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Data on the partial pressure of carbon dioxide (CO_2) in the surface waters from a large number of lakes (1835) with a worldwide distribution show that only a small proportion of the 4665 samples analyzed (less than 10 percent) were within ±20 percent of equilibrium with the atmosphere and that most samples (87 percent) were supersaturated. The mean partial pressure of CO_2 averaged 1036 microatmospheres, about three times the value in the overlying atmosphere, indicating that lakes are sources rather than sinks of atmospheric CO_2. On a global scale, the potential efflux of CO_2 from lakes (about 0.14 $\times 10^{15}$ grams of carbon per year) is about half as large as riverine transport of organic plus inorganic carbon to the ocean. Lakes are a small but potentially important conduit for carbon from terrestrial sources to the atmospheric sink.

Processes that add and remove CO_2 occur simultaneously in the surface waters of lakes. Lakes can thus act either as sources or as sinks for CO_2. Earlier studies have shown that Arctic lakes are strongly supersaturated in CO_2 and therefore are sources to the overlying atmosphere (*1*, *2*). In the Arctic the transport of tundra organic matter to surface waters leads to CO_2 supersaturation (*1*, *2*). Other regions that lack the vast soil carbon storage of the Arctic may behave differently. In fact, detailed studies on a limited number of temperate and boreal lakes have suggested that these lakes are net sinks for atmospheric CO_2 (*3*), but no comprehensive analysis exists. We report data from lakes with a worldwide distribution that show that boreal, temperate, and tropical lakes are typically supersaturated with CO_2 and thus are net sources to the atmosphere.

Data were obtained both from the literature and from our own direct measurements of the partial pressure of CO_2 (P_{CO_2}). The value of P_{CO_2} was calculated from pH and dissolved inorganic carbon (DIC) or acid-neutralizing capacity (ANC) with corrections for other physical and chemical variables (*4*). For the direct measurement of P_{CO_2}, we collected water from 0.1 to 0.25 m below the surface into a thermally insulated 2-liter glass bottle and equilibrated it with 50 ml of ambient air (*5*). Gas chromatography was used to measure CO_2 on the equilibrated head space. Simultaneously ambient air 1 m above the lake surface was collected for the measurement of atmospheric CO_2.

The lakes analyzed range in size from 8.2 $\times 10^6$ ha (Lake Superior) to 0.4 ha, span latitudes from 60°S to 62°N, and include both hard and soft waters (Table 1). For each data set there are differences in the type of measurements made, the intensity of those measurements over time, and geographic location (Table 1). For these reasons we discuss the data in terms of a series of individual data sets.

Of the 37 lakes (390 samples) where direct measurements of P_{CO_2} were made, 16 lakes (43%) were supersaturated at all samplings. Data for a persistently supersaturated lake are shown in Fig. 1. The mean measured P_{CO_2} for the 37 lakes was 801 ± 67 μatm (mean ± standard error), about 2.2 times the measured atmospheric value (Fig. 2A). Only 7% of the samples were within ±20% of atmospheric equilibrium (Fig. 2A).

In the larger data sets for which P_{CO_2} was calculated, we also see a consistent tendency toward supersaturation. For the 1612 lakes sampled in autumn [eastern lakes survey (*6*) (Fig. 2B)], mean P_{CO_2} was 1031 ± 19.4 μatm or three times the atmospheric equilibrium value. Relatively few lakes (6.6%) were within ±20% of the atmospheric equilibrium value.

Because of thermal mixing, autumn may be a time of elevated P_{CO_2} in surface waters. Nevertheless, a similar pattern of supersaturation was seen for 69 lakes from all over the world with full seasonal data for the entire ice-free season (Fig. 2C). For lakes with ANC-based data, calculated mean P_{CO_2} averaged 1122 μatm; for lakes with DIC-based data, calculated mean P_{CO_2} was 1039 μatm. Both of these values are well above atmospheric equilibrium (*7*) and similar to that from the lakes sampled only in autumn (Fig. 2B). For 34 of these 69 lakes, 100% of the samples were supersaturated, and for every lake the time-weighted average was above the atmospheric value.

The 60 lakes (179 samples) sampled only during summer stratification, a time of lower-than-average P_{CO_2}, were also supersaturated. The distribution is broader and the mean lower (680 ± 65 μatm) than for the other data sets (Fig. 2D). For these samples also, only 12.8% were within ±20% of the atmospheric equilibrium value.

Tropical African lakes were strongly supersaturated with the mean P_{CO_2} being about six times (2296 ± 409 μatm) the atmospheric value; few samples (11%) were within ±20% of atmospheric equilibrium (Fig. 2E).

For the lakes for which we both directly measured and calculated P_{CO_2}, we found relatively good agreement between measured and calculated values (*8*), but such agreement

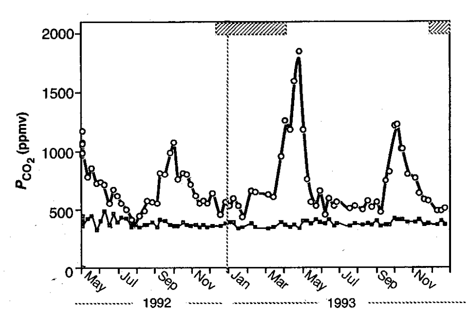

Fig. 1. Seasonal cycle of direct measurements of the P_{CO_2} in the surface water of Mirror Lake (circles) and in the overlying air (squares), showing persistent supersaturation. Mirror Lake is a soft water lake in New Hampshire (*15*); ppmv, parts per million by volume. The hatched areas represent ice cover.

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may not be universal. Electrode-based measurements of pH in lakes with high concentrations of dissolved organic carbon may be biased low by about 0.2 pH unit, which would lead to overestimates of P_{CO_2} (9). Recalculating our data with the assumption that the reported pH was in error by 0.2 pH unit lowers the mean P_{CO_2} to 797 μatm but still leads to the conclusion that lakes are generally supersaturated in CO_2.

Whether P_{CO_2} in the surface waters of lakes is measured directly or calculated from other chemical measurements, most of the lakes that we surveyed were out of equilibrium with the atmosphere and were supersaturated. Only 7% of the samples in the combined data set were within ±20% of equilibrium with the atmosphere, and 87% were supersaturated. Our analysis suggests that the surface water of lakes is rarely at equilibrium with the atmosphere. Furthermore, lakes showed an enormous range of CO_2 concentrations, from 175-fold below to 57-fold above atmospheric equilibrium at the extremes and 3.1-fold below to 16-fold above equilibrium for the means of the upper and lower 10% of the samples.

Lakes from boreal, temperate, and tropical regions appear to be similar to those of the Arctic in overall CO_2 supersaturation. The mean P_{CO_2} from the surface waters of Arctic lakes averaged 1162 ± 132 μatm (*1*, *4*), which compares closely to the mean P_{CO_2} of 1036 μatm for lakes from other regions. The Arctic lakes also show a small percentage (8%) of samples within ±20% of atmospheric equilibrium and a large range in P_{CO_2} [93 to 2758 μatm (*1*, *4*)]. Analyzing our data set by broad regions, we see supersaturation of comparable magnitude within each region. Lakes from boreal (non-Arctic) Sweden, for example, have a mean P_{CO_2} of 1469 ± 38 μatm; South American lakes, 1520 ± 101 μatm; non-Arctic lakes from North America, 1087 ± 23 μatm; and lakes from somewhat higher, tropical Africa, 2296 ± 409 μatm.

In the specific case of Arctic tundra lakes, the large accumulation of organic matter in the tundra and its respiration in soil or lake water is a probable explanation for the excess CO_2 (*1*, *4*). Our data suggest that the phenomenon of excess CO_2 in lake water is quite general and occurs in other regions without these accumulations. Lakes must either import excess CO_2 (derived from plant-root or soil respiration) in inflowing ground or surface waters or produce internally more CO_2 than they consume (that is, ecosystem respiration exceeds ecosystem primary production). If excess respiration within the lake is the cause, the organic matter that supports this process must come either from previously deposited lake sediments or from new inputs from the catchment. Either model would be at odds with published carbon budgets for some lakes (*10*), but both agree with some recent

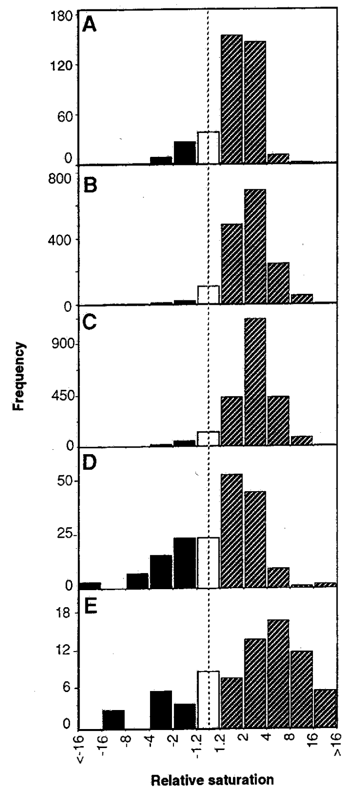

Fig. 2. Frequency diagram (by numbers of samples) for calculated P_{CO_2} in the surface waters of lakes from five different, nonoverlapping data sets: (**A**) direct measurements, (**B**) autumn survey, (**C**) full seasonal data, (**D**) summer survey, and (**E**) tropical Africa. Only values from the ice-free season are shown. Relative saturation (RS) is the degree of supersaturation (hatched bars) or undersaturation (solid bars) relative to atmospheric equilibrium. For supersaturation,

$$RS = P_{CO_2}(water)/P_{CO_2}(air)$$

For undersaturation,

$$RS = -P_{CO_2}(air)/P_{CO_2}(water)$$

On this scale, water with twice the P_{CO_2} of the atmosphere has a value of 2; water with half the value of the atmosphere has a value of −2. The vertical dotted line represents equilibrium with the atmosphere (RS = 1.0), and the open bars represent the samples in near equilibrium with the atmosphere (±20% of equilibrium). See Table 1 for characteristics of the data sets.

Table 1. Some characteristics of lakes in each data set. Only data from the ice-free period are included. The five data sets are nonoverlapping and are kept distinct because of the different information available in each. Letters refer to the panels in Fig. 2.

Parameter	Data set				
	A	B	C	D	E
	Direct P_{CO_2} measurements	Lakes in autumn	Full seasonal cycles	Lakes in summer	African lakes
Lakes (*n*)	37	1612	69	60	59
Samples (*n*)	390	1612	2395	179	79
Latitude (range)	44°25′N–41°21′N	47°13′N–27°14′N	62°00′N–60°43′S	44°5′N–28°00′N	7°26′S–23°17′S
Area (ha) (range)	1.5×10^6–5.8×10^6	1–89,358	0.5×10^6–8.2×10^6	0.4–3,075	1–59,900
pH (range)	4.7–9.5	3.8–9.4	4.2–9.8	4.9–9.3	6.0–9.9
DIC (μM) (range)	4.9–2,500	13.3–4,077	6.6–4,800	11–3,578	43–145,790
P_{CO_2} (μatm) (mean)	801	1031	1064	680	2296
P_{CO_2} (μatm) (range)	107–4,128	20–9,789	1–7,845	5–7,991	32–20,249
Basis of P_{CO_2} estimate	Direct measurement	pH, DIC	pH, DIC pH, ANC	pH, DIC	pH, ANC
Sampling intensity	Weekly to quarterly	Each once in autumn	Varied but more than 10 samples per year	Summer period only; each lake two to three times	One to three times
Source	This study	(*5*)	(*17*)	(*16*)	(*18*)

reassessments of the balance between pelagic production and respiration in lakes (*11*). Our data suggest that the transport of carbon from land to water is an important control on the carbon budget in most lakes.

We can use the frequency distribution of P_{CO_2} to estimate the potential contribution of CO_2 from lakes to the atmosphere. We assume an evasion coefficient of 0.5 m day^{-1} for all lakes, and for undersaturated lakes an enhancement factor of 3 (*12*). Globally, lakes (an area of 2×10^{12} m^2) could contribute CO_2 to the atmosphere in the amount of 0.14×10^{15} g of carbon per year. This flux is slightly less than half as great as the total export of organic plus inorganic carbon from rivers to the sea (*13*), is larger than recent estimates of total organic carbon burial in lake sediments [0.06×10^{15} g (*14*)], and is comparable to organic carbon burial in reservoirs [0.2×10^{15} g (*14*)]. Lakes have longer hydrologic residence times than do flowing waters, which may allow for both the degassing of CO_2 derived from soil respiration and possibly for increased respiration of organic materials derived from the catchment.

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7. During the calculation of P_{CO_2} from pH and ANC, overestimation of true P_{CO_2} may be caused by the presence of noncarbonate ANC. This effect is strongest at low values of ANC; we excluded from our ANC-based calculations samples with ANC below 40 μeq to minimize this effect.
8. We found a strong, unbiased relation between P_{CO_2} directly measured versus P_{CO_2} calculated from pH and DIC. A linear regression of measured versus calculated P_{CO_2} (N = 330 samples) has an r^2 of 0.88 and a slope of 1.03 ± 0.01.
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12. Evasion of CO_2 from supersaturated water was calculated as:

$$\text{Flux}=D/z[(CO_2)_{aq}-K_h(P_{CO_2})_{air}]$$

where K_h is Henry's constant, D is the temperature-dependent diffusion coefficient, and z is the surface boundary layer. An evasion coefficient (D/z) of 0.5 m day^{-1} would be equivalent to z = 300 μm at 22°C (or z = 200 μm at 10°C) and is well within published values for lakes. In undersaturated water, atmospheric CO_2 may react chemically with hydroxyl or carbonate ions more rapidly than it would diffuse passively [S. Emerson, *Limnol. Oceanogr.* **20**, 743 (1975)]. We used an enhancement factor of 3 to compute flux into undersaturated waters.
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