VARIABILITY IN WINTER LAKE COVER:
IMPLICATIONS FOR RADIATION RECEIPTS AND OXYGEN
DEFICITS IN TEMPERATE LAKES

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ABSTRACT

The importance of winter lake cover components (snow, slush, white ice and black ice) to underwater short wave radiation receipts is demonstrated. The temporal variability of the winter lake cover is related to the timing and extent of the winter oxygen deficit in a small Canadian Shield lake. In particular, the onset of the linear portion of the oxygen depletion curve is coincident with the first accumulation of snow on the ice surface. Calculations show that removal of snow or its incorporation into white ice can increase radiation receipts substantially; and the use of cover manipulation, especially by artificial slushing of the ice surface is suggested as a management technique in the control of winter oxygen deficits.

INTRODUCTION

At a previous Eastern Snow Conference, Dr. W.P. Adams (1980) presented an overview of the effects of winter cover on biological aspects of lakes, including oxygen and light regimes, nutrient loading and energy balance; based upon a variety of studies undertaken at Trent University, Peterborough, Ontario. Further to that paper, and in keeping with the theme of this conference (Snow and Man), we wish to discuss the relationship between winter lake cover, radiation received by the water column and the winter oxygen deficits of temperate lakes; and to propose manipulation of the winter lake cover as a management tool in the control of winter oxygen deficits.

Winter in temperate climates presents a unique set of conditions for lacustrine production. An ice cover eliminates wind induced mixing often allowing thermal stratification to occur, and photosynthesis is slowed by the reduction in light and by lower temperatures. Diffusion of oxygen to or from the lake surface is eliminated, so that the balance of oxygen in an ice covered lake may be represented by the equation:

$$O = (C + P + F + I) - (B + W + S + L)$$

where

O = total dissolved oxygen content of the lake

C = initial O_2 content at freeze-up

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P = photosynthetic production of O_2

F = freeze-out of oxygen in the formation of black ice

I = contribution of O_2 by inflowing water

B = benthic (sediment) respiration

W = water column respiration

S = loss of O_2 to slushing

L = loss of O_2 in outflowing water.

Although the initial oxygen content of the lake (C) at freeze-up is high (as it follows the period of autumnal turnover), and there is a concentration of dissolved oxygen in surface water by "freeze-out" (F) during ice formation, and often a contribution from inflow (I) depending upon the hydrology of the lake; there is generally a marked depletion of oxygen throughout the winter (O decreases). The initial lake oxygen content plus primary production (P) and inputs (F + I) is usually insufficient to meet the total requirement of respiration (of the benthic community (B) and the open water community (W)) and of water lost as outflow (L) and in upwelling of surface water through cracks in the ice (slushing = S). A period of winter stagnation characterized by depletion of oxygen often prevails and in some cases is severe enough or persists long enough to cause mass mortalities (winterkill) of fish (Greenbank 1945, Halsey 1968, Magnuson and Karlen 1970).

Identification of the factors controlling winter oxygen depletion in ice covered lakes may be of economic importance in the avoidance of winterkill in fish populations and is certainly of value in understanding lake metabolism (Welch 1974; Welch _et_ _al_. 1976).

Recent studies (Schindler 1971a; Welch 1974; Welch _et_ _al_. 1976; Barica and Mathias 1979; Mathias and Barica 1980) have demonstrated with only partial success the dependence of oxygen depletion rates on morphometric variables (including mean depth and lake surface area) and indices of lake trophic status (chlorophyll a, phosphorus, conductivity). Significantly lacking in all those studies has been the adequate consideration of what may be the most important, most variable and possibly most easily manipulated factor in winter oxygen depletion; the role of lake ice and snow cover in filtering short wave solar radiation (400-750 nm).

Most terms in equation (1) are relatively constant (seasonally) for a particular lake. Mathias and Barica (1980) reported that water column respiration (W) is constant and varies little with productive status and similarly that mean sediment respiration (B) is constant in both oligotrophic and eutrophic lakes. The terms C, F, I and L, are dependent upon lake size and morphometry.

There is evidence, however, that under-ice production of oxygen (P) may be variable. While Schindler and Nighswander (1970), Schindler (1971b), Welch and Kalff (1974) and others have reported negligible rates of photosynthetic production of oxygen under ice with significant snow cover, Wetzel (1966) reported nearly one quarter of the total annual primary productivity of phytoplankton during the three months of ice cover at Sylvan Lake, Indiana. Wright (1964) measured an exponential increase in standing crop of flagellated algae under ice cover during a snow free period and noted that a snowfall caused mass vertical movement of most species. Rigler (1978) showed near maximal rates of phytoplankton ^{14}C fixation below maximum ice with an attenuating snowcover in the Arctic, and Schindler (1971a) presented data indicating that phytoplankton photosynthesis continues below a cover of black or clear ice, but drops to undetectable levels under 0.4 m of snow.

While photosynthesis by algae is strongly suppressed by snow cover on ice, "parallel variegated photosynthesis and oxygen production below the ice" occurs in response to patchy accumulation of snow on windswept ice (Wetzel 1975). To date, however, only minimal attention has been given to the role of ice and snow in the winter oxygen balance. Welch _et_ _al_. (1976) estimated oxygen loss due to slushing and Mathias and Barica (1980) discussed implications to the oxygen budget of the effective changes in lake volume during ice formation. Further, these studies have been based only on mean ice cover measurements.

In this paper we will first demonstrate the importance of all components of lake ice cover composition - snow, slush, white ice and black ice layers - and their temporal variability, to underwater short wave radiation receipts. We will then show how this may be related to the timing and extent of winter oxygen depletion and discuss how cover manipulation could influence winter oxygen deficits.

Radiation Receipts

Three lake cover components can be distinguished: snow, white ice and black ice (Adams 1976; Michel 1971). At the base of the lake cover is a highly transparent "black" or "blue" ice layer formed by in situ freezing of the water column. Snow accumulates on this primary ice layer, resulting in its gradual depression and the creation of a positive-relative to the surface of the ice sheet - hydrostatic water level. During periods of large diurnal temperature fluctuations, the underlying layer of ice tends to crack, permitting lake water to flood the surface ("slushing") and to be absorbed by the snow. Refreezing of this mixture of snow and water forms a relatively opaque white ice layer, characterised by ice grains smaller and less organised than those in black ice.

The three cover components differ in their effect on light penetration. By far the greatest reduction in sunlight to the water column occurs as a result of surface reflection, especially over a snow cover. In reviewing the optical properties of snow and ice, Maguire (1975) notes that the albedo of snow may vary from a low of approximately 0.25 for dirty, old melting snow to as high as 0.95 for fresh, new fallen snow. In general, albedo varies as a function of snow density, grain size, grain shape, free water content and the presence of impurities. White ice, because of its characteristic high density of small ice grains has a structure and an albedo similar to that of old snow. In contrast, black ice, because of its large crystal size and arrangement has a high transparence and correspondingly low albedo.

In addition to surface losses, attenuation of solar energy also occurs within the cover components and is usually measured by an extinction coefficient as defined by the relation:

$$I_x = (I - \alpha)e^{-\nu x} = I_o e^{-\nu x} \qquad (2)$$

where

I = total incoming radiation

I_o = total radiation incident at surface after reflective loss

I_x = total radiation penetrating to depth x

α = albedo

ν = extinction coefficient (m^{-1})

x = depth or thickness of layer (m).

Based on equation 2 and a full range of extinction coefficients found in the literature (see Maguire 1975, 1976), Figure 1 was constructed. It illustrates the percentage transmission of light at various depths for a variety of extinction coefficients, and the range of coefficients which apply to the three cover components: snow, white ice and black ice. Although the extinction coefficients for black ice are limited to a narrow range about the value of 2.0, the coefficients for white ice and snow vary markedly. As a result of structural similarities in these latter two components at specific stages of their development or under particular environmental conditions, some overlap also exists in their coefficients. For example, an aged snow cover which has undergone extensive equi-temperature and melt-freeze metamorphism has a structure very similar to that of a white

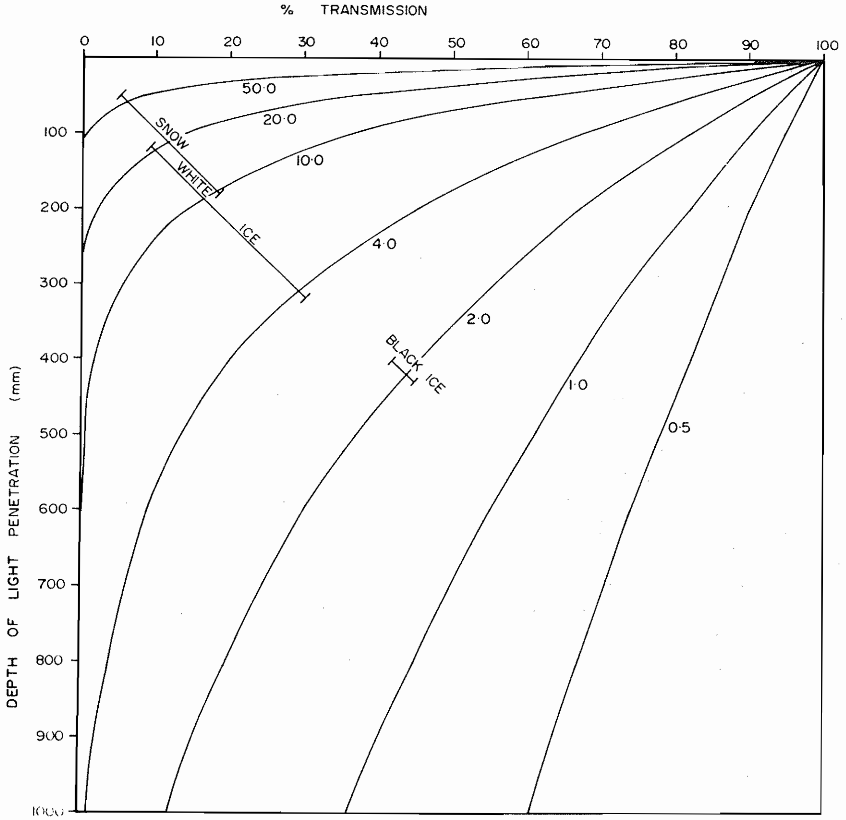

Figure 1. Light transmission (% transmission vs depth; D) at a variety of extinction coefficients (v) based on the transmissivity equation (2) and a range of extinction coefficients from the literature.

ice layer formed by the rapid freezing of snow and lakewater mixture. In general, the extinction coefficient for snow increases as a function of density and grain or crystal size. Similarly, extinction coefficients for white ice are a direct function of grain size and the volume of refrozen water. Hence, a conversion of snow to white ice by the slushing process could only result in a decrease of the extinction coefficient.

In view of the relatively high surface albedos and strong attenuation powers of snow and ice, it is readily apparent that they present a formidable barrier to the passage of solar radiation to the water column. While this may not be significant in high Arctic lakes, where production is low and a sizeable proportion of the cover is black ice, it is in cool temperature lakes where warm weather production is high and heavy snowfalls produce extensive and irregular layers of snow and white ice (Adams and Prowse 1981).

METHODS

In order to establish relationships between the properties of winter lake cover, radiation receipts and oxygen depletion, work was carried out at Coon Lake, Canada (44°36'N, 78°12'W) during the winters of 1975/1976 and 1976/1977. The lake is relatively small 34.6 ha, mean depth 2.9 m, max. depth 18.0 m) and situated on the granite bedrock of the

Canadian Shield. It is characterised by a low flushing rate and is mesotrophic and dimictic. It is located within the Dbf zone of the Köppen climatic classification. Total annual precipitation amounts to approximately 730 mm. Twenty percent of this falls as snow over seven months (from October) although only in five of these months is it normal for the lake to be ice covered.

The winter oxygen depletion rate for the 1975/1976 season was calculated from a weekly series of dissolved oxygen determinations at 2 m intervals from a single station near the deepest part of the lake (18 m) (Stephenson, 1976). Oxygen concentrations were multiplied by the water volume of that stratum, the results summed to give total oxygen content of the lake, then divided by lake surface area to give g O_2 m^{-2} (Welch 1974; Welch et al. 1976). Concurrent with the oxygen sampling and at the same location, single point measurements were made of the thicknesses of snow, white and black ice.

More extensive ice surveys were conducted during the 1976/1977 winter season to ascertain the spatial aspects of the cover components. Weekly measurements of snow, white ice and black ice thickness were made to obtain measures of central tendency and to define spatial distributions. A systematic random grid pattern of 100 individual sample sites was permanently located on the lake. At each site measurements were made with the use of depth probes, ice augers and non-slushing ice devices (Adams and Prowse 1978, 1980). The maximum error of estimate in the thickness of any one cover component was only 15 mm at the 95% confidence level.

The results of a light regime study conducted in conjunction with this research (Adams 1978; Prowse 1978) point to the strong spatial and temporal variations which can exist in the albedo and extinction coefficient of the cover components. However, for this study the complete measurement of variations in these parameters was impractical and logistically impossible. Instead, consistent values for the albedo and extinction coefficient of the three cover components were used in the calculation of radiation receipts. The albedo of snow was set at 0.7 which corresponds to a snow condition midway in the metamorphic progression from 'fresh' to 'old' (Geiger, 1961). As outlined earlier, white ice has an albedo similar to that of old snow and was therefore set at 0.4. A value of 0.2 was used for the albedo of black ice which is similar to that of many other forms of transparent ice and approximately twice that of water (Geiger, 1961).

The extinction coefficients were set as: 10.0 for snow, 4.0 for white ice and 2.0 for black ice. These values correspond to the lower range of coefficients for each cover component as noted in Figure 1. They must therefore be considered as conservative estimates and may lead to the underestimation of filtering effects, especially for snow and white ice.

The calculation of light penetration through a single cover component can be made using equation 2 and values for the surface albedo and extinction coefficient of the particular ice or snow stratum. However when I_x is to be calculated for a multi-layered cover, reflective losses at, and attenuation within all of the cover components must be considered. Unfortunately, little is known about the reflection properties of buried surfaces such as at the snow-white ice, snow-black ice or white ice - black ice interfaces. In the past, most researchers have incorporated such losses in their derivation of surface albedos and extinction coefficients. It is also reasonable to assume that such surfaces do not retain their original surface reflectance properties because once buried within a cover their structure is altered rapidly. Over time such interfaces become increasingly poorly defined and less distinguishable from the surrounding ice strata.

In view of the lack of data concerning sub-surface reflective losses, I_x was calculated for two extreme cases; one in which reflection at buried surfaces was completely ignored and the second using surface albedo values for the buried surfaces. The methods for the calculation of combined transmittance are described in Bolsenga (1981). The values of I_x derived for two cases differed only slightly, primarily because losses from sub-surface reflection were relatively minor in comparison to the much greater losses resulting from surface reflection and attenuation within the thick cover components. The relative importance of losses from sub-surface reflection is expected to be much greater in very thin covers where attenuation is minimized, or in cases where a highly reflective surface underlies one of lower reflectively (such as snow under black ice) although for lake cover, the components are normally arranged in a vertically descending order of reflectivity.

In view of the minor differences between the results for the two test cases, and the fact that some of the extinction coefficients derived from the literature may already account for sub-surface reflection, it was decided to ignore the role of sub-surface albedos in the calculation of I_x.

RESULTS

Cover Development

During the 1975/1976 season four phases of winter cover development were identified on Coon Lake (Fig. 2a). During the first, which lasted from 3 to 24 December, the cover was almost entirely black ice. The second phase was initiated by a snowfall of 40 mm on 24 December and continued as snow accumulated steadily throughout January. The third phase of cover development, involving white ice formation, was temporally variable, the actual timing in any place being dependent upon environmental conditions suitable for slushing and subsequent refreezing. A white ice layer was present on Coon Lake from 5 January to 10 March. Phase 4, characterised by ablation of the ice cover, started on 10 March.

Radiation Receipts

Relative theoretical radiation receipts for columns representing each phase of cover development are shown in Fig. 3. A black ice layer of 250 mm would decrease the net radiation reaching the water column by approximately 40%, relative to open water; 48.52% of total radiation would then still reach the water. The initiation of the second phase of cover formation by the first snowfall increases both albedo and radiation attenuation especially in the case of fresh snow, and decreases net radiation drastically. Assuming a snow depth of 250 mm, overlying 250 mm of black ice (Fig. 3c) I_x is calculated as 1.49% of total incoming radiation (I) incident on the lake.

During the third phase of cover development the snow is flooded and is later incorporated into the layer of white ice. Attenuation of radiation is reduced and I_x increases (Fig. 3d). The difference in the degree of slushing is significant in terms of I_x. Complete flooding of the snow and incorporation into white ice (phase four - Fig. 3c) results in a dramatic increase in I_x; the difference being not only due to the lower extinction coefficient of white ice than snow but also to the marked decrease in albedo.

Based on the thicknesses of the individual cover components and conservative estimates of their respective extinction coefficients, temporal variations in radiation receipts at the water column were calculated (Fig. 2b). As previously discussed, values of I_x remained high during black ice formation, decreased markedly at the time of the first snowfall and then fluctuated during periods of white ice growth and further snow inputs. Only at the end of March, during the rapid ablation of surface snow, did the radiation receipts increase noticeably.

Development of the Oxygen Deficit

Depletion of oxygen began with the formation, at the lake bottom, of an anaerobic zone which progressively incorporated water toward the surface. The rate of oxygen depletion was linear ($0.248\ g\ O_2 \cdot m^{-2} \cdot d^{-1}$) between early January and late March, when oxygen levels increased (Fig. 2c).

DISCUSSION

A comparison of the timing of oxygen deficit and development of the winter ice cover (Fig. 2) shows that initiation of the linear phase of oxygen depletion was delayed until snow had accumulated on the black ice cover (phase two). Values of I_x (radiation reaching x metres) remained high during phase one but decreased suddenly about the time when oxygen depletion first became evident.

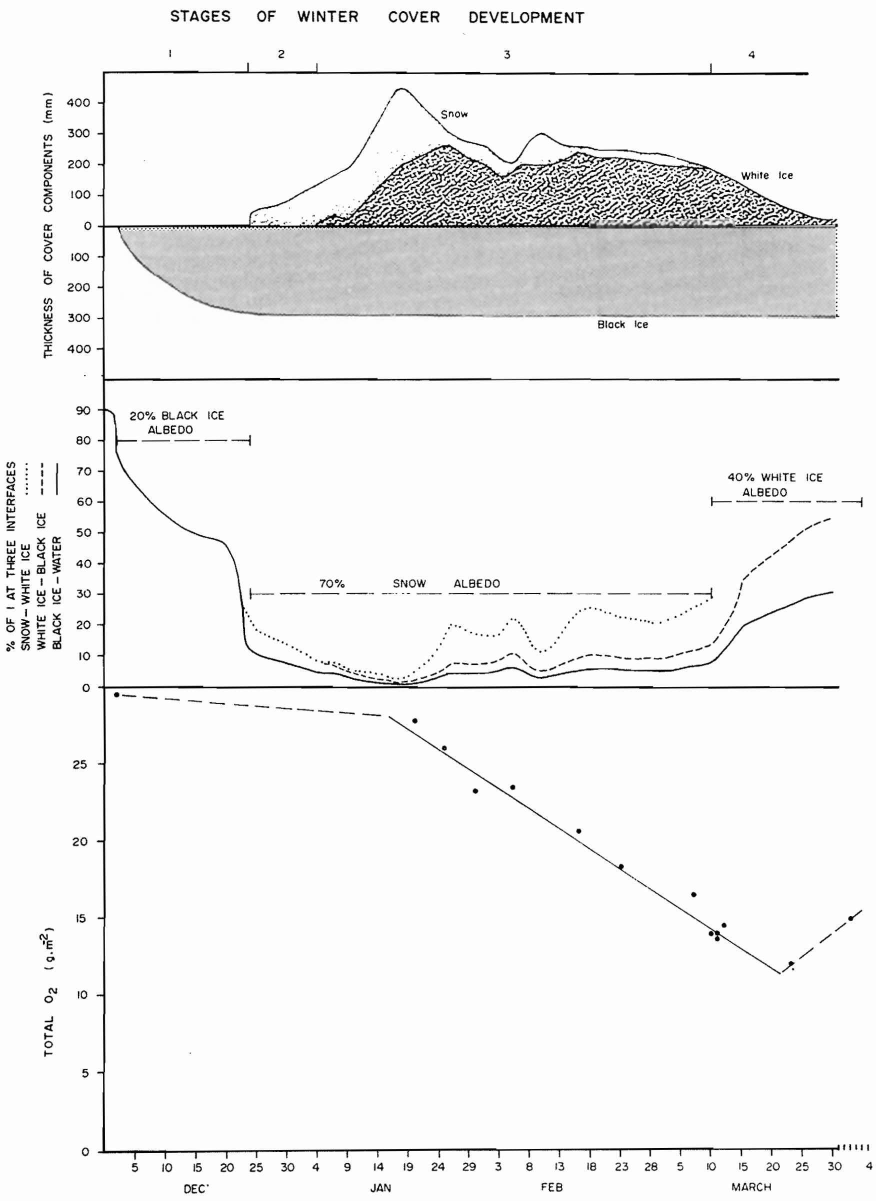

Figure 2. Temporal distribution of cover components (A) radiation receipts (B) and oxygen content (C); Coon Lake, 1975/1976.

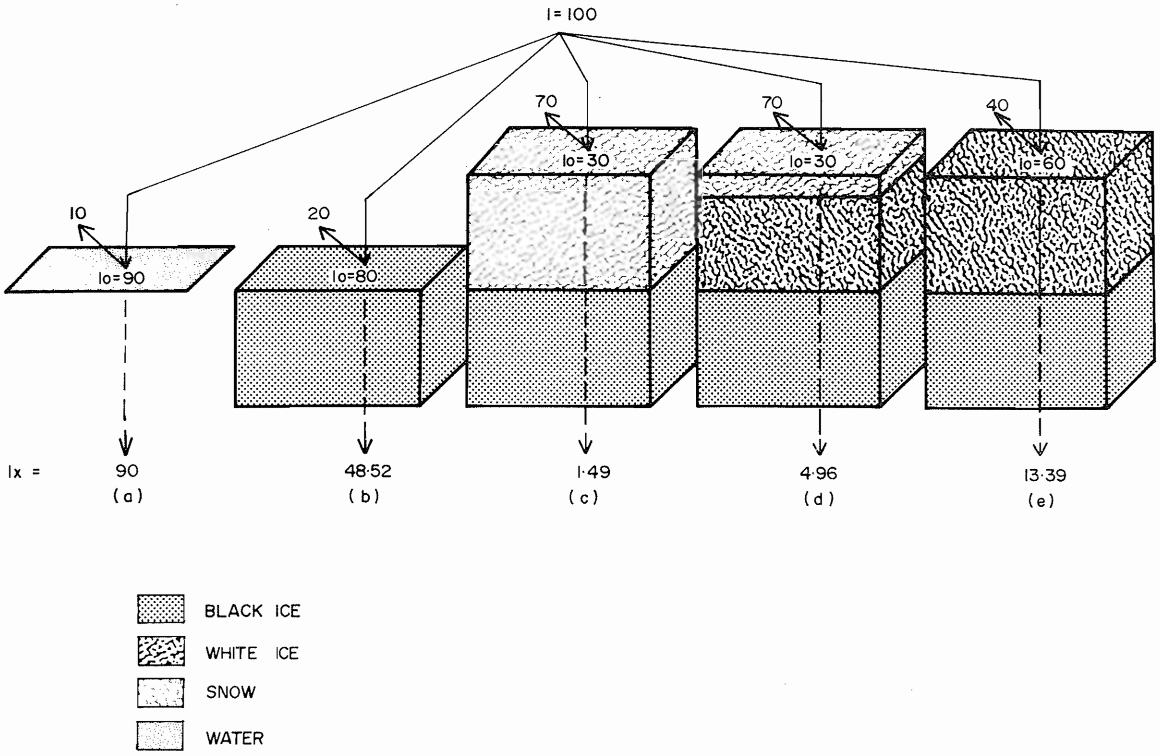

Figure 3. Transmission of total incoming solar radiation (I) through representative stages of winter lake cover. Incident radiation (I_o) is the percentage of the total remaining after reflective loss. I_x is the percent of ^{o}I reaching the water column after additional losses due to attenuation within the cover components.

Fee (1980) discusses the relationship between phytoplankton production and light. Although less accurately predicted at low light levels because production is low and errors proportionately great (Fee 1978) and due to light quality changes (Steeman-Nielsen and Wellemoës 1971, Kiefer and Strickland 1970) it is reasonable to predict that phytoplankton production and therefore oxygen evolution are related to radiation receipts. The apparent relationship between ice cover characteristics, radiation receipts and the timing of the oxygen deficit supports Schindler's observation (1971a) that photosynthesis continues under a cover of black ice but is severely limited by a snow cover.

It is expected that changes within the snow/ice layer, especially white ice formation, which influence I_x would also influence O_2 production. Minor amounts of white ice formation had little effect on I_x when snow thickness was great, as on 9 January (Fig. 2). However, whenever slushing reduced snow depth (as on 26 January), radiation receipts to the water column increased. The computed value of I_x increased from 0.6% on 17 January during just such an event. Additional snowfall (such as on 10 February) did, however, again reduce I_x. We hypothesize that during phase three of cover development (characterized by slushing and white ice formation events) a decrease in the slope of the oxygen deficit curve will occur. Although the available data are insufficient to prove this statistically, they lend support to it. In particular, the slight increase oxygen content at the begin-

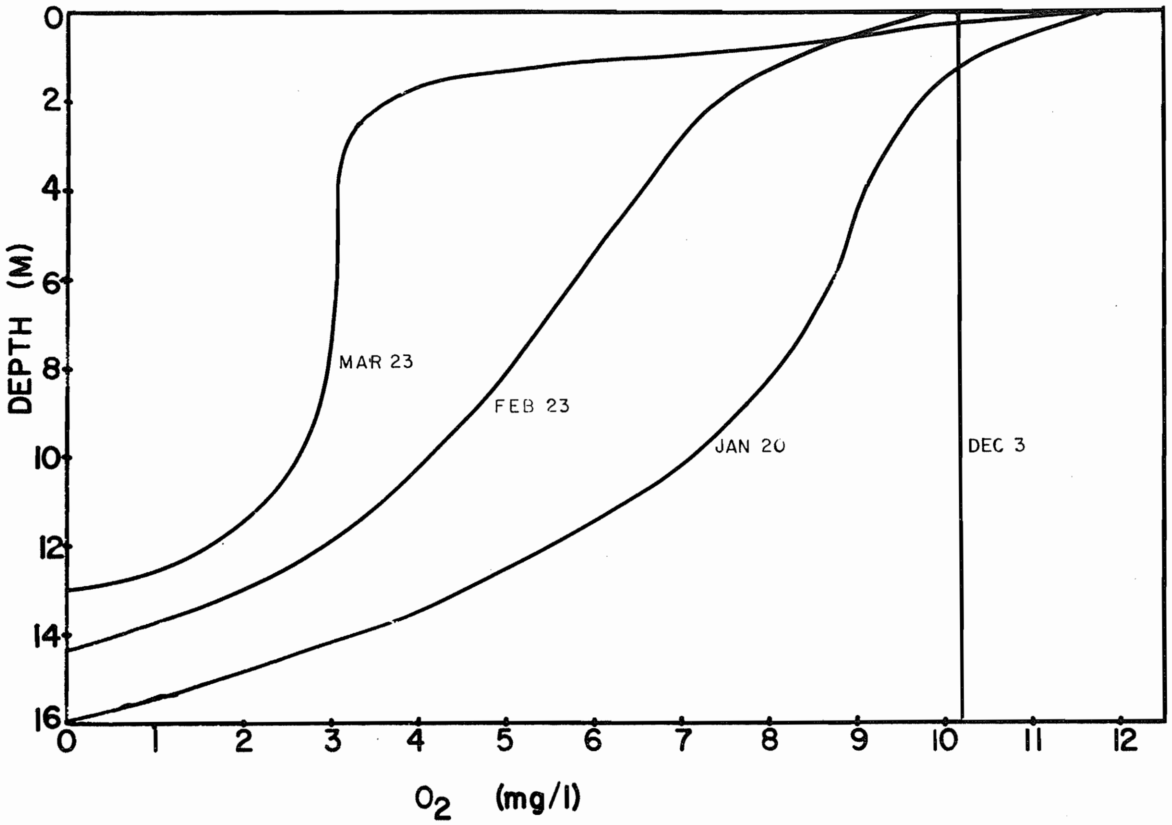

Figure 4. Curves of dissolved oxygen concentration against depth; Coon Lake, Ontario, December 1975 - March 1976.

ning of February may have been attributable to the white ice formation at the end of January.

It appears that the timing and extent of winter oxygen deficit formation may be closely linked to the temporal and morphological variability of the winter lake cover and that the actual timing of the first post freeze-up snowfall is important in initiating oxygen deficit formation. The longer the delay, the lower the risk of the ice cover persisting long enough to reach a critical O_2 content and to cause winterkill.

In the 1976/1977 winter season, on Coon Lake, the first snowfall occurred only ten days after the freeze-up, compared with 21 days in 1975/1976. Fig. 5 demonstrates the large annual variation in I_x which may occur as a result of difference in the timing of ice formation and snowfall accumulation. Years of heavy snowfall or of late break-up of the ice cover might be expected to have lower final values of 0.

As well as a temporal variation in cover composition, a spatial variability has been observed in both sub-Arctic and temperate lakes (Adams 1976, Adams and Brunger 1975, Andrews 1962; Jones 1979). Adams and Prowse (1981) demonstrated an increase in the thickness of snow and ice toward the margins of the lake as well as "downwind" of its major axis. They concluded that, as a result of a 'compensation process' related to insulatory effects, black ice is thickest near the lake centre and in upwind portions of the lake.

Based on the extinction coefficients discussed previously and the spatial distribution of snow and ice on Coon Lake at the time of maximum cover thickness (26 February 1977 - Adams and Prowse 1981), the spatial variation in radiation was calculated (Fig. 6). Low radiation receipts are detected where depths of snow and white ice were maximized;

in many bays, at lake margins and in downwind areas. By contrast, maximum radiation receipts are found in the upwind and central portions of the lake. Localized zones of high I_x values have been noted in field observations as being areas of major slushing events. Locations with low radiation receipts tend to be concentrated in the littoral zone. Although much of the oxygen production is accomplished by phytoplankton, a great deal is normally also produced by rooted vegetation in the littoral zone and the extreme attenuation of radiation in these zones, therefore, compounds the problem of increasing the value of P in the winter oxygen balance equation (eqn. 1).

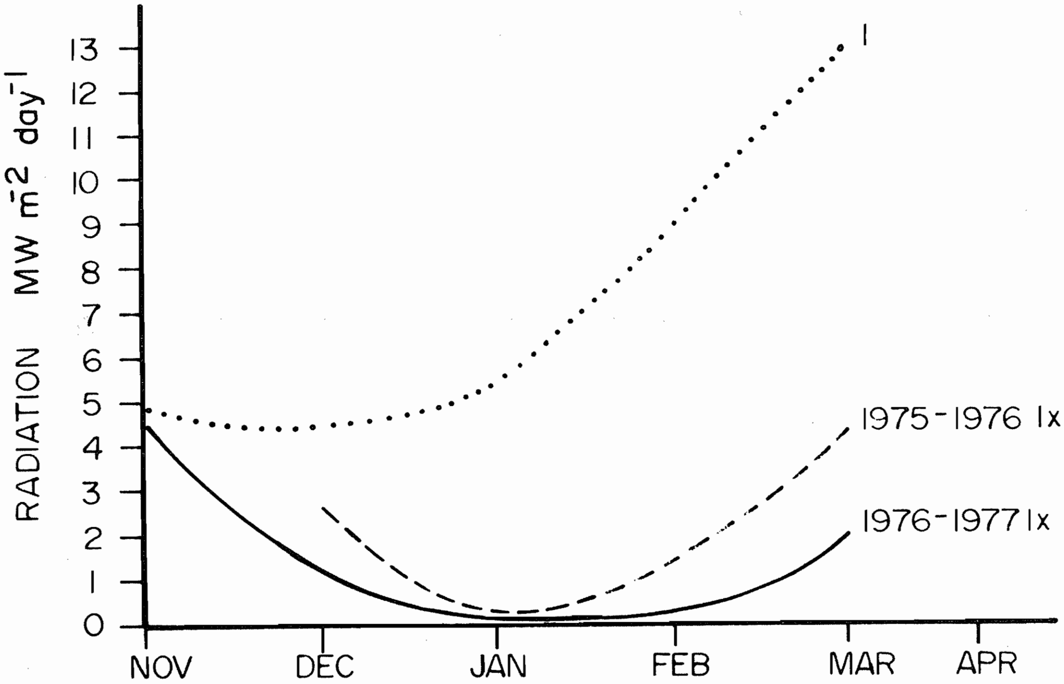

Figure 5. Radiation receipts at the water surface (I_x) and total incoming radiation (I) to Coon Lake during the 1975/1976 and 1976/1977 winter seasons; calculated from mean monthly average radiation and cover component thickness.

Potential for Manipulation of the Oxygen Deficit

It is hypothesized that production of oxygen (P of eqn. 1) may be accelerated by increasing radiation receipts through modification of albedo, cover thickness, cover composition or a combination of all three.

As is evident from Fig. 6, calculated radiation receipts were notably higher in zones of slushing and white ice formation. Clearly, therefore, one method of increasing

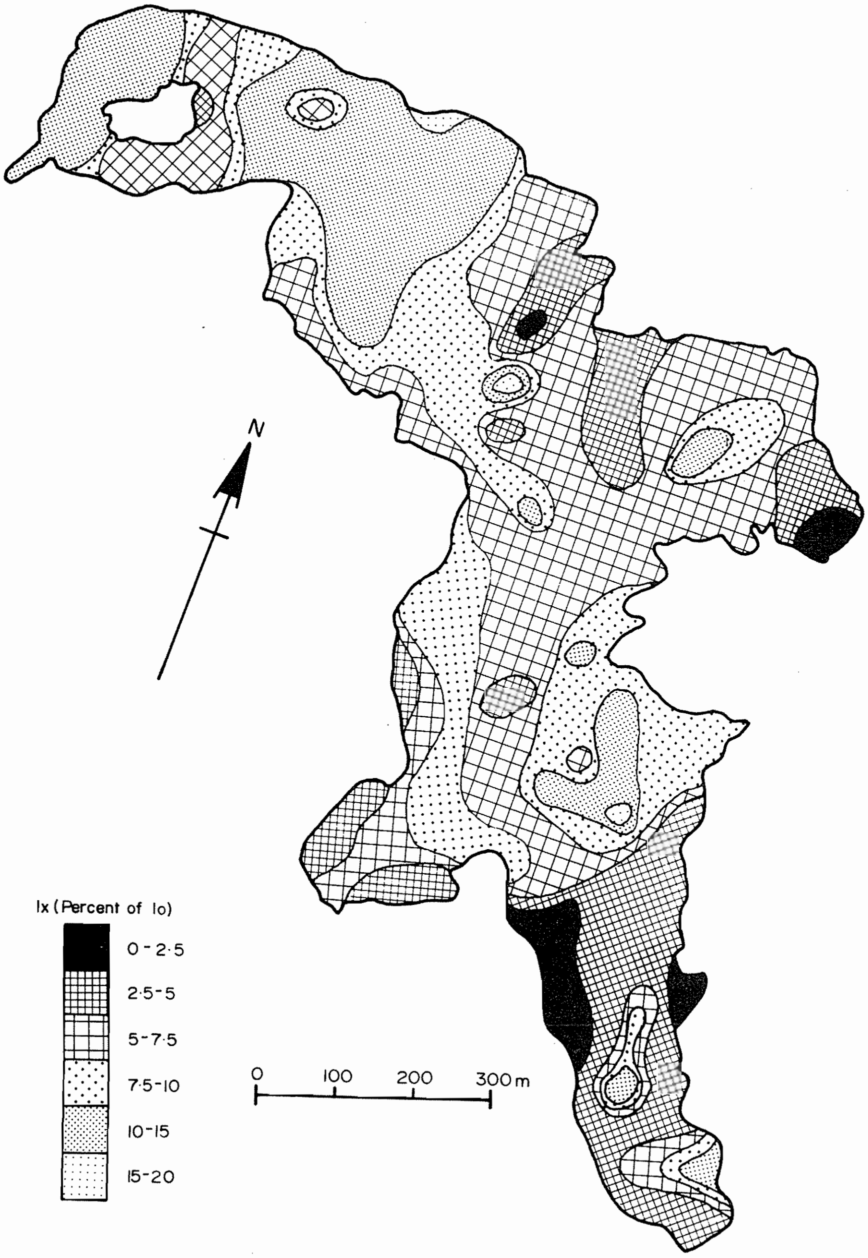

Figure 6. Spatial variation of I_x based on peak ice and snow surveys (n = 102); Coon Lake, 1976/1977. I_x is expressed as a function of I_o, ice and snow depth, and the following extinction coefficients: snow, 10.0; white ice, 4.0; black ice, 2.0. Prevailing wind is from the north-east.

radiation receipts would be to increase the frequency of slushing, especially where the snow cover is thick.

Under natural conditions, the potential for slushing is greatest in areas where there is a positive hydrostatic water level (as a result of snow accumulation). However, thermal insulation provided by the snow cover (Wilson 1941) against major temperature fluctuations which may cause cracking, and the elasticity of the underlying ice are usually sufficient to prevent slushing. These areas normally experience white ice growth only as a result of the horizontal spread of water from other slushed areas.

It is possible, however, to produce slushing in such areas artificially. A single slushing event can be induced simply by drilling a hole through the ice. Thermal erosion serves to keep the hole open until the positive hydrostatic pressure is negated.

The degree of slushing is important in terms of the change in radiation receipts. Fig. 3c, d and e depict the additional I_x receipts resulting from slushing 250 mm of snow to both 200 mm of white ice with 50 mm of snow on top, and to 250 mm of white ice. By far the greatest receipts are from the latter situation because it also causes a decrease in reflective loss.

A number of measurements were made of the areal extent of slushing events in 1976/1977. Commonly these exceeded 75 m in radius (4000 m^2) after only two or three days. Based on one such event occurring in January (incident radiation = 5.43 MJ m^{-2} d^{-1}) the radiation receipt at the water column (Fig. 3c to 3d) could be increased from 324 to 1077 MJ d^{-1} over the 4000 m^2 slushed area. Similarly, if the entire depth of snow cover over the area was transformed to white ice the radiation load would increase to 2908 MJ d^{-1}.

A more costly method of modifying cover composition, and hence increasing the radiation penetrating the underlying column involves mechanically removing the snow. Removal of snow from 4000 m^2 would increase radiation at the water column to over 10539 MJ d^{-1}. (Fig. 3c): an effect greater than that for the slushing method. Snow clearing as an intervention routine would have to be frequent, to annul the effects of subsequent drifting. It would be feasible in areas where snow clearing equipment is already available; the bearing strength of ice being sufficient to allow the operation of heavy equipment in all but the early and late seasons when snow removal is not a necessity.

Curves of lake oxygen content throughout the winter are of two types (Barica and Mathias 1979); U-shaped, with the horizontal section near zero if the lake becomes completely anaerobic; and V-shaped if the ice cover is removed and oxygen content is replenished before anaerobic conditions develop (Fig. 7). Winterkill follows when conditions leading to a U-shaped curve are observed - although its onset is dependent upon the tolerance of local fish species to low levels of oxygen. It may be a regular (i.e. annual) or occasional phenomenon (Barica and Mathias 1979) and is prevalent in small shallow temperate lakes and ponds which support high biomass (Welch 1975).

It is proposed that artificial slushing could be undertaken to modify the shape of the oxygen deficit curve (as in Fig. 7c). The timing of such action is important and would probably have to be done repeatedly, from the time of major snow accumulation until ablation of the snow cover.

The linearity of oxygen deficit formation noted in this study has been noted in other lakes (Welch 1974) and it appears that the rate of winter oxygen deficit formation of a particular lake may be similar each year (Barica and Mathias 1979).

Of the processes contributing to the winter oxygen deficit (eqn. 1), benthic respiration (B) has been implicated as the most important (Hargrave 1969, 1972; Stephenson 1976). Further, it appears as if benthic respiration may be similar for a variety of lake types and conditions (at about 0.2 g O_2 m^{-2} d^{-1}; Hargrave 1973, Welch 1972, Stephenson 1976), and constant throughout the winter (Schindler *et al.*, 1973). Given the uniformity and magnitude of the major loss of oxygen to the sediments (B), it seems reasonable that lake respiration rates should be related to lake morphometry; and a positive correlation has been reported with mean depth (Welch *et al.*, 1976, Barica and Mathias 1979, Mathias and

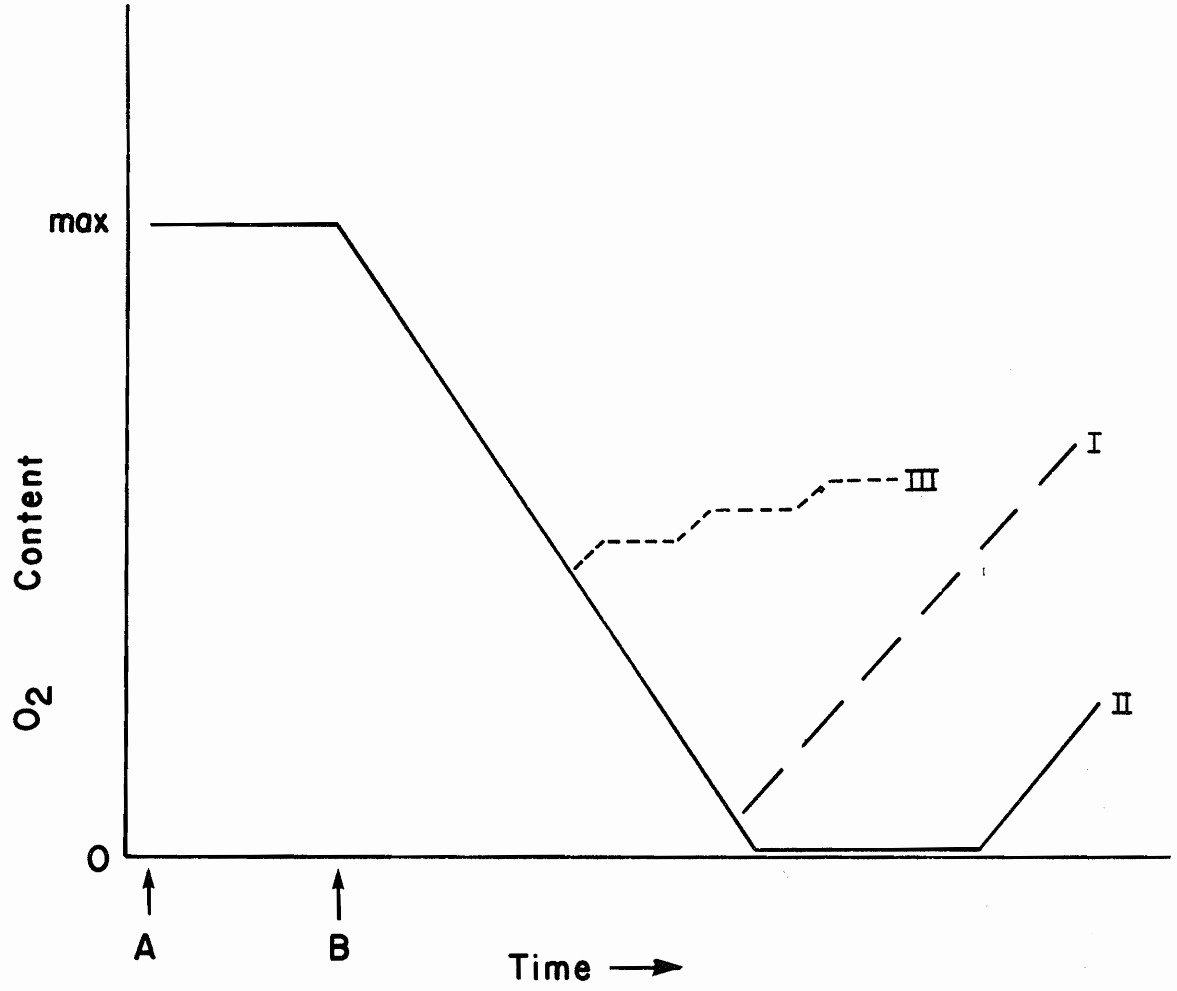

Figure 7. Hypothetical curves of oxygen depletion: I) V-shaped, typical of a situation where oxygen is replenished before the development of totally anaerobic conditions; II) U-shaped, representing total oxygen depletion and the possibility of winterkill; III) a theoretical curve brought about by cover manipulation. "A" represents the time of first black ice formation and "B" marks the onset of snow accumulation.

Barica 1980).

Our analysis of published values of winter lake respiration rate and lake morphometry, reveals that the rate of winter oxygen depletion can be related to mean depth ($\bar{Z}$) for two groups of lakes; those with significant winter flow, and those without. (Fig. 8).

From the time of first major snowfall, an approximate rate of winter oxygen depletion ($R \cdot m^{-2}$ total lake surface area) may be calculated from the equations:

Lakes with flow: $R = 0.01\ \bar{Z} + 0.10$, $R = .760$, $n = 32$ (3a)

Lakes without flow: $R = 0.06\ \bar{Z} + 0.14$, $R = .835$, $n = 10$ (3b)

When combined with a measurement or estimate of the initial lake oxygen content, these equations should allow estimation of the time until possible winterkill; and will provide a guide to the need for, and timing of ice cover manipulation.

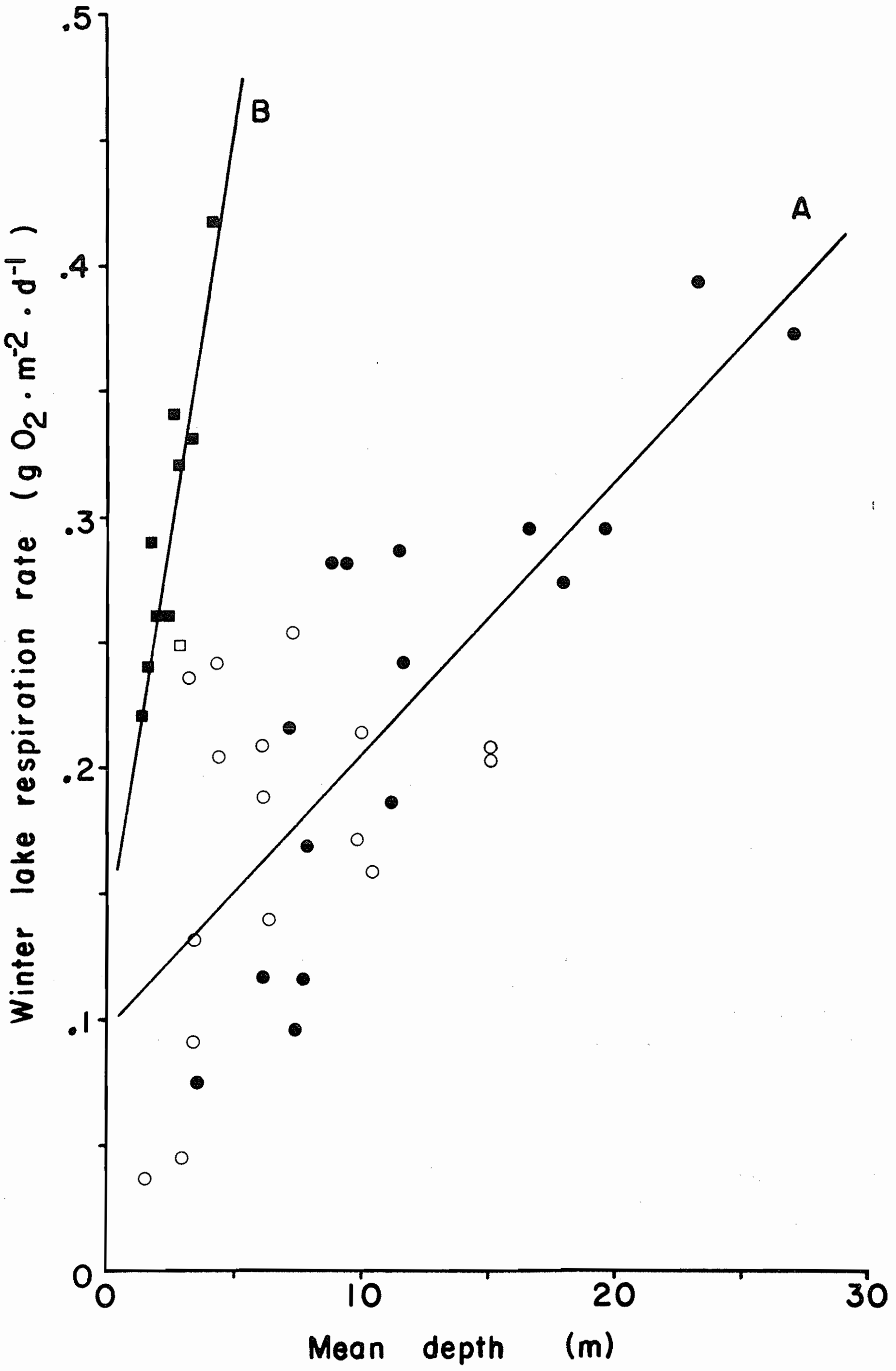

Figure 8. Winter lake respiration rate vs mean depth of lakes a) with (○ from Schindler 1971a; ● from Welch et al., 1976) and b) without (□ this study; ■ from Barica and Mathias 1979) winter flow.

Concluding remarks

The purpose of this paper is to propose modification of winter lake cover as a possible management tool in the control of winter oxygen deficits. We have shown the relationship between cover characteristics and radiation receipts and that radiation can be increased relatively easily by artificial slushing. We have demonstrated that winter oxygen depletion is related to aspects of ice and snow cover; especially that it is linked to the period of snow cover (severe light reduction). We have not quantified the degree of modification of oxygen depletion that may be possible through cover manipulation and suggest this is a necessary and valuable area of further research.

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