The Laurentian Great Lakes

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Introduction

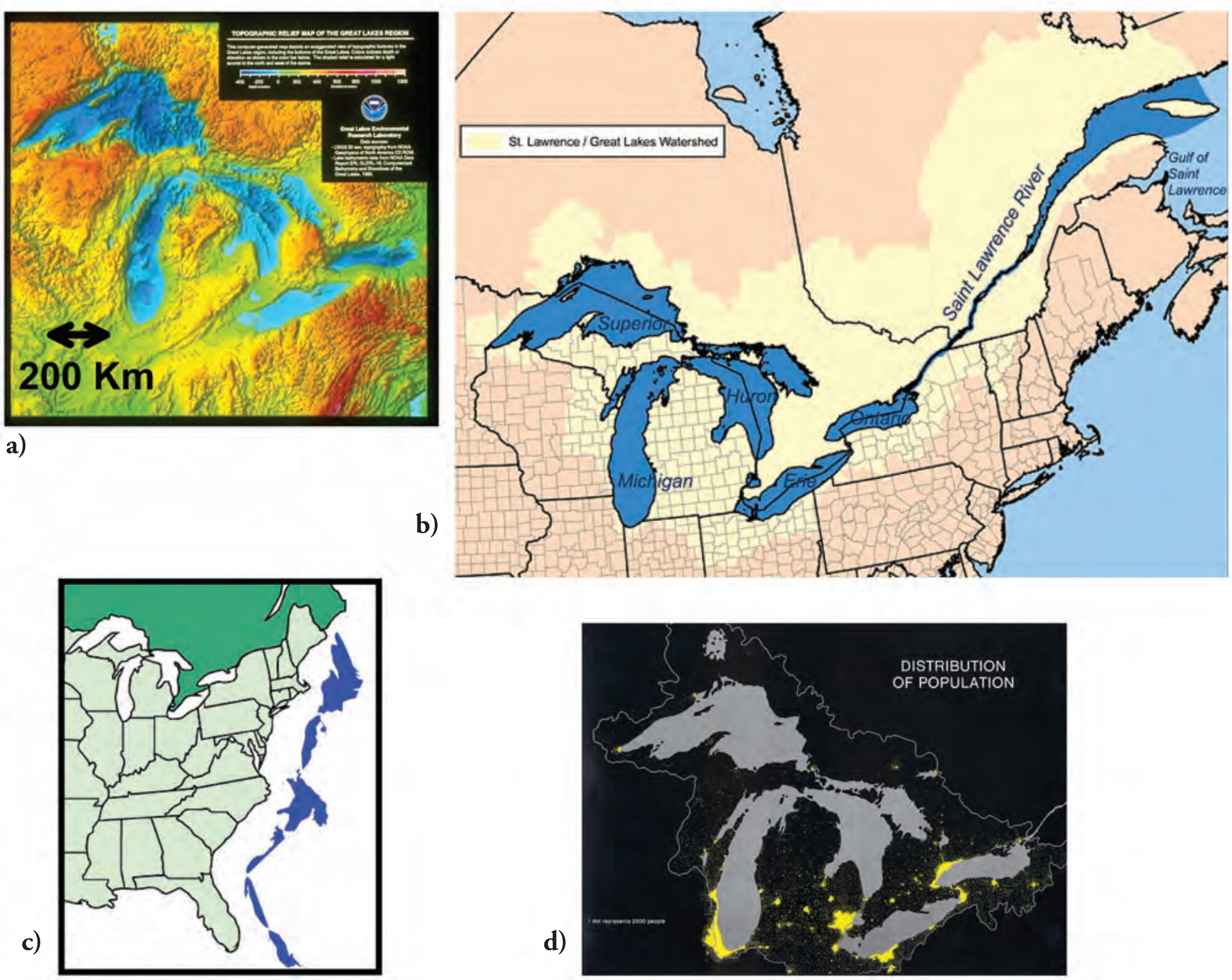
North America's inland ocean, the Great Lakes (Figure 7.1), contains about 23,000 km^3 (5,500 cu. mi.) of water (enough to flood the continental United States to a depth of nearly 3 m), and covers a total area of 244,000 km^2 (94,000 sq. mi.) with 16,000 km of coastline. The Great Lakes comprise the largest system of fresh, surface water lakes on earth, containing roughly 18% of the world supply of surface freshwater. Reservoirs of dissolved carbon and rates of carbon cycling in the lakes are comparable to observations in the marine coastal oceans (e.g., Biddanda et al. 2001) (Table 7.1). The drainage area of the Laurentian system (including the Saint Lawrence River) is approximately 1.0 million km^2—approximately one-third of the Mississippi River watershed or roughly 4% of the surface area of North America. The Great Lakes drain through the Saint Lawrence River, which flows approximately 1200 km before emptying into the largest estuary in the world, the Gulf of Saint Lawrence. This feature of the Great Lakes system is unique in relation to the other marginal regions: exchange with the open ocean is in only one direction, to the ocean. Because of the large size of the watershed, physical characteristics such as climate, soils, and topography vary across the basin. Terrestrial and atmospheric forcing is strongly latitude-dependent in this large basin. To the north, the climate is cold and the terrain is dominated by a granitic bedrock called the Canadian (or Laurentian) Shield consisting of Precambrian rocks under a generally thin layer of acidic soils. Conifers dominate the northern forests. In the southern areas of the basin, the climate is much warmer. The soils are deeper with layers or mixtures of clays, carbonates, silts, sands, gravels, and boulders deposited as glacial drift or as glacial lake and river sediments. The lands are usually fertile and have been extensively drained for agriculture. The original deciduous forests have given way to agriculture and sprawling urban development. This variability has strong impacts on the characteristics of each lake. The lakes are known to have significant effects on air masses as they move in prevailing directions, as exemplified by the 'lake effect snow' that falls heavily in winter on communities situated on the eastern edges of lakes. If the Lakes can frequently experience the degrees of CO_2 undersaturation shown below, then the CO_2 of the airmasses must be impacted as well.

Subregions of the Laurentian System

Although part of a single system, each lake is different (Table 7.1), and the system can be classified into three broad sub-categories: Lake Superior, an oligotrophic lake with low anthropogenic impact; the remaining four lakes, which are more productive and extensively anthropogenically impacted; and the Saint Lawrence River. In volume, Lake Superior is the largest, deepest, and coldest of the lakes. Because of its size, Superior has a retention time of 191 years based on the volume of water in the lake and the mean rate of outflow. Most of the forested, granitic Superior Basin is sparsely populated, with little agriculture because of a cool climate and poor soils.

The other four lakes reside in carbonate basins with deeper, more fertile soils, and are subjected to more extensive human activities. Lake Michigan, the largest of these, spans the upper and lower regions of the Laurentian Basin. The northern part is in the colder, less developed, upper Great Lakes region. It is sparsely populated, except for the Fox River Valley, which drains into Green Bay. This bay has one of the most productive Great Lakes fisheries but receives wastes from the world's largest concentration of pulp and paper mills. The more temperate southern basin of Lake Michigan is among the most urbanized areas in the Great Lakes system, containing the Milwaukee and Chicago metropolitan areas. This region is home to about 8 million people or about one-fifth of the total population of the Great Lakes Basin. Lake Huron, which includes Georgian Bay, is the third largest of the lakes by volume. The Saginaw River Basin is intensively farmed and contains the Flint and Saginaw-Bay City metropolitan areas. Lake Erie is the smallest of the lakes in volume and is exposed to the greatest effects from urbanization and agriculture. Because of the fertile soils surrounding the lake, the area is intensively farmed. The lake receives runoff from the agricultural area of southwestern Ontario and parts of Ohio, Indiana, and Michigan. Seventeen metropolitan areas with populations over 50,000 are located within the Lake Erie Basin. It is the shallowest of the five lakes (average depth is only about 19 m) and therefore warms rapidly in the spring and summer, and frequently freezes over

Figure 7.1. Geographic representations of the Laurentian Great Lakes showing a) topography/bathymetry; b) the size of the lakes relative to their drainage basin; c) the size of the lakes relative to the North American Atlantic coastal ocean; and d) the population distribution in the Laurentian basin.



in winter. It also has the shortest retention time of the lakes, 2.6 years. Lake Ontario, although slightly smaller in area, is much deeper than Lake Erie, with an average depth of 86 m (283 ft) and has a retention time of about 6 years. Major urban industrial centers, such as Hamilton and Toronto, are located on its shore. The US shore is less urbanized and is not intensively farmed, except for a narrow band along the lake.

The Saint Lawrence River is born at the outflow of Lake Ontario before draining into the Gulf of Saint Lawrence, the largest estuary in the world. It runs over 3000 km from source to mouth (1,197 km from the outflow of Lake Ontario). Its drainage area covers 1.03 million km². The average discharge at the mouth (into the North Atlantic) is 10,400 $m^3 s^{-1}$.

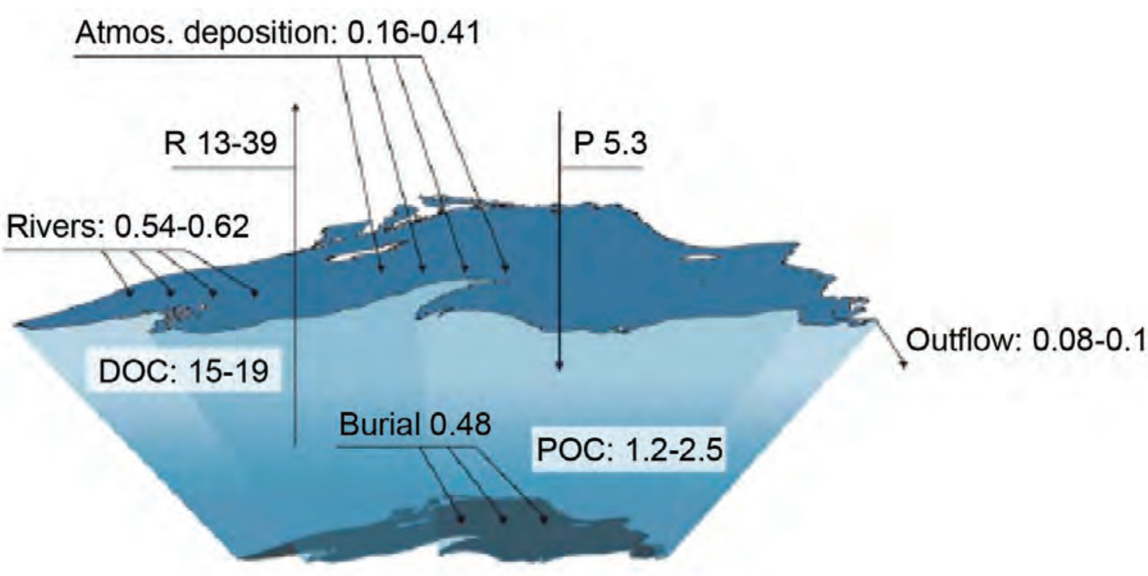
Table 7.1. Relevant statistics for the Laurentian Great Lakes, and comparative nominal values for the coastal oceans.

Lake	Average Depth (m)	DIC (mM)	DOC (µM)	PP (mmol $m^{-2} d^{-1}$)	Sediment C burial (mol $m^{-2} yr^{-1}$)
Superior	147	1	100		0.25
Michigan	85	2.3	400	12	8e11 g C/y
Huron	59	1.7	400		
Erie	19	2.2	400		2
Ontario	86	2.2	400		2e11 g C/yr
Coastal Oceans	≈100	≈2	≈100		

Carbon Cycling in the Laurentian System

Carbon cycling is quite different among the lakes. At one extreme (Figure 7.2) is Lake Superior, a unique, ultra-oligotrophic system with many features similar to the oligotrophic oceanic gyres, such as dominance of microbial biomass and dissolved organic carbon (DOC) in biogeochemical processes (see e.g., Biddanda et al. 2001). The combination of cold temperature, low nutrient concentrations (total phosphorus <2 µg L^{-1}), and low municipal/industrial pressure leads to rates of primary production, estimated at 2.0 to 6.7 Tg C yr^{-1} (Urban et al. 2005), or approximately 6 to 20 mmol C $m^{-2} d^{-1}$, that are among the lowest measured in any aquatic system. Low primary production and the soil-starved granitic drainage basin result in low

Figure 7.2. Schematic of a carbon budget for Lake Superior, the most oligotrophic of the lakes. Reservoirs are expressed in units of Tg C, and fluxes (arrows) in Tg C yr^{-1} (Cotner et al. 2004).



DIC, DOC, and POC concentrations in the lake. Allochthonous riverine organic carbon inputs were estimated at 0.5 to 0.6 Tg C yr^{-1}, which is about 10% of photo-autotrophic production. Atmospheric carbon deposition has not been measured to any significant extent but we estimate it at 0.16 to 0.41 Tg yr^{-1} (Cotner et al. 2004). All together, allochthonous carbon sources provide 13 to 19% of photo-autotrophic production. The main loss of organic matter in the lake is through respiration in the water column at a lake-wide total of 13 Tg C yr^{-1} (estimate range: 13–81 Tg C yr^{-1}; Urban et al. 2005; Cotner et al. 2004). Respiration is (at a minimum) double all estimated organic carbon sources combined and therefore sources are likely underestimated.

The other lakes are quite different. Much warmer than Superior and receiving more substantial carbon and nutrient inputs from the increased anthropogenic activity and deeper soils in their drainage basins, their primary production averages approximately 25 (±8) mmol C m^{-2} d^{-1}, or higher than the upper-bound estimates seen in Lake Superior. As a result, DIC and DOC concentrations are much higher as well, ranging from 1.7 to 2.3 mmol L^{-1} and 200 to 400 µmol L^{-1}, respectively. Complete carbon budgets for the other lakes have not been rigorously performed, however, the budget for the eutrophic southern Green Bay (Figures 7.3 and 7.4) may serve as an example of these systems.

Net CO_2 Exchange with the Atmosphere

The magnitude of the net air-water CO_2 flux has not been systematically measured in any of the lakes. The lakes are generally agreed to be net heterotrophic, and thus a source of CO_2 to the atmosphere. However, this is based largely on poorly constrained estimates of primary production and respiration. We are aware of only a few direct measurements of pCO_2 in the Great Lakes. These include the efforts of Jim Waples (Great Lakes WATER Institute-UWM) in Green Bay, Lake

Figure 7.3. Schematic of a carbon budget for Green Bay, Lake Michigan that is exemplary of the more eutrophic lakes (from Klump et al. 2007).

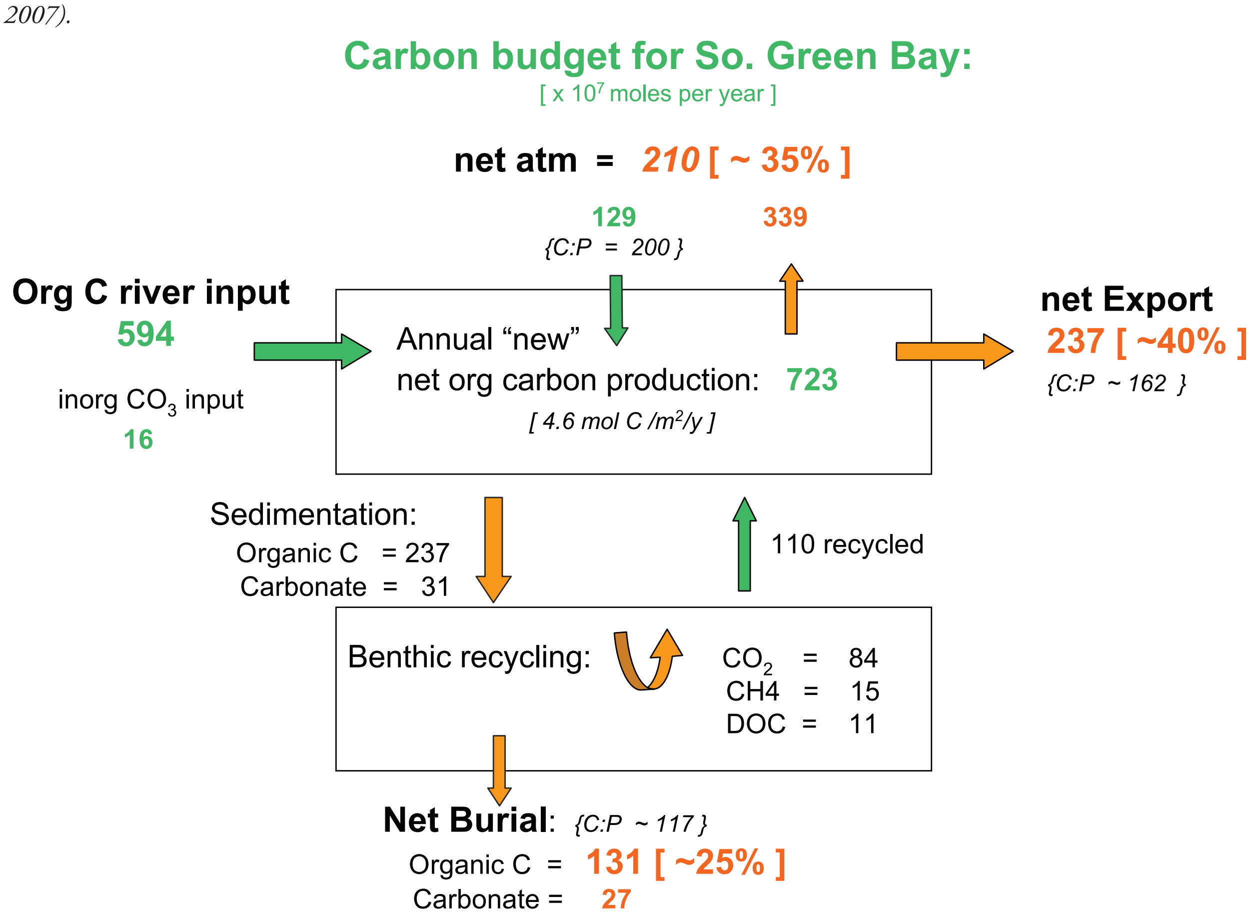
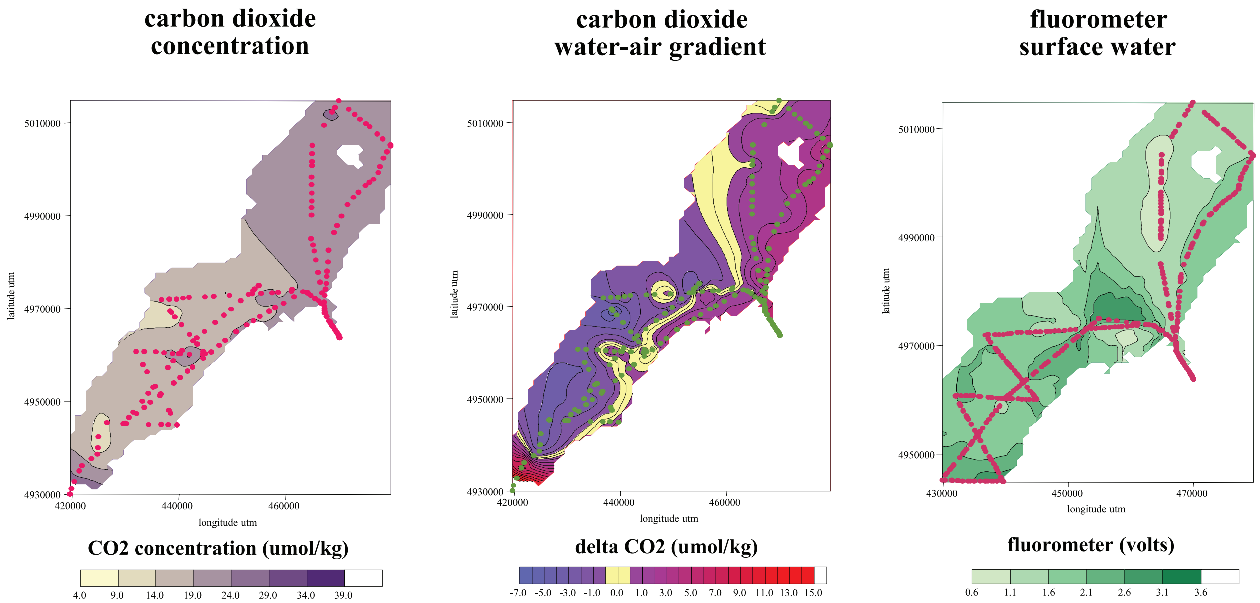


Figure 7.4. Surface $CO_{2(aq)}$ distributions in Green Bay (from Waples, 1998). Net CO_2 efflux (~15 g C m^{-2} yr^{-1}) driven in part by degradation of external inputs of organic C to the system.

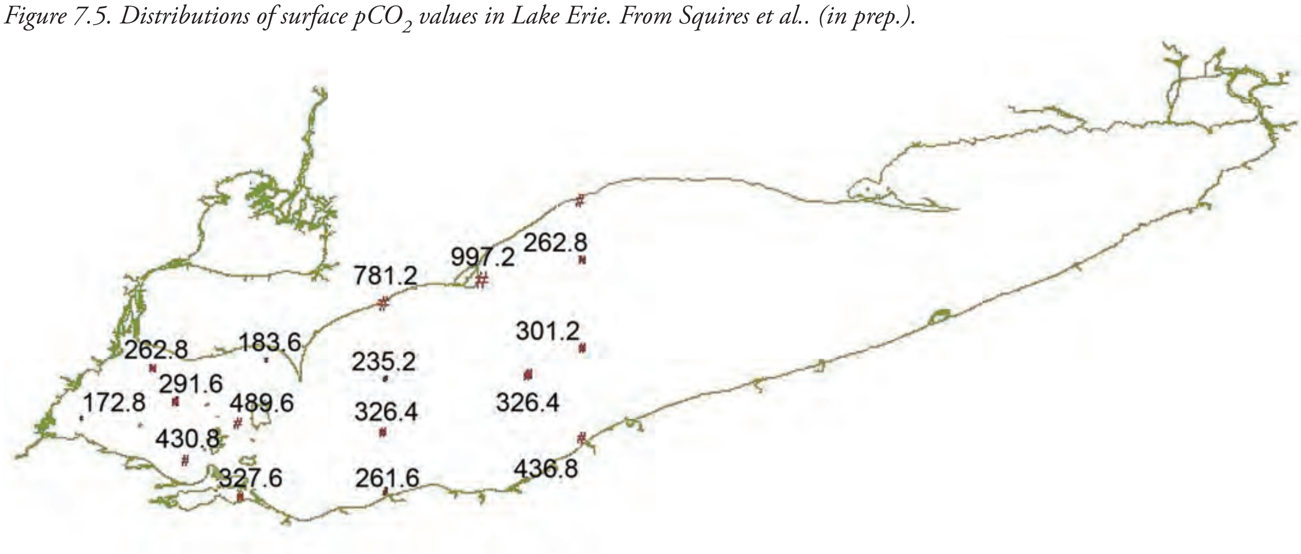


Michigan, and Maggie Squires (University of Waterloo) in Lake Erie. The results of these measurements are equivocal and highly variable. Squires' measurements (Figure 7.5) show surface pCO_2 values as low as 120 µatm, far below atmospheric saturation. Waples' measurements in Green Bay (Figure 7.4) showed a net export of about 0.2 Tg CO_2 to the atmosphere in 1994 and 1995. However, the spatial and temporal direction and magnitude of flux were far from uniform. Riverine loading and annual temperature cycles generate spatial and temporal gradients in carbon processing, such that isolated measurements in time or space would significantly miss the dynamic nature of the carbon air-sea interactions.

Historical Measurement Programs

There have been no large, coordinated measurement programs focusing on the C cycle in the Great Lakes. This, coupled with the high temporal and spatial

Figure 7.5. Distributions of surface pCO_2 values in Lake Erie. From Squires et al.. (in prep.).



variability in the lakes leaves many key questions regarding net transport and processing of C in the lakes only weakly constrained (Table 7.2).

Anthropogenic impacts on the Great Lakes system

Direct anthropogenic forcing on the Great Lakes is intense, and has probably been a factor in the carbon budget since harvesting of the basin's conifer forests in the late 1800s began to release excess phosphorus, the nutrient limiting primary production in the Great Lakes, to the system. The loads of phosphorus to the lakes due to agricultural and industrial pollution accelerated until the early 1970s, when restrictions were imposed by international treaty (Figure 7.6). Target P loads were established for each lake, based on various ecosystem models, to achieve agreed chlorophyll levels. Because of its small size and high population, Lake Erie was the most impacted. There was a rapid drop in both P and chlorophyll concentrations. However recent (post-1995) concentrations of P in Lake Erie have risen and the cause is not known, although several theories have been proposed (increased P loads, warmer temperatures, and zebra mussel effects). In any case, changes in P cycling imply changes in C cycling, although there have been few C measurements in recent years.

In addition to discharge of pollutants, the carbon cycle in the Great Lakes has been impacted by invasive species. A major pathway for invasive introduction is via international maritime shipping. The lakes were opened to the Atlantic when the St. Lawrence Seaway was completed in the 1950s. Since then there have been several devastating invasions: the most recent in this category are Dressenid mussels (Zebra and Quagga), first discovered in the lakes in 1989. Dreissenid mussels have been found in all of the Great Lakes and have spread from there into the rivers of the Northeast and Midwest. Illustrating the impact that mussels have had on carbon cycling is the approximately 0.1 mmol L^{-1} drop in calcium concentration seen in Lake Erie since the mussels' invasion. This is due to formation of $CaCO_3$ shell material (Figure 7.7), and accompanies an equivalent drop in DIC, and a two-fold greater decrease in alkalinity. This extrapolates to a loss of approximately $1x10^{12}$ g dissolved C for Lake Erie alone, and translates to significant changes in the carbonate equilibria (and hence the pCO_2 distributions) in the lakes. The mussels may also bring about greater retention and recycling of nutrients in the nearshore (i.e., the 'near shore phosphorus shunt'; Hecky et al. 2004) and in turn increased production in the benthic community. An important question relevant to carbon cycling processes is the magnitude and long-term fate of both

Table 7.2. Knowledge matrix for the carbon cycle in the Great Lakes, where a score of 1 represents a high degree of knowledge about a certain process within a certain lake, and a score of 3 represents a low degree of knowledge.

Process	Superior	Michigan	Huron	Erie	Ontario	Mean "score"
Outflow	1	1	1	1	1	1.0
Hydrodynamic models	2	1	2	1	2	1.6
C Inputs	3	1?	3	1	1	1.8
Sedimentation	3	1	3	2	2	2.2
PP	3	2	3	2	2	2.4
Respiration	3	2	3	2	2	2.4
BGC models	3	3	3	2	3	2.8
CO_2 Exchange	3	3	3	3	3	3.0
Mean "score"	2.6	1.8	2.6	1.8	2.0	

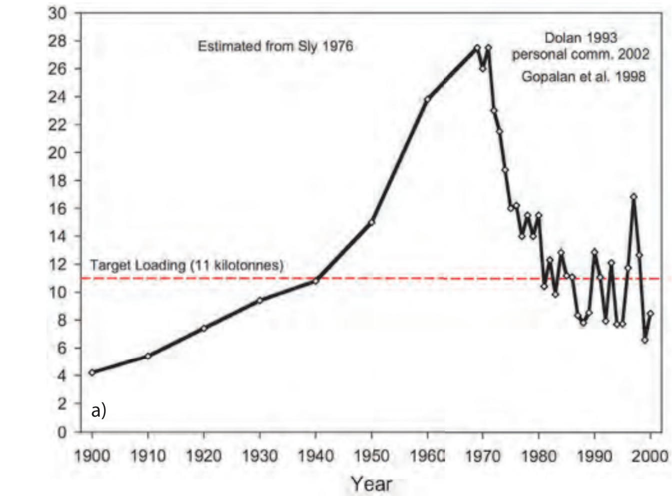


Figure 7.6. The history of phosphorus loading in Lake Erie (a) showing the steady rise in inputs prior to the US-Canadian treaty in 1973, and the sharp drop afterwards. The concentrations of phosphorus in the lake (b) and chlorophyll levels (c) both decreased in response.

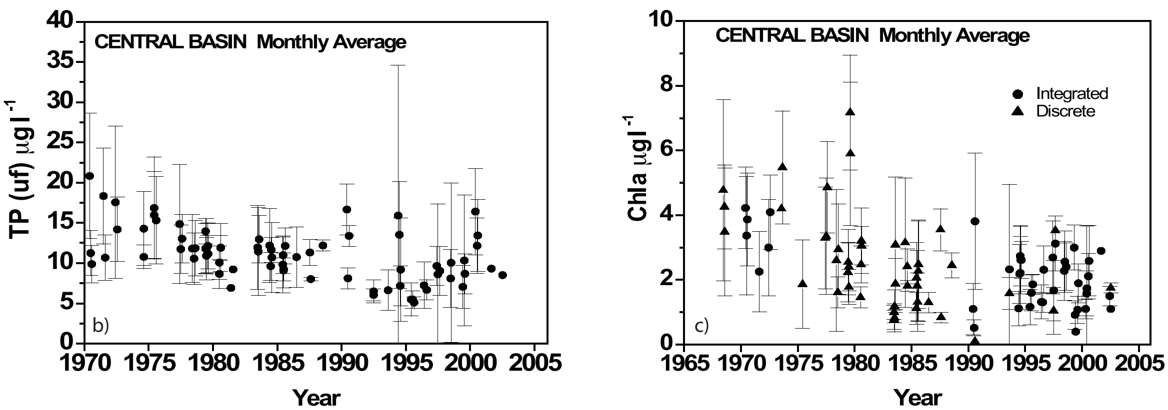
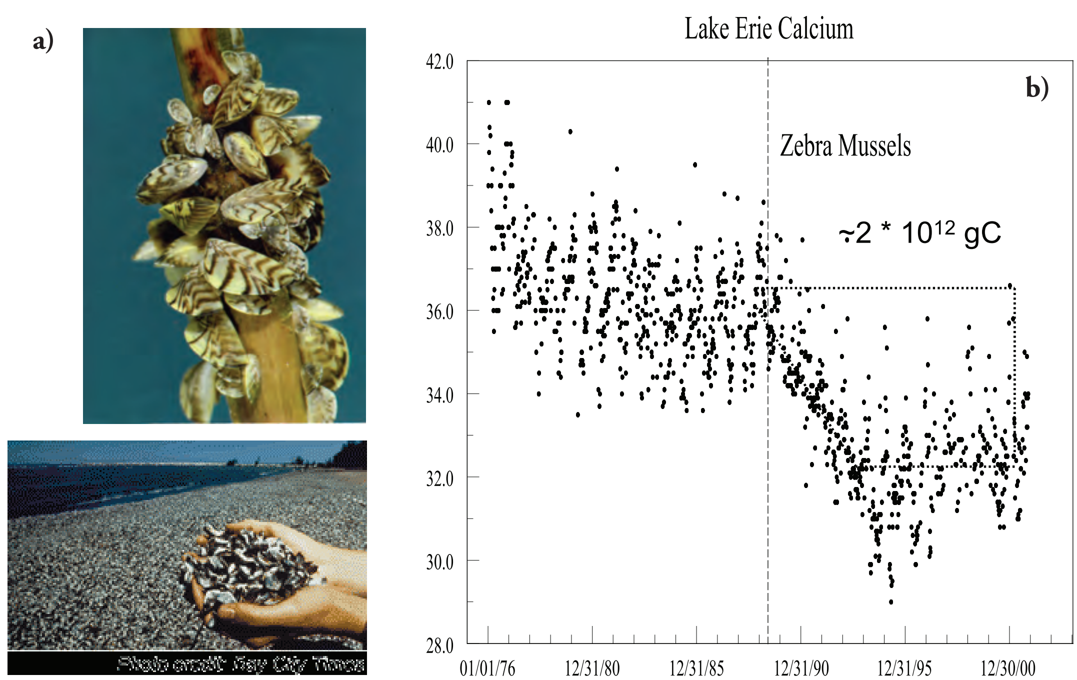


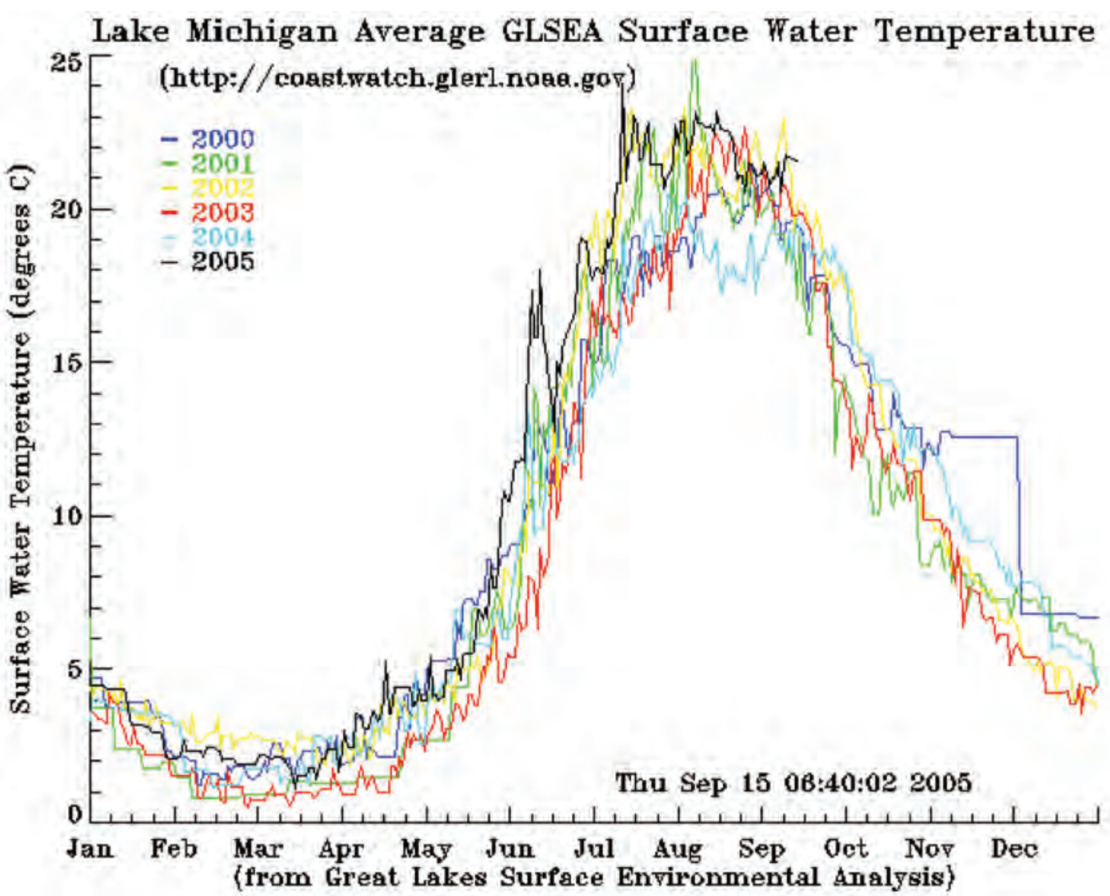
Figure 7.7. The Zebra mussel invasion in the Great Lakes. The large deposits of calcareous shell material (a) led to a significant drop in the alkalinity and (b) calcium content of Lake Erie after the accidental introduction of Dressenid mussels to the lake.



Dreissenid biodeposits and benthic algal biomass. Benthic organic carbon may be transported down-lake and lost at the outflow (Williams et al. 2000), rapidly buried in the nearshore (Howell et al. 1996) or pelagic zone. Evidence suggests that carbon burial rates in the pelagic zone may be decreasing, thereby reducing offshore nutrient availability and respiration rates and phytoplankton production.

The Lakes are also sensitive to large-scale climate change. Nine of the ten warmest years on record in the Great Lakes Basin have occurred since 1990 (Figure 7.8). 1998 was the warmest year, with the mean temperature at the mid point of the regional forecast for 2050. When all data have been collected, 2005 will either replace 1998 or be the second warmest year. The consequences for carbon cycling are complex and not yet fully modeled. Less ice cover, earlier thermal stratification, warmer/thicker upper mixed layers, and generally faster rates for carbon-related processes all need to be evaluated. Another immediate concern relates to a recently observed shift in the mean summer wind field over the Great Lakes Basin. Waples and Klump (2002) examined hourly, NDBC buoy-recorded, summertime wind vectors spanning a 20-year period beginning in 1980 and found that a major shift in wind direction occurred at—and has persisted since—the end of the 1980s. The most likely explanation for this shift in wind direction is a southward displacement of the dominant summer storm track. Wind-driven changes in estuarine circulation and coastal hydrodynamics have been shown to affect water column profiles of temperature, salinity, and dissolved oxygen (Goodrich et al. 1987; Welsh and Eller, 1991) as well as fish and invertebrate populations (Kilgour et al. 2000; Officer et al. 1984).

Figure 7.8. Temperature history of Lake Michigan. Nine of the warmest years on record occurred within the last ten years, with 1998 and 2005 ranking first and second, respectively. This trend has coincided with a decrease in the duration of ice cover on Lake Michigan.



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NORTH AMERICAN CONTINENTAL MARGINS

A Synthesis and Planning Workshop

Report of the
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the U.S. Carbon Cycle Scientific Steering Group
and Interagency Working Group

U.S. Carbon Cycle Science Program
Washington D.C.

Editors
Burke Hales, Wei-Jun Cai, B. Greg Mitchell,
Christopher L. Sabine, and Oscar Schofield

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