Geoderma 147 (2008) 197–210

Contents lists available at ScienceDirect

Geoderma

journal homepage: www.elsevier.com/locate/geoderma

Reconstructing palaeoenvironment from $\delta^{13}C$ and $\delta^{15}N$ values of soil organic matter: A calibration from arid and wetter elevation transects in Ethiopia

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ARTICLE INFO

Article history:
Received 16 February 2008
Received in revised form 24 August 2008
Accepted 1 September 2008

Keywords:
Stable isotopes
Palaeoclimates
Soil organic matter

ABSTRACT

One difficulty with reconstructing palaeoclimate from stable isotopic analyses of continental proxies is to determine whether changes occurred in temperature and/or precipitation. The resolution with which $\delta^{13}C$ and $\delta^{15}N$ values of soil organic matter (SOM) can be used to infer climate characteristics were examined from soils along two elevation transects in Ethiopia. Two transect characteristics permitted evaluation of temperature and precipitation effects separately and in tandem on δ values. First, transects differed from one another in precipitation but not in temperature. In addition, precipitation did not co-vary with elevation or temperature in the wetter transect. Vapour pressure deficits (physiologically meaningful measures of aridity affected by both temperature and precipitation) thus decreased more with elevation gain in the drier than in the wetter transect. In both transects, $\delta^{13}C$ values of surface (<10 cm depth) SOM were highest at middle elevations and lowest at both the highest and lowest elevations. This humped relationship was preserved in presumably older SOM samples up to 300 cm depth. These trends support hypotheses about climate influences on $\delta^{13}C$ values of SOM only from the middle to highest elevations. From the lower to middle elevations, the trends suggest the hypothesis that historical differences in land use pressures may have a greater and opposing influence than climate on $\delta^{13}C$ values of SOM. The $\delta^{15}N$ values were negatively related to elevation in the drier transect alone, supporting hypotheses that precipitation is the principal influence on $\delta^{15}N$ values of SOM. Elemental analyses provide some affirmation for the hypothesis that the influence of precipitation on openness of local nitrogen cycling can cause $\delta^{15}N$ values to increase with aridity. A problem in reconstruction of continental environments, per se, is to discern changes in climate from changes in land use. If differences in land use history have larger effects than climate on $\delta^{13}C$ values of SOM then $\delta^{15}N$ values of SOM may be valuable in conjunction with $\delta^{13}C$ analyses for reconstructing aspects of land use and climate.

1. Introduction

At least four factors place Ethiopia among the most critically important locations for testing hypotheses about relationships between environmental changes and fundamental developments in human communities (e.g., Carneiro, 1970). First, it is a contender for the longest history of habitation by *Homo sapiens* (White et al., 2003). Second, a multi-millennial succession of highly organized kingdoms and empires has resided in the highlands of its northern half. These include a probable centre of origin of agriculture and the once internationally powerful commercial empire, Aksum (Phillipson, 1998). These two factors alone; lengthy, and varied human history, make Ethiopia a compelling region for reconstructing past environments.

Third, Ethiopia's range of elevations (ca. −120 to 4620 m a.s.l.), and tropical latitudes (ca 3–15° N) offer climates ranging from those with regular frosts to among the hottest on terrestrial earth. This virtually unexploited factor makes Ethiopia a superior location in which to calibrate continental palaeoproxies for climate.

Past land use is an important aspect of palaeoenvironmental reconstruction for understanding developments in human societies and may provide keys to predict future societal developments as well (e.g., Diamond, 2005; for Ethiopia, Butzer, 1981). Land use may also confound efforts to reconstruct climate, however (Butzer, 2005). Studies of modern analogues could be as useful for identifying proxies

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0016-7061/$ – see front matter
doi:10.1016/j.geoderma.2008.09.001

for past land use as for calibrating palaeoclimate. Ethiopia's fourth attribute is that ancient land uses are more widely practiced in Ethiopia today than are modern technologies (Bard, 1997; Bard et al., 1997, 2000).

Factors three and four mean that Ethiopia has an unusually good array of modern analogues with which to develop means of separating climate from land use in environmental reconstruction. Herein, we make use of factors 3 and 4 to calibrate relationships of stable carbon and nitrogen isotopic compositions of soil organic matter to climate, and land use.

Soil organic matter (SOM) is among the most ubiquitous of terrestrial materials with potential to provide insights about past environments. An increasingly facile avenue for obtaining those insights is through carbon and nitrogen stable isotopic analyses (δ^{13}C and δ^{15}N) of SOM. Analyses of δ^{13}C values in SOM have become regular means of reconstructing past C_3/C_4 compositions of vegetation and their associated environmental conditions (Boutton et al., 1998) because δ^{13}C values of C_3 plants are, on average, 15‰ lower than those of C_4 plants (O'Leary, 1988), and plants are the primary sources of SOM. The proportions of C_4 and C_3 vegetation in a landscape are often related to climate (Ehleringer et al., 1997; Sage et al., 1999; Huang et al., 2001; Street-Perrott et al., 2004).

Biogeochemical factors can weaken the resolution of vegetation reconstructions from δ^{13}C values of bulk SOM. Most notably, differences in decomposition rates among compounds that vary in δ^{13}C can cause carbon isotopic fractionations in SOM (Agren et al., 1996). In addition, <200 y old SOM is ^{13}C depleted by ça. 1.5‰ due to increases in organically derived CO_2 in the atmosphere that, in turn, is fixed by plants (Balesdent and Mariotti, 1996). Although the effects of decomposition on the δ^{13}C values of SOM can be eliminated by analyzing specific, highly refractory compounds (Huang et al., 1999), such effects are apparently small relative to those caused by shifts in vegetation cover, even after millions of years (Cerling et al., 1989). Consequently, δ^{13}C analyses of bulk material remain common for reconstructing past vegetation (Koch, 1998).

In contrast to δ^{13}C, the principal source of an association of δ^{15}N values of bulk soil organic matter with environment is via biogeochemical factors. Specifically, ^{14}N is favoured in many outfluxes of inorganic nitrogen, leaving the remaining soil pool enriched in ^{15}N. SOM pools from more closed biogeochemical cycles may have less ^{15}N enrichment than SOM pools in more open cycles because there will be less ^{14}N loss from denitrification and more ^{14}N return of dead plant matter in the former than in the latter (Högberg, 1993). How closed or open an ecosystem's nitrogen cycle is may be influenced by climate and land use (Eshetu and Högberg, 2000a,b; Amundson et al., 2003; Miller et al., 2004).

Most of the change in δ^{15}N of SOM occurs within the first few tens of centimetres of the soil surface (Nadelhoffer and Fry, 1988; Martinelli

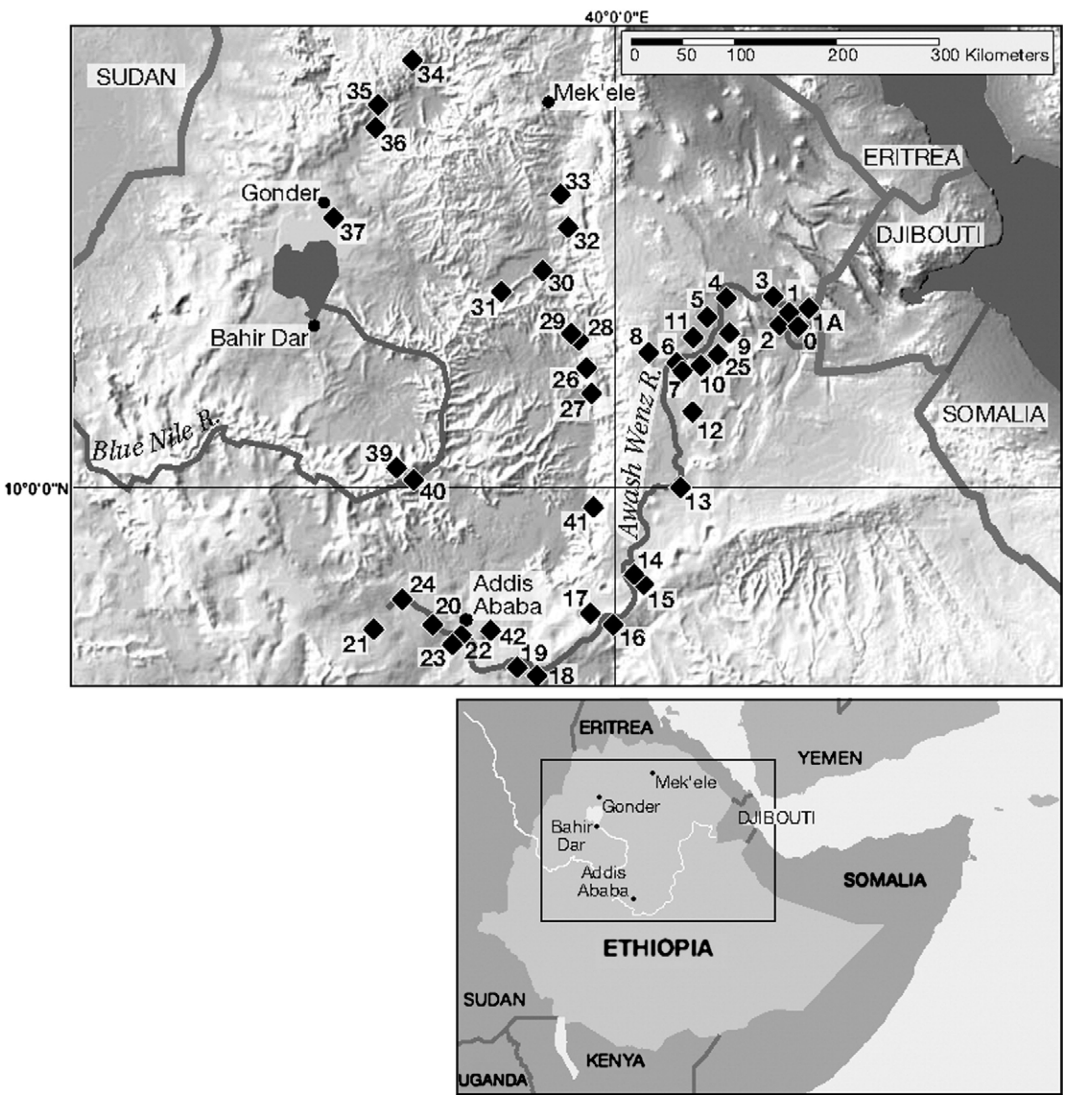

Fig. 1. Locations of sampling sites. See Table 1 for additional information.