Defining isotopic signatures of potential procurement sources: A case study in the Mesa Verde Region of the US Southwest

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Abstract

Combining strontium and oxygen isotope analyses has proved useful in determining animal procurement sources in archaeological case studies. In this paper, we analysed $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ of 55 rodents from archaeological contexts and 94 plants of the Mesa Verde and McElmo Dome regions (US Southwest) to estimate their regional isotopic signatures. We asked to what extent the new isotopic data would allow to isolate one region from another in view of providing a background for interpreting fauna acquisition strategies. The results clearly show trends in bioavailable Sr across the Mesa Verde landscape. The lower $^{87}Sr/^{86}Sr$ values are synonymous with areas composed of igneous rock, while the highest values correspond, for the most part, to the San Juan Mountains, a region that likely provided large game hunting opportunities. Moreover, the McElmo Dome area associated with the sites under study, is represented by a uniquely narrow range of Sr values suggesting that prey acquired outside a 10 km foraging range from such sites will be identifiable. Although plant oxygen isotope data did not further differentiate specific zones within the studied area, the significant correlation of plant $\delta^{18}O$ with elevation will be useful for archaeologists to examine large game hunting

strategies. Furthermore, this study expands the existing database of isotopic signatures for the American Southwest and in particular the one on the San Juan Basin and its surroundings.

Keywords

Strontium isotopes; Oxygen isotopes; Baseline; Mesa Verde; American Southwest

1. Introduction

Changes in resource acquisition patterns are important components of larger social transformations in the US Southwest and worldwide (Gumerman et al., 2003; Kohler, 1992; Kuckelman, 2010; Minnis, 1985; Redman, 1999). In the Mesa Verde region, a period of increasing human population aggregation and shifting settlement locations from AD 750 through 1280 was accompanied by growing pressure on local wild and cultivated food resources, including prey taxa (Driver, 2002; Schollmeyer and Driver, 2013). Previous studies suggest that over time, declining availability of animals important for both nutrition and social practices contributed to heightened social tensions which eventually culminated in episodes of violence and subsequent regional depopulation (Kuckelman, 2010).

Our global project, which involves three successive studies, uses isotope analysis to examine temporal changes in resource acquisition to assess how shifts in the source areas and transport patterns of important animal resources were associated with episodes of dramatic social change. The extent of prehistoric transport of animal resources in the area is currently unknown, and archaeological chemistry provides an opportunity to assess existing arguments about localized food resource depletion and its role in social changes culminating in widespread migration out of the region in the late 13th century. Contextualizing archaeological samples requires an extensive baseline environmental (both biological and geological) dataset for comparison. This article, that presents the first of our three studies, focuses on the field collection, analytical procedures, and geographic patterns of the isotopic background dataset to determine its potential for interpretation of archaeological data.

1.1 Sr and O isotope analyses to study animal mobility and provenance

$^{87}Sr/^{86}Sr$ is a geochemical signature frequently used to source archaeological fauna to a geographic area (Bentley, 2006). Strontium, an alkali earth metal, is found in all rock and has four naturally occurring isotopes (^{84}Sr, ^{86}Sr, ^{87}Sr, and ^{88}Sr), but only one (^{87}Sr) is the direct result of radioactive decay. The production of ^{87}Sr involves the β-decay of ^{87}Rb, so its abundance is directly related to the amount of initial Rb and Sr in a geologic unit and the time since its formation (Faure, 1986). Thus, older and/or Rb-rich bedrock present higher ratios of $^{87}Sr/^{86}Sr$ facilitating the use of Sr as a geochemical tracer (Faure, 1986). The structural similarity of strontium to calcium permits its substitution into biological structures such as bone and its mass prevents measurable fractionation.

Strontium isotope ratios in bone hydroxyapatite and tooth enamel record the strontium isotope ratio of the food web that contributes to their formation (Hodell et al., 2004; Laffoon et al., 2012). However, $^{87}Sr/^{86}Sr$ values in vegetation track geographic variation not only in the $^{87}Sr/^{86}Sr$ of bedrock, from which soils are formed, but also in loess deposits, meteoric water and atmospheric dust, since plants metabolize Sr from soil waters containing trace elements from all such sources both local and distant (see Bentley, 2006; Capo et al., 1998; Reheis et al., 2018). In this regard, Mesa Verde loess deposits, reaching a maximum thickness of 3-5 m, reflect volcanic sediments transported by the San Juan River and its tributaries as well as adjacent sandstone formations (Reheis et al., 2018). Atmospheric input is also particularly impactful in the arid American Southwest, where carbonate dust contributes heavily to the strontium isotopic composition of the soil (English et al., 2001; Ericson, 1985; Naiman et al., 2000; Reynolds et al., 2005). In this regard, English et al. (2001, p. 11892) report that in timber from the Sangre de Cristo Mountains of northern New Mexico "[a]bout 20% of the bioavailable strontium was…derived from bedrock and 80% from atmospherically transported dust." Thus, although the $^{87}Sr/^{86}Sr$ found in animal bone and tooth enamel is an indication of the geographic setting during formation and turnover of sampled tissues (Hedman et al., 2009), vegetation and/or small mammals with constrained foraging ranges must be widely sampled to accurately characterize baseline, bioavailable Sr signatures.

Despite these issues, strontium isotope analyses in skeletal tissues have been effectively utilized to investigate mobility of animals from a multitude of archaeological contexts (e.g. Evans et al., 2019; Laffoon et al., 2012), by comparing isotopic signatures from archaeological animal bones to the biologically-available signatures at possible locations of origin (Bentley, 2006). In some studies, the incorporation of additional isotopic 'mobility' indicators such as oxygen ($\delta^{18}O$) can clarify ambiguous strontium data (e.g., Pederzani and Britton, 2019; Slovak and Paytan, 2012).

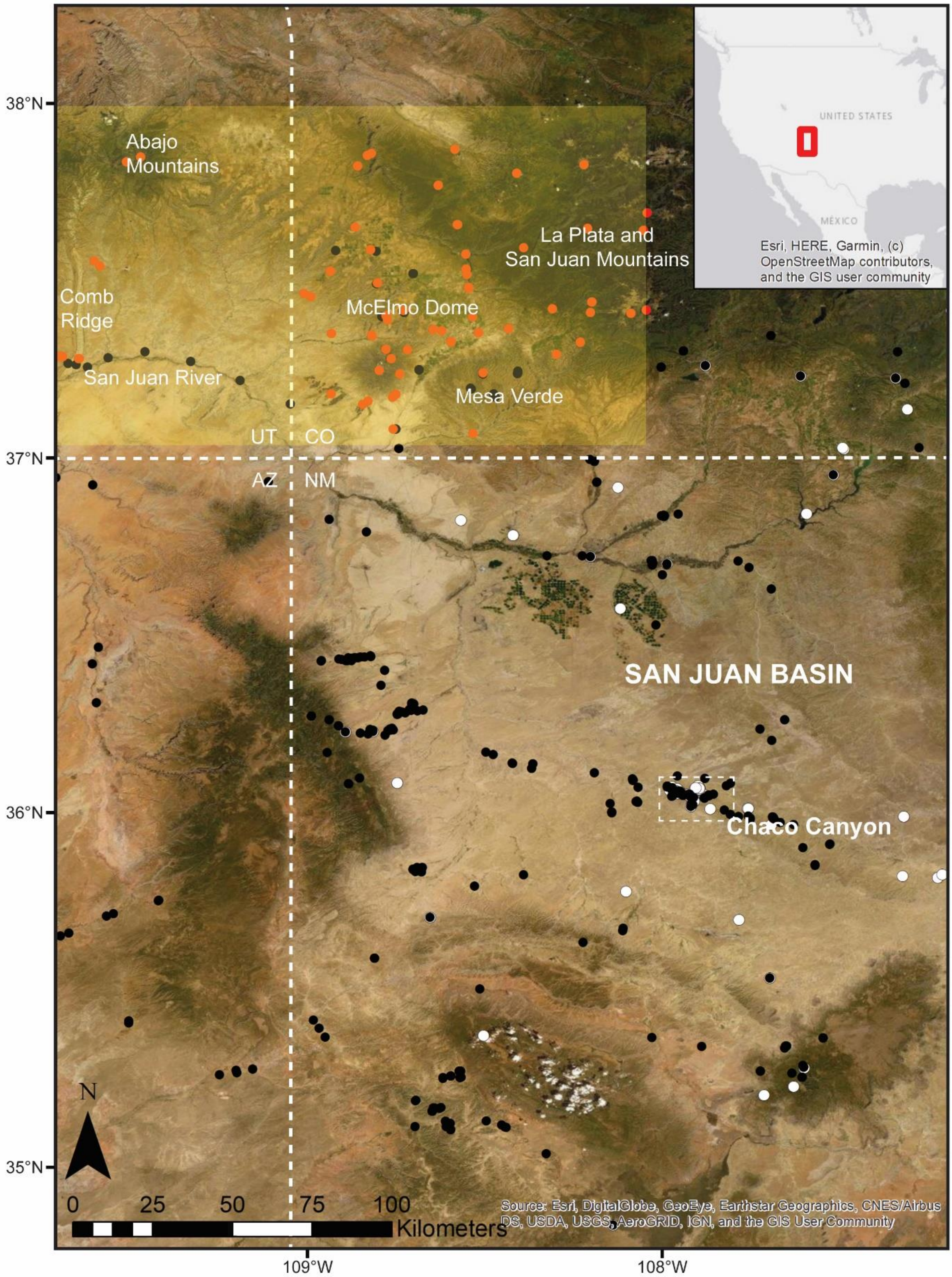
Bone apatite $\delta^{18}O$ values covary with the oxygen isotope chemistry of meteoric water, which fractionates with increases in elevation, distance from a coastline, the seasonality or temperature of precipitation, and also over time due to evaporation. As water vapor masses move upslope, the heavier isotope $H_2{}^{18}O$ preferentially rains out, accelerated by declines in temperature. $H_2{}^{18}O$ also preferentially rains out as water vapor masses move inland, progressively depleting inland $\delta^{18}O$ values relative to coastal moisture, although this effect is less marked in warm versus cold precipitation events (Daux et al., 2005; Fricke and O'Neil, 1999; Fricke et al., 1995). Thus, $\delta^{18}O$ values in faunal tissue reflect the $\delta^{18}O$ in drinking water, which in turn depends on several factors including temperature, distance from the sea, and elevation (e.g., Price et al., 2019; Slovak and Paytan, 2012).

Among faunal taxa that are obligate drinkers, skeletal $\delta^{18}O$ values primarily record the oxygen isotope chemistry of drinking water sources (Fricke et al., 1995; Hoppe, 2006). In taxa that are not obligate drinkers, however, bone apatite $\delta^{18}O$ values are enriched by intake of plant waters (Pederzani and Britton, 2019). For example, during cool, wet seasons, leaf water, fractionated +10-25‰ by evapotranspiration (Bryant and Froelich, 1995; Fricke and O'Neil, 1996), meets most mule deer moisture requirements, and the $\delta^{18}O$ value of bone apatite is enriched accordingly. A known relationship between preformed (leaf) and meteoric water reported for modern deer (D'Angela and Longinelli, 1990, Equation 1; Iacumin et al., 1996, Equation 1), allows for the calculation of imbibed water $\delta^{18}O$ values.

The high topographic relief and localized rainfall patterns in the study area may allow oxygen isotopic data to discern small-scale spatial differences independently or in combination with the strontium isotopic data. As Pederzani and Britton mentioned in their review (2019, p. 90), combining both $\delta^{18}O$ with $^{87}Sr/^{86}Sr$ analyses provides a powerful tool to determine seasonal movements of animals in archaeological case studies because it "helps to overcome the limitations of single systems and strengthen interpretations, offering valuable insights that are impossible to gain from any other archaeological science methods."

1.2 Current isotopic baseline used in Southwest Archaeology

The first research using isotope analyses to examine the archaeology of the Four Corners region appeared in the early 2000's with studies on Chacoan architectural timber procurement (English et al., 2001; Reynolds et al., 2005). It was followed by numerous studies on the location of maize fields and faunal kill sites in and around Chaco Canyon, which is located in the San Juan Basin approximately 150 km southeast of the study area (Fig. 1) (Benson, 2010, 2012; Benson et al., 2003, 2006, 2008, 2009, 2019; Cordell et al., 2008; Grimstead et al., 2015).



[2-column fitting image]

Figure 01. Map showing the regions mentioned in the text and samples used for isotope analyses (from publications mentioned in the text: black dots: Sr, white dots: O; from the present study: red dots for Sr and O). The yellow highlighted zone corresponds to the study area. Coordinates referenced to WGS 1984 datum; basemap sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, and the GIS User Community.

For the Sr isotope baseline used to study procurement of Chacoan architectural timbers, 52 fir and spruce beams from six great houses were analysed as well as rocks, streams, soil water and cores from live fir and spruce growing at various elevations in three mountain ranges surrounding Chaco Canyon (English et al., 2001). The authors report that the Sr isotope ratios differed "substantially" between the three mountain ranges presenting different ages and lithologies and could be used to source Chacoan Great House timbers to a specific mountain range. They also report that "$^{87}Sr/^{86}Sr$ ratios in modern trees constitute a surprisingly well-behaved isotopic system…[with] little scatter…among individual trees or different species within the same stand and surprisingly little scatter among stands within a given mountain range" (English et al., 2001, p. 11896) suggesting that if Mesa Verde bioavailable Sr has an homogeneous and narrow isotopic signature at high elevations, it may be possible to source large prey taxa in archaeological faunal assemblages to upland procurement sites.

In research on the location of maize fields provisioning Chacoan Great Houses, soils were taken from nearly 200 sites within the San Juan Basin and adjacent regions, covering an area of approximately 100,000 km², generally at multiple depths within the rooting zone of maize (around 1.5 m) (Benson, 2012). In this regard, Benson et al. (2003; Benson, 2012) developed an acid-leaching method that yielded soil-water containing biologically available $^{87}Sr/^{86}Sr$ as it would have been fixed by vegetation growing on sampled soils. Modern maize, water, and to a lesser extent deer mice, were also sampled. Deer mice obtain Sr from plants and insects that primarily use the upper several centimetres of soil-water and thus can be used as proxies for browsing animals such as deer (Benson et al., 2008). Finally, in more recent studies, rabbitbrush was used to develop an isotopic baseline since both maize and rabbitbrush have similar rooting depths expressing like $^{87}Sr/^{86}Sr$ ratios if grown in the same location (Grimstead et al., 2015). Strontium ratios identified numerous possible maize field sites both within Chaco Canyon and in upland areas surrounding the canyon. These sites included McElmo Dome and other locations in our study area (Benson et al., 2009, Figure 8), further illustrating the confounding effects of wind-borne dust on bioavailable Sr in arid landscapes (English et al., 2001; Naiman et al., 2000). Given the difficulty identifying maize field sites based on bioavailable Sr, Benson and Grimstead (2019) then turned to a study of in canyon effective moisture, arguing that Chaco Canyon lacked adequate growing season moisture to bring maize crops to maturity, hence the necessity to import maize from the Chuska slopes and other upland field sites.

Only in the last ten years have studies using Sr isotope analysis addressed the sourcing of archaeofaunas in Chaco Canyon, often in conjunction with carbon and oxygen isotope data. Using both bioapatite carbon and strontium, Grimstead et al. (2016a) argued that all Chacoan wild animal protein from both large and small taxa, including rabbits and prairie dogs, was transported into Chaco from procurement sites greater than 40 km, whereas turkey were managed within small, local home ranges suggesting they were undergoing domestication (Grimstead et al., 2016b). Adding bone collagen carbon values to bioapatite carbon and Sr data, Grimstead et al. (2019) provided evidence for the absence of garden hunting in deer, reaffirming that deer in Chacoan faunal assemblages were taken at elevations higher than the maize farming niche and at distances in excess of 40 km from the canyon. Finally, Hamilton et al. (2018) used variation in the oxygen isotope chemistry of small versus large mammals in Chacoan assemblages to counter Grimstead's finding that small mammals were transported long distances into the canyon (Grimstead et al., 2016a).

These studies demonstrate both the utility and complexity of strontium isotope chemistry across the arid Four Corners region. High elevation sites seem to exhibit diagnostic $^{87}Sr/^{86}Sr$ values on deep rooted trees suggesting strong, site specific bedrock signals with less input from confounding aeolian dust or other sources. Also, it seems clear that the geolocation of faunal kill sites can be improved with the addition of oxygen isotope values, but disagreement remains regarding their implications for long distant transport of small fauna. Finally, the need for a comprehensive sampling regime is clearly illustrated by more than a decade of work in and around Chaco Canyon. In this regard, our study enriches an already substantial Four Corners isotopic database with the integration of plants and local archaeological rodents from numerous locations across the Mesa Verde landscape.

2. Objectives

The present study identifies zones around the Mesa Verde and McElmo Dome regions based on the isotopic signatures of strontium and oxygen isotope data. The area we investigate encompasses southwest Colorado and southeast Utah (Fig. 1, highlighted), extending to Comb Ridge and the Abajo Mountains on the west, and to the La Plata and San Miguel Mountains on the east. The southern portion is delimited by the San Juan River and its tributaries. This study area combines a long-term record of human occupation with dating precision from a large number of tree ring dates, allowing us to identify both short-term variation and broader temporal trends in animal acquisition from different parts of the study area.

We focus on four multicomponent villages spanning the Pueblo I through late Pueblo III periods: Albert Porter (5MT123), Duckfoot (5MT3868), Sand Canyon (5MT765), and Shields (5MT3807) located in the centre of Mesa Verde, more precisely in the large valleys between the McElmo Dome and the La Plata Mountains (Fig. 2). All these sites were excavated by Crow Canyon Archaeological Center, and the excavated materials are curated at the Canyons of the Ancients Museum. The goal of the broader project is to examine whether people travelled farther to acquire game animals as human populations grew and as the impacts of human hunting and anthropogenic landscape change accumulated over time around farming villages. In particular, we hypothesize that human activities created "sink" areas, areas with very little large game but where village residents spent most of their time in farming and related tasks, a distance many studies have suggested is 5 km or less from residential sites (Bradfield, 1971; Chisholm, 1968; Dennell, 1980; Herhahn and Hill, 1998; Higgs and Vita-Finzi, 1972; Hudspeth, 2000; Kohler et al., 1986; Varien, 1999, p. 153–154). This daily use area is also where small animals, like rodents and rabbits, would have been acquired (often in the course of other activities) and carried back to the village. Large game and a subset of plant resources would typically have been obtained within a slightly greater distance, about 10 km around villages, until game resources were depleted (e.g., Alvard et al., 1997; Hill et al., 1997; Novaro et al., 2000). Although the four archaeological sites studied are geographically close, we nonetheless test for potential isotopic differences between them. If no significant variation is observed, the interval of cumulative measurements in each 10 km radius around these sites will define a local isotopic signature.

If resource depletion occurred, hunters likely travelled to more distant hunting sites, over 10 km away, to find large game; ethnographic studies tend to show game depletion within about 10 km from features like villages and roads (Hart, 2000; Hill and Padwe, 2000; Hill et al., 1997; Mittermeier, 1991; Peres and Nasciemento, 2006). These more distant game "source" areas where game animal births exceeded deaths could include higher altitude regions with too short a growing season for farming, or areas where social tensions made travel more dangerous (Driver, 2010; Kay, 1994; Martin and Szuter, 1999). The Sleeping Ute Mountain, the McElmo Creek drainage and the area alongside the Dolores River contained very few or no villages during the time period of our study, which could make these regions potential deer procurement areas, as well as the somewhat more distant La Plata and San Juan Mountains; thus, we sampled these areas as well.

Here, we present the Sr and O isotopic baseline generated with new measurements and, where possible, identify isotopic intervals to define likely procurement regions. The present study asks to what extent isotopic data make it possible to isolate one region from another in order to provide a background for interpreting fauna acquisition strategies.

3. Context of the archaeological sites

The Mesa Verde area provides an excellent case study with fine chronological and spatial control. Systematic survey coverage, dendrochronology, and a series of well-dated changes in pottery style allow fine-grained dating of assemblages within 40- to 80-year time intervals and a detailed understanding of shifting settlement patterns in this area (Ortman et al., 2007; Varien et al., 2007).

An influx of immigrants in the period from AD 500 to 750 established the first well-documented sedentary multi-household villages in the study area, but much of the population remained in scattered single-family households (Varien et al., 2007; Wilshusen, 1999a). Our study begins with the subsequent period, Pueblo I (AD 750-900), when settlement first coalesced into substantial farming villages of 100 households or more (Johnson et al., 2005). These villages were short-lived, with occupations of 40 years or less, and by AD 880 a large-scale emigration reduced human populations in the region (Judge, 1989; Wilshusen, 1999b). The Pueblo II period began with an interval of low human population and widely dispersed households (AD 900-1060), some of which were loosely clustered into spatially dispersed communities (Lipe and Varien, 1999a; Varien et al., 2007). In the second half of this period (AD 1060-1140), another episode of immigration increased the area's population, and residence became increasingly aggregated in community centres built in the style of Chacoan communities to the south (Lipe and Varien, 1999a). Several decades of drought ushered in the early Pueblo III period (AD 1140-1225), but the end of the drought around AD 1180 coincided with another period of rapid population growth and increasingly aggregated clustering of residential communities on mesa tops (Lipe and Varien, 1999b). The late Pueblo III period (AD 1225-1300) saw continued population growth, with peak populations around AD 1260 (Varien et al., 2007). During this time the majority of people lived in tightly aggregated villages, which had shifted in location from mesa tops to canyon edge locations, including cliff dwellings and canyon rim villages at the heads of canyons (Lipe and Varien, 1999b; Varien et al., 2007). The end of the Pueblo III period (terminal Pueblo III, AD 1260-1280+) encompassed a number of rapid social and environmental changes, including the “great drought” of AD 1276-1299 and shorter growing seasons associated with the onset of the Little Ice Age, as well as increased evidence of violent conflict (Ahlstrom et al., 1995; Crown et al., 1994; Kuckelman, 2010; Lightfoot and Kuckelman, 2001; Lipe and Varien, 1999b; Wilcox and Haas, 1994). Residential use of the region by Pueblo people ended shortly after AD 1280 (Lipe, 1995; Varien et al., 2007).

Kuckelman (2010) links the decades of climatic downturn to a dramatic change in resource acquisition patterns and accompanying interpersonal violence. She argues that the inhabitants of Sand Canyon Pueblo, for instance, reverted to an emphasis on hunting and gathering during the last decades before abandonment of that village. At this time, domesticated turkeys decline in frequency in deposits at the site and wild game remains increase, shifts she ties to repeated maize crop failures that forced people to stop provisioning turkey flocks and to forage farther afield for wild plants and animals. After AD 1277, Sand Canyon Pueblo was attacked and abandoned. Many other villages in the region were also abandoned after violent episodes at this time, a pattern Kuckelman links in part to resource stress associated with both previous human impacts on local resources and increased competition for food among human social groups. To date, only Sand Canyon Pueblo has sufficient temporal control in its deposits to allow the immediate preabandonment deposits to be examined separately from the rest of the late Pueblo III period, but Kuckelman’s analysis suggests an interesting scenario for the kinds of circumstances faced by many villages in the decades before the regional abandonment around AD 1280. Isotope analysis provides a great opportunity to assess whether large game animals came from more distant areas over time as human impacts on local resources accumulated. It also allows us to examine wild game was indeed transported more often and/or across greater distances in Late Pueblo III than in previous periods, and whether turkey transport patterns and/or provisioning systems shifted with the climate and social upheavals.

4. Material and Sampling Strategy

We selected 55 rodents from archaeological contexts, 37 pocket gophers and 18 prairie dogs, and 94 plants of 11 different taxa as environmental samples to estimate regional Sr signatures (Table 1). The use of archaeological animal remains decreases the risk of anthropic factors such as pollutants and fertilizers on the strontium values of modern animals (Bentley, 2006; Laffoon et al. 2012).

At least three archaeological rodent samples were selected from each of the four village sites in the study. Additional samples derive from the McElmo Dome region and south to the Sleeping Ute Mountain. Rodent samples from outlying regions were not available due to the lack of excavated archaeological sites. Rodents are considered very unlikely to have been transported. Ethnographically, these animals were considered low ranked foods and often hunted casually around villages in the course of other tasks (Szuter, 1991, 2000). They are very unlikely to have been the focus of long-range hunting activities or inter-village transport. Rodent home ranges and dispersal distances are normally only a few hundred meters or less. The rodent sample in this study consists largely of pocket gophers (*Geomyidae*), which have maximum home ranges of about 585 m^2 (often much less) in the Southwest (Knight, 2005; Pigage and Pigage, 2010). These rodents are expected to provide local environmental signatures for the sites in which they are found, and in combination with the plant samples, will enable us to establish general isotopic ranges for sub-regions. Rodent samples were collected from mandibles, and each consisted of 0.25 g of bone; the remaining portion of each sampled mandible was retained in the museum collection.

Plant sample locations were selected by an initial assessment of a regional geological map (Fig. 2). Areas with the same primary surface geology were presumed to likely exhibit similar Sr isotope ratios. Specific sampling locations were selected in order to target diverse areas within a presumed geologic zone. Additional criteria included accessible roads and available public property. Initial plans focused on collecting samples of sagebrush (*Artemesia tridentata*), but the plant diversity associated with differences in topographic relief exceeded expectations and thus other plant species were selected when sage was unavailable. Samples from three different individual plants were collected at each location, and when sage was not present, a diversity of plants were selected (including annuals and perennials). Plant samples were placed into paper bags in the field and precise GPS coordinates for each sample were recorded along with a photograph of each plant for species identification confirmation. The plant samples from each day were rinsed with deionized water, and dried in a food dehydrator. Once dry, plant samples were placed into plastic bags for long-term storage.

All plant and rodent samples were analysed for strontium isotopes, while a subset of 50 rodent samples and 65 samples plants were analysed for oxygen isotopes (Table 1). Leaves were preferentially used although other parts such as stems or flowers were used when necessary.

Sample no.	Sample description	Site name	Site/Field ID	UTM location North	UTM location East	masl	$^{87}Sr/^{86}Sr$	2σ error	Cluster	$\delta^{18}O_{vSMOW}$
Rodents										
MVSR001 B	pocket gopher	Windy Wheat	5MT4644	4156400	716300	2166	0.70958	0.00002	4	20.4
MVSR002 B bis	pocket gopher	Windy Wheat	5MT4644	4156400	716300	2166	0.70965	0.00001	4	21.8
MVSR003 B	pocket gopher	Windy Wheat	5MT4644	4156400	716300	2166	0.70960	0.00001	4	24.0
MVSR004 B	pocket gopher	Grass Mesa	5MT23	4161074	716044	2114	0.70991	0.00002	5	23.8
MVSR005 B	pocket gopher	Grass Mesa	5MT23	4161074	716044	2114	0.70982	0.00001	5	25.7
MVSR006	pocket gopher	Grass Mesa	5MT23	4161074	716044	2114	0.70985	0.00001	5	24.3
MVSR007	pocket gopher	McPhee	5MT4475	4154750	716504	2114	0.70963	0.00001	4	23.8
MVSR008	pocket gopher	McPhee	5MT4475	4154750	716504	2114	0.70957	0.00001	4	
MVSR009	pocket gopher	McPhee	5MT4475	4154750	716504	2114	0.70971	0.00001	4	23.2
MVSR010	pocket gopher	Castle Rock	5MT1825	4134930	693400	1688	0.70944	0.00002	4	26.5
MVSR011	pocket gopher	Castle Rock	5MT1825	4134930	693400	1688	0.70942	0.00001	4	27.4
MVSR012	pocket gopher	Castle Rock	5MT1825	4134930	693400	1688	0.70955	0.00001	4	25.9
MVSR013	pocket gopher	Stanton's	5MT10508	4140060	697040	2115	0.70934	0.00001	4	25.7
MVSR014	pocket gopher	Stanton's	5MT10508	4140060	697040	2115	0.70939	0.00001	4	25.9
MVSR015	pocket gopher	Stanton's	5MT10508	4140060	697040	2115	0.70949	0.00001	4	24.9
MVSR016	pocket gopher	Albert Porter	5MT123	4151564	694278	2053	0.70946	0.00002	4	24.0
MVSR017	pocket gopher	Albert Porter	5MT123	4151564	694278	2053	0.70952	0.00001	4	25.0
MVSR018	pocket gopher	Albert Porter	5MT123	4151564	694278	2053	0.70954	0.00001	4	26.1
MVSR019	pocket gopher	Shields	5MT3807	4143050	701000	2052	0.70947	0.00001	4	25.2
MVSR020	pocket gopher	Shields	5MT3807	4143050	701000	2052	0.70945	0.00001	4	25.5
MVSR021	pocket gopher	Shields	5MT3807	4143050	701000	2052	0.70948	0.00001	4	24.3
MVSR022	pocket gopher	Shallow House	5MT8822	4161920	692350	2095	0.70955	0.00001	4	24.3
MVSR023	pocket gopher	Shallow House	5MT8822	4161920	692350	2095	0.70954	0.00001	4	22.8
MVSR024	prairie dog	Shallow House	5MT8822	4161920	692350	2095	0.70956	0.00001	4	27.3
MVSR025	pocket gopher	Escalante	5MT2149	4150476	717089	2165	0.70924	0.00001	3	24.0
MVSR026	pocket gopher	Escalante	5MT2149	4150476	717089	2165	0.70873	0.00001	2	23.5
MVSR027	pocket gopher	Escalante	5MT2149	4150476	717089	2165	0.70887	0.00001	3	23.9
MVSR028	pocket gopher		5MT7723	4116765	699733	1747	0.70868	0.00001	2	27.6
MVSR029	prairie dog		5MT7723	4116765	699733	1747	0.70870	0.00001	2	30.6
MVSR030	prairie dog		5MT7723	4116765	699733	1747	0.70855	0.00001	2	27.3
MVSR032	prairie dog		5MT8943	4115933	698997	1737	0.70843	0.00001	2	28.3
MVSR033	prairie dog		5MT8943	4115933	698997	1737	0.70843	0.00001	2	29.8
MVSR034	prairie dog		5MT8943	4115933	698997	1737	0.70845	0.00001	2	27.9
MVSR035	prairie dog		5MT10207	4114512	692777	1734	0.70875	0.00001	2	28.8
MVSR036	pocket gopher	Roundtree	5MT2544	4155000	682480	1969	0.70941	0.00001	4	23.9
MVSR037	pocket gopher	Roundtree	5MT2544	4155000	682480	1969	0.70941	0.00001	4	24.8
MVSR038	pocket gopher	Roundtree	5MT2544	4155000	682480	1969	0.70940	0.00001	4	25.0
MVSR039	pocket gopher		5MT8899	4136600	719960	1905	0.70979	0.00001	5	24.8
MVSR040	prairie dog		5MT8899	4136600	719960	1905	0.70967	0.00001	4	29.2
MVSR041	prairie dog		5MT8899	4136600	719960	1905	0.70924	0.00001	3	30.6

MVSR042	prairie dog		5MT8934	4141470	718320	1932	0.70914	0.00001	3	29.3
MVSR043	prairie dog		5MT8934	4141470	718320	1932	0.70876	0.00002	2	27.7
MVSR044	prairie dog	Mitchell Springs	5MT10991	4133440	713170	1834	0.70900	0.00001	3	30.2
MVSR045	prairie dog	Mitchell Springs	5MT10991	4133440	713170	1834	0.70907	0.00001	3	29.5
MVSR046	pocket gopher	Mitchell Springs	5MT10991	4133440	713170	1834	0.70924	0.00001	3	25.4
MVSR047	pocket gopher	Mitchell Springs	5MT10991	4133440	713170	1834	0.70915	0.00001	3	25.7
MVSR048	pocket gopher		5MT2564	4113461	691506	1685	0.70850	0.00001	2	26.3
MVSR049	pocket gopher		5MT2564	4113461	691506	1685	0.70822	0.00001	1	27.0
MVSR050	prairie dog		5MT2564	4113461	691506	1685	0.70844	0.00001	2	31.8
MVSR053	prairie dog		5MT8653	4116566	683556	1606	0.70857	0.00001	2	
MVSR054	prairie dog		5MT8653	4116566	683556	1606	0.70859	0.00001	2	29.4
MVSR055	prairie dog		5MT8653	4116566	683556	1606	0.70858	0.00001	2	
MVSR056	prairie dog	Duckfoot	5MT3868	4137330	708620	1936	0.70942	0.00001	4	
MVSR057	pocket gopher	Duckfoot	5MT3868	4137330	708620	1936	0.70949	0.00001	4	
MVSR058	pocket gopher	Duckfoot	5MT3868	4137330	708620	1936	0.70940	0.00002	4	24.8
Plants										
MVSrP 001	Artemisia tridentata		1.1.1	4168843	688340	1996	0.70951	0.00001	4	27.4
MVSrP 002	Artemisia tridentata		1.1.2	4168870	688337	1996	0.70942	0.00001	4	
MVSrP 004	Artemisia tridentata		1.2.1	4188068	688543	2235	0.70951	0.00001	4	31.6
MVSrP 005	Artemisia tridentata		1.2.2	4188086	688535	2233	0.70971	0.00001	4	
MVSrP 007	Artemisia tridentata		2.1.1	4192018	691797	2337	0.70999	0.00001	5	29.0
MVSrP 008	Artemisia tridentata		2.1.2	4192025	691803	2336	0.71014	0.00001	5	
MVSrP 010	Artemisia tridentata		2.2.1	4193817	712499	2013	0.70906	0.00001	3	33.0
MVSrP 011	Artemisia tridentata		2.2.2	4193836	712476	2012	0.70899	0.00002	3	
MVSrP 013	Artemisia tridentata		2.3.1	4191384	690855	2329	0.70977	0.00001	5	22.2
MVSrP 014	Artemisia tridentata		2.3.2	4191349	690875	2327	0.70972	0.00001	4	
MVSrP 016	Pinus ponderosa		3.1.1	4170273	713707	2501	0.71002	0.00001	5	28.5
MVSrP 017	Quercus gambelii		3.1.2	4170288	713750	2500	0.71004	0.00002	5	30.7
MVSrP 018	Symphoricarpos albus		3.1.3	4170288	713750	2501	0.70984	0.00001	5	28.4
MVSrP 019	Pinus ponderosa		3.2.1	4163552	730396	2521	0.71005	0.00002	5	29.8
MVSrP 022	Pinus edulis		3.3.1	4144556	738089	2385	0.70940	0.00001	4	30.7
MVSrP 023	Pinus edulis		3.3.2	4144556	738089	2386	0.70944	0.00002	4	
MVSrP 025	Abies sp.		4.1.1	4189963	744704	3308	0.70937	0.00001	4	28.6
MVSrP 026	Picea sp.		4.1.2	4189963	744704	3309	0.70931	0.00001	4	
MVSrP 028	Symphoricarpos albus		4.2.1	4186739	728029	2759	0.71050	0.00002	6	32.0
MVSrP 029	Symphoricarpos albus		4.2.2	4186739	728029	2759	0.71019	0.00001	5	
MVSrP 030	Populus tremula		4.2.3	4186739	728029	2760	0.71062	0.00001	6	27.3
MVSrP 031	Artemisia cana		4.3.1	4182450	708639	2539	0.71009	0.00002	5	25.9
MVSrP 032	Quercus gambelii		4.3.2	4182450	708639	2539	0.70984	0.00002	5	33.6
MVSrP 033	Pinus ponderosa		4.3.3	4182450	708639	2540	0.70978	0.00001	5	29.0
MVSrP 034	Abies sp.		5.2.1	4175354	760835	2837	0.70821	0.00001	1	28.4
MVSrP 035	Picea sp.		5.3.1	4169864	760089	2621	0.71060	0.00001	6	29.4
MVSrP 036	Picea sp.		5.3.2	4169822	760076	2621	0.71067	0.00001	6	29.7
MVSrP 038	Abies sp.		5.4.1	4169954	746167	2958	0.71069	0.00001	6	28.9

MVSrP 039	Abies sp.	5.4.2	4170022	746210	2960	0.71020	0.00002	5	
MVSrP 041	Picea sp.	6.1.1	4143697	757786	3088	0.70908	0.00001	3	30.6
MVSrP 042	Picea sp.	6.1.2	4143697	757786	3088	0.70919	0.00002	3	
MVSrP 044	Abies sp.	6.2.1	4144870	761533	2968	0.70895	0.00001	3	29.1
MVSrP 045	Picea sp.	6.2.2	4144870	761533	2968	0.70951	0.00002	4	
MVSrP 047	Artemisia tridentata	7.2.1	4124127	721377	2313	0.70970	0.00002	4	26.5
MVSrP 048	Artemisia tridentata	7.2.2	4124074	721356	2309	0.71006	0.00001	5	
MVSrP 050	Artemisia tridentata	7.3.1	4105016	719360	1812	0.70953	0.00001	4	33.2
MVSrP 051	Artemisia tridentata	7.3.2	4105010	719346	1812	0.70952	0.00002	4	
MVSrP 053	Atriplex canescens	8.2.1	4105953	699297	1588	0.70846	0.00002	2	32.2
MVSrP 054	Artemisia tridentata	8.3.1	4130458	739489	2069	0.70893	0.00001	3	26.3
MVSrP 055	Artemisia tridentata	8.3.2	4130458	739489	2069	0.70897	0.00001	3	
MVSrP 057	Quercus gambelii	8.4.1	4134317	745394	2482	0.70983	0.00001	5	31.9
MVSrP 059	Symphoricarpos albus	8.4.3	4134278	745399	2480	0.70999	0.00002	5	28.7
MVSrP 060	Quercus gambelii	8.5.1	4143716	747618	2695	0.70886	0.00002	3	31.6
MVSrP 061	Symphoricarpos albus	8.5.2	4143716	747618	2695	0.70884	0.00001	2	26.0
MVSrP 063	Abies sp.	8.6.1	4147068	747893	2790	0.70793	0.00001	1	35.9
MVSrP 065	Symphoricarpos albus	8.6.3	4147025	747915	2792	0.70783	0.00001	1	
MVSrP 066	Artemisia tridentata	9.1.1	4138105	727416	2021	0.70883	0.00001	2	32.7
MVSrP 067	Artemisia tridentata	9.1.2	4138105	727416	2021	0.70914	0.00001	3	
MVSrP 069	Artemisia tridentata	9.2.1	4136959	710747	1873	0.70973	0.00002	5	28.6
MVSrP 070	Artemisia tridentata	9.3.1	4130862	702244	2030	0.70916	0.00001	3	30.4
MVSrP 071	Artemisia tridentata	9.3.2	4130862	702244	2029	0.70914	0.00002	3	
MVSrP 073	Artemisia tridentata	9.x.1	4133591	713146	1976	0.70898	0.00001	3	33.6
MVSrP 074	Artemisia tridentata	9.x.2	4133521	713087	1974	0.70922	0.00002	3	31.5
MVSrP 075	Artemisia tridentata	9.x.3	4133595	713092	1976	0.70905	0.00002	3	31.3
MVSrP 076	Artemisia tridentata	10.1.1	4124182	695343	2439	0.70940	0.00001	4	27.5
MVSrP 077	Artemisia tridentata	10.1.2	4124169	695328	2439	0.70937	0.00001	4	27.6
MVSrP 079	Artemisia tridentata	10.2.1	4130833	696881	2195	0.70895	0.00001	3	30.0
MVSrP 080	Artemisia tridentata	10.2.2	4130833	696881	2195	0.70957	0.00002	4	28.8
MVSrP 082	Artemisia tridentata	10.3.1	4123129	700498	2065	0.70892	0.00002	3	31.7
MVSrP 083	Artemisia tridentata	10.3.2	4123129	700498	2063	0.70908	0.00002	3	
MVSrP 085	Artemisia tridentata	10.4.1	4127973	698256	2448	0.70784	0.00001	1	31.6
MVSrP 086	Artemisia tridentata	10.4.2	4127973	698256	2448	0.70813	0.00001	1	
MVSrP 087	Artemisia tridentata	11.1.1	4135056	693288	1665	0.70938	0.00002	4	36.0
MVSrP 088	Artemisia tridentata	11.1.2	4135084	693274	1666	0.70939	0.00002	4	34.4
MVSrP 089	Artemisia tridentata	11.1.3	4135109	693252	1667	0.70965	0.00002	4	33.2
MVSrP 090	Artemisia tridentata	11.2.1	4141517	696762	2063	0.70950	0.00002	4	30.6
MVSrP 091	Artemisia tridentata	11.2.2	4141385	696672	2064	0.70952	0.00001	4	34.5
MVSrP 092	Artemisia tridentata	11.2.3	4141416	696811	2072	0.70951	0.00002	4	30.6
MVSrP 093	Ephedra genus	11.3.1	4135411	683256	1667	0.70925	0.00001	3	23.5
MVSrP 094	Juniperus scopulorum	11.3.2	4135411	683256	1668	0.70926	0.00001	3	35.8
MVSrP 095	Atriplex confertifolia	11.3.3	4135411	683256	1668	0.70924	0.00002	3	34.6
MVSrP 096	Artemisia tridentata	11.4.1	4146920	677792	1787	0.70933	0.00001	4	32.4

MVSrP 097	Artemisia tridentata	11.4.2	4146898	677786	1785	0.70925	0.00001	3	
MVSrP 099	Artemisia tridentata	11.5.1	4147829	676061	1718	0.70951	0.00002	4	30.0
MVSrP 100	Artemisia tridentata	11.5.2	4147828	676098	1716	0.70940	0.00001	4	
MVSrP 102	Atriplex canescens	12.1.1	4127017	615233	1529	0.70927	0.00002	3	32.3
MVSrP 104	Ephedra genus	12.1.3	4127017	615233	1529	0.70918	0.00001	3	
MVSrP 105	Purshia tridentata	12.2.1	4127074	616192	1456	0.70888	0.00001	3	27.1
MVSrP 106	Purshia tridentata	12.2.2	4127074	616192	1456	0.70903	0.00001	3	
MVSrP 108	Artemisia tridentata	12.3.1	4126407	620102	1426	0.70936	0.00001	4	30.5
MVSrP 109	Artemisia tridentata	12.3.2	4126407	620102	1426	0.70924	0.00001	3	
MVSrP 111	Atriplex canescens	12.4.1	4126438	620303	1434	0.70922	0.00001	3	31.9
MVSrP 112	Atriplex canescens	12.4.2	4126438	620303	1434	0.70927	0.00002	3	
MVSrP 114	Juniperus scopulorum	12.5.1	4157092	623640	1730	0.70857	0.00001	2	44.1
MVSrP 115	Juniperus scopulorum	12.5.2	4157092	623640	1730	0.70859	0.00001	2	
MVSrP 117	Artemisia tridentata	12.6.1	4155492	625017	1777	0.70931	0.00002	4	27.9
MVSrP 118	Artemisia tridentata	12.6.2	4155492	625017	1777	0.70932	0.00001	4	
MVSrP 120	Abies sp.	12.7.1	4188182	631134	2901	0.70842	0.00001	2	25.9
MVSrP 121	Abies sp.	12.7.2	4188182	631134	2901	0.70825	0.00001	1	
MVSrP 123	Picea sp.	12.8.1	4189776	634587	3088	0.70915	0.00001	3	26.4
MVSrP 124	Picea sp.	12.8.2	4189776	634587	3089	0.70927	0.00001	3	
MVSrP 126	Artemisia tridentata	13.1.1	4150716	717038	2191	0.70918	0.00002	3	29.3
MVSrP 127	Artemisia tridentata	13.1.2	4150701	717040	2190	0.70902	0.00002	3	26.7
MVSrP 128	Artemisia tridentata	13.1.3	4150685	717005	2189	0.70873	0.00002	2	29.4

Table 01. Description, location and $^{87}Sr/^{86}Sr$ and $\delta^{18}O$ information of rodents and plants from the Mesa Verde region.

5. Methods

5.1 Sr isotope analysis

The bone samples were first mechanically cleaned using a brush and were then cut using a diamond cutting disk to isolate a fragment of approximately 20-40 mg. To remove diagenetic strontium, the samples were subjected to an acid cleaning. The samples were sonicated for thirty minutes in mQ 18MΩ water, twenty minutes in 5% acetic acid, five minutes in 5% acetic acid, left to leach in 5% acetic acid for seven hours, and then sonicated for five minutes in the mQ 18MΩ water. After each step, the samples were rinsed three times, and finally left overnight to dry. The samples were digested overnight using 2 ml of Optima grade 7 N HNO_3 at 125 ˚C.

For the plants, depending on the Sr concentration, a sample of 50-400 mg was used. The plant samples were first dried overnight and then ground using a mortar and pestle. The samples were then calcined at 550°C for four hours. The plant ashes were digested in a mixture of 1 ml Trace Metal Grade 24N HF and 1 ml Optima Grade 14 N HNO_3, for 24h at 120°C. The samples were evaporated, and the re-digested in 2 ml 7 N HNO_3.

Sr was extracted using EiChrom Sr-spec^{TM} resin following a protocol adapted from De Muynck et al. (2009). The extracted Sr samples were then evaporated at 90˚C. The dry residues were redissolved in 0.05 N HNO_3. Sr isotope analyses were conducted on the Nu Plasma II MC-ICP-MS (Nu Instruments) in operation at MURR, following the procedure and analytical conditions described in Renson et al. (2019). Values obtained for the SRM987 were 0.710263 ± 0.000041 (2SD) and 0.710252 ± 0.000041 (2SD), during the analytical sessions of the rodents and the plants, respectively. To control the reproducibility of the entire protocol, the SRM1400 (Bone Ash) was analysed and values obtained were 0.713111 ± 0.000025 (2SD) and 0.713113 ± 0.000030 (2SD), during the analytical sessions of the rodents and the plants, respectively. These values are in agreement with the range of 0.713122 ± 0.000037 (2SD) previously obtained by De Muynck et al. (2009).

5.2 Carbonate O isotope analysis

Bone hydroxyapatite (apatite) is a calcium phosphate mineral containing carbonate ions (CO_3^{2}) substituted in the phosphate (PO_4^{3-}) position or adsorbed into the crystal hydration layer.

During isotope analysis, the adsorbed (or labile) carbonate ions subject to exchange with ground water are removed, preserving in vivo $\delta^{18}O$ signals.

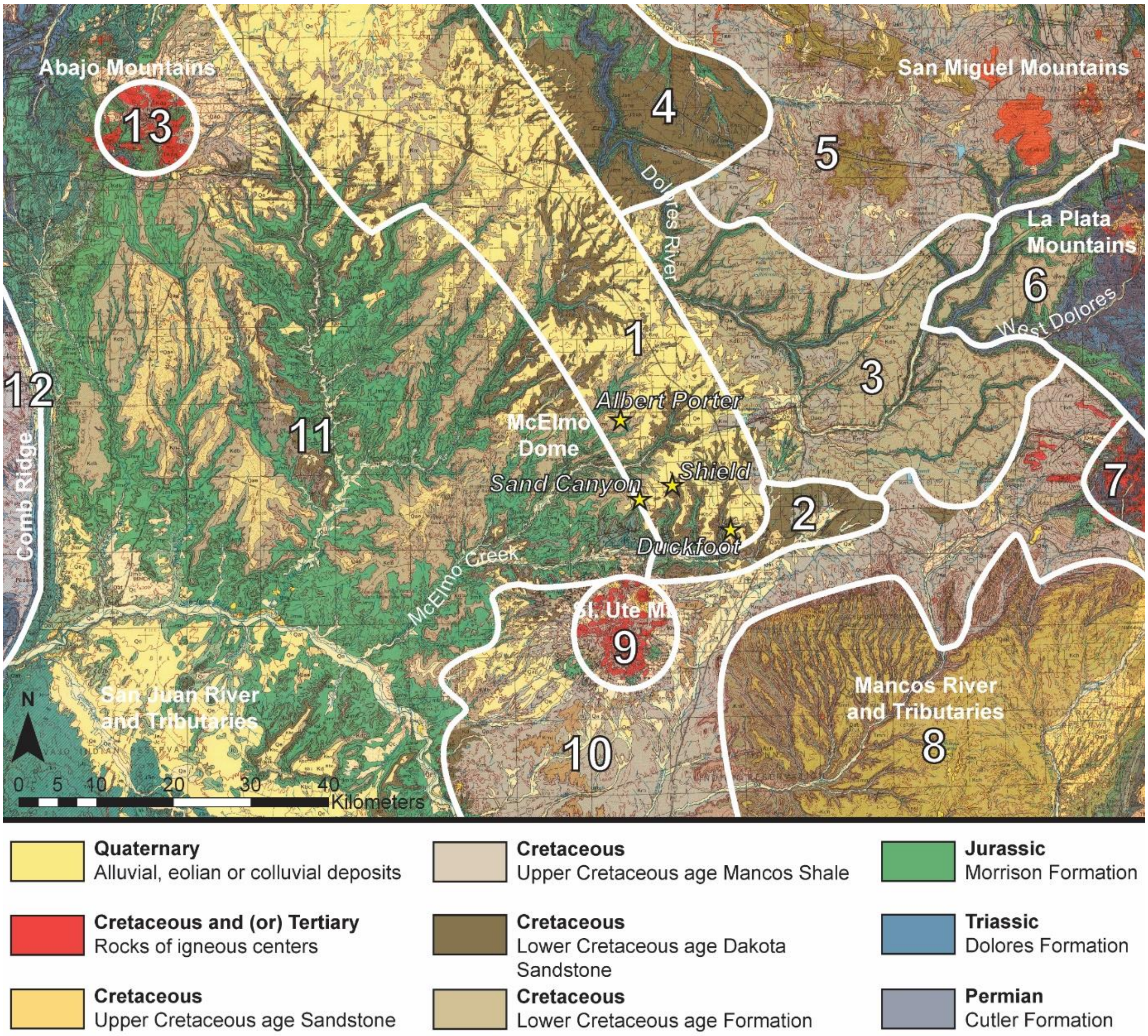
Sample preparation for plant and bone hydroxyapatite $\delta^{18}O$ was conducted at the Archaeological Center Research Facility for Stable Isotope Chemistry at the University of Utah. Plant samples were cleaned of surface contaminants and ground by mortar and pestle prior to gas bench analysis. Samples of faunal bone were pre-treated as follows: 100 mg of powdered bone was soaked 24 hours in 3% hydrogen peroxide to remove organics, rinsed to neutrality and dried. Samples were then treated 30 minutes in 0.1 m buffered acetic acid to remove labile carbonates, again rinsed to neutrality and dried. Stable oxygen isotopic values were determined relative to vPDB on a Thermo Gasbench coupled to a Thermo Finnigan Delta Plus XL IRMS at the University of Wyoming Stable Isotope Facility. QA normalized standard uncertainty was 0.2‰ (ref material UWSIF17 [GS-1]). QC standard uncertainty was 0.3‰ (ref material UWSIF19 [rock] and 0.1‰ (ref material UWSIF06 [$CaCo_3$].

We finally reported the $\delta^{18}O_{vPDB}$ values on the vSMOW scale using a conversion established by Coplen et al. (1983) (see Eq. (1)):

$$\delta^{18}O_{vSMOW} = 1.03091\ \delta^{18}O_{vPDB} + 30.91 \quad (1)$$

6. Results and discussion

For the present study, we have divided the area within a 75 km radius of sites under study into thirteen zones that represent geologic and geographical variabilities (Fig. 2; also see Text S1 from supplementary materials for a description of the thirteen zones).

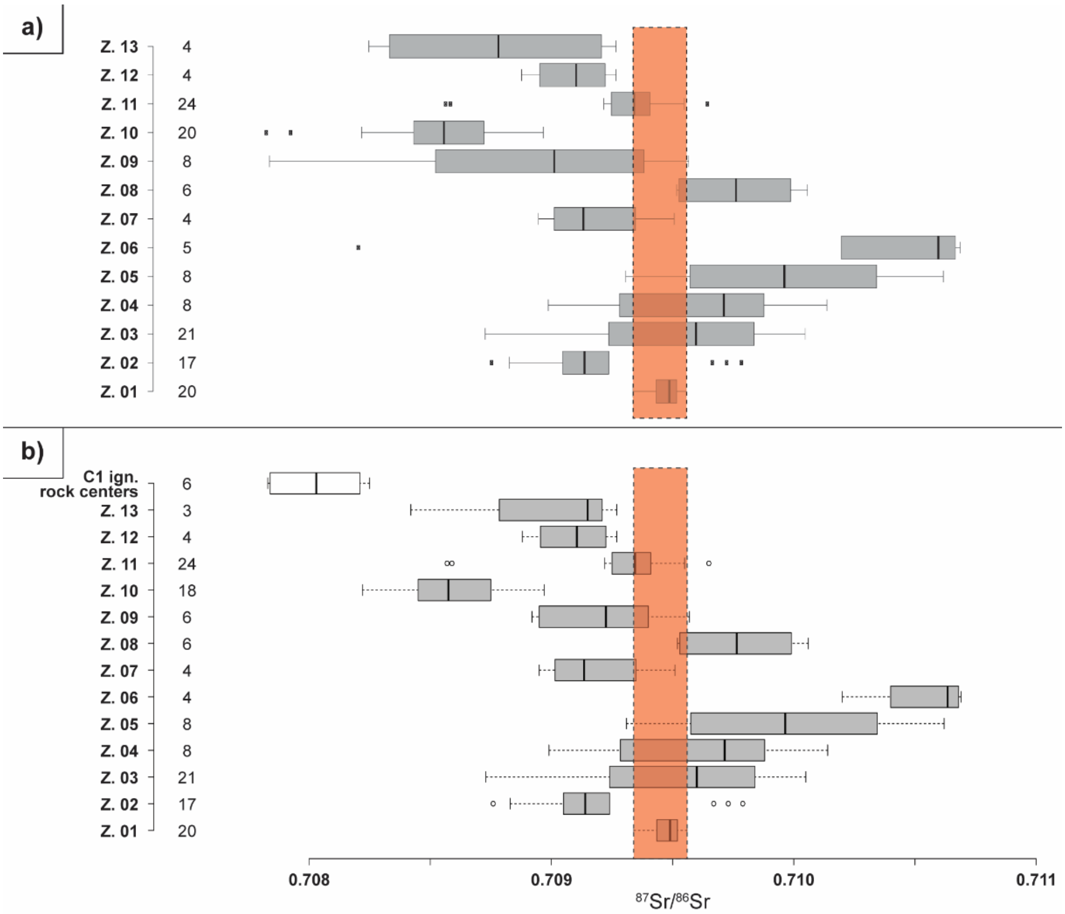


[2-column fitting image]

Figure 02. Map of the Mesa Verde region showing the thirteen main geologic and geographical zones (basemap source: Department of the Interior, United States Geological Survey). Legend simplified from the original map. A description of the thirteen zones in provided in the supplementary materials.

6.1 Strontium isotopes

The strontium data presented in Fig. 3 and Table 1 include all measurements carried out on both rodents and plants. $^{87}Sr/^{86}Sr$ values measured for both sample categories collected at the same location are relatively tightly clustered with a maximum range of 0.00062 and 0.00055, respectively. In cases where more than one taxon of rodents or plants was collected at the same site, no taxon-specific variability in Sr values was observed (see Fig. S1 from supplementary materials).



[1.5-column fitting image]

Figure 03. Strontium isotope ranges of combined plants and rodents from the thirteen zones. In b) ranges have been recalculated after subtraction of the samples from igneous rock centers of cluster 1. The red band illustrates the "McElmo Dome interval".

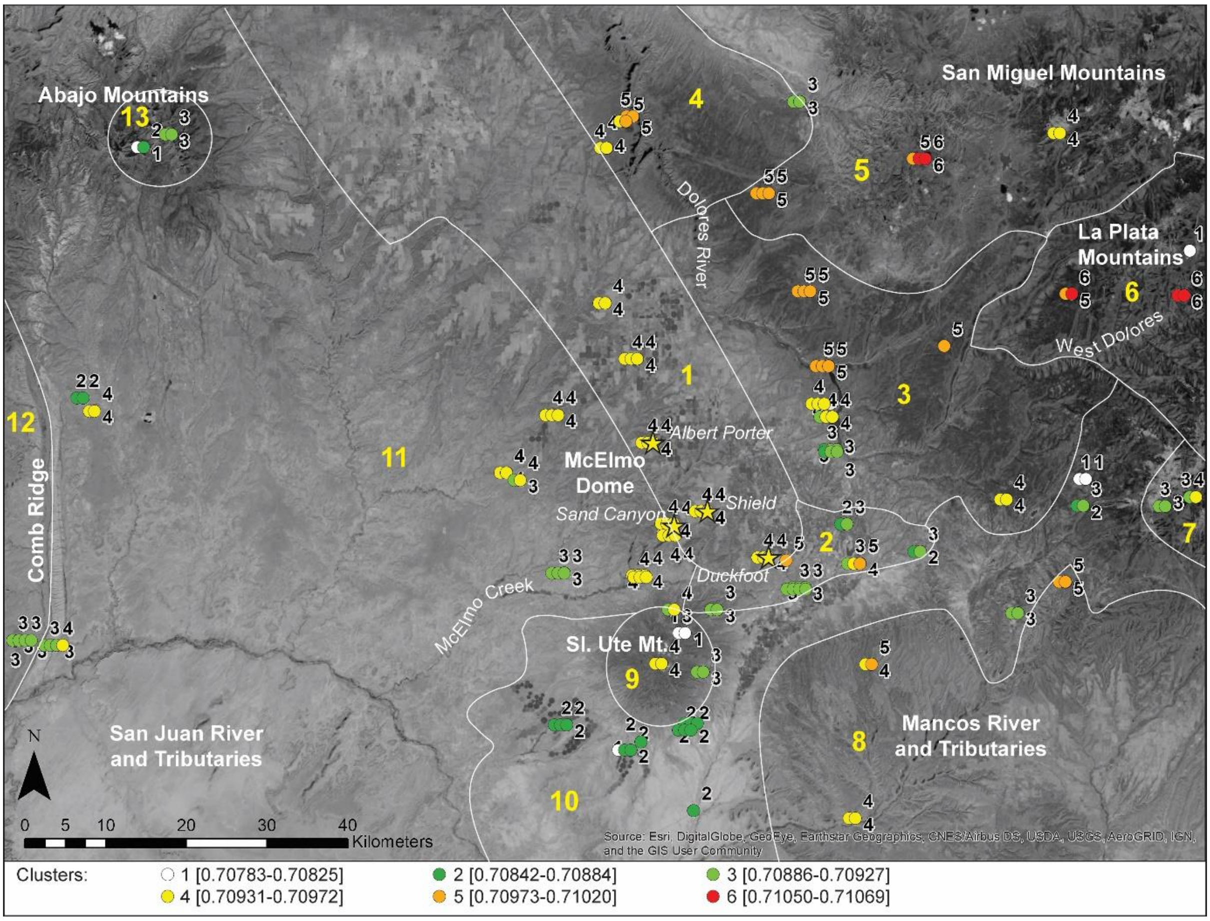
It is clear in Fig. 3 and Table 2 that reported Sr values do not sort discretely by zone. Values from several zones overlap the McElmo Dome interval, characteristic of sites under study (Fig. 3a). Thus, in order to place samples into several groups of distinct strontium ratio intervals, we used *K*-means cluster analysis (IBM SPSS Statistics for Windows, version 26). For a fixed *K* that corresponds to the number of groups (clusters) we initially specified, the *K*-means algorithm, based on Euclidean distance, starts an initial clustering based on *K* group means (centroids) (Baxter, 2015; Everitt et al., 2011). Clusters are formed by associating with them those points to which they are the closest centroid. The statistical software recalculated the centroids and reallocated points between clusters when a new centroid was closer; and proceeded until no changes occurred (Baxter, 2015). We tested several classifications with *K* varying from three to seven, and the one that best separated certain regions of interest consisted of six groups (clusters) whose $^{87}Sr/^{86}Sr$ values are distinct from those of the members of other groups (Table 3). The first cluster includes the samples with the lower Sr ratios and the sixth contains the samples featuring the higher ones (Figs. 4-5).

Zone	Mean	Range	Zone	Mean	Range
1 (n=20)	0.70948	0.70934-0.70956	8 (n=6)	0.70977	0.70952-0.71006
2 (n=17)	0.70919	0.70876-0.70979	9 (n=8)	0.70891	0.70784-0.70957
3 (n=21)	0.70952	0.70873-0.71005	10 (n=20)	0.70854	0.70783-0.70897
4 (n=8)	0.70961	0.70899-0.71014	11 (n=24)	0.70930	0.70857-0.70965
5 (n=8)	0.70996	0.70931-0.71062	12 (n=4)	0.70909	0.70888-0.70927
6 (n=5)	0.71007	0.70821-0.71069	13 (n=4)	0.70877	0.70825-0.70927
7 (n=4)	0.70918	0.70895-0.70951			

Table 02. $^{87}Sr/^{86}Sr$ values (mean and range) of the thirteen geologic and geographical zones.

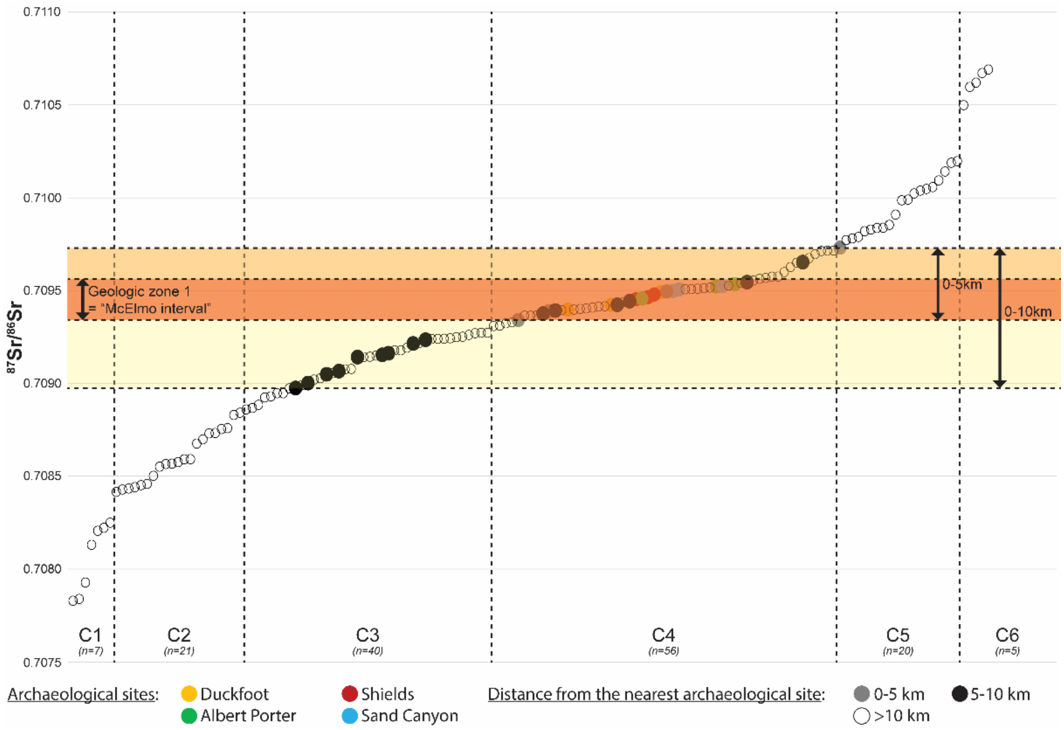
K-means Cluster	Center	Range	*K*-means Cluster	Center	Range
1 (n=7)	0.70806	0.70783-0.70825	4 (n=56)	0.70949	0.70931-0.70972
2 (n=21)	0.70860	0.70842-0.70884	5 (n=20)	0.70995	0.70973-0.71020
3 (n=40)	0.70911	0.70886-0.70927	6 (n=5)	0.71062	0.71050-0.71070

Table 03. $^{87}Sr/^{86}Sr$ values of cluster centers and ranges calculated using *K*-means cluster analysis. Cluster numbers correspond to those illustrated in Figure 4.



[2-column fitting image]

Figures 04 Map of the Mesa Verde region showing the results of the *k*-mean cluster analysis on the basis of $^{87}Sr/^{86}Sr$ measurements of rodents and plants (basemap sources: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, and the GIS User Community). Overlapped dots correspond to samples selected at a same location. The numbers written in yellow refer to the thirteen zones.



[1.5-column fitting image]

Figure 05. $^{87}Sr/^{86}Sr$ measurements of plants and rodents from the Mesa Verde region classified by *k*-mean clusters.

6.1.1 Low $^{87}Sr/^{86}Sr$

Igneous rocks centres

All samples featuring a $^{87}Sr/^{86}Sr$ value less than 0.70825, with one exception (MVSR049), are located on or very close to intrusive igneous rocks centres dated to the Cretaceous and/or the Tertiary (Fig. 4) and comprise Cluster 1. Moreover, the sample from Cluster 2 with the lowest $^{87}Sr/^{86}Sr$ measurement (MVSRP120) also comes from a sector of similar type. However, not all samples from zones with igneous rock express low Sr values.

South of Sleeping Ute Mountain

Fourteen samples were from locations on the south side of Sleeping Ute Mountain (Fig. 4). Thirteen of them belong to Cluster 2 and feature among the lowest $^{87}Sr/^{86}Sr$ values in this cluster. The single exception (MVSR049) is from Cluster 1. This region is part of the geologic Zone 10 mainly characterized by Mancos shale from the Cretaceous, but there are also small Quaternary alluvial and aeolian deposits originating from the southern slopes of the mountains.

Five other samples from Zone 10 belong to Cluster 3 (Fig. 4 and Table S1 from supplementary materials), selected in sectors located north-east of Sleeping Ute Mountain.

6.1.2 High $^{87}Sr/^{86}Sr$: The La Plata and San Miguel Mountains

The La Plata and the San Miguel Mountains are located east of the Dolores River (Fig. 4), comprising Zones 5 and 6 with the former composed primarily of Cretaceous age Mancos shale and the latter the only Triassic and Permian period formations in the region. All five samples in Cluster 6 were collected from the La Plata Mountains and represent the only Sr ratios higher than 0.71050. Whereas, the San Miguel Mountains exhibit a more heterogeneous topography and a wider range of positive Sr values.

Thus, the most extreme $^{87}Sr/^{86}Sr$ measurements are found in two zones, Zone 10 south of Sleeping Ute Mountain represented by low values; and Zone 6, east of the study area in the La Plata Mountains represented by the highest ones. These two zones that contained few known villages during this time period (Varien et al., 1996) likely have provided large games hunting opportunities. In fact, a recent study combining the concept of maize niche modelling with isotopic data suggests the La Plata Mountains as areas of origin of the majority of the deer consumed at Chaco Canyon at that time (Grimstead et al., 2019).

Otherwise, remaining zones express wide and/or overlapping Sr isotopic signatures, with the exception of Zone 1 where sites under study are located.

6.1.3 Introduction to the "McElmo Dome Interval"

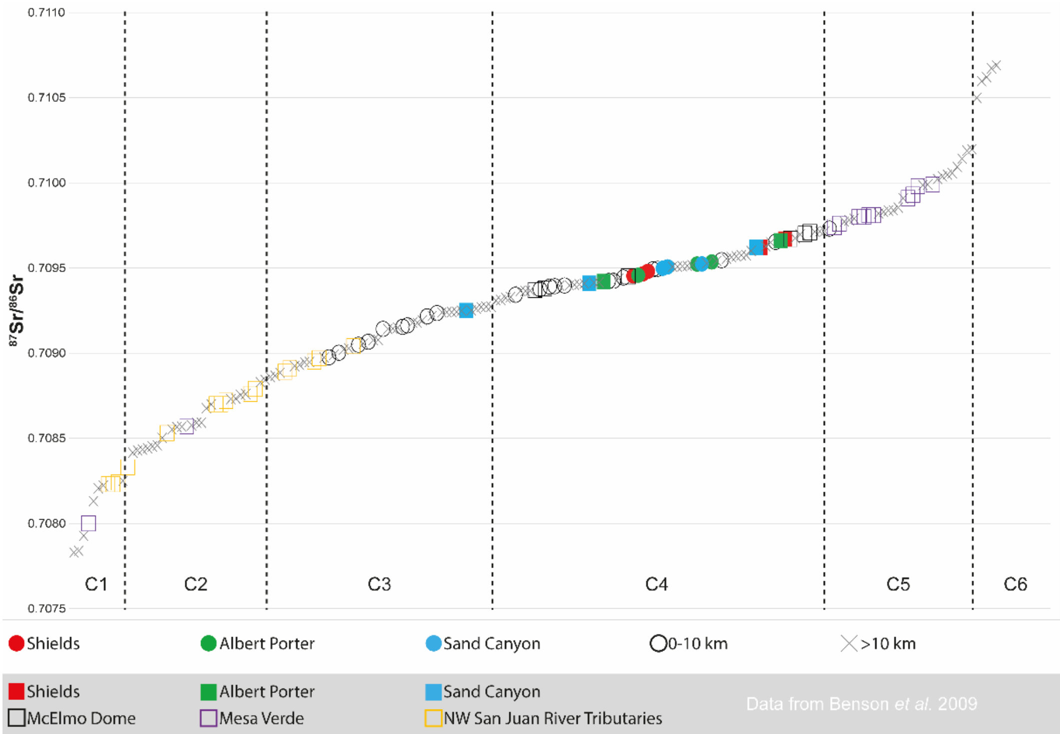
All of the villages with faunal assemblages included in this study are located on or near the southeastern edge of McElmo Dome (Fig. 4). It corresponds to the southern part of the well-defined Zone 1 and is composed of Quaternary aeolian deposits with exposures of Cretaceous and Jurassic sandstone formations in the canyons. This zone contained numerous villages during the time period examined here. Twenty-three samples are from Zone 1, fifteen of which were collected at archaeological sites or within a 5 km radius from them. Their Sr values group tightly, all belonging to Cluster 4 which exhibits a very narrow $^{87}Sr/^{86}Sr$ range (Fig. 3) we label the "McElmo Dome Interval." The $^{87}Sr/^{86}Sr$ values of this interval vary between 0.70934-0.70956. Variation is relatively tight but includes numerous samples from other regions (Figs. 3 and 5), particularly those collected along the Dolores River (Zones 3 and 4) and west of the McElmo Dome (Zone 11). Although this Sr interval is not unique to the

McElmo Dome, samples of unknown origin whose strontium measurements fall outside the "McElmo Dome Interval" are unlikely to have come from sectors near the archaeological sites and may instead represent non-local animal procurement strategies. Moreover, since all reported $^{87}Sr/^{86}Sr$ values higher than that of the "McElmo Dome Interval" were measured on samples from regions either to the east (Dolores River area), the northeast (La Plata and San Miguel Mountains) or the southeast (Mancos River and tributaries) (Fig. 4), and all lower values derive primarily from samples located to the west and southwest, the regional focus of long range hunting activities may be evident in faunal assemblages from sites under study.

6.1.4 Comparison with previous data

We compared our Sr isotopic values with data from the same region reported by Benson et al. (2009) (Fig. 6). The authors classified Sr data into three groups following their origin: 1) "NW San Juan River Tributary Soils" which corresponds to the south and southwest sectors of the study area south of Zone 10 and southwest of Zone 11; 2) "McElmo Dome Soils" (Zone 1); and 3) "Mesa Verde Soils" which corresponds to Zone 8, the "Mancos River and tributaries."

Fig. 6 shows that our study in in agreement with the Sr data from Benson et al. (2009). The samples from "NW San Juan River Tributary Soils", i.e. from the south and southwest of the study area, feature among the lowest $^{87}Sr/^{86}Sr$ values, integrating only clusters 1 to 3. Conversely, with only two exceptions, the samples from the "Mesa Verde Soils" have high $^{87}Sr/^{86}Sr$ measurements that place them in cluster 5. As for the samples from McElmo Dome, their $^{87}Sr/^{86}Sr$ measurements all fall within the isotopic interval defined by our samples from the same region.



[1.5-column fitting image]

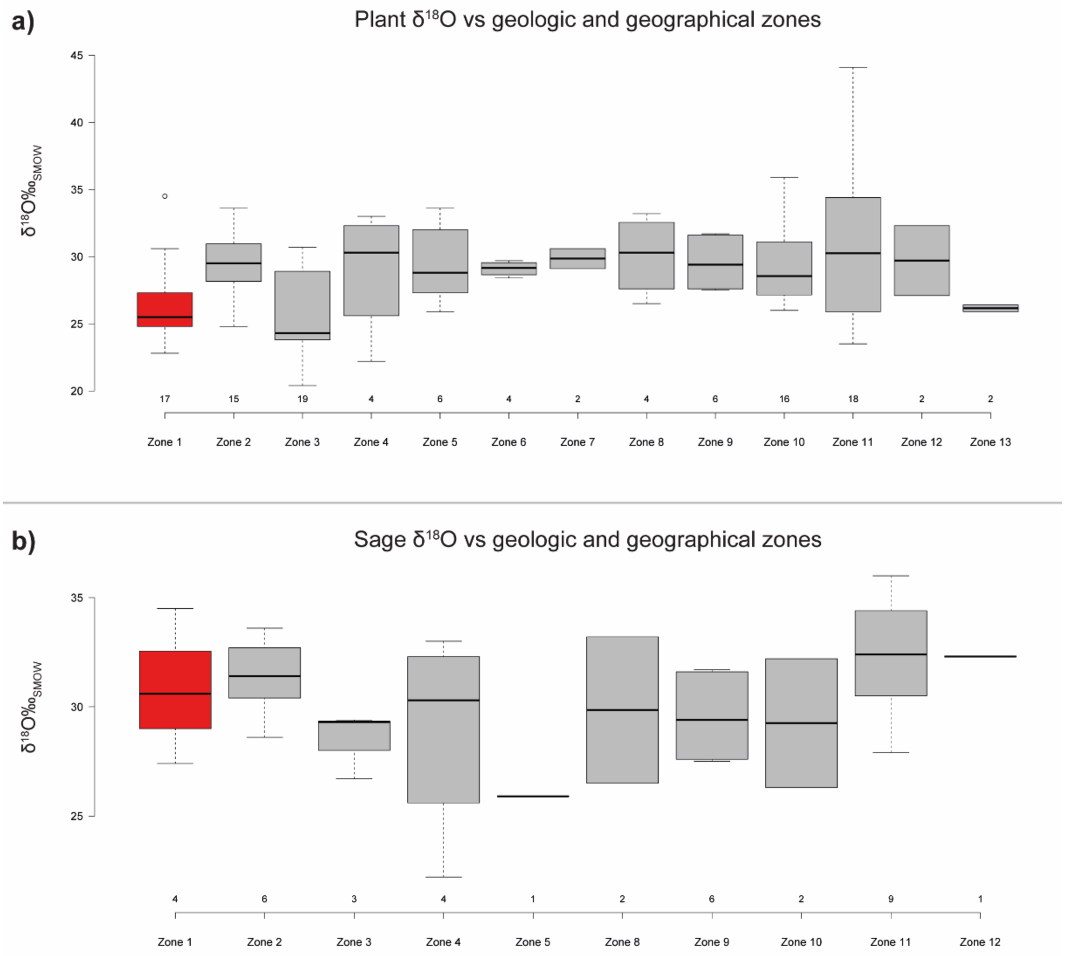
Figure 06: $^{87}Sr/^{86}Sr$ measurements of plants, rodents, and synthetic soil-waters* from the Mesa Verde region classified by *k*-mean clusters. *Data from Benson et al., 2009.

6.2 Oxygen isotopes

6.2.1 Plants $\delta^{18}O$

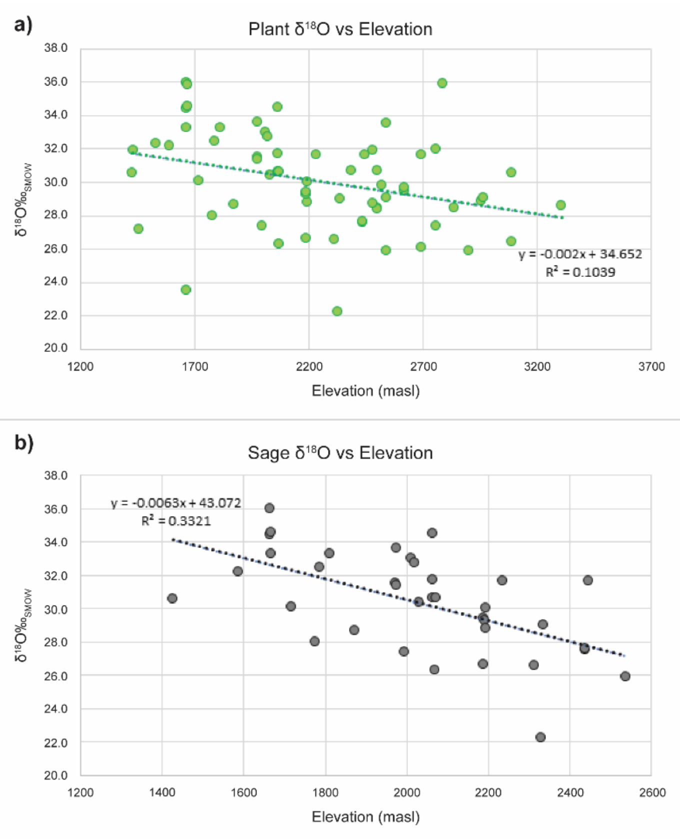
Leaf or needle tissue samples from 65 plants that may have provided forage for prey taxa such as mule deer (*Odocoileus hemionus*) were analysed for $\delta^{18}O$ (Table 1), 36 of which were sagebrush (*Artemesia tridentata*). Plant values ranged from 22.2‰ to 36.0‰ $\delta^{18}O_{VSMOW}$, exhibiting a mean of 30.1 ± 2.9‰, with elimination of one outlier (44.4‰).

Although collection sites spanned an elevational range of 1426 to 3309 masl, given the varied topography of the study area, it was not surprising that oxygen isotopic values did not sort by region (Fig. 7a). For example, sagebrush $\delta^{18}O$ does not clearly distinguish the archaeological sites area (Zone 1) from other regions in the study area (Fig. 7b). Yet, despite taxonomic differences in plant rooting depth and leaf anatomy, oxygen isotopic values are weakly but significantly correlated with elevation across the study area (R^2=0.1039, F=7.189, df=63, p=0.009) (Fig. 8a). When controlling for taxonomic diversity, the relationship between sage δ^{18}O (x=30.4 ± 3.0‰) and elevation improves (R^2=0.3321, F=16.905, df=35, p<0.000) with plants collected at upland sites exhibiting significantly more depleted oxygen isotopic values as expected (Fig. 8b). Ten plant taxa in addition to sage are present in this assemblage (Table 1), ranging from high elevation fir (*Abies* sp.) and spruce (*Picea* sp.) to xerically adapted four-wing salt bush (*Atriplex canescens*) but in no case did taxon sample size exceed eight, limiting the value of additional statistical analyses. Nonetheless, the significant relationship between elevation and the δ^{18}O of plant forage suggests that the oxygen isotope chemistry of prey taxa such as mule deer found in Mesa Verde faunal assemblages may assist in sourcing prey to hunting locals.



[1.5-column fitting image]

Figure 07. δ^{18}O ranges from Mesa Verde' main zones: a) All plant samples; b) Sage samples only.



[1-column fitting image]

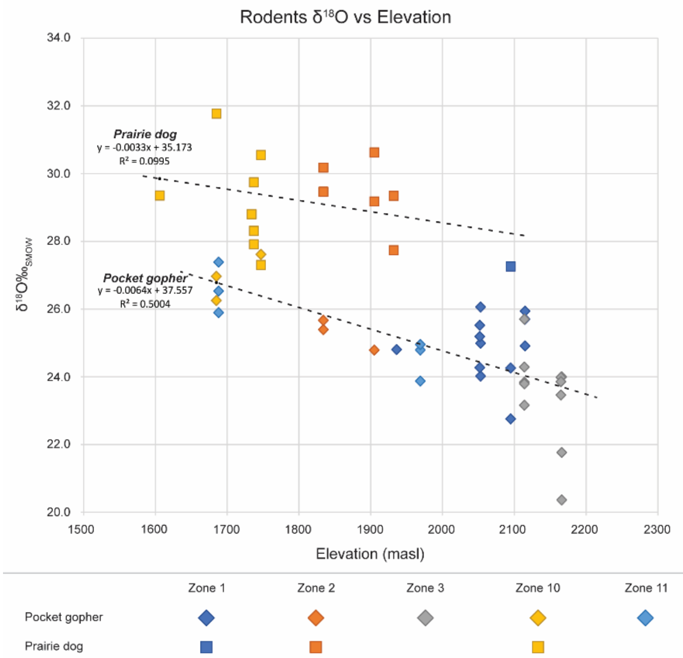
Figure 08. Mesa Verde, δ18O vs elevation : a) All plant samples; b) Sage samples only.

6.2.2 Rodents $\delta^{18}O$

In order to determine the oxygen isotope chemistry of vegetation near archaeological sites of interest, we analysed the mandibular or maxillary bone fragments of 15 prairie dogs (*Cynomys*) and 35 pocket gophers (the latter variously identified as *Thomomys bottae* [n=5], *Thomomys sp* [n=22], or *Geomyidea* [n=8]). Prairie dogs exhibited a $\delta^{18}O_{VSMOW}$ range of 27.3-31.8‰ and mean of 29.2 ± 1.3‰, whereas pocket gophers were significantly depleted in $\delta^{18}O$ (t=2.042, p<0.001) with a distinct range of 20.4-27.4‰ and mean of 24.8 ± 1.5‰ (Fig. 9).

Although small rodent $\delta^{18}O$ values are significantly correlated with site elevation (R^2=0.5138, F=50.728, df=49, p<0.001), it is clear in Fig. 9 that elevation is not the sole determining factor in prairie dog versus pocket gopher oxygen isotope chemistry since both taxa are commonly found at elevations below 2100 masl. Instead, we argue that feeding ecology is the primary driver of mean differences in rodent $\delta^{18}O$. Prairie dogs feed nearly exclusively on above ground grasses and small seeds, occasionally taking insects in the process

(Lomolino and Smith, 2003; Longhurst, 1944, p. 33; Weltzin et al., 1997, p. 254), whereas pocket gophers are primarily reliant on subterranean roots and tubers, at times pulling stems of young vegetation into their burrows (Foster and Stubbendieck, 1980; Reichman and Smith, 1985). During feeding prairie dogs ingest highly fractionated, preformed (leaf) water enriched in $\delta^{18}O$ (Bryant and Froelich, 1995; Fricke and O'Neil, 1996) largely meeting their moisture requirements through intake of above ground herbaceous plants. In contrast pocket gophers are heavily reliant on moisture derived from subterranean roots and tubers. Due to fractionation during respiration, roots are depleted in $\delta^{18}O$ relative to soil moisture (e.g., Angert and Luz, 2001) and both roots and tubers are not subject to atmospheric evapotranspiration, thus exhibiting depleted $\delta^{18}O$ relative to preformed (leaf) waters as illustrated by pocket gopher oxygen isotopic values.



[1-column fitting image]

Figure 09. Mesa Verde, Rodents $\delta^{18}O$ vs elevation.

Sorting by taxon, pocket gophers span an elevational range of 1685-2166 masl and exhibit $\delta^{18}O$ values significantly correlated with elevation (R^2=0.5004, F=33.052, df=34, p<0.000). Although prairie dogs span a nearly identical range, 1606-2095 masl, most cluster between 2000-1700 m in elevation and their $\delta^{18}O$ values are not similarly correlated

(R^2=0.0995, F=1.436, df=14, p=0.25) (Fig. 9). A larger prairie dog sample would be needed to further examine this relationship.

Ironically, reported preformed (leaf) water $\delta^{18}O$ with a mean of 30.1‰ is within less than a per mil of prairie dog oxygen isotope chemistry (29.2‰) suggesting that above ground feeding, small rodent, bone hydroxyapatite $\delta^{18}O$ can provide a reasonably accurate estimate of the elevation of feeding locations if the species chosen is present over a broad elevational range.

6.3 Sr- vs O-isotope data

The main objective of this paper is to define variations in isotopic signatures correlated with distinct regions. There are some apparent trends thanks to the Sr isotope data, but the combination with O isotope data does not enable us to isolate any additional regions (Figs. 7 and 9). However, for the latter, certain correlations with elevation seem to be relatively significant, which could be decisive for specific situations.

For instance, while considering as non-local all samples whose Sr isotope measurement fall outside the McElmo Dome interval, on the basis of our sampling and in the area that we are studying, it would seem that, the more a $^{87}Sr/^{86}Sr$ value is distant from this interval, the more the sample analysed is likely to come from further distances. Among the surrounding potential distant source areas, meaning regions containing few known villages during this time period (Varien et al. 1996) that likely have provided large game hunting opportunities for instance, appear the Dolores River area, La Plata and San Miguel Mountains to the west and northwest, and perhaps the Sleeping Ute Mountain and areas to the southwest. In fact, a recent study combining the concept of maize niche modeling with isotopic data suggests the La Plata Mountains as areas of origin of the majority of the deer consumed at Chaco Canyon at that time (Grimstead et al. 2019). Among these regions, the La Plata and San Miguel Mountains could be identified as a probable area of origin for faunal samples whose $^{87}Sr/^{86}Sr$ is higher than 0.71050 (Fig.03b).

Furthermore, for very low Sr isotopic ratios, less than 0.70821, there is a non-negligible probability that the analyzed samples come from areas located on or very close to igneous rock centers. In such cases, these centers may correspond to sectors located at the top of La Plata Mountains in the east, of the Sleeping Ute Mountain in the south, or even of the more distant Abajo Mountains in the north-west. The oxygen isotope data, in these scenarios, seem to be able to support those of the strontium isotopes. The $\delta^{18}O$ from plant forage correlate with elevation. A depletion in their $\delta^{18}O$ values is recorded with increasing altitude. This observation leads us to think that the measurement of low $\delta^{18}O$ on artiodactyl samples featuring low $^{87}Sr/^{86}Sr$ values could still suggest as potential provenance, one of these high-altitude regions located outside the local inter-village area. Here, the combination of Sr and O isotopic values seems to distinguish certain high-altitude regions from others, which may be decisive to source large game.

However, at the local scale, the combination of the two methods seems less complementary. The area encompassing the four main archaeological sites of our study has a relatively tight strontium isotopic signature comprised between 0.70934 and 0.70956. All the samples collected within 5 km of the sites, except one, as well as five of the fifteen samples selected within a radius of 5-10 km feature a $^{87}Sr/^{86}Sr$ ratio that fall in this range. This pattern means that small game locally domesticated and/or procured are not likely to give multiple different strontium signatures. In this scenario, that would make difficult to distinguish potential exchanges at the inter-village and sub-regional scales.

Because the sites within this area are located at various altitudes, we might expect $\delta^{18}O$ data proving to be decisive by making it possible to distinguish certain local variations linked to the topography. We have indeed shown with $\delta^{18}O$ obtained from rodents that, for a given taxon, correlations exist between these values and site elevation in the entire study area. At present, the $\delta^{18}O$ data measured on rodents in this local region does not enable us to differentiate the sites of provenance of these samples; the correlation with altitude being not that marked in this restricted area (Fig. 9). Conversely, it seems more the case within other areas such as zones 2 and 11, and possibly even 3 to a lesser extent. The non-correlation within zone 1 is perhaps due to our sampling which needs to be more extensive. The analysis of turkeys in the second part of our project should provide us with additional new data.

7. Conclusion and perspectives

The present isotopic data from 55 rodents and 94 plants samples collected the Mesa Verde and McElmo Dome regions clearly show trends in bioavailable Sr across the Mesa Verde landscape. The lower $^{87}Sr/^{86}Sr$ values are synonymous with areas composed of igneous rock, while the highest values correspond for the most part to the San Juan Mountains. Moreover, the McElmo Dome Interval associated with sites under study, is represented by a uniquely narrow range of Sr values suggesting prey acquired outside a 10 km foraging range from such sites will be identifiable. Although plant oxygen isotope data did not further differentiate specific zones within the study area, the significant correlation of plant $\delta^{18}O$ with elevation will be useful in examining large game hunting strategies.

Thus, the first phase of our project on social transformations in the Mesa Verde Region of the US Southwest (AD 750-1280) by isotopic zooarchaeology involved documentation of a bioavailable strontium and oxygen isotopic baseline as presented here. The geological variability of this region suggests that Sr isotopic signatures may differentiate likely animal procurement sources. As noted, it seems possible to isolate certain regions of the study area based on their $^{87}Sr/^{86}Sr$ ratios, particularly the La Plata Mountains. Almost all enriched Sr isotope ratios were measured on samples from this region. Furthermore, we also report that the lowest $^{87}Sr/^{86}Sr$ values were measured on samples collected in areas featuring Cretaceous and/or Tertiary igneous rocks. These distinctions will be significant in cases where analysed faunal express Sr values outside the McElmo Dome Interval.

Moreover, plant $\delta^{18}O$ data are correlated with altitude, especially strongly when separated by taxon. Thus, the relationship between elevation and $\delta^{18}O$, observed in plant forage, will provide a second assessment of prey taxa provenances. Concerning the rodents, it appears that differences in feeding ecology, not geolocation, are the main driver of patterning. At similar elevation, prairie dogs that feed nearly exclusively on above ground grasses and small seeds feature higher $\delta^{18}O$ values than pocket gophers relying on subterranean roots and tubers, a finding that may prove useful in future studies that rely on small mammal isotope chemistry. Finally, we note that this study expands upon a database of isotopic signatures for the American Southwest and in particular the San Juan Basin and its surroundings.

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CRediT authorship contribution statement

Jacques Burlot: Conceptualization, Formal analysis, Investigation, Writing - Original Draft, Writing - Review & Editing, Visualization, Supervision; **Karen Schollmeyer**: Conceptualization, Resources, Writing - Review & Editing, Funding acquisition; **Virginie Renson**: Conceptualization, Methodology, Validation, Investigation, Writing - Review & Editing, Funding acquisition; **Joan Brenner-Coltrain**: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Writing - Review & Editing, Funding acquisition; **Jeffrey R. Ferguson**: Conceptualization, Resources, Writing - Review & Editing, Project administration, Funding acquisition; **Amanda Werlein**: Investigation, Writing - Review & Editing

Appendix A. Supplementary data

The following are the Supplementary data to this article:

Text S1. Geology of the Mesa Verde region. → See Word file "MV_Isotopic_Baseline_Text.S1".

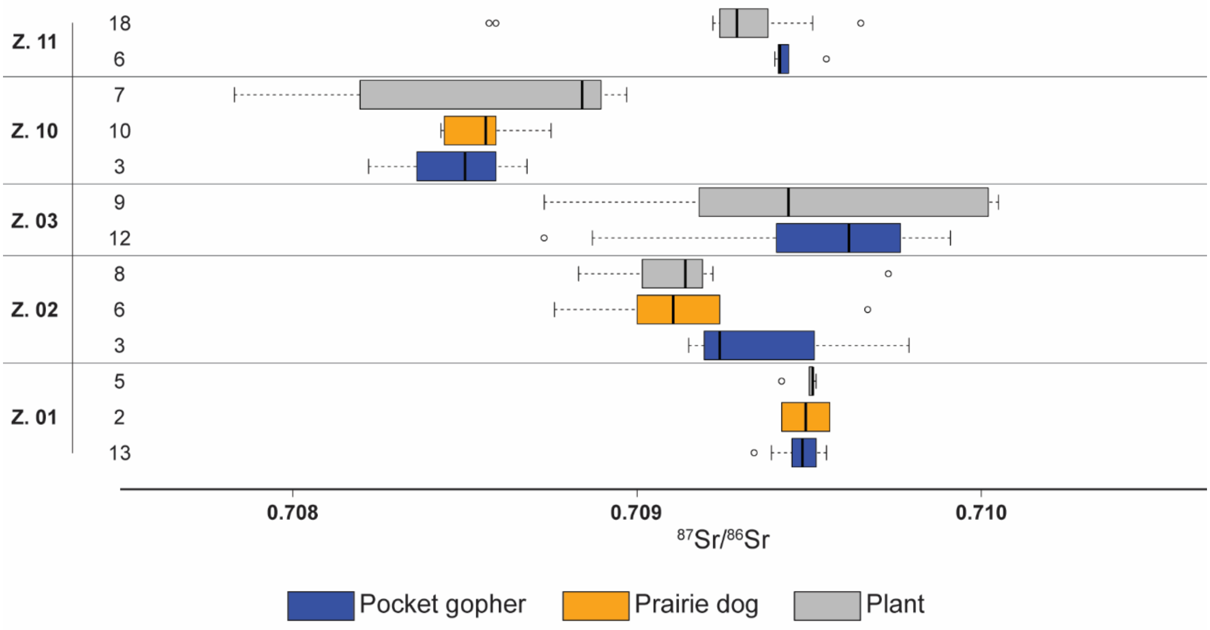

Figure S1. $^{87}Sr/^{86}Sr$ ranges of pocket gophers, prairie dogs and plants from the Mesa Verde region classified by common zones.

Table S1. Geographic, geologic, and Sr- and O-isotopic data of rodents and plants from the Mesa Verde region. → See Excel file "MV_Isotopic_Baseline_Tab.S1".

References

Ahlstrom, R.V.N., Van West, C.R., Dean, J.S., 1995. Environmental and Chronological Factors in the Mesa Verde-Northern Rio Grande Migration. J. Anthropol. Archaeol. 14, 125–142. https://doi.org/10.1006/jaar.1995.1007

Alvard, M.S., Robinson, J.G., Redford, K.H., Kaplan, H., 1997. The Sustainability of Subsistence Hunting in the Neotropics. Conserv. Biol. 11 (4), 977–982. https://doi.org/10.1046/j.1523-1739.1997.96047.x

Angert, A., Luz, B., 2001. Fractionation of oxygen isotopes by root respiration: Implications for the isotopic composition of atmospheric O_2. Geochim. Cosmochim. Acta 65, 1695–1701. https://doi.org/10.1016/S0016-7037(01)00567-1

Baxter, M., 2015. Spatial K-Means Clustering in Archaeology–Variations on a Theme. https://www.academia.edu/18142974/Spatial_k-means_clustering_in_archaeology_–_variations_on_a_theme (accessed 18 June 2021).

Bradfield, M., 1971. The Changing Pattern of Hopi Agriculture. Royal Anthropological Institute of Great Britain and Ireland, London.

Benson, L.V., 2010. Who provided maize to Chaco Canyon after the mid-12th-century drought?. J. Archaeol. Sci. 37, 621–629. https://doi.org/10.1016/j.jas.2009.10.027

Benson, L.V., 2012. Development and application of methods used to source prehistoric Southwestern maize: a review. J. Archaeol. Sci. 39, 791–807. https://doi.org/10.1016/j.jas.2011.08.022

Benson, L.V., Grimstead, D.N., 2019. Prehistoric Chaco Canyon, New Mexico: Residential population implications of limited agricultural and mammal productivity. J. Archaeol. Sci. 108, 104791. https://doi.org/10.1016/j.jas.2019.104971

Benson, L.V., Cordell, L., Vincent, K., Taylor, H., Stein, J., Farmer, G.L., Futa, K., 2003. Ancient maize from Chacoan great houses: Where was it grown?. Proc. Natl. Acad. Sci. 100 (22), 13111–13115. www.pnas.org/cgi/doi/10.1073/pnas.2135068100

Benson, L.V., Stein, J., Taylor, H., Friedman, R., Windes, T.C., 2006. The agricultural productivity of Chaco Canyon and the source(s) of pre-Hispanic maize found in Pueblo Bonito, in: Staller, J., Tykot, R., Benz, B. (Eds.), Histories of Maize. Elsevier, New York, pp. 289–314. https://doi.org/10.1016/b978-012369364-8/50273-4

Benson, L.V., Taylor, H.E., Peterson, K.A., Shattuck, B.D., Ramotnik, C.A., Stein, J.R., 2008. Development and evaluation of geochemical methods for the sourcing of archaeological maize. J. Archaeol. Sci. 35, 912–921. https://doi.org/10.1016/j.jas.2007.06.018

Benson, L.V., Stein, J.R., Taylor, H.E., 2009. Possible sources of archaeological maize found in Chaco Canyon and Aztec Ruin, New Mexico. J. Archaeol. Sci. 36, 387–407. https://doi.org/10.1016/j.jas.2008.09.023

Benson, L.V., Grimstead, D.N., Stein, J.R., Roth, D.A., Plowman, T.I., 2019. Prehistoric Chaco Canyon, New Mexico: Importation of meat and maize. J. Archaeol. Sci. 111, 105015. https://doi.org/10.1016/j.jas.2019.105015

Bentley, R.A., 2006. Strontium Isotopes from the Earth to the Archaeological Skeleton: A Review. J. Archaeol. Method Theory 13 (3), 135–187. https://doi.org/10.1007/s10816-006-9009-x

Bryant, J.D., Froelich, P.N., 1995. A Model of Oxygen Isotope Fractionation in Body Water of Large Mammals. Geochim. Cosmochim. Acta 59 (21), 4523–4537. https://doi.org/10.1016/0016-7037(95)00250-4

Capo, R.S., Stewart, B.W., Chadwick, O.A., 1998. Strontium isotopes as tracers of ecosystem processes: theory and methods. Geoderma 82 (1–3), 197–225. https://doi.org/10.1016/S0016-7061(97)00102-X

Chisholm, M., 1968. Rural Settlement and Land Use. Hutchinson and Co., London.

Coplen, T.B., Kendall, C., Hopple, J., 1983. Comparison of stable isotope reference samples. Nat. 302, 236–238. https://doi.org/10.1038/302236a0

Cordell, L.S., Toll, H.W., Toll, M.S., Windes, T.C., 2008. Archaeological corn from Pueblo Bonito, Chaco Canyon, New Mexico: dates, contexts, sources. Am. Antiq. 73 (3), 491–511. https://doi.org/10.1017/S0002731600046837

Crown, P.L., Orcutt, J., Kohler, T.A., 1994. Pueblo Cultures in Transition: The Northern Rio Grande, in: Adler, M. (Ed.), The Prehistoric Pueblo World: A.D. 1150–1350. University of Arizona Press, Tucson, pp. 188–204.

D’Angela, C., Longinelli, A., 1990. Oxygen Isotopes in Living Mammal’s Bone Phosphate: Further Results. Chem. Geol. 86 (1), 75–82. https://doi.org/10.1016/0168-9622(90)90007-Y

Daux, V., Lécuyer, C. Adam, F., Martineau, F., Vimeux, F., 2005. Oxygen Isotope Composition of Human Teeth and the Record of Climate Change in France (Lorraine) During the Last 1700 Years. Clim. Change 70, 445–464. https://doi.org/10.1007/s10584-005-5385-6

Dennell, R., 1980. The Use, Abuse, and Potential of Site Catchment Analysis. Anthropol. UCLA 10 (1–2), 1–20.

De Muynck, D., Huelga-Suarez, G., Van Heghe, L., Degryse, P., Vanhaecke, F., 2009. Systematic evaluation of a strontium-specific extraction chromatographic resin for obtaining a purified Sr fraction with quantitative recovery from complex and Ca-rich matrices. J. Anal. Atomic Spectrom. 24, 1498–1510. https://doi.org/10.1039/b908645e

Driver, J.C., 2002. Faunal Variation and Change in the Northern San Juan Region, in: Varien, M.D., Wilshusen, R.H. (Eds.), Seeking the Center Place: Archaeology and Ancient Communities in the Mesa Verde Region. University of Utah Press, Salt Lake City, pp. 143–160.

Driver, J.C., 2010. Human Impacts on Animal Populations in the American Southwest, in: Nelson, M.C., Strawhacker, C. (Eds.), Movement, Connectivity, and Landscape Change in the Ancient Southwest. University Press of Colorado, Boulder, pp. 339–390.

English, N.B., Betancourt, J.L., Dean, J.S., Quade, J., 2001. Strontium isotopes reveal distant sources of architectural timber in Chaco Canyon, New Mexico. Proc. Natl. Acad. Sci. 98 (21), 11891–11896. https://doi.org/10.1073/pnas.211305498

Ericson, J.E., 1985. Strontium Isotope Characterization in the Study of Prehistoric Human Ecology. J. Hum. Evol. 14, 503–514. https://doi.org/10.1016/S0047-2484(85)80029-4

Evans, J., Pearson, M.K., Madgwick R., Sloane, H., Albarella, U., 2019. Strontium and oxygen isotope evidence for the origin and movement of cattle at Late Neolithic Durrington Walls, UK. Archaeol. Anthropol. Sci. 11, 5181–5197. https://doi.org/10.1007/s12520-019-00849-w

Everitt, B.S., Landau, S., Leese, M., Stahl, D., 2011. Cluster Analysis, fifth ed. Wiley, London.

Faure, G., 1986. The Rb-Sr Method of Dating, in: Faure, G. (Ed.), Principles of Isotope Geology, second ed. Wiley and Sons, New York, pp. 117–140.

Foster, M.A., Stubbendieck, J., 1980. Effects of the plains pocket gopher (Geomys bursarius) on rangeland. J. Range Manag. 33, 74–78.

Fricke, H.C., O'Neil, J.R., 1996. Inter- and Intra-Tooth Variation in the Oxygen Isotope Composition of Mammalian Tooth Enamel Phosphate: Implications for Palaeoclimatological and Palaeobiological Research. Palaeogeogr., Palaeoclimatol., Palaeoecol. 126 (1–2), 91–99. https://doi.org/10.1016/S0031-0182(96)00072-7

Fricke, H.C., O'Neil, J.R., 1999. The Correlation Between $^{18}O/^{16}O$ Ratios of Meteoric Water and Surface Temperature: Its Use in Investigating Terrestrial Climatic Change Over Geologic Time. Earth Planet. Sci. Lett. 170 (3), 181–196. https://doi.org/10.1016/S0012-821X(99)00105-3

Fricke, H.C., O'Neil, J.R., Lynnerup, N., 1995. Oxygen Isotope Composition of Human Tooth Enamel from Medieval Greenland: Linking Climate and Society. Geol. 23 (10), 869–872. https://doi.org/10.1130/0091-7613(1995)023<0869:SROICO>2.3.CO;2

Grimstead, D.N., Buck, S.M., Vierra, B.J., Benson, L.V., 2015. Another possible source of archeological maize found in Chaco Canyon, NM: The Tohatchi Flats area, NM, USA. J. Archaeol. Sci. Rep. 3, 181–187. https://doi.org/10.1016/j.jasrep.2015.06.003

Grimstead, D.N., Quade, J., Stiner, M.C., 2016a. Isotopic evidence for long-distance mammal procurement, Chaco Canyon, New Mexico, USA. Geoarchaeol. Int. J. 31 (5), 335–354. https://doi.org/10.1002/gea.21545

Grimstead, D.N., Reynolds, A.C., Hudson, A.M., Akins, N.J., Betancourt, J.L., 2016b. Reduced population variance in strontium isotope ratios informs domesticated turkey use at Chaco Canyon, New Mexico, USA. J. Archaeol. Method Theory 23 (1), 127–149. https://doi.org/10.1007/s10816-014-9228-5

Grimstead, D.N., Pailes, M.C., Bocinsky, R.K., 2019. Refining potential source regions via combined maize niche modeling and isotopes: A case study from Chaco Canyon, NM, USA. J. Archaeol. Method Theory 26 (1), 25–51. https://doi.org/10.1007/s10816-017-9359-6

Gumerman, G.J., Swedlund, A.C., Dean, J.S., Epstein, J.M., 2003. The Evolution of Social Behavior in the Prehistoric American Southwest. Artif. Life 9 (4), 435–444. https://doi.org/10.1162/106454603322694861

Hamilton, M.I., Drake, B.L., Wills, W.H., Jones, E.L., Conrad, C., Crown, P.L., 2018. Stable oxygen isotope sourcing of archaeological fauna from Chaco Canyon, New Mexico. Am. Antiq. 83 (1), 163–175. https://doi.org/10.1017/aaq.2017.61

Hart, J.A., 2000. The Impact and Sustainability of Indigenous Hunting in the Ituri Forest, Congo-Zaire: A Comparison of Unhunted and Hunted Duiker Populations, in: Robinson, J.G., Bennett, E.L. (Eds.), Hunting for Sustainability in Tropical Forests. Columbia University Press, New York, pp. 106–153.

Hedman, K.M., Brandon, B.B., Johnson, T.M., Fullagar, P.D., Emerson, T.E., 2009. Variation in Strontium Isotope Ratios of Archaeological Fauna in the Midwestern United States: A Preliminary Study. J. Archaeol. Sci. 36, 64–73. https://doi.org/10.1016/j.jas.2008.07.009

Herhahn, C.L., Hill, J.B., 1998. Modeling Agricultural Production Strategies in the Northern Rio Grande Valley, New Mexico. Hum. Ecol. 1998 (3), 469–487. https://doi.org/10.1023/A:1018760316892

Higgs, E.S., Vita-Finzi, C., 1972. Prehistoric Economies: A Territorial Approach, in: Higgs, E.S. (Ed.), Papers in Economic Prehistory. Cambridge University Press, Cambridge, pp. 27–36.

Hill, K., Padwe, J., 2000. Sustainability of Ache Hunting in the Mbaracayu Reserve, Paraguay, in: Robinson, J.G., Bennett, E.L. (Eds.), Hunting for Sustainability in Tropical Forests. Columbia University Press, New York, pp. 79–105.

Hill, K., Padwe, J., Bejyvagi, C., Bepurangi, A., Jakugi, F., Tykuarangi, R., Tykuarangi, T., 1997. Impact of Hunting on Large Vertebrates in the Mbaracayu Reserve, Paraguay. Conserv. Biol. 11 (6), 1339–1353. https://doi.org/10.1046/j.1523-1739.1997.96048.x

Hodell, D.A., Quinn, R.L., Brenner, M., Kamenov, G., 2004. Spatial variation of strontium isotopes ($^{87}Sr/^{86}Sr$) in the Maya region: a tool for tracking ancient human migration. J. Archaeol. Sci. 31, 585–601. https://doi.org/10.1016/j.jas.2003.10.009

Hoppe, K.A., 2006. Correlation Between the Oxygen Isotope Ratio of North American Bison Teeth and Local Waters: Implications for Paleoclimatic Reconstructions. Earth Planet. Sci. Lett. 244 (1–2), 408–417. https://doi.org/10.1016/j.epsl.2006.01.062

Hudspeth, W.B., 2000. The Evolutionary Ecology of Behavioral Response to Risk among Prehistoric Agriculturalists of the Lower Rio Chama, New Mexico, Unpublished PhD Thesis, Anthropology, University of New Mexico, University Microfilms, Ann Arbor.

Iacumin, P., Bocherens, H., Mariotti, A., Longinelli, A., 1996. Oxygen Isotope Analysis of Co-Existing Carbonate and Phosphate in Biogenic Apatite: A Way to Monitor Diagenetic Alteration of Bone Phosphate?. Earth Planet. Sci. Lett. 142 (1–2), 1–6. https://doi.org/10.1016/0012-821X(96)00093-3

Johnson, C.D., Kohler, T.A., Cowan, J., 2005. Modeling Historical Ecology, Thinking About Contemporary Systems. Am. Anthropol. 107, 96–107. https://doi.org/10.1525/aa.2005.107.1.096

Judge, J., 1989. Chaco Canyon - San Juan Basin, in: Cordell, L.S., Gumerman, G.J. (Eds.), Dynamics of Southwest Prehistory. Smithsonian Institution Press, Washington D.C., pp. 209–262.

Kay, C.E., 1994. Aboriginal Overkill: The Role of Native Americans in Structuring Western Ecosystems. Hum. Nat. 5 (4), 359–398. https://doi.org/10.1007/BF02734166

Knight, J.E., 2005. Controlling Pocket Gophers in New Mexico. Cooperative Extension Service Guide L-109. New Mexico State University, Las Cruces.

Kohler, T.A., 1992. Field Houses, Villages, and the Tragedy of the Commons in the Early Northern Anasazi Southwest. Am. Antiq. 57 (4), 617–635. https://doi.org/10.1017/S0002731600054767

Kohler, T.A., Orcutt, J.D., Peterson, K.L., Blinman, E., 1986. Anasazi Spreadsheets: The Cost of Doing Agricultural Business in Prehistoric Dolores, in: Breternitz, D.A., Robinson, C.K., Gross, G.T. (Eds.), Dolores Archaeological Program: Final Synthesis Report. Bureau of Reclamation, Engineering and Research Center, Denver, pp. 525–538.

Kuckelman, K.A., 2010. The Depopulation of Sand Canyon Pueblo, a Large Ancestral Pueblo Village in Southwestern Colorado. Am. Antiq. 75 (3), 497–525. https://www.jstor.org/stable/25766213

Laffoon, J.E., Davies, G.R., Hoogland, M.L.P., Hofman, C.L., 2012. Spatial Variation of Biologically Available Strontium Isotopes ($^{87}Sr/^{86}Sr$) in an Archipelagic Setting: A Case Study from the Caribbean. J. Archaeol. Sci. 39, 2371–2384. https://doi.org/10.1016/j.jas.2012.02.002

Lightfoot, R.R., Kuckelman, K.A., 2001. A Case of Warfare in the Mesa Verde Region, in: LeBlanc, S.A., Rice, G.E. (Eds.), Deadly Landscapes: Case Studies in Prehistoric Southwestern Warfare. University of Utah Press, Salt Lake City, pp. 51–64.

Lipe, W.D., 1995. The Depopulation of the Northern San Juan: Conditions in the Turbulent 1200s. J. Anthropol. Archaeol. 14, 143–169. https://doi.org/10.1006/jaar.1995.1008

Lipe, W.D., Varien, M.D., 1999a. Pueblo II (A.D. 900–1150), in: Lipe, W.D., Varien, M.D., Wilshusen, R.H. (Eds.), Colorado Prehistory: A Context for the Southern Colorado River Basin. Colorado Council of Professional Archaeologists, Denver, pp. 242–289.

Lipe, W.D., Varien, M.D., 1999b. Pueblo III (A.D. 1150–1300), in: Lipe, W.D., Varien, M.D., Wilshusen, R.H. (Eds.), Colorado Prehistory: A Context for the Southern Colorado River Basin. Colorado Council of Professional Archaeologists, Denver, pp. 290–352.

Lomolino, M.V., Smith, G.A., 2003. Prairie dog towns as islands: Applications of island biogeography and landscape ecology for conserving nonvolant terrestrial vertebrates. Glob. Ecol. Biogeogr. 12, 275–286. https://doi.org/10.1046/j.1466-822X.2003.00041.x

Longhurst, W., 1944. Observations of the ecology of the Gunnison prairie dog in Colorado. J. Mammal. 25, 24–36. https://doi.org/10.2307/2424208

Martin, P.S., Szuter, C.R., 1999. War Zones and Game Sinks in Lewis and Clark's West. Conserv. Biol. 13 (1), 36–45. https://doi.org/10.1046/j.1523-1739.1999.97417.x

Minnis, P.E., 1985. Social Adaptation to Food Stress: A Prehistoric Southwestern Example. University of Chicago Press, Chicago.

Mittermeier, R.A., 1991. Hunting and Its Effect on Wild Primate Populations in Suriname, in: Robinson, J.G., Redford, K.H. (Eds.), Neotropical Wildlife Use and Conservation. University of Chicago Press, Chicago, pp. 93–107.

Naiman, Z., Quade, J., Patchett, P.J., 2000. Isotopic evidence for eolian recycling of pedogenic carbonate and variations in carbonate dust sources throughout the southwest United States. Geochim. Cosmochim. Acta 64 (18), 3099–3109. https://doi.org/10.1016/S0016-7037(00)00410-5

Novaro, A.J., Redford, K.H., Bodmer, R.E., 2000. Effect of Hunting in Source-Sink Systems in the Neotropics. Conserv. Biol. 14 (3), 713–721. http://dx.doi.org/10.1046/j.1523-1739.2000.98452.x

Ortman, S.G., Varien, M.D., Gripp, T.L. 2007. Empirical Bayesian Methods for Archaeological Survey Data: An Application from the Mesa Verde Region. Am. Antiq. 72, 241–272. https://doi.org/10.2307/40035813

Pederzani, S., Britton, K., 2019. Oxygen isotopes in bioarchaeology: Principles and applications, challenges and opportunities. Earth-Sci. Rev. 188, 77–107. https://doi.org/10.1016/j.earscirev.2018.11.005

Peres, C.A., Nascimento, H.S., 2006. Impact of Game Hunting by the Kayapó of South-Eastern Amazonia: Implications for Wildlife Conservation in Tropical Forest Indigenous Reserves. Biodivers. Conserv. 15, 2627–2653. https://doi.org/10.1007/s10531-005-5406-9

Pigage, J.C., Pigage, H.K., 2010. Summer Activity Pattern and Home Range of Northern Pocket Gophers in an Alfalfa Field. Prairie Nat. 42, 142–144.

Price, T.D., Frei, R., Brinker, U., Lidke, G., Terberger, T., Frei, K.M., Jantzen, D., 2019. Multi-isotope proveniencing of human remains from a Bronze Age battlefield in the Tollense Valley in northeast Germany. Archaeol. Anthropol. Sci. 11, 33–49. https://doi.org/10.1007/s12520-017-0529-y

Redman, C.L., 1999. Human Impact on Ancient Environments. The University of Arizona Press, Tucson.

Reheis, M.C., Goldstein, H.L., Reynolds, R.L., Forman, S.L., Mahan, S. A., Cararra, P.E., 2018. Late Quaternary loess and soils on uplands in the Canyonlands and Mesa Verde areas, Utah and Colorado. Quat. Res. 89 (3), 718–738. https://doi:10.1017/qua.2017.63

Reichman, O.J., Smith, S.C., 1985. Impact of pocket gopher burrows on overlying vegetation. J. Mammal. 66, 720–725. https://doi.org/10.2307/1380798

Renson, V., Navarro-Castillo, M., Cucina, A., Culleton, B. J., Kennett, D. J., Neff, H., 2019. Origin and Diet of Inhabitants of the Pacific Coast of Southern Mexico during the Classic Period - Sr, C, and N Isotopes. J. Archaeol. Sci. Rep. 27, 101981 https://doi.org/10.1016/j.jasrep.2019.101981

Reynolds, A.C., Betancourt, J.L., Quade, J., Patchett, P.J., Dean, J.S., Stein, J., 2005. $^{87}Sr/^{86}Sr$ sourcing of ponderosa pine used in Anasazi great house construction at Chaco Canyon, New Mexico. J. Archaeol. Sci. 32, 1061–1075. https://doi.org/10.1016/j.jas.2005.01.016

Schollmeyer, K.G., Driver, J.C., 2013. Settlement Patterns, Source-Sink Dynamics, and Artiodactyl Hunting in the Prehistoric U.S. Southwest. J. Archaeol. Method Theory 20, 448–478. https://doi.org/10.1007/s10816-012-9160-5

Slovak, N.M., Paytan, A., 2012. Applications of Sr Isotopes in Archaeology, in: Baskaran, M. (Ed.), Handbook of Environmental Isotope Geochemistry. Advances in Isotope Geochemistry, Springer, Berlin, pp. 743–768.

Szuter, C.R., 1991. Hunting by Hohokam Desert Farmers. Kiva 56 (3), 277–291. https://www.jstor.org/stable/30247277

Szuter, C.R., 2000. Gender and Animals: Hunting Technology, Ritual, and Subsistence, in: Crown, P.L. (Ed.), Women and Men in the Prehispanic Southwest: Labor, Power, and Prestige. School of American Research Press, Santa Fe, pp. 197–220.

Varien, M.D., 1999. Sedentism and Mobility in a Social Landscape: Mesa Verde and Beyond. University of Arizona Press, Tucson.

Varien, M.D., Lipe, W.D., Adler, M.A., Thompson, I.M., Bradley, B.A., 1996. Southwestern Colorado and Southeastern Utah Settlement Patterns: A.D. 1100 to 1300, in: Adler, M.A. (Ed.), The Prehistoric Pueblo World: A.D. 1150-1350. University of Arizona Press, Tucson, pp. 86–113.

Varien, M.D., Ortman, S.G., Kohler, T.A., Glowacki, D.M., Johnson, C.D., 2007. Historical Ecology in the Mesa Verde Region: Results from the Village Ecodynamics Project. Am. Antiq. 72, 273–299. https://doi.org/10.2307/40035814

Weltzin, J.F., Dowhower, S.L., Heitschmidt, R.K., 1997. Prairie dog effects on plant community structure in southern mixed-grass prairie. Southwest. Nat. 42, 251–258.

Wilcox, D.R., Haas, J., 1994, The Scream of the Butterfly: Competition and Conflict in the Prehistoric Southwest, in: Gumerman, G.J. (Ed.), Themes in Southwest Prehistory. School of American Research Press, Santa Fe, pp. 211–238.

Wilshusen, R.H., 1999a. Basketmaker III (A.D. 500–750), in: Lipe, W.D., Varien, M.D., Wilshusen, R.H. (Eds.) Colorado Prehistory: A Context for the Southern Colorado River Basin. Colorado Council of Professional Archaeologists, Denver, pp. 166–195.

Wilshusen, R.H., 1999b. Pueblo I (A.D. 750–900), in: Lipe, W.D., Varien, M.D., Wilshusen, R.H. (Eds.), Colorado Prehistory: A Context for the Southern Colorado River Basin. Colorado Council of Professional Archaeologists, Denver, pp. 196–241.