



Earliest isotopic evidence in the Maya region for animal management and long-distance trade at the site of Ceibal, Guatemala

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This study uses a multiisotope (carbon, nitrogen, oxygen, and strontium) approach to examine early animal management in the Maya region. An analysis of faunal specimens across almost 2,000 years (1000 BC to AD 950) at the site of Ceibal, Guatemala, reveals the earliest evidence for live-traded dogs and possible captive-reared taxa in the Americas. These animals may have been procured for ceremonial functions based on their location in the monumental site core, suggesting that animal management and trade began in the Maya area to promote special events, activities that were critical in the development of state society. Isotopic evidence for animal captivity at Ceibal reveals that animal management played a greater role in Maya communities than previously believed.

Maya archaeology | isotope analysis | zooarchaeology

Unlike other regions of the world where intensive animal domestication developed as a means to sustain growing human populations in early urban communities, in Mesoamerica mounting evidence suggests that captive rearing and animal trade were directly linked to displays of political and social strength (1–3). To better understand the origins of animal management in the Maya area, we conducted a multifocal isotopic investigation on the archaeological fauna from Ceibal, Guatemala. Ceibal was an important Maya urban center with a nearly 2,000-y occupational history (1000 BC to AD 950), allowing for a long-term examination of animal-related activities. Ceibal's Central Plaza and monumental site core were among the earliest in the Maya region (4–6). We demonstrate that animals deposited in construction fills and midden material in and around the Central Plaza contained a mix of local and nonlocal individuals. This study reveals the earliest isotopic evidence of live animal trade in the Americas, coinciding with the Maya Middle Preclassic period (700–350 BC), as well as early evidence of possible captive animal rearing or garden hunting. These activities likely promoted the community's economic growth and political development. Our results suggest that captive animal rearing and long-distance trade took place in Mesoamerica far earlier than has been believed, and that such activities were integral for the development of ceremonial and political power in the Maya region.

The Site of Ceibal

Ceibal has one of the earliest and longest occupations of any site in the Maya region, due to its strategic location on the Pasión River (Fig. 1; refs. 4–7). Radiocarbon and ceramic dating suggest that the Central Plaza and surrounding platforms were constructed at the beginning of Ceibal's history (~1000 BC; Table S1), and were among the first monumental construction efforts in the Maya lowlands. These projects and public ceremonies, possibly sponsored by the emerging elites, likely attracted inhabitants of the surrounding region. Ceibal grew to be the largest community in the southwestern Maya lowlands during the Late and Terminal Preclassic periods (350 BC to AD 175; refs. 7–9).

Ceremonial deposits of greenstone axes and obsidian artifacts attest to Ceibal's trade relations with various areas, including the Gulf Coast and Guatemalan highlands (4, 10, 11). After a significant demographic decline during the Early Classic period (AD 175–600), Ceibal recovered to become a major political power under a dynastic rule during the Late Classic period (AD 600–810). Ceibal's two-millennia history allows archaeologists the unique opportunity to examine the early use of animals and its long-term trend.

Isotope Analysis and Animal Management

Isotope analysis was used in this study to assess whether animals were reared in captivity at Ceibal, and whether any terrestrial mammals were imported to Ceibal from another region. A detailed description of isotope methods used in this study is presented in *Isotope Analysis Methods*. We sampled 10 taxa (Table 1), with a focus on the mammals most commonly found at the site, dogs and deer (*Canis lupus familiaris* and *Odocoileus virginianus*), to assess how the Ceibal inhabitants used different species. Specimens were selected from multiple locations around the central site core (group A; Fig. S1), from the outlying residential groups, and from a satellite community, Caobal (12, 13). Specimens were selected from multiple time periods to gauge changes over time.

Significance

The nature of animal management in Mesoamerica is not as well understood compared with other state-level societies around the world. In this study, isotope analysis of animal remains from Ceibal, Guatemala, provides the earliest direct evidence of live animal trade and possible captive animal rearing in the Maya region. Carbon, nitrogen, and oxygen isotopes show that domesticated and possibly even wild animals were raised in or around Ceibal and were deposited in the ceremonial core. Strontium isotope analysis reveals the Maya brought dogs to Ceibal from the distant Guatemalan highlands. The possible ceremonial contexts of these captive-reared and imported taxa suggests animal management played an important role in the symbolic development of political power.

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Fig. 1. Map of the Maya region with strontium and oxygen isotope values. $^{87}\text{Sr}/^{86}\text{Sr}$ values from ref. 44, with 2σ range around each regional average. Carbonate $\delta^{18}\text{O}$ values using human bone apatite and tooth enamel from previously reported studies (refs. 34 and 35 for the lowlands; ref. 36 for the highlands). Reprinted with permission from ref. 5.

Stable carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotopes from bone collagen can assess whether animals were fed maize-based diets, the primary grain in Mesoamerica, while held in captivity (14, 15). The $\delta^{13}\text{C}$ values in terrestrial animals vary depending on the proportion of plants they consume that undergo either C3 or C4 photosynthesis. C3 plants have $\delta^{13}\text{C}$ values that average -26‰ , whereas C4 plants, such as maize (*Zea mays*) and arid-adapted tropical grasses, average -12‰ (16–18). At Ceibal, high $\delta^{13}\text{C}$ values would be expected from animals consuming predominantly maize, or animals consuming maize-eating prey, since there are relatively few other elevated $\delta^{13}\text{C}$ sources. $\delta^{13}\text{C}$ in bone apatite and

tooth enamel apatite ($\delta^{13}\text{C}_{\text{ap}}$ and $\delta^{13}\text{C}_{\text{en}}$) reflects the total diet, whereas $\delta^{13}\text{C}$ from collagen ($\delta^{13}\text{C}_{\text{co}}$) comes from protein. Due to this fractionation, $\delta^{13}\text{C}_{\text{ap}}$ and $\delta^{13}\text{C}_{\text{en}}$ values are often shifted toward more positive values compared with collagen. $\delta^{15}\text{N}$ values in bone collagen reflect the amount of protein in an animal's diet (19), which may show whether carnivores or omnivores like dogs were given different diets intentionally by their human owners (for example, hunting dogs as opposed to dogs reared for human consumption).

Previous studies of animal diet in Mesoamerica have focused on the Classic and Postclassic periods (AD 200 and later), since there have been more sites excavated from these later periods. Dogs and turkeys have been the focus of many of these investigations since they were domesticated. Isotope studies found evidence that some dogs consumed high quantities of maize (15, 20), corroborating Spanish accounts and Classic period art that depict dogs fattened for human consumption and ritual sacrifice (21–23); however, this has not been consistently demonstrated at every center (24). Evidence of maize-fed turkeys has proven to be more complex and is dependent on whether the turkey is of the northern (*Meleagris gallopavo*, also known as the “wild” and “domesticated” turkey) or ocellated (*Meleagris ocellata*) species, as well as the chronological period and region, likely due to the long and complex history of turkey domestication (3, 25, 26). Similarly, while recent isotope studies at the large Classic period city of Teotihuacan in Central Mexico have found evidence of captive-reared rabbits (14) and even ceremonially killed felines, wolves, and eagles (2), comparable evidence has been absent in the Maya area, as well as from the Preclassic record across Mesoamerica in general.

Strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) and oxygen ($\delta^{18}\text{O}$) isotopes were used in this study to assess whether terrestrial animals were imported to Ceibal from distant locations. Strontium isotope ratios in animal bones and teeth reflect the $^{87}\text{Sr}/^{86}\text{Sr}$ value of the local geology in a region (Fig. 1 and Dataset S1; refs. 27 and 28). Nonlocal animals have $^{87}\text{Sr}/^{86}\text{Sr}$ values that differ from the local area. Migration studies in Mesoamerica have focused on human remains (29), although a handful have assessed the movement of animals across the landscape as well (30, 31). Thornton (31) found evidence of occasional nonlocal deer and peccaries at Maya sites in Guatemala and Belize, indicating that such animals were exchanged during the Classic and Postclassic periods, perhaps as part of the market economy that existed by that time (32, 33). Before the present

Table 1. Summary mean statistics to 1 SD by taxon for bone and tooth enamel sampled for all time periods

Taxon	Bone			$^{87}\text{Sr}/^{86}\text{Sr}$	Tooth enamel		
	$\delta^{15}\text{N}_{\text{co}}$ (‰, vs. AIR)	$\delta^{13}\text{C}_{\text{co}}$ (‰, vs. PDB)	$\delta^{13}\text{C}_{\text{ap}}$ (‰, vs. PDB)		$\delta^{13}\text{C}_{\text{en}}$ (‰, vs. PDB)	$\delta^{18}\text{O}_{\text{en}}$ (‰, vs. PDB)	$^{87}\text{Sr}/^{86}\text{Sr}$
Domestic dog	9.2 ± 1.4 (10)	-11.5 ± 2.4 (10)	-7.9 ± 1.1 (9)	0.70737 ± 0.0003 (4)	-5.5 ± 2.6 (22)	-3.7 ± 1.0 (22)	0.70742 ± 0.00053 (23)
White-tailed deer	4.9 ± 1.6 (21)	-21.3 ± 1.1 (21)	-10.9 ± 1.6 (22)	0.70761 ± 0.0001 (9)	-13.5 ± 0.6 (3)	-2.0 ± 0.7 (3)	0.70758 ± 0.00012 (3)
Peccary	4.6 ± 0.9 (6)	-19.7 ± 2.8 (6)	-10.5 ± 1.7 (6)		-6.7 (1)	-3.6 (1)	0.70745 (1)
Large feline	9.1 ± 1.9 (2)	-17.4 ± 3.0 (2)	-10.6 ± 2.7 (2)	0.70752 (1)	-8.4 (1)	-3.4 (1)	0.70753 ± 0.00002 (2)
Margay					-15.1 (1)	-2.9 (1)	0.70749 (1)
Tapir					-15.2 ± 1.7 (2)	-6.1 ± 2.3 (2)	0.707432 ± 0.00008 (2)
Lowland paca	4.6 (1)	-21.0 (1)	-11.1 (1)	-2.9 (1)			
Opossum					-13.5 (1)	-2.1 (1)	0.70750 (1)
Northern turkey	7.6 ± 1.8 (2)	-8.9 ± 1.1 (2)	-5.2 ± 0.1 (2)	0.70747 ± 0.00001 (2)			
Ocellated turkey	8.6 (1)	-17.8 (1)	-9.1 (1)				
Unidentified turkey	5.3 ± 0.2 (2)	-18.4 ± 6.1 (2)	-8.9 ± 3.6 (2)				

Parentheses indicate number of individuals sampled. See Dataset S2 for all data.

study, no investigation had assessed whether animals were moved across the landscape before the Late Classic period.

Oxygen has largely been used in studies of human migration in the Maya area in conjunction with strontium (34–36). Recent studies (37) of modern $\delta^{18}\text{O}$ annual variability in rain and surface water found that some sources, particularly closed sources like ponds, demonstrate significant $\delta^{18}\text{O}$ variability throughout the year and might complicate sourcing studies that rely on regional oxygen baselines (38). Physiological investigations have also found that $\delta^{18}\text{O}$ reflects the extent to which an animal obtains water either from terrestrial water sources or from plant material, the type of plant matter an animal consumes (i.e., C3 plants tend to have higher $\delta^{18}\text{O}$ than C4 plants), and metabolic variation, three factors that must be taken into consideration when interpreting $\delta^{18}\text{O}$ among several taxa (39–42). Due to the number of variables that may affect $\delta^{18}\text{O}$ values, the present study only uses $\delta^{18}\text{O}$ to corroborate the strontium and carbon data.

Results

Table 1 lists a statistical summary of the 10 species' isotope values, expanded in [Dataset S2](#). Regarding collagen, results of the $\delta^{13}\text{C}_{\text{co}}$ and $\delta^{15}\text{N}$ analysis of animal diet show that the Ceibal fauna tend to fall into two groups (Fig. 2). One group has lower $\delta^{15}\text{N}$ (<8.0‰) and $\delta^{13}\text{C}_{\text{co}}$ (less than -17.0 ‰), whereas the other has greater values of both isotopes ($\delta^{15}\text{N} \sim$ more than 6.0‰, $\delta^{13}\text{C}_{\text{co}} \sim$ more than -17.0 ‰). The former group's values are expected of animals that consume C3 plant material in the forest (17); the latter group with higher values are expected from animals that eat a partial maize diet or prey that has eaten maize. The group with higher $\delta^{15}\text{N}$ and $\delta^{13}\text{C}_{\text{co}}$ values includes the dogs from all periods, the two northern turkeys (*M. gallopavo*, confirmed by ancient DNA analysis), and one of the two large wild cats (mandible specimen no. 34 and its molar, specimen no. 35), possibly a jaguar (*Panthera onca*) based on mandibular morphology and size. The ulna of another large feline and the molar of a smaller feline identified as a margay (*Leopardus wiedii*; specimen nos. 36 and 37), both found behind the Terminal Classic (AD 810–950) palace, had much lower $\delta^{13}\text{C}_{\text{co}}$ and $\delta^{13}\text{C}_{\text{en}}$ values, respectively, indicating the two felines from this period consumed the meat of forest-dwelling animals. One turkey that could not be identified to the species level (specimen no. 78) and one peccary (specimen no. 64) have

$\delta^{13}\text{C}_{\text{co}}$ values above -15 ‰ and $\delta^{15}\text{N}$ values below 6‰, indicating that they may also have been consuming higher quantities of maize than the cluster of animals with lower carbon isotope values, but also lower quantities of protein than the dogs and northern turkeys. The bone $\delta^{13}\text{C}_{\text{ap}}$ values corroborate this division (Fig. S2), with one Middle Preclassic dog (specimen no. 12) exhibiting lower carbon isotope values than the others ($\delta^{13}\text{C}_{\text{ap}} = -10.3$ ‰) and overlapping with the deer that appear to be consuming a mainly C3 forest diet.

Carbon isotope results from tooth enamel apatite also reflect the division between animals consuming a mainly C3 plant diet and a C4 grass (likely maize) diet (Fig. 2). One peccary tooth from the Early Classic period (specimen no. 68, AD 400–500) had elevated $\delta^{13}\text{C}_{\text{en}}$ (-6.7 ‰), indicating that it also may have been consuming C4 plants when the enamel formed while it was young. The enamel and bone apatite and collagen was tested from seven of the dogs (dogs A through G on [Dataset S2](#)), and the large feline with the elevated $\delta^{13}\text{C}$, to determine whether these animals had consumed similar diets from a young age (the enamel $\delta^{13}\text{C}$) to adulthood (bone apatite and collagen $\delta^{13}\text{C}$). The elevated carbon ratio was found in both the bone and enamel of the adult feline (specimen nos. 34 and 35, $\delta^{13}\text{C}_{\text{co}} = -15.2$ ‰, $\delta^{13}\text{C}_{\text{ap}} = -8.7$ ‰, and $\delta^{13}\text{C}_{\text{en}} = -8.4$ ‰), implying that it had consumed the same elevated $\delta^{13}\text{C}$ diet since it was a cub and so may have been raised in captivity. Collagen from this feline's mandible bone and molar roots were radiocarbon dated to the end of the Middle Preclassic period (450–350 BC; [Table S2](#)).

The $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ data show compatible evidence that terrestrial fauna were imported to Ceibal, although only during the Preclassic period. The local $^{87}\text{Sr}/^{86}\text{Sr}$ baseline value for Ceibal is 0.70749 ([Dataset S1](#)). $^{87}\text{Sr}/^{86}\text{Sr}$ results of the archaeological fauna show that 44 of the 46 animals tested fall within the local Ceibal and southern lowlands range (Fig. 3 and [Fig. S3](#)). Local $\delta^{18}\text{O}$ values for the southern lowlands vary between -4.5 and -1 ‰ (Fig. 1), which also appears to be the case for all but three of the animals. Two Preclassic dogs (specimen nos. 1–2 and 5–6, hereafter dog A and dog C) and one Preclassic tapir (*Tapirella bairdii*, specimen no. 70) may have come far from Ceibal based on their anomalous $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ values, and likely even outside the Maya lowlands in the case of the dogs. These two dogs' enamel $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ values were outliers, but their bone apatite values

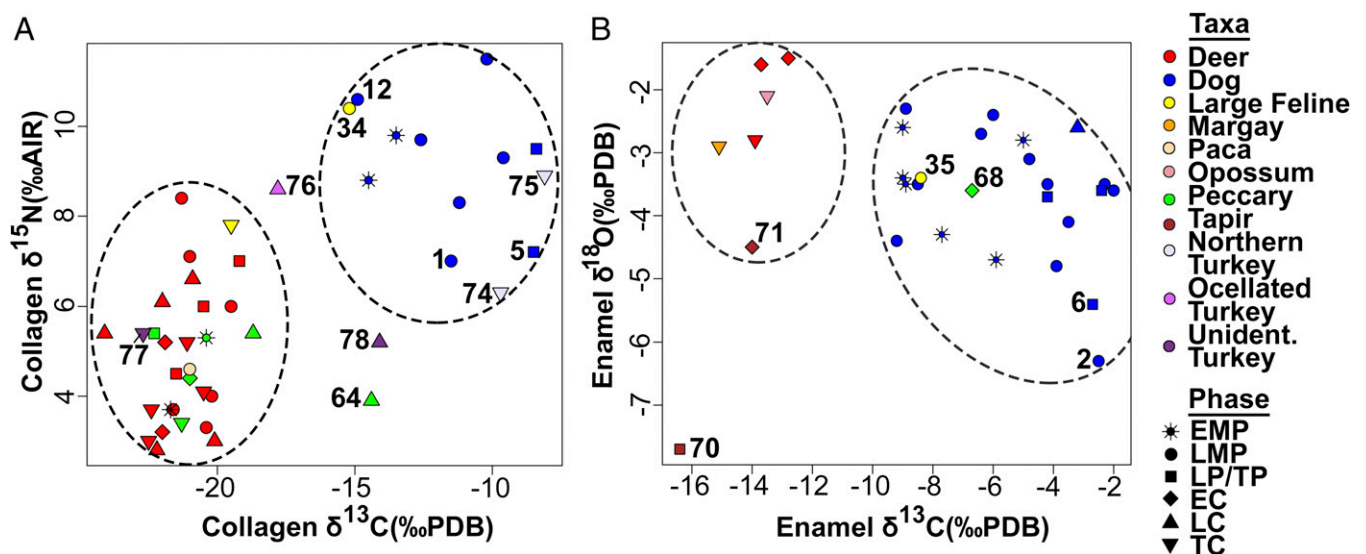


Fig. 2. Ceibal fauna (A) bone collagen and (B) tooth enamel. Specimens mentioned in the text are numbered. The two encircled regions on both graphs denote greater reliance on C3 (Left) and C4 (Right) plants. EC, Early Classic (AD 175–600); EMP, Early Middle Preclassic (1000–700 BC); LC, Late Classic (AD 600–810); LMP, Late Middle Preclassic (700–350 BC); LP/TP, Late Preclassic/Terminal Preclassic (350 BC to AD 175); TC, Terminal Classic (AD 810–950).

of felines living near modern agricultural plots in lowland Mesoamerica, to use for comparison. At the Classic period city of Teotihuacan, Sugiyama et al. (2) determined that jaguars, pumas, wolves, and eagles that had been buried in elaborate deposits in the Moon and Sun Pyramids had high $\delta^{13}\text{C}$ values (complete feline skeletons had significantly higher $\delta^{13}\text{C}_{\text{co}}$ than incomplete skeletons, ranging $-12 \pm 3.9\%$, with three values exceeding -10%). They posited that these animals were held in captivity for ceremonial functions and were fed the meat of maize-eating animals, including possibly humans, thus contributing to their ^{13}C -enriched diets. Classic period Maya art also shows live spotted feline cubs in captivity, as depicted on several stelae from Xultun (46). It is possible that the feline found in the Middle Preclassic monumental structure at Ceibal was reared for similar ceremonial performances, perhaps under the aegis of one of the members of the developing class of elite as a symbol of political power.

A Late Preclassic tapir molar found in the Central Plaza (specimen no. 70) had a $\delta^{18}\text{O}_{\text{en}}$ value that fell far below the lowlands' range. The tapir's $^{87}\text{Sr}/^{86}\text{Sr}$ value (0.70737) is low but within the lowland 2σ range. It may have originally come from an area to the south of Ceibal where strontium ratios are lower (44), although the Chiapas area in Mexico is also a possibility since it has not been extensively tested for baseline $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ values. Previous studies (47) of modern tapir enamel $\delta^{18}\text{O}$ have found that such low values ($\sim 7\text{--}8\%$) are often dependent on low regional precipitation, which means the tapir may have come from an area with low rainfall. The second tapir tooth in this study (specimen no. 71), which came from an Early Classic (AD 175–300) outlying residence, had a local lowland $\delta^{18}\text{O}_{\text{en}}$ value of -4.5% . The Late Preclassic tapir tooth may have been an adornment that belonged to a visitor to Ceibal, or was imported to the site. Its discovery in the Central Plaza suggests that its deposition may have been related to activities that took place in that area, including ceremonies.

Of the other Preclassic period animals tested in this study, the remaining dogs show consistently elevated $\delta^{13}\text{C}$ values. Specimen no. 12's unusual $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values (Fig. 2) indicate it had a unique low-maize, high-protein diet and may have been a hunting dog. The other taxa have much lower $\delta^{13}\text{C}$ characteristic of C3 plant consumption or, in the case of the carnivores, meat from animals that consumed C3 plants. These animals were likely hunted from the local forest based on their $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ values (Fig. 3).

The Classic Period (AD 175–950). The Ceibal inhabitants appear to have continued hunting animals from the forest during the Classic period, with several significant exceptions. Few dog remains were recovered in the Classic period at Ceibal, resulting in only a single dog tooth (specimen no. 28) tested from this time in the site's history. The isotopic data reveal two instances of maize-reared and possibly domesticated turkeys (*M. gallopavo*), and two peccaries that were possibly consuming maize as well, all within the monumental site core. This suggests that wild animal rearing, which perhaps began during the Preclassic period, was more taxonomically diverse during the Classic period, and included potentially early domestication of the *M. gallopavo* species of turkey.

No turkeys have been recovered from the Preclassic contexts at Ceibal, although representatives of both turkey species are present throughout the Classic phases. The northern and ocellated turkey are distinct isotopically. The two northern turkeys had higher $\delta^{15}\text{N}$ than many of the herbivores (Fig. 2), consistent with their omnivorous diet that includes insects and possibly human feces that are enriched in $\delta^{15}\text{N}$ (26, 48). They also had higher $\delta^{13}\text{C}_{\text{co}}$ (more than -10%) than the majority (39 of 45) of specimens tested in this study, perhaps because much of their diet consisted of maize. These values conform with previous reports of northern turkey values during the Classic and Colonial periods, where $\delta^{13}\text{C}_{\text{co}}$ tends to exceed -11% and $\delta^{15}\text{N} > 6\%$ (26). The confirmed ocellated turkey and the two unidentified

turkeys have lower $\delta^{13}\text{C}$, suggesting they lived in a forested environment or, in the case of specimen no. 78, occasionally browsed on C4 vegetation. Although more work is still needed to distinguish maize-fed from garden-foraging turkeys (16), it is possible the latter bird was hunted from an agricultural field.

The majority of the peccaries tested in this study had $\delta^{13}\text{C}$ values indicative of C3 plant consumption, likely from the forest. However, two peccaries (specimen nos. 64 and 68) consumed higher quantities of C4 plants than the other individuals. Specimen no. 64 came from the Late Classic (AD 600–700) palace, and, because its carbon signature ($\delta^{13}\text{C}_{\text{co}} = -14.4\%$) is not as high as the dogs, may have consumed maize from an agricultural field as a crop forager. Like turkeys, more actualistic data are needed to isotopically distinguish crop foraging peccaries from maize-fed individuals. Specimen no. 68, an incisor from an elite Early Classic (AD 400–500) structure, had a high $\delta^{13}\text{C}_{\text{en}}$ value (-6.7%) like that of the dogs at the site (Fig. 2), suggesting it had an elevated C4 diet when it was very young and the tooth enamel originally formed, and so may have been raised in captivity.

The remaining animals of the Classic period, including the 14 deer, the three other peccaries, a tapir, a large feline, a margay, and an opossum (*Philander opossum*), had very low carbon isotope values and local oxygen and strontium isotope ratios (Table 1 and Dataset S2). This suggests that these animals were locally hunted. The differences in $\delta^{15}\text{N}$ values exhibited among the deer are possibly due to variations in the N-fixing bacteria in the soil where the deer browse, as well as varying processes of nitrification and denitrification as a result of climatic effects on soil runoff (49). There is no temporal pattern exhibited in the isotope values in the deer remains, suggesting the reliance on locally hunted deer did not change over the centuries.

Conclusions

The presence of nonlocal dogs, an imported tapir tooth, and several possible cases of captive-reared animals in and around the ceremonial core of Ceibal suggests that Maya communities managed and moved animals across the landscape centuries earlier than has been believed. The Preclassic dogs found in the early monumental structures that appear to have been born in or near the Guatemala highlands indicate the original purposes of animal trade may have been to augment ceremonial events as the first state-level communities developed. Increased evidence of potentially maize-fed animals during the Classic period, particularly the northern turkey, a species that was in the process of domestication during that time, suggests animal management practices intensified during the Classic period. It is also possible that some animals like peccaries and turkeys were hunted as crop foragers, but further isotope studies to more clearly distinguish captive-reared and foraging animals are needed. Overall, the complex human–animal interactions identified in this study demonstrate the need for further multiisotope investigations in the Maya area, for it appears that live animal trade and management may have played a significant role in societal development.

Methods

Archaeological faunal specimens used in this study were collected by the Ceibal-Petexbatun Archaeological Project and imported to the United States with permission of the Guatemala Institute of Anthropology and History (Instituto de Antropología e Historia), under permit no. DAJ-DGPCYN/196/2013. Specimens were identified using the Florida Museum of Natural History's comparative skeletal collections. Cleaning and initial preparation of specimens, including enamel drilling, sample grinding, separation of bone collagen and apatite fractions, and removal of contaminants through chemical washes, was performed in the Bone Chemistry Laboratory of the University of Florida (UF) Department of Anthropology (*Isotope Analysis Methods*). The isotopes $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and $\delta^{18}\text{O}$ were analyzed with Carlo Erba-Delta V and Finnegan MAT 252 isotope ratio mass spectrometers in the Light Stable Isotope Mass Spectrometer Laboratory at the UF Department of Geological Sciences. Bone apatite and enamel $^{87}\text{Sr}/^{86}\text{Sr}$ were extracted through ion chromatography in the class

1000 clean laboratories at the UF Department of Geological Sciences and analyzed with a Nu-Plasma multiple-collector inductively coupled plasma mass spectrometer. Radiocarbon dating was performed on bone collagen of specimen nos. 1, 5, and 34 at Beta Analytic. We refined these dates using Bayesian analysis with the OxCal 4.2 program and the IntCal13 calibration curve (Fig. S4 and Table S2).

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