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Late-glacial to Holocene transition in northern Spain deduced from land-snail shelly accumulations

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ABSTRACT

Shells of the helicid *Cepaea nemoralis* were studied using taphonomic, isotopic and morphometric measurements to estimate late glacial–Holocene (~12.1–6.3 cal ka BP) environmental conditions in northern Spain. Higher taphonomic alteration among Holocene shells suggests lower sedimentation rates or higher shell-destruction rates than during glacial conditions. Shells preserved the aragonitic composition despite differing degree of skeleton damage. Shell δ^{13}C values were -10.3 ± 1.1‰, -8.2 ± 2.3‰, and -7.3 ± 1.6‰ for modern, Holocene and late-glacial individuals, respectively. Higher δ^{13}C values during the late-glacial and some Holocene periods imply higher water stress of C_3 plants and/or higher limestone contribution than today. Intrashell δ^{13}C values were higher during juvenile stages suggesting higher limestone ingestion to promote shell growth. Shell δ^{18}O values were -1.1 ± 0.7‰, -0.9 ± 0.8‰ and -0.1 ± 0.7‰ for modern, Holocene and late-glacial specimens, respectively. A snail flux-balance model suggests that during ~12.1 − 10.9 cal ka BP conditions were drier and became wetter at ~8.4 − 6.3 cal ka BP and today. Intrashell δ^{18}O profiles reveal that glacial individuals experienced more extreme seasonality than interglacial shells, despite possible larger hibernation periods. Shell size correlated positively with δ^{18}O values, suggesting that growth rates and ultimate adult size of *C. nemoralis* may respond to climate fluctuation in northern Spain.

Introduction

Land snails have been exploited by humans as a food resource and/or for ornamentation purposes since early human civilizations, as evidenced by numerous shell middens globally (e.g., Bobrowsky, 1984; Evans, 1972; Lubell, 2004a,b), however, they have received comparatively less scientific attention than other zooarchaeological remains. Land snail shells are potential retrospective environmental and ecological archives (reviews in Goodfriend, 1992, 1999) which may complement and expand the information extracted from other (more commonly studied) organisms. Land snails interact with the habitat where they live and therefore, their taphonomic condition, geochemical composition and body size reflect the conditions of the environment in which they grew, died and were subsequently buried.

Land-snail taphonomy (= snail fossilization process) is used to estimate shell burial mechanisms and the quality and fidelity of the fossil record (e.g., Cameron et al., 2010; Carter, 1990; Rundell and Cowie, 2003; Schilthuizen et al., 2003; Yanes, 2012; Yanes et al., 2008a, 2011a). Strongly altered shells are often associated with low sedimentation rates or multiple burial–exhumation cycles (i.e., longer exposure of shells to biostratinomic processes). In contrast, weakly damaged samples reflect rapid sedimentation rates and therefore, a rapid burial process and reduced residence time in the taphonomically active zone (e.g., Brett and Baird, 1986). Hence, some important information regarding postmortem processes can be inferred from the study of the taphonomic condition of shells. Yet, these kinds of studies are uncommon for terrestrial gastropod shelly accumulations, especially those from archeological sites (cf. Carter, 1990; Evans, 1972; Gutiérrez-Zugasti, 2011).

The carbon (δ^{13}C) and oxygen (δ^{18}O) stable isotope values of fossil aragonitic shells are used to reconstruct the paleovegetation and past atmospheric conditions (e.g., Colonese et al., 2010a,b, 2011; Kehrwald et al., 2010; Yanes et al., 2011b, c, 2012). The shell δ^{13}C values represent values of consumed plants (Metref et al., 2003; Stott, 2002). Field studies indicate that the relationship between plant and shell is not straightforward because snails ingest limestone (Goodfriend, 1987; Goodfriend and Hood, 1983; Goodfriend et al., 1999; Yanes et al., 2008b; Yates et al., 2002). The contribution of limestone into the shell appears to be negligible among minute (length <10 mm) gastropods (Pigati et al., 2004, 2010), but can be substantial among medium-large size (length >10 mm) snails that inhabit carbonate-rich areas. There is an isotopic offset between shell and diet, varying between ~8 and 22‰ (e.g., McConnaughey and Gillikin, 2008; Metref et al., 2003; Stott, 2002; Yanes et al., 2008b, 2009). Such isotopic offset is the consequence of carbon isotope exchanges between respiratory CO_2 and HCO_3^- of the hemolymph from which the shell is precipitated (e.g., McConnaughey and

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Gillikin, 2008). The shell $\delta^{13}C$ values may be used to estimate the proportion of C_3/C_4 plants, variations in atmospheric CO_2 levels, or the degree of water stress of C_3 plants in C_3-dominated landscapes (e.g., Goodfriend and Ellis, 2000, 2002).

The shell $\delta^{18}O$ values are linked to rain $\delta^{18}O$ values and air temperatures (e.g., Balakrishnan et al., 2005b; Lécolle, 1985; Yanes et al., 2008b, 2009; Zanchetta et al., 2005). A snail evaporative steady-state flux-balance model by Balakrishnan and Yapp (2004) demonstrates that such relationship can be complicated because other important atmospheric variables, such as relative humidity and water vapor $\delta^{18}O$ values, should be considered when interpreting $\delta^{18}O$ values of snail shells. Thus far, the model by Balakrishnan and Yapp (2004) is the most sophisticated mathematical approach available that incorporates the highest number of environmental variables jointly to explain quantitatively shell $\delta^{18}O$ values of land snails. The shell $\delta^{18}O$ values are fractionated (~1–8‰) with respect to unmodified ambient water as a consequence of body-water loss through evaporation (Balakrishnan and Yapp, 2004). The isotopic offsets between shell and water are larger at drier/hotter sites, where evaporation processes are enhanced (e.g., Yanes et al., 2009). Altogether, the shell $\delta^{18}O$ values of land snails are complex to understand though useful to reconstruct ancient atmospheres at the soil-air interface during snail active periods (e.g., Zaarur et al., 2011).

Land-snail body size responds to multiple environmental and biological factors operating jointly, which are sometimes difficult to identify and quantify. Moisture is one of the best-documented environmental driving factor to which shell size responds (see review in Goodfriend, 1986). In arid environments, where water is a limiting factor, snails tend to be larger because they lose less water as a consequence of their lower surface to volume ratio (e.g., Nevo et al., 1983). Other studies have however observed opposite trends (e.g., Goodfriend, 1986), whereas some studies found no correlation between body size and rainfall (e.g., Hausdorf, 2006). Even though humidity may be an important factor, the link between body size and the environment seems to vary in scale and direction across taxa and localities.

In this study, *Cepaea nemoralis* (Gastropoda: Helicidae) shells from late-glacial period (~12.1 cal ka BP), earliest Holocene (~10.9 cal ka BP) and early mid-Holocene (~8.4–6.3 cal ka BP) archeological sites were studied using taphonomic descriptors, stable isotopes and morphometric measurements combined to infer the average (dominant) and seasonal (high-resolution) atmospheric conditions at the late glacial–Holocene transition in Cantabria and Asturias, northern Spain (43°N). This study represents one of the few published works using snail assemblages from the Iberian Peninsula as a paleoenvironmental proxy (cf. Yanes et al., 2011b, 2012). The isotopic results are compared to other published European and Mediterranean snail data and the shell $\delta^{18}O$ values are interpreted in the context of a snail evaporative steady-state flux-balance mixing model.

Methodology

Geographical and archeological context

Shells were recovered from five archeological sites in Cantabria and Asturias, northern Spain (Fig. 1), including four Holocene stratigraphic units: Arenillas (AR) shell midden level; Cubío Redondo spit 3 (CR3); Cubío Redondo spit 6 (CR6); El Mazo (EM) level 105; one earliest Holocene unit: La Fragua (LF) level 3; and one late-glacial unit: El Piélago II (EP) level 2. Shells were found directly associated with other archeological remains including vertebrates, charcoal, lithic artifacts and marine mollusks. Land snails were almost certainly collected and probably consumed by ancient human groups (Gutiérrez-Zugasti, 2011).

Radiocarbon dating of charcoal and bones indicates that shell remains range from ~12.1 to 6.3 cal ka BP, embracing the late glacial–Holocene transition (Bohígas and Muñoz, 2002; García-Guinea, 1985; González-Morales, 2000; Gutiérrez-Zugasti, 2011; Ruiz-Cobo and Smith, 2001).

Environmental setting

The study area is characterized by mild winters and cool summers, with an average temperature of ~14°C, ranging from 9.5°C in January to 19.9°C in August (www.aemet.es), and a total annual precipitation above 1200 mm (Table 1; Fig. 2). Precipitation mostly occurs in winter (Table 1; Fig. 2A), associated with mid-latitude Atlantic Ocean storms. The weighted mean $\delta^{18}O$ values of the rain vary from −3.4‰ (SMOW) in May to −6.9‰ (SMOW) in February (Table 1; Fig. 2B). The annual weighted mean $\delta^{18}O$ value of the rain is −6‰ (SMOW) (www.iaea.org). Average relative humidity (RH) ranges from ~73% in March to ~78% in August (Table 2; Fig. 2B). Average annual maximum RH is ~88% at night and dawn, but can reach up to 100% at certain seasons due to the short distance from the coast. Weighted mean $\delta^{18}O$ values of the rain correlate positively with temperature (Fig. 2C) and negatively with precipitation (Fig. 2D).

Samples

The archeological sites were excavated between 1967 and 2010 (Bohígas and Muñoz, 2002; García-Guinea, 1985; González-Morales, 2000; Ruiz-Cobo and Smith, 2001). Shells were obtained from collections archived in the University of Cantabria and the Museum of Prehistory and Archaeology of Cantabria. A total of 172 shells of *C. nemoralis* (Linnaeus, 1758) were available. In addition, living specimens ($n=12$) were collected in Cantabria during the winter of 2010 to establish a modern analog previously unavailable for the region.

C. nemoralis is an air-breathing pulmonate gastropod natural from Western Europe but introduced in other continents. *Cepaea* is usually abundant at carbonate-rich and humid localities. In the Iberian Peninsula *Cepaea* is only abundant in the northern (wetter) region (e.g., Gutiérrez-Zugasti, 2011). It typically takes ~1−2 yr for newly hatched snails to reach adulthood, and the average lifespan is ~2.3 yr. In occasional cases *Cepaea* can live up to ~5 yr more after the lip is segregated. Growth rates seem to vary depending on the ecological context like population density (e.g., Wolda, 1970) and environmental conditions such as temperature and calcium content in soil and decayed vegetation (e.g., Bengtson et al., 1979).

Shell taphonomy and morphometrics

Shells were evaluated for taphonomic condition and diagenetic alterations to assess their quality. X-ray diffraction analyses of two archeological shells (one ~12.1 ka shell from El Piélago and another ~6.3 ka shell from Arenillas) were performed at the Instituto Andaluz de Ciencias de la Tierra (IACT), CSIC-Universidad de Granada. Several taphonomic descriptors, including breakage, corrasion (=biochemical dissolution and/or mechanical abrasion; e.g., Brett and Baird, 1986), carbonate coating and color loss, were also studied under a binocular microscope to evaluate macroscopic damage of shells. The taphonomic study was carried out following Yanes et al. (2008a, 2011a) methodology for twelve modern and 172 archeological shells. The taphonomic data were recorded as binomial variables, where (=1) was assigned for poorly preserved shells and (=0) was assigned for well-preserved shells. The total taphonomic grade (TTG) was scored for each shell as the sum of all taphonomic features (for further details see Yanes and Tyler, 2009). The TTG in this study ranged from 0 (=well preserved) to 4 (=poorly preserved).

Six measurements, including length, width, height of the two last spires, height of the last spire, aperture height and aperture width, were obtained from twelve modern and 164 ancient *Cepaea* individuals following Kerney and Cameron (1979) and Huntley et al.