

1. PROJECT SUMMARY

Depleted oxygen levels in Lake Erie once resulted in massive fish die-offs and changes in the gross chemistry and biology. Given the reductions in phosphorus loads to the lake and recent invasion by zebra and quagga mussels, it is likely that the sources of primary production within the lake will shift (benthic versus planktonic), and that these changes may influence the lake's oxygen balance. From 1997-98, I measured the distribution and metabolic activity of major algal assemblages (epilimnetic, metalimnetic, and benthic) in the eastern basin of Lake Erie. A total of 100 samples were collected from 16 sites throughout the entire lake (75 water, 25 benthic).

Following thermal stratification, a metalimnetic phytoplankton assemblage developed in the deep waters (15-40 m depth) of all three basins in Lake Erie, and its biomass was significantly greater than epilimnetic phytoplankton (2.70 versus 1.91 mg chl • m⁻³). In the eastern basin, samples collected from lake sediments contained chlorophyll pigments (chlorophyll-a plus phaeopigments); however, only 32% of the samples contained active chlorophyll (8 of 25 samples). Microscopic analysis confirms that viable benthic algae were present in all six samples analyzed (range from 6.8 to 35.2 mg • m⁻²). It is likely these algae are mainly phytoplankton that have settled out the water column; however without further study, it is premature to evaluate their role and relative importance.

Dissolved oxygen concentrations varied 10-fold among the 57 samples taken in Lake Erie from July-October (range 1.35 to 13.26 mg • liter⁻¹). Most of this variation was related to changes in concentration with water column depth, with the low values being measured in bottom waters. In the eastern basin, hypolimnetic depletion rates were similar to those measured during the 1970's (1.6 to 2.2 mg O, liter ^{Month} ~~h~~⁻¹). Therefore, despite the occurrence of substantial metalimnetic phytoplankton and benthic algal assemblages, their metabolism does not appear to offset the rate of hypolimnetic oxygen depletion in the eastern basin of Lake Erie.

2. INTRODUCTION

The eutrophication of Lake Erie gained international recognition, and to this day, references made to the lake typify the concept that excessive anthropogenic inputs can lead to aquatic habitat degradation (Sweeney 1993). Excessive phosphorus loads to the lake promoted phytoplankton growth, which in turn led to degrading habitat quality (algal blooms, reduced water clarity, oxygen depletion of deep waters, fouling of municipal intakes, see Bums 1985). The reduction in phosphorus loads to Lake Erie since 1970 have been credited with a return of the lake to more pristine conditions (Makarewicz and Bertram 1991).

The recent invasion of the exotic zebra (*Dreissena polymorpha*) and quagga (*Dreissena bugensis*) mussels appears to have augmented such desirable changes in the lake's water quality (Nicholls and Hopkins 1993). These changes are likely to impart significant and unique habitat and food web changes in the eastern basin. Current basin-wide estimates for zebra and quagga mussel densities indicate high numbers exist in a limited area in the littoral-zone in the western basin, while the population is distributed throughout the eastern basin (Mills 1993). Mussel water column filtering rates are the highest in the eastern compared with the other basins, despite its large volume (filtering of water in <1 year duration). More recently, the zebra mussels have had measurable effects on water quality in nearshore regions like Saginaw Bay, Lake Huron (e.g., Fahnenstiel et al. 1995) and Lake Erie (Holland 1993); however, their influence on the lake as a whole, is not well understood (Nalepa and Fahnenstiel et al. 1995). Historical data

obtained from lead-210 dated sediment cores retrieved from Lake Erie indicate that benthic and deep-water algal species were abundant in the eastern basin prior to human settlement, and these populations appear to be reestablishing themselves (Stoermer et al. 1996).

P-reduction coupled with the reduction of plankton standing stocks by Dreissenid mussels are important habitat modifications that will likely alter the ecology and biogeochemistry of Lake Erie. Such changes could enhance oxygen production by benthic and deep phytoplankton communities, that in turn could reduce hypolimnetic dissolved oxygen depletion and phosphorus regeneration rates in the basin (see Charlton et al. 1993). In fact, the degree of oxygen depletion in the central basin have lessened (Bertram 1993), although the instability of the water column there and predominant lake circulation patterns can complicate interpretation (Lam et al. 1987).

Given these recent environmental changes in the water quality of Lake Erie, in this report I evaluated whether such changes have altered the structure and function of the lower food web in the eastern basin. The specific objectives of the project were to evaluate: i) the occurrence of a deep phytoplankton community in the metalimnion, ii) the occurrence of a significant benthic algal assemblage, and iii) a lessening of hypolimnetic oxygen depletion. From 1997-98, I measured the biomass and metabolic status of three algal assemblages (epilimnetic, metalimnetic, and benthic), as well as changes in water column oxygen concentrations in the eastern

basin of Lake Erie. Finally, these results were placed within the context of the entire Lake Erie ecosystem through a comparison of all three basins.

3. METHODOLOGY

3A. Study Site

The Saint Lawrence Great Lakes constitute 20% of the world's supply of freshwater (Wetzel 1983). While Lake Erie is the smallest of the five Great Lakes (average depth 19 m) in terms of volume, world-wide, it is the thirteenth largest lake in terms of surface area (26,657km²) and the volume of water it holds (483km³) ranks eighteenth (Herdendorf 1982). Lake Erie supports one of the most productive fisheries in the Great Lakes, whereby the fish harvest each year rivals that taken from all four of the other Great Lakes combined (Beeton 1969; Burns 1985). The lake is an important resource for several major metropolitan areas in the United States (Buffalo, **NY**; Erie, PA; Cleveland, OH; and Toledo, OH; Detroit, MI) and many smaller cities in Canada. Given this, it is not unexpected that none of the other four Great Lakes has been so impacted by human settlement than Lake Erie.

3B. Lake Sampling Scheme

The sampling scheme was designed to assess variation in algal biomass, algal metabolic activity, and water column oxygen concentrations in Lake Erie. Three major levels of variation were assessed: seasonal trends, spatial and temporal trends throughout the eastern **basin**, and trends among all three basins in the lake. During the entire period of study (October 1997- August 1998), a total of 100 samples (75 water, 25 benthic) were collected from 16 sites situated throughout the entire lake (Table 1).

The seasonality of limnological conditions were determined from samples collected at a single, nearshore station (LE-1, depth = 10 m) in the eastern basin off the coast of Buffalo, New York (Fig. 1, Table 1). Twelve sampling cruises were conducted between October 97 to August 1998, that produced information in each of the five thermal periods that are known to characterize the bulk of seasonal variation in the Great Lakes (see Scavia and Fahnenstiel 1987). The periods include, inverse winter stratification (January-March), spring isothermy (April), initial-stratification (June), mid-stratification (July-September) and late-stratification just prior to fall isothermy (October-November). Second, basin-wide variation in algal biomass (epilimnetic, metalimnetic, and benthic) and seasonal oxygen depletion DO in the eastern basin of Lake Erie was determined by sampling 5 sites along a transect extending from Buffalo, **NY** to Long Point, Ontario (Fig. 1, Table 1). The sites were situated at major depth contours in the eastern basin (10, 20, 30, 50, 60 m depth) and were established by the State University of New York as LE-1, LE-2, LE-3, LE-5, and LE-6, respectively. These sites were sampled during both mid-stratification (July) and late stratification (October) periods. Third, lake-wide variation in algal biomass (epilimnetic and metalimnetic) and water column oxygen profiles were determined from sampling at 16 sites situated throughout the entire Lake Erie ecosystem (Fig. 1, Table 1). These comparisons were made from samples collected during the mid-stratification (July 1998) period only.

3C. Sample Collection and Processing

At each lake station, water column profiles for temperature, dissolved oxygen, and conductivity were logged from surface to near bottom using a Hydrolab Surveyor 11. Water samples were collected using Niskin bottles

lowered to depths that characterized the thermal strata in the water column (epilimnion, metalimnion, and hypolimnion). At shallow stations (20 m or less), water needed to be collected from only 1-2 depths in order to characterize the water column. Dissolved oxygen concentrations were determined by transferring lake water directly from the Niskin bottle to duplicate or triplicate 300-ml BOD bottles. The BOD bottles were allowed to overflow three times their volume and were immediately fixed with standard Winkler chemicals (*see* below). Additional lake water was collected and transferred from Niskin bottles into 4-L amber carboys that were stored in a cooler and transported to the laboratory (within 1-4 hours). Once in the laboratory, these water samples were subsequently processed to determine algal biomass (as chlorophyll and cellular carbon) and primary production (see below).

On four dates throughout the year (April, July, October, and November), paired benthic samples were collected with water column samples (see above) using a Ponar Dredge (0.25 m²). The dredge was lowered onto the sediments and representative samples (2-4 replicates) were trapped and retrieved. Once on board, the contents of the dredge were gently placed into a cooler. The sediments were then sampled by collecting 2-3 subsamples using a coring tube (surface area=13.2 cm²), whereby the top 2 cm of sediment was removed, placed into whirl-pak bags, and the bags were stored in a cooler and transferred to the laboratory (within 1-4 hours). Once in the lab, sediment samples then diluted to a known volume with distilled water, and processed to determine algal biomass (as chlorophyll and carbon) and primary production (see below).

3D. Analytical Procedures

Algal Biomass Based on Chlorophyll-a Determinations- Algal biomass was estimated from chlorophyll-a concentrations extracted from water and sediment samples. Duplicate lake water or sediment subsamples were concentrated onto membranes (Whatmann EPM 2000, pore-size = 0.3 μm) and chlorophyll-a extracted in a 50:50 mixture of acetone:DMSO (Shoaf and Lium 1976) without grinding (see Carrick et al. 1993). Chlorophyll-a concentrations corrected for phaeophytin were determined fluorometrically on a Turner 10-AU-005. Coefficients of variation among subsamples were typically < 5%.

Algal Biomass Based on Cellular Carbon Determinations- Algal biomass was estimated from cellular carbon estimates measured from water and sediment samples. Subsamples were analyzed microscopically using a stratified enumeration technique in order to estimate the abundance of algal species within each sample (see Carrick and Schelske 1997). Due to the range in cell size and abundance of the phytoplankton, picoplankton (>0.2 and <2 μm in cell size), and cells in the nano- (> 2- and < 20- μm) to micro- (> 20- and < 200- μm) plankton *size* range were measured separately. Duplicate water or sediment samples were collected and transferred into 125-ml amber bottles for microscopic analyses; the first sample was preserved with 1% glutaraldehyde (picoplankton) and immediately refrigerated and the second received 1% Lugol's acid iodine (nano- and micro-plankton) and was stored at room temperature.

Pico were enumerated using epifluorescence microscopy from slides prepared within 24 h of sampling. Subsamples (~1.0 ml) were filtered onto

pre-stained (irgalan black) 0.2 μm pore size Nuclepore filters and mounted between a microscope slide and cover-slip with immersion **oil**. Slides were stored at $-20\text{ }^{\circ}\text{C}$, and counted within one week to minimize the fading of fluorescence (Carrick and Fahnenstiel 1989). Biomass was estimated by counting a total of 400-500 individuals from two duplicate slides using a Olympus BX-60 Research Microscope (1000X) equipped for chlorophyll-a fluorescence (blue light 450-490 nm excitation and $> 515\text{ nm}$ emission), and determination of phycobilin proteins (green light 530-560 nm excitation and $> 580\text{ nm}$ emission). Dominant pigment fluorescence of individual picoplankton cells was used to assign general taxonomic (phylum) position (Tsuji et al. 1986).

Nano- and micro-plankton were determined using settling chambers (Utermohl 1958) by enumerating 500-1500 cells using a Wild M-40 inverted research microscope. Cell volumes for all taxa were determined by measuring the cellular dimensions of at least 10 cells on two dates. These estimates were converted to carbon using a cell volume to carbon conversion factor developed by Verity et al. (1992). The algal taxonomy applied herein conforms to that outlined by Prescott (1973) making provisions for changes by Rippka et al. (1979) for some of the cyanobacteria; diatoms were identified using Patrick and Reimer (1966) including the modifications discussed by Round et al. (1990). Coefficients of variation among duplicate counts were typically $< 10\%$.

Water Column Dissolved Oxygen Determinations ~~The concentrations of~~ The concentrations of dissolved oxygen in water samples were determined using a modified Winkler technique (see Fahnenstiel and Carrick 1988). Once filled, BOD

bottles were fixed with 2.0 ml of $MnCl_2$ followed by 2.0 ml of alkali-iodide (Carpenter 1965). Bottles were shaken, allowed to settle, then placed in a cooler until titration. Just prior to titration (20-30 mins), 2.0 ml of sulfuric acid was added to each BOD bottle. Whole bottles were then titrated with 0.2 N sodium thiosulfate using a Brinkman Metrohm potentiometric end-point detection system similar to that described by Bryan et al. (1976). Standardization of thiosulfate and blank determinations were performed as outlined in Carpenter (1965). Coefficients of variation among replicate samples were typically $< 5\%$.

Primary Production Estimates- Primary production was measured using a modification of the standard light-dark bottle technique (see Fahnenstiel and Carrick 1988). Experiments were set-up by dispensing freshly collected lake water into a clean carboy equipped with a spigot. For each water column experiment, 4-10 light BOD bottles and 2-5 dark BOD bottles were all filled with lake water from the carboy through a hose attached to a spigot to avoid adding oxygen to the samples (overflowing three times). For benthic samples, a consistent mass of sediment material was added to 4-10 light BOD bottles and 2-4 dark BOD bottles containing $0.2 \mu m$ filtered lake water. All bottles were thoroughly mixed. Once filled, **half** of the light bottles (2-5) were immediately fixed with Winkler reagents and titrated to determine oxygen concentrations at the start of the experiment. The remaining bottles were incubated at ambient temperature and light in a controlled incubator (Percival model E30-B). Following an incubation period of between 4-6 hours, all bottles were fixed with reagents and titrated as previously described to determine final oxygen concentrations.

Primary production was calculated as oxygen produced during the incubation period minus respiration (Wetzel and Lichens 1992).

Data Analysis- The relative importance of algal assemblages in the eastern basin of Lake Erie were assessed by direct comparison. Areal estimates of phytoplankton biomass were made by multiplying water column chlorophyll and carbon values by the depth of the water column stratum from which they were sampled (see Wetzel and Lichens 1992). Benthic algal biomass values were converted to areal estimates by multiplying concentrations against the area of original core sample taken (see above). Finally, pair-wise comparisons were made between areal plankton and benthic algal biomass (chlorophyll and carbon in $\text{mg} \cdot \text{m}^{-2}$) using a Wilcoxon signed rank test ($p < 0.05$). Similarly, pair-wise comparisons were made between volumetric estimates of epilimnetic and metalimnetic phytoplankton biomass (chlorophyll and carbon in $\text{mg} \cdot \text{m}^{-3}$) using a Wilcoxon signed rank test.

The hypolimnetic oxygen demand was measured as the differences in oxygen concentrations in the bottom waters between July and October (50-60 m depth). Changes in dissolved oxygen concentrations with depth were characterized using linear regression. Water column profiles of dissolved oxygen with depth were measured following thermal stratification (July) and just prior to fall isothermy when season depletion is expected to be greatest (October). Because the October sample was taken in 1997 as the result of project logistics, we assume it is representative for oxygen levels during the late stratification period in 1998 as well. Demand estimates measured in

this study for the eastern basin were compared with those determined for the other two basins in July, as well as with previous measurements made for Lake Erie (Charlton et al. 1983; Charlton 1987). Data were log transformed and met assumptions of normality. Statistical analyses were performed using Statview (v.4.5) for the Macintosh.

4. RESULTS & DISCUSSION

4A. Ambient Conditions

Environmental conditions were measured at the nearshore station LE-1 during the five major thermal periods that occur as part of the lake's annual cycle. Water temperatures ranged from 4 to greater than 24 °C (Table 2). Water clarity in the eastern basin of Lake Erie, as estimated from Secchi depth transparency, ranged from 1.4 to 8.5 m (average \pm one sd, 4.5 ± 1.8 , $n=10$). These measures agree well with transparency estimates made at a nearshore station near Long Point in the eastern basin during 1993-94 (Dahl et al. 1995; Graham et al. 1996). Chlorophyll levels ranged from 0.92 to 9.4 mg m³ through the year (2.42 ± 1.97 , $n=19$), **with** levels peaking in April that corresponded with the spring phytoplankton bloom that is characteristic throughout the Great Lakes (e.g., Fahnenstiel and Scavia 1987a; Makarewicz 1993). Again, the chlorophyll concentrations measured here appear to be typical for recent conditions in the eastern basin (Dahl et al. 1995; Graham et al. 1996). What's more, phytoplankton chlorophyll and carbon estimates closely correlated with one another ($r^2 = 0.81$, $F=112.4$, $p<0.0001$, $n=29$).

Collectively, environmental conditions at LE-1 appear to be representative of conditions throughout the eastern basin (Table 3). For instance, chlorophyll levels in the surface waters measured along a near to offshore transect were relatively constant (coefficient of variation, CV=30%), indicating that phytoplankton biomass did not vary greatly from near to offshore. Moreover, phytoplankton biomass (as chlorophyll and carbon) was no different at the most nearshore station (LE-1) compared with the other four more offshore sampling stations (Wilcoxon Signed Rank Test, $z=1.4$, $p=0.18$). Differences in volumetric oxygen concentrations were noted between near and offshore sites, but these are slight when expressed on an areal basis (see below).

4B. Metalimnetic versus Epilimnetic Algal Assemblages

Following thermal stratification, a metalimnetic phytoplankton assemblage developed in the deep waters (15-40 m depth) of all three basins in Lake Erie (Fig. 2, Table 4). On average, chlorophyll estimates for metalimnetic phytoplankton (average \pm one sd: $2.70 \pm 1.48 \text{ mg} \cdot \text{m}^{-3}$) were higher compared with epilimnetic phytoplankton ($1.91 \pm 0.71 \text{ mg} \cdot \text{m}^{-3}$) throughout the lake ($z=2.03$, $p=0.04$). Similarly, carbon estimates for deep phytoplankton carbon ($143 \pm 70 \text{ mg} \cdot \text{m}^{-3}$) were 35 % higher compared with surface phytoplankton carbon ($106 \pm 41 \text{ mg} \cdot \text{m}^{-3}$), although these differences were not statistically significant ($z=1.46$, $p=0.14$). While the two assemblages did not markedly differ in terms of their gross taxonomic composition (Fig. 2, Table 5), several taxa were more abundant in the deep waters (e.g., *Fragilaria crotonensis* Kitton, *Stephanodiscus niagare* Ehrenb.). The development of this metalimnetic assemblage diminished by October,

seemingly as the result of eventual mixing of the water column (see Fahnenstiel and Scavia 1987b).

The development of a MAM in Lake Erie may represent a truly historic change in the ecosystem. Metalimnetic algal maxima (MAM) are common feature in low productivity (oligotrophic) freshwater and marine ecosystems (e.g., Reynolds 1986). The development of MAM in the Great Lakes appears to be a function of water clarity and relative productive (e.g., Fahnenstiel and Scavia 1987b). For example, the most pristine of the Great Lakes, Lake Superior, supports a large MAM while turbid Lake Ontario show no distinct subsurface assemblage (Fahnenstiel and Glime 1983; Pick and Caron 1987, respectively). The occurrence of a MAM in Lake Erie is a new phenomenon (Burns 1985), and it's presence is likely related to the increased water clarity related to P-reduction and Dreissenid reduction of particles in the water column. What's more, the species composition of the MAM in Lake Erie is similar to that present in oligotrophic Lake Michigan (Fahnenstiel and Scavia 1987b) and Lake Superior (Fahnenstiel and Glime 1983). Paleolimnological evidence from Lake Erie indicates that many species we observed in the MAM and benthos (*Cyclotella* species, *Stephanodiscus niagare*) have only recently become abundant again in Lake Erie after a prolonged absence or reduced numbers dating back prior to 1900 (Stoermer et al. 1996).

4C. Planktonic versus Benthic *Algal* Assemblages

Overall, phytoplankton biomass (as carbon) varied more than 40-fold among the 22 samples in the eastern basin of Lake Erie that were enumerated over the 12-month study (range 2.9 to 134.7 mg • m⁻³). Most of this variation was related to changes in phytoplankton abundance with water column depth, with very low values being measured in near bottom samples (50-60 m depth). As mention above, phytoplankton were more abundant in April, although seasonal changes in the surface waters varied 3-fold over the year (range 23.8 to 80.0 mg • m⁻³). A total of fifty-nine taxa were observed in the eastern basin, with diatom and cryptophyte taxa constituting >50% of total phytoplankton carbon (Table 5).

Total algal chlorophyll pigments (chlorophyll-a plus phaeopigments) were present in all benthic samples collected in the eastern basin of Lake Erie (Fig. 3); however, only 32% of the samples contained active chlorophyll (8 of 25 samples). Microscopic analysis confirms that viable benthic algal were present in all six 6 samples analyzed (range from 6.8 to 35.2 mg • m⁻²). Diatoms constituted the majority of benthic biomass (average 86.6 % of total carbon), with the planktonic species *Stephanodiscus niagare* Ehrenb. and *Cyclotella ocellata* Pant. making up more than 50% of total carbon (Table 5). Some individuals collected contained very little chlorophyll and may have been present as vegetative resting cells; truly benthic species constituted less 20% of total biomass. Interestingly, benthic carbon correponded with total chlorophyll pigments ($r^2=0.54$, $F=4.73$, $p=0.09$, $n=6$), although the slope was very low, suggesting that benthic algal cells contained very little chlorophyll. Seasonally, total chlorophyll pigments in the sediments at LE-1 tended to accumulate late in the year from July to October (Fig. 3).

Areal total chlorophyll pigments in the sediments were high throughout the eastern basin (Fig. 4), with higher concentrations at the most near and offshore sites (6.1 to 83.0 mg • m⁻²). Benthic biomass as total chlorophyll were not different compared with the phytoplankton (z=1.40, p=0.16). However once corrected for phaeophytin, benthic algal chlorophyll (0.0 to 9.6 mg • m⁻²) was significantly lower than planktonic chlorophyll (9.7 to 93.0 mg • m⁻²) by several fold (z=2.52, p=0.01). Similarly, benthic algal carbon (6.8 to 35.2 mg • m⁻²) was nearly 2-orders of magnitude lower than planktonic carbon (825 to 2,921 mg • m⁻²), and these differences were statistically significant (z=2.02, p=0.04). These data indicate that the majority of chlorophyll in the sediments consists of phaeopigments, common degradation products of once active chlorophyll (Wetzel 1983).

Algae collected from the sediments in the eastern basin are likely phytoplankton sedimented from the water column, rather than a resident benthic assemblage. In the 1970's, this phenomenon was observed in the central basin of Lake Erie and was referred to as "algal rain" (Braidech et al. 1972). Algal rain events formed considerable layers atop the sediments throughout the central basin and remained photosynthetically active for a time, even at depths of > 20 m. The associated oxygen production by the layer did offset the sediment oxygen demand (SOD) during a portion of the day (Lucas and Thomas 1972). However, their ultimate decay created a large biochemical oxygen demands that contributed to hypolimnetic oxygen depletion (Burns and Rosa 1972) due to the large concentration of sedimentary bacteria (Menon et al. 1972). In study, primary production of

benthic algae in the eastern basin was measured in light-dark experiments on two occasions at nearshore LE-1 (Table 6). In both cases, benthic algae did not exhibit positive rates of oxygen evolution in the sediments, but rather respiration rates were several-fold higher compared with primary production. These preliminary results indicate that the SOD in the eastern basin is large relative to oxygen production by the benthic assemblage.

Thus at present, it is difficult to evaluate the role and relative importance of the benthic algae in the eastern basin of Lake Erie. The SOD for Lake Erie can be considerable and could mask primary production by benthic algae. The apparent discrepancy between benthic carbon and chlorophyll may be attributable to prevalence of phaeopigments that can interfere with determinations of active chlorophyll (see Wetzel and Lichens 1992). Also, many of the species occurring in the sediments are capable of existing in vegetative resting cells for prolonged periods of time (Schelske et al. 1996), a condition that could account for abnormally low chlorophyll content per cell (Sicko-Goad 1986). For instance, 20-years old sediments collected from Douglas Lake, Michigan supported diatoms that were in resting cells (reduced cellular contents). Once exposed to light, the diatoms became physiologically competent within a 1-4 hour period (Sicko-Goad et al. 1986). Along these lines, diatom resting cells reside on the bottom of a shallow, productive Florida lake (Lake Apopka), and are reintroduced into the water column during high wind periods. This phenomenon has a marked effect on phytoplankton biomass and community structure and can account for a significant portion of temporal variation in the lake (Carrick et

al. 1993). Thus, it is premature to draw conclusions about the contribution of benthic algae to the ecology of the system, particularly because their biomass may be more substantial in other areas not sampled here.

4D. Water Column Oxygen Balance

Dissolved oxygen concentrations varied 10-fold among the 57 samples taken in Lake Erie from July to October (range 1.35 to 13.26 mg • liter⁻¹). Most of this variation was related to changes in concentration **with** water column depth, with the low values being measured in near bottom samples. Across the entire lake, surface water oxygen concentrations ranged from 8.3 to 11.9 mg • liter⁻¹, while concentrations in the bottom water showed the greatest variation and ranged from 1.4 to 13.3 mg • liter⁻¹.

Oxygen profiles with water depth in lakes are a function of ecosystem productivity (Wetzel 1983). This fact is clearly visible from data collected among the three basins in Lake Erie (Figs. 5 and 6). For instance, both the western and central basins (stations 341 and 954, respectively) exhibited clinograde oxygen curves, characterized by a steady decline in oxygen concentration with depth. Concentrations in surface waters were approximately 10 mg • liter⁻¹ and declined to 5 mg • liter⁻¹ near the bottom. This curve is characteristic of higher productivity systems, where photosynthesis (and associated oxygen production) sharply decreases **with** depth due **to** limited light penetration. On the other hand, the eastern basin supported an orthograde oxygen curve, where levels increased **with**

depth (Figs. 5 and 6). Oxygen levels were approximately 10 mg • liter⁻¹ throughout the epilimnion and increased to 12 mg • liter⁻¹ in the metalimnion; concentrations remained high throughout the hypolimnion. This curve is indicative of lower productivity systems, where physical factors such as water temperature strongly influence the concentration of oxygen throughout the water column (Wetzel 1983).

Depleted oxygen levels in large volumes of the lake once resulted in fish die-offs, leading to significant modifications of the habitat that were manifested as changes in the gross chemistry and biology (see Beeton 1969). Seasonal hypolimnetic oxygen depletion in the lake is a consequence of increased nutrient loadings and eutrophication of the ecosystem (Makarewicz and Bertram 1991). Given the sustained reductions in phosphorus loads to the lake and the invasion of the zebra and quagga mussels, it is likely that the sources of primary production will change (benthic versus pelagic), which may in turn influence the water column oxygen balance.

Hypolimnetic oxygen depletion is used as an index of the degree of the lake eutrophication process, as well as the potential for lake recovery (Charlton et al. 1993). Hypolimnetic oxygen depletion rates have long been studied in Lake Erie, because historic changes are responsible for depleting oxygen in the lake (Beeton 1969). Depletion rates in the central basin increased between 1929-1980 causing a cumulative decrease of 4-5 mg • liter⁻¹, apparently due to increased phosphorus loads to the lake (Rosa and Bums 1987). However, hypolimnetic depletion in the eastern basin has not

changed much since 1930, with levels ranging from 13.5 mg • liter⁻¹ in May to between 7-8 mg • liter⁻¹ by mid October (Charlton 1987). The hypolimnetic depletion rates measured here fall within the range for those measured during the 1970's (see Table 6) and indicate that despite significant food web changes, the hypolimnetic oxygen depletion rate may be resilient to further change (Charlton et al. 1993). Moreover, the primary production rates measured here agree well with previous studies (e.g., Munawar and Munawar 1981; Fahnenstiel and Carrick 1988), and indicate that additional water column sources of oxygen are not event (Table 7). In addition, on the two dates we made measurements, no net photosynthesis occurred in the sediments, but rather a high demand for oxygen (high respiration rates) was evident. Therefore, despite the occurrence of metalimnetic phytoplankton and benthic algal assemblages, their metabolism does not appear to offset the rate of hypolimnetic depletion in the eastern basin of Lake Erie.

5. PROJECT MANAGEMENT

The research was originally begun at Buffalo State College (1997-98). The project was transferred to the University of Buffalo in September of 1998, when the principal investigator took faculty research appointment at that institution. The funding was used to support staff time, purchase useable supplies and materials, and supplement some travel. Several students were trained as result of this research. Funds were used to support **3** undergraduate assistants (part-time) and one Master of Science graduate student was hired as a Technician to assist with the project.

6. RESEARCH PRODUCTS

Funds were used to facilitate the training of undergraduate students at Buffalo State College (BSC) through the completion of independent research projects. These projects were jointly designed by the principal investigator and the student to meet the specific objectives of the project. This effort lead to the completion of three student independent projects and two professional presentations (student and one facility presentation).

6A. Student Research Support (* Graduated with Honors)

- 1. Ms. Chrissy Plotner: B.A. Biology from BSC, Graduated May 1998**

Independent Study Entitled- Growth response of Lake Erie phytoplankton following enrichment with nitrogen and phosphorus, 20 pages (BIO499 Biogeochemistry, 4 credits).

- 2. *Ms. Kelly Jo Driskel: B.S. Science Ed. from BSC, Graduated May 1998**

Undergraduate Assistant. Lake Erie plankton dynamics and biogeochemistry.

- 3. *Ms. Laurie Weaver: B.A. Biology from BSC, Graduated December 1998**

Undergraduate Assistant. Lake Erie plankton dynamics and biogeochemistry.

- 4. Mr. Brent Higley: M.S. Biology, BSC, Graduated December 1998**

Research Aide: Buffalo State College, June-August 1998

Research Technician II. University at Buffalo, January-June 1999

6B. Professional Research Presentations

Carrick, H.J., A. Padmanabha, L. Weaver. 1998. Importance of the microbial food web in large lakes. Special session on Biotic Processes in Large Lakes, **Society of International Limnology**, Dublin Ireland, August 9-14 (**Invited Talk**).

Plotner, C., and H. Carrick. 1998. Growth response of Lake Erie phytoplankton following enrichment with nitrogen and phosphorus. **Sigma Xi Student Organization**, Buffalo State College, **NY**, April 18.

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8. LITERATURE CITED

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Table 1. The location of fixed sampling stations in eastern, central, and western basins of Lake Erie where data were collected for this study (1997-98). The LE series are SUNY-Great Lakes Center sampling stations while the number series are those established by Canadian Center for Inland Waters (CCIW). Where n denotes the total number of samples collected.

<i>Basin</i>	<i>Depth</i>	<i>Sampling Date</i>	<i>Station Location</i>	
<i>Station</i>	<i>(m)</i>	<i>(nfor Water, Benthic)</i>	<i>Latitude (N)</i>	<i>Longitude (W)</i>
<i>Eastern Basin (5 stations)</i>				
LE-1/931	10.0	Mar to Oct (10, 8)	42° 49' 99"	78° 55' 35"
LE-2	20.0	Mar to Oct (3, 9)	42° 45' 11"	79° 09' 43"
LE-3/935	30.0	July, Oct (12, 4)	42° 38' 02"	79° 29' 77"
LE-5/23	50.0	July, Oct (5, 2)	42° 35' 81"	79° 36' 17"
LE-6/939	60.0	July, Oct (12, 2)	42° 31.08'	79° 69' 64"
<i>Central Basin (5 stations)</i>				
954	24.5	14 July (6, 0)	42° 01' 30"	81° 26' 30"
945	22.0	17 July (3, 0)	42° 24' 00"	80° 38' 30"
946	22.0	14 July (1, 0)	42° 10' 00"	80° 38' 30"
953	22.0	16 July (5, 0)	42° 12' 30"	81° 26' 30"
1047	25.0	17 July (3, 0)	42° 21' 30"	80° 16' 30"
<i>Western Basin (6 stations]</i>				
974	8.0	15 July (2, 0)	41° 43' 30"	83° 09' 00"
357	10.5	15 July (2, 0)	41° 49' 36"	82° 58' 12"
338	8.0	15 July (2, 0)	41° 42' 00"	82° 38' 00"
339	10.5	15 July (1, 0)	41° 43' 42"	82° 31' 00"
340	11.0	15 July (2, 0)	41° 45' 24"	82° 24' 00"
341	17.0	15 July (6, 0)	41° 47' 06"	82° 17' 00"

Table 2. Environmental characteristics of epilimnetic waters (depth of 5 m) monitored at a nearshore station (LE-1) in the eastern basin of Lake Erie.

sampling Date	Thermal Period	Temperature °C	Cbl-a mg • m⁻³	secchi m
1998				
3 March	Inverse	4.2	1.35	-
†22 April	Mixing	5.0	4.80	4.0
	Mixing	5.0	9.38	4.0
19 June	Initial	18.0	2.36*	8.5
1 July	Initial	20.0	0.99	1.4
13 July	Mid	22.0	1.08	-
17 July	Mid	22.0	3.03	-
23 July	Mid	24.0	0.92	5.0
6 August	Mid	23.8	1.08	5.3
25 August	Mid	24.0	-	-
1997				
†8 October	Late	18.0	2.06	4.0
	Late	18.0	2.32	4.5
10 November	Late	10.0	0.97	4.0
		10.0	1.04	4.0
	Average	15.8	2.41	4.5
	Standard Deviation	7.9	2.37	1.8

† Denotes samples collected at both LE-1 and LE-2.

Table 3. Environmental characteristics of epilimnetic waters (depth of 5 m) along a near to offshore transect from Buffalo, NY to Long Point, Ontario in the eastern basin of Lake Erie.

Date Year	Station ID	Distance k m	Chl-a mg . m ⁻³	Carbon mg . m ⁻³	Dissolved O ₂ mg . Liter ⁻¹
<i>Mid-stratification</i>					
July 1998	LE-1	4.0	1.80	64.1	8.9
	LE-3	25.0	2.51	-	8.4
	LE-5	56.0	2.31	-	12.0
	LE-6	81.5	2.18	74.1	12.0
<i>Ute-stratification</i>					
October 1997	LE-1	4.0	2.06	82.4	9.2
	LE-2	25.0	2.32	77.9	9.5
	LE-3	56.0	3.56	134.7	10.0
	LE-5	69.0	2.47	81.1	9.6
	LE-6	81.5	2.37	73.9	9.2

Table 4. Comparisons of carbon and chlorophyll biomass for epilimnetic (0-15 m depth) and metalimnetic phytoplankton (15-40 m depth) assemblages collected from all three basins in Lake Erie during mid-stratification (July).

Basin	Station	Meta	Epi	Ratio
<i>Carbon (mg • m⁻³)</i>				
Eastern	LE-6/939	68.5	74.1	0.92
Central	945	174.9	123.7	1.44
	954	104.9	71.3	1.47
Western	338	223.5	156.5	1.43
<i>Chlorophyll (mg • m⁻³)</i>				
Eastern	LE-5/23	2.31	1.65	1.40
	LE-6/939	2.61	2.18	1.20
Central	945	4.40	2.13	2.07
	946	1.13	0.88	1.28
	954	2.39	1.96	1.22
Western	338	4.94	3.14	1.57
	357	1.11	1.42	0.78

Table 5. A summary of dominant **algal** species **and** their percent contribution (based on carbon) to several assemblages in Lake Erie during 1997-98.

Phylum	Taxon (authority)	Average %
<i>Epilimnetic Assemblage (n=19)</i>		
BACILLARIOPHYTA	Cyclotella kutzingiana Thwaites	4.7
	Fragilaria crotonensis Kitton	7.3
CHLOROPHYTA	Nanochloris sp.	2.5
CHRYSOPHYTA	Mallomonas producta (Zach.) Iwanoff	4.5
	Ochromonas ovalis Doflein	10.8
	Ophiocytium cochleare (Eichw.) Braun	3.7
CRYPTOPHYTA	Cyptomonas erosa Ehrenb.	5.1
	Cryptomonas erosa v. reflexa Marsson	4.7
	Cyptomonas ovata Ehrenb.	2.8
	Rhodomonas minuta Skuja	18.8
CYANOBACTERIA	Synechococcus sp.	3.5
PYRROPHYTA	Gymnodinium varians Maskell	3.1
	Peridinium inconspicuum Lemm.	2.6
	SUM	74.1
<i>Metalimnetic Assemblage (n=7)</i>		
BACILLARIOPHYTA	Fragilaria crotonensis Kitton	34.6
	Stephanodiscus niagare Ehrenb.	7.4
CHRYSOPHYTA	Ochromonas ovalis Doflein	10.7
	Ophiocytium cochleare (Eichw.) Braun	5.5
CRYPTOPHYTA	Katablepharis ovalis Skuja	3.3
	Rhodomonas minuta Skuja	12.7
	SUM	74.2

Table 5. Continued.

Phylum	Taxon (authority)	Average %
Benthic Assemblage (n=6)		
BACILLARIOPHYTA	<i>Aulacoseira italica</i> (O.Mull) Sim.	3.5
	<i>Cyclotella kutziana</i> Thwaites	8.1
	<i>Cyclotella ocellata</i> Pant.	23.2
	<i>Epithemia adnata</i> (Ehrenb.)Kutz.	4.2
	<i>Pleurosigma delicatulum</i>	5.3
	<i>Stephanodiscus niagare</i> Ehrenb.	24.7
CHLOROPHYTA	<i>Pediastrum simplex</i> (Meyen) Lemm.	7.9
	SUM	76.9

Table 6. Rates of hypolimnetic oxygen depletion determined for two sites in the eastern basin of Lake Erie.

Station	Date	Oxygen mg•liter⁻¹	Duration Months	Oxygen Depletion mg•liter⁻¹•Month⁻¹
LE-5	17 July	13.261	2.87	2.23
	8 October	6.840		
LE-6	17 July	12.136	2.76	1.61
	8 October	7.680		

Table 7. Net primary production and respiration rates (as mg O, liter⁻¹ h⁻¹) measured in the eastern basin of Lake Erie for planktonic and benthic assemblages.

Assemblage	Date	Production	Respiration
Planktonic	1 July	0.083	-0.005
	17 July	0.049	-0.043
	25 July	0.066	-0.074
	6 August	0.234	0.133
	26 August	0.073	0.023
Benthic	1 July	0.000	-0.705
	17 July	0.000	-0.560

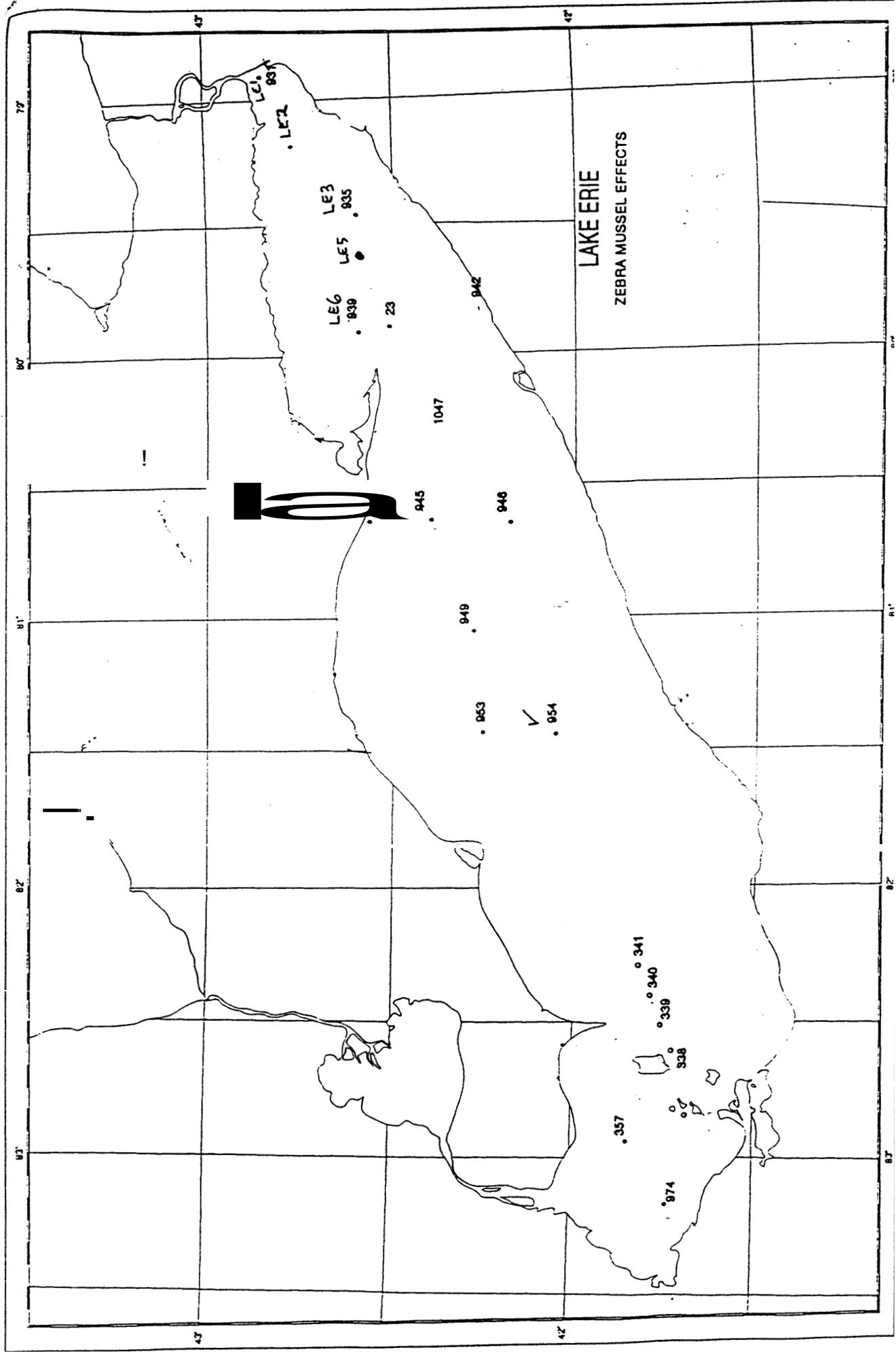


Fig. 1. Lake Erie sampling stations (1997-98).

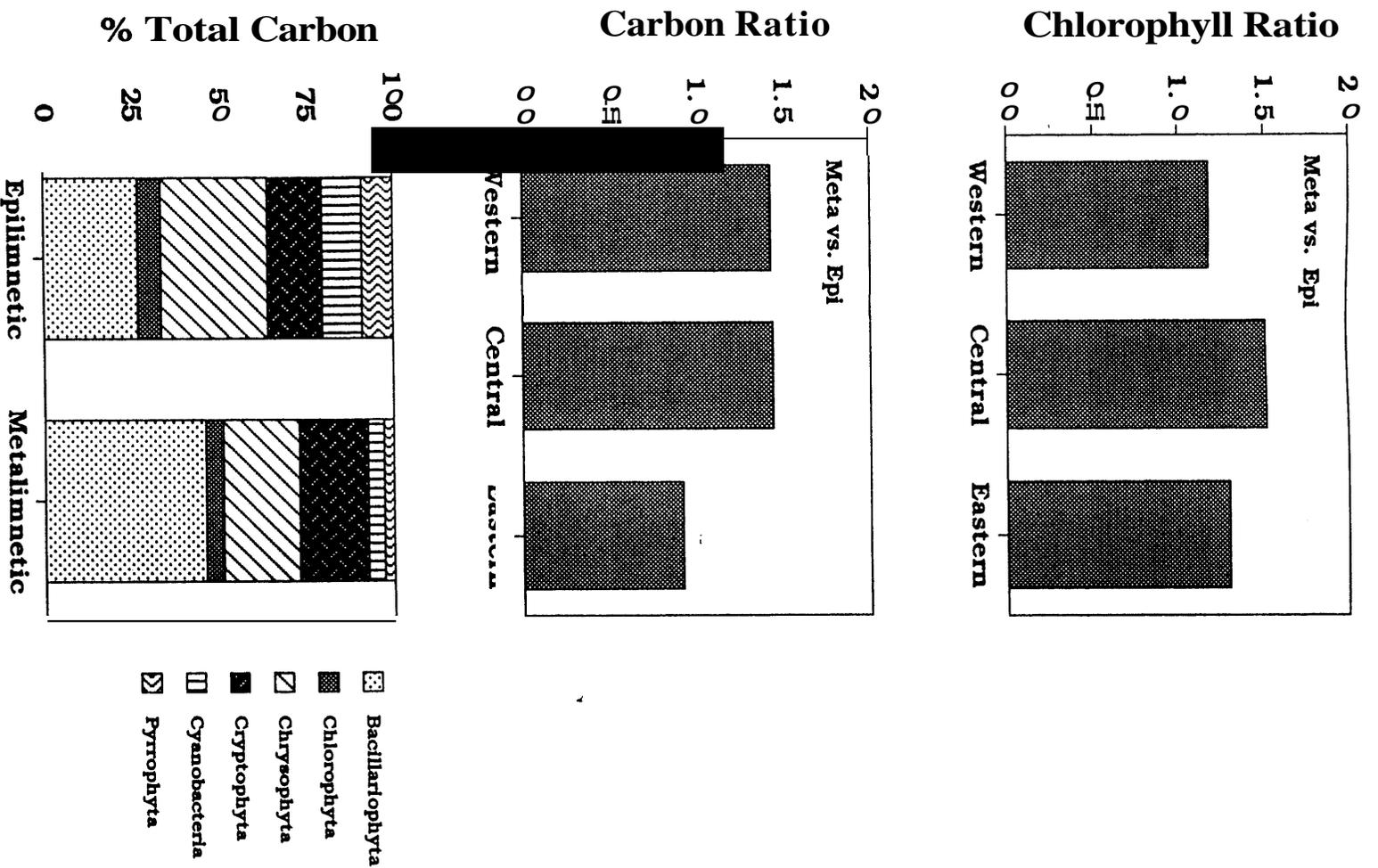


Fig. 2. Comparisons of surface and deep algal assemblages in the western, central, and eastern basins of Lake Erie during the mid-stratification period (July).

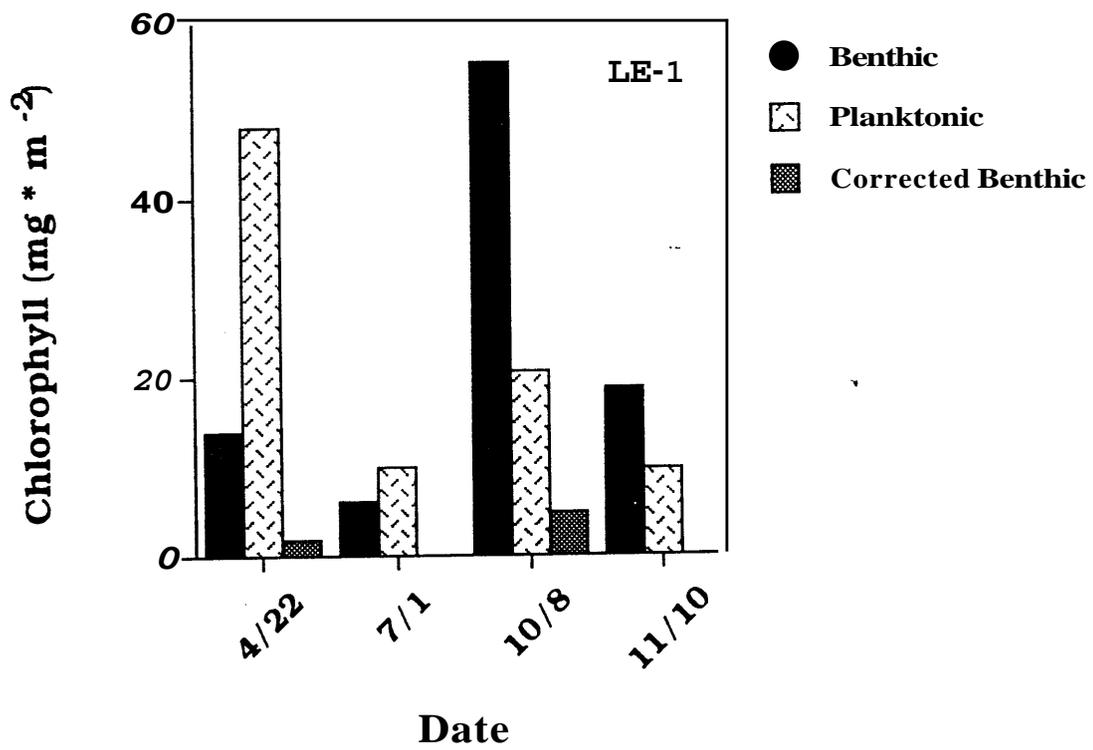


Fig. 3. Seasonal variation in planktonic and benthic biomass at a nearshore station in Lake Erie.

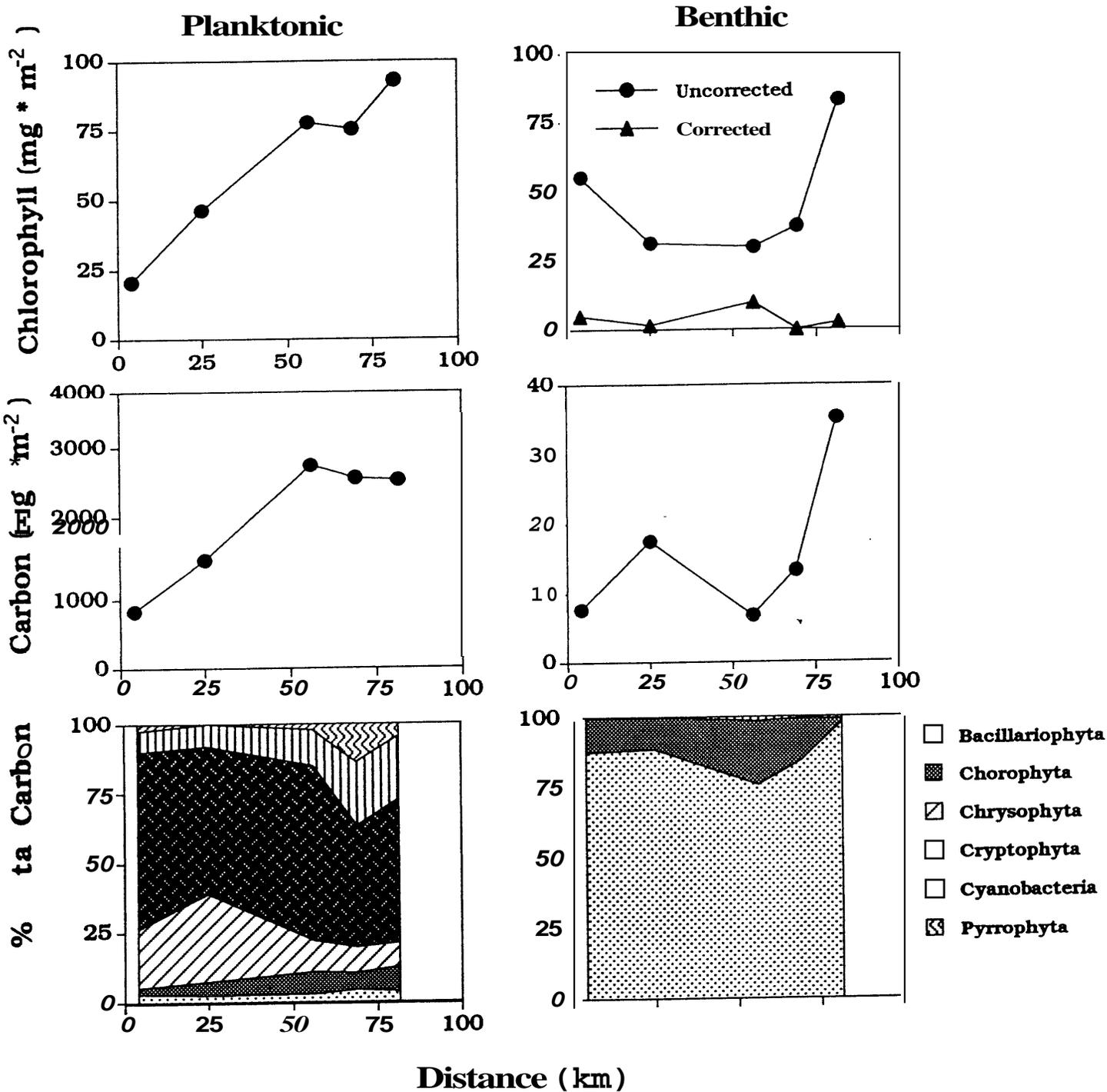


Fig. 4. Comparisons of planktonic and benthic algal assemblages along an east-west transect in Lake Erie from Buffalo to Long Point on October 8, 1997 (noted differences in scale for carbon estimates).

Dissolved Oxygen (mg * Liter⁻¹)

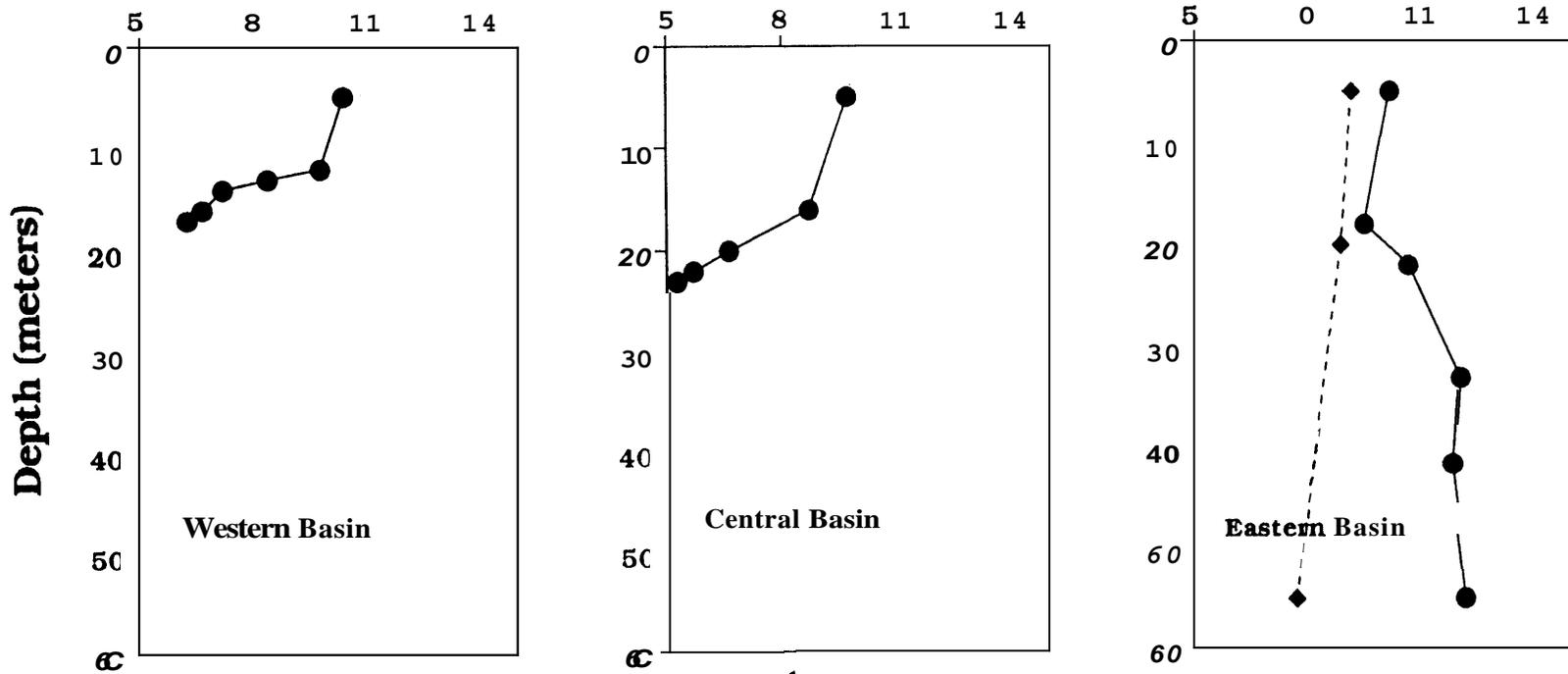


Fig. 5. Changes in dissolved oxygen with depth in the western, central, and eastern basin of Lake Erie during mid (July, circles) and late stratification (October, diamonds).

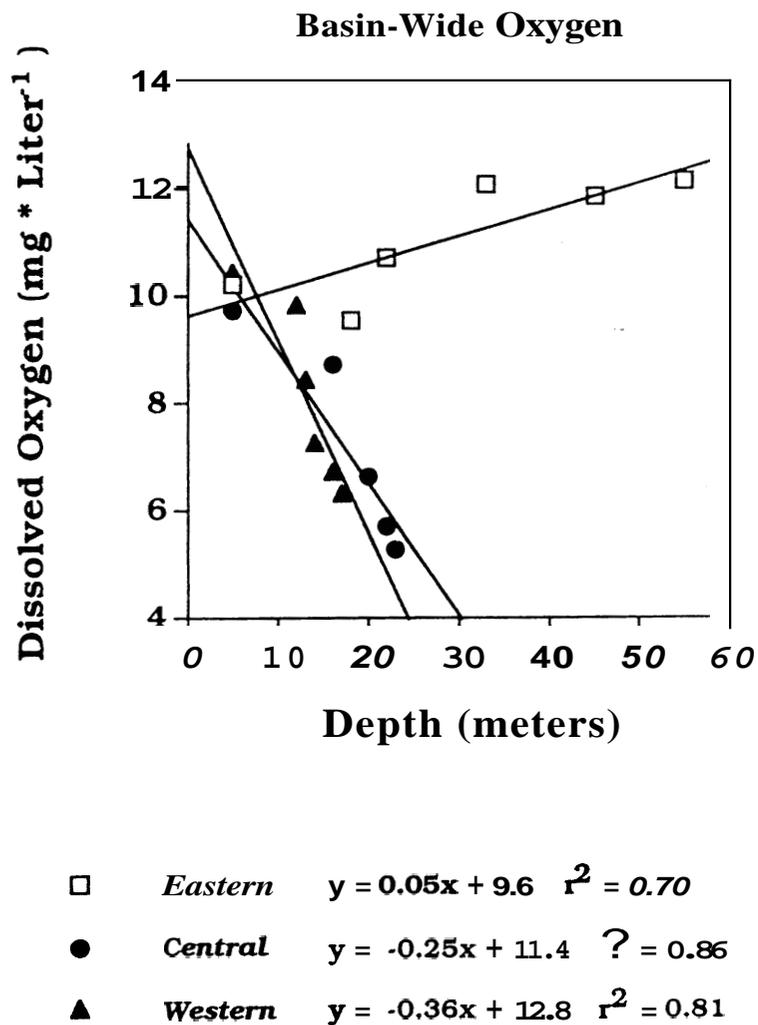


Fig. 6. Relationships between dissolved oxygen and water depth for all three basins in Lake Erie (July).