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Assessing nutrient inputs, sediment organic matter sources, and the potential for cyanobacteria in ancient water reservoirs at the Maya city of Ucanal, Guatemala: A glimpse at sustainable water management practices

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ABSTRACT

Although water storage infrastructure was crucial to ancient Maya society, relatively little is known about their potential contamination by biological pathogens and nutrient pollution within ancient Maya cities. At the site of Ucanal, Guatemala, inhabitants created an extensive water infrastructure landscape to manage both supply and drainage. Archaeological, geochemical and paleolimnological data were compiled from stratigraphically excavated and chronologically controlled dried sediments from 3 ancient water reservoirs in Ucanal to investigate potential cyanobacteria contamination from the Late Preclassic to the Terminal Classic periods. Elemental and isotopic analyses of carbon, nitrogen, and phosphorus reveal that none of the 3 reservoirs exhibited nutrient or organic carbon rich environments indicative of or conducive to cyanobacteria or eutrophication, regardless of time period. In addition, $\delta^{13}C$ data show a common pattern of C_4/CAM plants usage throughout the city core from the Preclassic to Terminal Classic periods, similar to settlement zones and agricultural fields identified elsewhere in the Maya area. These results suggest that inhabitants of Ucanal managed a sustainable water landscape system that remained relatively stable and without excessive nutrient inputs despite population increases at the end of the Classic period.

1. Introduction

Pre-Columbian peoples, including the Maya, regularly constructed water reservoirs, drainage canals, dams, terraces, and other features to more effectively access and manage water resources (Chase 2016; Chase and Cesaretti 2019; Chase and Chase 2017; Dunning et al. 1999; Lucero 2002; Lucero et al. 2011; Luzzadder-Beach et al. 2016; Scarborough 1998; Scarborough et al. 2012). These water reservoirs may have been in danger of being polluted due to increases in population, urban densities, intensive agriculture, and other anthropogenic environmental changes. For example, an aDNA study of ancient reservoirs at the large urban site of Tikal, Guatemala, revealed evidence of cyanobacteria or blue-green algae during periods of heavy occupation of the site (Lentz et al. 2020), and geochemical analyses of the western arm of Lake Petén Itzá revealed deteriorated aquatic ecological conditions during the Preclassic period (ca. 800 BCE – 300 CE), corresponding to a period of agricultural intensification and urban development at the nearby site of Nixtun-Ch'ich', Guatemala (Birkett et al. 2023) (Fig. 1). Nonetheless, the study of cyanobacteria blooms (Lentz et al. 2020; Waters et al. 2021) in ancient Maya reservoirs is relatively rare, and the available studies do not encompass the diverse range of cities and regional ecosystems found throughout the Maya area.

Here we report on the study of three water reservoirs from the medium-sized ancient Maya city of Ucanal located in eastern Petén, Guatemala (Fig. 2). The water infrastructure system at Ucanal included monumental-scale reservoirs, smaller reservoirs or water collection zones, and large-scale open-air canals, which were integrated with public plazas, roads, and civic-ceremonial buildings to drain excess rainwater to the nearby Mopan River to prevent flooding and erosion in residential areas of the ancient city (Halperin et al. 2019). Excavations of

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Fig. 1. Map of the Maya area showing the locations of Ucanal and sites mentioned in the text (drafted by C. Halperin).

three of the city's canals indicate that these water drainage systems were built at the beginning of the Terminal Classic period (ca. 810–950/1000 CE), a time when the polity underwent a large-scale renewal, including forging alliances with new political entities throughout the Maya Lowlands, undertaking major civic-ceremonial building campaigns in the city's site core, and erecting new monuments (Halperin et al., 2024; Halperin and Garrido 2020; Halperin and Martin 2020). These urban developments occurred during a time in which many other cities were becoming depopulated or were undergoing political crises. This research measures total organic carbon (TOC), total carbon (TC), total nitrogen (TN), total phosphorous (TP), and bulk nitrogen and carbon stable isotope ratios (δ^{13}C and δ^{15}N) from dried sediments stratigraphically excavated from three reservoirs to assess their aquatic health and potential for harmful cyanobacteria blooms. The results of these measurements suggest that the Terminal Classic Period urban renewal activities at Ucanal encompassed sustainable urban environmental management practices that likely avoided excess nutrient pollution and the growth of cyanobacteria in city reservoirs.

2. Archaeological, geochemical and paleolimnological contexts

2.1. Archaeology

Archaeological research at Ucanal (16°50′41′'N 89°22′26′'W (Halperin and Ramos Hermandez, 2024)) reveals an occupation from at least the Middle Preclassic to the Postclassic periods (ca. 800 BCE–1521 CE) (Halperin et al. 2021; Laporte and Mejía, 2002). It emerged, however, as an important ceremonial center in the Late Preclassic period (ca. 300 BCE – 300 CE) when evidence for the initial development of many of the site's civic ceremonial zones and dispersed residential occupation have been documented. All residential groups excavated to date (n = 33; 2024) have Terminal Classic occupation and many have multiple construction phases dating to the Terminal Classic period, which correspond to the site's demographic and political apogee (Halperin and Ramos Hermandez, 2024 Table 11.1). Based on the number of currently identified structures and standard individual per structure statistics (Canuto et al. 2018), the site population is preliminarily estimated to have been between 8000 and 11000 people at its peak, although these numbers would be larger with the inclusion of outlying settlement zones and unmapped areas. Population, however, diminished significantly during the Postclassic period with little evidence of major Postclassic building projects, and a relatively light occupation in the residential zones (Halperin et al. 2021).

All excavations reported in this paper were conducted within a national park managed by the Guatemalan Instituto de Arqueológía e Historia under a permit from the Departmento de Monumentos Prehistoricos y Coloniales from the Ministerio de Culture y Deportes in Guatemala. Excavations of reservoirs to date have targeted a large, monumental reservoir, Aguada 2, a small residential reservoir, Aguada 3, and a water reservoir integrated into a larger drainage canal, Piscina 2 of Canal 1. All reservoirs are currently located in a protected high canopy forest within this national park and, as such, are not exposed to contemporary farming, pastoral, or residential activities.

Aguada 2 is located at one of the highest elevations of the site and was surrounded primarily by large residential groups interpreted to

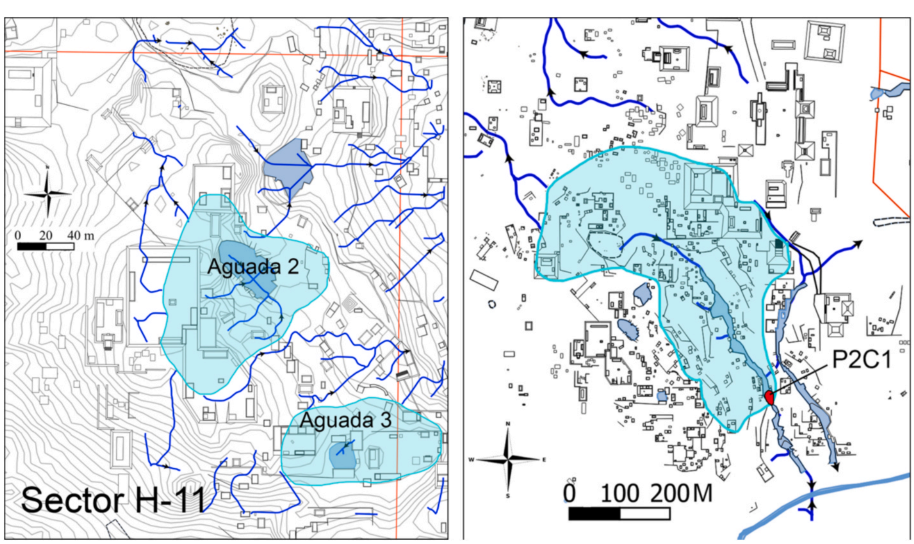

Fig. 2. Map of the 3 reservoirs studied in Ucanal. Aguadas 2, 3 (left) and Piscina 2 of Canal 1 (P2C1) (right) with their respective water catchment zones (in blue) (after Tremblay et al. 2024 Fig. 3).

have been occupied by elite households. It had an estimated holding volume of 2.6x10^6 L and a water catchment drainage area of 10,919 m^2 (Fig. 2) (Halperin et al. 2022). Although large for the site, Aguada 2 is 30 times smaller by volume than the Palace reservoir at Tikal (Scarborough et al. 2012). It was first constructed during the Late Preclassic period (Cruz Gómez and Quezada 2023) when it probably also served as a quarry to obtain raw materials for building projects, and was not subject to any renovations after initial construction (Figs. 3 and 4). Ceramic analysis and AMS radiocarbon dating reveal that Aguada 2 has the longest chronology of the 3 reservoirs with a 3.5 m sediment profile spanning from the Late Preclassic to the Terminal Classic periods (Supplementary Appendix A – Fig. A.1). The complete chronology of the reservoirs including AMS dates can be found in Tremblay et al. (2024 Appendix A).

Aguada 3 is nested tightly between mid- and small-sized residential groups interpreted to have been occupied by middle or non-elite households (Halperin et al. 2023) (Fig. 2). It was also at a high elevation, restricting its water drainage area to a small zone of densely packed residences. The reservoir had a much smaller holding volume than Aguada 2 and is estimated to have held 450 x 10^3 L associated with a drainage area of 6057 m^2. Aguada 3 has a shorter use life than Aguada 2, as it appears to have been first constructed at the end of the Late Classic period (ca. 600–810 CE) or the beginning of the Terminal Classic period with sediment accumulation having occurred primarily during the Terminal Classic period in levels 1–6. Levels 7–12 comprised a compact construction fill and *sascab* stratum (Halperin et al. 2023:135–136) dated to the Late Classic period (Tremblay et al. 2024). Correspondingly, these lower levels were characterized by a powdery cream-colored (10YR 7/2) matrix containing large quantities of calcium carbonate mixed with 40–60 % coarse fraction composed of limestone.

Piscina 2 (P2C1) is located at the lower part of Canal 1 close to the floodplain zone where the canal drains into the Mopan River (Fig. 2). It has the largest drainage area of the three reservoirs at 158,805 m^2. This water drainage area includes public ceremonial plaza spaces as well as elite and non-elite residential sectors. The pool is integrated into the canal and serves as a water attenuation tank to slow the flow of water and erosion during the rainy season and, as such it was a dynamic water retention zone (Gauthier and Flynn-Arajdal 2024). Excavations revealed a sediment profile at the center of the reservoir 1.5 m in depth. Canal 1 was constructed at the beginning of the Terminal Classic period (Halperin et al. 2019), but the Piscina 2 reservoir itself may have been a zone of soil and water accumulation dating back to earlier periods, with levels 9–15 containing ceramics of mixed time periods primarily dating to the Late Preclassic (ca. 0–300 CE) and Early Classic (ca. 300–600 CE) periods (Gauthier and Flynn-Arajdal 2024). This sedimentation perturbation is reflected in an AMS radiocarbon dating inversion between

Fig. 3. Dried sediment profile of excavated Aguada 2 reservoir. With a noticeably dark A horizon extending 40 cm deep with organic material and humus rich upper section (with Mollisols qualities) and a lighter color, low organic carbon content lower section and well-structured horizons in between (with Vertisols qualities). Orange tape markers are positioned at 10 cm intervals. Photograph by C. Cruz Gómez.

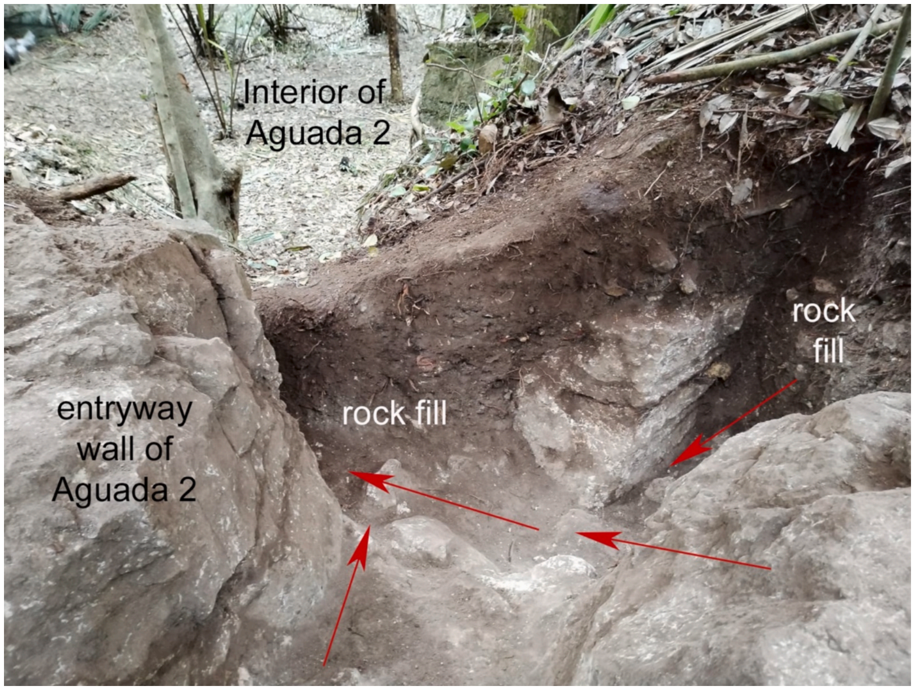

Fig. 4. Human built drainage canals leading to Aguada 2 that may have controlled the entry of bulk material and detritus into the reservoir. Arrows indicate water flow direction. Photograph by C. Cruz Gómez.

levels 9 and 10 (Tremblay et al. 2024 Appendix A) as well as in the sediment's coarse fraction vertical profile (Supplementary – Table C.12).

2.2. Geochemistry and paleolimnology

The Petén region of Guatemala is mostly composed of Tertiary karstic rocks (Beach et al., 2006a) with the omnipresence of limestone which dominates soil composition along with continental and marine sediments (West 1964). While Petén soils are characterized by the presence of both Vertisols and Mollisols (Beach et al., 2006a; Donado 1996), dried sediments found in water reservoirs may have followed various pedogenesis processes linked to the erosion of movable material located within their respective drainage areas. Petén top soils are characterized by the presence of an A horizon with the top soil layer typically darker in color with high organic matter content and active biological activity (Christopherson 2009). Sediments preserved within water reservoirs can derive from runoff from ancient agricultural fields or mixed-use (residential settlement, fields, gardens) lands such as the La Milpa Aguada or the Corriental Reservoir at Tikal (Beach et al. 2011; Scarborough et al. 2012). In other cases, runoff came from large-scale architectural constructions including large, stuccoed patios such as the Temple and Palace reservoirs at Tikal where rainwater was collected along with dust, leaves, and occasional discarded solids on these paved surfaces (Lentz et al. 2020; Scarborough et al. 2012). In addition, the presence of trees, other vegetation, and human-built barriers adjacent to reservoirs affected the nature of the material collected by the rainwater, having the potential to slow down or restrict the transport of bulker material before it reached the reservoirs. For example, Aguada 2 was lined at its edges in certain areas with large rocks, and water entry was channeled into the reservoir in particular zones cut into the bedrock that were filtered by fill rocks (Fig. 4). Excavations also reveal that water entry and exit points of Piscina 2 were also lined with medium-sized (10–30 cm) rocks which impeded the passage of larger waste products and detritus (Gauthier and Flynn-Arajdal 2024). Excavations of the small reservoir, Aguada 3, did not target its edges and thus it is unknown if water entry was controlled in any way. The sediment profiles found in the reservoirs therefore result from a combination of multiple factors such as the presence of residential and ceremonial zones, land-use practices within the city, agricultural fields and gardens (Benjamin et al. 2001; Ford and Nigh 2009; Lentz et al. 2014, Lentz et al., 2018, Lentz et al., 2015), and potential mechanical manipulation of the sediment through construction activities over time.

Elements such as phosphorus (P), nitrogen (N), and carbon (C), measured in dried sediments within reservoirs can serve as key indicators of management practices and ancient biological activity. Phosphorus is often used as a proxy for increased organic deposition in archaeological sites because it is associated with human activities such as food waste management (Beach et al., 2006a; Bleam 2017; Hutson et al. 2009; Lentz et al. 2020; Terry et al. 2004). Carbon and nitrogen stable isotopes associated with organic matter can help identify past land management practices, such as C_3 or C_4/CAM plant cultivation, or the presence of aquatic organisms (Amundson et al. 2003; Beach et al. 2009; Luzzadder-Beach et al. 2012; Martinelli et al. 1999; Meyers, 1994; Piccolo et al. 1996; Tankersley et al. 2023). Together, N and P are critical nutrients for the development of aquatic ecosystems driven by photosynthesis (Larkum et al. 2020). Cyanobacteria blooms may emerge following a series of cascading events including: eutrophication due to an excess of nutrients (Waters 2016); algae growth and associated periphyton (Jones et al. 2024; Waters et al. 2015; Wu 2017; Zastepa et al. 2017) and; hypoxia which alters water ecosystem equilibrium, potentially leading to cyanobacteria proliferation (Funkey et al. 2014; Whitton 2012). Since cyanobacteria have the capacity to fix atmospheric N (Drew et al. 2008), excess P is usually the dominant factor controlling their presence and abundance (INRS 2007; Maya et al. 2007; Schindler et al. 2016; Waters et al. 2015). In a N limiting environment, P also becomes essential for periphyton growth as it can effectively remove or uptake P from waters through assimilation, adsorption and coprecipitation mechanisms (Adey et al. 1993; Wu 2017). Soils that dominate humid temperate and tropical regions easily adsorb and geochemically fix P, in many cases leading to P limitations for primary productivity (Cross and Schlesinger 1995; White and Hammond 2008). As such, this nutrient is often in short supply across the Maya Lowlands (Das et al. 2011; Lentz et al. 2015; Tankersley et al. 2016). As discussed below, P values are highly variable between various detection methods, and thus we rely heavily on inter-method comparative values here.

Other proxies include $\delta^{13}C$, $\delta^{15}N$ as well as C:N ratios (molar ratio of TOC to TN found in sediments or soils) measured from the sediments of a stratigraphic profile (Brenner et al. 1999; Köster et al. 2005; Obrist-Farner et al. 2019; Teranes and Bernasconi 2005; Torres et al. 2012; Wu et al. 2006). C:N ratios have long been used to distinguish between algal and land-plant origins of sedimentary organic matter (Graham et al. 2001; Gu et al. 2017; Jasper and Gagosian 1993; Kubo and Kanda 2017; Meyers, 1994), with algae typically having a ratio between 4 and 10, whereas vascular land plants have a ratio above 20 (Meyers, 1994:291). This distinction arises from the absence of cellulose and other C-rich structural molecules in algae. In aquatic ecosystems such as closed reservoirs, periphytic biofilms play a significant role in the cycling of ambient nutrients as they trap particulate material and assimilate or uptake nutrients from the water column (Matheson et al. 2012; Wu 2017). These biofilms are active sites for nitrogen transformation and have been documented to account for up to 50 % of nitrate uptake (Baldwin et al. 2006; Sobczak et al. 2003). Therefore, these processes contribute to lower C:N ratios by increasing TN in sediments. Similarly, higher TN associated with the presence of nitrogen rich microorganisms within the A horizon of soils (Bleam 2017; Kirkby et al. 2011; Tipping et al. 2016) leads to lower C:N ratios. In land plants, C:N ratios vary widely in different organs, by taxa, and forest types with typical values around 20 for leaves and 50 for roots (Zhang et al. 2020). C:N ranges between 30 and 40 have been shown to be directly associated to cellulosic terrestrial plants as a whole (Ertel and Hedges 1985; Gaudel et al. 2024) while some aquatic plants have ratios between 15 and 20 (Xia et al. 2014). Since these latter ratios do not tend to overlap, they have the potential to provide clues on the sources of sediment organic matter.

Leaves from tropical tree species have been reported to have $\delta^{15}N$ values averaging +6 ‰, while top soils from Brazil have values of +10 ‰ (Martinelli et al. 1999). For instance, Piccolo et al. (1996) report tropical Amazon leaf litter values between +2 ‰ and +8 ‰. Likewise, for soils from the Maya area, Amundson et al. (2003) reported values ranging from + 4.8 ‰ to + 9.0 ‰. In aquatic systems, since cyanobacteria are capable of fixing atmospheric nitrogen, their sustained presence leads to a $\delta^{15}N$ signature closer to 0 ‰ (Drew et al. 2008; Wu et al. 2006).

$\delta^{13}C$ profiles provide clues to the source of organic carbon found in the reservoirs. In aquatic ecosystems, an increase in $\delta^{13}C$ in accumulated sediments can indicate a strong phytoplanktonic productivity in the epilimnion and a response to increasing eutrophication (Torres et al. 2012; Wu et al. 2006). Consequently, $\delta^{13}C$ values from cyanobacteria have been reported to be between −14 ‰ and −16 ‰ (Bupphamanee 2019; Tankersley et al. 2023). On the other hand, in tropical soils located at low elevations, such as the Maya Lowlands, $\delta^{13}C$ is mainly controlled by the relative abundance of C_3 and C_4 plants (Douglas et al. 2015; Yoneyama et al. 2006). C_3 plants have been documented to have an average $\delta^{13}C$ of −27 ‰ (IAEA 2017:51) with typical values for forested C_3 vegetation between −30 and −26 ‰. C_4 plants, such as maize, tropical sedges and grass fall between −17 ‰ and −8‰ (Basu et al. 2015; Cotrufo and Pressler 2023; Guo et al. 2013; IAEA 2017; Nkoue Ndondo et al. 2020; O'Leary 1988; Sage 2017; Winemiller et al. 2011). Maize was a staple crop central to Maya peoples and has been part of Maya and other Mesoamerican belief systems since the beginning of the Preclassic period (Miller 2019; Miller and Taube 1993; Staller et al. 2010; White 1999; White et al. 2006). By statistically combining climate data and $\delta^{13}C$ values from A horizon soils at 55 native North American grasslands, a mathematical relationship describing the relative proportion of C_3 and C_4 plant biomass has been proposed (Von Fischer et al. 2008). Using this mixing model with archaeological $\delta^{13}C$ data provides a means to reconstruct the changes in C_4 biomass over time. Since maize was a prevalent crop, high $\delta^{13}C$ values could be indicative of its production and/or consumption within the reservoirs' drainage areas. Worldwide, about 4 % of plants are C_4 (Sage 2017).

Early diagenesis of organic matter in lacustrine sediments, defined as the alteration and degradation of organic matter during sinking and early sedimentary deposition, may modify the overall character of sedimented material, potentially impacting C:N ratios and $\delta^{13}C$ values (Meyers et al., 1993). Diagenetic processes occurring under both oxic and anoxic conditions (Lehmann et al. 2002) are generally found to be most strongly expressed in the most recently deposited sediment (top 10–15 cm) (Herczeg 1988; Lehmann et al. 2002; Trolle et al. 2010). These processes are highly dependent on the specific environmental and microbiological context (Gälman et al. 2009) which, for instance, includes the presence of microbial communities affecting fermentation processes and subsequent methane and/or CO_2 degassing. In general, within the upper 10–15 cm of lacustrine sediments, $\delta^{13}C$ has been documented to vary by 0.4–1.5 ‰, in either direction, while $\delta^{15}N$ decrease by 0.3–0.7 ‰ (Gälman et al. 2009; Herczeg 1988; Lehmann et al. 2002). Shifts in C:N ratios between 0.5 and 3 have also been measured (Herczeg 1988; Kohzu et al. 2011; Lehmann et al. 2002). These diagenetically overprinted values tend to then stabilize within the remainder of the sedimentary column.

Other documented natural processes may include bacterial fractionation associated with heterotrophic biodegradation within the organic rich topsoil. Heterotrophic bacteria obtain energy from breaking down organic compounds as their carbon source for growth and, by doing so may induce variations of −1‰ to −2.5 ‰ in $\delta^{13}C$ (Beach et al. 2011; Blair et al. 1985; Krüger et al. 2024:113,124; Martinelli et al. 1996).

3. Materials and methods

3.1. Dried sediments sampling

Excavations of the reservoirs followed 10 cm level changes until bedrock. After reaching bedrock, dried sediment samples were taken from a cleaned side of the excavation wall every 10 cm using a stainless steel spatula, working from the bottom layer to the top humic layer of the reservoirs, following current environmental research practices (Keenan et al. 2021, Keenan et al., 2022; Köster et al. 2005; Lentz et al. 2020; Tankersley et al. 2023). With a depth of 3.5 m, Aguada 2 recovered samples from 35 distinct levels. Aguada 3 had 12 levels (1.2 m deep), and Piscina 2 of Canal 1 (1.5 m deep) provided 15 levels of dried sediments. To identify background levels of all tested parameters, 3 extra subsurface soil samples were collected (Fig. 5). Collected dried sediments and carbon (charcoal) samples were placed in sterile Whirl Pak bags, kept at room temperature, and transported to the Earth and Planetary Sciences laboratory at McGill University in Canada after excavation. A duplicate of all the samples was kept at the Proyecto Arqueológico Ucanal (PAU) laboratory in Flores, Guatemala, and some samples were split for Quality Assurance and Quality Control (QA/QC) purposes (see section 3.5). Upon reception in Canada the samples were freeze dried to remove any water content, weighed, ground, and sieved (USA STD Testing Sieve No.8, 2.36 mm). Both coarse and fine fractions were thereafter kept in a − 20 °C freezer (Tremblay et al. 2024).

3.2. Dating of the reservoirs

Reservoir chronologies were established by combining AMS radiocarbon measurements and ceramic analyses. AMS radiocarbon analyses were conducted at the University of Ottawa in Canada and complemented by ceramic analyses performed at the PAU lab in Flores, Guatemala. For radiocarbon measurements, sample pretreatment techniques, processing and definitions of media codes can be found in (Crann et al. 2017) and (Murseli et al. 2019). Calibration was performed using OxCal v4.4 (Ramsey 2009). Calibrated results are given as a range (or ranges) with associated probabilities (Millard 2014). Ceramics were found in all levels of the three reservoirs and classified by PAU personnel based on regional ceramic type-variety and their ceramic complexes

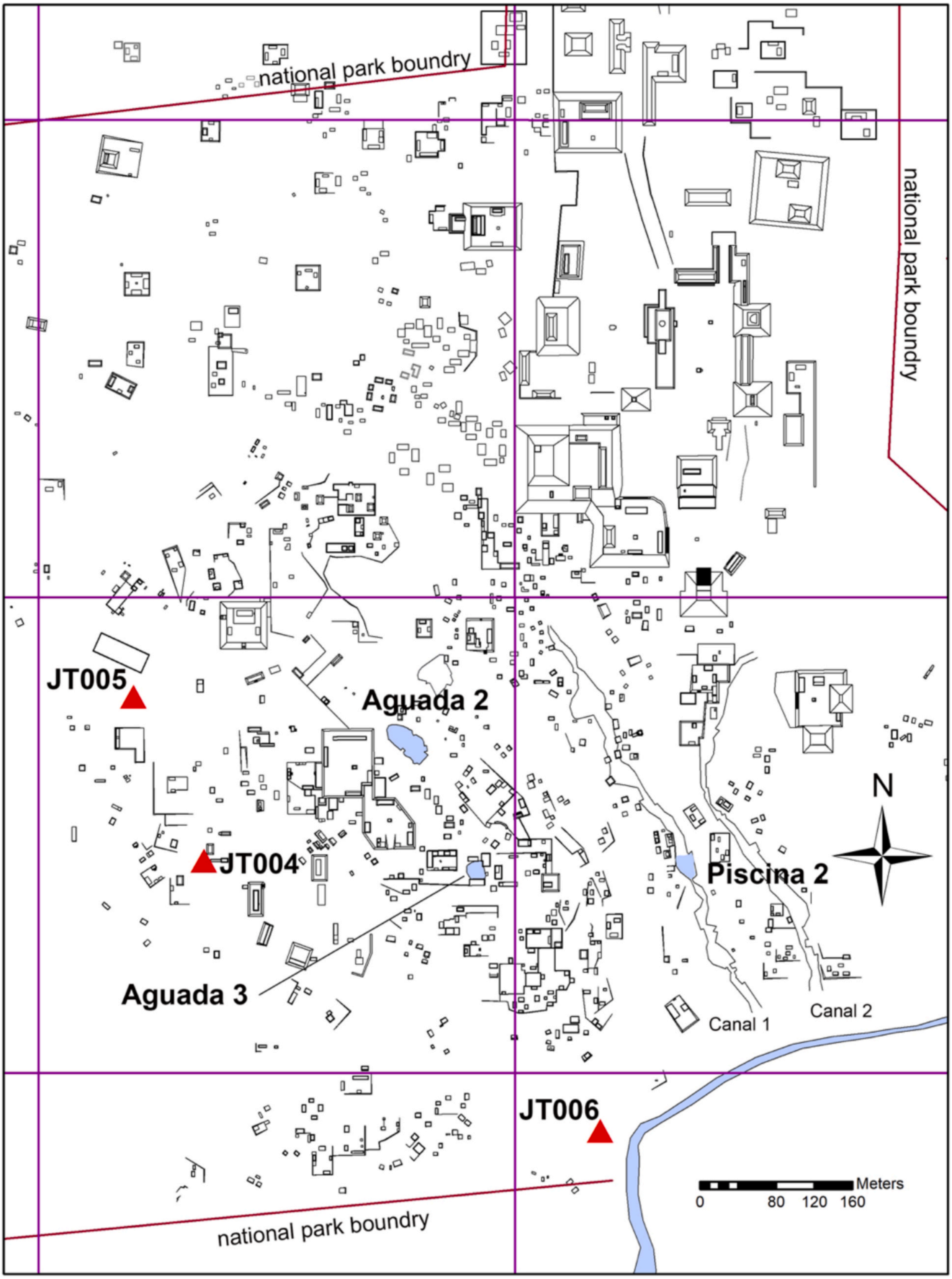

Fig. 5. Map of part of the city of Ucanal showing the locations of Aguadas 2, 3 and Piscina 2, and location of background test samples collected around the city core.

(Gifford 1976; Laporte 2007; LeCount 2018; Salas et al. 2018), providing 100 % chronological coverage. The Age/Depth model for Aguada 2 shows a millennia of undisturbed sediment accumulation (Supplementary Appendix A – Fig. A.1). Chronological data for all 3 reservoirs are documented in Tremblay et al. (2024).

3.3. Elemental and isotopic analyses

All elemental and isotopic analyses were performed at the Geotop Research Centre on Earth System Dynamics in the Light Stable Isotopes Geochemistry Laboratory at the Université du Québec à Montréal, Canada. Between 5 and 10 mg (±0.001 mg) of sample were weighed and placed in a 5 mm x 8 mm tin capsule. TN, TC and TOC measurements were carried out by combustion and separation of elements using a Carlo Erba NC2500 gas chromatograph coupled with a thermal conductivity detector. Analytical precision for these parameters was respectively, 0.01 %, 0.1 % and 0.1 %. Due to the high inorganic carbon abundance (9.6–11.1 %) throughout the stratigraphic columns, our samples were first treated with a 1 N HCl solution for 24 h and centrifuged at 4000 rpm for 20 min to remove the supernatant liquid. This process was repeated until all excess calcium carbonate was removed as indicated by the absence of CO_2 gas. It was then brought to neutral pH with de-ionized water and freeze-dried (Labconco Freezone 12) prior to TOC and $\delta^{13}C$ determination. TN and $\delta^{15}N$ measurements were conducted on samples that were not treated with acid because acidification may induce losses of nitrogen (see Vigeant et al. 2021). $\delta^{15}N$ and $\delta^{13}C$ measurements were conducted using an Isoprime 100 isotope ratio mass spectrometer with triple universal collectors coupled to an Elementar Vario MircroCube in Continuous Flow mode as per recommendations of the International Union of Pure and Applied Chemistry (see Skrzypek et al. 2022). The method is described in the Supplementary materials of Hélie et al (2021). For $\delta^{15}N$, results were normalized on the AIR (Ambient Inhalable Reservoir) isotope delta scale using 2 internal standards (leucine $\delta^{15}N = -0.06 \pm 0.09$ ‰ and DORM-2 $\delta^{15}N = +14.81 \pm 0.08$ ‰). A control (casein $\delta^{15}N = +6.35 \pm 0.13$ ‰) was also measured. The standards and control were normalized on the AIR scale using IAEA-N1 (International Atomic Energy Agency Material N1) ($\delta^{15}N = +0.43 \pm 0.04$ ‰), IAEA-N2 ($\delta^{15}N = +20.41 \pm 0.07$ ‰) and IAEA-N3 ($\delta^{15}N = +4.7 \pm 0.2$ ‰). For $\delta^{13}C$, results were normalized on the VPDB-LSVEC (Vienna Pee Dee Belemnite – Lithium carbonate from the Svec Mine) isotope scale (see Camin et al. 2025) using 2 internal standards (leucine $\delta^{13}C = -28.74 \pm 0.02$ ‰ and sucrose $\delta^{13}C = -11.80 \pm 0.03$ ‰). A control (DORM-2 $\delta^{13}C = -17.06 \pm 0.02$ ‰) was also measured. The standards and control were normalized on the VPDB-LSVEC scale using NBS-19 (National Bureau of Standards Material 19) ($\delta^{13}C = +1.95$ ‰ exactly), LSVEC ($\delta^{13}C = -46.6$ ‰ exactly), IAEA-CH6 ($\delta^{13}C = -10.45 \pm 0.03$ ‰) and IAEA-CH7 ($\delta^{13}C = -32.15 \pm 0.05$ ‰). All standards and controls were measured every 24 samples for a total of more than 5 replicates per sequence. Uncertainties for the standards were calculated by propagating all uncertainties on the certified reference materials and standards deviations on the measurements as per Meija and Chartrand (2018). The overall analytical uncertainty is calculated for each sample as per Hélie and Hillaire-Marcel (2021) and is better than 0.2 ‰ for $\delta^{15}N$ and 0.1 ‰ for $\delta^{13}C$. For each analytical sequence, the measurements of controls were within analytical uncertainty.

3.4. Total phosphorus

TP measurements, based on a protocol originally developed by Tiessen and Moir (Carter and Gregorich 2007), were conducted at the McGill University Geography Department in Montréal, Canada, using a Biotek Epoch Colometric Reader. One gram of sample, 2.5 ml of a piranha solution (6.72 g Lithium Sulfate, 0.192 g of Selenium Powder and 150 ml of H_2O_2) and 5 ml of concentrated H_2SO_4 were inserted into a 75 ml quartz tube and left on a heat digestion block for 90 min at 360 °C. If the end solution was not clear, 1 ml of H_2O_2 was added and left at 360 °C for another 90 min. Once clear, deionized water was added to the solution and centrifuged to remove all remaining solids. 15 ml of the solution was titrated to pH 5.5 using a 4 M NaOH solution before colorimetric measurements at 630 nm using the Malachite green color indicator (Ohno and Zibilske 1991).

3.5. Global data set statistical errors

A total of 62 levels of dried sediments were collected from the 3 reservoirs, of which 8 (13 %) were collected for QA/QC: 4 for Aguada 2 (levels 5, 14, 22 and 30), and 2 for both Aguada 3 (levels 3 and 8) and Piscina 2 of Canal 1 (levels 6 and 14). Samples from these levels were split into triplicates were subjected to parallel manipulations and analyses. The global error on our data set was evaluated using three different approaches which included the standard error to the mean and two published alternate methods based on the use of the standard deviation (Polissar and D'Andrea 2014:152,155) and the variation coefficient (Reed et al. 2002:1238) (Table 1). C:N error was established through error propagation calculations. Since $\delta^{13}C$ is a dimensionless parameter, we report the SD of all our QA/QC samples as the error associated with this parameter. Complete data from QA/QC samples and subsequent global error calculations tables can be found in Supplementary – Appendix B.

4. Results

4.1. Background samples

The 3 samples collected in A horizon soil within the city core but outside the drainage basins of the reservoirs were representative of what is likely to be found within the city core terrestrial environment of Ucanal. The samples were taken at 10 cm depth below the ground surface. Average $\delta^{13}C$ (−27.6 ‰), $\delta^{15}N$ (+6.0 ‰), TC (11.5 %), TN (0.50 %), TOC (6.34 %), TP (349 ppm), C:N (14.84) and soil pH (7.32) were similar to values from the A horizon of the reservoir excavations (Figs. 6–8). There are two noticeable exceptions: first, the background $\delta^{13}C$ values are lower than observed in the reservoirs and are typical of present day C_3 forest environments; and second, TN on average is

Table 1
Comparison of error determination methods. [1]No error calculated for $\delta^{15}N$ as the sample size was too small. None but 1 (Aguada 3, level 3) of our QA/QC samples contained enough TN to allow measurements.

Parameter	Standard error	(Polissar and D'Andrea 2014)	(Reed et al. 2002)
TN	3 %	2.62 %	4.69 %
TC	1 %	1.69 %	1.69 %
TOC	5 %	10.54 %	8.59 %
$\delta^{13}C$ (‰ VPDB-LSVEC)	0.26 (SD)	N/A	N/A
$\delta^{15}N$ (‰ AIR)[1]	N/A	N/A	N/A
TP	6 %	9.45 %	9.80 %
C:N	5.83 %	9.78 %	10.86 %

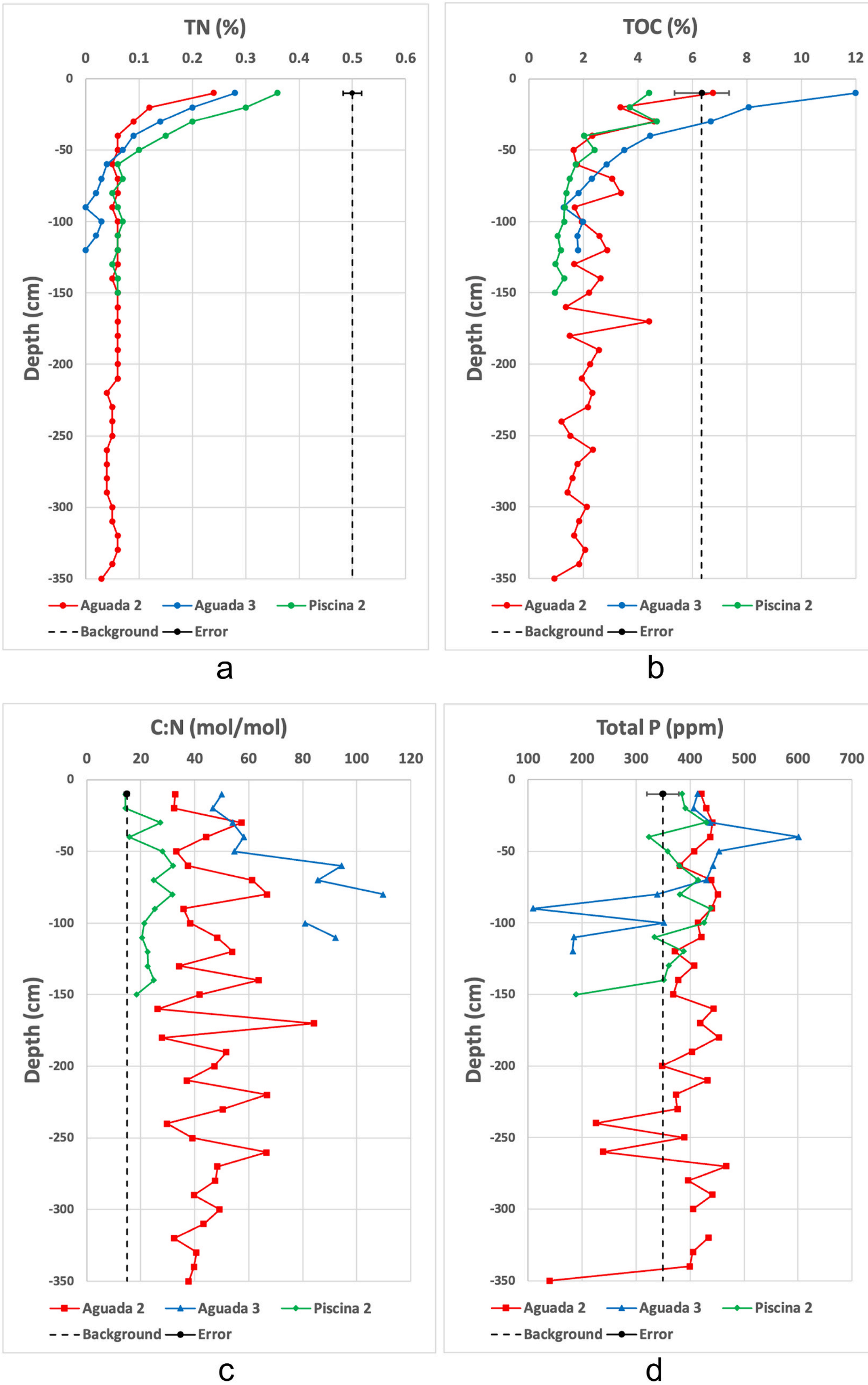

Fig. 6. Elemental measurements of sediments by depth in Ucanal Aguada 2[1], Aguada 3, and Piscina 2: (a) TN; (b) TOC; (c) C:N ratios; (d) TP. [1]No data available for TP Level 31.

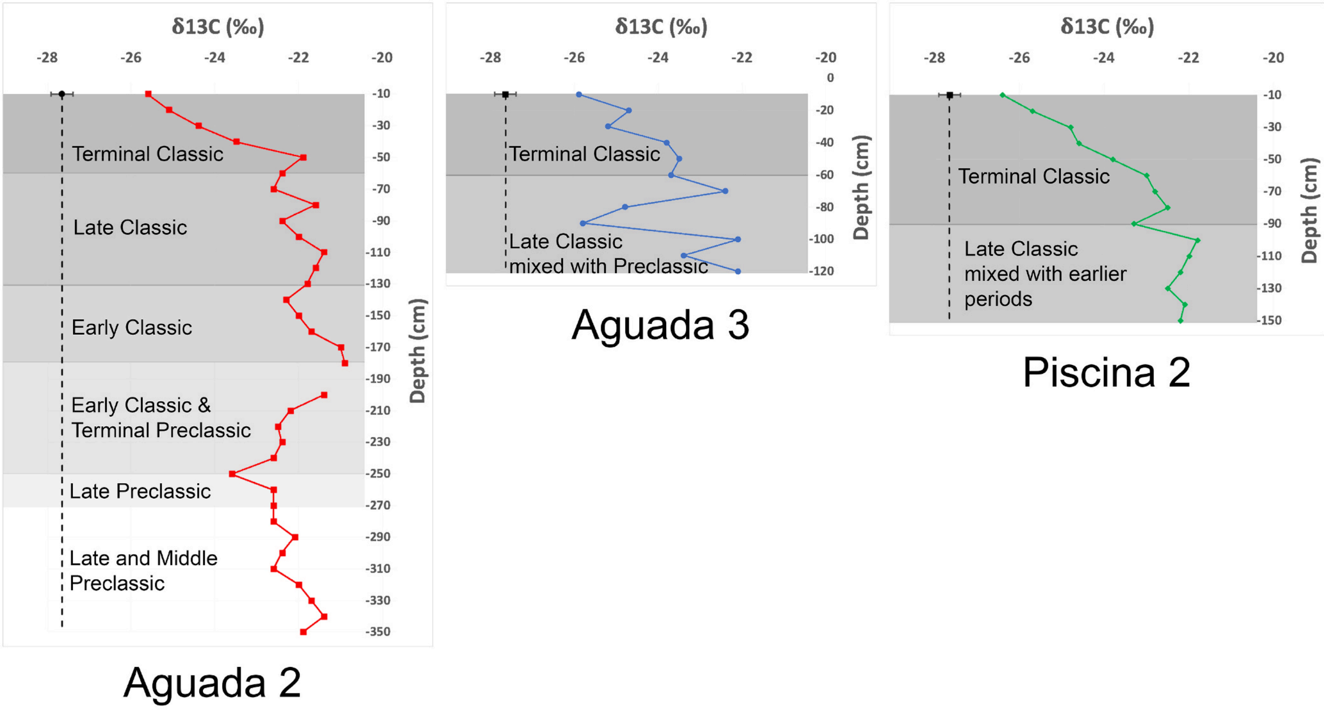

Fig. 7. δ^{13}C profiles and ceramic chronologies for Ucanal's Aguada 2[1], Aguada 3 and Piscina 2. For more details see (Tremblay et al. 2024 Appendix A). Background values with errors indicated. [1]No data available for Aguada 2, Level 19.

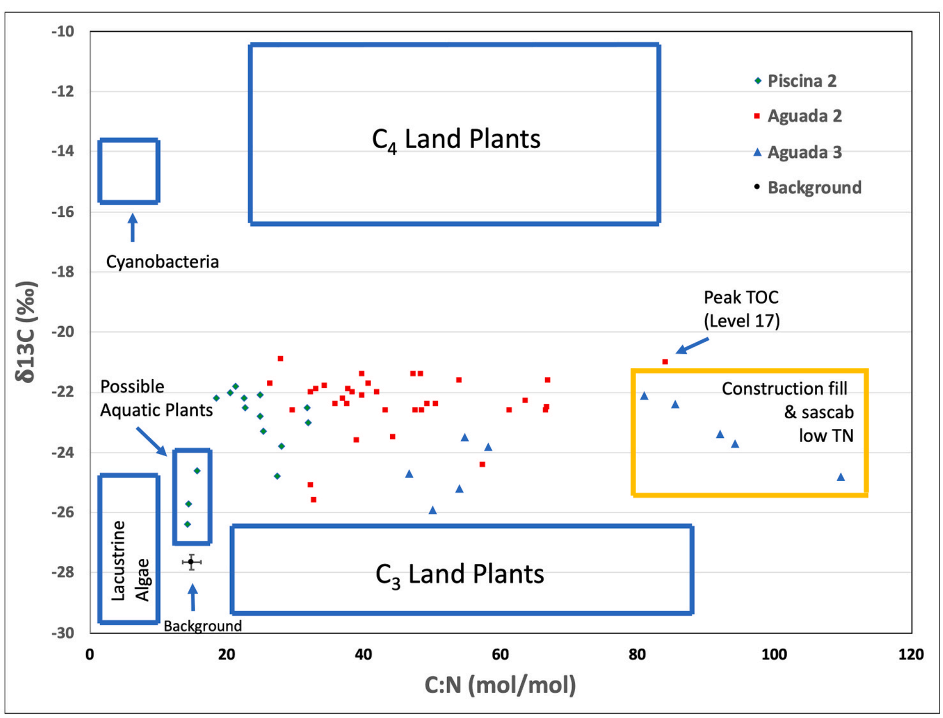

Fig. 8. Relationship between δ^{13}C and C:N ratios for Ucanal's Aguada 2, Aguada 3 and Piscina 2. Typical C:N ranges are indicated for land and aquatic base biota (blue box) (Ertel and Hedges 1985; Gaudel et al. 2024; Graham et al. 2001; Gu et al. 2017; Jasper and Gagosian 1993; Kubo and Kanda 2017; Meyers, 1994; Xia et al. 2014; Zhang et al. 2020). Subset of Aguada 3 samples (yellow box). Background with error bars indicated.

slightly higher than the reservoirs A horizon values, probably reflecting a larger presence of nitrogen rich microorganisms in the topsoil which translates into lower C:N (Supplementary – Appendix C, Tables C.4 and C.8).

4.2. Reservoirs

All dried sediment samples collected from the 3 reservoirs had very high calcium carbonate content with mean TC values for Aguada 2 (10.1 %, SD = 0.6, N = 35), Aguada 3 (11.1 %, SD = 0.3, N = 12) and P2C1 (9.6 %, SD = 0.6, N = 15). Most samples had a coarse fraction (> 2.36 mm) in the 20–30 % range with some exceptions in some levels from Aguada 3 and Piscina 2 (Supplementary – Appendix C, Table C.12). As reported elsewhere (Tremblay et al. 2024), pH readings were between 7.28 and 7.87 indicative of a slightly alkaline environment regardless of reservoir and depth and corresponded to a calcite rich environment (Supplementary – Appendix C, Table C.13).

All 3 reservoirs show the same TN pattern with the highest values registered in the A horizon followed by a stabilization to lower values for the remaining chronological sequence (Fig. 6a). Only a few levels of the three reservoirs, all dated to the Terminal Classic, contained enough nitrogen to allow $\delta^{15}N$ determination: Aguada 2 with an average of + 8.5 ‰, SD = 0.08, N = 3; Aguada 3, with an average of + 7.1 ‰, SD = 0.16, N = 4 and; Piscina 2, with an average of + 8.3 ‰, SD = 0.1, N = 5. TN remained extremely low, to the point of being effectively absent in levels 9 and 12 in the *sascab* stratum of Aguada 3. All 3 reservoirs show the same TOC pattern with a steep decrease from maximum concentrations in the A horizon to stable concentrations at around 2 % for the rest of the dried sediment profiles (Fig. 6b). For Aguada 2, beside the A horizon readings, TOC peaks were recorded at Level 8 (3.36 %) dating to the Late Classic and Level 17 (4.39 %) at the beginning of the Early Classic. C:N ratios for all 3 reservoirs remained higher than 20, except for Piscina 2 in the A horizon. The highest results were recorded in the nitrogen depleted construction fill and *sascab* stratum of Aguada 3 (with a range from 85 to 109, Fig. 8 yellow box). C:N patterns are indicative of distinctive organic matter sources within the three reservoirs (Aguada 2 range from 26 to 84, mean = 44.5, N = 35; Aguada 3 range from 49 to 109, mean = 70.6, N = 10; Piscina 2 range from 14 to 31, mean = 22.9, N = 15) (Fig. 6c). TP remained very stable throughout the complete profile of Aguada 2 with an average concentration of 394 ppm (SD = 67, N = 34) except for Levels 24, 26 and 35 with lower concentrations at 225, 238 and 139 ppm respectively in the Terminal Preclassic and Late Preclassic periods. The sediment accumulation history of Aguada 3 was characterized by more variation in TP concentrations than the other reservoirs with an average of 362 ppm (SD = 134, N = 12) and a peak of 600 ppm at Terminal Classic level 4, and a minimum of 108 ppm at Late Classic level 9, both readings representing respectively the highest and lowest concentrations measured in our study. Piscina 2 TP concentrations remained relatively constant with an average of 370 ppm (SD = 58, N = 15) but lower concentrations at 189 ppm at the very bottom of the reservoir (Fig. 6d).

$\delta^{13}C$ values varied significantly within the respective sediment columns, indicative of changing organic carbon sources or possibly alteration related to early diagenesis or bacterial biodegradation (Table 2 and Fig. 7). The relationship between $\delta^{13}C$ and C:N is shown in Fig. 8: ranges of typical values associated with various land and aquatic biomass are indicated.

5. Discussion

5.1. C:N ratios

C:N ratios of all 3 reservoirs are high, consistent with low TN values, and are incompatible with the presence of nitrogen rich algae, cyanobacteria or periphyton as they are characterized by C:N ratios between 5 and 10. The bulk of our results range between 20 and 60, within the published C:N ranges for terrestrial plants even when we factor in statistical error (Figs. 6c and 8). In addition, the variability of C:N values observed are an order of magnitude larger than any potential diagenetic effects based on previous studies of lacustrine sediments (Herczeg 1988; Kohzu et al. 2011; Lehmann et al. 2002; Meyers et al., 1993).

Three readings from Piscina 2 could indicate the presence of aquatic plants, all of which were in the upper A horizon dated to the Terminal Classic period from ceramic materials and to the Postclassic period based on an AMS date. TN levels were higher in the top layers of this reservoir compared to the same horizon from Aguadas 2 and 3. These slightly higher values may have been due to the presence of aquatic organisms or could be representative of a build-up of contemporary plant litter coupled with N-rich microorganisms in topsoils (Kirkby et al. 2011; Tipping et al. 2016). Published TN data from archaeological Maya Lowlands soils are scarce. Beach et al. (2002) reported TN at 0.33 % in the A horizon of soils from Northwestern Belize with 0.05–0.09 % in lower horizons, which are similar to what was found in this study.

TOC readings in Piscina 2 also show an abrupt change at the chronological AMS dating inversion layer (levels 9 and 10) with an increase from an average of 1.17 % below the inversion levels to an average of 2.91 % above the date inversion. These levels are thought to be associated with the construction of the reservoir itself. Regardless, overall TOC levels in Piscina 2 remain lower than in the other reservoirs, likely because of its hydrodynamic nature. Dissolved organic matter as well as smaller particles, may have passed through this settling tank and flowed downstream. As mentioned earlier, the water coming into Piscina 2 had to percolate through a barrier composed of a rough alignment of medium-sized (10–30 cm) rocks. Since about 95–98 % of the TN in soil is present in organic matter as proteins, peptides, amino acids, sugars, and nucleic acids largely associated with micro-organisms or bacteria in particular (Bleam 2017), smaller N-rich material may have easily filtered into this sedimentary reservoir. On the other hand, the porous entryway wall may have prevented the accumulation of C-rich material such as roots and wood, as opposed to leaves. The combined effects of this filtration and downstream flow probably led to lower C:N ratios in Piscina 2 than in the other two sampled reservoirs.

Aguada 2 results also systematically fall within the range of an environment dominated by land plants. The peak ratio of 84 for Aguada 2 is associated with a peak in TOC at Level 17, dating to the Early Classic period. Interestingly, visible flecks of charcoal were noted during excavations (Levels 12–16) in the Early Classic levels above it (Cruz Gómez and Quezada, 2023), and coarse charcoal has been observed to have relatively high C:N ratios (Nocentini et al. 2010).

Finally, the high ratios recorded for Aguada 3 are all derived from the construction fill and *sascab* stratum (Fig. 8, yellow box), an artificial medium particularly low in TN and not representative of natural sediment formation processes. This material may have had some structural plant tissues as part of the fill itself. As a result, this context yielded much higher C:N ratios.

Table 2
Recorded total $\delta^{13}C$ variation registered within the sediment columns of Aguada 2, Aguada 3 and Piscina 2.

Reservoir	$\delta^{13}C$ Min	$\delta^{13}C$ Max	$\delta^{13}C$ Max stratigraphic location	Δ
Aguada 2	−25.6 ‰	−20.9 ‰	Level 18 at the transition between the Terminal Preclassic and the Early Classic periods	−4.7 ‰
Aguada 3	−25.9 ‰	−22.1 ‰	Level 10 *sascab* stratum	−3.8 ‰
Piscina 2	−26.4 ‰	−21.8 ‰	Level 10, date inversion layer	−4.6 ‰

5.2. δ ^{13}C

Based on Ucanal's settlement history, local inhabitants likely stopped making use of their water reservoirs sometime during the Postclassic period or later (Halperin et al. 2019, Halperin et al., 2021). Forest vegetation likely partially regrew in these contexts during this time. The C, N, and P values in the top 40 cm, the A horizon, were partially affected by this reforestation through inputs of root or litter organic matter, even though they date primarily to the Terminal Classic period based on ceramic dating.

Aguada 2, Aguada 3, and Piscina 2 possessed total $\delta^{13}C$ variations of −4.7 ‰, −3.8 ‰ and −4.6 ‰ (Table 2), and of −3.7 ‰, −2.8 ‰ and −3.6 ‰ when compared to the average A horizon values. Possible natural variations of −1‰ to −2.5 ‰ have been reported with increasing depth in sediment profiles and may be representative of several processes including bacterial fractionation associated with organic matter decomposition (Beach et al. 2011; Blair et al. 1985; Krüger et al. 2024:113,124; Martinelli et al. 1996) and diagenetic effects documented to occur in lake sediments (Gälman et al. 2009; Herczeg 1988; Lehmann et al. 2002). $\delta^{13}C$ changes measured in Ucanal reservoirs surpass variability associated with diagenetic and bacterial fractionation, indicating changing organic matter sources with time. The significant, non-monotonic downcore variability in the Ucanal reservoir sediments, along with the high C:N ratios, also imply that $\delta^{13}C$ values are primarily recording changes in vegetation inputs as opposed to diagenetic alteration. This variability also greatly exceeds the statistical error associated with our data.

Such variations in $\delta^{13}C$ towards higher values could originate from changes in the relative abundance of C_4 or CAM plants within the city, including maize, agave, or sedges, or from middens, waste, and daily food preparation and consumption such as nixtamalized corn water being discarded around households. Tankersley et al. (2023)'s study of sediment $\delta^{13}C$ from the Corriental, Perdido and Temple reservoirs at Tikal reported values higher than those from Ucanal. With $\delta^{13}C$ changes respectively at −9.6 ‰, −5.4 ‰ and −4.9 ‰, they argued that cyanobacteria blooms in those reservoirs may have been a possible contributor, a finding that was supported by aDNA evidence of cyanobacteria in those contexts (D.L. Lentz et al. 2020). Considering both the overall recorded lower $\delta^{13}C$ changes and the measured C:N values from the reservoirs at Ucanal, however, we infer that cyanobacteria was likely not present and did not affect $\delta^{13}C$ variability.

The model of organic matter $\delta^{13}C$ values in relation to C_4 plant biomass developed by Von Fischer et al. (2008) can be used as a guide to estimate changes in C_4 biomass in Ucanal. Using this model, we estimated the contribution of C_4 plant biomass within the Ucanal reservoir drainage areas to have been on average 32 % between the Early Classic and beginning of the Terminal Classic periods for Aguada 2 with a maximum of 41 % at the transition from the Terminal Preclassic and Early Classic periods (Level 18). These higher percentages during this time could be associated with an intensification of maize cultivation and/or due to natural changes associated with bacterial fractionation. The latter process would lead to a lower-than-average C:N ratio for this reservoir, which is registered at Level 18 (C:N = 27.8), although this value is still indicative of a dominantly plant-derived organic matter source. These elevated $\delta^{13}C$ values indicative of a larger contribution in C_4 or CAM plants are surprising since populations were lower during the Terminal Preclassic and Early Classic periods in this neighborhood, and throughout the site in general, than recorded for later in the Late Classic and Terminal Classic periods. Our expectation was that C_4 plant biomass would increase during the Late Classic and Terminal Classic periods when population was at its peak. Instead, C_4 plant biomass was found to be lower, perhaps due to a decreased reliance on C_4 plants and/or due to C_3 contemporary forest influence on $\delta^{13}C$ values within the A horizon. Alternatively, this could reflect that as the city population grew, food production within the core urban area decreased.

Estimates for C_4 biomass for Aguada 3 resulted in an average of 23 % during the early Terminal Classic period with a maximum of 32 % in the earlier Late Classic *sascab* stratum located below a construction fill layer at the very bottom of the reservoir. Similar to Aguada 2, this decrease over time does not support arguments for an intensification of maize cultivation that would be expected with increases in population into the Terminal Classic period. Nevertheless, the same contemporary process involving C_3 growth in the A horizon could also be at play here.

Finally, we estimated an average of 24 % C_4 biomass for Piscina 2 of Canal 1 during the Terminal Classic period after the reservoir's construction (levels 1–9). A maximum of 32 % was recorded in the earlier Late Classic mixed layers below. With a much larger drainage area than the other two reservoirs, Piscina 2's C_4 signal is likely more representative of what was found across the Ucanal city core during the Terminal Classic period. As a comparison, estimates of contemporary C_4 biomass within the limit of the national park as indicated by $\delta^{13}C$ data from the very top layers of Aguada 2, 3 and Piscina 2 and our background samples are 7.7 %, 5.6 %, 2.1 % and < 1 % respectively.

Lower $\delta^{13}C$ values associated with a larger contribution of C_3 plants clearly dominates the top levels of all three reservoirs; contexts that are undoubtedly influenced by contemporary forest growth but are dated to the Terminal Classic period. Within the A horizon, all three stratigraphic profiles show a gradual $\delta^{13}C$ shift with depth, indicative of a gradual remaining influence of C_4/CAM biomass from ancient sediments. For Aguada 2, all deeper levels dating to the Late Classic, Early Classic and Late Preclassic periods were not influenced by current vegetation, leading to a clearer change in the signal associated with a greater C_4 plant presence. None of these results, however, are consistent with aquatic ecosystems populated by algae and/or cyanobacteria based on combined ^{13}C and C:N results, even when accounting for likely changes associated with early diagenesis (Fig. 8).

$\delta^{13}C$ studies in other areas of the Maya Lowlands also demonstrate a reliance on C_4 foods during the Pre-Columbian period that was undoubtedly linked, in part, to maize agriculture. For example, with reported $\delta^{13}C$ changes of −1.08 to −8.56 ‰ in wetlands, −1.88 to −5.66 ‰ in terraces, and −1.00 to −7.30 ‰ in aguadas, Beach et al. (2015, Beach et al., 2011) concluded that, overall, C_4 plants could have made up to 25 % of the vegetation in the Classic period at selected sites in the Maya Lowlands of Belize and Guatemala. In a study of human and natural changes in wetland contexts of the Maya Lowlands, Beach et al. (2009) documented $\delta^{13}C$ values varying from −28.2 ‰ in the Late Preclassic to −24.1 ‰ in the Late Classic to Postclassic periods at the small farming village of Chan Cahal near Blue Creek, Belize. They attribute this change to an increase in C_4 plants cultivation. Likewise, $\delta^{13}C$ results ranging from −29 ‰ to −23 ‰ with the highest values corresponding to wetland contexts in Northern Belize dating to the Terminal Classic Period were reported by Luzzadder-Beach et al. (2012). Such patterns contrast with changes recorded at Ucanal in which C_4/CAM plant exploitation appears to have been relatively stable or decreased from the Late Classic to Terminal Classic periods in Aguada 3 and Piscina 2 or decreased from the Terminal Late Preclassic to Terminal Classic periods in Aguada 2.

5.3. δ ^{15}N

TN values were too low to allow $\delta^{15}N$ measurements except for a limited number of samples, all of which were from the A horizons. For each reservoir $\delta^{15}N$ values were stable. They compare well between the reservoirs (+8.5 ‰ to + 7.1 ‰) and the background samples (+7.3 ‰ to + 5.1 ‰). If these results were representative of the Terminal Classic aquatic ecosystems of the reservoirs, they might suggest the presence of organisms potentially associated with periphyton or phytoplankton (Finlay and Kendall 2007; Montoya 2007) at a time when the reservoirs were extremely shallow. Cyanobacteria is capable of fixing atmospheric nitrogen, and its presence would have a $\delta^{15}N$ signature much lower and closer to 0 ‰ (Drew et al. 2008; Wu et al. 2006). As discussed, however, the contemporary humic phase is impacted by current biomass, and the

$\delta^{15}N$ data from this context was likely impacted by leaf litter and roots of a contemporary forested environment with typical values of + 6 ‰ – +9.0 ‰ (Amundson et al. 2003; Martinelli et al. 1999; Piccolo et al. 1996). Although it is not possible to draw definitive conclusions due to the lack of data available from deeper in the reservoirs, we interpret the $\delta^{15}N$ values in the A horizon samples to have resulted largely from current tropical leaf litter and soil organic matter rather than ancient aquatic biota.

5.4. Total phosphorus

While the average world TP concentration is 524 ppm (Sparks et al. 2023) with values for Mollisol and Vertisol ranging from 400 to 600 ppm (Cross and Schlesinger 1995; Roberts et al. 1985; Sharpley et al. 1985; Wagar et al. 1986), average phosphorus results from Ucanal reservoirs and the background samples from the core of the city were in the 350–400 ppm range. Even when we factor in the statistical error associated with our measurements, they do not display signs of human induced enrichment. Rather they are potentially indicative of a phosphorus limiting environment.

Total phosphorus incorporates a number of sub-fractions associated with inorganic, organic, and biological compartments, and the reporting of TP is highly dependent on the soil extraction methodology used (Cross and Schlesinger 1995; Frossard et al. 2000; Zbíral and Němec 2002). Direct comparison with other studies in the Maya area is difficult to establish because of the different methodologies implemented by researchers. Phosphorus results, obtained through the Bray II extractable methodology, a relatively soft extraction designed to measure P available to growing crops including some organic P as well as iron and aluminum bound P, have been reported to be below 1 ppm for the Tikal Palace and Temple reservoirs (David L. Lentz et al. 2020). Using the Mehlich II extractable procedure, targeting plant-available and bound exchangeable P, as well as some P associated with primary (apatite) and secondary minerals (Fe, Al, Ca), Hutson et al. (2009) reported TP results between 150–1200 ppm in at the site of La Milpa, Belize. The highest concentrations recorded were likely influenced by modern day fertilization. As a comparison, natural environment soil samples from several forested regions of Guatemala had Mehlich I extractable P between 0.2 and 1.6 ppm which is a method, that targets plant-available and weakly bounded exchangeable P as well as some organic P (Kollmann et al. 2008). In an archaeological investigation using the Mehlich II method, Terry et al. (2004) measured 45 ppm from a midden context where food refuse may have been discarded. Beach et al. (2006a), Beach et al. (2006b) followed the Bray II extractable method and reported results between 10 and 60 ppm from non-archaeological soils from mixed chronological periods at the sites of Blue Creek and La Milpa in Belize. They also collected samples from the Classic period Maya city of Cancuén, Guatemala, and reported 781 ppm in the humic horizon dating to the Late Classic period, a contrast with lower values of 320–350 ppm at depths of 40–110 cm and of 90–150 ppm near bedrock. Those measured concentrations below the A horizon are surprisingly similar to our study, despite different extraction methods.

Our methodology extracted all sub-fraction P components present within the reservoirs. Aguada 2 and Piscina 2 show relatively stable concentrations throughout the sediment column with no enrichment. Overall, they are indicative of the P deficient soils found in the Maya Lowlands (Das et al. 2011; Lentz et al. 2015; Tankersley et al. 2016). Results from Aguada 3 possessed the greatest variability with higher values in Level 4. Levels 3–4 (30–40 cm depth) possessed the highest concentration of midden materials from this reservoir. Also found in Level 4 was a burial of an elderly adult male (Burial 23-1) who may have been wrapped in a cloth burial shroud (Halperin et al. 2023). Both the burial and higher density of midden materials may have contributed to the small spike in P.

5.5. Effects of reservoir characteristics on sediment geochemistry

In comparison with many other regions of the world, ancient Maya cities are generally considered to have been green cities with low density occupation interspersed with gardens, green zones, and agricultural plots between households (Chase et al. 2022; Graham 1999). At Ucanal, these activities, as well as basic consumption and discard practices in middens and zones around households and public plazas may have been intense enough to modify soil and sediment geochemistry.

Lentz et al. (2020) reported cyanobacteria blooms at specific depths in some Tikal reservoirs including Planktothrix and Microsystis which are known to produce deadly toxins. These blooms, which appear to have been sporadic, occurred in the reservoirs throughout the periods of Maya occupation in the city. Tikal reservoirs, however, were massive compared to Ucanal's as they supplied water to a large population in an environment with no rivers nor lakes. By comparison, Ucanal inhabitants built relatively small reservoirs as they had access to the Mopan River. Aguada 2 and 3 were at higher elevations, with smaller water catchments that helped prevent the intake of urban pollution while Piscina 2 was dynamic in nature, with water infrastructure features promoting movement, aeration, and filtration of the water. They were all part of an elaborate water management system which helped provide residents with clean water that was aided by the creation of evacuation canals. These canals drained excess water from the city core during extreme rain events, possibly minimizing exposure to water related pathogens and/or parasites and also helped control erosion.

All lines of evidence from this study, as well as a study of mercury concentrations (Tremblay et al. 2024) indicate, however, that Aguada 3 exhibited the most contaminated environment of the three investigated reservoirs. The high concentrations of midden materials and a burial found in Level 4 suggest that Aguada 3 was used as an area to dispose of 'grey' or wastewater at some point during its life history or that it was treated as a small *bajo* conducive for the growing of reeds and other uses. Regardless of these possible uses, its geochemistry is not suggestive of conditions that would have induced harmful algae blooms.

Being a more dynamic water collecting environment, Piscina 2 of Canal 1 did not accumulate sediments in the same way as the other more stagnant water reservoir systems at the site. It was also in use largely during the Terminal Classic, a period in which the reservoir served as a holding tank with an extensive drainage area encompassing a large portion of the residential city core. It did not hold a specific volume of water as it filled and emptied itself by gravity and was also subject to evaporation. As mentioned earlier, these hydrologic features, in addition to crude wall alignments serving as filtration walls, likely contributed to keeping its water clean.

Finally, Aguada 2 with its undisturbed sediment sequence which covers a millennium of local history, offers the most convincing evidence of sustainable water management practices. Based on the combined results of the measured geochemical parameters, no signs of algae or cyanobacteria blooms were found throughout the sedimentary sequence. The possibility that this reservoir dried out during extended low precipitation periods cannot be excluded, which perhaps inhibited water stagnation more typical of larger reservoirs. Its sedimentation history shows the uninterrupted presence of C_4/CAM plant growth within its water catchment area. There is no evidence, however, of C_4/CAM plant agricultural intensification or increased reliance on C_4/CAM plants use over the Terminal Classic period compared to earlier periods as one might expect for a site with increasing population. Similar to Piscina 2, Aguada 2 also accumulated water that passed through entryway canals lined with rock fill, potentially avoiding the accumulation of large nitrogen and/or phosphorus rich detritus. Moreover, Aguada 2 is located at one of the highest elevations in the city of Ucanal with a relatively small water drainage area. As such, its water was less exposed to intensive human activity. It is possible that these features may have contributed to cleaner water. In contrast, Tikal reservoirs were much larger and were designed to hold water through the annual dry season. Being larger, the surrounding vegetation could not offer much shade. Therefore, at Tikal, access to light could have supported the buildup of algae and eventually cyanobacteria proliferation within large bodies of potentially hot and stagnant water. At Ucanal, tree canopy potentially covered a larger portion of the reservoirs, somewhat restricting photosynthesis and water heating in an environment already deprived of excess nutrients.

6. Conclusion

Across all the investigated reservoirs at the site of Ucanal, evidence was found for relatively invariant sedimentary environments dominated by terrestrial plant organic matter and lacking in evidence for cyanobacteria or excess nutrients. Furthermore, the individual or combined geochemical proxies from Aguada 2, Aguada 3, and Piscina 2 do not indicate an increase or peak in conditions conducive to cyanobacteria that may have corresponded to significant population increases, urban developments, and growing political importance of the city during the Late Classic and Terminal Classic periods. Stable isotope data signal cultivation and consumption of C_4/CAM plants during the Preclassic to Terminal Classic periods with values relatively consistent with other Pre-Columbian settlements in the Maya Lowlands. Although some increases in C_4/CAM plant biomass were recorded, they did not correlate with increases in population or settlement density during the Late and Terminal Classic periods. In sum, the geochemical analyses combined with an understanding of the hydrological functioning of the water systems itself indicate that Ucanal inhabitants created a relatively sustainable urban environment with access to water free of algae and/or cyanobacteria blooms and possible terrestrial plant diversity. Future research will focus on other geochemical proxies as well as DNA studies to refine our understanding of Ucanal urban ecology.

Disclosure statement

The authors report there are no financial or non-financial competing interests to declare.

CRediT authorship contribution statement

Jean D. Tremblay: Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Peter M.J. Douglas:** Writing – review & editing, Validation, Supervision, Methodology, Investigation. **Christina T. Halperin:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **Christian von Sperber:** Validation, Methodology. **Jean-François Hélie:** Validation, Methodology. **Laurianne Gauthier:** Methodology, Investigation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jasrep.2025.105389.

Data availability

Data will be made available on request.

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