winter, 1977-1978.
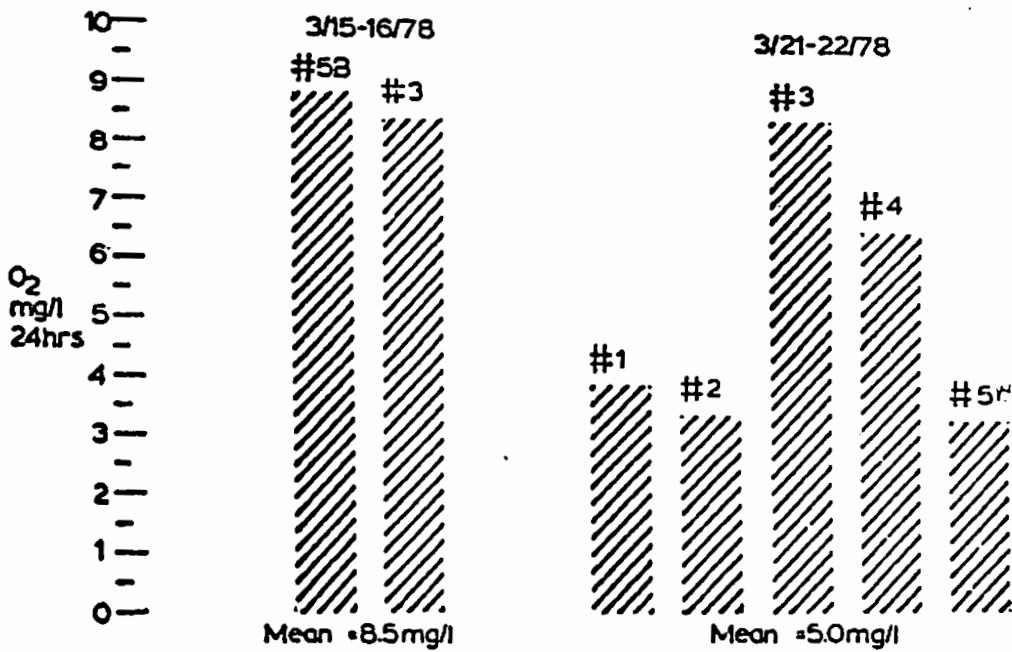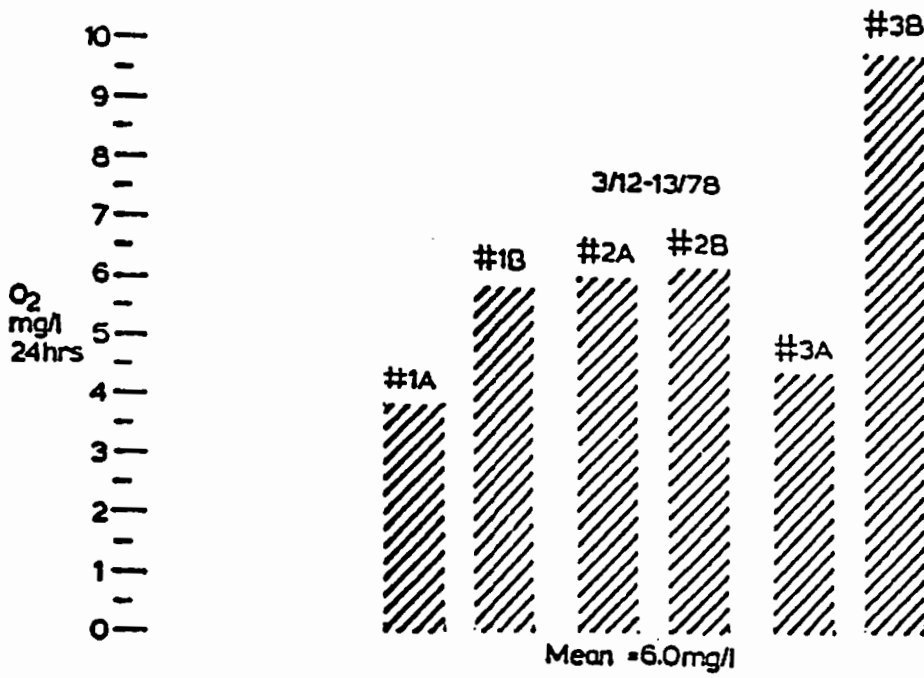
Fig. 12. (continued)

determinations were made only of BOD. Johnson (1960)
in his study on Christie Pond in Brookings County, also
found no difference between light and dark bottles sus-
pended under the ice during winterkill.

Water samples 12-13 and 24-25 February, 1978 were
not diluted. The BOD determination 5-6 March, 1978 was
made with water diluted 45% and samples after that date
were diluted 80%. This dilution was necessitated by
increasing lake water oxygen demand. In the final BOD
calculation, a correction is made for the dilution so all
values in Figure 12 are expressed as undiluted lake water
BOD.

Bottle incubation under the ice instead of the stan-
dard 5 day BOD at 25 C was done to obtain an in site
measurement of BOD. The 24 hour incubation time was chosen
because longer incubation often resulted in complete
dissolved oxygen depletion in the sample bottles. In
addition, removal of the bottles and suspending ropes from
under the ice with longer incubation was difficult due to
freezing of the holes.

The values measured by the undiluted and diluted water
BOD method, are within the range measured by the community
metabolism method. This would lead to the assumption
that measurements of community respiration obtained by

both methods are comparable. The pattern shown through-
out the entire sampling period, revealed that CR values
generally declined to the end of January and BOD values
increased until the middle of March. Johnson (1960),
measuring 5 day BOD, obtained similar results on Christie
Pond. A severe winterkill occurred on Christie Pond
during the study. If the 5 day BOD values he obtained
are averaged into 24 hour values, they are within the
range of 24 hour water BOD values recorded for Round Lake.

The high BOD values in February and March can be
explained by the reduction processes resulting from
bacterial action. These bacteria remove oxygen from the
sulfates and to a lesser extent the phosphates, nitrates,
and other organic compounds. All of these can then be
oxidized in the presence of dissolved oxygen. BOD tests
with anaerobic water and oxygenated dilution water result
in oxygen being utilized in initial organic content
oxidation, in reforming the sulfates, phosphates, and
nitrates, and in oxidation of residues resulting from
anaerobic bacterial action. Oxygen demand of anaerobic
water exhibits an increase in BOD over that expected with
aerobic conditions as a result (Johnson 1960).

Samples taken outside the oxygenation site generally showed gradual increase in BOD until ice breakup. A complete set of samples taken outside the oxygenation site March 21 (Fig. 12), indicated that dilution due to melt water had begun to decrease the BOD in the lake water.

Due to their reductive characteristics and high content of soluble nutrients, the sediments of prairie pothole lakes are the major source of reducing matter causing depletion of dissolved oxygen during the winter (Barica 1974). Edberg and Hofsten (1973) stated that the sediment is of maximal significance for the oxygen balance when the water depth is shallow and the overlying water contains only a minimal amount of oxidizable matter. Hayes and MacAulay (1959) and Hargrave (1972) showed that sediment oxygen consumption could account for all the observed hypolimnetic oxygen deficit in their lakes. A determination of sediment BOD was therefore important to the determination of the total lake BOD.

The alum flocculation modification of the Winkler method was chosen to determine the dissolved oxygen in the sediment BOD bottles because it removes iodine consumption interference in samples high in suspended solids. Ruchhoft and Moore (1940) found that with the alum flocculation procedure there was little interference in the

initial dissolved oxygen determination. In their studies
the results obtained following the alum flocculation
procedure were more reliable and produced closer approx-
imations to the total oxygen demand of the mud under
examination.

The depth to which the lake sediment effects the
dissolved oxygen content in the overlying water is a
matter of conjecture. Edberg and Hofsten (1973) found
that a layer a few mm deep on top of the sediments was
aerobic, but that the reduced products of decomposition
could be transported from the anaerobic zone to the
aerobic sediment and further into the water. Hayes (1955)
showed that almost all activity in the mud is concentrated
in a layer at the surface estimated as less than 0.5 mm
thick. Neame (1975) in his study on Castle Lake, California,
determined that oxidation-reduction profiles usually showed
a distinct minimum at 2-3 cm below the interface. Edwards
and Rolley (1965) found that oxygen consumption was
independent of sediment depth at depths greater than about
2 cm. The results of 24 hour sediment BOD analyses on
Round Lake during February and March (Fig. 13) indicated
that the sediment BOD during the sample period was 10 to
15 times that of the water in the lake.
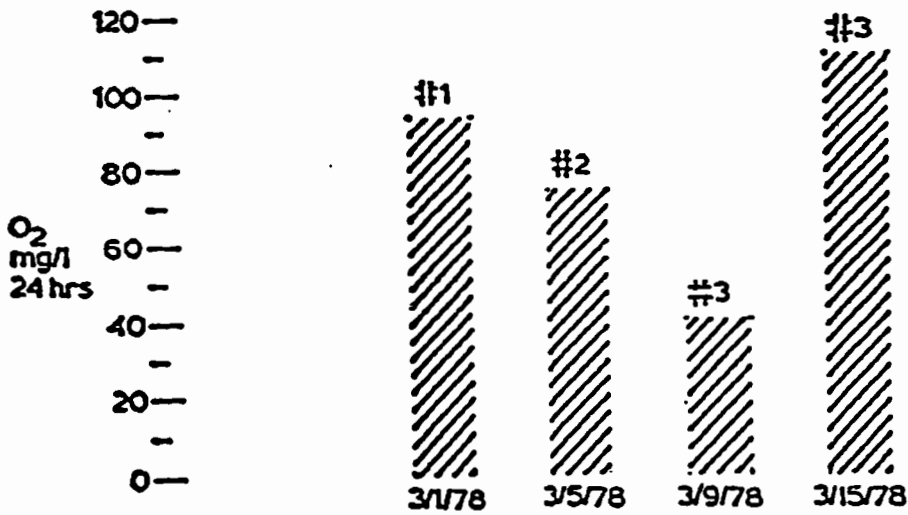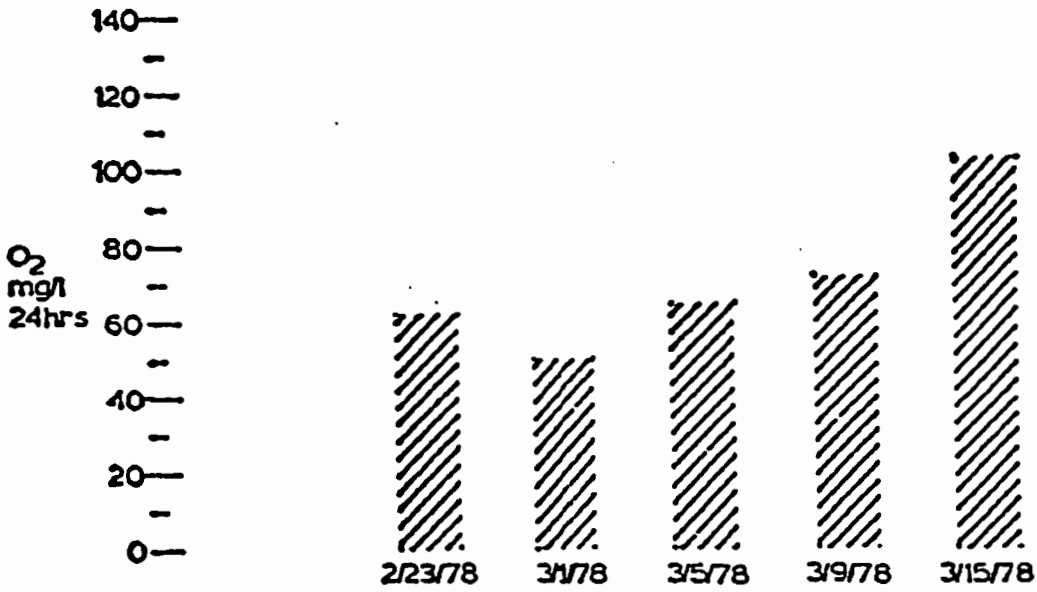
Fig. 13. 24 hour sediment BOD in Round Lake, winter, 1977-1978.
Above: Station 5B by date. Below: Stations 1,2, and 3 by date

Phytoplankton cell counts (Fig. 14) indicated that during ice cover no phytoplankton species was particularly predominant or exhibited any significant increase. Four genera, <u>Ankistrodesmus</u>, <u>Aphanocapsa</u>, <u>Chlamydomonas</u>, and <u>Euglena</u>, were most abundant. Identifiable phytoplankton comprised from 6.3% to 13.0% by number of total cells counted throughout the winter. Mean identifiable phytoplankton numbers increased from 3167/ml 2 December to 6175/ml 20 December, 1977, then steadily declined the duration of the winter to a 1668/ml level 15 March, 1978. It is possible that some of the small unicellular flagellates that predominate under ice cover may have been lost or destroyed due to centrifuging and preservation.

In conjunction with phytoplankton cell counts and utilizing identical sampling and preservation techniques, an evaluation was made of bacteria and aquatic fungi numbers. The results indicated that bacteria and fungi comprised from 87.0% to 93.7% by number of the total cells (phytoplankton, bacteria, and fungi) in the lake water under ice cover (Fig. 14).

Counting and identifying bacteria and fungi is difficult, and many cells probably were overlooked. In addition, identification to genus is tentative. Knowledge of the physiology, biochemistry, and reproduction of bacteria and
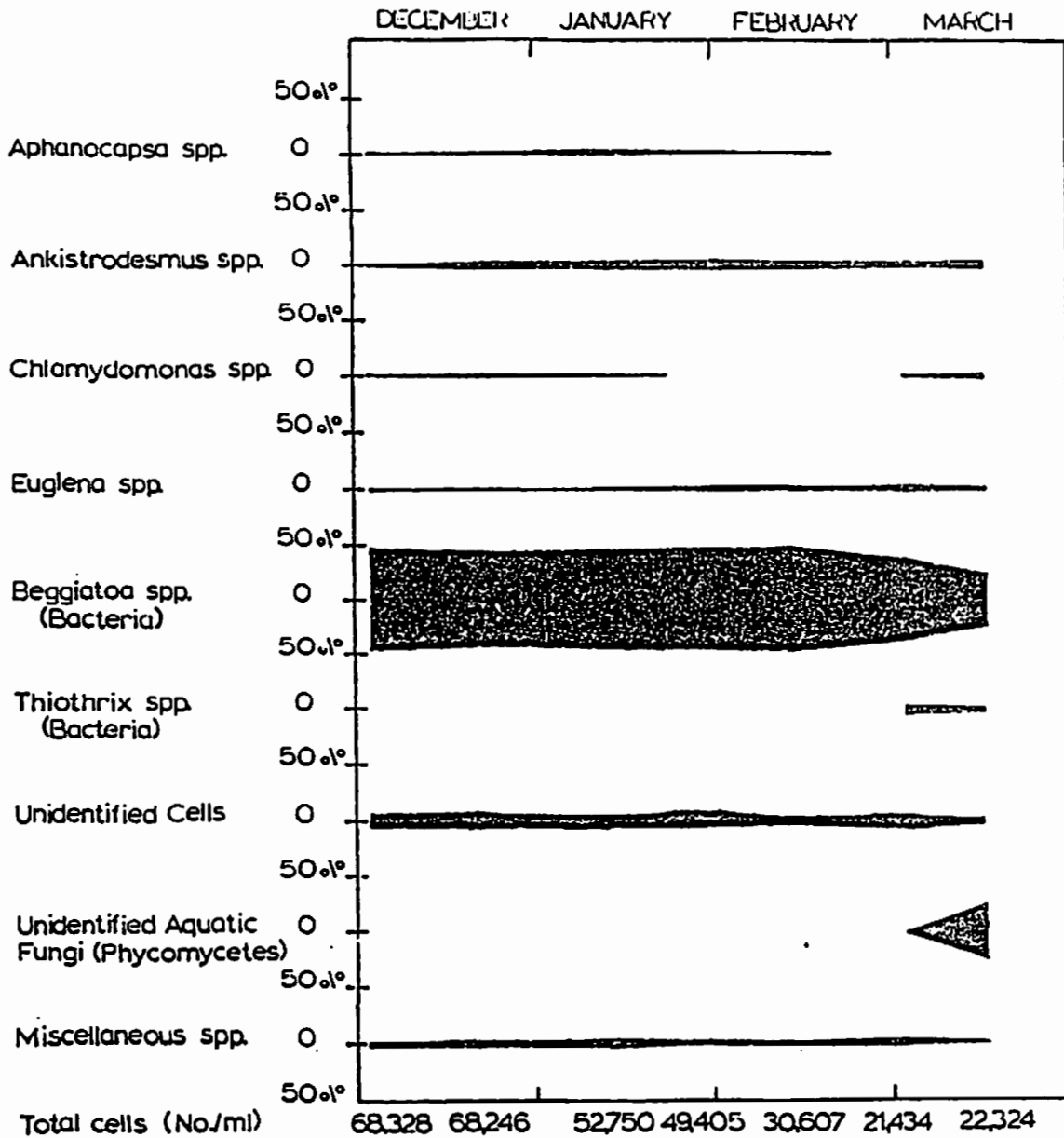
Fig. 14. Plankton percent composition by number of cells, colonies, or filaments, and total cells (no./ml). Miscellaneous genera comprising less than 1% of the population were: Agmenellum, Scenedesmus, Kirchneriella, Actinastrum, Glenodinium, Cryptomonas, Stichosiphon, Micractinium, Melosira, Phacus, Tetraedron, Schroederia, Navicula, and Golenkinia.

fungi is required for positive identification. All identification in this study was done on the basis of morphology and limited knowledge of the physiology of the organism. <u>Beggiatoa</u>, a long filamentous bacterium, and <u>Thiothrix</u> are common bacteria that oxidize hydrogen sulfide with deposition of sulfur intracellularly and occur in areas where hydrogen sulfide is being formed (Wetzel 1975). Many aquatic fungi (Phycomycetes) species are parasitic on algae in the plankton and benthos as well as saprobic on dead organic matter (Cooke 1963), which may explain their presence.

Chlorophyll and plant pigment analysis was conducted as another measure of phytoplankton abundance during ice cover. The decline in mean chlorophyll <u>a</u> concentrations (Table 3) correspond closely with the decline in identifiable phytoplankton numbers. Phytoplankton numbers declined 73% from 29 December to 15 March, 1978, while mean chlorophyll <u>a</u> concentration during the same time period declined 70%. The increase in chlorophyll <u>b</u> concentration may have been related to the slight increase in <u>Euglena</u> spp. numbers. <u>Euglenophyceae</u> have been shown to contain quantities of chlorophyll <u>b</u>, unlike most other phytoplankters (Wetzel 1975).

Table 3. Mean chlorophyll and plant carotenoid levels in Round Lake during the 1977-1978 winter

Date	Chlorophyll a (Mean mg/l)	Chlorophyll b (Mean mg/l)	Chlorophyll c (Mean mg/l)	Plant Carotenoids (Mean mg/l)
12/20/77	46.6	0	5.7	6.0
1/12/78	20.8	0	0	3.2
1/19/78	29.2	0	7.2	6.0
2/12/78	26.0	0.8	5.6	5.4
3/2/78	22.5	0.8	6.0	5.5
3/15/78	14.1	1.9	5.5	3.2

Chlorophyll concentration is often used as an estimator of phytoplankton biomass. However, much of this chlolophyll may be non-active. This could be expected expecially during winterkill conditions. Degraded forms of inactive chlorophyll (phaeopigments) interfere with the spectrophotometric determination of chlorophylls because they absorb light in the same region of the spectrum. Strickland and Parsons (1968) presented a procedure whereby the concentration of phaeopigments could be measured and a correction made for the chlorophyll a determination. This procedure was included as part of the standard pigment analysis on Round Lake, but meter drift after acidification rendered the spectrophotometer absorption readings inaccurate. Consequently, chlorophyll readings should be interpreted as a measure of both the active and inactive fractions.

Oxygenation Experiment 1

The mean dissolved oxygen level in Round Lake 12 January, 1978 was 2.6 mg/L. Two days later, 14 January, prior to oxygenation, the mean dissolved level (from sample sites 1A-4A, and 5) had declined in the oxygenation site to 1.9 mg/L. After 4 hours of oxygenation, a total of 1,200 L of molecular oxygen gas was released at 5 L/min., and the mean dissolved oxygen level (from sample sites

1A-4A, and 5) had increased to 2.4 mg/L. The dissolved
oxygen increase was significant at sample sites 2A, 3A,
and 4A as determined by the Student's $\underline{t}$ test.

To determine how the molecular oxygen effects had
dispersed from the oxygenation site, dissolved oxygen
measurements were taken at the B and C holes; located 3
and 6 m respectively from each air stone. The mean
dissolved oxygen level at both the B and C sampling sites
was 1.9 mg/L. There was a significant decrease at all
B and C sampling sites compared to those in the oxygenation
area (1A-4A, and 5). Therefore, no dissolved oxygen
dispersal was indicated outside the immediate area of
the air stones. The mean dissolved oxygen level (from
sample sites 1A-4A, and 5) had declined to 1.3 mg/L 24
hours after oxygenation. The decline was significant
at all sample sites. From these results and the community
metabolism findings, it was concluded that oxygenation
experiment 1 had little immediate effect and no permanent
effect towards winterkill prevention.

Oxygenation Experiment 2

The mean dissolved oxygen level in the oxygenation
site prior to oxygenation experiment 2, 21-23 January, 1978
had declined to 0.8 mg/L. After 24 hours of oxygenation
at 10 L/min., a total of 28,800 L of molecular oxygen gas
was released and the mean dissolved oxygen level (from

sample sites 1A-4A, and 5) had increased to only 0.9 mg/L.
The increase was not significant at any of the sampling
sites (1A-4A, and 5). After oxygenation for 48 hours at
the same rate no dissolved oxygen could be detected at
any of the sampling sites. There was a significant
decrease at all sample sites.

Test netting conducted during oxygenation collected no
fish. From these results and the community metabolism
findings, it was concluded that continuous oxygenation
utilizing the stone pattern and strategy employed in
experiments 1 and 2 would not be effective in preventing
winterkill. It was evident that BOD of the lake was
exceeding the capacity of the molecular oxygenation
apparatus to reaerate the water.

Oxygenation Experiment 3

The interval between oxygenation experiment 2 and 3
showed dissolved oxygen reduced to anoxic conditions
throughout Round Lake. More stones (6) were placed closer
together than in experiments 1 and 2 to present a more
concentrated oxygenation effect (Fig. 5). Between 1
February and 14 March, 1978, 681,400 L of molecular oxygen
gas was released under the ice. After oxygenation for 72
hours, the mean dissolved oxygen level (from sample sites
5A, 5B, and 5C) had increased to 1.1 mg/L. However, 48
hours later the mean dissolved oxygen level from the same

sample sites had decreased to 0.1 mg/L and no dissolved oxygen was detected in the oxygenation site for the remainder of the experiment. The decrease was significant at sample sites 5B and 5C.

Observations during oxygenation indicated first that oxygen bubbles after ascending to the ice, were immediately migrating to sample holes drilled in the ice and escaping to the atmosphere. An effort was made to allow the holes to freeze over, but the oxygen bubbles invariably kept most of the holes partially open. A green hydrogen sulfide smelling foam was consistently emitted from the sample holes. Sampling at newly drilled holes (5E), 9 March did however indicate from the gas pressure released upon breaking through the ice, that some molecular oxygen gas was being trapped under the ice and retained.

Ice loss above the oxygenation site was not observed until 16 February, 15 days after the initiation of oxygenation experiment 3. Open water did not appear above the oxygenation site until 12 March, 40 days after the initiation of oxygenation. Measurements at the end of all oxygenation 14 March, indicated that ice thickness in approximately 300 m^2 around the oxygenation site was affected. The area immediately above the oxygenation site represented about 45 m^2.

The failure of molecular oxygenation to increase and sustain dissolved oxygen in Round Lake led to comparisons between the oxygenation area and unoxygenated areas of the lake. Water BOD tests conducted during oxygenation (Fig. 12) indicated that BOD outside the oxygenation site was usually more than twice the values at the oxygenation site (5B). The comparison 12-13 February, 1978 indicated no significant difference between the BOD at sample site 5B compared to that outside the oxygenation site at sample site 5. A BOD sample series taken at sample sites 5B, 5D, and 5E 9-10 March, 1978, showed that the BOD increased significantly with distance from the oxygenation site. The same significant BOD increase was indicated from the analysis 12-13 March, 1978 comparing sample sites 1A to 1B and 3A to 3B. Oxygenation experiment 3 was concluded 14 March, 1978. A comparison between sample site 5B and sample site 3, 15-16 March, indicated that within 24 hours after oxygenation no significant difference could be detected. No pattern of BOD decline or increase within the oxygenation site (sampling site 5B) was revealed.

Sediment BOD analyses during the same time period (Fig. 13) demonstrated no significant oxygenation effects. The lowest BOD measured, 9 March, 1978, was at sample site 3, outside the oxygenation area.

Water temperature measurements were taken 2 March,

after 30 days of continuous oxygenation, both in (5B) and
outside the oxygenation site. Fig. 6 summarizes the
temperature stratification and ice cover measurements on
the lake. Since 92 cm of ice covered the lake by this date
it was not possible to take readings at the 0.5 m level.
Mean temperature for the entire lake at 1.0 m was 1.4 C
and 5 cm above the bottom 2.4 C. Ice cover in the oxygen-
ation area by 2 March had decreased to 25 cm at sample site
5B. Temperature readings of 1.4 C at 0.5 m, 1.4 C at 1.0 m,
and 2.0 C 5 cm above the bottom were obtained at sample
site 5B. Compared to the entire lake mean value, these
readings indicated mixing and homogenization of the temper-
ature stratification due to aeration.

On the same date, secchi disk visibility readings
outside the oxygenation site averaged 0.4 m, while the
reading at sample site 5B was 0.3 m, indicating sediment
mixing could be the cause of the decreased light penetration
because the aeration stones rested on the bottom. This
situation was unavoidable, but may have been a source of
increased water BOD in the oxygenation site.

Tables 4 and 5 contain the results of chemical analyses
comparing stations outside and inside the oxygenation site
14-15 March. Spring water was observed flowing into Round
Lake in the vicinity of station 2: thus the analysis at
station 2 indicated melt water inflow.

Table 4. Chemical analysis comparing stations on Round Lake, March 15, 1978

	Station				
	1	2	3	4	5B
Free Carbon Dioxide (Mean mg/l)	63	54	58	60	62
HCO_3 Alkalinity (Mean mg/l as $CaCO_3$)	445	412	454	449	454
pH (Mean units)	7.26	7.32	7.29	7.28	7.27
Hydrogen Sulfide (Mean mg/l)	0.4	0.4	3.5	3.5	1.5
Total Hardness (Mean mg/l as $CaCO_3$)	1340	1227	1375	1362	1345

Table 5. Chemical analysis comparing stations on Round Lake, March 14, 1978

	Station				
	1	2	3	4	5B
Sulfate (SO_4) (Mean mg/l)	1213	1013	1163	1175	1213
Nitrate (N) (Mean mg/l)	0.22	0.22	0.22	0.26	0.26
Nitrogen (NH_3) (Mean mg/l)	18.00	17.00	17.00	18.00	18.00
Nitrogen (Organic) (Mean mg/l)	2.07	1.29	2.51	7.20	2.67
Phosphate (Ortho) (Mean mg/l)	0.14	0.15	0.15	0.12	0.09
Phosphate (Total) (Mean mg/l)	0.34	0.40	0.40	0.49	0.34

Cost-Benefit Discussion

Attempts to prevent winterkill on Round Lake utilizing molecular oxygen during the winter of 1977-1978 were unsuccessful. It was shown however that molecular oxygenation did have an effect in reversing the chemical and biological interactions leading to anoxic conditions.

From measurements of the water and sediment oxygen demand throughout the winter and knowledge of the lake and sediment volume, it was possible to make an estimate of the total lake oxygen demand for the 4 month winter period. Extending the closest measurement time-wise to include periods in which measurements were not taken, would bias the total lake oxygen demand estimation, so it must be remembered that this is only an approximation. The approx-imation was undertaken solely to estimate how much mole-cular oxygen might have been required to prevent anoxic conditions in Round Lake during the 1977-1978 winterkill. It should be noted that the 1977-1978 winterkill was severe throughout the state and consequently would not be indicative of an average winter. The measurements taken were valuable however, in that they approached the worst extreme that could be expected.

The approximate total lake oxygen demand determined in Round Lake for the period from December through March was 1.50×10^5 kg O_2 or 1.05×10^8 L at 0 C and 760 mm Hg

pressure. From these figures and assuming 100% molecular
oxygen gas dissolution into the lake water, the amount of
oxygen pumped into Round Lake would represent approximately
0.7% of the amount that would have been required to satisfy
the oxygen demand and raise the dissolved oxygen level to
5 mg/L.

The total lake oxygen demand (1.05 X 10^8 L) would require
823 Gas Pack 45 oxygen tanks over a 4 month winter period.
At a cost (during the period of this study) of approximately
$85.00 per tank or 46¢/kg of molecular oxygen, this would
represent an indicated total expenditure of $70,000 for oxygen
alone. Speece (1969) indicates that for a 3 month per year
usage the cost of molecular oxygen would be 2¢ to 6¢/kg
depending on the location and quantity used. Apparently, the
cost of molecular oxygen is variable dependent upon the total
amount used and source of supply.

The assumption of 100% molecular oxygen dissolution effi-
ciency is obviously invalid. Speece (1969) investigated use
of molecular oxygen under various conditions and found 100%
oxygen absorption in a 2 mm diameter bubble released in 20 C
water at 30 m. His studies indicated that a 2 mm diameter
bubble released at a 1.5 m depth would have a total oxygen
absorption of about 19%. Since the bubbles released from
the graphite air stones averaged about 2 mm diameter and
the depth in the oxygenation area on Round Lake was 1.4 m,

a total oxygen absorption efficiency of only about 19% may
have been realized. This would consequently increase the
amount of oxygen required for reaeration and the indicated
cost approximately 5 times to $350,000 on Round Lake.

It may be more feasible to create a "refuge" situation
within a larger lake, oxygenating only a limited lake area,
probably the deepest contour. Speece (1969) found that the
deeper a bubble of molecular oxygen is released the greater
the total oxygen absorption into the water before it reaches
the surface. Thus a 2 mm bubble released in 3 m of water,
(such as occurs in East and West Oakwood Lakes) would have
a predicted 33% total oxygen absorption before reaching the
surface.

Much more research is needed in this area. More effic-
ient molecular oxygenation systems such as the downflow
bubble contact system proposed by Speece (1969), and the
side stream pumping system proposed by Fast et al. (1975)
warrant investigation. However, it must be remembered that
oxygenation of any body of water is a "cosmetic" approach,
treating only the symptoms of the disease, not solving
the problems. Eutrophication and sedimentation of prairie
pothole lakes are the primary winterkill causative factors,
and the long term solution is to prevent these factors.

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