Carbon Cycling and Accumulation in Lakes
Generalized Models for DIC Isotopic Behavior

B31A-08

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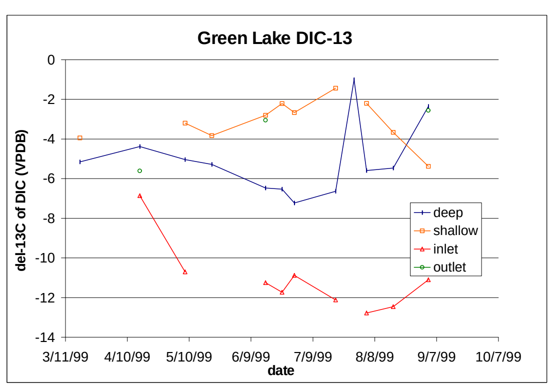
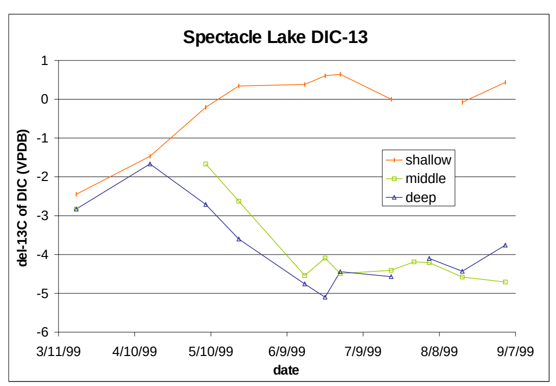
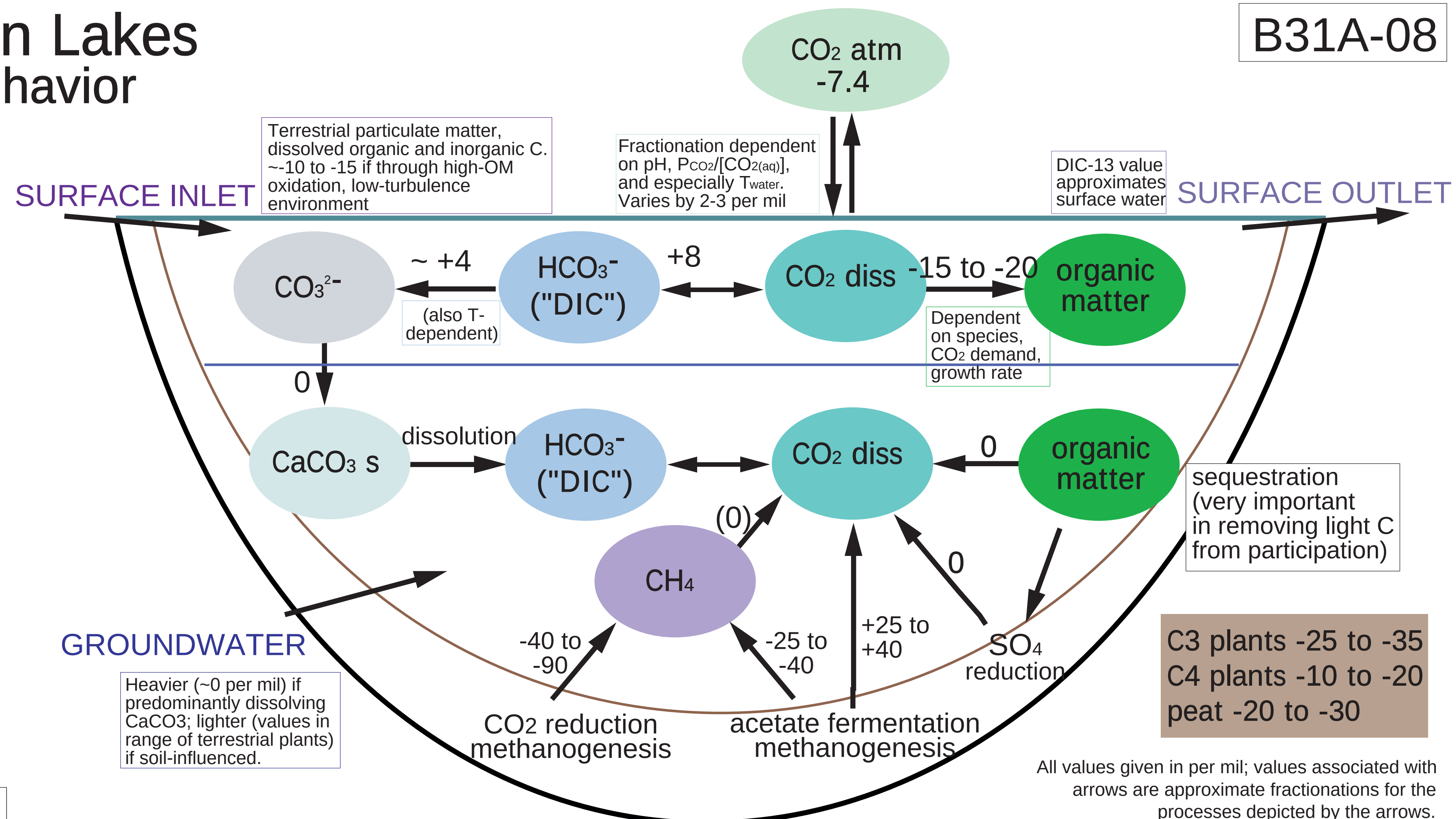
ABSTRACT

Lake sediments provide unique archives of the dynamics of the terrestrial carbon cycle and thus ecosystems on continents. Lacustrine systems, however, are very complex and individual in comparison to ocean basins, integrating as they do signatures of both organic and inorganic carbon storage derived from the lake itself as well as from the landscape. Stable carbon isotopes are among the best tracers of lake carbon processes, but $d^{13}C$ values are controlled by too many factors; the numbers can not provide unique solutions in the absence of good calibration, process models, and independent complementary proxies. Our challenge in utilizing the global lacustrine carbon record is to shoehorn the diversity into a few groups of lake system types with common physical-chemical behavior. For example, some lakes such as Victoria or Superior are atmospherically controlled. Others, such as the natural experiments described here, are controlled by landscape processes: their carbon balances depend on chemistry, morphemetry, circulation, hydrology, biology, and catchment vegetation. Understanding changing carbon dynamics requires that we be able to differentiate the signatures in the sediments in terms of the components representing these processes. A comparative study demonstrates the unique sensitivity of nearly identical systems. Two small Minnesota lakes 1 km apart on the same substrate and with similar water chemistry show divergent response to the same environmental controls. Differences are apparent both in sediment composition and its changes over time, and in the isotopic values of the dissolved inorganic carbon (DIC) in the water. Green Lake, a eutrophic open basin, has organic-rich carbonate sediments throughout the Holocene. Although shallow (max 7m) and large enough (325 Ha) to be thoroughly wind-mixed during the summer, its $d^{13}C$ values are not homogeneous throughout: we see evolution of surface waters to heavier values (from -4 to -1 per mil [VPDB]) and of bottom waters to lighter values (from -5 to -7.5 per mil) as productivity exports light carbon from the surface to depth, where it is degraded. Spectacle Lake, a transparent, smaller (97 Ha), deeper (15m max) closed basin, shows a Holocene transition from carbonate-rich to carbonate-free sediments marked by dramatic swings in sediment composition. Surface waters reach steady-state with the atmosphere (at +0.5 per mil) by late spring, while deep waters lag. The two systems share a familiar and typical behavior, but it is clear that they are processing carbon quite differently. http://www.visi.com/~cosa/carbon





Evolution in stable isotopic values of dissolved inorganic carbon (DIC) for shallow (2m below surface), deep (1m above bottom), and middle (below thermocline) water masses, and inlet and outlet, in Green and Spectacle Lakes through 1999 ice-free season. Note that the much more eutrophic Green Lake shows lighter surface $d^{13}C$ than the transparent, more stably stratified Spectacle Lake. We suggest that Green Lake values are the result of intra-seasonal recycling of sedimented organic C, while Spectacle Lake sequesters light organic C over the season.



All values given in per mil; values associated with arrows are approximate fractionations for the processes depicted by the arrows.

Providing conceptual limits on the system:
Which processes dominate?

In an attempt to reduce the complexity of factors that contribute to a lacustrine sedimentary $d^{13}C$ record, generalizations may be made according to broad lake "types," for instance:

"Bowl" lakes:

Relatively deep compared to surface area or long axis; stable seasonal stratification. Evolved (heavy) surface d13C values: biological processes dominate, as light organic C is sequestered in sediments over the growing season. Bottom-water anoxia; methanogenesis and redox chemistry. Lake-to-atmosphere CO2 transfer episodic (spring and fall mixing). "Reset" mixed values may be heavier than in shallower, more productive lakes.

"Plate" lakes:

Shallow or having a long fetch. Wind mixing recirculates hypolimnetic light C derived from sedimentary organic matter. Anoxic microbial processes in water column minor.

Great lakes:

Dominated by atmospheric exchange. Little or no terrestrial influence; internal biological processes may overprint, but atmosphere-surface system is too large to be sensitive to biology, especially on short timescales.

Saline, meromictic or oligomictic:

Extreme sequestration, only resets/mixes infrequently if at all. Multiple mineral phases. Dolomitization / other exchange in the pore waters. Frequently major influence of microbial processes.