Why a Standardization of Strontium Isotope Baseline Environmental Data Is Needed and Recommendations for Methodology

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In archaeology, early applications of strontium isotope sourcing (isotopes of strontium include 87-strontium and 86-strontium expressed as a ratio of $^{87}Sr/^{86}Sr$) primarily focused on identifying local versus extra-local human skeletons (e.g., Ericson 1985; Ezzo et al. 1997; Price, Grupe, et al. 1994; Price, Johnson,

ABSTRACT

Since initial applications of strontium isotope human sourcing in the early 1990s, the use of the method has steadily increased in archaeology and in anthropology more broadly. Despite this trend, the collection of necessary baseline environmental data has not been standardized and sometimes does not occur at all. A thorough environmental sampling strategy will ensure that all the variability within a selected region is documented, which is a critical step to improving the accuracy of sourcing studies. Furthermore, shared strontium baseline data collections are needed to improve the intercomparability of datasets and results. This paper provides a case study from a semiarid region in northwestern New Mexico, USA, highlighting the need for a bottom-up approach to baseline data collection (from bedrock to animal) and describes the methods of pre-field planning and collecting, including rationales for what samples to collect for Sr isotope baseline data. The authors hope that this paper will lay a foundation for the implementation and standardization of Sr isotope baseline data collecting, which does not currently exist.

Desde las primeras aplicaciones del estudio de isótopos de estroncio para determinar la procedencia de restos humanos en la década de 1990, el uso de este método ha incrementado de manera constante en la arqueología y la antropología en general. A pesar de tal aumento, la colección de datos ambientales de referencia no ha sido estandarizada y a veces no ocurre. Una estrategia de muestreo ambiental exhaustiva garantiza que se documente toda la variabilidad dentro de una región, lo que es un paso crítico para mejorar la precisión de los estudios de procedencia. Además, es necesario mantener bases de datos de referencia compartidas para mejorar la comparabilidad de datos y resultados. En este artículo se presenta un estudio de caso desde la zona semiárida del noroeste de Nuevo México, EE.UU., donde se destaca la necesidad de un enfoque ascendente a la colección de datos de referencia, desde la roca madre hacia los animales. También se describen los métodos para la planificación pre-campo y la recolección de datos. Se describe el uso conjunto de las muestras de estroncio, oxígeno y carbono, y los factores que se deben considerar en la selección de muestras de referencia. No hay manera de reemplazar la formación en el campo con instrucción profesional; sin embargo, en caso que los nuevos practicantes no tengan acceso a este tipo de formación, esperamos que este artículo sirva como guía de campo.

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et al. 1994; Sealy et al. 1991, 1995). As the use of strontium isotopes increased, so too have the applications to a variety of archaeological materials. Looking at the *Journal of Archaeological Science* by decade, there is an exponential increase in the use of ^{87}Sr/^{86}Sr ratios as a sourcing tool (Figure 1). Everything from textiles (Benson et al. 2006) to food resources (Bendrey et al. 2009; Benson 2012; Grimstead, Quade, et al. 2016; Grimstead, Reynolds, et al. 2016; Koch et al. 1992) and architectural materials (Durand and Shelley 1999; English et al. 2001; Reynolds et al. 2005) has been sourced using ^{87}Sr/^{86}Sr ratios.

Despite becoming a standard and befitting method, few archaeologists conduct the extensive field collections that can provide greater confidence in the sourcing of archaeological materials. Benson's (2012) work in corn sourcing stands is an exceptional example to the contrary, along with others (e.g., Evans et al. 2009; Frei and Frei 2011; Kootker et al. 2016). Furthermore, plants and animals, including humans, metabolize Sr from a variety of sources (e.g., soil, dust, water, plants, etc.). By not establishing baseline minimum and maximum ^{87}Sr/^{86}Sr ratios within an environment and spatially across bedrock lithologies, the true variability can be significantly under- or overestimated (as demonstrated in the case study that follows). Such under- or overestimation can have significant impacts on archaeological interpretations. There is thus a need to standardize field collection activities to (1) obtain local and extra-local ^{87}Sr/^{86}Sr baseline ratios from modern materials, (2) collect sufficient samples to be confident that all the variability within a system and geologic region has been sampled, and (3) identify potentially problematic phenomena during sampling (e.g., rivers with extra-local origins, varying plant rooting depths, variation in animal home range sizes, etc.).

Capturing the total ^{87}Sr/^{86}Sr ratio variability among the local and nonlocal regions relative to a site is critical for sourcing interpretations. These ratios can vary considerably across a landscape, which is why ^{87}Sr/^{86}Sr ratios are used as a sourcing tool, but they can also vary considerably through the biogeochemical cycle. This latter point is demonstrated in a dust-derived strontium study from El Malpais National Monument, New Mexico, USA (Reynolds et al. 2012). While this was not the intent of their study, Reynolds and colleagues' (2012) data demonstrates that plant ^{87}Sr/^{86}Sr ratios may overlap with soil ratios, but may also look more like atmospheric dust on one end and bedrock on the other. Further complicating this scenario is the knowledge that some animals may obtain a significant quantity of bioavailable strontium directly from consumed soils and/or dust (Kohn et al. 2013). This means that animal ^{87}Sr/^{86}Sr ratios may not reflect the minimum or maximum ^{87}Sr/^{86}Sr ratios observed in consumed plants. Moreover, humans consuming these plants and animals will represent a mixture from all sources. Without thoroughly sampling the entire chain, these details could be missed, resulting in incorrect minimum and maximum ^{87}Sr/^{86}Sr ratios.

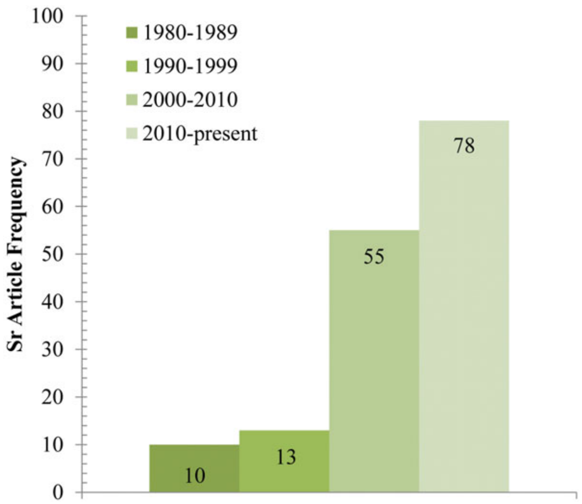

FIGURE 1. Frequency of publications in the *Journal of Archaeological Science* using, investigating, or discussing strontium as a sourcing tool, by decade.

^{87}Sr/^{86}Sr VARIABILITY THROUGH A SYSTEM

The Strontium System

Strontium (Sr) is a stable alkaline earth metal that substitutes for calcium in a variety of materials. ^{87}Sr/^{86}Sr ratios are useful as a sourcing tool because the ratios are time- and rock-type dependent. That is, rocks of various ages have unique ^{87}Sr/^{86}Sr ratios due to the radiogenic decay of ^{87}Rb to ^{87}Sr and inheritance of Sr at the time of mineral formation ($\lambda_{½} = 4.88 \times 10^{10}$ years). Generally speaking, ^{87}Sr/^{86}Sr ratios in vegetation reflect geographical variations in the ^{87}Sr/^{86}Sr of soil, dust, and water because plants metabolize Sr from these local sources (e.g., Capo et al. 1999; Graustein and Armstrong 1983; Reynolds et al. 2012; Sillen and Kavanagh 1982). Plants biometabolize Sr from slow chemical weathering of local substrates and/or shallow soils that contain varying quantities of carbonate rich sediments (Figure 2). The rooting depth and canopy structure of different plants largely control the biometabolic mixing of end members (Figure 2) (Reynolds et al. 2012). It should be noted that some animals do consume small quantities of soil and may obtain some bioavailable Sr directly from ingested soils, rather than solely from consumed plants and other animals (Beyer et al. 1994; Kohn et al. 2013). Airborne dust also contributes to the local measured soil ratios through the rest of the trophic system, which can contribute significant quantities of extra-local strontium, particularly in arid regions (Graustein and Armstrong 1983; Naiman and Quade 2000; Reynolds et al. 2012). Because there is no biological fractionation of strontium isotopes, animal and human bone and teeth chemically reflect the ^{87}Sr/^{86}Sr ratio of local soils, dust, consumed plants, meteoric waters, and other animals within their home range (Flockhart et al. 2015).

El Malpais Nutrient Source Case Study

Plant rooting depths and the sources of sediments from which the plant uptakes soil waters can vary based on plant rooting

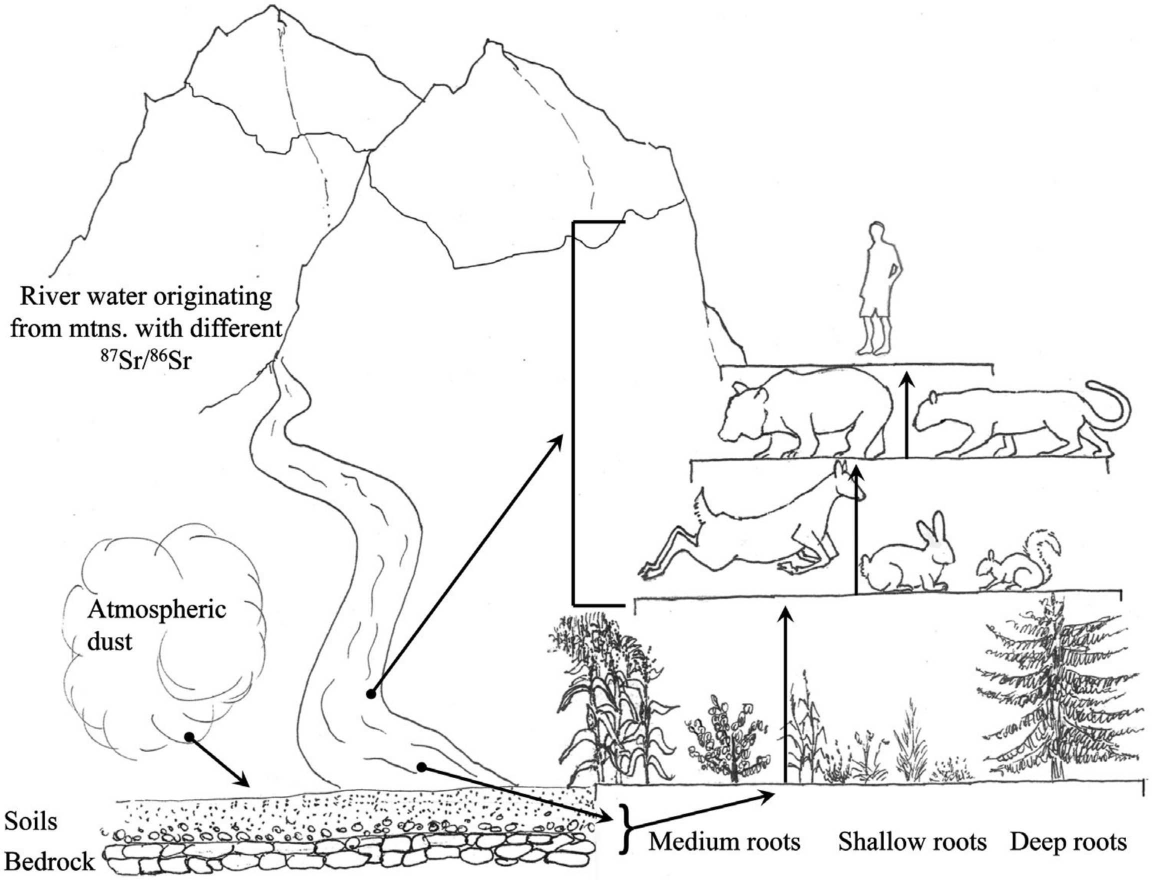

FIGURE 2. Sketch of the Sr system. Tiered structure represents averaging from sources below.

depth. Thus, animals and humans may be consuming plants and animals that have different ratios even when grown next to each other. This point is emphasized in the case study that follows, and it is for this reason that a standard field collection protocol is necessary that will be able to improve archaeological interpretations through better understanding of baseline variation.

During a nutrient source study, Reynolds and colleagues (2012) utilized previously published data (Capo and Chadwick 1999; Van der Hoven and Quade 2002) and measured ^{87}Sr/^{86}Sr ratios from trees, shrubs, grasses, bedrock, soils, and dust from three basalt flows of differing ages with varying stages of soil development in El Malpais National Monument, New Mexico, USA: McCarty's Flow (3 mya; Figure 3a), Bandera flow (9 mya; Figure 3b), and El Calderon Flow (120 mya; Figure 3c). The study area was a pinyon-juniper and ponderosa pine forest commingled with a variety of shrubs and grasses, all having varying rooting depths and different nutrient acquisition sources. In all scenarios, soils represent a mixture between eolian dust and rock ratios, but plant variation reflects rooting depth and canopy structure (Figure 3a-c). Tree ^{87}Sr/^{86}Sr ratios vary the most, owing to their deep root systems and broad canopy access to eolian inputs. Grasses from all basalt flows overlap with soil ^{87}Sr/^{86}Sr ranges, but also show mixing between dust and bedrock derived ratios, as does the bushy plant taxa.

This study highlights several important points for archaeologists undertaking environmental sampling for ^{87}Sr/^{86}Sr sourcing. First, collected modern samples should target the material in question. The above case study demonstrates that, if the sourcing of architectural timbers were to be undertaken, then the collection of soils and grasses would be insufficient for understanding the true range of ^{87}Sr/^{86}Sr ratios. It would also be important to sample each potential end member (bedrock, soil, and dust) to understand the mixing of nutrient sources. Secondly, plants draw on different nutrient sources, while animals and humans consume a variety of plant taxa depending on preference and availability. It is imperative to sample across this spectrum to ensure that the intraspecies variation is captured. For example, if sampling the Bandera or El Calderon flow (Figure 3b and 3c), exclusively measuring the ratios of bushy plants would not provide the true minimum and maximum ratios of grasses and trees. In all cases, sampling only soils, bedrock, and/or dust would not be an accurate gauge of the minimum and maximum values of the region and would greatly overestimate that range. Third, animals consume some quantity of soil and dust, which requires sampling of animals, as plant sampling would not accurately reflect the bioavailable Sr for animals and humans. Because human and animal diets represent a mixture of sources, it is imperative to completely sample across the environmental system to ensure that the complex mixing of nutrient sources is understood.

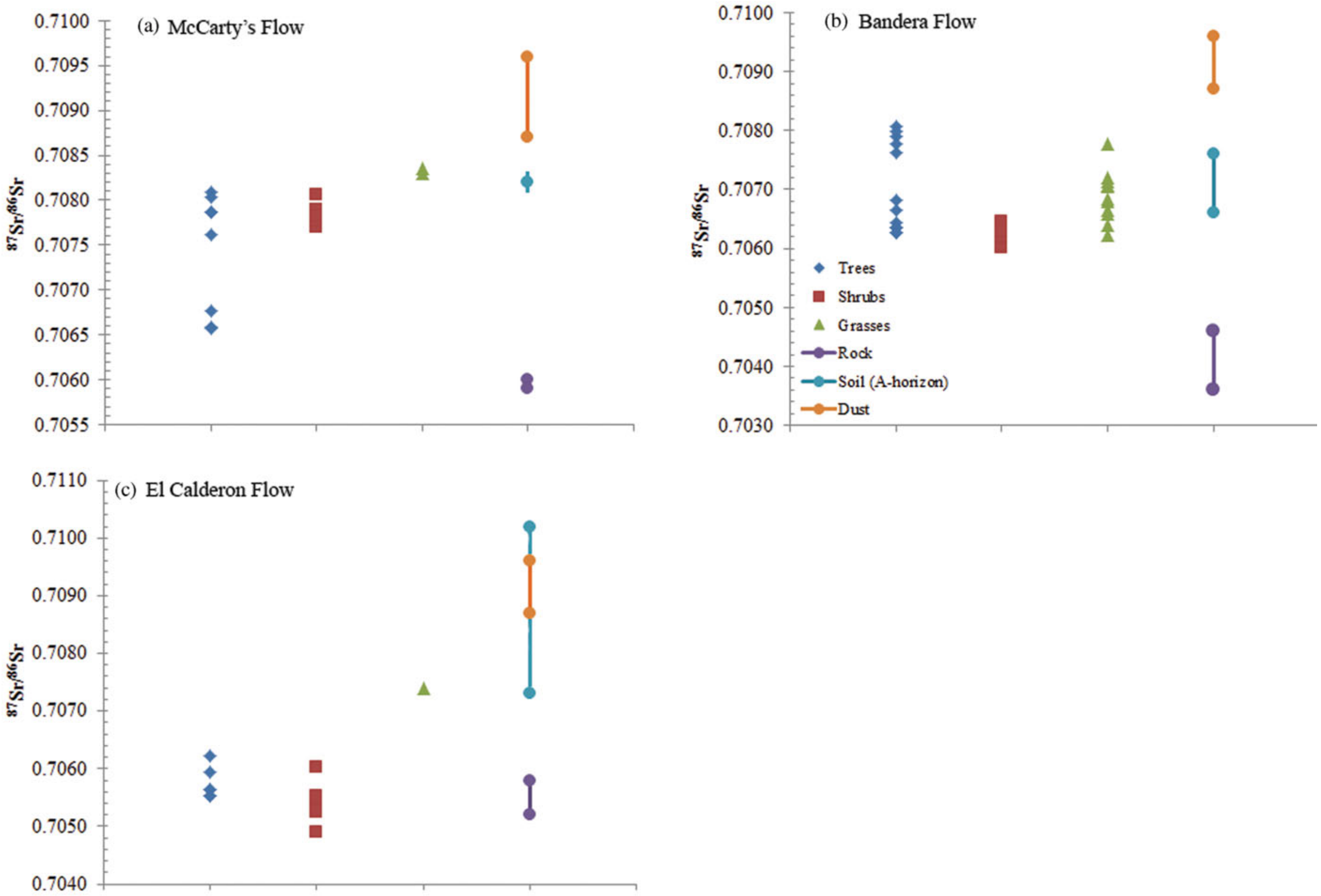

FIGURE 3. Rock, soil, dust, tree, bush, and grass $^{87}Sr/^{86}Sr$ ratios (y-axis) from (a) McCarty's, (b) Bandera, and (c) El Calderon basalt flows in the El Malpais National Monument. Symbols depicted in figure. Ages of flows provided in text. Data from Reynolds et al. (2012).

The mixing of sources presents an additional problem, which we address in detail in another publication (Grimstead et al. 2017). Not only do humans and animals ingest Sr from a variety of sources, but these sources also have varying concentrations of Sr (hereafter [Sr]) (e.g., Wright 2005). This problem was termed *masking by high strontium foods* by Ericson (1985:508) and has not been adequately addressed by the archaeological community. To the authors' knowledge, studies of bioavailable Sr of foods do not exist, but if we look to the U.S. Department of Agriculture (USDA) nutrient database (https://ndb.nal.usda.gov/ndb/) and calculate [Sr] based on Ca concentration, then we see that there is huge variability in [Sr]. For example, squirrel and deer meat have an average [Sr] of 0.21 and 0.49, respectively, while, on the other end of the spectrum, agave, prickly pear cactus, and smelt have concentrations of 32.2, 12.6, and 112.0 ppm, respectively. Steelhead Salmon have a [Sr] of 5.95 ppm. Imagine a prehistoric inland landscape where salmon, deer, and squirrels constituted the primary food sources, and the deer and squirrels are local and have a non-marine $^{87}Sr/^{86}Sr$ ratios. Salmon meat retains a marine $^{87}Sr/^{86}Sr$ ratio, as salmon do not feed when returning inland for breeding. Because of the high [Sr] of salmon, the [Sr] of deer and squirrels would contribute very little to the mixture that results in an individual's $^{87}Sr/^{86}Sr$ ratio. Thus, individuals who regularly consumed salmon would appear to be nonlocal and look as if they came from a coastal setting. Grimstead and others (2017) propose a total system modeling approach for understanding what a local should look like. Inherent within the proposed modeling approach is the calculation of [Sr] and $^{87}Sr/^{86}Sr$ ratios in different foods, as well as calculations of consumed food proportions and the sourcing of foods that may themselves be nonlocal. The field collection method proposed herein will generate the necessary data to model the complete biogeochemical system, which is the solution to masking by high strontium foods in archaeological research.

DETERMINING LOCAL VERSUS EXTRA-LOCAL ORIGINS

In archaeological research, $^{87}Sr/^{86}Sr$ sourcing is a method capable of informing the power structure in a community as it relates to native versus immigrant individuals (e.g., Buzon and Simonetti 2013; Gregoricka 2013; Price et al. 2000), the relationships between sociopolitically centralized communities and outlier communities or colonies (e.g., Bendrey et al. 2009; Knudson et al. 2012; Montgomery et al. 2005; Price and Gestsdóttir 2006), the social and trade networks lying behind regional economic systems (e.g., Benson et al. 2009; English et al. 2001; Reynolds et al. 2005), and human interactions with prey or domesticated populations (e.g., Balasse and Ambrose 2002; Britton et al. 2011; Hoppe 2004; Pellegrini et al. 2008). All of these investigations have very important implications for understanding archaeological societies and the plasticity of these relationships through time. However, the accuracy of interpretations that result from ^{87}Sr/^{86}Sr ratio data necessitates a clear understanding of what a local looks like from a biogeochemical perspective. To this end, isoscapes have been particularly useful (e.g., Evans et al. 2009; Frei and Frei 2011; Kootker et al. 2016) and are a possible end result of the field collection methods proposed herein.

While Sr isotope sourcing is broadly defined as a sourcing tool, it is actually a tool that rules out the source of a material and suggests potential regions that may have been the source. In both ruling out and identifying potential sources, the size of the region to be studied can vary significantly based on questions asked and any previous research that may be useful in determining the region to be studied. To date, biogeochemical definitions of being local have relied on four primary methods: (1) using archaeological fauna ^{87}Sr/^{86}Sr ratios to define the "local" ratio (e.g., Price, Grupe, et al. 1994; Price et al. 2007); (2) comparing enamel to bone, which, in the absence of diagenesis, should reflect different periods in an individual's life (e.g., Price, Johnson, et al. 1994; Price et al. 2000; Schweissing and Grupe 2003); (3) a statistical approach based on standard deviation from the mean ^{87}Sr/^{86}Sr ratios of local modern and archaeological small ranging taxa (e.g., Evans and Tatham 2004; Knudson 2008; Knudson et al. 2012; Price et al. 2002); and (4) using a trimmed mean of archaeological human teeth coupled with environmental sampling from the region and archaeological animals (e.g., Slovak et al. 2009; Wright 2005). The first is problematic, as archaeological fauna may in fact be extra-local themselves (e.g., Grimstead, Quade, et al. 2016; Knudson et al. 2012) and/or may not adequately reflect the variability within the local geochemical system. Archaeological faunas should be included in sourcing studies, but not as the only baseline definition of local. The second approach has fallen out of favor as the recognition of bone's susceptibility to postmortem diagenesis has been recognized. In the case of the more statistically based approach, Price and colleagues recognized that ^{87}Sr/^{86}Sr ratio variation was dependent on the geological history of a region, and their standard deviation approach was indeed arbitrarily selected (2002:121, 132). The fourth method has validity for humans because it is likely that they are consuming a variety of nonlocal foods. Thus, some individuals may appear nonlocal if their ratios are compared only to the local environmental ratios (cf. Wright 2005). By using both environmental ^{87}Sr/^{86}Sr ratios and the trimmed human mean, Wright (2005) was able to suggest nonlocal food sources for those that appeared to be local, which is an added benefit of using the trimmed mean method in tandem with environmental data. There is some difficulty with this application, however. As sample size increases, it may be more and more difficult to identify where trimming should occur. This problem relies heavily on the extent to which the central limit theorem is applicable to humans.

Extensive field collections will reflect variation in the environmental system and aid archaeologists in identifying potentially problematic sources within a system. For example, one can imagine an archaeological settlement near a river originating from a mountain range with a different lithology than that of the settlement. Simply sampling soil and plants from the area of the settlement may fail to capture the differing ^{87}Sr/^{86}Sr ratio of river water. This lack of sampling could be compounded if some inhabitants of the site relied more heavily on riverine resources, which would make them look extra-local even if they were local. Another example is the sourcing of various macrobotanical remains, such as corn, squash, architectural timbers, willow, etc., but these plants have varying rooting depths and foliage structure, meaning that they access potentially different nutrient sources, as discussed above. In this instance, environmental sampling strategy should capture both vertical (soil profile) and horizontal (across the targeted lithological soils) ^{87}Sr/^{86}Sr ratio variability. Selecting modern plants with similar rooting depths and natural histories to the archaeological plants would additionally benefit this approach. A similar case can be made for sourcing a variety of archaeological faunal remains. In this case, it is imperative to obtain animals with home range sizes, foraging preferences, and natural histories similar to the taxa to be sourced. Large carnivores have exceptionally large home ranges that may sample numerous lithologies, and they obtain a large quantity of dust and soil-derived Sr from their grooming behavior (Kohn et al. 2013). In contrast, the narrow home range of small rodents reduces the risks of identifying an animal as extra-local. These are only three scenarios among many that call for an intensive total system sampling strategy that pays due diligence to the place of archaeological materials within the biogeochemical system and region.

The sampling strategy outlined below is fundamentally uniformitarian in nature. That is, the strontium isotope variability observed in the modern era is what was observed in the past. Perhaps this is a relatively safe assumption when sites are more recent, but, as sites become older, this assumption becomes precarious. The older the site, the more likely that the surrounding region has been exposed to a variety of geologic processes that may alter ^{87}Sr/^{86}Sr ratios of soils, plants, and animals. An extreme example would be the transportation of glacial till, which creates a mixing of parent and foreign soils (see discussion in Warham 2012). In this case, a researcher may be forced to rely on archaeological fauna and, if available, paleontological deposits to establish local ratios. It also may be possible to work with a geoarchaeologist or soil geologist to collect paleosols with date ranges similar to those of the study site. ^{87}Sr/^{86}Sr ratios from the paleosols may be compared to modern values to evaluate any differences that may exist.

SAMPLING THE SYSTEM

Above it has been demonstrated that the Sr isotope system can be complex and should be thoroughly studied prior to conducting irreversible destructive analyses on archaeological materials. In fact, due diligence may save artifacts from destructive analyses in systems where the results will not produce the intended results. A uniform substrate across space would make sourcing impossible, as would complex mixed substrates. Not all regions are equally suited for sourcing questions, and adequate field sampling will elucidate the quality of a particular region for such questions. These complexities are relative and should be considered in tandem with the specific material desired for sourcing and the questions to be answered.

Pre-field Planning

A thorough sampling strategy is critical for knowing the complexities of the system and the unique place the selected material holds within that system. For example, if attempting to source plants, critical background knowledge includes rooting depth and bulk of roots. Sampling the same taxa of modern plants as the plant to be sourced is preferable, but this is not always possible due to habitat alterations or changes in modern agricultural practices, and other plants may serve as substitutes. For example, rabbit brush may serve as an appropriate substitute for maize, when maize cannot be grown in the targeted region (see Grimstead et al. 2015), but may not serve as an adequate substitute if one is seeking to obtain Sr concentrations and ^{87}Sr/^{86}Sr ratios. If humans are the focus of the study, then the fourth method described above may be used.

The sampling strategy and number of samples will be variable depending on the geology and material to be sourced. For example, in a relatively homogeneous geologic system, fewer sample locations will be needed, but, where it is heterogeneous, more locations will need to be sampled. If architectural timbers are to be sourced, then one can forego other vegetation, animals, and even waters, as the trees will be accessing mostly deep soil waters, but the researcher will need to sample soils, rocks, and a variety of tree sizes and species, again dependent on the archaeological materials. The authors have primarily done field collections for animals and humans; thus, at each sample location, they collect at a minimum rock, soil, vegetation, and, when available, water and animal/materials (e.g., hair, dung, scat, etc.). When in foreign countries, the authors have tended to over-collect, owing to the difficulty of returning to the field if it is decided that more is necessary.

Mapping Collection Locations

Once the types of samples have been selected, then a bedrock geology map should be consulted to identify sampling locations across different lithologies (Figure 4). If access is possible, then sampling the centroid should be a bare minimum with several additional sample locations that expand outward toward the boundaries of other lithologies. The sampling of springs and spring-fed waters should be identified, as their origin may not be near the surface. In the United States, Bureau of Land Management (BLM) and U.S. Forest Service (USFS) maps have been exceptionally helpful to the primary author for identifying access, land rights, and the locations of springs. International fieldwork has been a bit more challenging in this regard, and this information was obtained by asking locals.

Adequately sampling the specified region is a critical step toward identifying the strontium isotope baselines and, if done thoroughly enough, can be used to generate easily interpretable isoscape figures (e.g., Evans et al. 2009; Frei and Frei 2011; Warham et al. 2012). Regional sampling density will be highly dependent on the geologic complexity, but, within a specific lithology geochemical sampling, studies suggest that a density of one sample per 500 km^2 or less is sufficient to capture regional patterns (e.g., Davenport and Nolan 1991; Fordyce et al. 1993; Garrett et al. 1990). However, a more fine-grained sampling strategy may be required when geologic complexity is encountered. Evans and colleagues (2009) demonstrated that areas near transitional geologic zones can have significant variability that may distinguish them from samples within the same bedrock. Such areas, for example, may include foothills at the base of mountain ranges where erosional processes have produced soils that may be alluvially or fluvially transported down into the foothills. Rivers may be another such example, where river water transports materials from foreign parent rocks and then alters course, exposing the foreign soils. Of course, this strategy cannot be divorced from the fact that funding is becoming more and more elusive, and a bare minimum of one sample per 500 km^2 may not be feasible.

FIELD COLLECTIONS

The targeted materials should be sampled at all preplanned sampling locations, if possible. In addition to basic field notes of the sampling location (i.e., location, elevation, sample type, etc.), notes about the vegetation regime, observed fauna, geology, and other pertinent information should be recorded. Excerpts from typed field notes from two different projects are provided in supplemental material (Supplemental Materials 1).

Water

As a general rule, waters from rivers, springs, and seeps should be sampled. Rivers represent the mixing of origin waters that may have different quantities of source waters, representing a mixing of ^{87}Sr/^{86}Sr ratios. Sampling at multiple locations will enable the researcher to completely model the river system. Collect 50 mL of water in a centrifuge tube. Waters should be collected even if there is a high mineral or sediment content, as this can be dealt with in the lab. To prevent leakage, the tube should be prepared prior to water collection by wrapping the threads with Teflon$^{\mathrm{TM}}$ tape, purchased at any hardware store (Figure 5). Then the tube should be filled to the brim, capped, and sealed with electrical tape. As soon as possible, the water samples should be chilled to below ~40°F but above freezing. Chilling serves to retard any biotic activity.

Rocks and Soils

Soils produced from rock weathering and airborne dust provide the bulk of bioavailable Sr for plants. By sampling both rock and soils, it is possible to quantify extra-pedogenic ^{87}Sr/^{86}Sr derived from dust or even past fluvial/alluvial activity. For rocks, it is important to sample the bedrock, rather than surficial rocks, as they may not necessarily be representative of the local bedrock. When possible, fresh bedrock should be exposed via a rock hammer, and then the fresh exposure should be sampled, again via rock hammer (Figure 6a). Obtaining fresh rock limits the possibility that erosional processes have already acted to remove Sr from more readily exchangeable minerals. To collect soils, expose soil by scrapping back plants and any duff that may be present. Fill a 50 mL centrifuge tube or field specimen bag with soil (Figure 6b). Both are more than enough for ^{87}Sr/^{86}Sr leaching experiments, having plenty leftover for multiple analyses and/or archiving. Do not be concerned if roots or plant materials are sampled, as these can be removed in the lab. A similarly small quantity of rock is required for ^{87}Sr/^{86}Sr

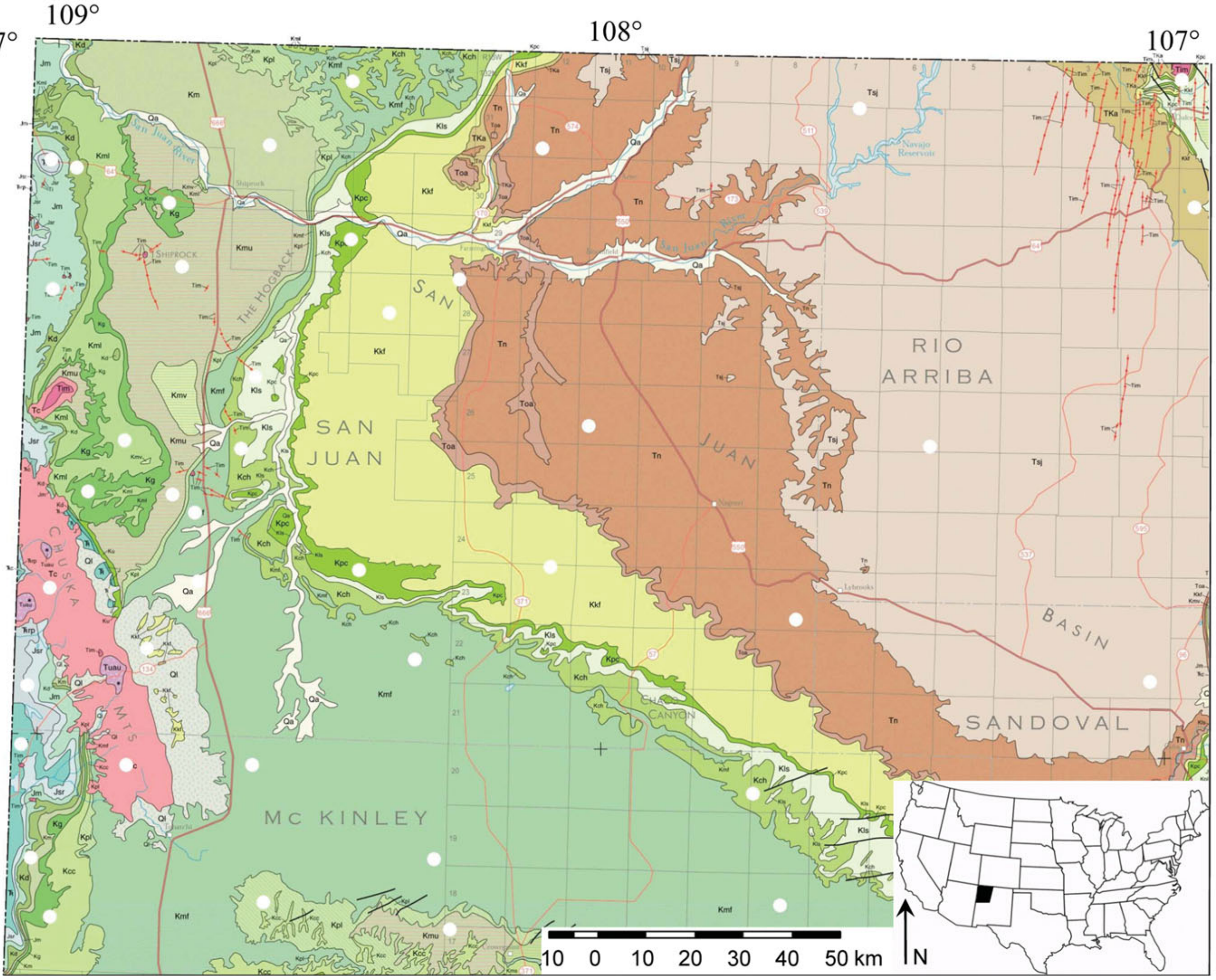

FIGURE 4. Sampling map of northwestern New Mexico. Collection locations were chosen to capture geological diversity. White circles are sample location centroids.

analyses (Figure 6). If working abroad, one must apply for a soil importation permit from the USDA (https://www.aphis.usda.gov/aphis/ourfocus/planthealth/import-information/permits/regulated-organism-and-soil-permits/sa_soil/ct_soil_permit_process). This process can take a while, so apply at least six months prior to fieldwork.

Vegetation

The case study demonstrated that the varying rooting depths and natural histories of plants will alter the observed $^{87}Sr/^{86}Sr$ ratios. Selections of modern vegetation sampling should be based on the artifact to be sourced. For example, if it is architectural timbers, then trees should be sampled; if willows or tules, then target these taxa. It may not always be possible to do this, owing to environmental change or landscape/usage alterations, and in this case one should identify a plant that has similar root structures as the species to be sourced. This problem will most often be encountered when trying to source agricultural materials. Planting the taxa in the sample location is an option (e.g., Grimstead et al. 2015), but this method obviously adds a new layer of complications and is not feasible in most situations.

Enough plant material should be sampled to produce approximately 100 mg of ashed material for $^{87}Sr/^{86}Sr$ analysis. Plant Sr concentrations vary widely, but this quantity will provide enough material for even the lowest concentrations. The authors have found that, in the case of sedges (Cyperaceae), grasses (Gramineae), and rushes (Juncaceae), a completely filled 4" by 6" Ziploc bag provides enough material for ashing (Figure 7). Multiple plants of the same species from the same collection locality can be combined in order to obtain the proper quantity. Focusing on dead and dried plant material prevents the buildup of moisture within the sample bag, and dead plants do not require a USDA importation permit, but care should be taken to ensure that the plant was in fact local to the collection location. For example, one would not want to sample leaves that may have

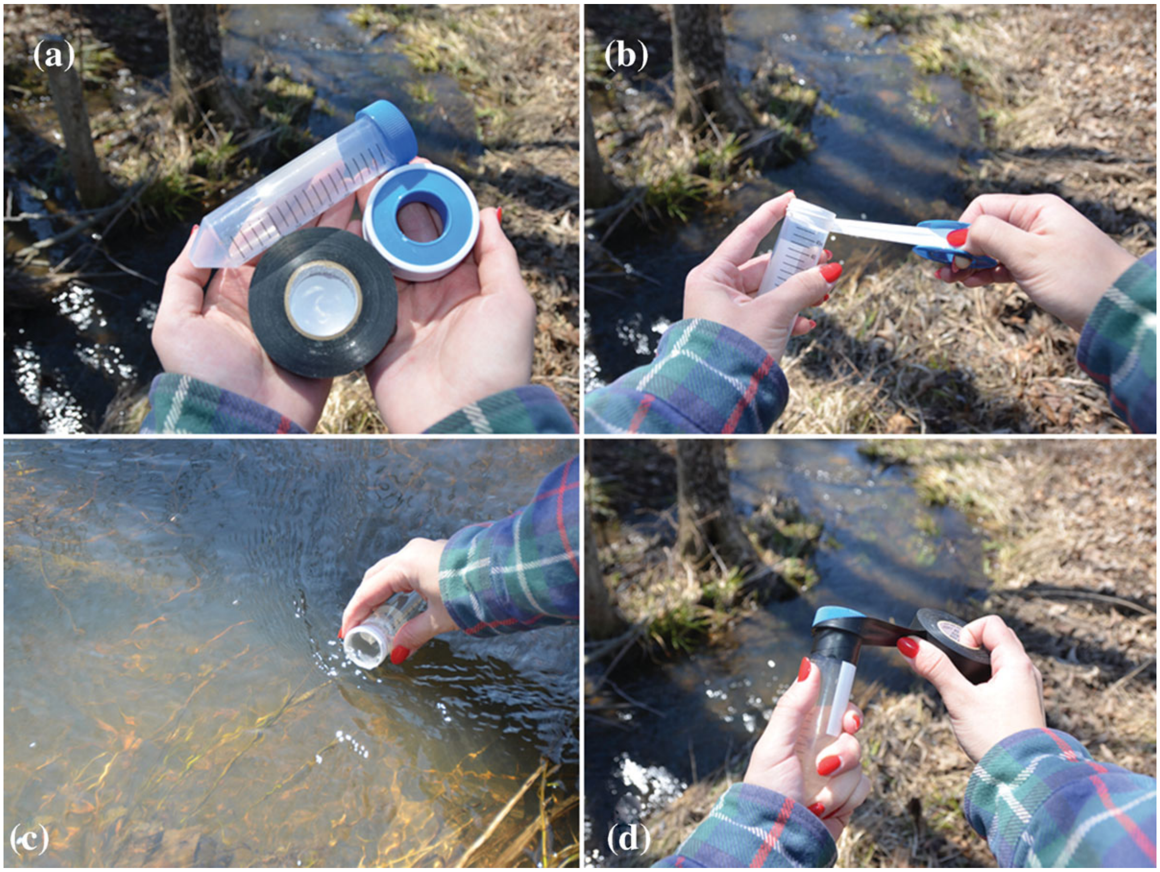

FIGURE 5. Water sampling methods: (a) use a 50 mL centrifuge tube, electrical tape, and Teflon^{TM} tape for water sampling; (b) wrap the threads of the container with Teflon^{TM} tape, following the direction of cap tightening; (c) fill water clear to the brim, away from stagnant water in the case of running water samples; (d) cap and seal the tube with electrical tape, pulling tension slightly as wrapping across tube and cap.

been blown in from afar. It is also a possibility to dry the plants after field collection. The authors have taken to applying for a USDA permit, which results in a letter stating, "We have determined that these various types of dried plant material are not prohibited in accordance with 7 CFR319 for research purposes and do not require a permit" (letter available upon request). This letter accompanies the samples, reducing the risk of confusion and seizure in customs.

Animals

Current archaeological literature employing ^{87}Sr/^{86}Sr sourcing has shifted away from utilizing archaeological fauna to derive baselines, and we strongly encourage the continuation of this trajectory, as even rodents may not be local (e.g., Grimstead, Quade, et al. 2016). The procurement of animal samples is critical if the archaeological material targeted for sourcing is animal or human. Because of the unique behavior and subsistence practices of individual taxa, the same animals to be sourced should be targeted for field collections or sampled from museum collections (c.f. Price et al. 2002). For wild game, if the same species cannot be obtained, then an animal with similar food choices, ranging behavior, and grooming practices should be selected. If studying domesticates, then the same animals should always be targeted, and it may be exceptionally beneficial to add an ethnoarchaeological component to field collections. Knowing the relationship between human management decisions, mobility, and biogeochemistry will prove to be exceptionally valuable in interpreting results from archaeofauna. If bioarchaeological materials are to be sourced, then it would be prudent to obtain omnivorous animals from the geological region where the site is located. This can serve as a modern comparison of what a strictly local omnivorous diet might look like, but care should be taken because omnivores can be quite mobile over short and long periods of time. Furthermore, animals with known death locations are of paramount importance. Collections of modern animals require appropriate permitting from the respective state, federal, and local agencies. In foreign lands, this permission may not be obtainable, and museum collections may be the only solution where available. Purchasing locally raised animals (e.g., sheep/goat, fowl, etc.) or animal products is one potential solution, but one should take care to ensure that that the animals were always local, that they are not foddered with nonlocal foods, and that provided water is also from the local natural sources. Animal materials require a USDA import permit (https://www.aphis.usda.gov/aphis/ourfocus/animalhealth/animal-and-animal-product-import-information).

FIGURE 6. Rock and soil sample methods: (a) use a very small sample of rock for $^{87}Sr/^{86}Sr$, which can be collected via 50 mL centrifuge tubes or standard field collection bags; use a rock hammer to expose and collect samples with fresh surfaces (i.e., not exposed to previous erosional processes); (b) collect soil samples in a 50 mL centrifuge tube or standard field collection bag; expose a fresh surface and collect at least 5 mg of soil.

Field collections of fauna follow zooarchaeological field collection methods and opportunistic encounters. Zooarchaeology-based field collection includes road kill collection, sampling of previously collected museum specimens, and coordinating with government agencies (e.g., Fish and Game, Department of Transportation, etc.) and local hunters. Opportunistic encounters may include scat, owl pellets, or the remnants of a carnivore's meal. In the former two cases, every effort must be made to identify the species from which the scat or pellet was derived. This will allow the collector to estimate a potential land area foraged by the animal, which would represent averaging in $^{87}Sr/^{86}Sr$ space. The use of scat and owl pellets introduces potential error into the system, however. For example, if we collect mountain lion scat, do we know whether that individual was on the edge of its home range or in the middle? Caution should be taken with these samples, and they should be compared to the other environmental samples collected at the location and surrounding areas. The authors have also used land snails.

Museum specimens, while readily available, can be problematic. Many zooarchaeological and ecology/biology comparative collections contain only general collection locations, if any location was recorded at all. In museum collections, one must be concerned with how the specimen was skeletonized. Two methods are ideal for isotopic analyses: dermestid processing and bucket rotting in deionized waters. Dermestids have no adverse isotopic affects, but macerating in tap water potentially exposes the skeleton to a foreign ion environment. The burial method of

FIGURE 7. Vegetation collection. Care should be taken to collect only from one species of plant. Dead and dried samples are preferable. If live plants cannot be dried immediately, then the sample bag should be left open to allow for evaporation. Once back in the lab, remove from the bag to allow for complete drying.

maceration should be completely avoided, as this method offers a particularly fruitful soil environment for the exchange of ions.

To this end, collecting road kill is a very reliable source for animal specimens. For isotopic analyses, the entire animal is not required, meaning that only a portion of the animal is necessary for field collections. The authors prefer the removal of the mandible, as this provides both teeth and bone for isotopic analyses, but any element may be used. Bucket rotting with deionized water or dermestid processing should be the only methods employed to remove non-osteological tissue. Maceration with deionized water can occur in any plastic container, but metal containers should be avoided. The animal should be checked periodically to assess whether a rinse with more deionized water is required for further maceration. Once all soft tissue has been removed, the specimen can be air-dried.

The primary author has found coordinating with local agencies to be a very productive avenue for animal collecting. Fish and game departments keep poached animals as evidence for extended periods of time, and they have been very happy to share these specimens as long as the remnants continue to be archived as evidence. Poached animals can be problematic unless the fish and game officer collected the evidence at the location of the kill. Particularly when a law is broken, one cannot trust the offender to reliably report the kill location to the law enforcement officer; thus, these specimens may be useless as a sourcing baseline. Similarly, local hunters and trappers can be a valuable resource, but many hunters are wary about sharing kill locations, as they vigilantly protect knowledge of productive hunting territories. If the researcher is already an accomplished hunter or trapper, then this may also be a fruitful avenue, as these methods are the single most reliable way to ensure a known death location and date. The date of death can be critically important for isotopic baselines, especially if seasonality or migration behaviors are being investigated.

CONCLUSIONS

$^{87}Sr/^{86}Sr$ ratios are a powerful sourcing tool for archaeologists and anthropologists, and it is a sourcing method that has no sign of diminishing in its prominence. Despite its current importance in the literature, few studies conduct extensive field surveys to create a baseline dataset to which archaeological materials can be compared, and the discipline has not established a universal protocol and methodology for the collection of such modern datasets. These baseline datasets are of paramount importance for the ways archaeologists employ isotopic sourcing. The paper demonstrated why extensive field collections are necessary, and why the material or species to be sourced should be targeted. Guidelines were provided for how to undertake modern field collections, including pre-field mapping and planning, and the specifics of what and how to collect. We hope that this manuscript will advance the field in three ways. First, field collection methods will be standardized. Second, datasets will be improved to more fully inform the archaeological record. Finally, by following this protocol, we can identify regions where sourcing studies are potentially problematic due to an overly complex system. The method recommended in this paper is easily adaptable for the collection of materials that could be used to establish baseline data for other isotopic (e.g., carbon, oxygen, sulphur, etc.) and trace element methods that have been shown to be helpful in further delineating potential source regions (e.g., Benson et al. 2006; Dufour et al. 2007; Zazzo et al. 2011). Field training is critical for all aspects of the archaeological discipline, and the methods of collecting environmental isotopic baselines are no different. Where such field training is not accessible, the authors hope this paper will serve as a field guide for the ambitious.

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Data Availability Statement

Data for Figure 1 is available upon request from the first author.

Supplementary Material

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