

Isotopic paleolimnology of Lake Kinneret

Y. Dubowski¹ and J. Erez

Institute of Earth Science, Hebrew University of Jerusalem, Jerusalem, Israel

M. Stiller

Environmental Sciences and Energy Research, Weizmann Institute of Science, Rehovot, Israel

Abstract

The carbonate, organic C, and N contents and their respective $\delta^{13}\text{C}$ were measured in four cores from Lake Kinneret, Israel. Using these data and the isotopic difference between coexisting carbonate and organic C, $\Delta\delta^{13}\text{C}$, we attempted to reconstruct the lake's productivity and regional climatic conditions during the late Holocene. The sedimentary record of the last 120 yr (for which climatological data are available) demonstrates that during periods of intense productivity, organic C content and its $\delta^{13}\text{C}_{\text{org}}$ are high, whereas the $\Delta\delta^{13}\text{C}$ values are low. During wet periods, characterized by intense input of particulates and nutrients from external sources, the CaCO_3 content, its $\delta^{13}\text{C}_{\text{car}}$ and $\delta^{18}\text{O}_{\text{car}}$, and the organic C:N ratios are low. Based on these correlations, the longer sedimentary record of the last ca. 3,300 yr was divided into five stages, which differ in productivity and/or climatic characteristics. This longer sedimentary record indicates that the primary production in Lake Kinneret has varied in the past over a range similar to that observed presently, but the rate of these changes was much slower. The rainiest period recorded in the sediments was from about 200 B.C. to A.D. 200, i.e. during the Roman period, when the region was heavily populated. The recent decrease in $\delta^{13}\text{C}$ of atmospheric CO_2 that accompanies the global anthropogenic CO_2 rise seems to be recorded by a commensurate decrease in $\delta^{13}\text{C}_{\text{car}}$ of the sediments. The concomitant increase in $\Delta\delta^{13}\text{C}$ expresses an increase in the isotopic fractionation of the lake's primary producers, which may also be related to the atmospheric CO_2 rise.

During the last decade it has been well established that the C isotopic fractionation of marine and freshwater phytoplankton is controlled by their rate of growth, the ambient concentration of dissolved CO_2 ($\text{CO}_{2(\text{aq})}$), and the phytoplankton size and shape (e.g., Degens 1969; Goericke et al. 1994; Laws et al. 1995; Rau et al. 1996). Thus, the fractionation of C isotopes is becoming an important tool for deciphering paleoenvironmental changes in aquatic systems (e.g., Hollander et al. 1993; Jasper et al. 1994).

Because of their smaller size and higher sedimentation rates, lakes are more sensitive than oceans to climatic and environmental changes. Their sedimentary records therefore allow finer time resolution and direct comparison with known historic and climatic records on nearby land.

Lake Kinneret (35°31'E, 32°53'N) is a warm monomictic lake characterized by an annual winter–spring bloom of *Per-*

idinium gatunense. This dinoflagellate is present all year round but during the bloom represents >95% of the phytoplankton biomass. The lake surface, at 211 m below mean sea level, is about 167 km² in area, and its maximum depth is 42 m (average depth, 24 m). Most of the lake's watershed is located on the north side and is drained by the Jordan River, which is the main nutrient supplier to the lake. The moderate size of the lake and its relatively large watershed (2,730 km²) makes it very sensitive to both climatic and anthropogenic changes in the region. Significant climatic changes in the region occurred during the upper Pleistocene to late Holocene and during historical times (e.g., Neev and Emery 1995; Bar-Matthews et al. 1999). During the last century, many environmental changes have resulted from intensive anthropogenic activity in the lake watershed. The effects of these activities on the biogeochemical system are still unclear, despite the many studies that have been carried out in the lake (e.g., Berman et al. 1992; Zohary et al. 1994; Berman-Frank et al. 1998). Because the lake is the main source of freshwater in Israel, it is of great importance to study and understand the effects of global and local changes on this ecosystem. Detailed monitoring of the lake and its ecosystem has been conducted since 1969, and meteorological data and measurements of the lake surface levels have been recorded since 1880. The longer record of environmental change preserved in the lake sediments provides an additional perspective that may help us to understand and better manage the recent changes in the lake.

Previous paleolimnological studies on Lake Kinneret were performed in the early 1980s as part of an interdisciplinary study (Stiller et al. 1984). These studies were based upon three cores, about 5 m long, collected in 1979 by Thompson and coworkers (1985) at stations U, D, and F (see Fig. 1).

¹ To whom correspondence should be addressed. Present address: Department of Earth, Atmospheric, and Planetary Sciences, Massachusetts Institute of Technology, 54-1320, 77 Massachusetts Ave., Cambridge, Massachusetts 02139 (yaeldu@mit.edu).

Acknowledgments

This research was supported by the Belfer Foundation for Energy Research, by grant DISUM-BMBF 0033-01421 from the Israeli Ministry of Science and the German Ministry of Science and Technology, and by the Moshe Shilo Minerva Center for Marine Biogeochemistry. We thank E. Halicz and A. Ayalon for their help with the isotopic analyses and A. Kaufman and Y. Kolodny for their help in radioactive dating of the sediments. We thank U. Pollinger and T. Zohary from the Yigal Alon Kinneret Limnological Laboratory (KLL) for their algal biomass data, and the boat crew of KLL for their help in obtaining the cores. We thank reviewers J. M. Hayes and M. R. Talbot for their productive remarks and efforts to improve this manuscript.

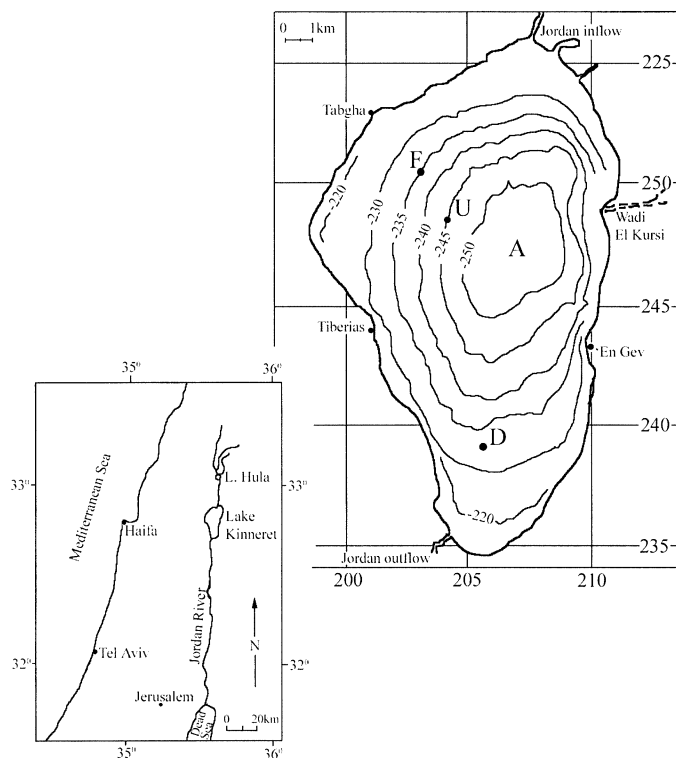


Fig. 1. Map of Lake Kinneret, Israel. The short cores (1, 4, and 5) were obtained at station A (43 m depth), and the long core (KINU8) was obtained in 1979 at station U.

The analyses included paleomagnetic profiles and radioactive dating using ^{14}C (Thompson et al. 1985), pollen records (Baruch 1986), distribution of diatoms and nonsilicate algae (Ehrlich 1985; Pollinger et al. 1986), and isotopic composition of carbonate (Stiller and Kaufman 1985).

The present study provides a high-resolution analysis of the sedimentary carbonates and organic matter in three short cores, representing the last century. Contemporaneous limnological and climatological data from the area allow a better understanding of the sediment records and the effects of recent anthropogenic activities in and around the lake. The organic C and N contents and the isotopic composition of organic C were also analyzed on one of the longer 1979 cores (core KINU8 from station U). Combining these data with previous paleolimnological findings and with the information gained from the study of the short cores allowed an improved estimate of the lake's paleoproductivity and of the region's paleoclimate over the last 3,300 yr.

Methods

Three short gravity cores were retrieved in November 1993 (core 1) and in April 1994 (cores 4 and 5) at station A, located at the center of Lake Kinneret (Fig. 1). Cores 1 and 4 (ca. 40 cm long) were sliced at room temperature into 1-cm-thick slices. Core 5 (60 cm long) was frozen at -70°C and cut into 5–7-mm slices in its upper 40 cm and 1-cm slices below that. On each slice, the following parameters were measured (Web Appendix 1 at <http://www.aslo.org/lo/>

[toc/vol_48/issue_1/0068a1.html](http://www.aslo.org/lo/toc/vol_48/issue_1/0068a1.html)): carbonate content and its isotopic composition ($\delta^{13}\text{C}_{\text{car}}$ and $\delta^{18}\text{O}_{\text{car}}$), organic C content and its isotopic composition ($\delta^{13}\text{C}_{\text{org}}$), and organic N content. C, N, and $\delta^{13}\text{C}_{\text{org}}$ were analyzed also on a 430-cm-long core (core KINU8), taken in 1979 by Thompson et al. (1985). The carbonate content in this core and its isotopic composition were measured by Stiller and Kaufman (1985).

Stratigraphy—The chronology of core KINU8 is based on ^{14}C dating and on stratigraphic correlation (Thompson et al. 1985) with core KIND4 (taken at station D; Fig. 1). Core KINU8 is missing its upper 22 cm and has a hiatus equivalent to 42 cm of sediments at 220 cm. The missing 22-cm section was detected by stratigraphic correlation with a shorter gravity core (1 m) taken at the same site. The missing 42-cm section was detected by correlation with cores KIND4 and KINF5 (KINF5 was taken at station F; Fig. 1).

Stratigraphic correlation of the three short cores is based mainly on the organic C content and on its $\delta^{13}\text{C}_{\text{org}}$. The dating of the three short cores relies on the following limnological and climatological events: extreme floods in 1874, 1893 (Ashbel 1951), and 1969 (Gophen and Yitzhaki 1992), strong blooms of *Aulacoseira granulata* in 1982 and 1988 (Berman et al. 1992), and starting at 1950 a sharp increase in sedimentary organic content and $\delta^{13}\text{C}_{\text{org}}$, related to the drainage of Lake Hula. These stratigraphic markers were confirmed by ^{210}Pb dating (Erel et al. 2001).

Analytical techniques—To measure $\delta^{13}\text{C}_{\text{org}}$ (in ‰ relative to Pee Dee Belemnite [PDB] standard), the carbonate fraction was removed from the sediment samples with HCl (7%). In the short cores, the residue was filtered and washed through precombusted GF/F filters, which were then combusted in closed Pyrex ampoules under vacuum for 12 h at 540°C in the presence of CuO and Ag wire (Zohary et al. 1994). During filtration, some of the organic matter was lost, causing a decrease in $\delta^{13}\text{C}_{\text{org}}$ of 0.42‰ (average decrease obtained by comparing the filtered and unfiltered $\delta^{13}\text{C}_{\text{org}}$ in core 5) and lower C:N ratios. Therefore the filtration was omitted, the excess HCl was evaporated, and the sample was dried. The chemical and isotopic analysis was then carried out using an automatic C and N analyzer (ANCA, Europa Scientific) connected to a VG 602 mass spectrometer. The $\delta^{13}\text{C}_{\text{org}}$ values measured in the filtered samples of cores 1 and 4 were corrected accordingly, by adding 0.42‰.

The organic C:N ratio was lower in filtered samples (7–14 in the unfiltered samples, 3–6 in the filtered samples). This decrease was caused mainly by C loss during the filtration. Therefore, we report here only the organic C and N that was measured in unfiltered samples, i.e., cores 5 and KINU8.

The carbonate isotopic composition of the sediments was measured following the method of McCrea (1950). To minimize CO_2 production from organic matter during the analysis, the sediments were first reacted with a dilute (1:1) NaOCl solution. After two rinses, the dried and weighed samples were reacted at 25°C for ca 20 h with 100% phosphoric acid using evacuated side-arm flasks. The released CO_2 was collected manually with a vacuum line. This procedure was used for short cores 1 and 4. Samples from core 5 were

reacted at 90°C and measured at the Israel Geological Survey using an ISOCARB (VG-Micromass) automated system. For all samples, the results are expressed in ‰ relative to a PDB standard.

The carbonate content in the filtered samples from cores 4 and 5 was calculated from the measured amount of CO₂ evolved during reaction with phosphoric acid. In core 1, the carbonate content was estimated based on weight loss after HCl treatment.

Results and discussion

The basis for interpretation—Recent studies in Lake Kinneret (Berman-Frank et al. 1998; Stiller and Nissenbaum 1999; Erez et al. pers. comm.) and in other lakes (e.g., Hollander et al. 1993) have revealed that the isotopic fractionation between CO_{2(aq)} and phytoplankton is reduced during periods of high productivity associated with high growth rates. Because the authigenic carbonate is assumed to be in isotopic equilibrium with the lake's carbonate system, the isotopic difference between the inorganic and organic C in the sediments, Δδ¹³C, is linearly related to the isotopic fractionation between CO_{2(aq)} and phytoplankton. Thus, high δ¹³C_{org} and low Δδ¹³C values indicate high community production in the lake, which leads to higher flux of organic matter to the sediments.

The allochthonous (external) particulate supply to Lake Kinneret, which comes mainly from the Jordan River, is fairly uniform (Serruya 1977). It contains mainly aluminosilicates (~72%) and calcium carbonate (about 25%), characterized by relatively low δ¹³C_{car} and δ¹⁸O_{car} values (about -4.1‰ and -7.1‰, respectively; Stiller and Kaufman 1985). The organic C content in the allochthonous material (about 1.5%) has a mean δ¹³C_{org} value of -26.9‰ ± 0.9‰ (Stiller et al. 1988) and consists mainly of algal debris from the riverbed, with very little terrestrial plant debris. The contribution of the allochthonous component to sedimentation increases markedly during very wet winters. In our paleolimnologic interpretation, we assumed that the allochthonous component did not change its chemical and isotopic composition. CaCO₃, with higher δ¹³C_{car} and δ¹⁸O_{car} values (about -1.3‰ and -1.7‰, respectively; Stiller 1977), dominates the authigenic sedimentation. Figure 2 shows that very low carbonate content in the short cores (<50%) is characteristic of extremely rainy years that have been recorded independently (i.e., 1874, 1891–1893, 1969, and 1992; Ashbel 1951; Israeli Meteorological Service pers. comm.). Therefore, lower carbonate content in the sediments with a more depleted isotopic composition was used as a proxy for wet periods with frequent floods. Because the organic C content in the allochthonous material is also relatively low, the effect of enhanced allochthonous input would be to decrease both the organic and carbonate content in the sediments. The variability in organic C and N content of the sediment is therefore due, in part, to variability in the allochthonous contribution. To overcome this effect, we estimated the authigenic carbonate (Car_{authigenic}; expressed as CaCO₃) and the authigenic organic C (C_{authigenic}) mass fractions in the lake sediments (Eqs. 1, 2) by using the composition of allochthonous

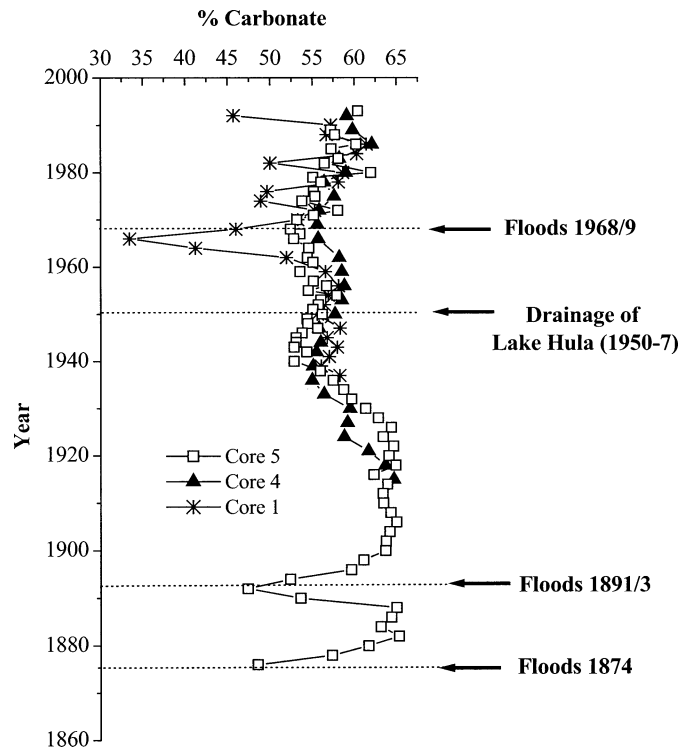


Fig. 2. Carbonate content, expressed as CaCO₃ (%), in the short cores versus sediment age. Sediment age was calculated based on average sedimentation rate of 0.45 cm yr⁻¹, as determined by ²¹⁰Pb dating. During very rainy years (1874, 1891–1893, 1969, and 1992), the carbonate content in the sediment decreased sharply, below 50%, most likely because of abundant clay-rich allochthonous sedimentation.

inflow (which is the sole source of aluminosilicates) and by assuming that organic matter contains 50% C. The calculated authigenic organic C (C_{authigenic}) was then “normalized” (C_{normalized}) by dividing it by the authigenic carbonate content (Car_{authigenic}) (Eq. 3):

$$AS_{\text{sediment}} = [1 - Car_{\text{sediment}} - (C_{\text{sediment}} \times 2)] \quad (1a)$$

$$Car_{\text{authigenic}} = Car_{\text{sediment}} - [Car_{\text{allochthonous}} (AS_{\text{sediment}}/AS_{\text{allochthonous}})] \quad (1b)$$

$$C_{\text{authigenic}} = \{(C_{\text{sediment}} \times 2) - [(C_{\text{allochthonous}} \times 2)(AS_{\text{sediment}}/AS_{\text{allochthonous}})]\}/2 \quad (2)$$

$$C_{\text{normalized}} = \frac{C_{\text{authigenic}}}{Car_{\text{authigenic}}} \times 100 \quad (3)$$

where AS_{sediment}, Car_{sediment}, and C_{sediment} are the mass fractions of aluminosilicate, calcium carbonate, and organic C in the lake sediment, respectively; the latter two contain both authigenic and allochthonous matter, and AS_{sediment} is of allochthonous origin only. The mass fractions of aluminosilicate, calcium carbonate, and organic C in the allochthonous material are represented by AS_{allochthonous} (=0.72), Car_{allochthonous} (=0.25), and C_{allochthonous} (=0.015), respectively.

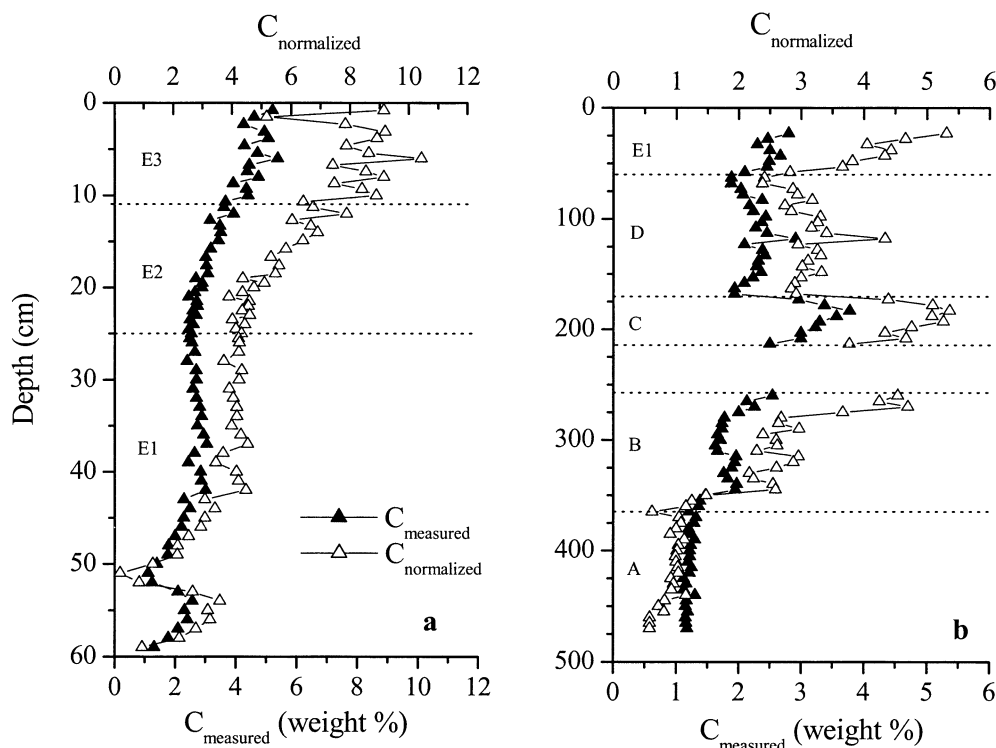


Fig. 3. A comparison between measured organic C content (in weight percentage of total sediment) and normalized authigenic organic C (in weight percentage of authigenic carbonate content, see Eqs. 1–3) in core 5 (a) and core KINU8 (b).

The normalized organic C content of the sediments ($C_{\text{normalized}}$, as a percentage) represents organic C of authigenic origin per authigenic CaCO_3 precipitation and may better reflect changes in the lake's productivity. A comparison between the measured and normalized organic C content is shown in Fig. 3.

The different organic C:N ratios of terrestrial and lower aquatic plants (algae), typically ≥ 20 and close to 10, respectively, have been used to evaluate the origin of organic matter in lake sediments (Talbot and Johannessen 1992). The molar organic C:N ratios in Lake Kinneret sediments (about 10–15) mainly represent those of the lake's phytoplankton, $C:N \sim 13 \pm 2$ (based on >25 measurements of clean algal fractions collected during the yearly cycle; Erez unpubl.). Because of selective loss of N upon burial in the sediments, these algal ratios may slightly increase (Talbot and Laerdal 2000). The relatively low organic C:N ratios of ≤ 10 in Jordan River suspended matter (JSM; attributed to large proportions of algal debris from the riverbed and a possible contamination of adsorbed inorganic ammonium; Avnimelech 1980) indicate low terrestrial contribution and seem to have a minor influence upon the sedimentary C:N ratios. During very wet periods with large allochthonous inputs of particulates and nutrients, the organic C:N ratios in JSM may become higher because of a larger proportion of terrestrial plant debris ($C:N \geq 20$; Meyers and Ishiwatari 1995) and organic matter from the Hula basin soils (12–18). Therefore it was expected that during wet periods the sedimentary C:N would increase. However, our data show that effects of intensive, nutrient-rich floods and drainage in the Hula basin

(Selinger 1991) are recorded in the lake sediments as a decrease of the organic C:N ratio. Nutrient-rich floodwaters could enhance the lake's productivity and the flux of authigenic C and N to the sediments, and their conspicuous N supply could induce a decrease in the C:N of the lake's algae to values ≤ 10 . This scenario would be in agreement with the low molar C:N ratios (< 9.7) observed in algae grown under nonlimiting N supply (Talbot and Laerdal 2000 and references therein; under severe N limitation, C:N ratios increase to > 17). During wet periods, the flux of authigenic organic matter with low C:N probably overrides the allochthonous JSM flux with higher C:N (because of a larger terrestrial contribution), resulting in lower sedimentary C:N values. The lower sedimentary C:N observed during wet periods could be due in part to an analytical artifact: our organic matter analysis was performed at low pH and therefore may include inorganic N adsorbed to the larger, clay-rich allochthonous input. A plot (not shown here) of organic C versus total N (assuming that our organic N analysis included bonded inorganic N) for all our data from the cores shows high linear correlation and does not indicate, as intercept, a significant portion of inorganic N.

For our paleolimnologic interpretation, we assumed that C:N values of authigenic organic matter dominated the C:N values in the sediments, and we used the latter in addition to other proxies to reconstruct past nutrient levels in the lake.

Comparison of available limnological biomass records (database of Yigal Allon Kinneret Limnological Laboratory) with the measured organic C and N in core 5 for the years

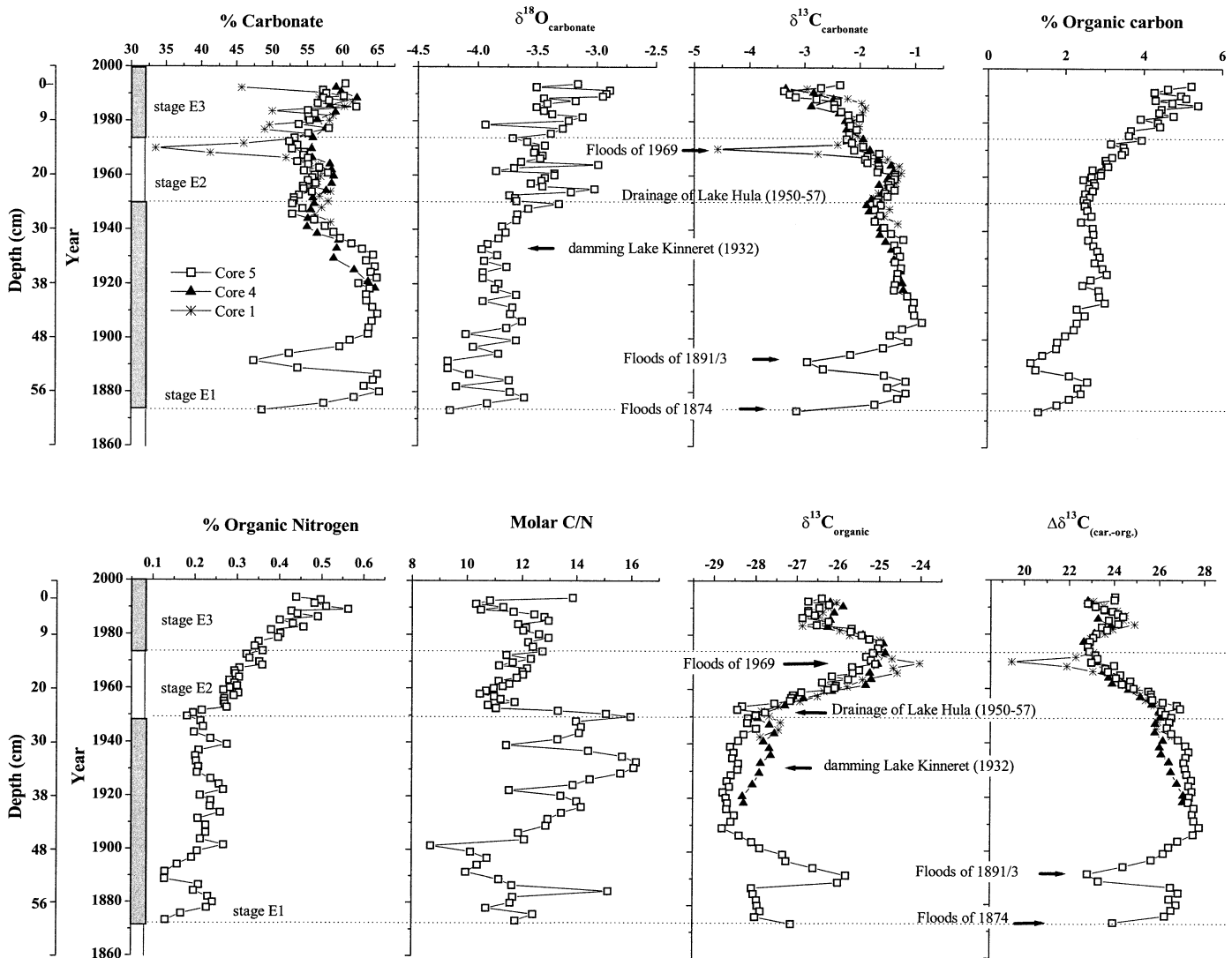


Fig. 4. The sedimentary records from cores 1, 4, and 5. Three trends are clear in these records: (a) a sharp decrease in carbonate content and in $\delta^{13}\text{C}_{\text{car}}$ accompanied by a decrease in $\Delta\delta^{13}\text{C}$ during flood periods (1874, 1891–1893, 1969, and to some extent 1992), (b) an increase in C and N accompanied by a decrease in $\Delta\delta^{13}\text{C}$ after the drainage of Lake Hula, and (c) a decrease in $\delta^{13}\text{C}_{\text{car}}$ since the mid 1950s.

1970–1994 shows that these two parameters may also be used to reconstruct the lake biomass in the past (Fig. 5). The weaker correlation during the early 1970s is in part an artifact due to the extreme floods of 1969. When comparing the biomass records to the accumulation rate of organic C and N (data not shown), the dilution effect is partly compensated for and the correlation for the early 1970s improves significantly.

The sedimentary record—The sedimentary records of core KINU8 were divided into five stages (Fig. 6). Centimeters 255–213, i.e., the section between stages B and C (1,600–1,250 yr before the present [B.P.]), are missing. The last 100 yr (stage E) are represented with much higher resolution in the three short cores (Fig. 4).

Stage A: 3,250–2,550 yr before the present (B.P.) (465–365 cm): This stage is oligotrophic with low nutrient flux

and low allochthonous input, suggesting more arid conditions. Dry conditions are indicated by low C and N values (approximately 1% and 0.1%, respectively), high C:N ratio (~ 14), high $\Delta\delta^{13}\text{C}$ values ($\delta^{13}\text{C}_{\text{car}} - \delta^{13}\text{C}_{\text{org}} = 27\text{--}28\text{‰}$), and high carbonate content (60–70%) (Fig. 6). The relatively high $\delta^{18}\text{O}_{\text{car}}$ of approximately -2.5‰ supports this conclusion (considering the dominant effect of evaporation on the $\delta^{18}\text{O}_{\text{car}}$ in subtropical lakes). The paleontological records also indicate that during this stage Lake Kinneret was oligotrophic, characterized by small centric diatoms (zone X of Ehrlich 1985).

Different conditions existed during the preceding period partially represented by the lowest 30 cm of this core (3,250–3,000 B.P.). Lower carbonate content (50–60%), lower C:N ratios (≤ 12), and relatively low $\Delta\delta^{13}\text{C}$ (26–27‰) indicate somewhat higher productivity under more humid conditions. In their study of the Dead Sea basin, Neev and Emery (1995) suggested that the period of 3,900–3,200 B.P.

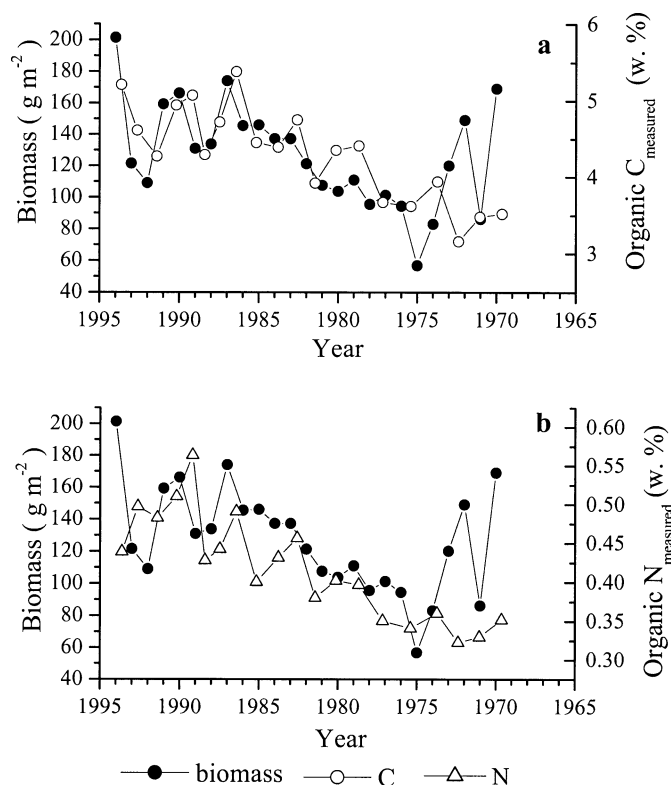


Fig. 5. A comparison between recent biomass measurements in Lake Kinneret (January to May averages; KLL database) and (a) sedimentary organic C content in core 5 and (b) sedimentary organic N content in core 5. Based on our calculations (see Eq. 2), about 70–90% of the measured organic C is authigenic. In general there is good agreement between these records except from during extreme allochthonous sedimentation (e.g., floods of 1969), when the sedimentary organic content underestimates the lake's biomass.

was cold and wet. The lowest part of KINU8 seems to represent the end of this period.

Stage B: 2,550–1,600 B.P. (365–255 cm): During this stage, C and N increased (from 1% to 2% and from 0.1% to 0.25%, respectively), whereas the C:N ratio decreased from 14 to 8. The $\Delta\delta^{13}\text{C}$ decreased sharply from 28‰ to 25‰, and the carbonate content decreased from 65% to about 50%, with even lower values of 40% in the upper part of this section. The $\delta^{18}\text{O}_{\text{car}}$ decreased by almost 1‰. These changes suggest that during this period more humid conditions prevailed, increasing the nutrient flux and the resulting productivity levels. The normalized authigenic C, compared with the C record, shows an even sharper increase (Fig. 3), further indicating enhanced productivity. This conclusion is also supported by the paleontological record, which shows high abundance of green algae (some of which are indicative of eutrophic conditions) and an increase in algal diversity (Ehrlich 1985; Pollinger et al. 1986). Independent evidence for this scenario is provided from historical and palynological records. Broshi (1982) suggested that during this time span (which includes the Greek, Roman, and Byzantine periods) the Galilee area was densely inhabited by flourishing agricultural populations of about 200,000 inhabitants, very

similar to the present population in the region. The influence of the agricultural activities on the flora is evident from the abundance of olive tree (*Olea*) pollen at the expense of the natural oak forests during this stage (Baruch 1986).

Stage C: 1,250–900 B.P. (213–170 cm): In this stage, the N values remain similar to those in stage B (ca. 0.23%), but the C values are very high (ca. 3.5%), yielding high C:N ratios (up to 17.3). $\delta^{13}\text{C}_{\text{org}}$ and $\delta^{13}\text{C}_{\text{car}}$ are higher than those in the previous stage (-25 ‰ and -0.25 ‰, respectively) but with the same low $\Delta\delta^{13}\text{C}$ (ca. 25‰). The high carbonate content (ca. 65%), its high $\delta^{13}\text{C}_{\text{car}}$, and its relatively high $\delta^{18}\text{O}_{\text{car}}$ (-2.7 ‰) suggest low allochthonous input and drier conditions and are in accord with the pollen records, in which the reappearance of the natural forest (Baruch 1986) indicates a decrease in agricultural activities. The values for all C-related parameters ($\delta^{13}\text{C}_{\text{org}}$, $\delta^{13}\text{C}_{\text{car}}$, and $\Delta\delta^{13}\text{C}$) imply that the productivity in the lake during stage C remained very high. Therefore, it is surprising that organic N content did not increase, suggesting N-limiting conditions and/or a different producer community with lower N affinity. Algae that have C concentration mechanisms (CCM) can maintain high levels of CO_2 fixation under N limitation (Yin and Raven 1998), yielding high organic C, high C:N ratios, and higher $\delta^{13}\text{C}_{\text{org}}$ (Goericke et al. 1994; Erez pers. comm.). The conditions in the lake during this period may have supported an abundance of dinoflagellates (i.e., *Peridinium*), which are the dominant algae in the lake's phytoplankton today and are known to have a CCM (Berman-Frank and Erez 1996). Unfortunately, the presence of *Peridinium* could not be confirmed by previous micropaleontological studies (Ehrlich 1985; Pollinger et al. 1986) because the conventional methods used were not able to detect it (Pollinger pers. com.). Overall, stage C was characterized by drier conditions, high productivity (low $\Delta\delta^{13}\text{C}$), and possible introduction of phytoplankton with CCM and high C:N.

Stage D: 900–170 B.P. (170–60 cm): At the beginning of stage D, concentrations of carbonate and organic C dropped and their respective $\delta^{13}\text{C}$ values decreased. During the rest of stage D (150–60 cm), the carbonate content and $\delta^{13}\text{C}_{\text{car}}$ returned to high values, whereas organic C and $\delta^{13}\text{C}_{\text{org}}$ remained lower than those in stage C (2.2% and -28.5 ‰, respectively). Because there was no change in N (ca. 0.22%), the C:N ratio decreased to about 12. These proxies indicate that after a short very wet period, the allochthonous contribution was lower and primary productivity was moderate. The similarity in $\delta^{13}\text{C}_{\text{org}}$ and $\Delta\delta^{13}\text{C}$ between stages A and D suggests that the algae maintained high isotopic fractionation at even moderate levels of primary productivity. Comparison of $\delta^{18}\text{O}_{\text{car}}$ and carbonate content in these two stages suggests cooler conditions for stage D. Thus, after a short very wet episode, drier but cooler conditions (relative to stage A) prevailed during which the primary productivity was maintained at a moderate level.

Stage E: 170 B.P.–present (60–0 cm): The beginning of stage E (ca. calendar years 1825–1895) is recorded in core KINU8 in its upper 38 cm (60–22 cm depth; the uppermost 22 cm are missing). The decrease in carbonate content, in

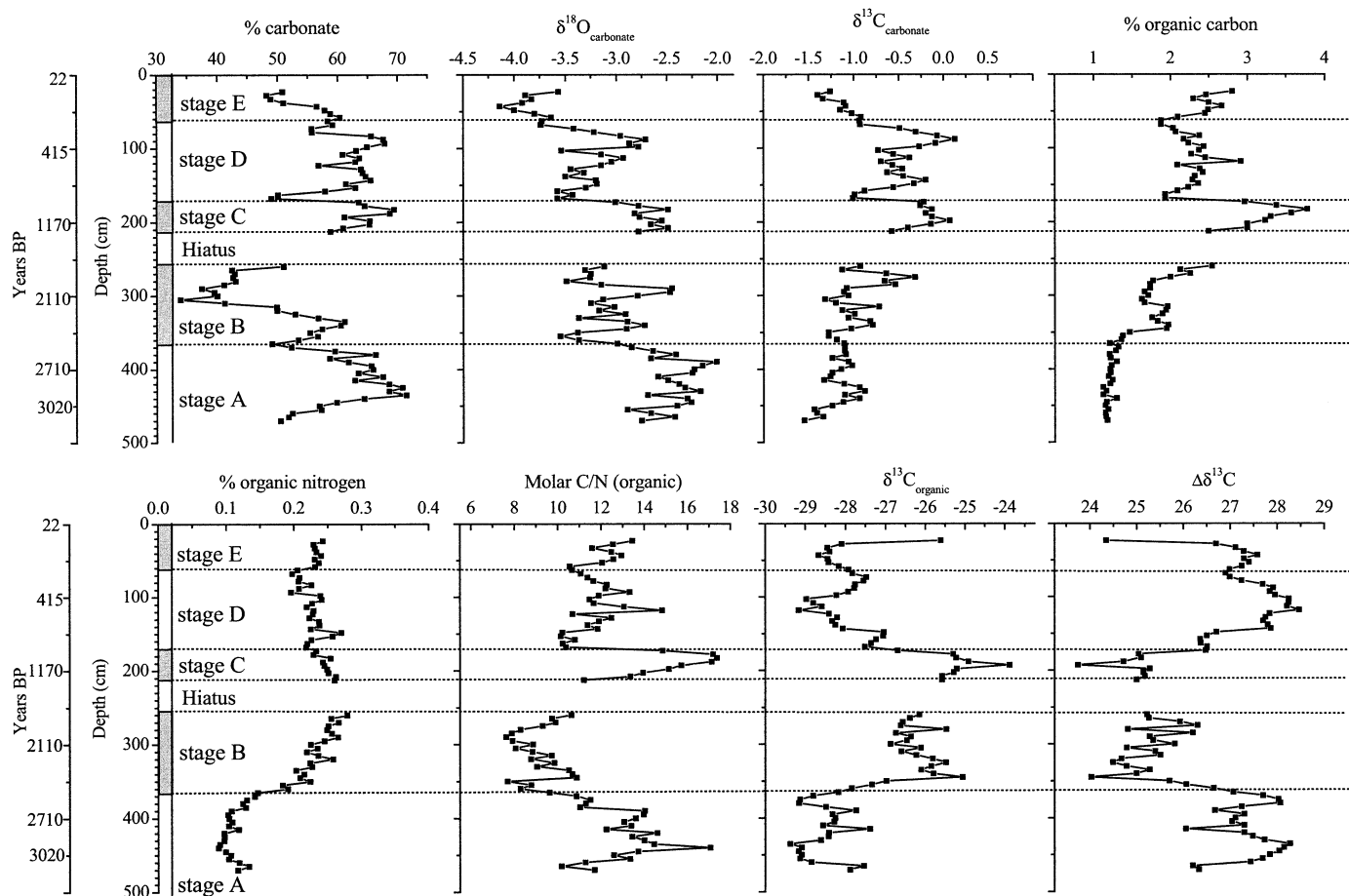


Fig. 6. The sedimentary records from core KINU8. Stiller and Kaufman (1985) measured the carbonate content and its isotopic composition. The hiatus was determined based on stratigraphic correlation with two other cores sampled at the same time (*see* Thompson et al. 1985 for discussion).

$\delta^{13}\text{C}_{\text{car}}$ and $\delta^{18}\text{O}_{\text{car}}$, the increase in C, N, and $\delta^{13}\text{C}_{\text{org}}$ (Fig. 6), and the sharp increase in “normalized” authigenic C (Fig. 3) suggest that allochthonous sedimentation and productivity increased at the beginning of stage E. Historical meteorological data show that the end of the 19th century was relatively wet (Ashbel 1951).

Most of stage E is well represented in the three short cores and was studied at a higher resolution than was that section in core KINU8. The part of stage E recorded in the short cores can be subdivided according to several anthropogenic operations, which took place in the area during the last century, and according to a few known flooding events.

During most of substage E1 (years 1872–1950; 59–25 cm), the $\delta^{13}\text{C}_{\text{org}}$ and $\delta^{13}\text{C}_{\text{car}}$ values were similar to those of stage D (-28‰ and -1.5‰ , respectively; Fig. 4). The carbonate content was relatively high (ca. 65%, except around 51 and 59 cm), with low $\delta^{18}\text{O}_{\text{car}}$ (ca. -4‰). After the increase in C and N at the beginning of this stage (observed in core KINU8), these parameters stabilized at moderate levels (2.4% and 0.2%, respectively), with a C:N ratio around 13. These parameters suggest that low to moderate allochthonous sedimentation and moderate primary productivity prevailed during most of this stage. At the beginning of this substage (which is recorded only in core 5), two episodes of

extreme floods were identified, around 51 and 59 cm, by their very low carbonate content and low $\delta^{13}\text{C}_{\text{car}}$ and $\delta^{18}\text{O}_{\text{car}}$ values. These two episodes fit the high precipitation of the mid 1870s and early 1890s recorded meteorologically (Ashbel 1951). As before, the isotopic record (high $\delta^{13}\text{C}_{\text{org}}$ and low $\Delta\delta^{13}\text{C}$) and the low C:N ratios suggest that these floods increased the nutrient load in the lake, causing an increase in primary productivity. From the beginning of the 1930s until the end of this substage (35–25 cm depth), the carbonate content and its $\delta^{13}\text{C}_{\text{car}}$ decreased, suggesting higher allochthonous sedimentation. This increase in allochthonous sedimentation was associated with an increase in $\delta^{18}\text{O}_{\text{car}}$. This increase may be the consequence of the 1932 damming of the lake’s outflow. The increase in water residence time also produced prolonged evaporation, which yielded higher $\delta^{18}\text{O}$ (Gat 1970). Reduced outflow may also cause lower loss of allochthonous suspended matter during winter floods, thus increasing the relative contribution of that fraction.

During substage E2 (1950–1975; 25–11 cm), the most conspicuous trend during was the sharp increase in C, N, and $\delta^{13}\text{C}_{\text{org}}$ values (increases of 1.5%, 0.15%, and 3‰, respectively), whereas the C:N ratio and $\Delta\delta^{13}\text{C}$ decreased sharply (from ~ 15 to ~ 11 and from 27‰ to 23‰, respectively). These changes, which were even more pronounced

in the normalized organic C content (Fig. 3), are most likely the result of the drainage of Lake Hula and its swamps, located ca. 25 km north of Lake Kinneret on the path of the Jordan River. Large amounts of nutrient-rich sediments from the Hula basin, with high $\delta^{13}\text{C}_{\text{org}}$ (ca. -17‰), reached Lake Kinneret as a result of the drainage project (Selinger 1991; Markel pers. comm.). If the observed increase in $\delta^{13}\text{C}_{\text{org}}$ were the result of only this Hula project, the $\delta^{13}\text{C}_{\text{org}}$ should have returned to its original value after the completion of the project (in 1958). Because this did not occur, we propose that the observed increase in nutrient flow to Lake Kinneret from exposed peat soils (Avnimelech 1980) triggered a continuous increase in the lake's primary production. Increased nutrient load in this period is also expected because of the cessation of nutrient trapping by the Hula swamps and by the increased agricultural activity in the region. This expectation is confirmed by the observed reduction in C:N ratio and $\Delta\delta^{13}\text{C}$. Very low carbonate content, low $\delta^{13}\text{C}_{\text{car}}$, and higher $\delta^{13}\text{C}_{\text{org}}$ measured in core 1 at 14 cm depth probably represent the extreme floods of 1969 (Gophen and Yitzhaki 1992). Unfortunately, this typical pattern for flood periods (e.g., end of the 19th century and the period 2,300–1,700 B.P.) can be observed clearly only in core 1 (sampled at station A) and not in cores 4 and 5, which were taken several hundred meters to the south away from the Jordan River inflow.

For substage E3 (1975–1993; 11–0 cm), there are detailed limnological and climatological records of the lake. From the beginning of this period, there was a decrease in $\delta^{13}\text{C}_{\text{org}}$ and in $\delta^{13}\text{C}_{\text{car}}$ toward the sediment surface (a decrease of 1.5‰ and 0.4‰ , respectively), but their concentrations increased toward the surface by ca. 1.5% and 5% , respectively. This trend in organic C could be explained by diagenesis, but this explanation would require a concomitant increase in $\delta^{13}\text{C}_{\text{org}}$ (Degens 1969; Fontugne and Calvert 1992), opposite to the observed change (Fig. 4). Moreover, the observed sedimentary increase in organic C and N matches the increase in the algal biomass measured independently as part of the lake's monitoring program (Fig. 5). The decrease in $\delta^{13}\text{C}_{\text{org}}$ and $\delta^{13}\text{C}_{\text{car}}$ is surprising in view of the documented increase in the lake's productivity (Fig. 5). The observed decrease of $\sim 0.4\text{‰}$ in $\delta^{13}\text{C}_{\text{car}}$ between 1975 and 1985 (Fig. 4) implies a similar decrease in $\delta^{13}\text{C}$ of the dissolved inorganic C ($\delta^{13}\text{C}_{\text{DIC}}$) of the lake water. Two $\delta^{13}\text{C}_{\text{DIC}}$ measurements performed in 1998 also suggest that this parameter decreased by at least 0.5‰ between 1975 (Stiller and Nissenbaum 1999) and 1998 (Stiller et al. 2001). This trend may be related to an increase in the flux of ^{12}C -rich wastewater associated with population growth in the lake vicinity. However, during stage B when the area's population was similar in size to the present one, no such trend (decrease in $\delta^{13}\text{C}_{\text{car}}$) was observed. Another possibility is that the observed $\delta^{13}\text{C}_{\text{car}}$ trend may be related to the decrease in $\delta^{13}\text{C}$ of atmospheric CO_2 , $\delta^{13}\text{C}_{\text{atm}}$ (Friedli et al. 1986). Continuous direct measurements of $\delta^{13}\text{C}_{\text{atm}}$ are available only since 1977 (Fig. 7; Keeling et al. 1989; Levin et al. 1995). Extrapolation back to the year 1975 suggests a decrease of 0.3 – 0.4‰ during the period 1975–1985, very similar to that observed in the sedimentary $\delta^{13}\text{C}_{\text{car}}$. Similar trends, although less abrupt, were also found in $\delta^{13}\text{C}$ records of corals, sponges, clams, and foraminiferans (e.g., Aharon 1991; Beveridge and Shackle-

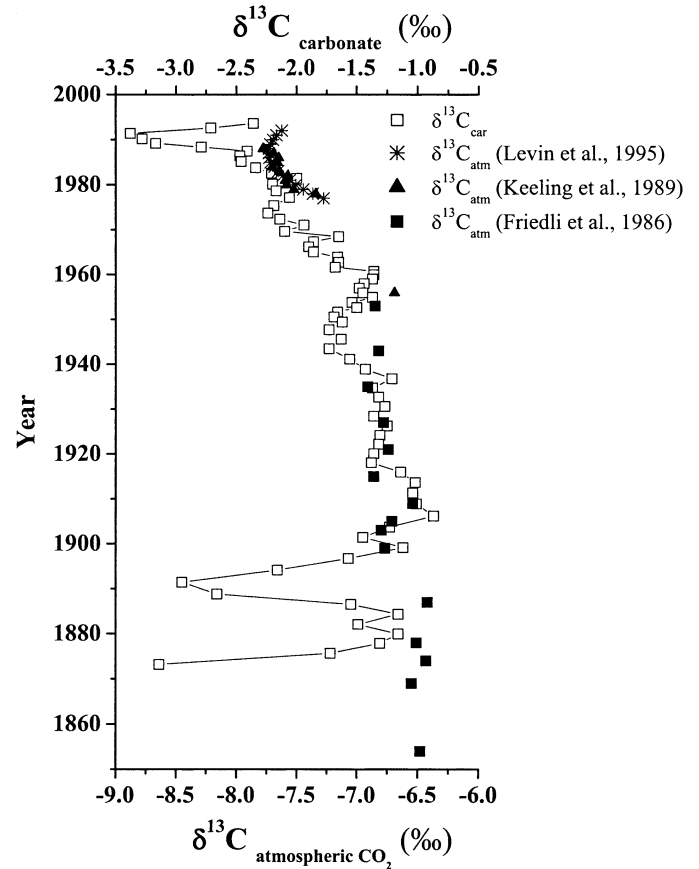


Fig. 7. $\delta^{13}\text{C}_{\text{car}}$ from core 5 and $\delta^{13}\text{C}_{\text{atm}}$ (after Friedli et al. 1986; Keeling et al. 1989; Levin et al. 1995; $\delta^{13}\text{C}_{\text{atm}}$ normalized according to Keeling's measurements). The similar trends in these two parameters suggest that $\delta^{13}\text{C}_{\text{car}}$ is related, at least partially, to the global $\delta^{13}\text{C}_{\text{atm}}$ trend. The deep minimum in $\delta^{13}\text{C}_{\text{car}}$ around 1991 is probably the result of floods in the winter of 1991–1992, which introduced allochthonous carbonates with relatively low $\delta^{13}\text{C}_{\text{car}}$.

ton 1994; Bohm et al. 1996), supporting the hypothesis that at least some of the observed trend in the $\delta^{13}\text{C}_{\text{car}}$ may be related to the global $\delta^{13}\text{C}_{\text{atm}}$ trend. The increase in atmospheric CO_2 concentration (9% increase between 1970 and 1990) most likely increased the $\text{CO}_{2(\text{aq})}$ of the lake's surface waters, in turn bringing about a larger isotopic fractionation during photosynthesis by the lake's phytoplankton (e.g., Goericke et al. 1994; Erez et al. pers. comm.). Therefore the 1.5‰ decrease observed in the $\delta^{13}\text{C}_{\text{org}}$ values may be a combination of these two effects (i.e., 0.4‰ due to decrease in $\delta^{13}\text{C}_{\text{DIC}}$ and 1.1‰ due to larger isotopic fractionation because of higher $\text{CO}_{2(\text{aq})}$). Recent data (Erez et al. pers. comm.) indicate that $\delta^{13}\text{C}$ of *Peridinium* (the dominant phytoplankton in Lake Kinneret) decreased by 1.8‰ between 1976 and 1992. Taking into account the assumed decrease in $\delta^{13}\text{C}_{\text{DIC}}$ of the lake, this finding suggests that *Peridinium* is displaying a larger isotopic fractionation by $\sim 1\text{‰}$, in agreement with the $\delta^{13}\text{C}_{\text{org}}$ data presented here. A similar decrease in $\delta^{13}\text{C}_{\text{org}}$ of marine plankton due to increasing atmospheric CO_2 concentrations was previously reported by Bentaleb and Fontugne (1996) and Fischer et al. (1997).

The decrease in $\delta^{13}\text{C}_{\text{atm}}$ is probably recorded in the $\delta^{13}\text{C}_{\text{car}}$

of the sediments since the 1950s (Fig. 7). According to Keeling's measurements at Mauna Loa (Friedli et al. 1986), $\delta^{13}\text{C}_{\text{atm}}$ decreased from 1956 to the early 1980s by about 1‰ (from -6.8‰ to -7.8‰). A similar decrease (0.8‰ – 0.9‰) was observed in the $\delta^{13}\text{C}_{\text{car}}$ values of the Lake Kinneret sedimentary record during this time interval (Fig. 7). The $\delta^{13}\text{C}_{\text{org}}$ does not follow the atmospheric changes during this period, most likely because of the dominant effect of enhanced productivity after the drainage of Lake Hula.

The major source of DIC to the Lake Kinneret is the Jordan River. The isotopic composition of this DIC source is dominated by soil respiration derived from land vegetation (directly in contact with the atmosphere) and by carbonate dissolution in the aquifer of the Jordan River springs. The systematics of C isotopes in such systems has been discussed recently (Wang and Veizer 2000 and references therein). In Lake Kinneret, the atmospheric CO_2 exchange is slow relative to inorganic C input from the Jordan River. Hence, the correlation between the $\delta^{13}\text{C}_{\text{atm}}$ and the sedimentary $\delta^{13}\text{C}_{\text{car}}$ implies that the Jordan River waters and its allochthonous carbonate (from which about 40% is due to authigenic precipitation within the Jordan River; Stiller et al. 1988) are sensitive to changes in $\delta^{13}\text{C}_{\text{atm}}$. A similar conclusion was reached by Carmi et al. (1985) based on ^{14}C measurements and is supported by (only) three $\delta^{13}\text{C}_{\text{DIC}}$ measurements in the Jordan River showing a change from -6.3‰ to -7.4‰ and then -9.8‰ from 1972 to 1983 and 1998, respectively (Stiller et al. 2001). Nevertheless, considering various anthropogenic activities in the lake's watershed that might also affect the $\delta^{13}\text{C}_{\text{DIC}}$ of the Jordan River (such as drainage from fish ponds and irrigated land crops), $\delta^{13}\text{C}_{\text{atm}}$ changes over the past few decades probably were not the sole driving force for these observed trends.

In the upper 6 cm of the cores, the sedimentary record is less clear. The strong floods of the winter of 1991–1992 probably influenced the upper few centimeters or the uppermost part of the sediments may have been disturbed during sampling.

Conclusions—During the last 3,300 yr, significant paleolimnological fluctuations occurred in Lake Kinneret. Although there were periods of very high primary productivity (e.g., between 2,500 and 800 B.P.), there is no record of extreme eutrophication nor of total collapse of the ecological system (such as sapropels, black sediments, or massive fish mortality) during the studied period. The observed changes in productivity that were attributed to anthropogenic activities in the lake's vicinity during the last century are of the same amplitude as those observed in the paleorecord. However, these changes have occurred about an order of magnitude faster in the last century than they did before then.

The comparison of the limnological and climatological records available for Lake Kinneret indicates that the sedimentary organic C and N contents combined with $\delta^{13}\text{C}_{\text{org}}$ and $\Delta\delta^{13}\text{C}$ data allow a reliable reconstruction of the lake's primary productivity. The carbonate content and its isotopic composition represent the extent of allochthonous sedimentation and the effect of enhanced productivity. Because of the many parameters that affect the $\delta^{18}\text{O}_{\text{car}}$ values (e.g., evaporation, water temperature, and allochthonous sedimentation)

and the analytical noise in its measurement, this parameter was not used independently in our study.

The sedimentary inorganic C record indicates that conspicuous flood periods (in which the carbonate content dropped below 50%) occurred at the beginning of the 14th century B.C., between 200 B.C. and A.D. 200, towards the end of the 12th century, and at the end of the 19th century. Although the studied record is relatively short ($\sim 3,300$ yr), these wet periods, extending for several decades, seem to occur with a periodicity of 700–1,000 yr.

During the time when it is believed that Jesus walked on water (1st century A.D.), humid environmental conditions prevailed (with high allochthonous inflows). Thus, at that time the Sea of Galilee was probably at its highest level ever.

The paleorecord of this study also supports the possible connection between climate and the political situation in the area. The Roman–Greek and Byzantine periods, with high population density and flourishing economic and cultural conditions, coincided with a wet, rainy period. The population and cultural decline in the early Arabic period took place when the climate was relatively dry.

Although the sedimentary record shows that Lake Kinneret experienced high levels of primary production in the past, the intensive anthropogenic development in the lake's vicinity during the last decades requires continuous monitoring of the lake ecosystem.

The lake may also be sensitive to recent global anthropogenic changes, namely the increase in atmospheric CO_2 partial pressure and the concomitant decrease in $\delta^{13}\text{C}_{\text{atm}}$, which seem to be recorded in the sediments by decreasing trends in $\delta^{13}\text{C}_{\text{car}}$ and in $\delta^{13}\text{C}_{\text{org}}$.

References

- AHARON, P. 1991. Recorders of reef environment histories—stable isotopes in corals, giant clams, and calcareous algae. *Coral Reefs* **10**: 71–90.
- ASHBEL, D. 1951. Regional climate of Israel [in Hebrew]. Department of Meteorology, Hebrew Univ.
- AVNIMELECH, Y. 1980. Studies on Lake Kinneret (Sea of Galilee) watershed. I: Characterization of water and suspended load in Lake Kinneret tributaries. *Water Air Soil Pollut.* **14**: 451–460.
- BAR-MATTHEWS, M., A. AYALON, A. KAUFMAN, AND G. J. WASERBURG. 1999. The eastern Mediterranean paleoclimate as a reflection of regional events: Soreq cave, Israel. *Earth Planet. Sci. Lett.* **166**: 85–95.
- BARUCH, U. 1986. The late Holocene vegetation history of Lake Kinneret (Sea of Galilee), Israel. *Paleorient* **12**: 37–47.
- BENTALEB, I., AND M. FONTUGNE. 1996. Anthropogenic CO_2 invasion of the surface ocean: Its influence on the organic carbon isotope composition of phytoplankton. *C.R. Acad. Sci. Ser. II* **322**: 743–748.
- BERMAN, T., Y. Z. YACOBI, AND U. POLLINGER. 1992. Lake Kinneret phytoplankton: Stability and variability during twenty years (1970–1989). *Aquat. Sci.* **54**: 104–127.
- BERMAN-FRANK, I., AND J. EREZ. 1996. Inorganic carbon pool in the bloom-forming dinoflagellate *Peridinium gatunense*. *Limnol. Oceanogr.* **41**: 1780–1789.
- , ———, AND A. KAPLAN. 1998. Changes in inorganic carbon uptake during the progression of a dinoflagellate bloom in a lake ecosystem. *Can. J. Bot.* **76**: 1043–1051.
- BEVERIDGE, N. A. S., AND N. J. SHACKLETON. 1994. Carbon iso-

- topes in recent planktonic-foraminifera—a record of anthropogenic CO₂ invasion of the surface ocean. *Earth Planet. Sci. Lett.* **126**: 259–273.
- BOHM, F., M. M. JOACHIMSKI, H. LEHNERT, G. MORGENROTH, W. KRETSCHMER, J. VACELET, AND W. C. DULLO. 1996. Carbon isotope records from extant Caribbean and South Pacific sponges: Evolution of delta C-13 in surface water DIC. *Earth Planet. Sci. Lett.* **139**: 291–303.
- BROSHI, M. 1982. The population of Israel during the Roman–Byzantine period, p. 442–455. *In* T. Bras, S. Safrai, Y. Tzafir, and M. Stern [eds.], *The land of Israel from the ruin of the second temple to the Moslem conquest* [in Hebrew]. V. 1. Yad Yitzchak Ben Tzvi.
- CARM, I., M. STILLER, AND A. KAUFMAN. 1985. The effect of atmospheric C-14 variations on the C-14 levels in the Jordan River system. *Radiocarbon* **27**: 305–313.
- DEGENS, E. T. 1969. Biogeochemistry of stable carbon isotopes, p. 304–329. *In* G. Eglinton and T. J. Murphy [eds.], *Organic geochemistry*. Elsevier.
- EHRlich, A. 1985. The eco-biostratigraphic significance of the fossil diatoms of Lake Kinneret. *Geol. Surv. Isr. Curr. Res.* **5**: 24–30.
- EREL, Y., Y. DUBOWSKI, L. HALICZ, J. EREZ, AND A. KAUFMAN. 2001. Lead concentrations and isotopic ratios in the sediments of the Sea of Galilee. *Environ. Sci. Technol.* **35**: 292–299.
- FISCHER, G., R. SCHNEIDER, P. J. MULLER, AND G. WEFER. 1997. Anthropogenic CO₂ in Southern Ocean surface waters: Evidence from stable organic carbon isotopes. *Terra Nova* **9**: 153–157.
- FONTUGNE, M. R., AND S. E. CALVERT. 1992. Late Pleistocene variability of the carbon isotope composition of organic matter in the eastern Mediterranean: Monitor of changes in carbon sources and atmospheric CO₂ concentrations. *Paleoceanography* **7**: 1–20.
- FRIEDLI, H., H. LOTSCHER, H. OESCHGER, U. SIEGENTHALER, AND B. STAUFFER. 1986. Ice core record of the C-13/C-12 ratio of atmospheric CO₂ in the past two centuries. *Nature* **324**: 237–238.
- GAT, J. R. 1970. Environmental isotope balance of Lake Kinneret, p. 109–127. *In* *Isotope hydrology, symposium on the use of isotopes in hydrology*. IAEA.
- GOERICKE, R., J. P. MONTAYA, AND B. FRY. 1994. Physiology of isotope fractionation in algae and cyanobacteria, p. 187–221. *In* K. Lajtha and R. H. Michener [eds.], *Stable isotopes in ecology and environmental science*. Blackwell.
- GOPHEN, M., AND G. YITZHAKI. 1992. *Lake Kinneret* [in Hebrew]. Ministry of Defense–Israel Press.
- HOLLANDER, D. J., J. A. MCKENZIE, K. J. HSU, AND A. Y. HUC. 1993. Application of an eutrophic lake model to the origin of ancient organic-carbon-rich sediments. *Global Biogeochem. Cycles* **7**: 157–179.
- JASPER, J. P., J. M. HAYES, A. C. MIX, AND F. G. PRAHL. 1994. Photosynthetic fractionation of ¹³C and concentrations of CO₂ in the central equatorial Pacific during the last 225,000 years. *Paleoceanography* **9**: 781–898.
- KEELING, C. D., AND OTHERS. 1989. A three-dimensional model of atmospheric CO₂ transport based on observed winds: 1. Analysis of observational data, p. 165–236. *In* D. H. Peterson [ed.], *Aspects of climate variability in the Pacific and the western Americas*. AGU.
- LAWS, E. A., B. N. POPP, R. R. BIDIGARE, M. C. KENNICUTT, AND S. A. MACKO. 1995. Dependence of phytoplankton carbon isotopic composition on growth-rate and [CO₂](Aq)—theoretical considerations and experimental results. *Geochim. Cosmochim. Acta* **59**: 1131–1138.
- LEVIN, I., R. GRAUL, AND N. B. A. TRIVETT. 1995. Long-term observations of atmospheric CO₂ and carbon isotopes at continental sites in Germany. *Tellus Ser. B Chem. Phys. Meteorol.* **47**: 23–34.
- MCCREA, J. M. 1950. On the isotopic chemistry of carbonates and a paleotemperature scale. *J. Chem. Phys.* **18**: 129–146.
- MEYERS, P. A., AND R. ISHIWATERI. 1995. Organic matter accumulation records in lake sediments, p. 279–291. *In* A. Lerman, D. M. Imboden, and J. R. Gat [eds.], *Physics and chemistry of lakes*. Springer-Verlag.
- NEEV, D., AND K. O. EMERY. 1995. *The destruction of Sodom, Gomorrah and Jericho*. Oxford Univ. Press.
- POLLINGER, U., A. EHRlich, AND S. SERRUYA. 1986. The planktonic diatoms of Lake Kinneret (Israel) during the last 5000 years—their contribution to the algal biomass, p. 459–470. *In* M. Richard [ed.], *Proceedings of the 8th International Diatom Symposium*. Koeltz.
- RAU, G. H., U. H. RIEBESELL, AND D. WOLF-GLADROW. 1996. A model of photosynthetic ¹³C fractionation by marine phytoplankton based on diffusive molecular CO₂ uptake. *Mar. Ecol. Prog. Ser.* **133**: 275–285.
- SELINGER, Y. 1991. *Geochemistry of phosphate in the watershed of Lake Kinneret* [in Hebrew]. Ph.D. thesis, Technion, Haifa.
- SERRUYA, C. 1977. Rates of sedimentation and resuspension in Lake Kinneret, p. 48–56. *In* H. L. Golterman [ed.], *Interaction between sediments and freshwater*. Junk.
- STILLER, M. 1977. Origin of sedimentation components in Lake Kinneret, traced by their isotopic composition, p. 57–64. *In* H. L. Golterman [ed.], *Interaction between sediments and freshwater*. Junk.
- , I. CARM, AND A. KAUFMAN. 1988. Organic and inorganic ¹⁴C concentrations in the sediments of Lake Kinneret and the Dead Sea (Israel) and the factors which control them. *Chem. Geol.* **73**: 63–78.
- , U. EHRlich, U. POLLINGER, U. BARUCH, AND A. KAUFMAN. 1984. The late Holocene sediments of Lake Kinneret (Israel)—multidisciplinary study of a five meter core. *Geol. Surv. Isr. Curr. Res.* **4**: 83–88.
- , AND A. KAUFMAN. 1985. Paleoclimatic trends revealed by the isotopic composition of carbonates in Lake Kinneret. *Z. Gletscherkd. Glazialgeol.* **21**: 79–87.
- , ———, I. CARM, AND G. MINTZ. 2001. Calibration of lacustrine sediment ages using the relationship between ¹⁴C levels in lake waters and in the atmosphere: The case of Lake Kinneret. *Radiocarbon* **43(B)**: 821–830.
- , AND A. NISSENBAUM. 1999. A stable carbon isotope study of dissolved inorganic carbon in hardwater Lake Kinneret (Sea of Galilee). *S. Afr. J. Sci.* **95**: 166–170.
- TALBOT, M. R., AND T. JOHANNESSEN. 1992. A high-resolution palaeoclimatic record for the last 27,500 years in tropical West Africa from the carbon and nitrogen isotopic composition of lacustrine organic matter. *Earth Planet. Sci. Lett.* **110**: 23–37.
- , AND T. LAERDAL. 2000. The late Pleistocene–Holocene palaeolimnology of Lake Victoria, East Africa, based upon elemental and isotopic analyses of sedimentary organic matter. *J. Paleolimnol.* **23**: 141–164.
- THOMPSON, R., G. M. TURNER, M. STILLER, AND A. KAUFMAN. 1985. Near-east paleomagnetic secular variation recorded in sediments from the Sea of Galilee (Lake Kinneret). *Quat. Res.* **23**: 175–188.
- WANG, X., AND J. VEIZER. 2000. Respiration–photosynthesis balance of terrestrial aquatic ecosystems, Ottawa area, Canada. *Geochim. Cosmochim. Acta* **64**: 3775–3786.

YIN, Z. H., AND J. A. RAVEN. 1998. Influences of different nitrogen sources on nitrogen- and water-use efficiency, and carbon isotope discrimination, in C-3 *Triticum aestivum* L. and C-4 *Zea mays* L. plants. *Planta* **205**: 574–580.

ZOHARY, T., J. EREZ, M. GOPHEN, I. BERMAN-FRANK, AND M. STILLER. 1994. Seasonality of stable carbon isotopes within the

pelagic food-web of Lake Kinneret. *Limnol. Oceanogr.* **39**: 1030–1043.

Received: 13 November 2001

Accepted: 7 August 2002

Amended: 5 September 2002