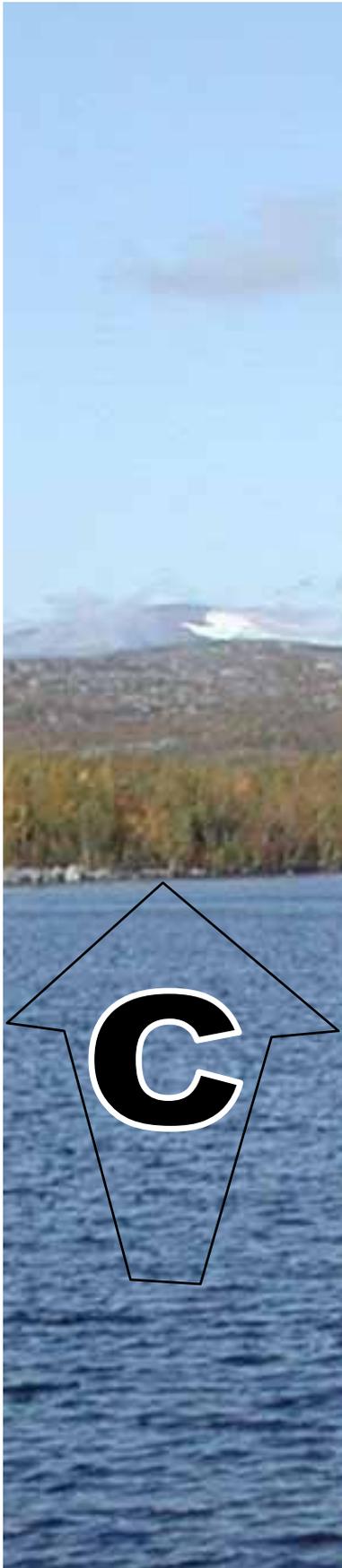


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MINERALIZATION OF ORGANIC CARBON IN NORTHERN LAKES

Jan Åberg

Introductory research essay no 1, 2005
PhD-education in Physical Geography

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TABLE OF CONTENTS

1	Introduction.....	1
2	The global carbon cycle – now and then.....	2
3	Carbon sources and forms in lakes	4
4	Carbon turnover in lakes.....	5
4.1	Mineralization.....	5
4.1.1	Respiration.....	5
4.1.2	Respiration in sediments	6
4.1.3	Methanogenesis.....	7
4.1.4	Photomineralization.....	7
4.2	Sediment burial of C	7
4.3	Groundwater input	8
4.4	Emission	8
4.4.1	Measuring emissions from lakes	8
5	Northern lakes and climate change	10
6	Conclusions	10
7	References	11

1 INTRODUCTION

Due to the expected decline of the sinks of CO₂ on Earth (Schimel et al. 2001) and the particular warming of the northern hemisphere (IPCC 2001), carbon cycle studies are of great interest in northern ecosystems. Today's knowledge can, however, only give us a general picture of the carbon flows in the ecosystems. Many details are yet unknown, raising specific questions about, for instance, how the carbon flows through ecosystems and how flows will change as a response to warming and thawing. (e.g. IPCC 2001, Schimel et al. 2001, Houghton 2003, Janssens et al. 2003).

Forests and undisturbed peatlands of the north are generally thought to be sinks of CO₂ (Janssens et al. 2003). Lakes and streams were also for a long time believed to be sinks of CO₂ (e.g. Wetzel 1983), but recent studies have shown that most lakes are net heterotrophic instead of autotrophic, i.e. the respiration of carbon to CO₂ exceeds the rate of CO₂ uptake by the photosynthesis (del Giorgio 1997, Jansson et al. 2000).

Unproductive lakes are among the few natural landscape compartments which contributes with a net release of carbon to the atmosphere. Since lakes are usually not accounted for in the estimates of the terrestrial sinks, the terrestrial carbon budgets can actually underestimate the magnitude of the sink. A relevant question is therefore: To what extent will lake processes affect the ecosystem exchange (NEE) of northern catchments? To answer that, the carbon flows of the important landscape units must be better assessed. Although important knowledge about forests and mires are lacking, the lack of knowledge about lakes may be even greater; the emission of CO₂ from lakes has, for instance, only on a few occasions been measured using direct methods (Anderson et al. 1999, Eugster et al. 2003).

A second relevant question is: How will global climate change affect the carbon flows? The answers to that can only be speculative, but certainly the predicted decreasing magnitudes of the terrestrial sinks (Schimel et al. 2001) makes it interesting to see how lakes are developing on a warming planet.

This essay aims to (1) briefly review the history and recent findings about global carbon cycling and how lakes are involved in the global carbon cycling, and (2) to describe important aspects of the carbon dynamics of lakes in northern ecosystems.

2 THE GLOBAL CARBON CYCLE – NOW AND THEN

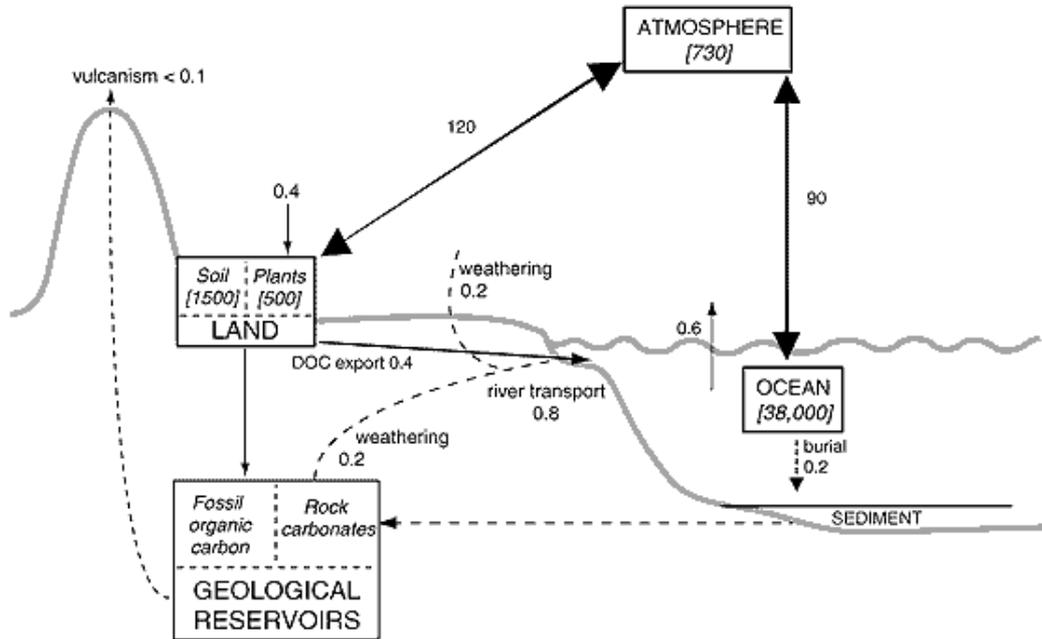
It is now more than 100 years ago the Swedish scientist Svante Arrhenius calculated that doubling the CO₂ in the atmosphere would raise the Earth's temperature some 5-6°C (Arrhenius 1896). Nevertheless, the greenhouse effect caused by CO₂ was questioned until the end of World War II when the expanding atmospheric research made it possible to distinguish the absorption signal of CO₂ from the signal of water vapor (Weart 2003). The human influence on the CO₂ concentration in the atmosphere was confirmed by Keeling (1960) who showed that the CO₂ concentration increased rapidly in the atmosphere. The new C-14 dating-method could also show that fossil carbon accounted for the major part of the increase (Suess 1955). In the beginning of 1970 it was discovered that less than half of the carbon emitted by humans could be found in the atmosphere (Weart 2003). Where did the rest go? The term “the missing sink” came into use and the era of carbon cycle studies began. The missing sink was found both on land and in the ocean, but only as a generalized picture (see below).

In the pre-industrial Holocene the atmospheric concentration of CO₂ was about 280 ppmv CO₂ (equivalent to 500 Gigatons of carbon), and during the last 420 000 years it was variable around 180-300 ppm (Petit et al. 1999). The recent atmospheric CO₂ content is about 370 ppmv (about 730 Gton C, IPCC 2001). However, on a longer timescale, non-ice age periods normally have had much higher concentrations than today (>1000 ppmv, Retallack 2001). These ancient periods are though hard to compare with today because of the different climate systems due to different spatial distribution of the continents.

The global undisturbed carbon cycle (before year 1800) was characterized by large flows of carbon between surface and atmosphere, in a quite steady state created by the living organisms of the planet (Figure 1a). Due to land use changes and the human utilization of geological carbon reservoirs, the atmosphere now receives more CO₂ than can be sequestered by land and ocean (Figure 1b). The main component of the human perturbation is that approximately 8 Gtons of carbon is added to the atmosphere each year, due to land-use changes and fossil fuel burning (e.g. Schimel et al. 2001). However, the increase in the atmospheric CO₂ concentrations only account for approximately 3 Gtons of carbon. Of the 5 missing Gtons of carbon about 2 Gton is taken up by land and ocean each (Schimel et al. 2001, Houghton 2003). This means that the budget is not in balance since more than 1 Gton of the sink can not be explained. The most reasonable explanation is that several small sinks (too small to measured) make up the “missing sink” (Schindler 1999).

The size of the terrestrial sink is expected to decrease with increasing atmospheric CO₂-content, mainly due to diminishing fertilization effects of CO₂ and N in the ecosystems (Schimel et al. 2001).

A Main components of the natural carbon cycle



B The human perturbation

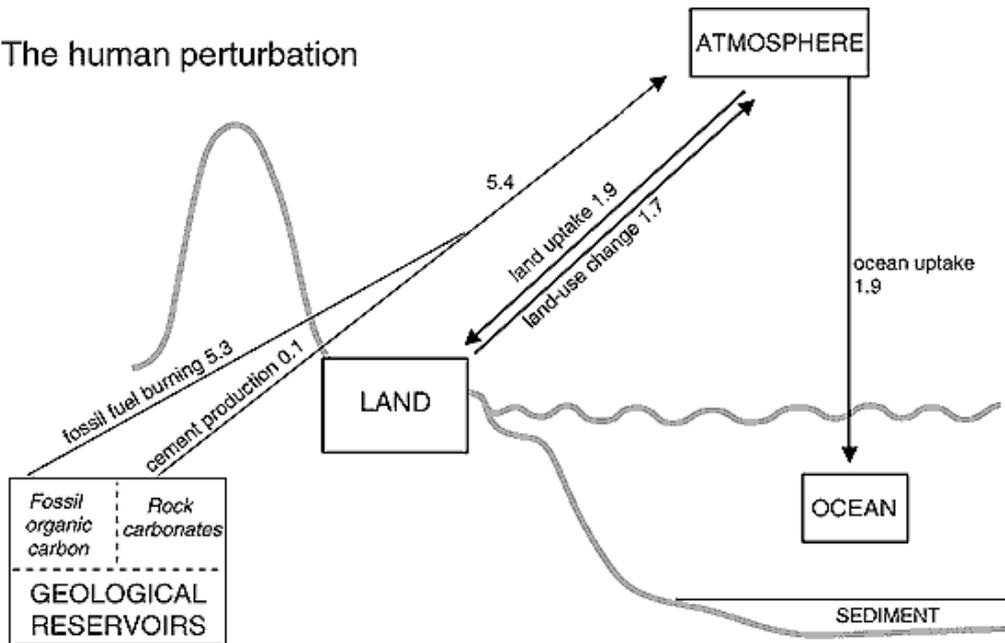


Figure 1. (A): the main components of the global carbon cycle in Holocene before industrialization. (B): the main components of the human perturbation of the global carbon cycle. Values refer to year 1980. Boxes denote the main carbon storages on earth (Land, Ocean, Atmosphere and Geological reservoirs). Arrows denote pathways of the carbon flows. From IPCC (2001).

3 CARBON SOURCES AND FORMS IN LAKES

The main forms of carbon in lakes and streams are dissolved and particulate organic matter (DOC and POC) and dissolved carbonates (Dissolved Inorganic Carbon, DIC). The DOC-fraction of the organic carbon mainly consists of organic molecules, colloids and viruses in, while plankton, plant litter, algal debris, invertebrates, eroded soil organic matter and soil detritus are found in the POC-fraction (Figure 2). The organic carbon is commonly subdivided into allochthonous and autochthonous carbon derived from terrestrial organic matter and in-lake biological production, respectively (Hope et al. 1994). The ultimate origin of practically all organic carbon is photosynthesis, including both recent and old photosynthate with ages ranging from hours to thousands of years (McDowell 2003).

Inorganic carbon (i.e. dissolved inorganic carbon and gaseous CO₂) originates from carbonate in soils and bedrock, dissolved CO₂ from the atmosphere and mineralized organic matter.

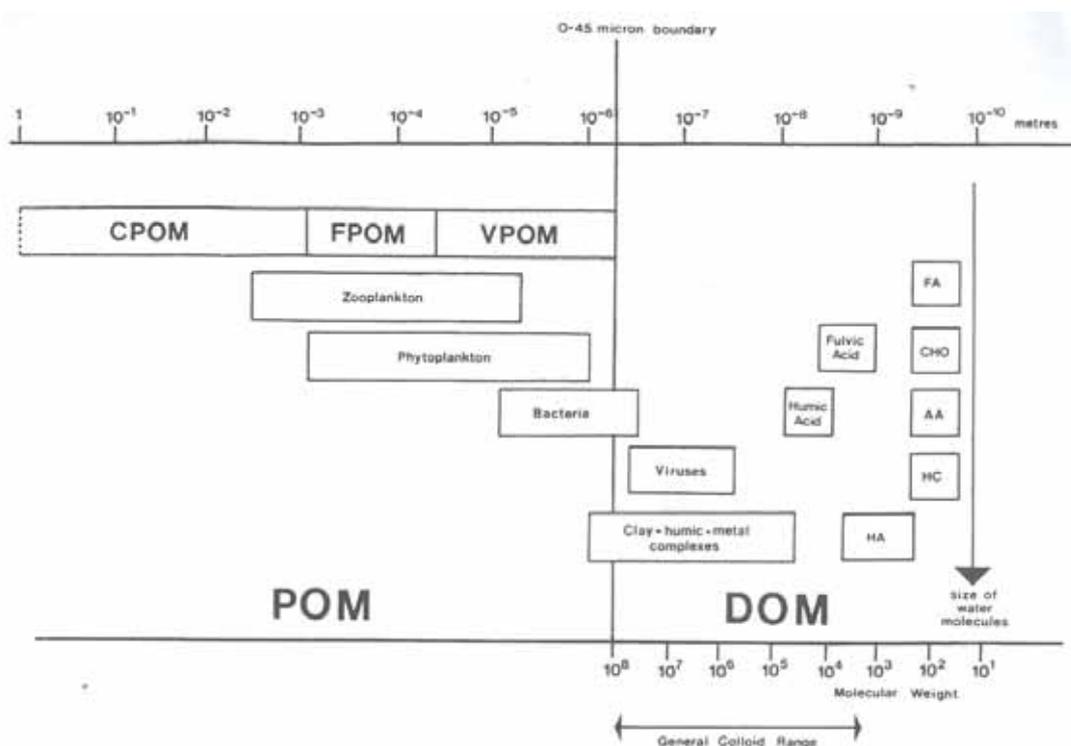


Figure 2. Size range of particulate and dissolved organic matter in natural waters. AA: amino acids. CHO: carbohydrates. FA: fatty acids. HA. hydrophilic acids. HC, hydrocarbons. CPOM, FPOM and VPOM: coarse, fine and very fine particulate organic matter (from Hope et al. 1994).

The inorganic carbon is usually classified as dissolved inorganic carbon (DIC), including CO₂ (H₂CO₃), HCO₃⁻, and CO₃²⁻. Particulate inorganic carbon (PIC) is usually not accounted for because it occurs in very low amounts in acidic waters (McConnaughey 1994).

4 CARBON TURNOVER IN LAKES

Carbon enters a lake via diffuse inflows of groundwater, water from inlets, atmospheric particulate deposition and uptake of gaseous carbon from the atmosphere (mainly through photosynthesis). Removal of carbon occurs via outlets, sedimentation and via gaseous emissions from the lake surface. Transformation of carbon occurs mainly through the different mineralization processes.

Turnover processes, very slow (or small) or not relevant, but worth mention, is (1) calcification, which occurs in alkaline waters, and means that calcium is precipitated while the CO₂ levels increase (McConnaughey et al. 1994), (2) chemoautotrophy, which contributes to losses of dissolved inorganic carbon besides photosynthesis (noted by den Heyer and Kalff 1998), and (3) atmospheric deposition, which contributes with only very small carbon input (Hope et al. 1994)

Lake carbon budgets have among others been published by McConnaughey (1994), Wachniew and Rozanski (1997), Striegl and Michmerhuizen (1998), Riera et al. (1999), Jonsson et al. (2001) Jones and Grey (2001) and Åberg et al. (2004).

4.1 Mineralization

In natural waters phototrophic organisms mobilize CO₂ into organic molecules, and consequently tend to reduce the concentration of DIC. On the other hand the C-uptake is counteracted by atmospheric replenishment and by mineralization processes; mainly organism respiration and photomineralization. The mineralization results by definition in carbon dioxide (CO₂, including the ionic forms of DIC: HCO₃⁻ CO₃²⁻ and H₂CO₃), and to some extent also methane (CH₄) and carbon oxide (CO). In addition to that a large fraction of the dissolved organic carbon, especially humic substances, is degraded very slowly and can in this context also be regarded as end products (Jones 1992).

4.1.1 Respiration

The food webs of lakes have two major energy sources, internally accumulated energy by photosynthesis and external energy from inflowing (allochthonous) organic carbon (Jones 1992). In lakes with no significant allochthonous loading, primary production by phytoplankton will form the base of the food web, mobilizing and transferring energy to higher trophic levels. If the allochthonous input is significant also bacteria can act as energy mobilizers (Figure 3). Lakes where organic carbon mineralization by heterotrophic organisms exceeds CO₂ fixation by phototrophic organisms are classified as net heterotrophic (Jansson et al. 2000).

Although several studies have shown that the heterotrophic respiration exceeds primary production in many oligotrophic lakes (del Giorgio et al. 1997, Jansson et al. 2000), parts of the heterotrophic respiration are fuelled by carbon from autochthonous primary production, and generally, autochthonous carbon seems to be the energy source preferred by the energy mobilizers (e.g. Kritzberg et al. 2004). However, significant importance of allochthonous organic carbon in aquatic food webs has been shown especially in humic waters where poor light climate and nutrient limitation favors bacteria (Grey et al. 2001, Pace et al. 2003). Also the food webs of oligotrophic

clearwater lakes can largely be based on allochthonous carbon if the organic carbon: inorganic nutrients-ratio favors bacterial growth (Karlsson et al. 2002, 2003).

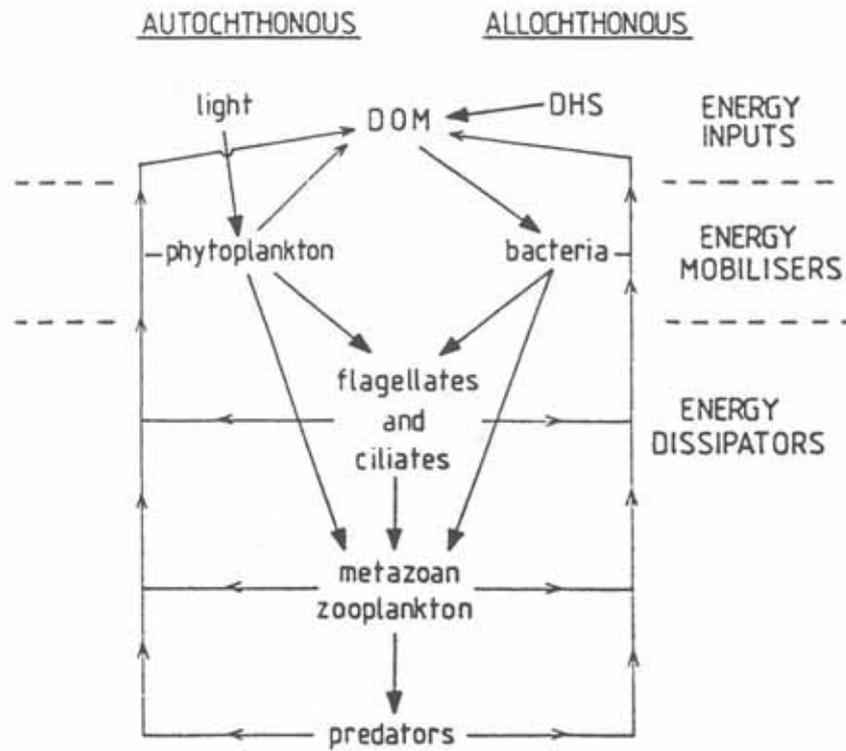


Figure 3. Generalized plankton food web in a freshwater system illustrating the separate input of autochthonous and allochthonous energy, i.e. light and dissolved humic substances (DHS). From Jones (1992).

The amount of CO₂ produced in the bacterial loop of the food-web is highly dependent on the nutrient status. Extreme oligotrophic systems show very low bacterial growth efficiency (BGE), resulting in high bacterial respiration in comparison to the production of bacterial biomass, and consequently a low energy mobilization to higher trophic levels (Smith and Prairie 2004). Del Giorgio et al. (1997) gives the range of BGE from <10% in oligotrophic systems to a plateau at ~40% in the most productive systems, which means that the ratio between bacterial production and bacterial respiration (BP:BR) ranges from less than 1:10 to ~7:10 in the gradient from oligotrophic to eutrophic lakes.

4.1.2 Respiration in sediments

Bacteria are some two to three orders of magnitude more abundant in the sediments than in the equivalent volume of overlying water (Schallenberg and Kalff 1993), and a general conclusion made by den Heyer and Kalff (1998) is that the relative importance of sediment mineralization increases with decreasing lake depth and nutrient status.

The partial pressure of CO₂ (pCO₂) in the surface water of lakes has been shown to be related to the epilimnetic sediments:epilimnion volume-ratio in 11 boreal lakes (Kelly

et al. 2001), suggesting that respiration of epilimnetic sediments are of great importance for the subsequent CO₂ flux (Kelly et al. 2001, Jonsson et al. 2001, Åberg et al. 2004).

In relation to the total lake respiration, den Heyer and Kalff (1998) estimated that sediment respiration in a 10 meter deep lake would contribute with 8-33% depending on trophic status. Jonsson et al. (2001) estimated that the sediments in humic Lake Öträsket contributed with about 40% of the net CO₂-production.

4.1.3 Methanogenesis

In anoxic environments a small group of organic molecules, including methanol, formate, and acetate, can be transformed into CH₄, by methanogenic bacteria. CH₄ can be important to study, since the global warming potential of the gas is 23-62 times higher than for CO₂ (in the 100 and 20 years time horizon, respectively, IPCC 2001). However, in lakes transformation of CH₄ to CO₂ occur by methanotrophic bacteria and since these bacteria occurs in most oxic waters (Madigan et al. 1997) a large part of the methane production of the lake sediments can be expected to transform into CO₂ before it reaches the surface and is released to the atmosphere (Wetzel 2001).

4.1.4 Photomineralization

The absorption of sunlight by dissolved organic matter (DOM) induces several photoreactions, bleaching the DOC and reducing its average molecular weight. A lot of substances have been identified as photochemical breakdown products, such as nutrients (ammonium and phosphate), carbon gases (carbon dioxide and monoxide), aliphatic carbonyl compounds, and carboxylic acids (Moran and Zepp 1997; Brinkmann 2003).

The photochemical breakdown could either directly mineralize the organic carbon (CO or CO₂ are then produced) or contribute to a more rapid organism respiration if the photodegradation products are more bioavailable than the original molecule. Humic (allochthonous) DOM is predominantly transformed into more bioavailable photodegradation products whereas the photodegradation products of algal-derived DOM gets decreased substrate quality (Tranvik and Bertilsson 2001). On the other hand the algal derived DOM is initially be more bioavailable than humic DOM (Kritzberg et al. 2004).

Photomineralization may be important when looking solely at the mineralization of the pelagial (e.g. Sobek et al. 2003). However, the more or less rapid light attenuation in natural waters (e.g. Wetzel 2001) dictates that most of the photomineralization will occur in the uppermost stratum of the lake. In 33 Swedish lakes it was not an important factor controlling the pCO₂ (Sobek et al. 2003), suggesting that the pelagic and benthic respiration is of greater importance for the pCO₂ in most lakes.

4.2 Sediment burial of C

Sediment burial of C in boreal lakes during Holocene has resulted in large C pools in the sediments (19 kg m⁻², to compare with forest soil (7.2 kg m⁻²) and woody biomass (3.4 kg m⁻²), Kortelainen et al. 2004). Data from Pajunen (2000) were used by

Algesten et al. (2004) and Huttunen et al. (2003), who calculated that the CO₂-C emission from Swedish (n=79 536) and Finnish (n=3) boreal lakes was about 5-14 times higher than the sediment burial of C. The sedimentation in the Swedish lakes was in absolute numbers 0.13–0.48 g C m⁻² yr⁻¹ (Algesten et al. 2004).

4.3 Groundwater input

Several studies show that groundwater input of DIC can account for a substantial part of the total CO₂ emission from lakes (e.g. Riera et al. 1997, Jones et al. 2001). However, those lakes are located in carbonate-rich catchments, contributing with CO₂ to the water. Recent studies in catchments with non-carbonate bedrock show that external DIC-input only is a small share of the total CO₂ emission from the lakes (Jonsson et al. 2001, Sobek et al. 2003, Åberg et al. 2004). This suggests that irrespective of the DIC input, lakes are important sources of carbon dioxide in the biological carbon cycles of a catchment.

4.4 Emission

The water columns of net heterotrophic lakes become supersaturated with respect to CO₂, which results in a net flux of CO₂ from the lake surface to the atmosphere (e.g. Cole et al. 1994, Cole and Caraco 1998). By combining Wetzel's (2001) estimate of the global lake surface area and the global C-emission from lakes (Cole et al. 1994), the average emission of C from lakes would be about 56 mg C m⁻² d⁻¹. However, such estimates likely have significant errors, since most emission estimates are based on models, and not direct measurements (see below).

Typical emissions from Swedish lakes and reservoirs are 79 and 128 mg C m⁻² d⁻¹ respectively (Algesten 2003, interpolation covering 79 536 lakes and reservoirs; Bergström et al. 2004, calculated for 24 hydroelectric reservoirs).

Global lake emissions of CH₄ have not been estimated as far as I know. However, there are recent measurements made by Huttunen et al. (2003): range in five Finnish lakes was 1.3-61 mg C m⁻² d⁻¹, and Riera et al. (1999): range 1.4 to 15 g C m⁻² d⁻¹. Both these studies were carried out in a gradient from clear water lakes to bog lakes. Riera et al. (1999) also gives a bibliography of earlier estimates of CH₄-emissions.

Emissions of both CO₂ and CH₄ show large temporal variation, with high values in spring and autumn, and low values during summer stratification (Riera et al. 1999, Åberg et al. submitted). Diurnal variation of gas loss can also be expected, and are mainly related to wind speed and periods of heat loss of the surface layer (MacIntyre et al. 2001).

4.4.1 Measuring emissions from lakes

Gas emissions from a water surface occur either through diffusion or the release of gas bubbles (ebullition). In northern lakes the major part of the CO₂ emission likely occurs through diffusive fluxes, while CH₄ to a greater extent is released through ebullition (e.g. Huttunen et al. 2001).

The direction of the diffusive flux of CO₂ and other gases through the air-water interface is dependent of the concentration gradient between the air and the surface water; and the magnitude of the flux depends additionally on the gas exchange coefficient, *k*, which depends on the particular properties of the micro boundary layer between air and water (e.g. Liss and Slater 1974, Cole and Caraco 1998). One widely used model for estimating CO₂ emissions from lakes was developed by Cole and Caraco (1998), who added the trace gas SF₆ into Mirror Lake (Hubbard Brook, USA), and measured different gas pathways and factors which characterized gaseous loss in the lake.

There are at least two main difficulties using models; (1) to get accurate predictions of *k*, and (2) to get representative samples on temporal and spatial scales. To solve the temporal problem, logger techniques can be applied (Sellers et al. 1995), but to obtain a reliable *k*, model for the particular system have to be used, or adaptations of already existing relationships.

An other approach for measuring gas fluxes is to capture the flux in chambers floating on the lake surface (e.g. St. Louis et al. 2000, Huttunen et al. 2003, Matthews et al. 2003). This method has the benefit of also capturing gas bubbles. However by putting chambers on the surface, the gas exchange coefficient will likely be altered in comparison to the natural state. Duchemin et al. (1999) compared the two techniques and found that the boundary layer method showed significantly lower values than those obtained from floating chambers, but that both methods gives values within the same order of magnitude. A more recent study (Matthews et al. 2003) shows that values from floating chambers can be overestimations, at least in low wind environments.

Direct measurements of the gas flux over lake surfaces have been made in only a few lakes, covering only short periods of time. The Eddy Covariance technique (e.g. Valentini et al. 2003) has in fact only been used on lakes by Anderson et al. 1999, who measured Williams Lake, Minnesota USA, for about three weeks distributed over three years, and by Eugster et al. (2003) who measured Toolik Lake, Alaska USA, and Soppensee, Switzerland, for about three days in each lake. As the Eddy Covariance technique has been made more affordable and easier to use, at least two new lake-projects using Eddy-Covariance technique are running today. One of the projects investigates a small boreal lake in southern Finland, and the other investigates subarctic lakes in a climate gradient in northern Sweden (Figure 4).



Figure 4. Eddy covariance setup at Lake Diktar-Erik in Abisko, Northern Sweden ($68^{\circ}27'N$, $18^{\circ}36'E$).

5 NORTHERN LAKES AND CLIMATE CHANGE

According to IPCC's climate change scenarios, large parts of the northern hemisphere will become warmer and more humid (IPCC 2001). Forsberg (1992) predicted that such future will increase the allochthonous organic carbon loading in Swedish lakes and rivers, which leads to the hypothesis that northern lakes are going towards increased emissions of CO_2 . In addition, the abundance of lakes in the drastically climate changing north in combination with the expected decreasing magnitudes of the terrestrial sinks, leads to the hypothesis that northern ecosystems in the future will play a relatively more pronounced role in the global carbon cycle.

6 CONCLUSIONS

- Most unproductive lakes in the world are net heterotrophic and thus net sources of CO_2 to the atmosphere.
- The source of CO_2 net emissions is allochthonous organic carbon.
- CO_2 is produced both in pelagic and benthic habitats.
- The distribution of pelagic and benthic sources of CO_2 depends on lake morphometry but there is so far no consensus of the relative importance of the two habitats.
- Since the role of lakes as mineralization sites for terrestrially derived organic carbon depends on loading of dissolved organic carbon and water retention times it can be hypothesized that emissions of CO_2 from lakes can change as a consequence of e.g. global warming.

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