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ORIGINAL PAPER

Aztec diets at the residential site of San Cristobal Ecatepec through stable carbon and nitrogen isotope analysis of bone collagen

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Abstract

This paper presents the first systematic study of Aztec diets using bone collagen stable carbon and nitrogen isotope analysis. The objective was to identify the dietary patterns of an Aztec community living in the Basin of Mexico. The collection analyzed includes adult and subadult skeletons from the residential site of San Cristóbal Ecatepec (in present-day Mexico State) (A.D. 900–1521). The isotopic data were compared with available ethnohistoric and archeological information about Aztec diets. We conclude that Ecatepec residents consumed mostly C_4 and CAM plants (as opposed to C_3 plants), terrestrial animals, and some lacustrine resources. They shared similar diets and foodways, as indicated by the fact that they belonged to the same socio-economic group and that there were no substantial sex-based differences indicated by the isotopic data. The slightly higher carbon isotope compositions of the men compared with the women could be evidence of *pulque* consumption by the men—as noted in the ethnohistoric record. The nitrogen isotope compositions of the subadults, however, show some variability related to breastfeeding and weaning practices, with infants weaning between 2 and 4 years of age.

Keywords Aztec diets · Ecatepec · Paleodiet · Stable isotope analysis · Carbon and nitrogen isotopes · Bone collagen

Introduction

The application of stable carbon and nitrogen isotope analysis of human skeletons has been a powerful tool for gaining insights into Mesoamerican foodways and paleodiets. Previous studies include the Maya region (e.g., Metcalfe et al. 2009; Powis et al. 1999; Tykot 2002; White and Schwarcz 1989; White et al. 1993, 2001) and Central Mexico at the Classic period site of Teotihuacan (Casar et al. 2017a, b; Morales Puente et al. 2012; Nado et al. 2017; White et al. 2004a, b). In the case of the Aztecs, most of the evidence about their diets and foodways has been provided by ethnohistoric, iconographic, and archeological records. Direct evidence of Aztec diets via stable isotope analyses of human skeletons has been lacking. This paper presents the first systematic paleodietary study of Aztec diets during the Postclassic period (A.D. 900–1521) via bone collagen stable carbon and nitrogen isotope analysis of adult and subadult skeletons from the residential site of San Cristóbal Ecatepec (in present-day Mexico State) (Fig. 1). Our first objective is to identify the overall dietary patterns of an Aztec community living in the Basin of Mexico using stable isotopes and to compare these patterns with the ethnohistoric and archeological evidence available on Aztec diets. Our second objective is to assess dietary variability within this Aztec community by exploring dietary similarities and differences by sex and age.

San Cristóbal Ecatepec (henceforth referred to as "Ecatepec") is located northeast of Tenochtitlan, near the Texcoco and Xaltocan lakes (Fig. 1), and is a residential site associated with lacustrine activities that features an

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ancient open-air artificial mound (*tlatel*); excavations in 2004–2005 recovered the remains of a house with eight rooms, a patio, a hearth (*tecuil*), and two pre-Hispanic sweat lodges (*temazcales*) (García Chávez et al. 2006; Trejo Rangel 2014). The excavations revealed that the site was occupied during the Classic (Tlamimilolpa phase (A.D. 200–350)) and Postclassic periods (Mazapa (A.D. 800–1150), Aztec III (A.D. 1430–1500), and Aztec IV phases (A.D. 1500–1521)). The site may have specialized in the production of salt and textiles, which eventually made it to Tenochtitlan as tribute (Trejo Rangel 2014). According to Trejo Rangel (2014), based on the ethnohistoric sources (i.e., *Matricula de Tributos*, *Lamina 5*), this site belonged to the lowest settlement level (i.e., *calpulli*) of the *altepetl* system[1] within the Basin of Mexico.

Thirty-four human burials composed of forty-five individuals including infants, children, and adults were found underneath the house floor throughout the site's occupation (García Chávez et al. 2006; Trejo Rangel 2014). Thirteen burials are associated with the Tlamimilolpa, one burial with the Mazapa, and twenty burials with the Aztec III–IV phases. For the purpose of this study, only Postclassic individuals from primary burials were sampled: ten infants (birth–3 years), three children (4–14 years), and eleven adults (15+ years) (six males, five females), two dating to the Mazapa and twenty-two to the Aztec III–IV phases. Dental pathologies, such as caries, dental calculus, and alveolar resorption, were present in the adult individuals but in low frequencies and at a low level of severity (Trejo Rangel 2014). Other pathologies include osteoarthritis (particularly in the spine) and infectious diseases, expressed in long bones and the clavicle. Given that these individuals resided in a single house, we assume that they belonged to the same socio-economic group. These individuals were long-term residents of the Basin of Mexico, based on the results of their bone phosphate-oxygen isotope analysis (Moreiras Reynaga 2019). Based on the geographic location of this site, the ethnohistoric information available on Aztec diets, and zooarchaeological and paleobotanical evidence recovered from nearby sites, we hypothesize that the individuals at Ecatepec had a diverse and well-rounded diet that included plant and animal protein from terrestrial as well as lacustrine ecosystems.

Stable carbon and nitrogen isotope systematics

Stable carbon ($^{13}C/^{12}C$) and nitrogen isotope ratios ($^{15}N/^{14}N$) are expressed in delta (δ) notation relative to an internationally accepted standard in parts per thousand (per mil; ‰): e.g., $\delta^{13}C = (^{13}C/^{12}C_{sample} - ^{13}C/^{12}C_{standard})/(^{13}C/^{12}C_{standard})$. The standard (VPDB for $\delta^{13}C$ and AIR for $\delta^{15}N$) is assigned a value of 0‰ exactly.

Stable carbon and nitrogen isotope analyses of skeletal remains have been extensively applied in bioarchaeology to reconstruct the diets of ancient populations. Plants, animals, and humans obtain their carbon and nitrogen isotope compositions based on their trophic position in the food web and the foods they consumed during their lifetime. This allows differentiation between consumers (e.g., herbivores, carnivores) and their respective diets. The $\delta^{13}C$ and $\delta^{15}N$ in bone collagen are commonly preserved after death and hence useful for paleodietary reconstructions—except when chemical alteration or contamination occurs after death.

The main drivers of isotopic variation at the base of food webs in terrestrial and aquatic ecosystems include multiple environmental and climatic factors and the photosynthetic pathways used by plant species (Dawson et al. 2002; Farquhar et al. 1989; Kohn and Cerling 2002; Lee-Thorp 2008). Most plants (e.g., wheat, trees, vegetables, fruits) follow the C_3 photosynthetic pathway, which preferentially incorporates ^{12}C. As such, they are characterized by very negative $\delta^{13}C$ (modern mean = − 27‰; range = − 35 to − 20‰) (Dawson et al. 2002; Kelly 2000; Kohn and Cerling 2002). Conversely, plants following the C_4 photosynthetic pathway incorporate less ^{12}C than C_3 plants, and as such C_4 plants have less negative $\delta^{13}C$ (modern mean = − 12‰; range = − 15 to − 10‰) (Kohn and Cerling 2002). Plants following the CAM photosynthetic pathways (e.g., *nopal*, maguey) include obligate and facultative varieties and are the most complex isotopically since light, temperature, and other environmental conditions drive their wide-ranging $\delta^{13}C$ (modern range = − 27 to − 12‰) (O'Leary 1981; White et al. 2004b). Of the CAM plants, the Aztecs mainly consumed prickly pear cactus (*Opuntia* sp.) and maguey (*Agave* sp.) in the form of *pulque*, which have a $\delta^{13}C$ within the C_4-plant range; as such, these two plant types are commonly grouped together isotopically (i.e., C_4/CAM) in paleodietary studies of Central Mexico (e.g., White et al. 2004b; Nado et al. 2017).

Marine plants tend to resemble the $\delta^{13}C$ of C_4 terrestrial plants more closely than the C_3 plants, and so the former plants are commonly grouped together in the interpretation of diets as "C_4/CAM or marine sources". Freshwater ecosystems, however, are very complex and have $\delta^{13}C$ that are much more variable than marine ecosystems (Casey and Post 2011). Once an individual consumes C_3 and/or C_4/CAM plants, or animals that fed on them, their respective $\delta^{13}C$ signals become

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[1] A form of physical settlement within the socio-political organization in which there is a religious or governmental center or capital for a group of communities or neighborhoods (*calpulli*) (Gibson 1971; Smith 2008). A hierarchy existed within the system based on settlement size, ranging from small hamlets (as the case of Ecatepec), villages, mid-sized towns, to large urban centers (Trejo Rangel 2014).

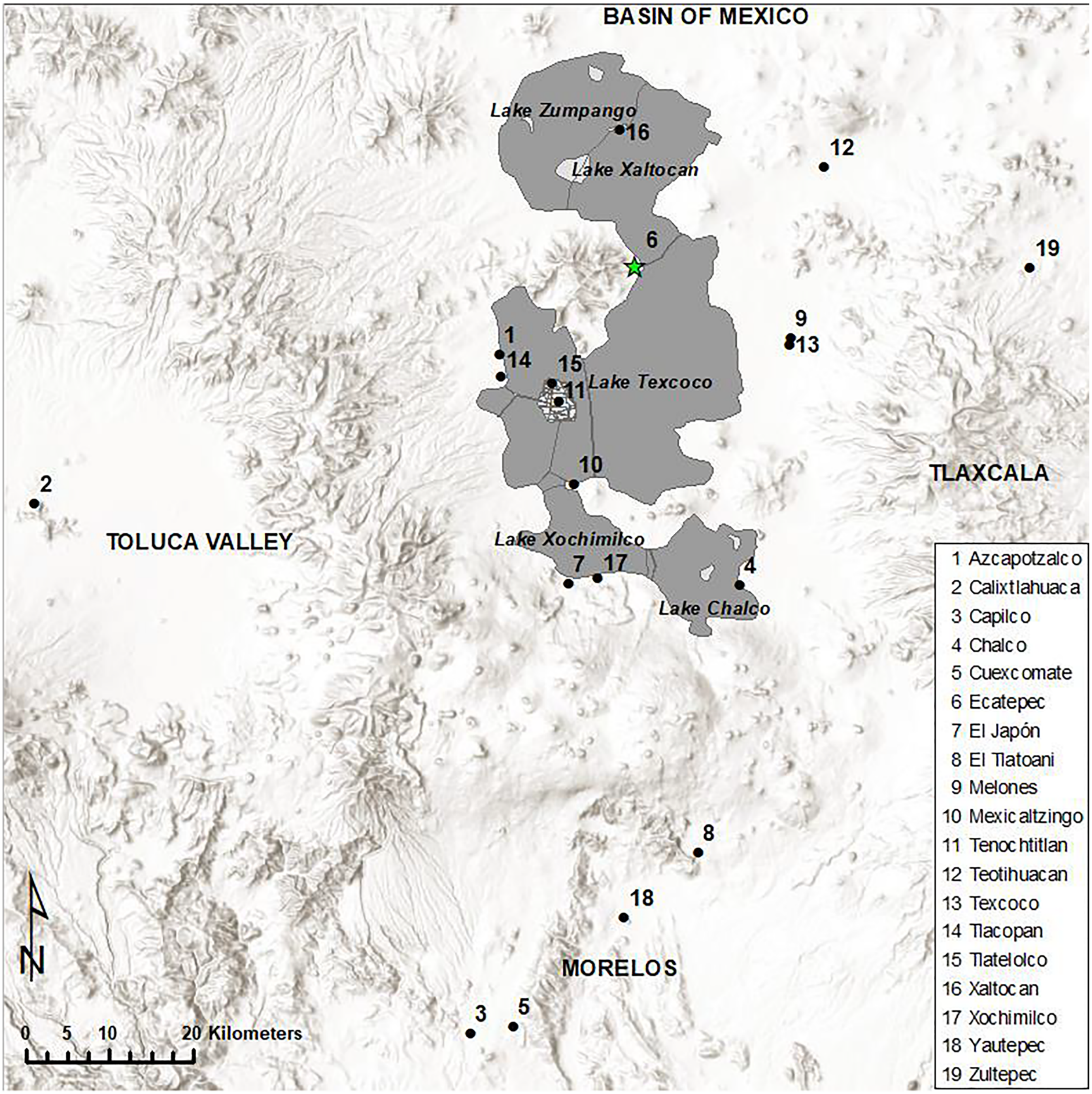

Fig. 1 Locations of the site of Ecatepec (star) in the Basin of Mexico and other Central Mexico archeological sites mentioned in the text

incorporated into that individual's bone collagen (Lee-Thorp 2008). The carbon isotope composition of bone collagen ($\delta^{13}C_{col}$) primarily reflects the intake of dietary protein (plus a small enrichment in ^{13}C, i.e., fractionation) (Ambrose and Norr 1993; Chisholm 1989; Krueger and Sullivan 1984). While a lot of variation in the degree of isotopic fractionation between diet and bone collagen has been reported (e.g., Ambrose and Norr 1993; Froehle et al. 2010), the generally accepted spacing ranges from ~ 1 to 5‰ (Keegan and DeNiro 1988; DeNiro and Epstein 1978, 1981; van der Merwe 1982). In summary, carbon isotope ratios can distinguish three types of diets in consumers (animals and humans): (1) mainly C_3 diet; (2) mainly C_4/CAM or marine diet; or (3) a mixed diet composed of C_3 and C_4/CAM.

Bone collagen nitrogen isotope ratios can inform us about the local food web, the trophic level of consumers, the kind of protein sources consumed, and the level of meat consumption in a consumer's diet. While multiple climatic and environmental factors can influence plant δ^{15}N (the base of food webs) (Ambrose 1991, 1993; Szpak et al. 2012, 2013), the overall plant δ^{15}N range from approximately − 3 to + 6‰ (including N-fixing plants) (Ambrose 1993; Hastorf and

DeNiro 1985). Early studies found a "stepwise trophic shift" in food webs involving an increase of 2–6‰ from plants to herbivores, herbivores to omnivores, and omnivores to carnivores (DeNiro and Epstein 1981; Schoeninger and DeNiro 1984; Schoeninger et al. 1983). This positive shift is variable and depends on the specific habitat and food web under consideration (Ambrose 1991, 1993). In the case of humans, those with vegetarian diets have low δ^{15}N, usually between + 3 and + 7‰ while meat eaters have δ^{15}N > + 7‰ (Nado et al. 2017; Wright 1994). The marine food webs begin at higher δ^{15}N and have more trophic levels compared with terrestrial ecosystems. As such, marine food sources have higher δ^{15}N relative to terrestrial ecosystems (Kelly 2000; Lee-Thorp 2008; Metcalfe et al. 2009). Individuals with a primarily marine diet can have a δ^{15}N of + 14 to + 17‰ (Lee-Thorp 2008; Nado et al. 2017; Schoeninger et al. 1983). Freshwater ecosystems experience much δ^{15}N variability so they tend to have higher δ^{15}N than terrestrial environments but not as high as those of marine ecosystems (Casey and Post 2011; DeNiro and Epstein 1981; Metcalfe et al. 2009). As with bone collagen carbon isotope compositions, the nitrogen isotope composition of bone collagen also reflects the protein content in a consumer's diet. The fractionation between collagen and diet ($\Delta^{15}N_{col-diet}$) has been estimated to be + 2.5 to + 3‰ (DeNiro and Epstein 1981; Keegan and DeNiro 1988; Metcalfe et al. 2009). The δ^{15}N trophic level shift also applies to breastfeeding infants, whose main source of protein is breast milk. Given that they are situated about one trophic level above their mothers, their δ^{15}N tends to be 2–3‰ higher compared with that of women of reproductive ages from the same population (Fogel et al. 1989; Fuller et al. 2006; White et al. 2001; Wright and Schwarcz 1999). Other factors such as climate, anthropogenic nutrient inputs like human sewage in lakes, physiology, water deprivation, stress, and disease can also influence the δ^{15}N signal incorporated into human bone collagen (Ambrose 1991; Katzenberg and Lovell 1999; Reitsema 2013; Olsen et al. 2014, 2018).

Bone continues to remodel by resorption of older bone and the formation of new bone throughout an individual's lifetime (Sealy et al. 1995). The precise turn-over rates for bone of healthy individuals are not certain, but we know that bone remodeling depends on age as well as bone type (e.g., rib vs. femur) and its composition: cortical vs. trabecular (Cox and Sealy 1997; Sealy et al. 1995; Tsutaya and Yoneda 2013). Infants experience the highest turn-over annually (100%), followed by children (70–50%), juveniles (30–10%), and adults (0.3–3%) (Cox and Sealy 1997; Martin et al. 2015; Tsutaya and Yoneda 2013; Welle 1999). As a result, the bulk bone collagen δ^{13}C and δ^{15}N provide an average isotope composition of an individual's lifetime—at least the last 10 or more years of life in adults and less time in children depending on age at death (Ambrose 1993; Kohn and Cerling 2002; White et al. 2000, 2004b).

Aztec diets based on ethnohistoric and archeological evidence

While Spanish chroniclers, like Bernardino de Sahagún, Diego Durán, Hernán Cortés, and Bernal Díaz del Castillo, among others, wrote about the Aztecs with particular intentions and biases, these ethnohistoric accounts provide researchers with valuable information about Aztec foodways and their connection to social, economic, political, and religious practices (Coe 1994; Staller and Carrasco 2010). Moreover, archeological studies in the Basin of Mexico and surrounding areas throughout the Postclassic period (A.D. 900–1521) have uncovered a wide range of data on Aztec foodways, including information on food processing, cooking techniques, and related utensils and serving vessels (Brumfiel 2009; Parsons 2010; Smith and Price 1994; Smith et al. 2002; Smith 2016).

Here we first provide an overview of the ethnohistoric and archeological evidence for food sources or menu items available to the Aztecs in their everyday diets. This helps to establish a dietary baseline against which to evaluate the diets of the Aztec residents at Ecatepec as determined from their collagen stable isotope compositions.

Overview of ethnohistoric evidence of Aztec foods

Maize (*Zea mays*) was the principal Aztec staple consumed in a variety of solid (e.g., tortillas, tamales) and liquid (e.g., gruel (*atole*)) forms, and it was highly regarded in ceremonial and symbolic contexts (Berdan and Anawalt 1997; Sahagún 1932; Smith 1996). Beans (*Phaseolus vulgaris*), another Aztec staple, were consumed with maize. This food combination provides full protein intake since beans contain amino acids lacking in maize (i.e., lysine and tryptophan) (Bressani et al. 1962; Coe 1994; Deng et al. 2017). Other common plants consumed by the Aztecs included amaranth (*Amaranthus* sp.), tomato (*Physalis*), avocado (*Persea*), squash (*Cucurbita* sp.), chili peppers (*Solanaceas*), chia (*Salvia* sp.), prickly pear cactus (*nopal*) and its fruit *tuna* (*Opuntia)*, and maguey (*Agave* sp.; as a nutritious beverage or fermented drink called *octli* in Nahuatl and *pulque* in Spanish, and in its raw and fermented form called *aguamiel* in Spanish) (Smith 1996; Soule 1979).

Díaz del Castillo's (2008: 174–175) description of the Tlatelolco market (*tianquitz*) mentions a type of blue-green spirulina algae (*tecuitlatl*) that grew on lake surfaces, which was collected by fishers and prepared for consumption: "… and the fisherwomen and others who sell some small cakes made from a sort of ooze which they get out of the great lake, which curdles, and from this they make a bread having a flavour something like cheese". Smith (1996) and others (Furst 1978; Parsons 2010; Ortíz de Montellano 1990) point out that the algae is very nutritious, rich in protein, and easily accessible for those who resided near the Basin of Mexico lakes. Cortés mentions that at the same market, "there is every sort of vegetable, especially onions, leeks, garlic, common cress and watercress, borage, sorrel, teasels and artichokes; and there are many sorts of fruit…" (1986:103–104).

Several plant foods were also imported to the Basin of Mexico through the Aztec tribute system. For instance, the Mesoamerica region referred to as the "hot country" by Durán (1964:129) (i.e., Southern Mexico and Central America) sent a range of fruits, including "pineapples, numerous types of sweet fruits such as guavas, wild pear-like fruits, yellow, black, and white sapotas, avocados, and two or three kinds of yams". Aztecs also used a range of plants as condiments, including coriander, fennel, and anise-like vegetables, and *epazote* (*Chenopodium* spp.), which was added to flavor drinks and tamales (Picó and Nuez 2000).

Aztec foods included meat from a range of animal species. According to Sahagún, some of the tortilla fillings included turkey eggs and water-fly eggs, and meats sold at the markets included "rabbit meat, hare, opossum, venison, and "meat of wild beasts"…duck, crane, goose, mallard, quail, and eagle" (Berdan and Anawalt 1997:155, 218). Díaz del Castillo (2008:174) mentions that the Mexicas at Tlatelolco "sold fowls, cocks with wattles, rabbits, hares, deer, mallards, and young dogs," while Cortés (1986:103–104) provides an even more detailed account of the animals sold for consumption at the same market:

> There is a street where they sell game and birds of every species found in this land: chickens [turkeys], partridges and quails, wild ducks, flycatchers, widgeons, turtledoves, pigeons, cane birds, parrots, eagles and eagle owls, falcons, sparrow hawks and kestrels…They sell rabbits and hares, and stags and small gelded dogs which they breed for eating…They sell chicken [turkey] and fish pies, and much fresh and salted fish, as well as raw and cooked fish. They sell hen and goose eggs, and eggs of all the other birds I have mentioned.

Durán describes the vast number of dogs that were sold at the Acolman market for consumption (Berdan and Anawalt 1997). The markets of Xochimilco, Zumpango, and Toluca sold the Mexican salamander or *axolotl* (*Ambystoma mexicanum*) that lived in the Basin lakes, alive or roasted for consumption (Tate 2010). Durán (1964:129) also mentions the terrestrial and aquatic species brought to Tenochtitlan as part of tribute payments:

> From other places were brought deer and rabbits and quails, some uncooked and other in barbecue. As tribute also came gophers, weasels, and large rodents, which thrive in the woods. Toasted locusts, winged ants, large cicadas and little ones, in addition to other small animals. Those living near lagoons sent everything that thrives in the water, such as algae, a certain type of insect that walks upon the water, and small worms…

In summary, the chroniclers' descriptions include food from the following groups: (1) grains, (2) legumes, (3) vegetables and fruits, (4) birds and waterfowl (terrestrial and lacustrine), (5) small game and insects, (6) lacustrine plants and animals, and (7) marine resources. This information reveals the wide variety of fauna and flora available for consumption in the Basin of Mexico (and beyond), even though it is likely that not everyone in Aztec society had access to these foods or consumed them with the same frequency due to socioeconomic differences.

Overview of archeological evidence of Aztec menu items

Carbonized plants such as maize and beans and skeletal remains of various animal species have been recovered from domestic contexts at several Postclassic Aztec city-states (Smith 2008). While this survey is not exhaustive, our goal here is to discuss the main animal and plant "menu" items that were part of the everyday Aztec "food plate" at multiple Postclassic Central Mexico archeological sites—Calixtlahuaca, Capilco, Chalco, Cuexcomate, El Japón, El Tlatoani, Melones, Mexicaltzingo, Xaltocan, Yautepec, and Zultepec-Tecoaque (Fig. 1). A summary of the animal and plant species recovered by archeological site is provided in Supplementary Tables 1 and 2.

At the in-land sites of Calixtlahuaca (near Toluca), Zultepec-Tecoaque (Tlaxcala), El Tlatoani, Yautepec, Capilco, and Cuextomate (Fig. 1) mammals such as dog and white-tailed deer as well as birds such as turkey were the most abundant fauna recovered (Corona et al. 2015; Fauman-Fichman et al. 2019; Heath-Smith and Wharton 2015; Manin 2017; Valadez Azúa and Rodríguez Galicia 2014). Smaller fauna such as rabbit, peccary, fox, and armadillo were also present at most of these sites. Turtle was a common lacustrine fauna encountered at Calixtlahuaca, Capilco, Cuextomate, and Yautepec, but only the latter two sites had evidence of fish consumption.

Dog, turkey, rabbit, and, to a lesser extent, white-tailed deer were also recovered from archeological sites closer to the Basin of Mexico lakes including Mexicaltzingo, El Japón, Chalco, Melones, and Xaltocan (Fig. 1) (Ávila López 2006; Corona 1997; Guzmán and Polaco 2008; Valadez Azúa and Rodríguez Galicia 2005, 2014). At the Melones site, Valadez Azúa and Rodríguez Galicia (2014) encountered turkey remains while excavating a kings' palace with domestic areas. The thighs, legs, and breasts were found in the kings' spaces, while head, feet, uropygium (parson's nose), and thoracic cavity remains were recovered from kitchen areas. Moreover, a wider range of fauna, including lacustrine species, were recovered at these sites. At these Basin of Mexico sites (except for Melones), amphibians (e.g., frogs), reptiles, a range of lacustrine waterfowl (e.g., ducks), fish, and marine mollusks and oysters were recovered (Supplementary Table 1). In summary, since these sites are located near the Basin of Mexico lakes, it appears that the Aztecs took advantage of their environment by consuming a variety of lacustrine species, in addition to more common terrestrial species.

Macro- and/or micro-botanical (e.g., pollen) remains of edible plants were recovered from the Aztec sites of Xaltocan, Mexicaltzingo, Capilco, Cuexcomate, Yautepec, and Chalco (only maize cobs were found at this site) (Fig. 1; Supplementary Table 2) (Ávila López 2006; Fauman-Fichman and Smith 2015; Fauman-Fichman et al. 2019; Guzmán and Polaco 2008; Heath-Smith and Wharton 2015; McClung de Tapia and Martínez Yrizar 2005; Valadez Azúa and Rodríguez Galicia 2005). The main C_4 plant was maize (*Zea mays*), while at most sites, varieties of another C_4 plant, amaranth (*Amaranthus* sp.), and its genetic relatives such as *quelite* (*Amaranthus hybridus*) and seepweed (*Suaeda torreyana*), were also present. The most common CAM plants are members of the *Opuntia*, *Cactaceae*, and *Agavaceae* families. These include plants such as prickly pear cactus and maguey. At Xaltocan, bilberry cactus (*Myrtillocactus geometrizans*) was also found, while a succulent known as purslane or *verdolaga* (*Portulaca oleracea*) was present at Xaltocan, Capilco, Cuexcomate, and Mexicaltzingo.

Several C_3 plants were recovered from these sites (Supplementary Table 2) (Ávila López 2006; Fauman-Fichman and Smith 2015; Fauman-Fichman et al. 2019; Guzmán and Polaco 2008; Heath-Smith and Wharton 2015; McClung de Tapia and Martínez Yrizar 2005; Valadez Azúa and Rodríguez Galicia 2005). Legumes (*Leguminosae*) were encountered, including beans (e.g., *Phaseolus coccineus*, *Phaseolus vulgaris*). Varieties of tomato (e.g., groundcherry, red tomato, tomatillo) and chili and bell peppers (*Physalis* and *Solanaceas*) were also found. Fruits of *Chenopodium* such as *epazote* were recovered at most sites. At Xaltocan and Mexicaltzingo, *chia* (*Salvia* sp.) and lacustrine plants such as bulrush (*Scirpus*), pondweed (*Potamogeton*), and spiral ditch grass (*Ruppia*) were identified, consistent with proximity to the Basin of Mexico lakes. At Capilco, Cuexcomate, and Xaltocan, *mesquite* from the leguminous family (*Prosopis*) was recovered. Fruits such as avocado (*Persea*), cherry (e.g., *Prunus seretina*), and soursop (*Annona*) as well as other vegetables like squash (*Cucurbita* sp.) and potato (e.g., *Solanum rostratum*) were found at Capilco, Cuexcomate, and Mexicaltzingo. Other edible C_3 flora recovered from at least one of these Aztec sites include nettles or *ortiga* (*Celtis*), *zapote* (*Casimiroa zapote*), grape (*Ribes*), chestnuts (*Fagaceae*), and cacao (*Theobroma cacao*). Soursop and cacao are exotic to the Basin since they grow in sub-tropical and tropical areas of Southern Mexico as well as Central and South America.

Based on the evidence discussed above, several aspects of the Aztec diets stand out. First, a wide diversity of animal and plant species were used in Central Mexico. This reflects the diverse ecosystems in this region that allowed many species to flourish as well as the range of Aztecs' activities, including hunting, fishing, farming, and managing domesticated animals (i.e., dog, turkey). Hence, there were likely plenty of meat and plant sources in Central Mexico available to the Aztecs. While some exotic plant and animal foods were identified at the Aztec markets and at a few archeological sites (e.g., Xaltocan, Chalco), the vast majority of food items consumed by the Aztecs in everyday life were indigenous to Central Mexico (or temporary residents in the case of migratory birds).

Second, the faunal results illustrate that the staple animals in the Aztec food plate included turkey, dog, rabbit, and white-tailed deer, and in some cases, waterfowl species (terrestrial and lacustrine), and a few reptiles and amphibians. The paleobotanical evidence available suggests that the Aztecs incorporated a variety of Central Mexico C_3, C_4, and CAM plants into their everyday food plate such as maize, beans, amaranth, chili peppers, tomato, squash, cacti, maguey, *chia*, avocado, and a variety of fruits and condiments. Third, the archeological evidence indicates that the Aztecs also took advantage of other food sources that were available depending on their particular ecological setting. For instance, Chalco, Mexicaltzingo, and Xaltocan are located near the Basin of Mexico lakes, which were home to a variety of readily accessible lacustrine species, including fish, waterfowl, and lacustrine plants.

The absence of fish remains at some sites (e.g., El Japón) may be a result of taphonomic processes (Serra and Valadez 1986) or different data collection methods. Additionally, species of small fish (e.g., *charales* (*Christoma*)) inhabit the Basin lakes and their bones are thin and soft enough for people to consume them whole in present-day Mexico (Muñoz Zurita 2012) and they may have done so in the past (Widmer and Storey 2017). While the zooarchaeological evidence is limited for most of the Central Mexico sites reviewed, consumption of lacustrine foodstuffs, including fish, is supported by the ethnohistoric and historic records. Sahagún mentions that lacustrine resources were important for the Aztecs, and more specifically for those from the lower socio-economic classes. A wide diversity of edible lacustrine species that inhabited the Basin of Mexico lakes could be obtained with little effort. Also, there was open access to the lakes, allowing everyone to easily acquire fish and other lacustrine food sources (Parsons 2010; Valadez Azúa and Rodríguez Galicia 2014).

It has been argued that access to some foodstuffs (e.g., meat) during the Classic period was largely determined by socio-economic status in large urban centers in Mesoamerica, such as Teotihuacan (Morales Puente et al.

2012; Nado et al. 2017; Valadez Azúa and Rodríguez Galicia 2014). This pattern seems to have continued through the Postclassic period, as exemplified by the Melones site, where the kings had access to meat products (the meatier cuts of turkey) (Valadez Azúa and Rodríguez Galicia 2014). Valadez Azúa and Rodríguez Galicia (2014:155) argue that the kings hosted "feasts at the plazas where they had different kinds of dishes that were shared with the community". This suggests that the elite members of Aztec society (e.g., city-state rulers, priests, the Aztec Emperor and his advisors) could consume meat frequently and in large quantities since they were wealthy and could purchase a variety of animal products. As for the lower socio-economic classes (e.g., commoners, slaves), they mainly consumed foods that they could access (mostly plant-based as well as lacustrine foods from the Basin lakes).

Materials and methods

Sample preparation and collagen extraction

Stable carbon and nitrogen isotope analysis was carried out on 24 individuals (2 Mazapa and 22 Aztec III–IV) from the site of Ecatepec. Ribs ($n = 22$) and femoral fragments ($n = 2$) were sampled from the skeletons. Bone sample weights ranged from 1.4 to 6.0 g, and a Dremel® rotary tool was used to extract the femoral fragments. Trabecular bone was mechanically removed using a dental pick leaving only cortical bone for analysis; the latter remodels more slowly than the former and is less likely to have undergone post-mortem alteration (Cox and Sealy 1997; Kohn and Cerling 2002; Sealy et al. 1995). Samples were cleaned with a toothbrush and deionized water followed by sonication in 40-mL beakers for ~ 15 min to remove remaining debris and dried overnight at 90 °C. The samples were then ground with a ceramic mortar and pestle to obtain a uniform size (< 850 μm) for collagen extraction.

Bone collagen was extracted following a modified Longin (1971) method as described in Olsen et al. (2018). To remove lipids, each sample (~ 500 mg) was soaked three times in 2:1 chloroform:methanol for 15 min and subsequently dried at room temperature overnight (Folch et al. 1957). The inorganic component of samples was dissolved in a 0.25-M HCl for 24 h, followed by a 0.5-M HCl solution until they reached full demineralization (8–10 days). The amount of humics was initially substantial in 16 out of the 24 samples since 5 to 7 rinses with 0.1 M NaOH were required to remove these contaminants. Once the collagen was fully solubilized and dried, ~ 0.4 mg was weighed into tin capsules for isotope analysis.

Isotopic analysis

All isotopic analyses were carried out in the Laboratory for Stable Isotope Science (LSIS) at The University of Western Ontario, London, Ontario, Canada. Bone collagen samples and standards were combusted at 1020 °C using a Costech 4010 Elemental Combustion System (EA). The produced gases were swept through a heated (60 °C) GC separation column using helium as the carrier gas to a Thermo Scientific™ DELTA^{plus} XL® isotope ratio mass spectrometer (IRMS) operating in continuous-flow (CF) mode via a Conflo III.

The carbon and nitrogen isotope compositions were calibrated to the international standards Vienna PeeDee Belemnite (VPDB) and atmospheric N_2 (AIR), respectively. The calibration standards used for $\delta^{13}C_{col}$ and $\delta^{15}N_{col}$ were USGS40 (L-glutamic acid, accepted $\delta^{13}C = -26.39‰$, $\delta^{15}N = -4.52‰$) and USGS41 (L-glutamic acid, accepted $\delta^{13}C = +37.63‰$, $\delta^{15}N = +47.57‰$) (Qi et al. 2003). The international standard IAEA-CH-6 (accepted $\delta^{13}C = -10.45‰$; Coplen et al. 2006) and the LSIS internal keratin standard (MP Biomedicals Inc., Cat No. 90211, Lot No. 9966H) (accepted $\delta^{13}C = -24.04 \pm 0.12‰$, $\delta^{15}N = +6.36 \pm 0.15‰$; LSIS running value) were analyzed to monitor analytical accuracy throughout each session. Every 10–12 collagen samples were analyzed in duplicate to monitor analytical precision and methodological consistency (based on independent sample aliquots).

Instrument precision based on the calibration standards ($n = 9$) was $\pm 0.10‰$ and $\pm 0.41‰$ for $\delta^{13}C$ and $\delta^{15}N$, respectively. The repeatability of isotopic measurements assessed with sample duplicates ($n = 3$) was $\pm 0.1‰$ or better. The average reproducibility of the same sample using an independent extraction of collagen was better than $\pm 0.1‰$ ($n = 3$) for $\delta^{13}C$ and $\delta^{15}N$. A mean $\delta^{13}C$ of $-10.34 \pm 0.05‰$ ($n = 3$) was obtained for IAEA-CH-6 and mean values of $\delta^{13}C = -24.00 \pm 0.04‰$ and $\delta^{15}N = +6.36 \pm 0.05‰$ ($n = 5$) were obtained for the LSIS keratin standard, all of which compare well with their accepted values. Based on these check standards, analytical accuracy is better than $\pm 0.04‰$ for $\delta^{13}C$ and $\pm 0.05‰$ for $\delta^{15}N$.

Data treatment and floral and faunal baseline isotope data

While the fractionation between human collagen and diet ($\Delta^{13}C_{col-diet}$) in mixed diets has been found to be quite variable (e.g., Froehle et al. 2010), in this study, we use the standard fractionation of + 5‰ in our interpretation (Table 1; DeNiro and Epstein 1978, 1981; Keegan and DeNiro 1988). Similarly, we have corrected our human $\delta^{15}N_{col}$ data by $-3.0‰$ to estimate $\delta^{15}N_{diet}$ (Table 1). We also compiled the available floral and faunal carbon

Table 1 Carbon and nitrogen isotope data and collagen quality indicator results for the Ecatepec collection

Sample ID	Burial	Sex	Age (years)	Postclassic phase	Skeletal element	$\delta^{13}C_{col}$ (VPDB, ‰)	$\delta^{13}C_{diet}$ (VPDB, ‰)[a]	$\delta^{15}N_{col}$ (AIR, ‰)	$\delta^{15}N_{diet}$ (AIR, ‰)[b]	Wt% C	Wt% N	C:N ratio	Wt% col
DM72	19	M	~ 23	Aztec III–IV	Rib	− 8.0	− 13.0	+ 11.3	+ 8.3	38.8	13.6	3.32	N/A
DM74	11a	M	~ 4	Aztec III–IV	Rib	− 8.3	− 13.3	+ 10.8	+ 7.8	42.6	15.3	3.24	N/A
DM76	11a	F	~ 1.5	Aztec III–IV	Rib	− 9.4	− 14.4	+ 12.6	+ 9.6	42.1	15.2	3.23	N/A
DM77	10a	F	~ 47	Aztec III–IV	Rib	− 8.1	− 13.1	+ 11.3	+ 8.3	42.3	15.2	3.26	N/A
DM78	10b	F	~ 1.5	Aztec III–IV	Rib	− 6.7	− 11.7	+ 14.9	+ 11.9	42.9	15.5	3.22	15.28
DM80	9a	M	~ 3	Aztec III–IV	Rib	− 8.2	− 13.2	+ 12.6	+ 9.6	44.2	16.1	3.21	17.56
DM81	14c	F	~ 2	Aztec III-IV	Rib	− 8.2	− 13.2	+ 12.3	+ 9.3	42.7	15.5	3.22	14.68
DM82	15	F	~ 2	Aztec III–IV	Rib	− 7.7	− 12.7	+ 14.3	+ 11.3	42.3	15.2	3.25	9.13
DM83	29	?	~ 1.5	Aztec III–IV	Rib	− 7.2	− 12.2	+ 15.1	+ 12.1	39.8	14.0	3.31	3.00
DM84	31b	M	~ 33	Mazapa	Rib	− 8.4	− 13.4	+ 12.0	+ 9.0	43.7	15.7	3.24	14.95
DM85	31c	F	~ 32	Mazapa	Femoral fragment	− 8.4	− 13.4	+ 10.8	+ 7.8	43.6	15.5	3.28	6.62
DM86	32	?	~ 1	Aztec III–IV	Rib	− 7.6	− 12.6	+ 15.6	+ 12.6	40.5	14.3	3.29	3.97
DM88	33	M	~ 32.5	Aztec III–IV	Rib	− 9.1	− 14.1	+ 9.0	+ 6.0	41.5	14.6	3.32	4.07
DM89	20	F	~ 36	Aztec III–IV	Femoral fragment	− 8.1	− 13.1	+ 11.3	+ 8.3	43.0	15.5	3.25	6.24
DM90	21	F	~ 4	Aztec III–IV	Rib	− 9.0	− 14.0	+ 12.7	+ 9.7	42.5	15.3	3.24	10.98
DM91	23	F	~ 1	Aztec III–IV	Rib	− 7.5	− 12.5	+ 14.8	+ 11.8	42.1	15.2	3.22	16.05
DM92	12	M	~ 43	Aztec III–IV	Rib	− 7.2	− 12.2	+ 11.2	+ 8.2	38.0	13.6	3.27	N/A
DM94	2	F	~ 36	Aztec III–IV	Rib	− 9.2	− 14.2	+ 11.0	+ 8.0	40.8	14.7	3.24	N/A
DM96	14a	F	~ 41	Aztec III–IV	Rib	− 8.0	− 13.0	+ 11.7	+ 8.7	42.6	15.3	3.24	N/A
DM98	14b	M	~ 3	Aztec III–IV	Rib	− 7.8	− 12.8	+ 12.1	+ 9.0	42.1	15.2	3.24	N/A
DM100	13	M	~ 45	Aztec III–IV	Rib	− 7.8	− 12.8	+ 12.2	+ 9.2	42.7	15.4	3.23	N/A
DM102	22	M	~ 30	Aztec III–IV	Rib	− 7.4	− 12.4	+ 12.1	+ 9.1	41.4	14.9	3.25	N/A
DM105	6a	F	~ 2.5	Aztec III–IV	Rib	− 8.2	− 13.2	+ 12.2	+ 9.2	41.8	14.9	3.27	N/A
DM106	6b	M	~ 11	Aztec III–IV	Rib	− 8.7	− 13.7	+ 11.3	+ 8.3	42.5	15.3	3.24	N/A

[a] $\delta^{13}C_{diet} = \delta^{13}C_{col}$–5‰

[b] $\delta^{15}N_{diet} = \delta^{15}N_{col}$–3‰

and nitrogen isotope data for the Basin of Mexico (e.g., Xochimilco, Texcoco, Xochicalco, Teotihuacan) to aid our interpretation of the isotope data for the Ecatepec individuals (Casar et al. 2017a; Lounejeva-Baturina et al. 2006; Manin et al. 2018; Morales Puente et al. 2012; Somerville et al. 2017). For comparison with the Ecatepec diets (i.e., $\delta^{13}C_{diet}$ and $\delta^{15}N_{diet}$), we have corrected the faunal collagen $\delta^{13}C$ by −2.0‰ to reflect flesh $\delta^{13}C$ (following DeNiro and Epstein 1981) (Table 2). There is no significant difference between flesh

Table 2 Summary δ^{13}C and δ^{15}N data for modern and archeological flora and fauna[a]

Common name	Scientific name	Plant type/habitat	Modern/ archeological	Native/exotic to the Basin of Mexico	*n*	Mean δ^{13}C (VPDB, ‰)[b]	SD	Range (‰)	*n*	Mean δ^{15}N (AIR, ‰)	SD	Range (‰)
Mezquite, squash, green tomato, tejocote, huauhtzontle, epazote, capulin fruit, huizache, zapote, calabaza, chilacayote, red tomato	*Prosopis, Cucurbita* sp., *Physalis ixocarpa, Crataegus mexicana*, *Chenopodium* sp., *Acacia pennatula*, *Casimiroa edulis*, *Solanum lycopersicum*	C_3	Modern	Native	18	− 24.0	1.9	− 26.8 to − 18.3	18	+ 3.7	3.1	− 1.0 to + 8.4
Bean	*Phaseolus vulgaris*	C_3	Modern	Native	1	− 24.1	N/A	N/A	1	− 1.5	N/A	N/A
Maize	*Zea mays*	C_4	Modern	Native	6	− 10.2	0.4	− 10.9 to − 9.9	5	+ 0.5	1.0	− 0.5 to + 1.7
Amaranth	*Amaranthus* sp.	C_4	Modern	Native	4	− 12.6	1.2	− 13.6 to − 10.9	4	+ 4.5	2.2	+ 2.8 to + 7.6
Prickly pear (nopal), tuna fruit, xoconostle, maguey, biznaga, chilies	*Opuntia*, *Agave* sp., *Echinocactus* sp.	CAM	Modern	Native	15	− 11.6	1.1	− 14.3 to − 10.2	11	+ 3.7	3.1	− 2.0 to + 9.2
Rabbit/hare	*Sylvilagus floridanus*, *Lepus* sp.	Terrestrial	Archeological	Native	67	− 17.4[c]	2.8	− 24.3 to − 12.2	67	+ 5.6	2.2	+ 0.3 to + 13.7
Cougar/puma	*Puma concolor*	Terrestrial	Archeological	Native	3	− 21.1[c]	0.6	− 21.8 to − 20.7	3	+ 7.1	0.0	N/A
Opossum (tlacuache)	*Didelphidae*	Terrestrial	Archeological	Native	1	− 14.6[c]	N/A	N/A	1	+ 8.9	N/A	N/A
Turkey	*Meleagris gallopavo*	Terrestrial	Archeological	Native	18	− 14.0[c]	3.3	− 20.7 to − 10.4	18	+ 6.6	1.7	+ 3.5 to + 8.9
Dog	*Canis familiaris*	Terrestrial	Archeological	Native	3	− 9.7[c]	0.3	− 10.0 to − 9.5	3	+ 9.7	0.9	+ 9.1 to + 10.8
Insects (C_3)	*Liometopum apiculatum*, *Hypopta agavis*, *Sphenarium* spp.	Terrestrial	Modern	Exotic (Oaxaca Valley)	7	− 24.2	3.5	− 26.9 to − 17.0	7	+ 6.1	1.6	+ 4.2 to +8.6
Insects (C_4/CAM)	*Acentrocneme hesperiaris*, *Hypopta agavis*	Terrestrial	Modern	Exotic (Oaxaca Valley)	3	− 9.9	0.5	− 10.4 to − 9.5	3	+ 5.5	1.0	+ 4.8 to + 6.7
Bobo mullet fish	*Joturus pichardi*	Riverine	Modern	Exotic	2	− 21.0	N/A	− 22.1 to − 19.8	2	+ 9.1	N/A	+ 7.7 to + 10.5
Red snapper, gray pampano, blue runner	*Lutjanus campechanus*, *Trachinotus carolinus*, *Caranx crysos*	Marine	Modern	Exotic	4	− 15.3	1.2	− 16.6 to − 13.7	4	+ 12.3	0.3	+ 12.2 to + 12.7

[a] Data from Casar et al. (2017a:Table 1), Lounejeva-Baturina et al. (2006: Table 1), Manin et al. (2018), Morales Puente et al. (2012: Table XI.3), Somerville et al. (2017), and Warinner (2010)

[b] The δ^{13}C of modern C_3 and C_4/CAM plants, insects, and fish has been corrected by + 1.5‰ to account for the "Suess effect"

[c] Archeological faunal $\delta^{13}C_{col}$ has been adjusted by − 2.0‰ to reflect flesh δ^{13}C

and collagen δ^{15}N; hence, no further correction is required (DeNiro and Epstein 1981). The modern fauna and flora δ^{13}C have been corrected by + 1.5‰ to account for the "Suess effect".[2] The baseline isotope data are presented in Table 2 and illustrated in Fig. 2.

While there is ethnohistoric and archeological evidence to suggest that the Aztecs consumed food sources from the Basin of Mexico lakes, there are several challenges in reconstructing this aquatic ecosystem's food web, and consequently, isotopic compositions during the Postclassic period. First and foremost, this water body of interconnected lakes has been mostly drained after the Spanish invasion and subsequent settlement of a growing population in the territory that today encompasses Mexico City. As a result, the original lake system has been lost to human settlement activities over the past ~ 400 years. Second, the surviving body of water, Xochimilco Lake, has undergone massive hydrological and environmental alteration, primarily due to agricultural production, use of fertilizers, groundwater pumping, wastewater inputs, and the introduction of exotic fish species such as carp (*Cyprinus carpio*) and tilapia (*Oreochromis niloticus*) (Zambrano et al. 2010). While there are isotopic data for modern species within this lake (Zambrano et al. 2010), these results, especially for δ^{15}N, likely do not provide a representative baseline for reconstructing Aztec diets, as has been demonstrated previously for other anthropogenically impacted terrestrial and lacustrine localities (e.g., Guiry 2019). Others have recovered archeological aquatic fauna from Aztec sites but a systematic stable isotope analysis of these samples has yet to be undertaken. Below, we include available δ^{13}C and δ^{15}N of modern freshwater and marine fish (Table 2) collected by Morales Puente et al. (2012) for their paleodietary study at Teotihuacan that are not from the Xochimilco Lake system and do not seem to have been affected by anthropogenic factors, as a way to tackle some of these challenges by incorporating some aquatic baseline isotope data in our paleodietary study.

Most Aztec plant foods including legumes, vegetables, and fruits fall into the C_3 category. The Valley of Mexico C_3 plants have a δ^{13}C ranging from − 26.8 to − 18.3‰ (Table 2; Lounejeva-Baturina et al. 2006; Morales Puente et al. 2012). Aztec C_4 plant staples include amaranth ($\delta^{13}C_{mean}$ = − 12.6 ± 1.2‰) and maize ($\delta^{13}C_{mean}$ = − 10.2 ± 0.4‰). The CAM plants (e.g., prickly pear cactus, tuna fruit, maguey) have δ^{13}C (range = − 14.3 to − 10.2‰) that overlap with the C_4-plant range (− 13.6 to − 9.9‰) in this region (Table 2). It is evident isotopically that cougars ($\delta^{13}C_{mean}$ = − 21.1 ± 0.6‰) had a C_3 diet and consumed animals with C_3 diets. There is much more variability in the diets of rabbits and hares; some had a C_3 diet, while others had a mixed C_3/C_4 diet (Table 2; Casar et al. 2017a; Somerville et al. 2017). The opossum (*tlacuache*) (δ^{13}C = − 14.6‰) and the domesticated turkey ($\delta^{13}C_{mean}$ = − 14.0 ± 3.3‰) both consumed C_3 and C_4/CAM plants (Table 2; Manin et al. 2018; Morales Puente et al. 2012). The domesticated dog ($\delta^{13}C_{mean}$ = − 9.7 ± 0.3‰) mostly consumed C_4/CAM food sources. Modern insect samples from the Oaxaca Valley can be divided into C_3 and C_4/CAM consumer groups (Table 2; Warinner 2010). Modern muscle samples of marine and riverine fish, which would have been exotic to Teotihuacan, have a $\delta^{13}C_{mean}$ = − 15.3 ± 1.2‰ and − 21.0‰, respectively (Table 2; Morales Puente et al. 2012).

A modern bean sample has a δ^{15}N of − 1.5‰, while the rest of the C_3 non nitrogen-fixing plants have a $\delta^{15}N_{mean}$ of + 3.7 ± 3.1‰ (range = − 1.0 to + 8.4‰) (Table 2; Lounejeva-Baturina et al. 2006; Morales Puente et al. 2012). The C_4/CAM plants have a $\delta^{15}N_{mean}$ of + 2.9 ± 2.9‰ (range = − 2.0 to + 9.2‰). Herbivores such as rabbits have a $\delta^{15}N_{mean}$ = + 5.6 ± 2.2‰ and an omnivore like the opossum has a δ^{15}N = + 8.9‰ (Table 2; Morales Puente et al. 2012; Somerville et al. 2017). Insects consuming C_3 or C_4/CAM plants have $\delta^{15}N_{means}$ = + 6.1 ± 1.6‰ and + 5.5 ± 1.0‰, respectively (Table 2; Warinner 2010). Two domesticated animals, turkey and dog, have $\delta^{15}N_{means}$ = + 6.6 ± 1.7‰ and + 9.7 ± 0.9‰, respectively (Table 2; Manin et al. 2018; Morales Puente et al. 2012). The dogs' δ^{13}C and δ^{15}N indicate that they were likely given similar foodstuffs as those consumed by the Teotihuacanos (Morales Puente et al. 2012). The two riverine fish have a δ^{15}N = + 7.7 and + 10.5‰, while the δ^{15}N of marine fish ranges from + 12.2 to + 12.7‰ (Table 2; Morales Puente et al. 2012). The freshwater fish have higher δ^{15}N than terrestrial animals, while marine fish have even higher δ^{15}N.

Results

Bone collagen preservation

We considered the common quality indicators in tandem to evaluate the preservation of the bone collagen before the $\delta^{13}C_{col}$ and $\delta^{15}N_{col}$ analysis and interpretation of these data (Table 1). Well-preserved collagen has elemental abundances of carbon (wt% C) and of nitrogen (wt% N) of at least 35% and 11%, respectively (Ambrose and Norr 1992; van Klinken 1999). The bone collagen samples average 41.9 ± 1.5 wt% C (range = 38.0–44.2%) and 15.0 ± 0.6 wt% N (range = 13.6–16.0%). The atomic C:N ratio for well-preserved collagen has been considered to range between 2.9 and 3.6 (Ambrose 1993; DeNiro 1985), but more recently van Klinken (1999) proposed a tighter range of 3.1 to 3.5. Our collagen samples fit well within this tighter range, averaging 3.25 ± 0.0 and ranging from 3.2 to 3.3. A third quality control measure is collagen

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[2] The increase in fossil fuel burning since the Industrial era has decreased the δ^{13}C of atmospheric CO_2 by about 1.5‰ in the early 1990s (Wahlen 1994) and the size of the decrease is now ~ 2‰. Our correction of + 1.5‰ is based on the time of collection of these plants and animals by Lounejeva-Baturina et al. (2006), Morales Puente et al. (2012), and Warinner (2010).

yield (wt.% col), given that it decreases variably from the time the bone was buried, depending on burial environment (e.g., wet, dry, sub-tropical) (van Klinken 1999). Modern bone contains 22–25% collagen by weight. Archeological bones tend to have collagen yields ranging from 20 to 1%; at < 1%, the collagen is likely too degraded for the preservation of original $\delta^{13}C_{col}$ and $\delta^{15}N_{col}$ (Ambrose 1993; van Klinken 1999). Our sample set has a mean collagen yield of 10.2 ± 5.4 wt.% (range = 3.0–17.5 wt.%). Based on these quality indicators, all 24 bone samples analyzed have well-preserved collagen for which the $\delta^{13}C_{col}$ and $\delta^{15}N_{col}$ can be considered original. Table 1 presents a summary of the Ecatepec bone collagen samples and their carbon and nitrogen isotope results and quality indicators.[3]

Carbon and nitrogen isotope data

Figure 3 illustrates Ecatepec bone collagen carbon and nitrogen isotope results (Table 1) plotted by age group. This collection has an overall mean $\delta^{13}C_{col} = -8.1 \pm 0.7‰$ ($n = 24$) (range = − 9.4 to − 6.7‰). The children ($n = 3$) and adults ($n = 11$) have a similar mean $\delta^{13}C_{col}$ (− 8.7 ± 0.4‰ and − 8.2 ± 0.6‰, respectively) but the adults have a slightly wider range (− 9.2 to − 7.2‰) compared with the children (− 9.0 to − 8.3‰). This suggests that there was more variability in the intake of C_3 and C_4/CAM foods by the adults, while the children consumed slightly less C_4/CAM foods than some adults (Fig. 3). The lack of $\delta^{13}C_{col}$ variability in the children group may also arise from the smaller sample size compared with the adult group. The infants ($n = 10$) have a slightly less negative mean $\delta^{13}C_{col}$ (− 7.8 ± 0.7‰) and the widest range within this collection (− 9.4 to − 6.7‰) (Fig. 3), likely because of different feeding practices.

This collection has an overall $\delta^{15}N_{col}$ mean of + 12.3 ± 1.6‰ (range = + 9.0 to + 15.6‰). The children and adults have similar $\delta^{15}N_{col}$ means (+ 11.6 ± 1.0‰ and + 11.3 ± 0.9‰, respectively), but the adults have a wider $\delta^{15}N_{col}$ range (+ 9.0 to + 12.2‰) relative to the children (+ 10.8 to + 12.7‰) (Fig. 3). One 4-year-old child (DM 90) has a $\delta^{15}N_{col}$ that is + 1.4‰ higher than the adult $\delta^{15}N_{col}$ mean (+ 11.3‰) (Fig. 3), which may be indicative of a partial nursing signal and reflect a weaning transition. There are differences in $\delta^{15}N_{col}$ *within* the adult group, which suggest that some adults consumed less animal protein than others; DM 88 is the adult male who consumed the least amount of meat, based on the lowest $\delta^{15}N_{col}$ (+ 9.0‰) (Fig. 3). The infants have the highest mean $\delta^{15}N_{col}$ + 13.7 ± 1.4‰ (range = + 12.1 to + 15.6‰) (Fig. 3). The difference between the infant and adult $\delta^{15}N_{col}$ means suggests that many infants (birth to 3 years) were nursing up until death.

Discussion

What did the Aztecs consume at Ecatepec?

The Ecatepec individuals' $\delta^{13}C_{diet}$ and $\delta^{15}N_{diet}$ are plotted alongside the Basin of Mexico floral and faunal $\delta^{13}C$ and $\delta^{15}N$ in Fig. 2. These Aztecs primarily consumed C_4/CAM foods (e.g., maize, amaranth, *nopal*, *pulque*), which have higher $\delta^{13}C$ ($\delta^{13}C_{C4/CAM} = -14.3$ to $-9.9‰$). There is a $\delta^{13}C_{diet}$ variability of approximately ± 2‰ among the adults. Those who consumed more C_3 foods (and perhaps some lacustrine foods with more negative $\delta^{13}C$ relative to those of C_4/CAM foods) have slightly more negative $\delta^{13}C_{diet}$ (e.g., DM 84 = − 13.4‰; DM 85 = − 13.4‰; DM 88 = − 14.1‰; DM 94 = − 14.2‰) (Table 1). As with these adults, the three children also incorporated more C_3-type foods into their diets. As for the infants, their wide range of $\delta^{13}C_{diet}$ (Table 3) is indicative of the variability in their intake of C_3 and C_4/CAM foods, directly or via breast milk.

Most Ecatepec individuals and terrestrial omnivores, such as the dogs and the opossum, have similar $\delta^{15}N$ (Fig. 2), which could be reflecting the consumption of these animals by humans but also that such animals thrived in human-modified environments eating the foods that humans left behind (e.g., scraps, organic refuse). These results indicate that (1) most individuals (except for an adult male (DM 88)) incorporated sufficient animal protein in their everyday diets, and (2) the animals consumed include those from the terrestrial ecosystem such as opossum, dog, turkey, insects, and perhaps in some cases from the Basin of Mexico lacustrine ecosystem. Based on the $\delta^{13}C_{diet}$ and $\delta^{15}N_{diet}$, it is very likely that these Aztec residents consumed C_4/CAM plants directly, as well as through consuming C_4/CAM-fed terrestrial animals, particularly turkey and dog (Fig. 2). As for the infants, at least five were nursing, as indicated by their higher $\delta^{15}N_{col}$ relative to the other individuals (Figs. 3 and 4) (see discussion below). These infants also have less negative $\delta^{13}C_{col}$. This result could suggest a maternal diet primarily based on C_4/CAM foods that was passed on to the infants through breast milk, as well as a trophic level effect of about + 1‰ (Fuller et al. 2006). In summary, the diets of Aztecs at Ecatepec incorporated mainly C_4/CAM plants, some C_3 plants, C_4/CAM-fed terrestrial animals, and perhaps some lacustrine foods. These results correlate well with the overall zooarchaeological and paleoethnobotanical menu items recovered at other Postclassic Aztec sites.

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[3] Collagen yields for samples DM 72–77 and DM 92–106 are not available. Based on the rest of the quality indicator results, however, these samples are well within the ranges of acceptable collagen preservation.

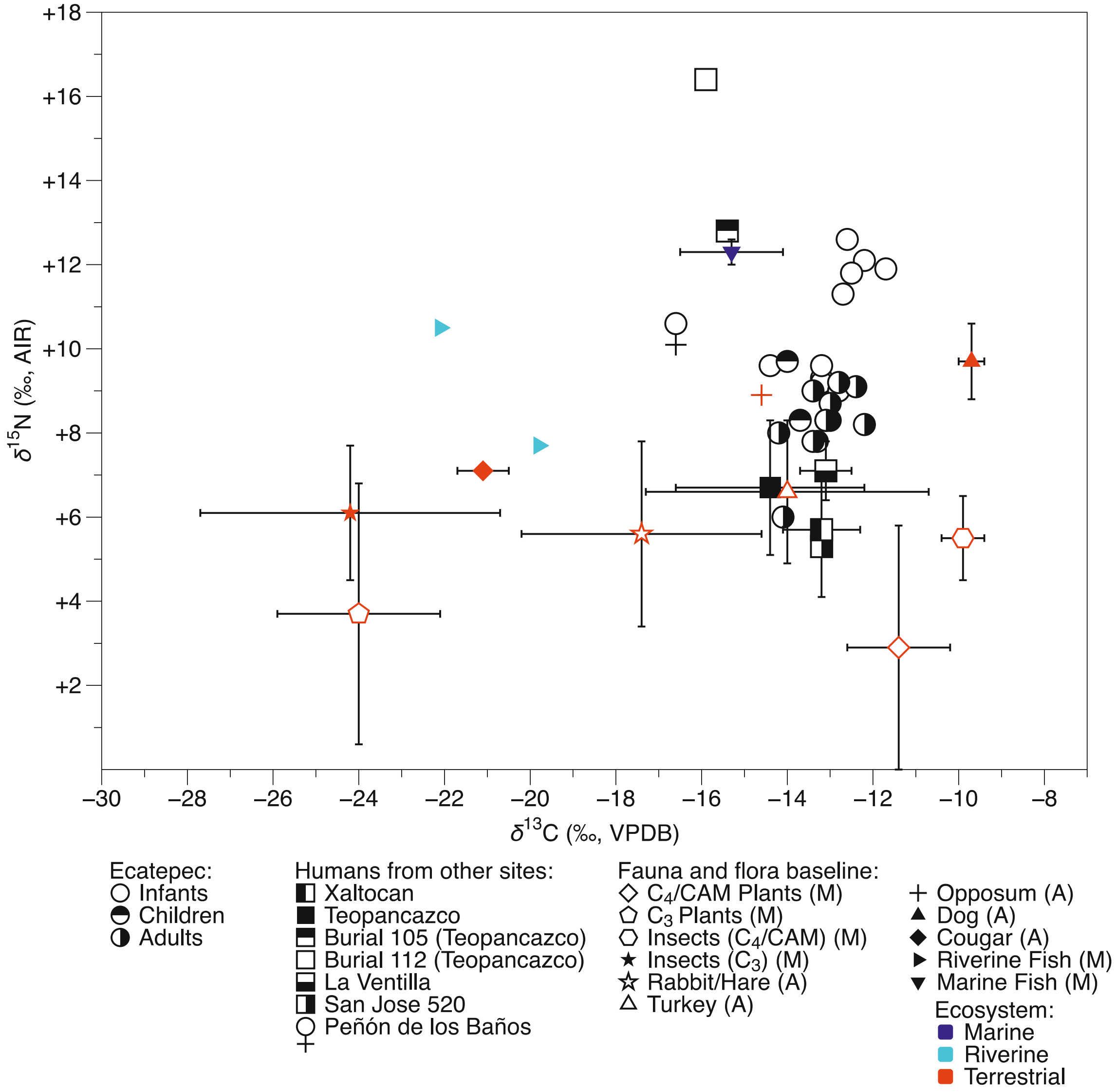

Fig. 2 Ecatepec $\delta^{13}C_{diet}$ and $\delta^{15}N_{diet}$ plotted alongside results for humans from other Basin of Mexico archeological sites, as well as Basin of Mexico plant and animal δ^{13}C and δ^{15}N data. Isotope data for humans as well as flora and fauna are plotted with their respective mean and range (SD, whiskers). "M" = modern and "A" = archeological flora and fauna. Color of means for flora and fauna indicates ecosystem (dark blue = marine; light blue = riverine; orange = terrestrial). The δ^{13}C for modern C_3, C_4, and CAM plants, insects, and riverine and marine fish has been corrected for the "Suess effect" by + 1.5‰. The δ^{13}C for collagen from archeological fauna has been corrected by − 2.0‰ to reflect flesh values. Repeatability of individual measurements was generally better than ± 0.1‰ (SD) for both carbon and nitrogen isotopes

Could the Aztecs have consumed lacustrine foods at Ecatepec?

As discussed above, anthropogenic alteration of the Basin of Mexico lakes makes it challenging to assess pre-Hispanic stable carbon and nitrogen isotope compositions using what is left of the ecosystem in present-day Xochimilco Lake. The absence of δ^{13}C and δ^{15}N data for archeological lacustrine species indigenous to the Basin of Mexico makes it difficult to evaluate quantitatively the possible consumption of lacustrine foods by the Ecatepec residents. Even so, the isotope results collected thus far are sufficient to hypothesize that there was at least *some consumption of lacustrine foods*.

The $\delta^{13}C_{diet}$ of the Ecatepec children and adults (range = − 14.0 to − 12.2‰) (Table 3) is more negative than the δ^{13}C of dogs, which had a 100% C_4 diet (Fig. 2); the dogs likely ate the old crusty tortillas that people gave them (as is often the case today) but no other vegetables and condiments (Morales Puente et al. 2012). These Ecatepec residents also have $\delta^{15}N_{diet}$ (range = + 7.8 to + 9.7‰) (except for DM 88) (Table 3) situated within the δ^{15}N range (+ 7.7 and + 10.5‰) of freshwater fish from a riverine context (Fig. 2). However, these riverine fish, albeit from outside of the study area, have much lower δ^{13}C (range = − 22.1 to − 19.8‰) (Table 2). There is some evidence, however, that the lacustrine food web within the study area may have a high δ^{13}C. A pre-

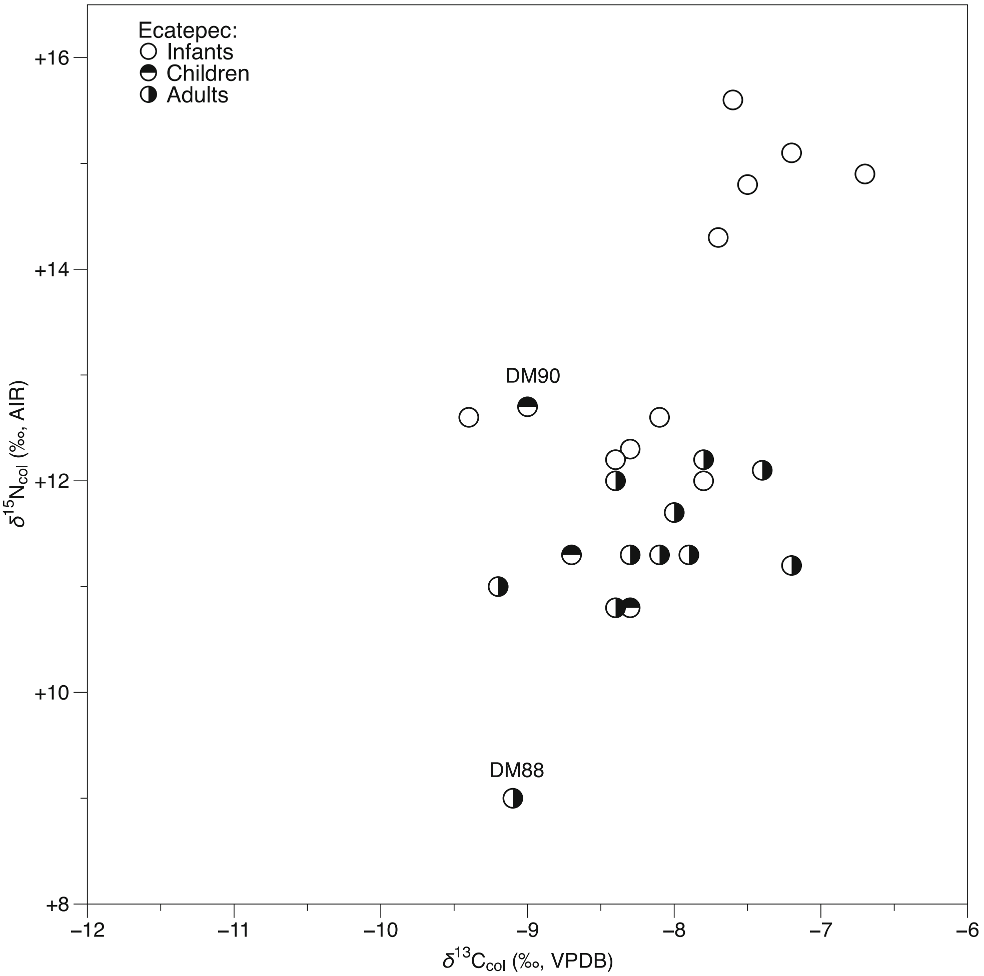

Fig. 3 Ecatepec bone $\delta^{13}C_{col}$ and $\delta^{15}N_{col}$ plotted by age group. Repeatability of individual measurements was generally better than ± 0.1‰ (SD) for both carbon and nitrogen isotopes

agricultural (12,683 cal. BP[4]) adult woman from Peñón III (Peñón de los Baños), an island in Lake Texcoco (Fig. 1) who had a diet primarily based on freshwater/lacustrine foods, has a $\delta^{13}C_{diet}$ of − 16.6‰ and a $\delta^{15}N_{diet}$ of + 10.6‰ (Fig. 2; Table 3) (González et al. 2003; Casar et al. 2017b). Given that this woman did not incorporate C$_4$/CAM plants (particularly maize) heavily into her diet, her $\delta^{13}C_{diet}$ suggests that the lacustrine food web in the Basin of Mexico likely had higher $\delta^{13}C$, not that dissimilar from the $\delta^{13}C$ of a diet dominated by C$_4$/CAM foods. Additionally, her $\delta^{15}N_{diet}$ is higher than all but one $\delta^{15}N$ of the terrestrial omnivores and only slightly more elevated (by ~ 2‰) than the mean $\delta^{15}N_{diet}$ of the Ecatepec residents (Fig. 2; Table 3).

To further test for the presence of lacustrine foods in the Ecatepec residents' diets, we compared their $\delta^{13}C_{diet}$ and $\delta^{15}N_{diet}$ with those of four other pre-Hispanic human groups recovered from other Basin of Mexico archeological sites between the Classic (AD 200–550) and Postclassic (AD 900–1521) periods. These groups include Xaltocan and the Teotihuacan (Fig. 1) residential districts (*barrios*) of Teopancazco, La Ventilla, and San José 520 (Fig. 2, Table 3) (Casar et al. 2017b; Danforth 2000; Morales Puente et al. 2012; Nado et al. 2017). While all of these groups have overlapping mean $\delta^{13}C_{diet}$, which reflect the primary consumption of C$_4$/CAM foods (60–70% of the overall diet and 50% C$_4$ protein), there are clear differences in $\delta^{15}N_{diet}$ (Fig. 2, Table 3). Xaltocan and the three Teotihuacan districts all have mean $\delta^{15}N_{diet,}$ ranging from + 5.3 to + 7.1‰. By comparison, the Ecatepec adults and children (excluding the nursing infants) have means $\delta^{15}N_{diet}$ of + 8.3‰ and + 8.6‰, respectively, which positions them a trophic level above the individuals from the other Basin of Mexico archeological sites (Fig. 2, Table 3). This suggests that while the Xaltocan and Teotihuacan individuals had mostly terrestrial diets, the Ecatepec group likely included lacustrine foods in their diets in addition to terrestrial resources. At Teopancazco, there are two outliers (burials 105 and 112), who likely consumed more C$_3$ (50% of the overall diet) *and* marine foods, based on their lower $\delta^{13}C_{diet}$ (− 15.4‰ and − 15.9‰, respectively) and even higher $\delta^{15}N_{diet}$ (+ 12.8‰ and + 16.4‰, respectively)

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[4] Uncalibrated date: 10, 755 ± 75 years before present (BP). This date was calibrated using the online software OxCal 4.3.2 (Bonk Ramsey 2009). IntCal 13 was the calibration curve used (Reimer et al. 2013).

Table 3 Summary of δ^{13}C and δ^{15}N data for humans from Ecatepec and other Basin of Mexico archeological sites[a]

Archeological site	Time period/date	Sample type	*n*	Mean $\delta^{13}C_{diet}$ (VPDB, ‰)[b]	SD	Range (‰)	Mean $\delta^{15}N_{diet}$ (AIR, ‰)[c]	SD	Range (‰)
Ecatepec infants	Postclassic (A.D. 900–1521)	Bone	10	−12.8	0.7	−14.4 to −11.7	+10.6	1.4	+9.0 to +12.6
Ecatepec children	Postclassic (A.D. 900–1521)	Bone	3	−13.7	0.4	−14.0 to −13.3	+8.6	1.0	+7.8 to +9.7
Ecatepec adults	Postclassic (A.D. 900–1521)	Bone	11	−13.2	0.6	−14.2 to −12.2	+8.3	0.9	+6.0 to +9.2
Peñón III (Peñón de los Baños)	12, 683 cal. BP	Tooth dentin	1	−16.6	N/A	N/A	+10.6	N/A	N/A
La Ventilla	Classic (A.D. 200–650)	Bone	9	−13.1	0.6	−14.0 to −12.2	+7.1	0.7	+6.0 to +8.5
San José 520	Classic (A.D. 200–550)	Bone	5	−13.2	0.2	−13.5 to −13.0	+5.3	0.2	+5.1 to +5.5
Teopancazco	Classic (A.D. 200–550)	Bone and tooth dentin	32	−14.4	2.2	−23.0 to −12.0	+6.7	1.6	+4.0 to +9.9
Burial 105-Teopancazco	Tlamimilolpa (A.D. 200–350)	Tooth dentin	1	−15.4	N/A	N/A	+12.8	N/A	N/A
Burial 112-Teopancazco	Tlamimilolpa-Xolalpan (A.D. 320–370)	Tooth dentin	1	−15.9	N/A	N/A	+16.4	N/A	N/A
Xaltocan	Postclassic (A.D. 900–1521)	Bone	9	−13.2	0.9	−14.5 to −12.0	+5.7	1.6	+2.8 to +8.3

[a] Data from this study, Casar et al. (2017b: Table 4.1), Danforth (2000: Table 7), González et al. (2003), Morales Puente et al. (2012: Table XI.4), and Nado et al. (2017: Table 1)

[b] The δ^{13}C data have been adjusted by + 5‰ to reflect $\delta^{13}C_{diet}$

[c] The δ^{15}N data have been adjusted by − 3‰ to reflect $\delta^{15}N_{diet}$

compared with the Ecatepec group (Fig. 2, Table 3). These observations allow us to more confidently assert that the Aztecs at Ecatepec consumed lacustrine foods in addition to the terrestrial plants and animals that were also part of their everyday diets.

The incorporation of lacustrine foods into the Aztec diets is supported by ethnohistoric and zooarchaeological evidence. Ethnohistoric accounts detail a wide variety of lacustrine foods available in the Basin of Mexico. For instance, in the Florentine Codex, Sahagún (1981) describes the wide variety of lacustrine sources in the Basin and provides several illustrations of Aztec hunting and fishing practices. Likewise, a mid-sixteenth century map depicts different fishing and waterfowl-netting activities at Lake Texcoco (Apnes 1947 in Parsons 2010). These ethnohistoric sources also note how the Aztecs actively controlled the water depths across the Basin, using each lake area for different lacustrine activities (e.g., hydraulic management, aquatic infrastructure) (Parsons 2010). The zooarchaeological evidence presented above further suggests that communities situated near the Basin lakes, such as Chalco, Xaltocan, and Mexicaltzingo, consumed a variety of lacustrine foods including waterfowl, turtle, frogs, and to a lesser extent fish and shellfish. As such, it is very likely that the Aztecs at Ecatepec, living so close to the Texcoco and Xaltocan lakes, also exploited the lacustrine landscape, as was hypothesized by Trejo Rangel (2014).

There is no ethnohistoric evidence to suggest that the elites had control over the lacustrine landscape or its products (Parsons 2010). This would have allowed lower status Aztecs to access lacustrine food sources with little effort and without restriction from the elites. According to Trejo Rangel (2014), this community could have belonged to a lower socio-economic group within the Basin of Mexico socio-political system. As such, it is possible that these Aztecs of low socio-economic status used lacustrine foods to fulfill some of their dietary needs, as described by Sahagún and later recorded during the historic period (Valadez Azúa and Rodríguez Galicia 2014).

The lack of major pathological conditions commonly associated with dietary deficiencies and nutritional stresses within this Aztec group suggests that, overall, they were healthy and well nourished (Trejo Rangel 2014). Access to a wide range of lacustrine food items, high in protein and overall nutrition, would have allowed the Aztecs at Ecatepec to fully take advantage of their surrounding environment and fulfill their dietary needs regardless of socio-economic standing. Conversely, a diet rich in carbohydrates, such as the heavy consumption of C_4 grains (e.g., maize, amaranth), causes the

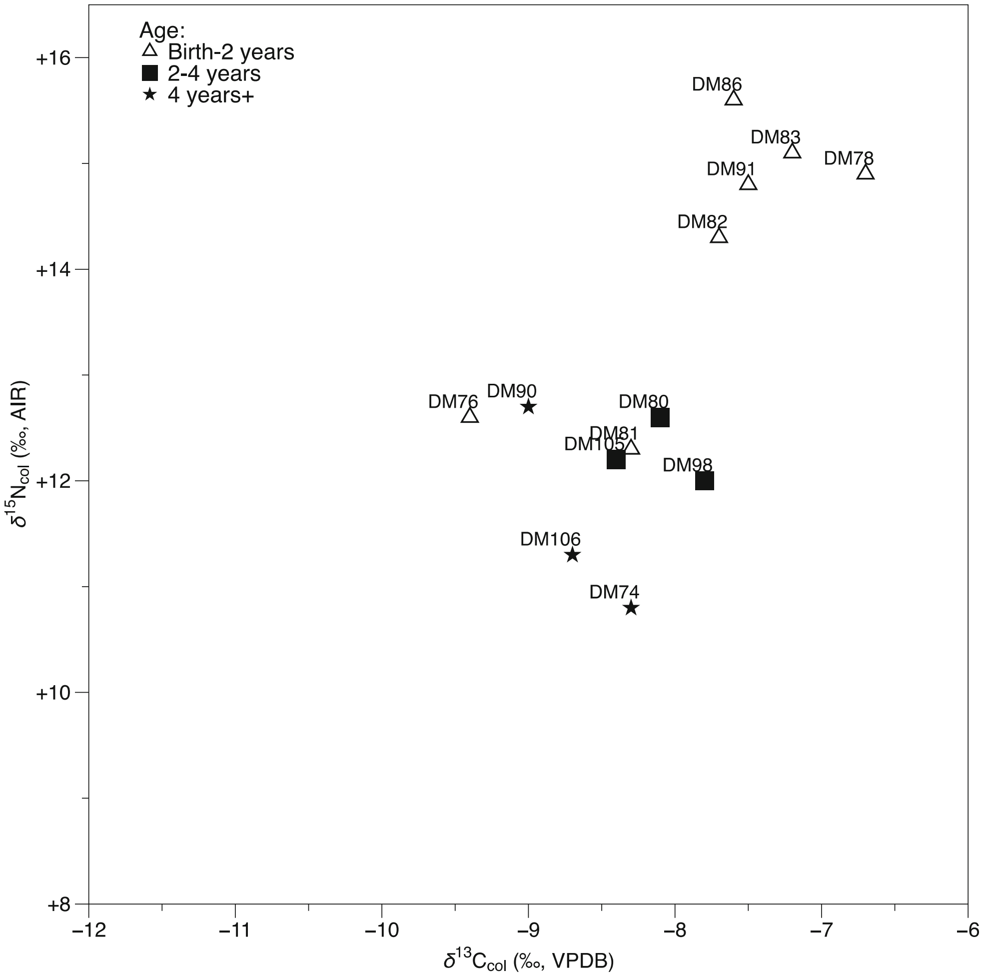

Fig. 4 Bone $\delta^{13}C_{col}$ and $\delta^{15}N_{col}$ of the Ecatepec subadults plotted by age. Repeatability of individual measurements was generally better than ± 0.1‰ (SD) for both carbon and nitrogen isotopes

development of lactic acid when metabolizing sugars and starches, which increases the prevalence of bacteria and dental caries (Hillson 2008; Larsen 1997). This further supports the hypothesis that these residents did not rely solely on C_4 grains and that lacustrine foods were likely a component of their diets.

Dietary variability based on sex

The Aztec members of the Ecatepec community likely resided within the Basin of Mexico throughout most of their lives (Moreiras Reynaga 2019). Accordingly, we have assessed whether there were sex-based differences visible in their diets based on the $\delta^{13}C_{col}$ and $\delta^{15}N_{col}$ results (Fig. 5). The two Mazapa phase adults, a male (DM 84) and a female (DM 85), have the same $\delta^{13}C_{col}$, but the male has a higher $\delta^{15}N_{col}$, which is similar to the $\delta^{15}N_{col}$ of a few males from the Aztec III–IV phase group (Fig. 5). The Mazapa individuals have lower $\delta^{13}C_{col}$ compared with the Aztec III–IV phase group, suggesting that they may have consumed less C_4/CAM foods in the early phase of the Postclassic period.

In terms of the Aztec III–IV adults, the females consumed slightly less C_4/CAM foods compared with the males based on their lower $\delta^{13}C_{col}$ (Fig. 5). Based on $\delta^{15}N_{col}$, however, the female and male adults seem to have consumed similar amounts of animal protein. These results suggest that the men in this group may have consumed *pulque* in addition to C_4 grains compared with the women. Based on the ethnohistoric record, we know that adult men had the freedom to consume *pulque* in moderation while women (up to the age of 60 years) were not allowed to drink or even sell *pulque* (Coe 1994; Soustelle 1961). Aside from this sex difference, their overall diets were quite similar as inferred from the isotopic data. Only the lower $\delta^{15}N_{col}$ (+ 9.0‰; Fig. 5) of an adult male (DM 88) provides evidence of less animal protein consumption compared with the rest of the group. This man likely consumed meat occasionally, while the rest of the group consumed meat more frequently. This adult male (DM 88) and an adult female (DM 94) also consumed the least amount of C_4/CAM foods within this group based on their low $\delta^{13}C_{col}$. These results suggest that this community shared similar diets overall. This trait is reflective of an Aztec population that shared similar foodways including their everyday

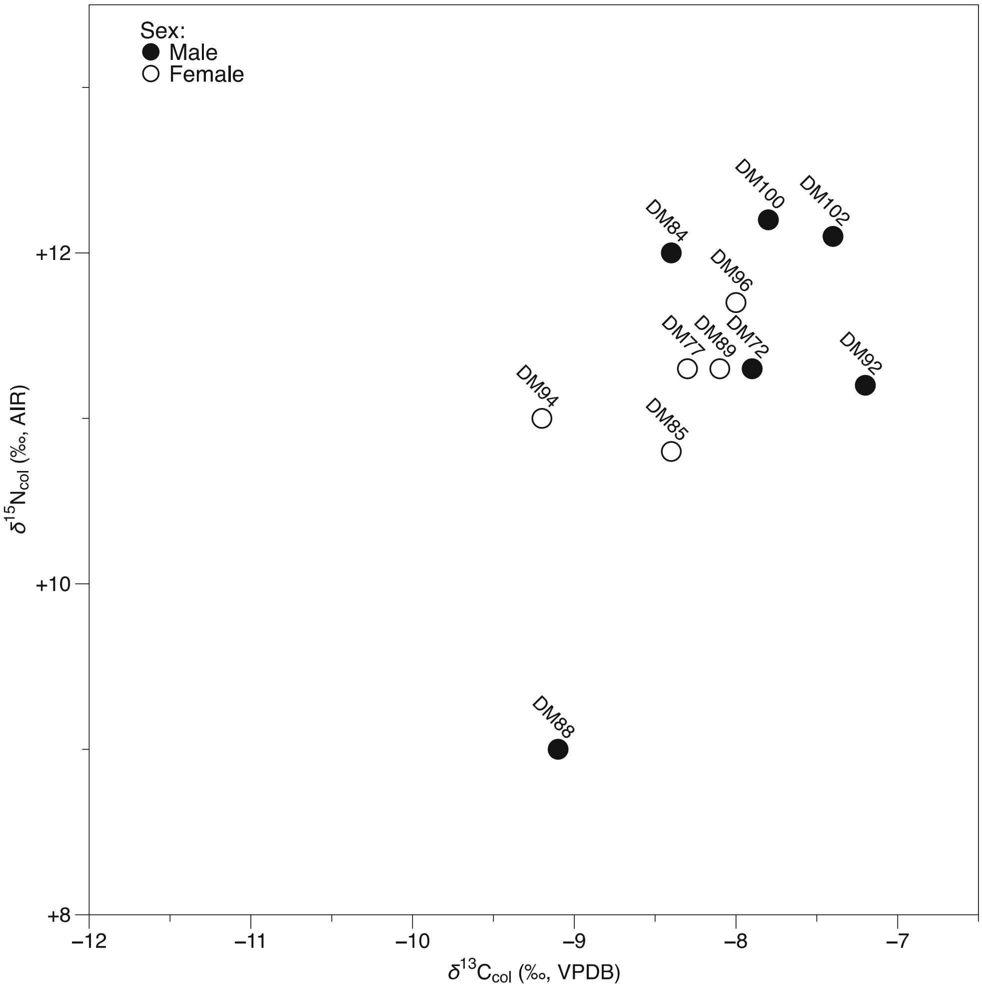

Fig. 5 Bone $\delta^{13}C_{col}$ and $\delta^{15}N_{col}$ of the Ecatepec adults plotted by sex. Individuals DM 84 and 85 date to the Mazapa phase, while the rest of the individuals date to the Aztec III–IV phase. Individuals DM 88 and 94 have the most distinct diets *within* the Aztec III–IV group. Repeatability of individual measurements was generally better than ± 0.1‰ (SD) for both carbon and nitrogen isotopes

consumption habits, availability of food products for the community as a whole, and access to specific foods based on their proximity to the Texcoco and Xaltocan lakes.

An example of Aztec feeding and nursing practices

The infant and child $\delta^{13}C_{col}$ and $\delta^{15}N_{col}$ data provide insights into the breastfeeding and weaning practices of this Aztec community. We infer that five infants between the ages of 1 and 2 years (DM 78, 82, 83, 86, and 91) were breastfed up to the time of death, given that their mean $\delta^{15}N_{col}$ (+ 14.9 ± 0.5‰) is higher by 3.7‰ than the adult females of reproductive ages ($\delta^{15}N_{col}$ + 11.2 ± 0.4‰) (Figs. 3 and 4). It is possible that their mother's milk was mostly composed of C_4/CAM protein. A 1.5-year-old infant (DM 76), a 3-year-old (DM 80), and a 4-year-old child (DM 90) have $\delta^{15}N_{col}$ (range = + 12.6 to + 12.7‰) intermediate to the ranges of the breastfeeding infants and the adult females (Fig. 3), which could indicate that these subadults were being weaned (Fig. 4). Three infants (DM 81, 98, and 105) between the ages of 2 and 3 years have $\delta^{15}N_{col}$ within the adult $\delta^{15}N_{col}$ range (Figs. 3 and 4), which suggests that some infants could have been weaned as early as 2 years of age. This is a small sample, however, and we do not know the cause of death of these individuals. Nonetheless, these results likely point to some variability in this community's subadult feeding practices. Some infants were likely fully weaned early on during infancy (between ages 2 and 3 years), while other subadults continued to breastfeed until about 4 years of age. This extended nursing practice has been previously reported at other Mesoamerican sites such as Teotihuacan (e.g., White et al. 2004a; Wright and Schwarcz 1998, 1999).

Conclusions

This study has shed light on several aspects of the dietary practices of the Aztec residents from Ecatepec. The carbon and nitrogen isotope results revealed overall dietary patterns that correlate well with the zooarchaeological and paleoethnobotanical data recovered at other Aztec sites located near the Basin of Mexico lakes (e.g., Xaltocan, Mexicaltzingo). The Aztecs at Ecatepec incorporated mainly

C_4/CAM plants as well as some C_3 plants, terrestrial animals, and probably lacustrine foods into their diets.

While C_4/CAM foods were important at this site, lacustrine foods likely also played a role in the Ecatepec residents' diets. Adult females consumed slightly less C_4/CAM foods compared with the males, perhaps suggesting that they likely did not consume *pulque*, but all the adults (except for one) had similar amounts of animal protein in their diets. The similarity in the Ecatepec diets, based on the Aztec III–IV group, could be due to sharing similar foodways as a community, the accessibility of specific food products based on their shared socio-economic status, and proximity to the Basin of Mexico lakes. We found that the two adults dating to the Early Postclassic period consumed less C_4/CAM foods compared with the majority of the adults from the Aztec III–IV phase, pointing to possible dietary differences across time periods.

Half of the infants in this group had nitrogen isotope compositions that signal breastfeeding, while the other half underwent the weaning transition as early as 2 years of age. Two infants and one child showed signs of the weaning transition between the ages of 2 and 4. To our knowledge, this is the first time that bone collagen isotope compositions have been measured systematically for a group of Aztec residents to reconstruct their diets. This study provides an initial baseline for everyday diets for Aztecs living close to the Basin of Mexico's lacustrine environment during the Postclassic period.

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Authors' contributions DKMR, J-FM, FJL, and REGC designed the research; REGC excavated and curated the collection; DKMR performed research; DKMR, J-FM, and FJL interpreted the data; DKMR wrote the initial manuscript with input from J-FM, FJL, and REGC.

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Data availability This project was approved by the Consejo de Arqueología of the Instituto Nacional de Antropología e Historia (INAH) with permit: 401.B[4]19.2016/36/0273.

Compliance with ethical standards

Competing interests The authors declare that they have no competing interests.

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