Open access • Journal Article • DOI:10.1130/0091-7613(1998)026<0535:MASOCB>2.3.CO;2

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Walter E. Dean, Eville Gorham

Institutions: United States Geological Survey

Published on: 01 Jun 1998 - Geology (Geological Society of America)

Topics: Carbon sink and Peat

Magnitude and significance of carbon burial in lakes, reservoirs, and peatlands

Walter E. Dean
U.S. Geological Survey, M.S. 980, Federal Center, Denver, Colorado 80225
Eville Gorham
Department of Ecology, Evolution, and Behavior, University of Minnesota, St. Paul, Minnesota 55108

ABSTRACT

Globally, lakes are currently accumulating organic carbon (OC) at an estimated annual rate of about 42 Tg·yr^{-1}. Most of the OC in all but the most oligotrophic of these lakes is autochthonous, produced by primary production in the lakes. The sediments of reservoirs accumulate an additional 160 Tg annually, and peatlands contribute 96 Tg annually. These three carbon pools collectively cover less than 2% of the Earth's surface and constitute a carbon sink of about 300 Tg·yr^{-1}. Although the oceans cover 71% of the Earth's surface, they accumulate OC at a rate of only about 100 Tg·yr^{-1}.

INTRODUCTION

Considerable coverage has been devoted to terrestrial carbon sequestration in soils, forests, and grasslands. Little attention has been given to carbon burial in peatlands, and even less attention has been paid to carbon burial in lakes and reservoirs. Lakes are generally discounted as significant sinks for carbon, and some evidence even suggests that they may be net sources of CO_2 to the atmosphere (e.g., Cole et al., 1994; Molot and Dillon, 1997). Nevertheless, the sediments of lakes and reservoirs constitute a large sink of organic carbon when compared with carbon burial in ocean sediments.

CARBON BURIAL IN LAKES

Moderately to highly productive (mesotrophic to eutrophic) temperate zone lakes typically contain olive-green sediments rich in organic matter (>20% organic matter by loss on ignition at 550 °C, >10% organic carbon) called *gyttja*. Many of these lakes are underlain by calcareous glacial drift and contain waters rich in calcium-magnesium bicarbonate. Those lakes precipitate calcium carbonate ($CaCO_3$), mostly as low-magnesium calcite producing a calcareous sediment called *marl*. For reasons discussed below, most of the organic matter in gyttja and marl is autochthonous, that is, produced by phytoplankton and aquatic macrophytes in the lake. The largest pool of organic carbon (OC) in a lake is dissolved organic carbon (DOC), which is usually about 10 times greater than particulate organic carbon (POC; Wetzel, 1975). POC, however, is the dominant source of OC in the sediments.

Studies of fossilized plant pigments in the surface sediments of Minnesota lakes (Sanger and Gorham, 1970; Gorham and Sanger, 1975) showed that (1) most of the organic matter in an average Minnesota lake is autochthonous, and (2) only in the least productive of the lakes in northeastern Minnesota does allochthonous terrestrial organic matter make a significant contribution to sedimentary organic matter. Autochthonous organic matter is enriched in proteinaceous, low-molecular-weight compounds high in H and N, with low C/N ratios (typically <10; Meyers and Ishiwatari, 1993). Allochthonous terrestrial organic matter has more abundant high-molecular-weight, humic compounds rich in C, with much higher C/N ratios, typically 20–30 (Meyers and Ishiwatari, 1993). The average OC concentration in surface profundal sediments of 46 representative lakes throughout Minnesota is 12% (range, 3%–29%; Dean et al., 1993). The average OC/N ratio in the sediments of those lakes is 9.0 (range, 7.6–14). The only sediments reported by Dean et al. (1993) with OC/N ratios >11 are from 5 of 10 relatively unproductive lakes in northeastern Minnesota.

Analyses of plant pigments in surface sediments from lakes in the English Lake District demonstrated that, as in Minnesota lakes, much of the organic matter in the more productive lakes is autochthonous (Gorham et al., 1974). The average OC concentration in the English lakes is 7.0% (range 4.0%–13%) and the average OC/N ratio is 12.2 (range 9.4–14.1) with little variation between lake productivity groups (Gorham et al., 1974). The average OC content and OC/N ratio in sediments of 23 Wisconsin lakes compiled by Brunskill et al. (1971) are 20% and 11, respectively. High concentrations of organic matter in the surface sediments of 16 lakes in the Experimental Lakes Area on the Precambrian shield of northwestern Ontario (OC = 20% ± 7%) are due to lack of clastic and carbonate dilution rather than high productivity, but this organic matter still has OC/N ratios (average = 9.7) typical of organic matter in more southerly lakes situated on glaciated sedimentary strata (Brunskill et al., 1971).

Most of the organic matter in sediments in the depositional basins of the Great Lakes is autochthonous (from plankton), has OC concentrations >1%, and C/N ratios of 7–9 (Kemp et al., 1977; Meyers and Ishiwatari, 1993). Glacial sediments in the Great Lakes with little organic matter have OC/N ratios >16 (Kemp et al., 1977).

From all these considerations, we conclude that most of the organic matter in most lakes is autochthonous, with OC/N ratios mostly <10. This conclusion is contrary to a common perception that the organic matter in most temperate lakes is derived from terrestrial sources (e.g., Mackereth, 1966; Brunskill et al., 1971; Molot and Dillon, 1996).

If the OC in lakes of the glaciated regions of the Northern Hemisphere, like that in the Minnesota lakes, Experimental Lakes Area, English lakes, and Great Lakes, comes from carbon that is fixed by photosynthesis, the carbon pool buried over the past 10 000 yr must be tremendous. To estimate the rates of OC burial in lakes, we shall start with Minnesota, a region with a particularly dense concentration of lakes, and one where we have a great deal of information and experience.

To calculate accumulation rates of carbon we need measurements of dry bulk density (DBD), a good chronology, and measurements of OC. Measured values of DBD for lake sediments are rare. One of the few examples of a lake for which all of these measurements have been made is Elk Lake, in Clearwater County, Minnesota (Dean, 1993). The Holocene sediments in Elk Lake consist of a continuous sequence of annual layers (varves) providing annual time resolution. The combination of varve-calibrated sedimentation rate and bulk density measured every 50 yr was used to calculate mass accumulation rates (MARs) of bulk sediment, which, when multiplied by the fraction of OC and carbonate carbon (CC), give MARs for these components (Fig. 1; Dean, 1993). Figure 1A shows that carbon accumulation rates over the past 4000 yr have been fairly constant but were generally higher and much more variable during the mid-Holocene

(8000 to 4000 yr B.P.). The average MARs for OC, CC, and TC (total carbon) over the past 4000 yr are 46, 36, and 82 $g \cdot m^{-2} \cdot yr^{-1}$, respectively. For comparison, OC MARs for the top 10 cm of eutrophic Lake Greifen, Switzerland, are 50–60 $g \cdot m^{-2} \cdot yr^{-1}$ and were about 10 $g \cdot m^{-2} \cdot yr^{-1}$ prior to the 1880s (Hollander et al., 1992).

We calculated carbon MARs for cores from two other Minnesota lakes (Fig. 1, B and C) for which there are bulk density and carbon measurements, but much lower age resolutions. Williams Lake is hydrologically closed, and has a residence time of about 4 yr (LaBaugh et al., 1995). For the past 4000 yr, Williams Lake has been accumulating high concentrations of OC (30%–35%), and, although $CaCO_3$ is precipitated, it is dissolved in the CO_2-charged bottom waters (Schwalb et al., 1995). Initially, Williams Lake did accumulate $CaCO_3$ (up to 75% dry weight of sediment) but that amount decreased to zero over the first half of the Holocene as the lake evolved into a closed lake and high concentrations of OC accumulated in the sediments (Schwalb et al., 1995). Nearby Shingobee Lake is hydrologically open, with a residence time of about 7 months, and has always accumulated high concentrations of $CaCO_3$ (60%–80%) and relatively low concentrations of OC (2%–6%). The average MARs for OC, CC, and TC for Shingobee Lake over the past 4000 yr are 17, 38, and 55 $g \cdot m^{-2} \cdot yr^{-1}$, respectively. No CC accumulated in the sediments of Williams Lake over the past 4000 yr, but the average MARs for OC and TC are both 21 $g \cdot m^{-2} \cdot yr^{-1}$. Therefore, the carbon MARs in these two lakes are within the same orders of magnitude as those for Elk Lake (10–100 $g \cdot m^{-2} \cdot yr^{-1}$; see Fig. 1).

How typical are these above-mentioned accumulation rates? The mean sediment accumulation rate in 164 midlatitude, Holocene lake sites in eastern North America (including Minnesota) reported by Webb and Webb (1988) is 81 $cm \cdot 10^{-3} \cdot yr^{-1}$ (i.e., an average of about 8 m of Holocene sediments). In contrast, profundal Holocene sediments in lakes of central Europe typically are 5–6 m thick (K. Kelts, 1997, personal commun.). The mean sediment accumulation rate for the historic period (postsettlement) in the midlatitude lake sites reported by Webb and Webb (1988) is 298 $cm \cdot 10^{-3} \cdot yr^{-1}$ (about 3 $mm \cdot yr^{-1}$), or about four times Holocene rates.

Dry bulk densities of sediment are dependent mainly on the OC content and vary considerably. The DBDs of Holocene sediments in Elk, Williams, and Shingobee Lakes decrease rapidly with increasing OC (Fig. 2A), emphasizing the importance of bulk density measurements. However, because DBD and OC contents are inversely related, the content of OC per unit volume of sediment is relatively constant at about 20 $mg \cdot cm^{-3}$ except for the least organic sediments (Fig. 2B). Thus, if the sedimentation rate ($cm \cdot yr^{-1}$) is known, the OC MAR can be estimated without measuring the OC content or the DBD.

The average OC and CC concentrations in surface sediments of 46 lakes chosen as a representative sample for Minnesota are 12% and 2%, respectively (Dean et al., 1993). The relationship of bulk density to OC content (Fig. 2A) indicates that a lake sediment with 12% OC should have a DBD of about 0.2 $g \cdot cm^{-3}$. At an average postsettlement sedimentation rate of 3 $mm \cdot yr^{-1}$ (the average midlatitude rate of Webb and Webb, 1988), this average sediment should have a bulk-sediment MAR of 600 $g \cdot m^{-2} \cdot yr^{-1}$, and OC and CC MARs of 72 and 12 $g \cdot m^{-2} \cdot yr^{-1}$, respectively. The mean OC MARs for small (<100 km^2) lakes compiled by Mulholland and Elwood (1982) are 27 $g \cdot m^{-2} \cdot yr^{-1}$ for oligotrophic lakes and 94 $g \cdot m^{-2} \cdot yr^{-1}$ for meso-eutrophic lakes.

How much carbon sequestration is occurring in Minnesota lakes alone? There are 15 291 lakes in Minnesota that have an area of >10 acres (4 ha or 40×10^3 m^2), and these 15 291 lakes have a total area of 3.4×10^6 acres = 1.4×10^{10} m^2 (Minnesota Conservation Department, 1968). If these lakes are accumulating OC at the average Minnesota lake rate of 72 $g \cdot m^{-2} \cdot yr^{-1}$, the total OC accumulation is about 10^{12} $g \cdot yr^{-1}$ or 1 $Tg \cdot yr^{-1}$. This value does not include lakes with areas <10 acres nor the extensive wetlands throughout Minnesota.

Sediments in the depositional basins of the lower Great Lakes (Michigan, Huron, Erie, and Ontario) usually contain more than 2% OC of predominantly algal origin (Kemp et al., 1977; Meyers and Ishiwatari, 1993). Linear sedimentation rates and measured values of DBD, however, are more difficult to come by. Data for Lake Michigan (Rea et al., 1980; Colman et al., 1990, 1994) suggest that the youngest sediments with an average DBD of about 0.25 $g \cdot cm^{-3}$ were deposited at an average rate of about 0.1 $cm \cdot yr^{-1}$ for a bulk-sediment MAR of 250 $g \cdot m^{-2} \cdot yr^{-1}$. At 2% OC, this bulk-sediment MAR yields an OC MAR of about 5 $g \cdot m^{-2} \cdot yr^{-1}$ (Rea et al., 1980). If we assume that the depositional basins of Lake Michigan where this OC MAR applies constitute about 75% of the area of Lake Michigan (5.8×10^4 km^2), then the present OC accumulation rate in Lake Michigan is about 0.22 $Tg \cdot yr^{-1}$ or about 22% of the rate for all Minnesota lakes.

Most people would agree that the continental margins of the oceans, particularly margins under upwelling areas, are significant sinks of organic carbon. The continental margin off California under the California Current upwelling system covers an area of 4×10^{10} m^2. The average Holocene OC MAR based on radiocarbon-dated cores with measured bulk densities from within this area was 0.06 $Tg \cdot yr^{-1}$ (Gardner et al., 1997). In other words, the area of the California continental margin is almost three times the total area of all lakes in Minnesota larger than 10 acres, but the OC burial rate along that continental margin is only about 6% of that in Minnesota lakes. Globally, continental margins only amount to 12% of the area of the world oceans, but they are estimated to account for 44% of the present burial of OC in the oceans (Emerson and Hedges, 1988).

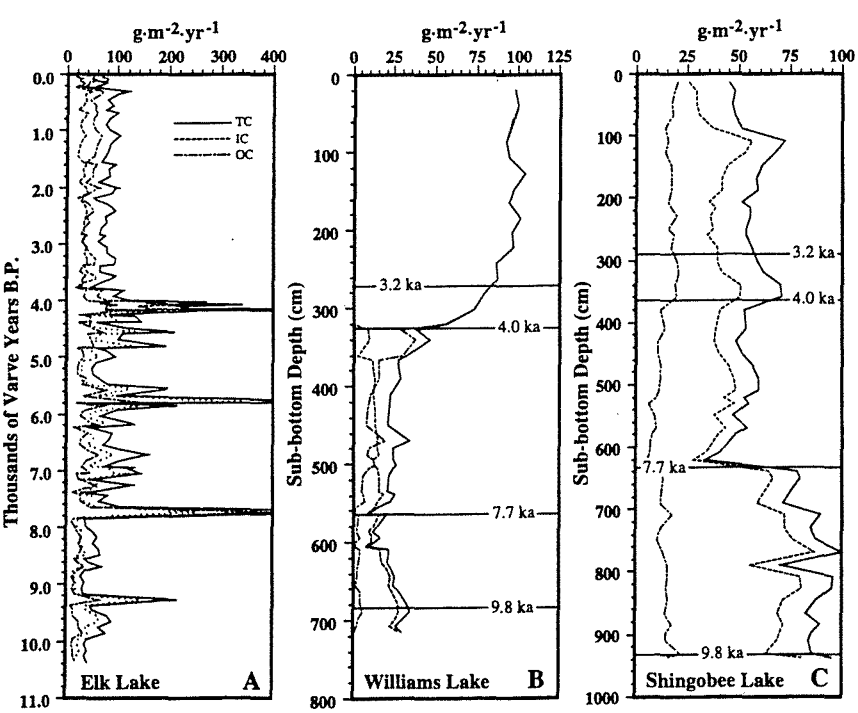

Figure 1. Mass accumulation rates of total carbon (TC), inorganic carbon (IC), and organic carbon (OC) in Holocene sediments of Elk Lake (A), Williams Lake (B), and Shingobee Lake (C), Minnesota. Horizontal lines with ages indicate the depths of pollen-zone boundaries of Schwalb et al. (1995).

The point that we want to make is that lake sediments are sequestering large amounts of carbon fixed mostly by aquatic primary productivity. This is emphasized by the fact that the OC burial rate in Minnesota lakes is 17 times that on the California margins. Together, the sediments of lakes in the glaciated regions of the northern hemisphere must constitute an important carbon sink.

Shiklomanov (1993) estimated that freshwater lakes in the world have a total area of about 1.5×10^{12} m^2 (Table 1). Including saline inland seas in this total would add another 1×10^{12} m^2. The 28 largest (area > 5000 km^2) freshwater lakes in the world have a total area of 1.18×10^{12} m^2 or about 79% of the total area of freshwater lakes. If the 28 large lakes bury OC, on average, at the same rate as Lake Michigan (5 $g \cdot m^{-2} \cdot yr^{-1}$), then the annual rate of OC burial in these 28 lakes is about 6 $Tg \cdot yr^{-1}$ (Table 1). If the smaller lakes bury OC, on average, at the same rate as an average Minnesota lake (72 $g \cdot m^{-2} \cdot yr^{-1}$), then the annual rate of OC accumulation in these smaller lakes is about 23 $Tg \cdot yr^{-1}$; Table 1). If saline inland seas bury OC at the Lake Michigan rate, this would be an additional 5 $Tg \cdot yr^{-1}$, for a total of 34 $Tg \cdot yr^{-1}$ for all freshwater lakes and saline inland seas (Table 1). Mulholland and Elwood (1982) estimated the OC burial in all lakes and inland seas (excluding the Black Sea) to be 60 $Tg \cdot yr^{-1}$ today (Table 1), and an average of 20 $Tg \cdot yr^{-1}$ for the Holocene. Another approach is to use Likens' (1975) estimate of 200 $g \cdot m^{-2} \cdot yr^{-1}$ for average net primary production of carbon in world lakes. If 5%–10% of that carbon production is buried, then the 2.5×10^{12} m^2 area of world lakes and saline inland seas are burying OC at a rate of 25–50 $Tg \cdot yr^{-1}$ (Table 1). Thus, the global annual OC burial rate in lakes is between 34 and 60 $Tg \cdot yr^{-1}$, with our estimate being the lowest. We will use an average of 42 $Tg \cdot yr^{-1}$ (Table 1, footnoted). The closeness of these estimates, calculated by different methods, suggests that this value is not in error by more than a factor of two.

CARBON BURIAL IN RESERVOIRS

Reservoirs throughout the world currently hold about 5000 km^3 of water, and more than half of that volume is in reservoirs in the United States, Canada, and the former Soviet Union (Shiklomanov, 1993). The volume of water in reservoirs increased by a factor of 10 between 1951 and 1980 and is projected to increase to more than 7000 km^3 by the year 2000 (Shiklomanov, 1993). The total area of reservoirs in the world (0.4×10^{12} m^2; Shiklomanov, 1993) is smaller than that of lakes, and the average percentage of OC in their sediments (about 2%; Mulholland and Elwood, 1982; Richie, 1989) is much less than in most lake sediments. However, because the average sedimentation rate in reservoirs (about 2 $cm \cdot yr^{-1}$; Mulholland and Elwood, 1982) is much higher than that in lakes, bulk-sediment MARs are higher, and OC MARs are higher. At an average sedimentation rate of 2 $cm \cdot yr^{-1}$, an average bulk density of 1 $g \cdot cm^{-3}$, and an average OC content of 2%, the average OC accumulation rate in reservoirs is 400 $g \cdot m^{-2} \cdot yr^{-1}$, and the total of world reservoirs is burying OC at a total annual rate of 160 $Tg \cdot yr^{-1}$ (Table 1). This is close to the 200 $Tg \cdot yr^{-1}$ estimated by Mulholland and Elwood (1982) for the annual accumulation of carbon in reservoirs.

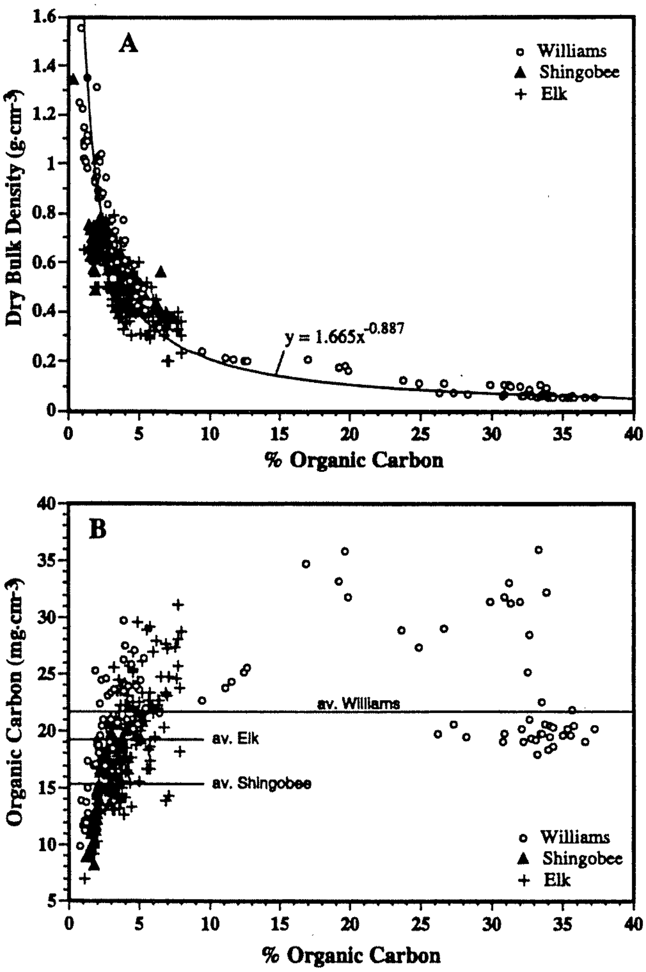

Figure 2. Plots of percent organic carbon versus (A) dry bulk density and (B) organic carbon content of Holocene sediments of Elk, Williams, and Shingobee Lakes, Minnesota. The curve through data in A is an exponential regression based on data for Williams Lake only.

TABLE 1. ORGANIC CARBON BURIAL RATES

Sediment carbon sink	Area (10^{12} m^2)	Burial rate ($g \cdot m^{-2} \cdot yr^{-1}$)	Burial ($Tg \cdot yr^{-1}$)
Lakes			
Large (28, >5000 km^2)	1.18	5	6
Small	0.32	72	23
Inland seas	1.00	5	5
Total	2.50		34[a]
			60[b]
			25–50[c]
			42[d]
Reservoirs	0.40	400	160[e]
			200[b]
Peatlands (present)	4.19	23	96[f]
Total (lakes, reservoirs, peatlands)	7.09		298[g]
Oceans			
Margins	42[h]		
Basins	320[h]		
Total	362[h]		60–130[h]
			82[i]
			115[j]
			97[k]
Inland/ocean quotient	0.02		3.1[l]

[a]This paper.
[b]Mulholland and Elwood. (1982)
[c]Assuming burial of 5%–10% of average net primary production estimated by (Likens, 1975).
[d]Mean of four burial estimates above.
[e]This paper; area estimate of Shiklomanov (1993).
[f]World peatland area from Kivinen and Pakarinen (1981), modified by a correction for Canada by Gorham (1991); burial rate from Gorham (1991).
[g]Total uses lake burial of 42 $Tg \cdot yr^{-1}$ (footnote d).
[h]Emerson and Hedges (1988).
[i]Sundquist (1985).
[j]Arthur et al. (1985).
[k]Mean of four estimates above.
[l]Using the means of burial estimated (footnotes d and k).

CARBON BURIAL IN PEATLANDS

Wetlands that accumulate more than 30 cm of highly organic peat are called peatlands (Gorham, 1991). In Europe, they are called mires. Peatlands are concentrated in northern Russia, the Baltic states, Fennoscandia, Canada, and the northern United States (particularly in Alaska) where they make up 9.7% of the total land surface (Gorham, 1995). We estimate the total area of world peatlands to be 4.19×10^{12} m^2 (Kivinen and Pakarinen, 1981, modified by Gorham, 1991). The estimated present average rate of OC accumulation in boreal peatlands is 23 $g \cdot m^{-2} \cdot yr^{-1}$ (Gorham, 1991). Using this rate for peatlands globally, their total OC burial amounts to 96 $Tg \cdot yr^{-1}$ (Table 1).

CONCLUSIONS

The total annual OC MAR in lakes (42 Tg), reservoirs (160 Tg), and boreal peatlands (96 Tg) is 298 Tg (Table 1). Despite the total area of these three carbon sinks being only about 2% of the world ocean's surface area, they bury three times more carbon than the oceans do (Table 1; inland/ocean quotient).

It should be noted that the drainage of peatlands for forestry and agriculture, and use of peat as fuel, is releasing carbon to the atmosphere. Gorham (1991) estimated that such processes release about 35 $Tg \cdot yr^{-1}$ from boreal peatlands, and more southerly regions may actually be releasing more carbon from drained peatlands than is fixed in undrained sites (Armentano and Menges, 1986). On the other hand, cultural eutrophication may have increased lake sedimentation of OC four- to fivefold in small lakes (Webb and Webb, 1988), an increase of 23–32 $Tg \cdot yr^{-1}$.

ACKNOWLEDGMENTS

Supported by the U.S. Geological Survey Global Change and Climate History Program. We thank Larry Benson, Gary Clow, and Dave Rea for helpful reviews.

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Manuscript received November 20, 1997
Revised manuscript received February 26, 1998
Manuscript accepted March 17, 1998