Comparison of multiple proxy records of Holocene environments in the midwestern United States

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ABSTRACT

We compare four emerging approaches to reconstructing Holocene vegetation and climate from south of the glacial border in northeastern Iowa, United States. Pollen, plant macrofossils, carbon isotopic ($\delta^{13}C$) values from alluvial organic matter, and carbon isotopic values in stalagmites from a nearby cave all show similar paleovegetational and paleoclimatic trends during the Holocene. Pollen and plant macrofossils show a rapid change from forest to prairie about 6000 cal. yr B.P., followed by a return of oaks to a presumably savanna-like community about 3500 cal. yr B.P. The $\delta^{13}C$ values in alluvial organic matter and the percentage of C_4 plants both increase ca. 6300 cal. yr B.P., and then decrease in the last 3500 years. In the cave, $\delta^{13}C$ values rise beginning at 6000 cal. yr B.P. to a broad peak ca. 4500 to 3000 cal. yr B.P., and decrease thereafter. Pollen and plant macrofossils record the composition of the vegetation that produced the isotopic signals, and verify C_3-C_4 interpretations based on the isotopic records. We demonstrate that these methods are complementary, but that any single method will provide an accurate reconstruction of past environments.

INTRODUCTION

Records of past environments are important to our understanding of modern climatic variability and future environmental change. The most common source of data used in Holocene models of continental climate and vegetation is pollen analyses from lake and wetland sediments (Bartlein et al., 1998; Webb, 1988; Webb et al., 1993, 1998). However, fossil pollen sites are sparse south of the Wisconsinan glacial border. Thus, for large areas of North America, we have little or no knowledge of past environmental change.

Several new approaches promise to fill in the distribution of paleoenvironmental sites. Studies of pollen and plant macrofossils in stream deposits show promise of extending these records widely into unglaciated areas (Baker et al., 1996). The advent of high precision instrumentation has led to the analysis of stable carbon isotopes, which are widespread in several depositional environments, and are strongly influenced by vegetation and climate. C_3 plants have $\delta^{13}C$ values averaging ca. –26‰, whereas C_4 plants average ca. –13‰ (Deines, 1980). C_4 plants are typically warm-season grasses and a few herbs found in tropical and temperate grasslands, whereas C_3 plants are mostly trees, shrubs, cool season grasses, and most herbs. Both proportion and biomass of C_4 plants in North American prairies are highly correlated with mean annual temperature (Boutton et al., 1980; 1998; Teeri and Stowe, 1976) and less strongly correlated with mean annual precipitation (Epstein et al, 1997). The $\delta^{13}C$ values reflect both the proportion (Teeri and Stowe, 1976) and biomass (Boutton et al., 1980) of C_4 plants. Preserved $\delta^{13}C$ signatures are thus a good indicator of the dominance of C_3 vs. C_4 plants through time, and are indirectly linked to temperature and precipitation.

The $\delta^{13}C$ values have yielded valuable paleoenvironmental information from pedogenic carbonates (Cerling et al., 1989; Humphrey and Ferring, 1994; Wang et al., 1996), soil organic matter (Boutton, 1996; Tieszen and Pfau, 1995; Wedin et al., 1995), and alluvial sediments (Nordt et al., 1994). Significant changes in $\delta^{13}C$ in soils through time have been interpreted in terms of changing vegetation and climate (Boutton et al., 1998; Fredlund and Tieszen, 1997; Tieszen and Pfau, 1995). Speleothems (Dorale et al., 1990) provide continuous, high-resolution $\delta^{13}C$ records reflecting the ratio of C_3 to C_4 plants growing on the surface above the cave (Baker et al., 1996). These new paleoenvironmental records are still sparsely distributed and untested against other approaches.

An ideal paleoenvironmental data set should (1) have a long, continuous record, (2) have a high-resolution time scale such that short-term events can be detected, (3) be precisely dated, (4) accurately reflect regional climatic and vegetational trends, and (5) be located along ecotones or in other climatically sensitive regions.

None of the data sets discussed above is an ideal paleoenvironmental indicator, and little is known about how results from any one method compare with those from another. Although pollen studies are abundant from depressions formed during the last glaciation (Webb, 1988), sites are uncommon beyond the glacial border. Pollen analyses have been extensively calibrated with modern vegetation and climate, making them useful in paleoclimate modeling (Webb et al., 1998), but identification is generally limited to the generic or familial level. Plant macrofossils can commonly be identified to the specific level, and can represent local lowland and upland vegetation, but their application to large-scale problems is just beginning, (Jackson et al., 1997), and their use in alluvium is largely untested. Caves are restricted to regions with carbonate bedrock, and not all caves contain long or continuous records. Furthermore, the changes in isotopic signatures from the ground surface to the cave are still only generally understood. Pedogenic carbonates are limited to soils formed in arid to semiarid climate, and the $\delta^{13}C$ in both soil

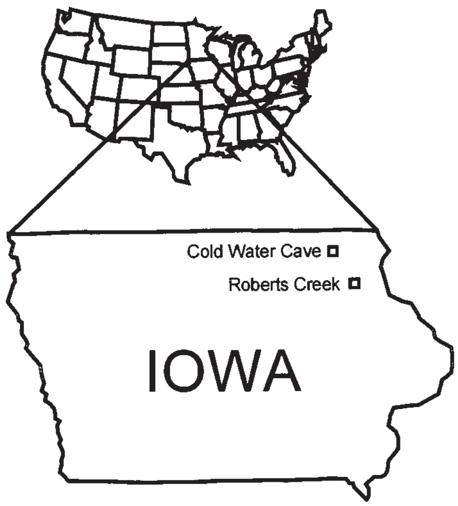

Figure 1. Location of sites.

organic matter (Torn et al., 1997) and pedogenic carbonates may integrate the $\delta^{13}C$ values over the interval of soil formation. Values of $\delta^{13}C$ in alluvium have rarely been analyzed in temperate North America (Nordt et al., 1994). In summary, reliable Holocene paleoenvironmental data are sparse over large areas of the continents, and new sources of information need to be explored and calibrated with vegetation and climate.

Here we report on the first Holocene-scale comparison of alluvial pollen, plant macrofossils, $\delta^{13}C$ values, and cave $\delta^{13}C$ values; we establish that the isotopic changes reflect changes in vegetation and thereby changes in climate. The results of all approaches fit well with the regional pattern of paleoenvironmental change in the Midwest (Baker et al., 1992).

Pollen and plant macrofossils recovered from each rapidly deposited alluvial sample from a small stream in northeastern Iowa (Figs. 1 and 2) reflect conditions during a short depositional interval (Baker et al., 1996). A chronological record is achieved by radiocarbon-dating wood from many samples, and arranging their biotic records in chronological order. Analyses of calcite in speleothems supply a $\delta^{13}C$ record with U-Th ages from the same area (Dorale et al., 1990; Baker et al., 1996). We compare these data with newly obtained $\delta^{13}C$ analyses of the same alluvial samples used for pollen and plant macrofossil analyses. The juxtaposition of all four data sources is somewhat unusual and allows us to assess their level of agreement, their potential regional utility, and their capabilities in the study of past vegetation and climate.

METHODS

Alluvial sediments from Roberts Creek and speleothems from Cold Water Cave were sampled, processed, and analyzed by using standard methods (Baker et al., 1996). Cold Water Cave is 60 km northwest of Roberts Creek, and stalagmites 1S and 3L (Fig. 3) were collected about 1 km apart in the same passage of the cave. The surface topography above the area where stalagmite 1S was collected is a southeast-facing slope along a ravine, whereas that over 3L is a broad, gently sloping upland facing northwest. Roberts Creek radiocarbon ages were calibrated to calendar ages with the CALIB program (Stuiver and Reimer, 1993).

From each site along Roberts Creek, ~500 ml of loamy sediment containing dispersed organic matter were sent to Massachusetts Institute of Technology for carbon isotopic analysis. Subsamples of these alluvial sediments were acidified with excess 1*N* HCl, rinsed in distilled water, and dried. The organic residue was combusted in a NA1500 Carlo Erba Elemental Analyzer, and the evolved CO_2 was carried in a helium stream to a VG Prism III mass spectrometer, where the $\delta^{13}C$ in the sample relative to PDB (the Peedee belemnite standard) was determined. All samples were prepared, acidified, and measured in triplicate at Massachusetts Institute of Technology (1σ errors on triplicate samples are shown in Fig. 3); the average standard deviation for standards (benzoic acid) is ±0.10‰.

Abundance of C_4 vegetation was estimated by assuming that end-member C_4 and C_3 $\delta^{13}C$ compositions were –13‰ and –26‰, respectively (Deines et al., 1974; Deines, 1980). The stalagmite estimate is based on the $\delta^{18}O$ and $\delta^{13}C$ composite record of Cold Water Cave stalagmites 1S and 3L. Composite isotopic records for each stalagmite were produced by generating an evenly sampled series at 10 yr intervals by interpolations on a spline of the original record using the routines in AnalySeries (Paillard et al., 1996). We used a fixed rock-carbon fraction of 0.47 (0.53 for soil carbon), temperatures were estimated from the composite speleothem $\delta^{18}O$ record (Baker et al., 1996), and the HCO_3-CO_2 carbon fractionation factor was calculated from the data in Deines et al. (1974).

RESULTS

The pollen and plant macrofossils from Roberts Creek, northeastern Iowa, show that a mesic deciduous forest was present in the early Holocene, from ca. 10000 to ca. 6300 calibrated ^{14}C yr B.P. (Fig. 2). This forest was rapidly replaced by prairie, which prevailed between ca. 6300 and ca. 3500 yr B.P., when mixed forest and prairie were established and coexisted until the area was settled in the mid-1800s A.D. (Baker et al., 1996).

Although the carbon isotopic composition of soil water is modified as infiltrating water interacts with carbonate bedrock above Cold Water Cave, it nevertheless reflects the relative importance of C_3 vs. C_4 plants in the vegetation, because fluid pathways and thickness of carbonates above the cave are unlikely to have changed greatly during the Holocene. The $\delta^{13}C$ record preserved in two stalagmites from Cold Water Cave shows steady values between –7‰ and –9‰ from ca. 9000 to ca. 6000 yr B.P. (Fig. 3), suggesting that C_3 plants were prevalent. This interval corresponds well with the period when deciduous forest was dominant at Roberts Creek (Fig. 2). No fossils of C_4 plants were found in sediments of this interval. Speleothem $\delta^{13}C$ rose to a broad peak of –4‰ to –6‰ between ca.

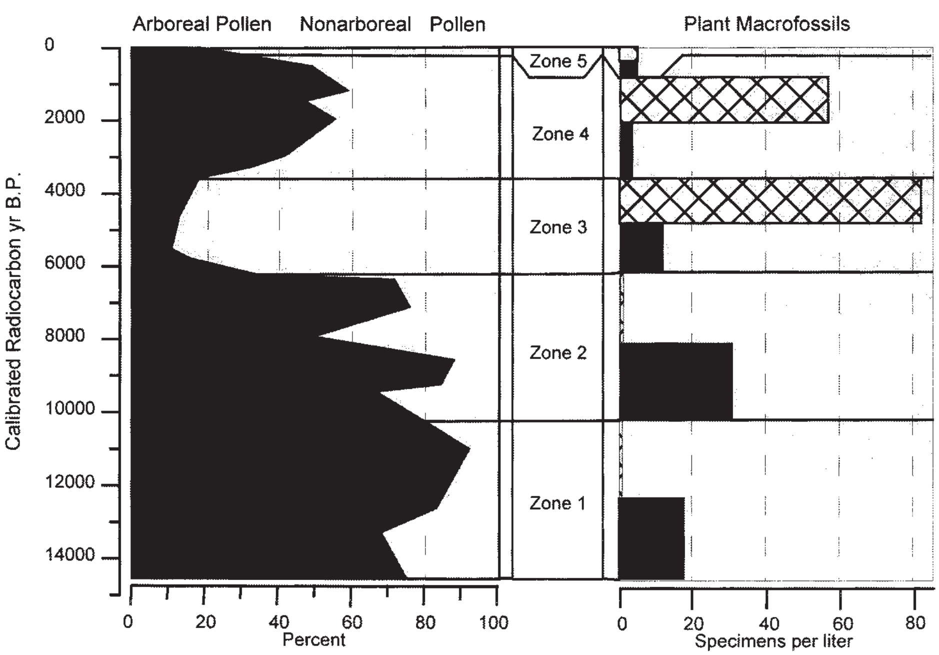

Figure 2. Generalized pollen (left) and plant macrofossil (right) diagrams from Roberts Creek, northeastern Iowa. Black bars in each zone on right represent deciduous forest species; patterned bars represent prairie species.

4500 and 3000 yr B.P. This change would be expected if C_4 plants became increasingly abundant in the vegetation. The dominant grasses of the tall-grass prairie are C_4 grasses, and several species of C_4 grasses are found as macrofossils in the peak of prairie vegetation at Roberts Creek. Speleothem $\delta^{13}C$ declined slowly during the last 3000 yr B.P., stabilizing at –7‰ to –8‰ ca. 2000 yr B.P. This period corresponds to the savanna (mixed prairie and forest) interval shown by the plant-fossil record.

The nearly identical $\delta^{13}C$ signature of Cold Water Cave stalagmites 1S and 3L, and their similarity to the Roberts Creek vegetational record (Fig. 2), indicate that the stalagmites are recording long-term changes in the isotopic composition of soil organic matter resulting from regional changes in vegetation; local topography and slope aspect are not important factors.

Alluvial $\delta^{13}C$ values ranged from –26‰ to –28‰ between ca. 9000 and ca. 6300 yr B.P. (Fig. 3). In contrast to speleothem records, these isotopic values were unmodified by carbonate bedrock, and thus the figures are more directly comparable with the values found in vegetation and soils (Boutton, 1996; Cerling, 1984, Deines et al., 1974). Ratios shifted rapidly from about –27‰ to –24‰ between ca. 6600 and ca. 6300 calibrated ^{14}C yr B.P., and then continued to gradually rise to –22‰ at ca. 3000 yr B.P. (Fig. 3). The $\delta^{13}C$ value decreased to ca. –24‰ after 3000 yr B.P. with the exception of one sample at ca. 2000 yr B.P. These trends correlate strongly with the changes in tree vs. prairie pollen in these sediments and the trends in abundance of prairie vs. deciduous forest plant macrofossils (Fig. 2), as well as the trends in $\delta^{13}C$ values from calcite in Cold Water Cave (Fig. 3).

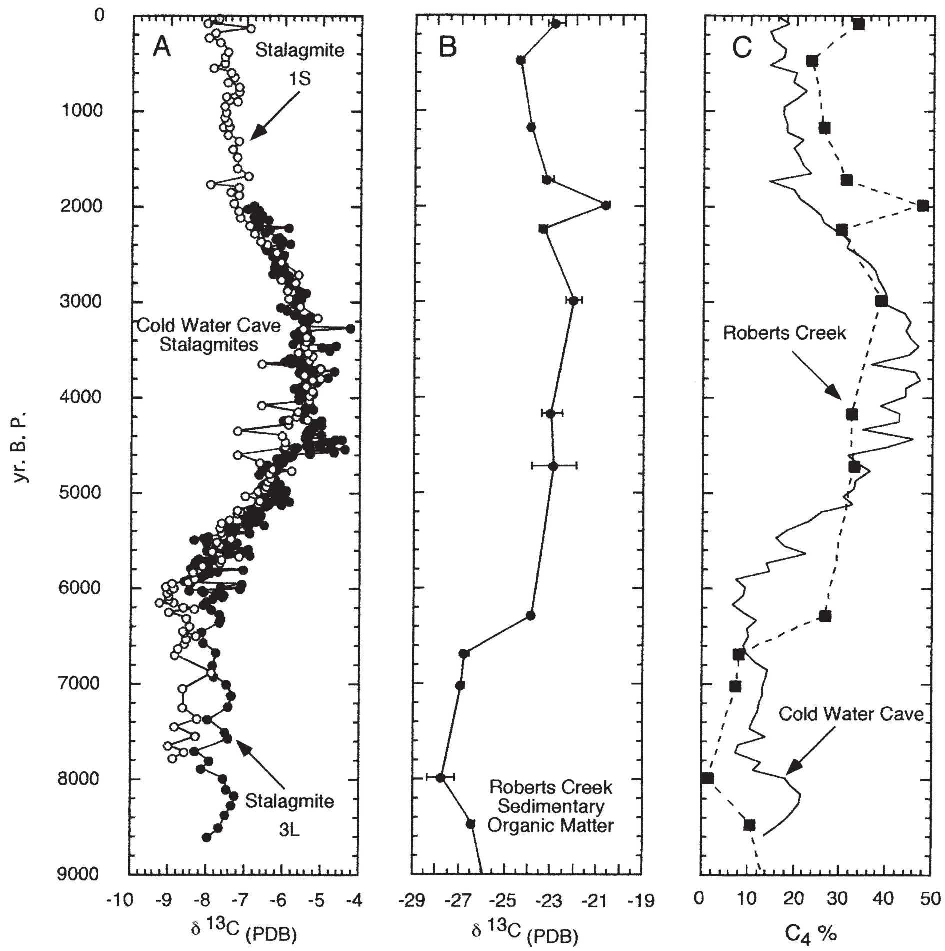

Figure 3. A: Carbon isotopic composition of speleothem calcite for Cold Water Cave stalagmites 1S and 3L. B: Carbon isotopic composition of Roberts Creek alluvial sedimentary organic matter. Values of $\delta^{13}C$ for sedimentary organic matter are averages of three analyses, and error bars represent standard deviation (1σ). Note similarity in timing of all three records, and correlation with plant records in Figure 2. C: Estimates of percent contribution of C_4 plants through time to the soil and sedimentary biomass over Cold Water Cave based on carbon isotopic composition of sedimentary organic matter and a composite of stalagmite carbon isotopic record.

DISCUSSION AND CONCLUSIONS

Table 1 evaluates these emerging approaches to reconstructing Holocene climate and vegetation. Because of the high resolution stratigraphy and dating, the cave isotopic record superbly records short-term (annual or even seasonal) oscillations in vegetation and climate, but the vegetation is reconstructed only in general terms through its C_3-C_4 contribution to soil biomass. The fossil plant record is well dated by ^{14}C, but the distribution of dated sites in space and time is uneven, and the ^{14}C method does not allow decadal-scale resolution. The genera and species of plants in the vegetation, however, are recorded by macrofossils, giving a much stronger paleoecological record. Both speleothem $\delta^{13}C$ and alluvial pollen and macrofossils are somewhat limited by site availability but are most often found south of the glacial boundary. The alluvial $\delta^{13}C$ record has the chronological resolution of the fossil plant record and the lower vegetational resolution of the cave record, but a potentially much wider geographic occurrence and greater speed and ease of analysis. The $\delta^{13}C$ of soils, not tested here, probably compares most closely with the alluvial $\delta^{13}C$ record.

Although the estimates of the proportion of C_4 plants in the soil biomass based on sedimentary organic matter (Roberts Creek) and on speleothem carbon isotopes (Cold Water Cave) differ slightly, the long term trends in C_4 vegetation percentage for both records are in good agreement (Fig. 3). Both records suggest that the percentage of C_4 vegetation was low in the early Holocene, increased from 10%–12% at 6000 to 6200 yr B.P. to 30%–40% between 5000 and 2500 yr B.P., and decreased to 20%–25% around 2000 to 2400 yr B.P. (Fig. 3). Long-term trends in the speleothem record reflect the rate of change in soil organic matter that followed substantial climatic and vegetational change over a large region, whereas the high-frequency spikes are caused by decadal-scale changes in composition, which probably reflect short local climatic oscil-

TABLE 1. COMPARISON OF APPROACHES MENTIONED IN TEXT

Type of record	Dating	Climate	Vegetation	Site distribution
Cave $\delta^{13}C$ and $\delta^{18}O$	excellent, (±2 yr)	very good	good	spotty
Alluvial pollen	good (±100 yr)	good	very good	wide
Alluvial plant macrofossils	good (±100 yr)	good	excellent	wide
Alluvial $\delta^{13}C$	good (±100 yr)	good	very good	very wide
Soils*	fair?	good?	very good?	very wide

*Not tested in this study.

lations rather than change in total soil organic matter. The ~500 yr offset between alluvial and cave records (Fig. 3) in the mid-Holocene may reflect the more rapid response of $\delta^{13}C$ in alluvial sediments to climatic change. An alternate hypothesis is that, if more dated sections were available, the offset would be an isolated peak like the one at 2000 yr B.P., perhaps due to very local ecological conditions. However, the peak at ca. 2000 yr may be widespread; a similar sharp $\delta^{13}C$ peak at about 2000 yr B.P. is seen in dated soil profiles from Texas (Nordt et al., 1994; Humphrey and Ferring, 1994) and North Dakota (Boutton et al., 1998).

Grasslands and savannas may have especially important links to climate through the carbon cycle; the deep root systems of many grassland taxa sequester large amounts of carbon in the soil (Fisher et al., 1994). The role of C_4 grass distribution through the Holocene and its role in the carbon cycle has been little studied (Fisher et al., 1994). Our study shows that four independent approaches, used in concert or separately, provide a powerful reconstruction of past trends in vegetation and climate, allowing us to extend the coverage of paleoenvironmental sites into many areas where data are lacking.

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