



Reconstructing ancient Maya animal trade through strontium isotope ($^{87}\text{Sr}/^{86}\text{Sr}$) analysis

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ABSTRACT

This study explores the potential for using strontium isotope analysis ($^{87}\text{Sr}/^{86}\text{Sr}$) to study ancient Maya animal exchange. Traditional zooarchaeological methods of studying trade rely on the identification of animals found outside their natural geographic or habitat ranges. Isotopic analysis provides an additional means of identifying and sourcing non-local animals. $^{87}\text{Sr}/^{86}\text{Sr}$ values from Maya zooarchaeological remains indicate that regional and long-distance transport and exchange of animal goods was more common than previously recognized. Widely distributed animals including deer and peccary were among the animals exchanged, which questions their common interpretation as locally-acquired resources. The isotopic results contribute to our understanding of how animal products were integrated into Maya economic and exchange networks. The research is also relevant to human mobility studies in Mesoamerica.

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1. Introduction

Traditional zooarchaeological approaches to identifying regional and long-distance acquisition and exchange of faunal resources are based on the morphological identification of exotic animals found outside their natural geographic ranges, or habitat zones. Within Mesoamerica, this technique has primarily been used to identify transport of species such as quetzals (*Pharomachrus mocinno*), macaws (*Ara macao*), jaguars (*Panthera onca*) and crocodiles (*Crocodylus* sp.) between the highlands and lowlands (Emery, 2002; Moholy-Nagy, 2004; Somerville et al., 2010), and trade in marine and terrestrial species between the coast and the interior (e.g., Andrews, 1969; Götz, 2008; Hamblin, 1984: 97–141; Masson and Peraza Lope, 2008). However, such methods are inadequate for identifying trade in species with large geographic distributions or broad habitat requirements, such as white-tailed deer (*Odocoileus virginianus*) and collared peccary (*Pecari tajacu*). When recovered at Maya archaeological sites, these species are often assumed to be local resources, but this assumption is at odds with ethnographic accounts of trade in deer haunches (Tozzer, 1941) and suggestions of specialized hunting in less populated areas such as the Maya Mountains of Belize (McAnany, 1989). These species may also have been exchanged and moved across the landscape as food, tribute and ritual items.

Strontium isotope ($^{87}\text{Sr}/^{86}\text{Sr}$) analysis is a promising means of identifying and sourcing non-local animal remains in Mesoamerica (White, 2004: 190). Within the region, the method has been used previously to identify human migration (Buikstra et al., 2003; Price, 2006; Price et al., 2000, 2008, 2010; White et al., 2007; Wright, 2005a, 2005b). Fewer studies have used the method to study animal movement and trade in either Old or New World contexts (Freiwald, 2010; Shackleton and Elderfield, 1990; Sykes et al., 2006; Thornton et al., in press; Vanhaerena et al., 2004; Viner et al., 2010; Yaeger and Freiwald, 2009). Strontium isotope analysis is therefore an under-utilized tool for exploring animal transport and trade.

Strontium isotope ratios measured in archaeological animal remains can be used to infer their region of origin because $^{87}\text{Sr}/^{86}\text{Sr}$ in rock, soil, groundwater and vegetation varies according to a region's underlying geology (Faure and Powell, 1972). As an animal feeds and drinks, the local strontium isotope composition of the water, plants and animals consumed is recorded in its skeletal tissues when strontium (Sr) substitutes for calcium (Ca) during bone and tooth mineralization (Graustein, 1989; Likins et al., 1960). Unlike light stable isotopes (e.g., $^{13}\text{C}/^{12}\text{C}$, $^{15}\text{N}/^{14}\text{N}$ and $^{18}\text{O}/^{16}\text{O}$), strontium isotopes ($^{87}\text{Sr}/^{86}\text{Sr}$) are incorporated into animal body tissues such as tooth, bone and shell without measurable fractionation, so signatures do not vary according to a species' diet, body size, or metabolism (Blum et al., 2000; Price et al., 2002).

The purpose of this study is to evaluate the potential for using strontium isotopes to reconstruct ancient Maya hunting ranges and exchange networks. Archaeological and modern faunal samples were tested from Maya archaeological sites across the lowlands of

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Mexico, Guatemala, Belize, and Honduras (Fig. 1). This study provides a novel means of identifying regional and long-distance acquisition, or exchange of animal resources, and also contributes to the growing body of baseline strontium isotope data for Mesoamerica, thus increasing our ability to use isotopic signatures to study the movement of prehistoric people, animals and other resources across the landscape.

2. Strontium isotope variation in Mesoamerica

The stable isotope ⁸⁷Sr derives from the radioactive decay of rubidium (⁸⁷Rb). In geological materials, the relative abundance of

⁸⁷Sr in comparison to ⁸⁶Sr varies according to a rock's age and original ⁸⁷Rb/⁸⁷Sr composition. Although the ⁸⁷Sr/⁸⁶Sr value of rocks changes over time, this occurs at a timescale irrelevant to archaeological investigations (⁸⁷Rb half life = 4.88 × 10¹⁰ years). Within the Maya cultural area, regions of distinct geology that vary in their strontium isotope composition include the northern and southern lowlands, volcanic highlands, Pacific coast, Maya Mountains, and the metamorphic province (Hodell et al., 2004) (Fig. 1).

A large portion of the Maya area is underlain by limestone bedrock. The age of the limestone increases from north to south with more recent Eocene-Pleistocene limestone in Mexico's Yucatan Peninsula and older Late Cretaceous to Paleocene carbonates in

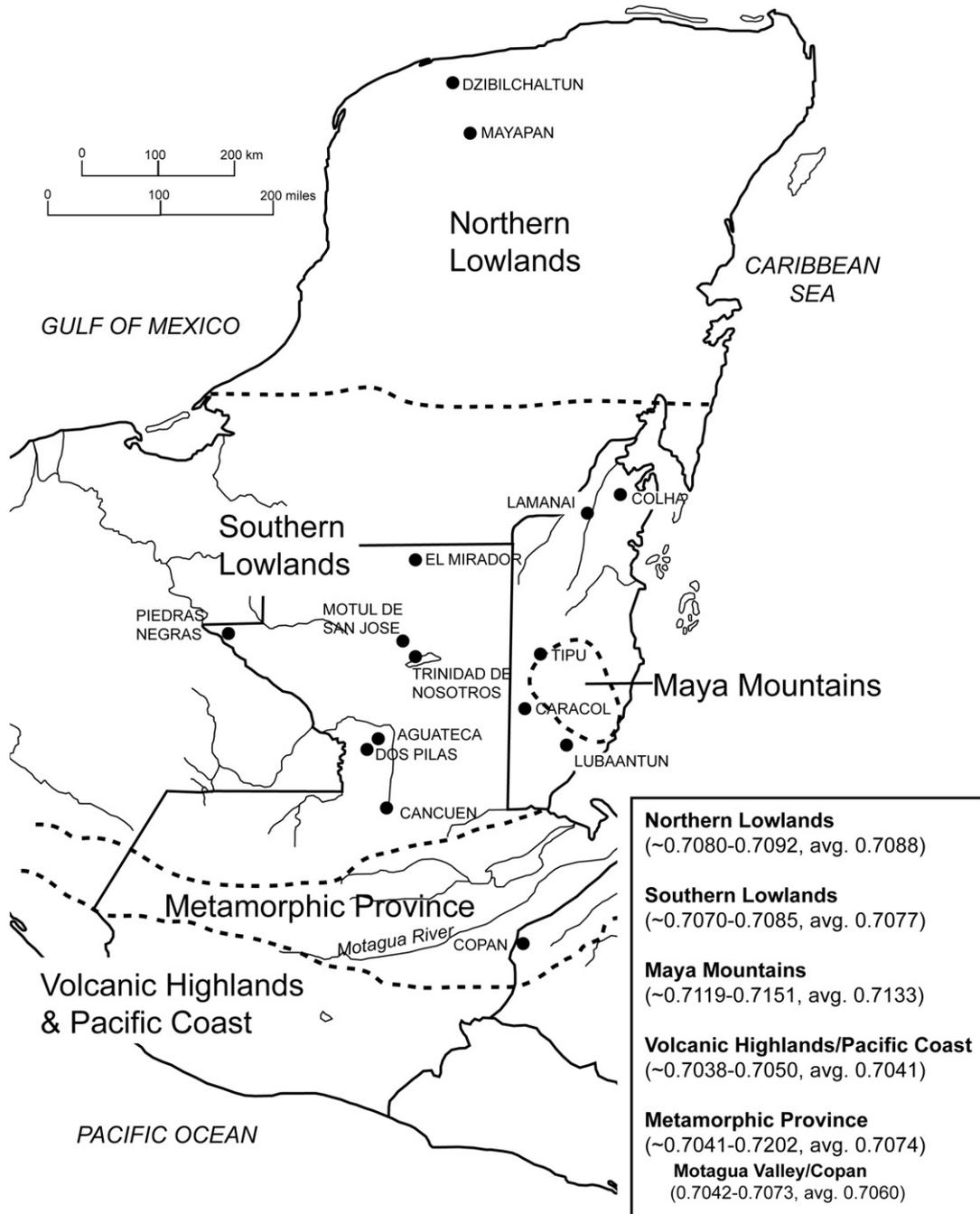


Fig. 1. Map of the Maya cultural region showing sites mentioned in the text and major strontium isotope regions (delineated with dashed lines). Regional ⁸⁷Sr/⁸⁶Sr ranges defined according to Hodell et al. (2004). Map modified from original by Kitty Emery.

the lowlands of Belize and northern Guatemala. The $^{87}\text{Sr}/^{86}\text{Sr}$ of marine carbonate rocks such as limestone is largely determined by the isotopic composition of seawater at the time of rock formation. The $^{87}\text{Sr}/^{86}\text{Sr}$ of seawater has increased over time from 0.7074 in the Late Cretaceous to 0.7092 in modern seawater (Howarth and McArthur, 1997). Strontium ratios therefore increase from south to north as the age of the limestone bedrock decreases. In terms of cultural regions, $^{87}\text{Sr}/^{86}\text{Sr}$ can distinguish between animals originating in the northern lowlands ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7080\text{--}0.7092$, $\bar{x} = 0.7088$) versus southern lowlands ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7070\text{--}0.7085$, $\bar{x} = 0.7077$) (Hodell et al., 2004).

The volcanic highlands lie to the south of the Maya lowlands in what is now southern Guatemala. This area is characterized by relatively young volcanic rocks with the lowest $^{87}\text{Sr}/^{86}\text{Sr}$ values in the Maya region ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7038\text{--}0.7050$, $\bar{x} = 0.7041$) (Hodell et al., 2004). Similar values are found along the Pacific coast of Guatemala where soils are derived from highland volcanics. Although the volcanic highlands and Pacific coast are readily distinguished from most other regions of the Maya world, similar $^{87}\text{Sr}/^{86}\text{Sr}$ values are found in the highland regions of Central Mexico (Price et al., 2000, 2008; White et al., 2007).

Between the volcanic highlands and the carbonate lowlands, lies the metamorphic province (Hodell et al., 2004). $^{87}\text{Sr}/^{86}\text{Sr}$ in this area varies greatly ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7041\text{--}0.7202$, $\bar{x} = 0.7074$), but a narrower range has been reported for the Motagua River valley and near the major archaeological site of Copan ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7042\text{--}0.7073$, $\bar{x} = 0.7060$) (Hodell et al., 2004). Although the geological diversity of the metamorphic province complicates strontium sourcing, non-local animals within the Motagua Valley/Copan area are still identifiable when their signatures lie outside the range for this sub-region of the metamorphic province.

The highest $^{87}\text{Sr}/^{86}\text{Sr}$ values ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7119\text{--}0.7151$, $\bar{x} = 0.7133$) in Mesoamerica are found in the Maya Mountains of Belize (Hodell et al., 2004). The volcanic and metamorphic Maya Mountains are surrounded by marine carbonates with much lower $^{87}\text{Sr}/^{86}\text{Sr}$ signatures. The region therefore has great potential for identifying animals acquired or transported over relatively short distances between the uplands of the Maya Mountains and the lowland areas surrounding them. Intermediate values ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7090\text{--}0.7096$) have been found along the margins of the Maya Mountains where upland and lowland sediments mix (Freiwald, 2011).

3. Materials and methods

3.1. Sample description

I tested 131 specimens from fourteen archaeological sites distributed across the Maya cultural region (Table 1, Fig. 1). Most of the sites are major settlements or polity capitals. The archaeological samples range in age from Late Preclassic (250 B.C.–A.D. 250) to Colonial (post-A.D. 1500), but the majority of samples date to the Late and Terminal Classic (A.D. 650–950).

Forty-six specimens of taxa with restricted home ranges (<0.2 km²) including modern land snails and both archaeological and modern small mammals were used as baseline samples for this analysis. Although geological, hydrological and botanical samples may also be used to establish local $^{87}\text{Sr}/^{86}\text{Sr}$ values, low mobility animals with restricted home ranges more accurately reflect the expected local $^{87}\text{Sr}/^{86}\text{Sr}$ range for larger animals such as deer or humans (Blum et al., 2000; Price et al., 2002). This is true because as animals move, feed and drink, the more heterogeneous $^{87}\text{Sr}/^{86}\text{Sr}$ values of the local water, soil and plant resources are averaged in their skeletal tissues. Baseline fauna were tested from ten of the

study sites. Baseline data from sites within close proximity to each other (<15 km apart) were pooled. The local strontium range for each site was defined as two standard deviations above and below the site's mean baseline fauna $^{87}\text{Sr}/^{86}\text{Sr}$ value (Price et al., 2002). Samples falling outside this range are referred to as isotopic outliers. Local $^{87}\text{Sr}/^{86}\text{Sr}$ ranges for Caracol, Colha, El Mirador and Lubaantun were defined according to published baseline geological and faunal values (Freiwald, 2011; Hodell et al., 2004; Price et al., 2008, 2010).

Eighty-five archaeological large and medium-bodied mammal specimens were tested and compared to the baseline fauna data for each site. I classify these specimens as primary samples and use the derived isotopic values to investigate whether these species were acquired non-locally. The large and medium-sized mammals include white-tailed deer, brocket deer (*Mazama* sp.), domestic dog (*Canis lupus familiaris*), peccary (Tayassuidae: *Pecari tajacu*, *Tayassu pecari*) and tapir (*Tapirus bairdii*). These are important subsistence and ritual species that archaeological and ethnographic evidence indicates may have been traded or acquired in areas far away from their eventual use and deposition. In most areas of Mesoamerica, the scale at which strontium ratios vary across the landscape is greater than the inferred home range and dispersal distance of these species (Foerster and Vaughan, 2002; Keuroghlian et al., 2004; Maffei and Taber, 2003; Saenz and Vaughan, 1998). Therefore, strontium isotope ratios should distinguish between animals acquired locally, and those imported into a site through human agency. However, the wide-ranging behavior of white-lipped peccaries (*T. pecari*) (home range = ~24 km²) (Reyna-Hurtado et al., 2009) makes them difficult to classify as local versus non-local animals in areas where strontium ratios vary significantly over distances of less than 50–100 km.

For all primary samples, $^{87}\text{Sr}/^{86}\text{Sr}$ was measured from tooth enamel because it has greater resistance to diagenetic contamination than bone (Nelson et al., 1986; Sillen and Kavanagh, 1982). Six of the small mammal baseline samples were also run on tooth enamel, but the remaining nine samples were cortical bone because tooth enamel was insufficient for sampling. Cortical bone samples were not tested for diagenetic alteration since they were consistent with enamel and shell samples tested from the same site.

3.2. Laboratory methods

Samples were cleaned and collected using a fine dental drill in the Bone Chemistry Laboratory, Department of Anthropology at the University of Florida. Sample pretreatment and strontium isolation was done in a University of Florida Department of Geological Sciences class 1000 clean lab. Enamel, bone and shell samples were pretreated for 30 min in a 5% acetic acid solution to remove post-depositional contaminants, and rinsed to neutral with 4× distilled water. This method is generally considered to be an effective means of removing contaminants (e.g., Nielsen-Marsh and Hedges, 2000; Price et al., 1992; Sillen and Sealy, 1995). After pretreatment, the samples were transferred to sterile Teflon beakers and hot-digested in 3 ml of 50% HNO₃ (optima). Samples were then loaded into cation exchange columns packed with strontium-selective crown ether resin to isolate strontium from other ions.

Sample $^{87}\text{Sr}/^{86}\text{Sr}$ was measured with at Micromass Sector 54 thermal ionization mass spectrometer (TIMS) housed in the University of Florida, Department of Geological Sciences. Multiple samples of the strontium standard NBS-987 were run to confirm instrument accuracy. External precision of analysis was ±0.00002 (2 sigma absolute) based on 314 analyses of NBS-987. Eight additional baseline samples were run by T. Douglas Price in the

Laboratory for Archaeological Chemistry at the University of Wisconsin, Madison (Price et al., 2010).

4. Results and discussion

All baseline samples fell within the broad $^{87}\text{Sr}/^{86}\text{Sr}$ ranges defined for each geographic region (e.g., northern lowlands, southern lowlands, Maya Mountains) by Hodell et al. (2004). In comparison to the baseline data, the majority of primary samples ($n = 66$) were acquired locally, or in areas isotopically similar to their site of deposition (Table 1). However, nine of the fourteen sites contained specimens classified as isotopic outliers ($n = 19$), suggesting that the animals were acquired non-locally. These include the sites of Lamanai, Motul de San José, Trinidad de Nosotros, Piedras Negras, Dos Pilas Aguateca, Caracol, Tipu and Copan. All baseline and primary samples from the five remaining sites (Cancuen, Colha, Dzibilchaltun, El Mirador, and Lubaantun) closely matched local $^{87}\text{Sr}/^{86}\text{Sr}$ values recorded in the baseline faunal samples, and reported in previous studies (Hodell et al., 2004; Price et al., 2008, 2010; Wright, 2005a). The focus of this study is on the sites with evidence for non-local animal acquisition.

4.1. Site interpretations: identifying and sourcing non-local animals

4.1.1. Motul de San José and Trinidad de Nosotros (Guatemala)

The neighboring sites of Motul de San José (hereafter referred to as Motul) and Trinidad de Nosotros (hereafter referred to as Trinidad) are located in the Petén Lakes region of northern Guatemala. The sites were politically and economically linked through their participation in the larger Motul de San José polity. The larger site of Motul was the polity's capital (Foias and Emery, in press), while the smaller lakeside community of Trinidad served as a secondary satellite center, and possibly as a port for the movement of goods and materials throughout the region (Moriarty, 2004).

Pooled baseline samples ($n = 14$) from Motul and Trinidad show a local $^{87}\text{Sr}/^{86}\text{Sr}$ range of 0.7073–0.7081. Although most of the primary samples from Motul and Trinidad may be classified as local animals, one white-tailed deer from Motul and one from Trinidad fall below the local $^{87}\text{Sr}/^{86}\text{Sr}$ range (Fig. 2a). Two other deer from Motul and one from Trinidad also have relatively low $^{87}\text{Sr}/^{86}\text{Sr}$ values falling just within the local range, but below the minimum value recorded in the baseline samples ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7075$). These individuals are identified as local, but they may come from outside the local area or region.

The non-local Motul specimen comes from a Late Classic midden within the site's acropolis. The midden is associated with an area of ceramic production, and a large public plaza possibly used as a marketplace (Halperin et al., 2009, Halperin and Foias, in press). Three other deer from the midden had local signatures, as did two deer tested from a nearby elite residential group. The Trinidad outlier was recovered from a residential group attached to the site's largest public plaza. Soil chemistry suggests that the plaza served as a marketplace (Dahlin et al., 2010). Another specimen from this same residential group yielded a local signature, as did three deer from a potential feasting deposit associated with the site's ballcourt (Moriarty and Thornton, 2007).

One explanation for the isotopic outliers at Motul and Trinidad is that they come from somewhere outside the southern lowlands. The most likely source is the metamorphic province. The distance from the Petén Lakes region to the metamorphic province (>200 km) precludes the possibility that these animals were procured directly by the site's inhabitants through extended, long-distance hunting trips. Instead, the deer would have been obtained through long-distance exchange. Another possibility is that there is an area of lower strontium values within the southern lowlands,

and possibly within the Petén Lakes region that has not yet been identified through baseline sampling. This possibility is unlikely because previous research has not recorded $^{87}\text{Sr}/^{86}\text{Sr}$ values below 0.7074 within most of the southern lowlands (Hodell et al., 2004; Price et al., 2008, 2010; Wright, 2005a).

4.1.2. Petexbatun polity sites: Dos Pilas and Aguateca (Guatemala)

Dos Pilas and Aguateca are located along a tributary of the Pasión River in southwestern Guatemala. The two nearby sites served as twin capitals of the Petexbatun polity during the Classic period. Baseline samples from Dos Pilas ($n = 3$) define the local $^{87}\text{Sr}/^{86}\text{Sr}$ range as 0.7073–0.7081. This is similar to other values (0.7075–0.7078) previously reported for the Pasión River region (Hodell et al., 2004; Price et al., 2010). Applying these baseline data to the neighboring sites of Dos Pilas and Aguateca, one deer specimen from each site has a non-local $^{87}\text{Sr}/^{86}\text{Sr}$ value (Fig. 2b). In both cases, the deer specimens have $^{87}\text{Sr}/^{86}\text{Sr}$ values below those typical of the southern lowlands. The isotopic outlier from Aguateca was recovered in a deep limestone chasm bisecting the site used for ritual purposes (Ishihara, 2008). Another deer recovered from the chasm yielded a local signature. The non-local deer specimen from Dos Pilas came from a Late Classic architectural group located just east of the site's main plaza and behind a large pyramid temple (structure L5-1). The local deer and peccary remains came from a high status residential group south of the Bat Palace, and ritual cave deposits near the site.

Strontium outliers from Dos Pilas and Aguateca have $^{87}\text{Sr}/^{86}\text{Sr}$ values (<0.7070) similar to those found in the metamorphic province located >100 km to the south. Interaction and exchange with sites in the metamorphic province could have occurred along the Pasión River, which served as a major trade route connecting the geologically and ecologically distinct volcanic highlands and southern lowlands. The movement of highland commodities such as jade, obsidian, and ceramics into the Pasión River sites and beyond is already well-documented (Arnauld, 1990; Demarest et al., 2006; Kovacevich et al., 2005). Animal products such as meat, hides, feathers and bone artifacts may also have been traded along this route, but prior to this study, documentation of such animal exchange was not possible.

4.1.3. Piedras Negras (Guatemala)

The site of Piedras Negras is located along the Usumacinta River near the modern border between Petén, Guatemala and Chiapas, Mexico. Baseline samples ($n = 7$) from Piedras Negras yielded $^{87}\text{Sr}/^{86}\text{Sr}$ values ($\bar{x} = 0.7079$) similar to those reported in previous studies ($\bar{x} = 0.7080$) (Price et al., 2010: 26 Figure 10). Seven archaeological white-tailed deer and two peccary specimens were also sampled from the site. All but one of these animals had local $^{87}\text{Sr}/^{86}\text{Sr}$ values (Fig. 2c). The local animals at Piedras Negras were recovered from non-burial contexts within the site's epicenter. The non-local animal ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7072$) was a peccary recovered from a Late Classic (A.D. 730–830) burial within the site's acropolis. Despite the burial's location, the single adult female interred within the grave may have been sub-elite or non-elite in status due to a lack of grave goods and formal burial features (Golden, 2002: 269). The non-local peccary specimen most closely matches $^{87}\text{Sr}/^{86}\text{Sr}$ values found in the metamorphic province. Similar to the Pasión River sites, Piedras Negras is strategically situated along a major riverine trade route running between the highlands and lowlands and on to the Atlantic Gulf coast.

4.1.4. Lamanai (Belize)

Eight white-tailed deer were tested as primary samples from Lamanai. The deer were recovered from a large 15th century (Postclassic) cache deposited inside a small (5 × 5 m) platform in

Table 1
Strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) isotope results for primary zooarchaeological samples. Specimens with non-local $^{87}\text{Sr}/^{86}\text{Sr}$ values are bolded. Sites are organized by country, and roughly north to south. Summary statistics [number of samples (n), mean (\bar{x}), standard deviation (SD)] for baseline faunal samples are reported in brackets, along with the local $^{87}\text{Sr}/^{86}\text{Sr}$ range defined for each site.

Lab #	Taxa (scientific name)	Common name	Element	$^{87}\text{Sr}/^{86}\text{Sr}$
Dzibilchaltun (Mexico) [$n = 3^a$, $\bar{x} = 0.7090$, $\text{SD} = 0.0000$, local range = 0.7089–0.7090]				
DZ-3	<i>Tapirus bairdii</i>	Tapir	Molar	0.7089
DZ-4	Tayassuidae	Peccary	PM ⁴	0.7089
Colha (Belize) [$n = 1^a$, local range = ~0.7082]				
CL-1	<i>Odocoileus virginianus</i>	White-tailed deer	M ₂	0.7082
CL-2	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7083
Lamanai (Belize) [$n = 6$, $\bar{x} = 0.7080$, $\text{SD} = 0.0004$, local range = 0.7072–0.7087]				
LA-1	<i>Odocoileus virginianus</i>	White-tailed deer	M¹	0.7092
LA-2	<i>Odocoileus virginianus</i>	White-tailed deer	M¹	0.7094
LA-3	<i>Odocoileus virginianus</i>	White-tailed deer	M ¹	0.7083
LA-4	<i>Odocoileus virginianus</i>	White-tailed deer	M ¹	0.7074
LA-4B ^c	<i>Odocoileus virginianus</i>	White-tailed deer	M ¹	0.7074
LA-5	<i>Odocoileus virginianus</i>	White-tailed deer	M ¹	0.7084
LA-6	<i>Odocoileus virginianus</i>	White-tailed deer	M¹	0.7093
LA-7	<i>Odocoileus virginianus</i>	White-tailed deer	M¹	0.7091
LA-8	<i>Odocoileus virginianus</i>	White-tailed deer	M ₂	0.7084
LA-8B ^c	<i>Odocoileus virginianus</i>	White-tailed deer	M ₁	0.7084
Tipu (Belize) [$n = 3$, $\bar{x} = 0.7116$, $\text{SD} = 0.0016$, local range = 0.7085–0.7147]				
TP-1	<i>Odocoileus virginianus</i>	White-tailed deer	M ₂	0.7084
TP-2	<i>Tayassu pecari</i>	White-lipped peccary	M ²	0.7117
TP-3	<i>Mazama</i> sp.	Brocket deer	M ₂	0.7087
TP-4	<i>Mazama</i> sp.	Brocket deer	M ₂	0.7088
TP-5	<i>Pecari tajacu</i>	Collared peccary	M ₃	0.7082
TP-6	<i>Pecari tajacu</i>	Collared peccary	M ₃	0.7085
TP-7	<i>Mazama</i> sp.	Brocket deer	M¹	0.7282
TP-8	<i>Odocoileus virginianus</i>	White-tailed deer	PM₄	0.7202
TP-9	<i>Tapirus bairdii</i>	Tapir	Molar	0.7099
TP10	<i>Tapirus bairdii</i>	Tapir	Molar	0.7095
TP-11	<i>Pecari tajacu</i>	Collared peccary	M³	0.7316
Caracol (Belize) [local range = 0.7074–0.7080 ^b]				
CR-1	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7077
CR-2	<i>Odocoileus virginianus</i>	White-tailed deer	PM ₄	0.7076
CR-3	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7076
CR-4	<i>Odocoileus virginianus</i>	White-tailed deer	M ²	0.7079
CR-5	<i>Odocoileus virginianus</i>	White-tailed deer	M ₁	0.7077
CR-6	<i>Mazama</i> sp.	Brocket deer	M ₂	0.7076
CR-7	<i>Mazama</i> sp.	Brocket deer	M ³	0.7076
CR-8	Tayassuidae	Peccary	M₁	0.7131
CR-9	Tayassuidae	Peccary	I ₂	0.7076
CR-10	<i>Odocoileus virginianus</i>	White-tailed deer	M ¹	0.7077
CR-11	Tayassuidae	Peccary	M ₁	0.7077
Lubaantun (Belize) [$n = 2^{a,b}$, $\bar{x} = 0.7072$, $\text{SD} = 0.0003$, local range = 0.7065–0.7078]				
LU-1	<i>Odocoileus virginianus</i>	White-tailed deer	M ²	0.7074
LU-2	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7076
LU-3	<i>Odocoileus virginianus</i>	White-tailed deer	M ₂	0.7078
LU-4	<i>Mazama</i> sp.	Brocket deer	M ₁	0.7074
El Mirador (Guatemala) [$n = 1^a$, local range = ~0.7079]				
EM-1	Cervidae	Deer	M ¹	0.7080
EM-2	<i>Odocoileus virginianus</i>	White-tailed deer	M ₂	0.7080
Motul de San José (Guatemala) [$n = 14^{a,d,e}$, $\bar{x} = 0.7077$, $\text{SD} = 0.0002$, local range = 0.7073–0.7081]				
MSJ-1	<i>Odocoileus virginianus</i>	White-tailed deer	M ¹	0.7075
MSJ-3	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7073
MSJ-4	<i>Odocoileus virginianus</i>	White-tailed deer	M¹	0.7072
MSJ-5	<i>Odocoileus virginianus</i>	White-tailed deer	M ₁	0.7073
MSJ-6	Tayassuidae	Peccary	I ₁	0.7075
MSJ-13	<i>Odocoileus virginianus</i>	White-tailed deer	M ²	0.7075
Trinidad de Nosotros (Guatemala) [$n = 14^{a,d,e}$, $\bar{x} = 0.7077$, $\text{SD} = 0.0002$, local range = 0.7073–0.7081]				
TRI-1	<i>Odocoileus virginianus</i>	White-tailed deer	M ₁	0.7074
TRI-2	<i>Odocoileus virginianus</i>	White-tailed deer	M³	0.7069
TRI-3	<i>Odocoileus virginianus</i>	White-tailed deer	PM ⁴	0.7073
TRI-4	Tayassuidae	Peccary	M ₃	0.7075
TRI-8	<i>Odocoileus virginianus</i>	White-tailed deer	PM ⁴	0.7076
Piedras Negras (Guatemala) [$n = 7$, $\bar{x} = 0.7079$, $\text{SD} = 0.0002$, local range = 0.7075–0.7084]				
PN-1	Tayassuidae	Peccary	M₃	0.7072
PN-2	Tayassuidae	Peccary	M ₂	0.7078
PN-3	<i>Odocoileus virginianus</i>	White-tailed deer	M ¹	0.7077
PN-4	<i>Odocoileus virginianus</i>	White-tailed deer	M ¹	0.7077
PN-5	<i>Odocoileus virginianus</i>	White-tailed deer	M ¹	0.7078
PN-6	<i>Odocoileus virginianus</i>	White-tailed deer	M ₁	0.7078
PN-7	<i>Odocoileus virginianus</i>	White-tailed deer	PM ⁴	0.7077
PN-11	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7076
PN-12	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7077

Table 1 (continued)

Lab #	Taxa (scientific name)	Common name	Element	$^{87}\text{Sr}/^{86}\text{Sr}$
Dos Pilas (Guatemala) [$n = 3^e$, $\bar{x} = 0.7077$, $SD = 0.0002$, local range = 0.7073–0.7081]				
DP-1	<i>Odocoileus virginianus</i>	White-tailed deer	M²	0.7066
DP-2	Tayassuidae	Peccary	Canine	0.7075
DP-3	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7077
DP-3B ^c	<i>Odocoileus virginianus</i>	White-tailed deer	M ₁	0.7077
DP-4	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7078
DP-7	Tayassuidae	Peccary	M ₃	0.7076
Aguateca (Guatemala) [$n = 3^e$, $\bar{x} = 0.7077$, $SD = 0.0002$, local range = 0.7073–0.7081]				
AG-1	<i>Odocoileus virginianus</i>	White-tailed deer	M ₁	0.7074
AG-2	<i>Odocoileus virginianus</i>	White-tailed deer	M₃	0.7069
AG-5	<i>Canis lupus familiaris</i>	Domestic dog	Canine ^f	0.7077
AG-6	<i>Canis lupus familiaris</i>	Domestic dog	Canine ^f	0.7076
Cancun (Guatemala) [$n = 3$, $\bar{x} = 0.7074$, $SD = 0.0002$, local range = 0.7070–0.7078]				
CAN-1	<i>Odocoileus virginianus</i>	White-tailed deer	M ₂	0.7073
CAN-2	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7076
CAN-3	<i>Odocoileus virginianus</i>	White-tailed deer	M ₂	0.7075
CAN-4	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7075
CAN-5	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7073
CAN-6	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7076
CAN-7	<i>Mazama</i> sp.	Brocket deer	M ₁	0.7073
CAN-8	<i>Tayassu pecari</i>	White-lipped peccary	PM ₃	0.7074
CAN-9	<i>Pecari tajacu</i>	Collared peccary	M ²	0.7074
CAN-10	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7074
CAN-11	Tayassuidae	Peccary	M ¹	0.7074
CAN-12	<i>Pecari tajacu</i>	Collared peccary	M ³	0.7074
Copan (Honduras) [$n = 3$, $\bar{x} = 0.7063$, $SD = 0.0008$, local range = 0.7046–0.7079]				
CO-1	<i>Odocoileus virginianus</i>	White-tailed deer	M ³	0.7067
CO-2	<i>Odocoileus virginianus</i>	White-tailed deer	M²	0.7089
CO-3	<i>Odocoileus virginianus</i>	White-tailed deer	PM₃	0.7123
CO-4	<i>Odocoileus virginianus</i>	White-tailed deer	M ₃	0.7046
CO-4B ^c	<i>Odocoileus virginianus</i>	White-tailed deer	M ₁	0.7047

^a Includes samples run by T. Douglas Price (Price et al., 2010).

^b Includes samples run by Carolyn Freiwald (personal communication).

^c Repeat sample run on same individual (e.g., CO-4 and CO-4B) represent different teeth sampled from same individual.

^d One modern land snail ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7069$) was excluded when calculating the local Sr signature. The specimen's low $^{87}\text{Sr}/^{86}\text{Sr}$ value was considered anomalous because it falls outside the range of $^{87}\text{Sr}/^{86}\text{Sr}$ values ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7074$ –0.7081) reported for the region (Hodell et al., 2004; Wright, 2005a). Since land snails burrow into the soil and have highly restricted home ranges, it is possible that this individual represents a very small isolated pocket of strontium variation. Wider-ranging animals such as deer would be expected to have strontium values closer to the local average.

^e Baseline samples pooled with those from a neighboring site.

^f Canine teeth with biconical perforation through root.

the center of one of the site's main plazas. The cache contained the remains of over 34 white-tailed deer and several smashed Mayapan-style figurines, in addition to other faunal remains, ceramic artifacts, and lithic projectile points and blades (Stanchly, 2007). Baseline data from the site define the local $^{87}\text{Sr}/^{86}\text{Sr}$ range as 0.7072–0.7087. Four of the deer fall above the local range, while the other four have local signatures (Fig. 2d).

Since the cache contained ceramic figurines that likely originated from Mexico's northern Yucatan Peninsula, and specifically from the site of Mayapan (Norbert Stanchly, personal communication), the non-local cache deer were also expected to come from this region. Two of the non-local deer fall within the $^{87}\text{Sr}/^{86}\text{Sr}$ range reported for the northern lowlands ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7080$ –0.7092, $\bar{x} = 0.7088$) (Hodell et al., 2004), while the other two non-local deer fall above this range (>0.7092). All of the non-local Lamanai deer specimens have higher values than those recorded for the site of Mayapan (Gilli et al., 2009). If the deer originated from the northern Yucatan, they likely came from sites located closer to the coast where soils are derived from recent Pleistocene carbonate deposits.

Another possible origin of the non-local deer is the upper Belize River Valley. This area is located ~70–80 km southwest of Lamanai, and includes the transitional zone between the Maya Mountains and the lowland areas of northern Belize. Baseline $^{87}\text{Sr}/^{86}\text{Sr}$ values from portions of the Upper Belize River Valley, especially along the Macal River are similar to all four of the Lamanai outliers (Freiwald, 2011; Yaeger and Freiwald, 2009). The most

parsimonious explanation therefore may be that the non-local deer from Lamanai originated in the Upper Belize River Valley, rather than the northern Yucatan. Regardless of where the non-local Lamanai deer originated, it is clear that they were brought into the site as trade or tribute items since the high strontium values cannot have been derived from the local geology.

4.1.5. Sites bordering the Maya Mountains: Caracol and Tipu (Belize)

Archaeological sites located in and around the Maya Mountains of Belize have great potential in terms of strontium isotope research because the Maya Mountains are isotopically distinct from the lowlands surrounding them. Ancient populations are already known to have used the Maya Mountains as an important source of resources such as granite, quartz and slate (Shipley and Graham, 1989). The area may also have served as a source of wild game (McAnany, 1989) because it was relatively less populated than the surrounding lowlands.

The site of Caracol is located approximately 15–25 km from the igneous and metamorphic bedrock of the Maya Mountains. Ten deer and peccary from the site match local $^{87}\text{Sr}/^{86}\text{Sr}$ values reported for modern fauna (Freiwald, 2011), but one peccary has an elevated strontium ratio ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7131$), indicating that it originated in the Maya Mountains (Fig. 2e). The non-local peccary was recovered from a Late Classic burial within the site's epicenter. Based on Caracol's close proximity to the Maya Mountains, the non-local peccary could have been obtained directly through a regional

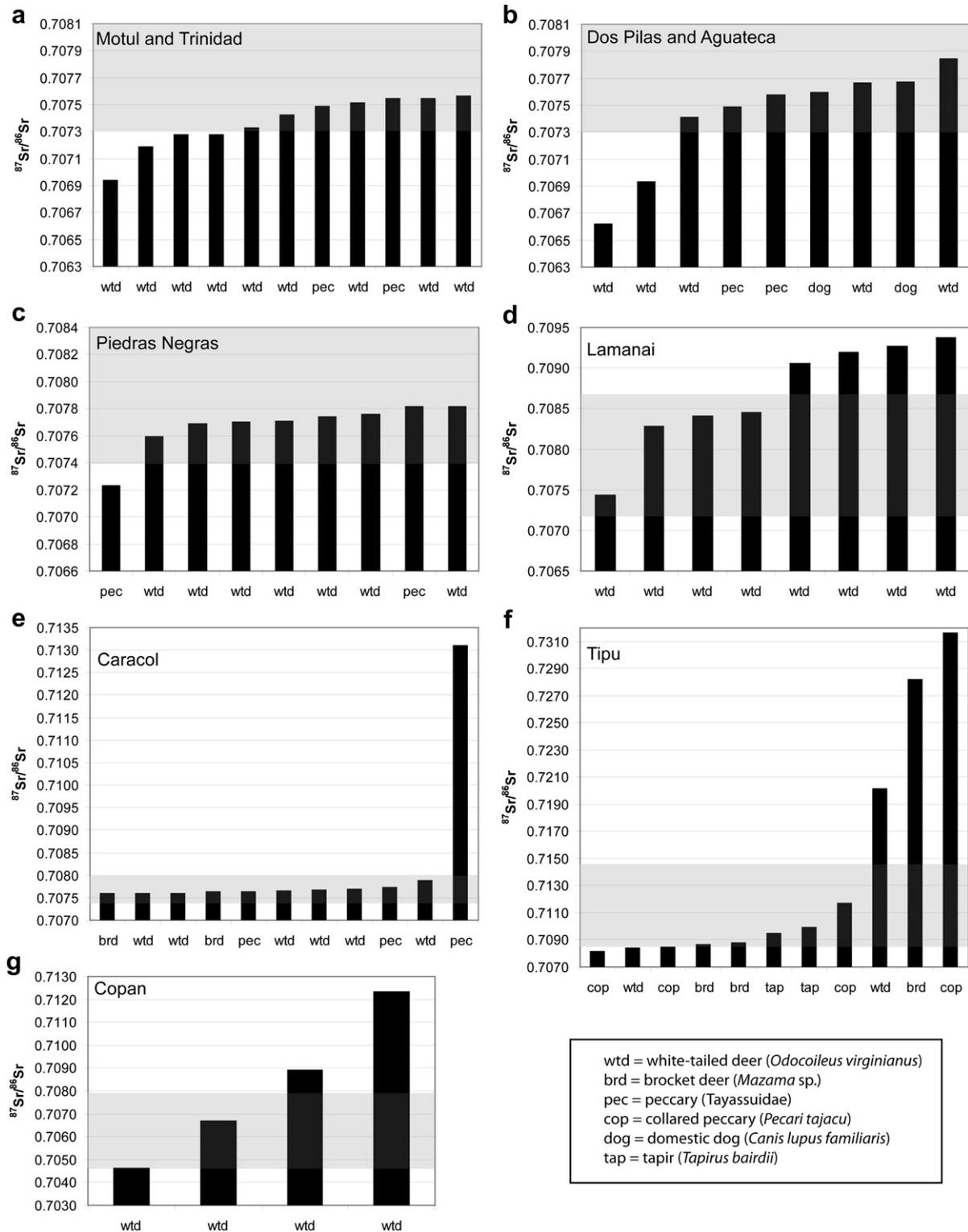


Fig. 2. $^{87}\text{Sr}/^{86}\text{Sr}$ values for primary zooarchaeological samples. Grey boxes delineate the local $^{87}\text{Sr}/^{86}\text{Sr}$ range defined for each site.

hunting excursion, or indirectly through exchange with outside communities. Another possibility is that the animal was acquired locally since the distance between Caracol and the Maya Mountains exceeds the typical home range and dispersal distance of collared peccaries, but is smaller than those reported for the wider ranging white-lipped peccary (the peccary could not be identified to the species level). Despite the peccary's possible local provenance, its

placement in a human burial suggests that greater effort was expended to acquire it through extended hunting excursions, or regional trade and tribute networks.

Unlike Caracol, which shows a lowland, carbonate-like $^{87}\text{Sr}/^{86}\text{Sr}$ signature, baseline specimens from Tipu have higher $^{87}\text{Sr}/^{86}\text{Sr}$ values due to the transport of water and sediment from the Maya Mountains into the upper Belize River valley via the Macal River.

Five of the eleven Postclassic (A.D. 1100–1520) large mammals sampled from Tipu middens have non-local strontium values (Fig. 2f). The non-local deer and peccaries with lower $^{87}\text{Sr}/^{86}\text{Sr}$ values (<0.7090) may have been acquired in the lowland valleys surrounding Tipu, while those with higher values (>0.7200) likely originated from farther away in the Maya Mountains. In all cases, the non-local specimens are examples of regional resources since $^{87}\text{Sr}/^{86}\text{Sr}$ varies over relatively short distances near Tipu. With additional baseline sampling, there is potential to use strontium isotope ratios along the borders of the Maya Mountains to study regional hunting territories or catchment zones.

4.1.6. Copan (Honduras)

Although Copan is located in the geologically diverse metamorphic province where strontium values vary greatly, previous studies have identified a much narrower local strontium signature for the site ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7063\text{--}0.7074$) (Buikstra et al., 2003; Price et al., 2007, 2008, 2010). Baseline samples from the current study indicate a slightly broader local range ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7046\text{--}0.7079$). Using this broader range, two of the four sampled white-tailed deer are non-local (Fig. 2g). Both the local and non-local deer date to the Early Classic (A.D. 400–650), and were recovered from the site's main acropolis (Bell et al., 2004). The deer with the highest $^{87}\text{Sr}/^{86}\text{Sr}$ signature was found in a disturbed royal tomb. Based on its strontium value, the tomb deer could have come from the Maya Mountains in Belize. The other non-local deer specimen ($^{87}\text{Sr}/^{86}\text{Sr} = 0.7089$) may have come from the northern lowlands.

There remains, however, the possibility that locations closer to Copan could have served as the source for both of these isotopic outliers. Within the metamorphic province, 25–50 km from Copan, $^{87}\text{Sr}/^{86}\text{Sr}$ values as low as 0.7043, and as high as 0.7202 have been recorded in plant, rock and water samples (Hodell et al., 2004). Although animals within a region should show more homogeneous $^{87}\text{Sr}/^{86}\text{Sr}$ values than those found in geological, or plant samples (Price et al., 2002), the presence of highly variable $^{87}\text{Sr}/^{86}\text{Sr}$ values within relatively close proximity to Copan leaves open the possibility that the isotopic outliers were obtained from within the metamorphic province. If this is the case, the fauna may still represent non-local resources from outside the immediate vicinity of Copan, but ones that were acquired at a regional, rather than inter-regional scale.

4.2. Faunal resource exchange and acquisition patterns

To interpret the site-specific strontium isotope results more broadly in terms of ancient Maya animal resource acquisition patterns and exchange networks, it is necessary to consider how far the animal resources were moving across the landscape, what parts of the animals were moving, and what the motivation might have been for acquiring non-local animal goods. Of these three questions, the distance at which animal resources were acquired is the most important, since the distance may determine the types of animal goods that were moved and the level and type of economic organization involved in obtaining them. For example, the non-local animals originating from within 25–30 km of the sites of Tipu and Caracol may have been acquired directly through extended hunting excursions, or through regional tribute and exchange networks established at the polity-level. At these distances, perishable subsistence resources such as meat could have been transported or traded. In contrast, animals originating from over 50 km away, as seen at Lamanai, Dos Pilas, Aguateca, and possibly Motul and Trinidad, were likely obtained through long-distance exchange networks designed to move resources between polities, or between major ecological resource zones of the Maya world. Although salt may have been used to preserve meat (Valdez

and Mock, 1991), faunal resources transported over long distances more likely included non-dietary items such as bone, shell, tooth, or hide that could have been used as ritual items, parts of costumes or regalia, personal adornments, containers, or tools. In the Lamanai cache, white-tailed deer crania are greatly over-represented (Stanchly, 2007). The non-local deer may therefore represent imported skulls, or pelt costumes rather than whole animals. This possibility is supported by zooarchaeological and ethnographic evidence for exchange (Masson and Peraza Lope, 2008) and ritual caching (Brown, 2001; Brown and Emery, 2008) of select skeletal elements such as crania within the Maya region. Other non-local deer and peccary identified in the study were found in association with post-cranial skeletal remains. These were not sampled due to potential problems with diagenesis. Future research, however, should include both cranial and post-cranial elements to determine whether whole animals, or just portions of animals (e.g., hides, teeth, crania, hind haunches) were transported and exchanged. This determination is important to understanding whether non-local animals were used for dietary or non-dietary purposes. If non-local animals were consumed, the strontium isotope composition of human dietary resources may have been much broader than previously thought. A similar possibility has been suggested by Wright (2005a, b) who hypothesized that consumption of imported marine salt could elevate human $^{87}\text{Sr}/^{86}\text{Sr}$ values above the expected local geological signature. These findings have important consequences for human mobility studies within Mesoamerica.

Future research should also focus on identifying the distribution of non-local animals within sites according to social status and archaeological context. All ritual contexts included in this study (two burials, one cache, and the Aguateca chasm) contained non-local animals. The small number of sampled ritual contexts ($n = 4$) could skew the results, but burials and caches often contain other non-local animal resources such as marine shells, pearls and stingray tail spines (Moholy-Nagy, 2004; Pohl, 1983). Strontium isotope analysis can determine whether many of the other animals included in ritual deposits were also non-local. If so, this would suggest that the distance and effort involved in obtaining burial goods, or the personal and community relationships that such acquisition implied, was important in determining what animals and animal products were used for ritual purposes.

All non-local animals identified in this study also come from high status deposits within the various sites' epicenters. The ruling elite could have maintained preferential access to non-local animals through the extraction of tribute and taxation from outside communities, or through gift exchange with rulers of other sites to forge or reaffirm alliances. Such economic interactions may have been critical components of Maya rulers' political power strategies (Ball, 1993; McAnany, 2004). Additional analysis of faunal samples from contexts of varying social status is needed to determine whether regional and long-distance exchange of animals primarily served to supply the Maya elite with high status items, or whether non-local animals were distributed to a wider segment of society, perhaps in response to local faunal scarcity due to over-hunting or deforestation.

5. Conclusions

Strontium isotope analysis is a promising means of identifying and sourcing non-local animals in the Maya region. Although most of the sampled animals have local $^{87}\text{Sr}/^{86}\text{Sr}$ values, non-local fauna identified at nine of the fourteen study sites indicate that regional and long-distance acquisition and exchange of animals among the ancient Maya was more common than previously assumed. Moreover, isotopic analysis revealed that large mammals such as

white-tailed deer and peccaries were also transported and exchanged over long distances. These taxa are almost always classified as local resources at non-coastal sites. The data therefore provide novel evidence for exchange of large-bodied terrestrial mammals within the interior of the Maya lowlands. This finding expands upon previously recognized regional and long-distance exchange of animals between major resource zones (i.e., coastal-inland and highland-lowland exchange). As baseline data for the Maya region increases, this method may shed additional light on faunal resource acquisition and exchange, especially since this method may be applied to highly modified bone and tooth artifacts, and wide-ranging species such as deer, peccaries, large felids, and dogs, which are usually unsourceable using traditional zooarchaeological methods. The strontium dataset further contributes to the rapidly growing database of strontium isotope ratios available for the Maya area. This will inform future studies of human migration in Mesoamerica, by establishing the biological strontium signature of known dietary commodities.

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