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Refining Potential Source Regions *via* Combined Maize Niche Modeling and Isotopes: a Case Study from Chaco Canyon, NM, USA

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Abstract The application of geochemical sourcing methods to archaeological questions continues to grow, as does the need for innovation in applying these methods. The process of sourcing materials is to rule out potential areas in favor of the most likely origin. It will foreseeably remain true that additional data could reveal other potential sources for an artifact. However, the use of multiple methods to further refine potential sources should not be neglected. In this paper, we use maize niche modeling in tandem with isotopic data to refine possible source regions of archaeological deer from Chaco Canyon, NM, USA (*ca.* AD 800–1250). Previous research on this prehistoric community demonstrated an extensive non-local procurement system where small mammals were garden-hunted in plots lying > 40 km from the canyon and the procurement of deer from upper elevations at > 90 km. The upper elevation procurement of deer will be tested by adding carbon isotopes and maize niche modeling to previously published strontium and oxygen isotopic data. As browsers with an affinity for maize, deer

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harvested in low to mid elevations within the maize farming niche should have carbon isotope ratios reflecting C_4 plant consumption. Growing degree days in this region place the most salient limits on the elevation of maize production and define the region corresponding to a maize-free diet. Analyses of archaeofaunal deer from Pueblo Bonito indicate that hunting occurred at a higher elevation than the maize farming niche. These results demonstrate the utility of combining geochemical sourcing methods with paleoenvironmental modeling.

Keywords Chaco canyon · Deer · Carbon isotopes · Maize niche modeling · Sourcing

One only needs to pick up the latest issue of American Antiquity, Journal of Archaeological Sciences, or more to the point the journal you are currently reading—Journal of Archaeological Method and Theory—to see the methodological importance of geochemical sourcing in archaeology. It could be argued that these methods are becoming standard practice as a means to understand past peoples and their relationships with other human and ecological communities. There is no doubt that these methods are an important window into the past, and a window that should be constantly refined, advanced, and expanded. Here, we propose combining isotope geochemistry with paleoecological modeling as one way to refine and advance sourcing methods.

There are problems with narrowing down the location of a source region using standard isotopic methods. A study might solely use strontium isotopes (typically measured as a ratio of strontium-87 to strontium-86: $^{87}Sr/^{86}Sr$, but see Knudson *et al.* 2010) to source an artifact, which will allow a researcher to narrow in on geographical lithologies that overlap with the measured ratios of an artifact (Bentley 2006; Grimstead *et al.* 2017). There may only be one lithology in a given region that will overlap, but typically there are multiple options. Thus, the researcher is left with a clear picture of where the artifact did not come from and several possibilities of the latitude and longitude of a source region. Oxygen isotopes ($\delta^{18}O$) may be able to rule out some of the possibilities because of its strong relationship with elevation (Dansgaard 1964; Ingraham and Taylor 1991; Rowley 2007), but the source of water can be an exceptionally confounding factor requiring a better picture of the paleoenvironment—a complication discussed below. Carbon isotopes ($\delta^{13}C$) are typically used in paleodietary studies to understand if an animal had access to tropical C_4 plants (typically maize) and in what proportions (*e.g.*, Coltrain *et al.* 2007; Matson and Chisholm 1991; McCaffery *et al.* 2014). Here, we suggest that when $\delta^{13}C$ is combined with maize niche modeling, the two can be used in conjunction to refine possible source regions revealed *via* $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ data. Artifacts from Chaco Canyon, NM, USA, have been extensively sourced using iso-mapping of the surrounding San Juan Basin ranges (*e.g.*, English *et al.* 2001; Grimstead *et al.* 2016; Reynolds *et al.* 2005), and the authors will return to this region to demonstrate the utility of this suggested comprehensive tactic.

Chaco Canyon is in the San Juan Basin of northwestern New Mexico (Fig. 1). Large populations resided in numerous sites in the canyon with peak population in the interval AD 850–1150. Chaco Canyon is most famous for its 12 great houses—large, multistory, room blocks with numerous ceremonial rooms or kivas. The ostentatious masonry architecture of great houses is amplified by elaborate material culture recovered

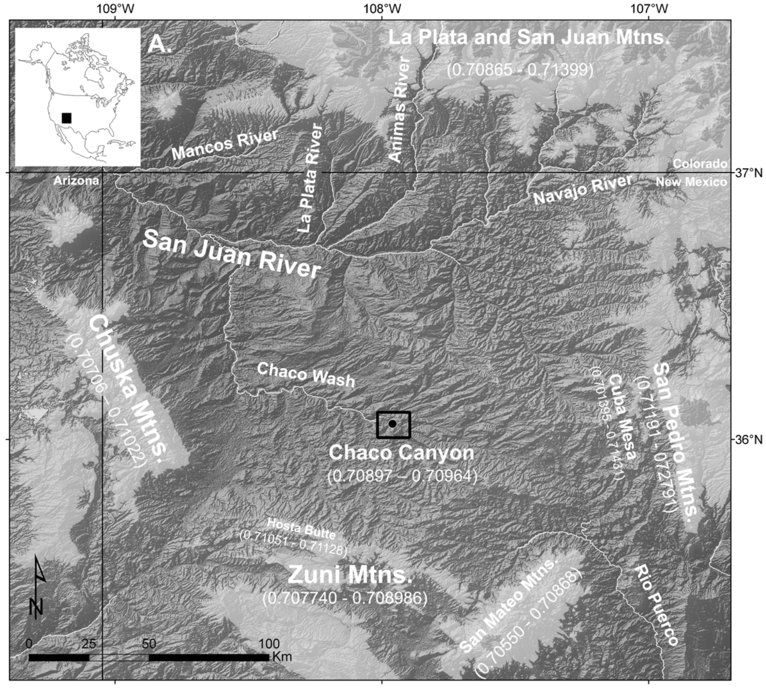

Fig. 1 Digital elevation model of San Juan Basin ranges with inset showing the map in the broader context of the North American continent. Labels refer to geographic features mentioned in text. Light gray (> 2250 to 3000 m) and medium gray atop light gray (> 3000 m) and ratios refer to the $^{87}Sr/^{86}Sr$ range associated with the feature. San Juan Basin encompasses the area between ranges ($^{87}Sr/^{86}Sr = 0.70871$–$0.71219$)

from these ruins (*e.g.*, Judd 1954). As reviewed below, there are multiple plausible interpretations for the sociopolitical organization that created and supported the Chaco Phenomenon. All interpretations confront the manifest disconnect between the productive limits of the San Juan Basin and the scale of human investment. As early as 1924 AV, Kidder (2000 [1924]) questioned how "…so large a population could have supplied itself with the mere necessities of life…" in such a marginal environment. The recognition that local resources were not sufficient to supply the local community spurred decades of research.

This study continues this tradition by considering procurement patterns of one critical resource, deer, within the broader contexts of the regional ecology and its sustainability (following Betancourt *et al.* 1986; Dean 1992; Dean *et al.* 1994; Mathien 2005; Vivian *et al.* 2006). A previous oxygen/strontium isotopic study inferred that deer recovered from the Pueblo Bonito great house came from high elevations (Grimstead *et al.* 2016). ^{18}O enrichment from rainfall is higher at lower elevations, and decreases with elevation gains. This relationship is best reflected in enamel $\delta^{18}O_{bioapatite}$ ratios, but requires a critical assumption: access to fresh river water was limited. This assumption in the previous study is only partially true; the San Juan River and the Rio Puerco both flow in this region. It is possible that some of the previously sampled deer came from the northern San Juan Basin and their $^{87}Sr/^{86}Sr_{bioapatite}$ and $\delta^{18}O_{bioapatite}$ ratios reflect river water discharged from the San Juan and La Plata Mountains.

By using carbon isotopes and existing models of the spatial extent of the maize farming niche in the region, this paper provides a means to assess if deer hunting focused on garden hunting at low to middle elevations, or was restricted to elevations above the maize niche. That is, we will evaluate the possibility that previous ratios simply reflected watersheds from high elevation regions, as opposed to direct high elevation procurement. We use modern mammals in the surrounding region to provide environmental reference data for archaeofaunal isotopic values. If archaeological deer present isotopic values similar to modern artiodactyls collected from outside of agricultural activity areas, then the conclusion by Grimstead *et al.* (2016) will be supported.

Long-distance procurement is inconsistent with goals of efficiency if prey animals are available locally. Ecological theory (Pianka 1994, Chapter 3; Schoener 1971) predicts that hunters will maximize the rate of energy intake while minimizing energy output. Presumably, energy and time conserved through efficient hunting can be spent on other fitness-enhancing activities. Under the assumptions of this model, prey items are ranked in terms of their potential energetic (caloric) payoffs. Thus, large animals are highly preferred over small prey due to their much larger body sizes and meat yields (*e.g.*, Bayham 1979; Broughton 1994; Ugan 2005). Dwindling local prey populations require hunters to travel further to find suitable game (Cannon 2003). Due to slower reproductive rates and greater human predation, large game often becomes locally extirpated before small game, but all games are susceptible to overhunting. If hunters must travel farther to find game, larger games are necessary to maintain a baseline energetic return rate. Accordingly, if the same prey animals are abundant within the local habitat, then energetically speaking, traveling long distances is unwise. However, animals likely hold more than simple economic value (*e.g.*, Grimstead and Bayham 2010; Hayden 1996; Hildebrandt and McGuire 2003). In the specific case of the Pueblo Bonito assemblage, deer possibly served as a form of social currency or tribute. That is, the energetic capital of hunting was transformed into social capital through contributions to events such as communal feasting. If non-residents (*i.e.*, pilgrims) (Renfrew 2004) supplied the deer, then hunting local Chaco Canyon deer possibly was prohibited. Visitors to Chaco Canyon presumably would adhere to such social taboos if their motives reflected ideological devotion and a desire to receive the beneficence of elites. However, it seems unlikely that such social interdictions would extend significant distances beyond the ritual landscape of Chaco Canyon. Such social explanations alone are unlikely to account for deer procurement at over 90-km distance from the point of consumption.

If critical resources had to be obtained non-locally to supply Chaco Canyon, procurement likely became increasingly organized and integrated with non-subsistence social systems and networks (cf. Beaton 1991). Corn sourcing studies suggest that Chaco Canyon consumers had no choice but to engage in long-distance subsistence procurement (*e.g.*, Benson *et al.* 2003; Cordell *et al.* 2008), and the costs of procurement were partially deferred by garden-hunting pest species (Grimstead *et al.* 2016). Garden-hunted, small game was thus collected outside of the immediate environs of Chaco Canyon (> 40 km), but from significantly closer localities than present estimates of deer acquisition (> 90 km) (Grimstead *et al.* 2016). Prehistoric hunters likely only expended considerable energy in capturing and transporting game when they offered sufficiently high caloric and likely social capital yields. The remainder of this paper tests these previous conclusions about long-distance procurement of deer by modeling maize agricultural constraints and evaluating the possibility that deer were garden-hunted like other small mammals sourced by Grimstead *et al.* (2016).

Archaeological Background

Prehistoric populations in Chaco Canyon peaked in the interval from Basketmaker III through Pueblo II (~AD 500–1150) (Reed 2000). The development of intensive agricultural practices, extensive trade networks, large community building projects, and probably hierarchical social organization characterizes the later part of this cultural trajectory (see chapters in Lekson 2006). Researchers place disparate emphasis on the variables contributing to the development of the Chaco Phenomenon, including ideological power, coercive force, ecological opportunity, and demographic scaling (*e.g.*, Akins 1985; Betancourt *et al.* 1986; Cameron 2001; Cameron and Toll 2001; Dean *et al.* 1994; Kantner 1996; Lekson 2006; Mills 2002; Neitzel 2003; Plog 2003; Toll 2001; Van Dyke 2004). Opinions on the sociopolitical nature of Chaco Canyon are diverse (see Wills 2000 for a review) and range from state-level hierarchical complexity (*e.g.*, Lekson 1999; Wilcox 1993) to more egalitarian scenarios with ritual and religious practices underlying the apparent regional connectedness and significant investment in large public building projects (*e.g.*, Judge 1989; Toll 1991; Vivian 1990). Many recent interpretations infer a form of organization characterized by ritualized power and religious leadership. In this general class of interpretations, competition does not drive the system, rather collective participation in ideological traditions attracted large aggregated populations to Chaco Canyon and the greater San Juan Basin during periods of peak productivity (*e.g.*, Saitta 1997; Wills 2000). Regardless of theoretical leanings, any interpretation of Chaco Canyon must consider the position of this community within the larger regional environment.

Recent re-excavations at the Pueblo Bonito great house conducted by Dr. W. Wills of the University of New Mexico, Albuquerque, provide the archaeofauna sample utilized to refine a high elevation hypothesis of deer procurement. Pueblo Bonito is the archetype great house of 12 large pueblo structures located in the valley. Pueblo Bonito was a large, five-story structure that contained more than 700 rooms and 40 kivas—a recognized form of ceremonial room. The architectural complex covered 0.8 ha and was built in phases over a span of 300 years (approximately AD 850–1125) (Neitzel 2003; Stein *et al.* 2003; Windes 2003).

During the period of cultural florescence (AD 950–1150), Chaco Canyon was the most significant regional consumer of both mundane goods and preciosities acquired from a vast region. The builders of great houses transported numerous architectural timbers to Chaco Canyon, traversing 80 to 150 km of montane forests and broad swaths of desert-scrub grasslands (Betancourt *et al.* 1986; Durand and Shelley 1999; English *et al.* 2001; Guiterman *et al.* 2016; Reynolds *et al.* 2005). Imported corn, grown at a minimum of 60 km from the canyon, was essential to the subsistence economy (Benson *et al.* 2003; Cordell *et al.* 2008). Provenance studies of ceramics and lithic artifacts indicate several non-local sources (Cameron 2001; Mathien 1997; Mills *et al.* 1997; Toll 2001), while exotic minerals and marine shell also originated outside of the immediate region (Mathien 1997; Thibodeau *et al.* 2007). Lastly, symbolically salient ritual paraphernalia, including scarlet macaws and cacao, arrived at Chaco Canyon from destinations as distant as Mesoamerica (Crown and Hurst 2009; Watson *et al.* 2015).

Long-distance transport evidently was both necessary and worthwhile for the Chacoans, whether facilitated by trade networks, direct procurement, or tribute. Increased population within Chaco Canyon and the surrounding basin by AD 1000 would have stressed the desert ecosystem (Dean *et al.* 1994), but resource stress could have been significant even if only a few people permanently resided within great houses (*e.g.*, Bernardini 1999; Grayson 2001; Stein *et al.* 2003; Vivian 1990, p. 447; Windes and McKenna 2001). Thus, importation of food may have been a response to local depletion or an endemic lack of specific resources.

Pueblo Bonito is clearly associated with unique ritual and symbolic behavior. Accordingly, non-local goods possibly arrived at Pueblo Bonito via a tribute or exchange system in which ritual wealth/knowledge was exchanged for material resources. Researchers disagree over whether the builders of great houses were permanent residents or visitors (Metcalfe 2003), with a growing consensus favoring the latter interpretation (*e.g.*, Lekson *et al.* 2006). The origin and procurement management of the food supply that supported the builders of Pueblo Bonito and any potential residents are topics of active research. This discussion contributes to an assessment of whether the immediate environs of Chaco Canyon provided the necessary food resources or if non-local resources were required to support activities at Chaco Canyon. Furthermore, this sourcing study demonstrates the utility of maize niche modeling applied in tandem with $\delta^{13}C$ data as a method to further refine potential source regions.

Ecological and Environmental Background

Chaco Canyon (2073 m) lies in the middle of a broad basin that is surrounded by many mountain ranges with distinct geologies, including the Chuska Mountains (2982 m—all elevations are maximums), the La Plata Mountains (4035 m), the San Juan Mountains (4361 m), the San Pedro Mountains (3232 m), the Zuni Mountains (2743 m), and Mount Taylor/San Mateo Mountains (3444 m). Springs located within or near Chaco Canyon provided the only reliable water supply, with no locally available perennial streams (Fig. 1). Desert-scrub grassland dominates the vegetation of Chaco Canyon, and modern annual rainfall averages 22.4 cm (Benson 2011a, b), with annual temperature extremes of − 10 °C in winter and 32 °C in the summer (Vivian 1990). There are approximately 150 frost-free days in the canyon, making it possible to grow crops (Hayes 1981; Vivian 1990). However, poor soil, as well as the overall xeric conditions, likely resulted in low agricultural productivity (Benson 2011a, b, 2017; but see Dorshow 2012; Vivian and Watson 2015).

Animal Ecology

Local deer species include white-tailed deer (*Odocoileus virginianus*) and black-tailed deer (*Odocoileus hemionus*). Both species are philopatric in many western areas and generally establish home ranges by the age of 1 or 2 years that are retained for the rest of their lives (Dasmann and Taber 1956; Longhurst *et al.* 1952; Rue 1988; Tierson *et al.* 1985; Zwickel *et al.* 1953). Male deer may have home ranges twice the size of females, and the breeding season can draw male deer well outside of their home ranges (up to 12 km; Koerth and Bryant 1982; Ragotzkie and Bailey 1991; Relyea *et al.* 2000; Rodgers *et al.* 1978; Taber and Dasmann 1958). High variance is typical of home range sizes with documented cases ranging from 1 to 2 to 60 km^2 (Dasmann and Taber 1956; Dickinson and Garner 1979; Gallina *et al.* 1997; Horejsi *et al.* 1988; Krausman 1985; Taber and Dasmann 1958), but most studies record home ranges at or below 10 km^2 (Fox and Krausman 1994; Haywood *et al.* 1987; Heffelfinger 2006; Koerth *et al.* 1985; Lawrence *et al.* 1994; Ragotzkie and Bailey 1991; Raught 1967; Relyea *et al.* 2000; Rodgers 1978; Wallmo 1981). Deer may exceed typical home ranges when food is seasonally scarce, traveling only as far as needed (5–30 km) to find forage (Haywood *et al.* 1987; Heffelfinger 2006; Mierau and Schmidt 1981). Even in these conditions, deer display seasonal philopatry, returning to the same summer and winter home ranges (Heffelfinger 2006; Longhurst *et al.* 1952). Herds of both sexes may form in winter, but rarely in great numbers. Females may form small groups during the rutting season, but disperse with their fawns during the rest of the year. Deer eat a variety of forbs, grasses, shrubs, and succulents, depending upon availability (Gill *et al.* 1983; Heffelfinger 2006; Illige 1956; Mierau and Schmidt 1981; Raught 1967; Taylor 1963).

This investigation utilizes modern desert cottontails (*Sylvilagus audubonii*), pronghorn (*Antilocapra americana*), and bighorn sheep (*Ovis canadensis*) to contextualize isotopic values of archaeological deer, necessitating a brief discussion of natural histories. The desert cottontail data was included because other Artiodactyla taxa lacked access to maize based upon recovery location (see "Results" section for two violations of no-maize access revealed via the carbon isotope data). The desert cottontail, mountain cottontail (*Sylvilagus nuttallii*), and eastern cottontail (*Sylvilagus floridanus*) all potentially inhabited the region available to prehistoric hunters of Chaco Canyon. Desert cottontails tolerate diverse habitats, but most can be found at or below elevations of 2000 m, leaving the upper elevations to mountain cottontails (Chapman 1975; Chapman and Willner 1978; Whitaker 1996). Cottontails will forage in open areas, but prefer areas with cover (Cushing 1939; Ingles 1941; Orr 1940). All species feed on a variety of grasses, shrubs, forbs, bark, and succulents (Turkowski 1975). Home ranges are 1 km^2 or less, with males using larger ranges than females (Fitch 1947; Ingles 1941).

In this region, two subspecies of Bighorn sheep occur: the Rocky Mountain bighorn (*Ovis canadensis canadensis*) and the Desert bighorn (*O. c. nelsoni*). Rocky Mountain bighorn are much larger than Desert bighorn, but both share a habitat affinity for rocky slopes, ridges, cliffs, and canyons (Geist 1971). Home range sizes are highly variable depending upon habitat and availability of water sources, but female home ranges are smaller than males regardless of these factors (DeCesare and Pletscher 2006; Geist 1971; Leslie and Douglas 1979). Female mean home range sizes are approximately 10 to 45 km^2, while male home ranges vary from approximately 20 km^2 up to 99 km^2, but most male ranges tend towards 30–40 km^2 (Geist 1971; Krausman *et al.* 1989; Leslie and Douglas 1979; Woolf *et al.* 1970). Males and females seasonally disperse along altitudinal gradients to wintering and summering grounds (Geist 1971; Herbert 1973), where female and male summer home ranges do not overlap until the fall mating season ensues or depleted water sources force the sexes to share water supplies (Festa-Bianchet 1988; Krausman *et al.* 1989; Leslie and Douglas 1979; Woolf *et al.* 1970). Females will disperse 1–10 km to summering grounds earlier than males and select habitats protected from predation during the lambing season (February–April) (DeCesare and Pletscher 2006; Festa-Bianchet 1988; Leslie and Douglas 1979; Spencer 1943). Males seasonally disperse over similar distances, but during breeding dispersals, males will often visit the home ranges of several female herds in a region (Geist 1971; Leslie and Douglas 1979; Welles and Welles 1961). Like deer, bighorn sheep are partially obligate drinkers and philopatric to home ranges and dispersal pathways (Leslie and Douglas 1979; Welles and Welles 1961; Spencer 1943). Bighorn sheep primarily eat grasses and sedges, but forbs and browse are also included in the diet (Krausman *et al.* 1989; Spencer 1943; Todd and Hansen 1973; Wikeen and Pitt 1992).

The pronghorn (*Antilocapra americana*) is known for its incredible speed and is the fastest animal in the Western hemisphere, having been clocked at 110 km per hour for short periods, but speeds of 30–40 km are sustainable by the animal for long distances (ca. 25 km) (Whitaker 1996). Like most ungulates, pronghorn are gregarious; often, winter groups contain both males and females and can contain hundreds of individuals (O’Gara 2004). In summer, females form into territorial bands, while male bands form after the spring dispersal and shift to territorial individuals at the onset of the rut. Typically, seasonal dispersals are significantly larger than other North American ungulates, traveling 200 km or more following the same migrational pathways to the same seasonal home ranges each year (*e.g.*, Hnatiuk 1972; Hoskinson and Tester 1980; Sawyer *et al.* 2005; Seton 1929). Winter ranges may be variable depending upon forage availability and snow cover, but pronghorn are philopatric to summering ranges (Amstrop 1978; Mills 1922; Hoskinson and Tester 1980). Home ranges vary based upon snow cover and food availability, ranging between 3 and 200 km^2 (*e.g.*, Bayless 1969; Pyra 1987; Seton 1929), but during the rut, males will guard smaller home ranges comparatively (Bromley and O’Gara 1977; Kitchen 1974 Min 1997). Forbs and shrubs are the primary constituent of pronghorn diets (Howard *et al.* 1982; Miranda Alamazán 2000; Roebuck 1982; Yoakum 2004), and they are partially obligate drinkers (O’Gara 2004).

Garden Hunting

Garden hunting is a well-documented practice of targeting species found in higher concentrations in disturbed habitats, such as cultivated plots (*e.g.*, Conklin 1975; Linares 1976; Peterson 1977). Garden hunting serves multiple roles: reduced loss of crops, acquisition of animal protein, and sport (cf. Conklin 1975). Hopi hunters of northeast Arizona set traps around crops and employed a variety of means to kill pests (Hammett 1997; Hill 1938). Garden hunting is also documented among the Tohono O’odham of southern Arizona (Rea 1979). Several archaeologists identify patterns they believe indicative of garden hunting (*e.g.*, Emslie 1981; Neusius 2008; Szuter 1991), but studies are complicated by the fact that relevant species are often preferred taxa and hunted in a variety of contexts. Based upon deer crop damage today, it is likely that prehistoric deer had a particular proclivity for garden plots of all sorts (*e.g.*, Drake *et al.* 2003; Humberg *et al.* 2007; Ohio Division of Wildlife 2007). In the Four Corners region, likely garden-hunted species include cottontail rabbits, prairie dogs, and deer, among others. Carbon isotopes help to identify this hunting practice when used in tandem with traditional zooarchaeological methods such as relative abundance indices, counts of archaeofauna versus natural distributions of taxa, and measurements of the diversity of assemblages. This study uses carbon isotopes coupled with maize niche modeling to assess whether deer show evidence of consuming maize, which would rule out the possibility that they derive exclusively from upper elevations.

Maize Environmental Constraints

Prehistoric residents of the greater Southwest relied on maize for a large component of their diet. The earliest dates for maize in the southwestern USA, at ca. 5700–5600 cal BP (Vint 2015), come from southern Arizona. By the Pueblo I to Pueblo II periods (AD 900–1150) that are the focus of this paper, maize fulfilled 70% or more of ancestral Pueblo diets in the Four Corners region (Decker and Tieszen 1989; see also Hard *et al*. 1996; Matson 2016). Given maize's central role in the subsistence economy, researchers have exerted considerable effort in modeling environmental potential for production; this is particularly true for the Chaco Canyon and nearby Mesa Verde regions (*e.g.*, Benson 2011a, b; Bocinsky and Kohler 2014; Bocinsky *et al*. 2016; Van West 1994).

Maize production faces a variety of constraints; paramount among them are sufficient moisture, adequate accumulated heat (usually quantified as growing degree days (GDDs)), and appropriate soil chemistry. Not all of these are relevant to the current research question. Soil quality had a significant effect on maize yield (Benson 2011a, b); however, ancestral Pueblo people grew maize in an impressively wide range of soil types, and today practice maize agriculture from the sandy Aeolian soils of the Hopi mesas to the alluvial soils of the Northern Rio Grande. Given that suitable soils are likely ubiquitous at the resolution of an average deer's home range—and certainly at the resolution of the archaeofauna assemblage composition—we do not consider soil quality in this study. Precipitation and GDD accumulation are much more pressing issues. Dryland farmers, farmers relying solely upon precipitation for crops, of the arid Southwest face a balancing act between selecting a field location of sufficient elevation to ensure adequate precipitation and low enough to ensure adequate heat accumulation before harvest, especially during key reproductive growth phases. Water control features that concentrated precipitation from a larger catchment are common across the region—including checkdams, diversions, and other ponding approaches (*e.g.*, Gauthier and Herhahn 2005; Force *et al*. 2002). Researchers at Chaco Canyon interpret water control mechanisms as central to Chaco Canyon's subsistence economy (Sebastian 1992; Vivian 1990). Some of these features, such as gridded irrigation fields (Gumerman and Lyons 1971), allowed for appreciable local maize production. Deer undoubtedly availed themselves of the maize grown in the near environs of Chaco Canyon. However, oxygen isotope analyses of deer remains from Pueblo Bonito demonstrate deer procurement outside of the meteoric water environment of Chaco Canyon (*i.e.*, at higher elevations; Grimstead *et al*. 2016).

Our attention thus turns to the more distant and principally upland areas, amenable to farming relying on direct precipitation (Bocinsky *et al*. 2016). ^{87}Sr/^{86}Sr isotope values from ancient maize recovered from great houses verify that maize traveled to Chaco Canyon from upland areas, principally the Chuska slopes and regions north of the San Juan River (Benson *et al*. 2003). ^{87}Sr/^{86}Sr and $\delta^{18}O_{bioapatite}$ isotope values from Pueblo Bonito archaeofauna show that these animals also could have been procured from both regions. The present research assesses whether deer likely came from this high maize productivity region or from elevations higher than the maize growing niche.

The upper elevation limit of maize farming is almost entirely a function of the length of the growing season. Following the earlier work by Benson (2011a, b), Bocinsky and Kohler (2014) modeled the extent of the maize niche as the area of land that in any given year met two thresholds: 1800 F growing degree days (FGDD) accumulated from May to September (the maize growing season) and 30 cm of precipitation from the previous October through the current September (the "water year" in most of the Southwest). Reconstructions of the maize niche utilize tree-ring data to retrodict the water year precipitation and growing season independently; those retrodictions are then thresholded and overlaid to derive the maize farming niche (Bocinsky and Kohler 2014). Bocinsky *et al.* (2016) refined and expanded the spatial scope of the niche reconstruction, and we use their results in the current study. We extracted the niche for our study area (defined as the region between 106° and 110° W and 34° and 38° N) and a 250-year period of interest (AD 900–1149). We then calculated the average maize niche across time (Fig. 2); this can be interpreted as the proportion of years from AD 900–1149 that each place on the landscape was in the niche. Then, we calculated the elevation along the 0.5-level isopleth (Fig. 3). On average, maize planted above this line would fail to produce an appreciable yield 50% or more of years for the defined period. The elevation of the isopleth varies per local climatology, generally between 2250 and 3250 masl. This approach is thus fairly liberal in its estimation of this upper boundary, though it is close to the upper boundary of maize cultivation Benson (2011a b) inferred for the Mesa Verde region. Within 100 km of Chaco Canyon, the maize niche isopleth corresponds approximately to 2400–2700 masl in the Chuska Mountains, 2500–2700 masl in the Mount Taylor/San Mateo Mountains, and 2500–2800 masl in the San Pedro Mountains (near Cuba, NM). Due to the relatively steep slope in most of these ranges, the different maximum elevation estimate of the maize niche elevation does not equate to significant linear distance. In this study, we compare these maximum elevations for maize cultivation with carbon, oxygen, and strontium isotope values of deer remains from Pueblo Bonito to infer where deer were being harvested in the Chaco region.

Carbon Isotopes in an Upland Desert

$\delta^{13}C$ values in tooth enamel are informative of where diets vary in the relative contributions of cultivated foods, such as maize, and wild plants that use the C_3 metabolic pathway (Katzenberg *et al.* 1995; Cerling *et al.* 1997; Coltrain *et al.* 2007). C_3 plants include cool season grasses, trees, and most bushy plants. C_4 plants include warm season grasses, such as maize, and some species of *Atriplex* (saltbush). CAM plants are cacti and succulents with alternating photosynthetic pathways. C_3, C_4, and CAM plants are isotopically distinct from one another. Measurement of $\delta^{13}C$ averages $-26.4 \pm 2.0‰$ (Cerling *et al.* 1997) for C_3 plants from the range of elevations spanning 2200–2900 m and rainfall 303–490 mm/year from which the analyzed archaeofauna likely derive. C_4 plants, in New Mexico and globally, should average around $-12.5 \pm 1.4‰$ (Cerling *et al.* 2003). CAM plants overlap these ranges (− 10 to − 20‰) (O'Leary 1988), but cacti constitute a very minor part of plant cover in the Chaco Canyon region.

All these values reflect modern industrial conditions uncorrected for fossil fuel burning. Correcting for this confounding factor (Tieszen and Fagre 1993) requires a

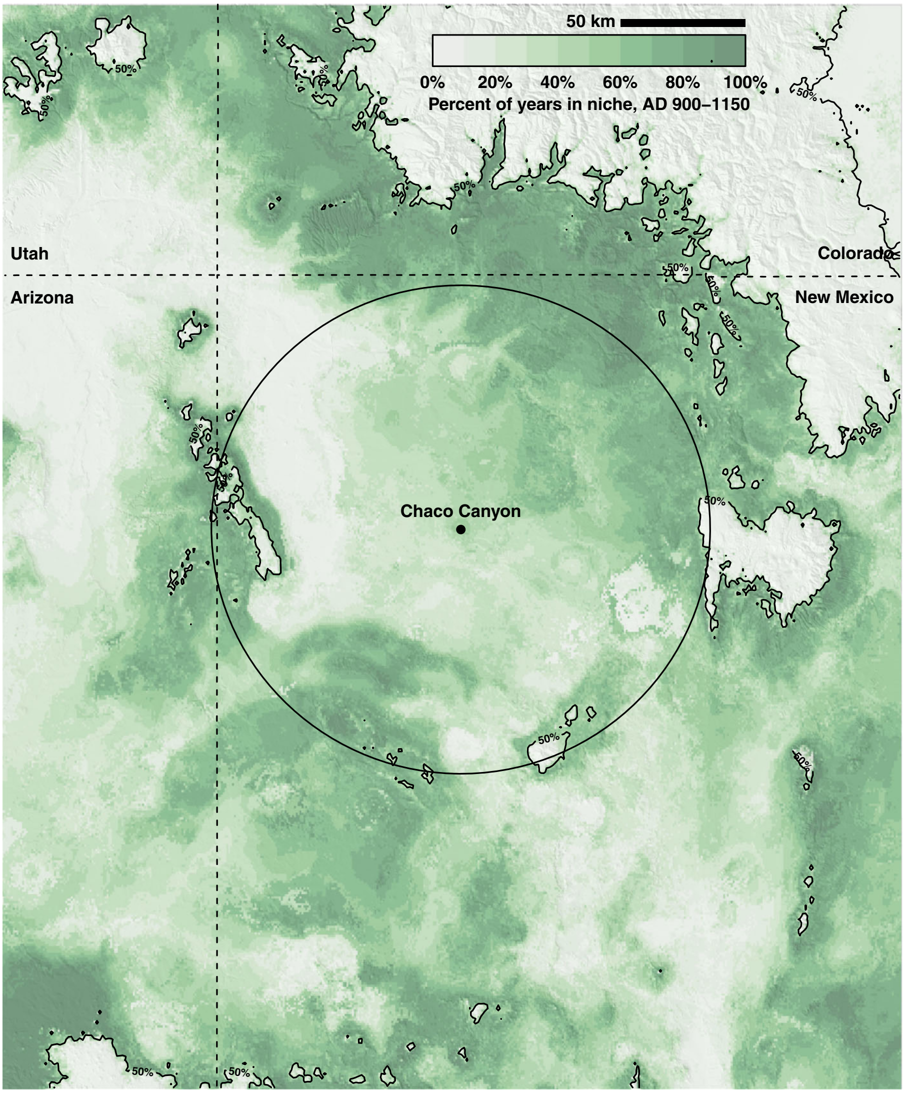

Fig. 2 The rain-fed maize farming niche in the Chaco World, AD 900–1150 (Bocinsky *et al.* 2016). Each cell is colored by the percentage of years it is in the niche; darker green represents more years in the niche. The 50% isopleth is plotted for reference. The circle around Chaco Canyon is 100 km from the canyon

consideration of ice-core data (Indermuhle *et al.* 1999), which suggests a $\delta^{13}C$ value of atmospheric CO_2 of − 6.5‰ for ~ 1000 AD. The present modern animal sample ranges from museum specimens to recent road kills, spanning the period 1980–2008. Over this period, the $\delta^{13}C$ value of atmospheric CO_2 decreased from approximately − 7.6 to − 8.4‰ (Levin *et al.* 2010), for an average difference of 1.5 ± 0.4‰ from CO_2 a thousand years ago. The addition of 1.5‰ to modern $\delta^{13}C_{bioapatite}$ values mostly corrects for this effect. Finally, $\delta^{13}C_{bioapatite}$ values in small, non-ruminant mammals, consuming their preferred forage plants, are enriched by ~ 11‰ ($\varepsilon_{apatite\text{-}diet}$ = + 11‰; Cerling and Harris 1999; Podelsak *et al.* 2008) compared to dietary intake.

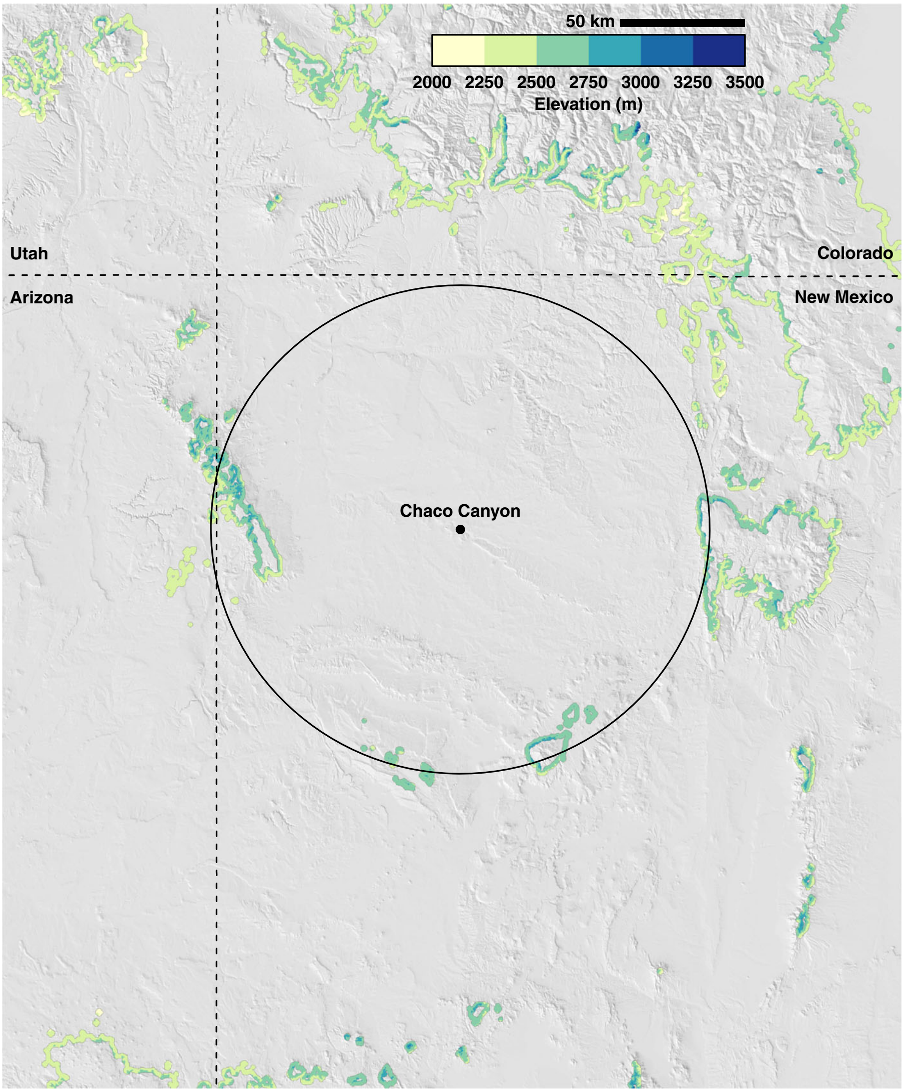

Fig. 3 The average elevation along the upper extent of the rain-fed maize farming niche, AD 900–1150. The edge of the niche is drawn along the 50% isopleth derived from Fig. 2. Due to orographic effects, the upper limit for maize farming ranges from 2000 m to almost 3500 m around the San Juan Basin. The circle around Chaco Canyon is 100 km from the canyon

Taking all the previous factors into account, the $\delta^{13}C_{\text{bioapatite}}$ of end-member C_3 feeders (or $\delta^{13}C_{C3}$) would be − 13.95 and − 0.1‰ for end-member C_4 feeders (or $\delta^{13}C_{C4}$) in pre-industrial Chaco Canyon. To calculate $\%C_4$ contribution to the diets of the small mammals from $\delta^{13}C_{\text{bioapatite}}$ values, we use

$$\%C_4 = \left[\left(\delta^{13}C_{measured} – \delta^{13}C_{C3}\right) / \left(\delta^{13}C_{C4} – \delta^{13}C_{C3}\right)\right] \times 100$$

Supp. Table 1 provides the details of each calculation step.

Table 1 Collection information, δ^{13}C data, and %C_4 calculations from modern mammals collected from the San Juan Basin ranges

Museum ID	Lab number	Species	Elevation (m)	Latitude	Longitude	Measured modern δ^{13}C bioapatite	SD	Calculated pre-industrial δ^{13}C bioapatite[b]	%$C_4 \pm 9.6$
MSB Mamm 353	35	*Antilocapra americana*	1456	35.2126014	−106.8432998	−12.07	0.05	−10.6	#NAME?
MSB Mamm 1879	1	*Odocoileus hemionus*	2621	36.8067	−106.0257	−12.27	0.03	−10.8	#NAME?
MSB Mamm 35606	2	*Odocoileus hemionus*	1981	36.1948	−107.0726	−11.66	0.04	−10.2	#NAME?
MSB Mamm 1880	4	*Odocoileus hemionus*	2621	36.8067	−106.0257	−13.87	0.02	−12.4	#NAME?
MSB Mamm 1878	5	*Odocoileus hemionus*	2803	36.8502	−106.2083	−12.25	0.04	−10.8	#NAME?
MSB Mamm 36069	7	*Odocoileus hemionus*	1829	36.9158	−108.1235	−12.89	0.02	−11.4	#NAME?
MSB Mamm 22301	8	*Odocoileus hemionus*	2671	35.9351	−106.6978	−12.21	0.03	−10.7	#NAME?
MSB Mamm 2099	9	*Odocoileus hemionus*	2560	See note		−12.66	0.02	−11.2	#NAME?
MSB Mamm 38225	11	*Odocoileus hemionus*	1999	34.4559	−107.0703	−11.16	0.02	−9.7	#NAME?
MSB Mamm 38224	12	*Odocoileus hemionus*	1999	34.4559	−107.0703	−10.96	0.03	−9.5	#NAME?
MSB Mamm 54634	13	*Odocoileus hemionus*	1681	34.353698	−107.1401979	−9.76	0.04	−8.3	#NAME?
MSB Mamm 55677	14	*Odocoileus hemionus*	2271	34.4267	−107.1052	−10.88	0.02	−9.4	#NAME?
MSB Mamm 56503	17	*Odocoileus hemionus*	1912	34.2527	−106.1068	−12.27	0.02	−10.8	#NAME?
MSB Mamm 55680	19	*Odocoileus hemionus*	1999	34.4559	−107.0703	−11.60	0.05	−10.1	#NAME?
MSB Mamm 54069	21	*Odocoileus hemionus*	2359	34.5874	−106.4069	−14.00	0.02	−12.5	#NAME?
MSB Mamm 71343	22	*Odocoileus hemionus*	2359	34.5874	−106.4069	−14.06	0.03	−12.6	#NAME?
MSB Mamm 12155	24	*Odocoileus hemionus*	1905	See note		−13.29	0.06	−11.8	#NAME?
MSB Mamm 1900	26	*Odocoileus hemionus*	2437	35.3699	−108.5026	−14.22	0.02	−12.7	#NAME?
MSB Mamm 55399	27	*Odocoileus hemionus*	2359	34.5874	−106.4069	−14.34	0.03	−12.8	#NAME?
MSB Mamm 114320	49	*Odocoileus hemionus*	2191	See note		−12.18	0.11	−10.7	#NAME?
MSB Mamm 116856	50	*Odocoileus hemionus*	2096	See note		−9.23	0.02	−7.7	#NAME?
MSB Mamm 32217	29	*Ovis canadensis*	3050	35.235001	−106.455833	−11.23	0.03	−9.7	#NAME?
MSB Mamm 13157	30	*Ovis canadensis*	3065	35.198055	−106.433052	−11.76	0.03	−10.3	#NAME?
MSB Mamm 53576	31	*Ovis canadensis*	3219	35.235001	−106.455833	−12.09	0.04	−10.6	#NAME?
MSB Mamm 53577	32	*Ovis canadensis*	3219	35.2100524	−106.4489908	−12.01	0.04	−10.5	#NAME?

Table 1 (continued)

Museum ID	Lab number	Species	Elevation (m)	Latitude	Longitude	Measured modern δ13 C bioapatite	SD	Calculated pre-industrial δ13 C bioapatite[b]	%C$_4$ ± 9.6
MSB Mamm 53578	33	*Ovis canadensis*	3219	35.2100524	− 106.4489908	− 11.72	0.02	− 10.2	#NAME?
MSB Mamm 53579	34	*Ovis canadensis*	3219	35.2100524	−106.4489908	− 10.72	0.03	−9.2	#NAME?
MSB Mamm 11371	51	*Ovis canadensis*	3065	35.1980565	− 106.4330557	− 12.45	0.02	− 11.0	#NAME?
MSB Mamm 54054	52	*Ovis canadensis*	2058	34.579657	− 106.492455	− 11.47	0.04	− 10.0	#NAME?
MSB Mamm 28201[a]	46a	*Sylvilagus auduboni*	1711	35.964000	− 106.097397	−9.0	0.03	−7.5	#NAME?
MSB Mamm 4325[a]	59a	*Sylvilagus auduboni*	1767	36.574601	− 108.117699	−7.5	0.14	−6.0	#NAME?
MSB Mamm 18509[a]	47a	*Sylvilagus auduboni*	1949	35.703500	− 108.653603	−6.2	0.17	−4.7	#NAME?
MSB Mamm 13205[a]	43a	*Sylvilagus auduboni*	2122	36.324100	− 107.144600	−7.3	0.02	−5.8	#NAME?
MSB Mamm 36064[a]	48a	*Sylvilagus auduboni*	2134	35.531686	− 107.696534	−5.3	0.04	−3.8	#NAME?

All specimens were sampled with permission from the Museum of Southwestern Biology. Four specimens, MSB Mamm 2099, 114320, 116856, and 12155, had rough geographic and elevation information only. The collection locations for these specimens are as follows: MSW Mamm 2088: Jemez Mountains, Sandoval County, NM; MSB Mamm 114320: Mancos Canyon—Northern San Juan Basin, Montezuma County, CO; MSB Mamm 116856: Lewis Mesa, Montezuma County, CO; MSB Mamm 12155: San Juan Basin, San Juan County, NM

SD standard deviation

[a] Collected in or near agricultural field

[b] 1.5‰ added to raw values to correct for the recent anthropogenic changes to atmospheric pCO$_2$

Material and Methods

The sample consists of $\delta^{13}C_{bioapatite}$ measurements performed on modern ($n = 34$) and archaeological ($n = 15$) teeth, as enamel is more resistant to postmortem diagenesis compared to bone (Passey and Cerling 2002) (Tables 1 and 2). The Museum of Southwestern Biology (MSWB) granted permission to sample modern skeletal materials with death dates from the 1980s through the early 2000s. The sample included five desert cottontails from agricultural contexts. All artiodactyls ($n = 25$) with detailed collection location information were not from agricultural contexts. Four of the modern artiodactyls had vague collection location information that could not be crossed referenced with agricultural activity, and as discussed below, specimen 50 may have spent some time in agricultural fields. Five desert cottontail specimens collected from in or near agricultural plots demonstrate the expected %C_4 for upland desert inhabitants with access to maize. Archaeological teeth are from a 2007 re-excavation of trenches at Pueblo Bonito originally excavated by Neil Judd in the 1920s. Because this material comes from a re-excavation of Judd's backfill, the archaeological sample can only be considered a bulk sample representing the entire span of Pueblo Bonito occupation (AD 850–1150).

The modern and archaeological teeth were mechanically cleaned with ultrapure water and allowed to dry thoroughly. Grimstead used a 1.0-mm carbide drill bit to extract enamel from each tooth (0.05–0.1 g dry weight). Powdered samples were placed in a 15-mL centrifuge tube with 3% pure NaOCl, ultra-sonicated for approximately 60 min, and then centrifuged. The 3% NaOCl solution was removed via pipette, and the sample was subjected to three successive stages of ultrapure water rinses. Samples were then pre-treated to isolate and purify the structural carbon fraction of the carbonyl apatite for

Table 2 $\delta^{13}C$ and %C_4 results for Pueblo Bonito deer

Lab ID	FS no.	Species	Elevation assignment[a]	$\delta^{13}C$ bioapatite	SD	%C_4 ± 9.6
PB104	39	Odocoileus sp.	2278	− 9.4	0.02	33%
PB4722	1986	Odocoileus sp.	3124	− 9.6	0.03	31%
PB7617	2148	Odocoileus sp.	2841	− 9.6	0.05	32%
PB8040	2451	Odocoileus sp.	3235	− 10.2	0.04	27%
PB8036	2451	Odocoileus sp.	2745	− 10.8	0.03	22%
PB2672	2948	Odocoileus sp.	2523	− 9.9	0.03	29%
PB3611	2044	Odocoileus sp.	3295	− 9.8	0.06	30%
PB226	153	Odocoileus sp.	2519	− 11.6	0.09	17%
PB5414	619	Odocoileus sp.	3015	− 10.6	0.08	24%
PB1434	1180	Odocoileus sp.	3098	− 11.0	0.06	21%
PB8039[b]	2451	Odocoileus sp.	2962	− 8.3	0.06	41%
PB3664[b]	2073	Odocoileus sp.	2984	− 8.7	0.04	38%
PB8219	2461	Odocoileus sp.	2482	− 10.1	0.04	28%
PB1855[b]	1318	Odocoileus sp.	2942	− 9.2	0.06	35%
PB2404	3026	Odocoileus sp.	2657	− 9.7	0.04	30%

[a] Elevation assignment from Grimstead *et al.* (2016)

[b] Some access to maize

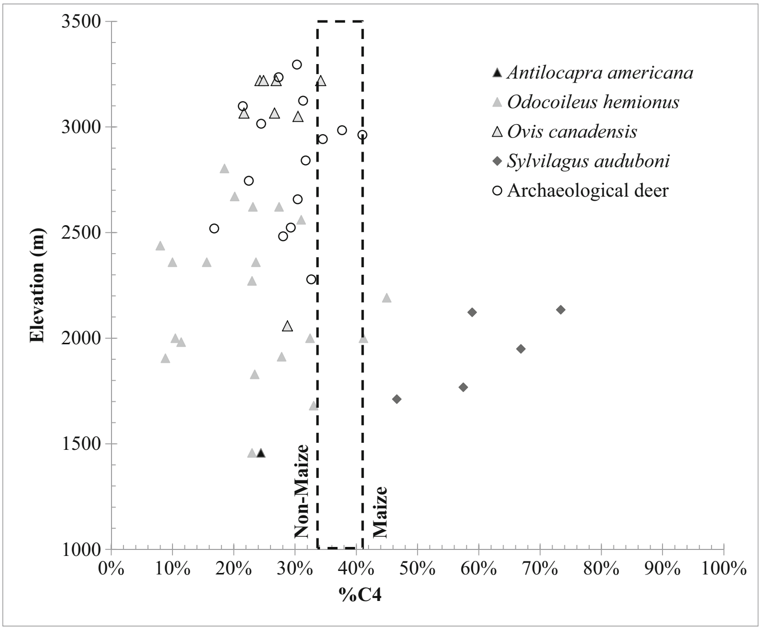

Fig. 4 $\%C_4$ (*x*-axis) plotted against elevation (*y*-axis). Note that there is no observed elevation pattern with $\%C_4$ in modern fauna. Symbols explained in the figure. Desert cottontail specimens (*Sylvilagus auduboni*) were collected from agricultural contexts. Dotted box indicates demarcation of maize and non-maize individuals

analysis. Acetic acid (1.0 M CH_3COOH) was added to the sample, ultra-sonicated for 1 h, and then allowed to sit for 12 h. The acetic acid was removed via centrifuge and pipette, and the sample was rinsed three times with ultrapure water and allowed to dry.

Grimstead measured $\delta^{13}C_{bioapatite}$ on an automated carbonate preparation device (KIEL-III) coupled to a gas ratio mass spectrometer (Finnigan MAT 252) housed at the University of Arizona Paleoenvironmental Laboratory. Powdered samples were reacted with dehydrated phosphoric acid under vacuum at 70 °C. The isotope ratio measurement is calibrated based on repeated measurement of NBS-19 and NBS-18 (standards are VPDB) throughout the run sequence. The reference values for the standards were derived from Gonfianti *et al.* (1995). Precision is 0.06‰ for $\delta^{13}C$ (1 sigma).

$\delta^{13}C_{bioapatite}$ Results

Because CAM and C_4 plants are naturally available within the Chaco Canyon desert ecosystem, it is necessary to use modern animals with known collection locations to understand the difference between non-maize versus an access-to-maize $\delta^{13}C$ diet. Of the modern mammals (Table 1, Fig. 4), five cottontail rabbits lived in or near agricultural fields and their $\delta^{13}C_{bioapatite}$ values range from − 7.5 to − 3.8‰ (corrected values for industrial carbon), which corresponds to a $\%C_4$ range of 47–73%. Most deer, excluding two (MSB Mamm 54634 and 116856) discussed below, present $\delta^{13}C_{bioapatite}$ ratios ranging from − 12.8 to − 9.2‰, which corresponds to 8–34% C_4 and/or CAM consumption. Archaeological deer range from − 11.6 to − 8.3‰ or 17– 41% C_4 consumption.

The cottontail sample alone indicates a %C_4 threshold of ~ 47%, but two deer that neared this threshold require further discussion (MSB Mamm 54634 and 116856). MSB Mamm 116856 apparently had access to agricultural fields, but this could not be confirmed, as the specimen's collection location was simply "Lewis Mesa, Montezuma County, CO." Specimen 54634 does have a good collection location, which was ~ 20 km from the Rio Grande River, where fields are plentiful. It seems likely that this male had wandered away from fields near the Rio Grande River in search of mates or to avoid hunting pressure, because significant seasonal dispersals are not seen in this region. Values of %C_4 for these two deer are 45 and 41%, respectively, which are still appreciably lower than that of the modern cottontails. In Fig. 4, there is a clear break between the access-to-maize $\delta^{13}C_{\mathrm{bioapatite}}$ values and the no-access values, which occurs between 34 and 41%. The conservative approach taken here considers any value greater than 34% as showing some evidence of access to maize. It is probable that more data will help to narrow this range in the future. Using the 34% threshold, three archaeological deer evidently had access to maize, despite $^{87}Sr/^{86}Sr_{\mathrm{bioapatite}}$ and $\delta^{18}O_{\mathrm{bioapatite}}$ data indicating that they came from well above the maize niche limit (Figs. 3 and 4). The remainder fall well below this threshold indicating a maize-free diet.

Discussion

Previous sourcing studies of deer from Pueblo Bonito used a tandem $^{87}Sr/^{86}Sr_{\mathrm{bioapatite}}$ and $\delta^{18}O_{\mathrm{bioapatite}}$ approach to demonstrate that no deer lived within the meteoric water environment consistent with the elevation of Chaco Canyon, and most of the deer sampled likely came from higher elevations that lay at a minimum of 90 km from Chaco Canyon. Prehistoric hunters procured five of these deer at elevations well above 3000 m, consistent with the San Juan, La Plata, San Pedro, or Mt. Taylor/San Mateo Mountains (Grimstead *et al.* 2016). The minimum distance south to Mt. Taylor is 90 km, while the highlands of the La Plata and San Juan Mountains are located 140 km from Chaco Canyon (Fig. 1). This paper further assessed the high elevation procurement hypothesis via another line of evidence: $\delta^{13}C_{\mathrm{bioapatite}}$ combined with maize niche modeling as a sourcing tool. Deer have an affinity for agricultural crops, especially in an upland desert ecosystem where forage is sparse. Thus, evidence of a C_4-rich diet would indicate a home range in lower to mid-elevations and would not support the conclusions of a high elevation procurement strategy. Conversely, diets that reflect the naturally low availability of C_4 and CAM plants would support the previously drawn conclusions.

Three of the archaeofaunal deer originally sourced to either the San Juan or Chuska Mountains show evidence of maize consumption, which does not support an inference of upper elevation procurement. The remainder ($n = 12$) fall well below the access to maize threshold, indicating high elevation procurement. At first glance, the three deer that consumed maize appear to undermine the original oxygen isotope sourcing conclusions of high elevation procurement; however, these data only narrow the potential source region. Now the question becomes: where in the region surrounding Chaco Canyon are there environments inside the maize niche with ^{18}O depleted waters and relatively high $^{87}Sr/^{86}Sr$ ratios? As described in the introduction, oxygen isotope sourcing requires an environment in which ^{18}O-depleted waters from snowmelt and high elevation precipitation do not confound interpretation. The San Juan River and its tributaries violate this condition. These waterways also transport water with high $^{87}Sr/^{86}Sr$ ratios from the San Juan and La Plata Mountains into a northern San Juan Basin lithology with much lower $^{87}Sr/^{86}Sr$ ratios. Surrounding Chaco Canyon, the basin, and surrounding foothills north of the San Juan River is the only region that matches the biogeochemical environment needed to produce the results from the three maize-eating deer. The Chuska Mountains are not near a river and the Rio Puerco to the south does not originate from montane regions and the strontium isotope ratios of that region are lower than required. While these deer were not obtained from upper elevations, the combined $\delta^{13}C_{bioapatite}$-maize niche modeling, $\delta^{18}O_{bioapatite}$, and $^{87}Sr/^{86}Sr$ results indicate these three deer still were procured at a significant distance from Chaco Canyon (~ 90 km) and likely the San Juan River drainage to the north of Chaco Canyon. The Chuska Mountains have a very small area that falls outside of the maize niche (Figs. 2 and 3), which suggests that any deer living in the Chuskas would have access to maize. When all isotopic lines of evidence are taken into account, the 12 non-maize deer most likely came from the San Juan and La Plata Mountains.

The results from applying $\delta^{13}C_{bioapatite}$-maize niche modeling are significant. This method when combined with previous results and interpretations showed that one of the primary assumptions of the previous study had been violated. Deer in the northern San Juan Basin have access to oxygen-depleted waters originating in upper elevations via the San Juan River and tributaries. The San Juan River also transports strontium-87-enriched sediments and waters from these older primarily granitic lithologies. Without combining the $\delta^{13}C_{bioapatite}$-maize niche modeling method, the violation of this assumption would have remained hidden. Instead, the results were able to correct previous interpretations and further refine the potential source regions of deer consumed at Pueblo Bonito, New Mexico, USA.

The geochemical sourcing results—even as corrected in this study from the previous interpretations of Grimstead *et al.* (2016)—seem to indicate a paucity of prey, small or large, near Chaco Canyon during the time of Pueblo Bonito. The results of this study cannot establish whether animal resources were ever abundant within the local habit or whether extensive procurement systems were a pre-requisite for occupation of Pueblo Bonito and Chaco Canyon more generally. Perhaps animal protein was so scarce in the immediate environs of Chaco Canyon that even small animals became valuable enough for importation. Another possibility is that animal protein came to Chaco Canyon as tribute. People who served as temporary laborers or pilgrims who came to partake in ritual gatherings are potential porters of such resources. Large game undoubtedly held an exceptionally high value as a food item, and likely served as a high prestige or tribute item. If Chaco Canyon drew people in from the hinterland for social or religious benefits, then the flow of material resources was possibly unidirectional. Regardless of motive, it is clear that food was being carried over long distances to supply consumers in Chaco Canyon. It remains unclear if the ultimate causation for deer transport was due to habitat deterioration, naturally low productivity, or, less likely, cultural taboos on hunting in the local Chaco Canyon region.

These results raise questions over the sustainability of the Chaco Canyon population and the system that supplied resources to Pueblo Bonito. In fact, the century-long persistence of the Chaco Phenomenon may prove more intriguing than its enigmatic downfall, likely due in part to unfavorable climatic conditions (Dean 1994; Benson *et al.* 2007). Based upon maize and animal source regions, it appears that the subsistence system of Chaco Canyon was stretched beyond its means soon after founding and perhaps from its inception.

This research also highlights the intriguing fact that deer were coming into the Canyon as complete carcasses, or at least the transported parts included the head. As noted, all the ungulate sourcing analyses targeted mandibular or maxillary teeth. Optimal foraging theory accounts for the carrying of highly preferred portions of big game over significant distances (Cannon 2003; Grimstead 2010, 2012), but the apparent less optimal transportation of low-yield heads requires consideration of the animal serving as a social signal. In southwest ethnographies, deer heads served as ritually powerful emblems. There was often a social and ritual imperative to display the head upon return to the pueblo or camp (Basehart 1960, p. 12; Buskirk 1986, p. 143; Gifford 1940, p. 114; Hill 1938, pp. 101–113; Spier 1928, p. 111; White 1962, pp. 303–304). Displaying the results of a successful hunt during public food sharing and distribution events was linked to prestige (Buskirk 1986, pp. 152, 154, 209; White 1962, pp. 303–304). White (1962, p. 304) provides a particularly poignant example from the Sia Pueblo, New Mexico (italics for emphasis):

> [in the hunting ground]… the deer is skinned so that the head and backbone are left attached to the skin…The hunter gets the head, the skin and part of the backbone and the chest from the neck down to and including the fourth rib, and a part of the belly. The rest goes to the cacique…[now back at the pueblo]…He lays the deer on the floor, covers it with a white embroidered manta (cotton textile), lays strings of beads on its neck, and sprinkles it with prayer meal (petana). *Neighbors come in* "*to visit and to welcome the deer.*" The mother of the hunter cooks the deer's head, after it has been skinned; she boils it whole in a large kettle. She also cooks the lungs and heart… *The mother or sister of the hunter goes through the village inviting the people of each household to come to her house to eat...* The hunter takes the deer's head and horns, with a handful of petana, to a medicineman… and asks him to paint it and "give it breath"… [The medicine man and fellow society members] "dress" the head... They stuff native-grown, unspun cotton into the eye sockets, nostrils, and foramen magnum… They paint a blue-green quarter moon on the forehead, and smear the entire skull with white clay. The face is sprinkled with stcamun. Turkey or eagle feathers are stuck into the nostrils. And, finally, a short turkey body feather is tied to each point on the horns. The medicinemen return the head and horns to the hunter... *He puts it on the roof of his house, close to the chimney, where he lets it remain for an indefinite time…The Sia have a reputation for being excellent hunters, and deer heads and horns are conspicuously numerous on their housetops.*

Through the display of the deer's head, the hunter and/or hunting party in the above quote communicate socially important messages about hunting prowess, environmental and landscape knowledge, physical abilities, and health. They also potentially signaled access to ritual knowledge or power. The southwestern ethnographies, cited above, further document the belief that not proper handling, butchering, and respecting the deer would bring bad luck, poor health, and disease to the hunter. In short, there was likely significant social currency to be gained by transporting the entire deer carcass with head for broader community display (*cf.* Smith *et al.* 2003; Sosis 2000). The deer transported to Pueblo Bonito simultaneously fulfilled caloric and social benefits, and in the case of the three maize-access deer, also served to minimize crop damage.

Conclusion

A previously employed tandem $^{87}Sr/^{86}Sr_{bioapatite}$ and $\delta^{18}O_{bioapatite}$ approach demonstrated that deer did not come from the immediate environs of Chaco Canyon, but could not conclusively exclude medium range procurement. The present study sought to exclude nearby to medium range deer hunting grounds by considering deer access to agricultural crops. The most productive maize niches in the region are located at middle elevations where direct precipitation is more abundant. Insufficient growing season at higher elevations mostly determines the upper boundary of the maize niche. Maize employs the C_4 photosynthetic pathway, whereas most other deer forage employs the C_3 pathway. Thus, deer procured at middle and lower elevations, in the maize niche, would reflect access to maize as a food source through their $\delta^{13}C_{bioapatite}$ values. A baseline of modern deer and lagomorphs clearly reflects C_4 enrichment in accordance with these predictions. Analyses of tooth enamel from 15 archaeofauna deer demonstrated that 12 of the specimens did not have access to significant maize in their diets and thus must have a provenance of high elevation. Hunters regularly transported deer carcasses in near intact condition with low yield heads included. Deer, and perhaps specifically deer heads, plausibly served as social capital and a form of signaling. Such displays could be a critical component of the non-material exchanges of prestige and esoteric knowledge that occurred at this ritual-political center.

These results confirm and improve upon previous observations and demonstrate the potential of using paleoecological modeling in tandem with geochemical sourcing methods. The authors believe that this approach has many benefits and a huge potential in a variety of applications. For example, preferred habitats of certain animals could be modeled based upon paleoclimate and vegetation records, then used to further refine source regions as was done in this paper. Wild turkeys, for example, require trees for roosting, and models of where tree roosting habitat existed could be derived based upon paleoclimate and vegetation records. Then, geochemical sourcing results could be further refined by being able to exclude certain regions where tree roosting was not possible. Perhaps it may even be possible to someday use paleorecords and known requirements of plants to model paleolandscapes where all three photosynthetic pathways overlap, such as the southwestern USA and Northern Mexico. This may improve any interpretations of carbon isotope data when CAM and C_4 plants are known to occur naturally and confound dietary interpretations.

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Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

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