**Research Article**

# The Pleistocene footprints are younger than we thought: correcting the radiocarbon dates of *Ruppia* seeds, Tularosa Basin, New Mexico

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**Abstract**

Past studies have demonstrated that *Ruppia cirrhosa* (*Ruppia*), which typically grows in brackish water, is far too unreliable to serve as the chronological basis for radiocarbon dating because of the hard water effect (HWE). Despite this unreliability, *Ruppia* seeds have been used to date footprints along the margins of paleo-Lake Otero in southern New Mexico to around 23,000–21,000 cal yr BP. In this study, we employ a modern analog approach using $\delta^{13}C$ values and radiocarbon dates from modern *Ruppia* plants growing in Salt Creek to calculate a maximum limiting age range for the footprints. Those plant samples with higher $\delta^{13}C$ values produced greater age discrepancies. This simple relationship can be used to correct for the HWE and demonstrates that the human footprints purported to have been made during the local last glacial maximum could be at least ∼7500 yr younger.

**Keywords:** Hard water effect, Pleistocene footprints, New Mexico, Modern *Ruppia*

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## INTRODUCTION

There is a great deal of controversy surrounding the radiocarbon dates of *Ruppia cirrhosa* (*Ruppia*) seed layers that have been used to constrain the age of footprints along the eastern shoreline of paleo-Lake Otero in southern New Mexico to around 23,000–21,000 cal yr BP (Bennett et al., 2021a; Haynes, 2022; Madsen et al., 2022; Pigati et al., 2022a, 2022b; Oviatt et al., 2022; Rachal et al., 2022). These ages are significantly older than ages suggested by current genetic models, archaeological data, or paleoecological data, which point to colonization of North America around or after 16,000 yr ago (Potter et al., 2018, 2022). The debate surrounding the *Ruppia* seed–based chronology focuses on two main issues. First, there is a question of whether a hard water effect (HWE) or reservoir effect, observed in *Ruppia* seeds, might have caused radiocarbon dates to appear much older (Kalanke et al., 2020; Madsen et al., 2022).

The HWE occurs when submerged aquatic plants that grow in alkaline "hard water" lakes utilize carbon during photosynthesis from dissolved inorganic carbon (DIC) sources (Lucas, 1983; Sand-Jensen and Gordon, 1984; Kantrud, 1991; Keeley and Sandquist, 1992; Hellblom and Axelsson, 2003). Such DIC is composed of ancient, $^{14}C$-depleted, dissolved carbonate that, in turn, is inherited from the limestone bedrock in the basin and does not reflect the $^{14}C$ activity of the atmosphere (Olsson, 1980). When this dead or depleted DIC is incorporated into the plant tissue through metabolic processes, it can make radiocarbon

ages based on plant material such as *Ruppia* appear thousands of years too old (Madsen et al., 2022). Pigati et al. (2022a) argue that the plant grew within a unique hydrological setting where a local, fresh shallow-water source removed or at the very least minimized the HWE at the human trackway site (Locality-2). However, Oviatt et al. (2022) provide support for the impact of the HWE by dating a modern *Ruppia* sample from a saline spring-fed wetland within the basin, yielding a date of 7400 cal yr BP.

A second part of the debate with the seed-based chronology is the character of the natural formation processes that delivered the seeds to the site. For instance, Haynes (2022) proposed a site formation model that uses wind as a seed delivery mechanism. Rachal et al. (2022) support this idea but also suggest an expanded site formation model, based on the discovery of *Ruppia* seed balls in the seed layers. In their site formation model, the *Ruppia* plants and seeds originated in deeper-water settings and were subsequently deposited as vegetative balls and seed detritus at Locality-2 by storm surge events during the Pleistocene. Both models provide mechanisms for how seeds that have been impacted—to an unknown degree—by the HWE could have been redeposited into the trackway stratum at Locality-2. If either of these cases apply, then the *Ruppia* radiocarbon dates used to constrain the footprints have been skewed by the HWE. Pigati et al. (2022b) argue that the wind as a seed delivery mechanism is a highly improbable and a realistically impossible scenario. However, they have yet to rebut the more complex *Ruppia* seed ball hypothesis. To maintain their argument for dating the footprints between 23,000–21,000 cal yr BP effectively, they must address the seed ball site formation model.

To complicate matters further, the HWE is not a static attribute of a given body of water. Instead, the magnitude of the HWE and its degree of variability can differ significantly over

space and time. For instance, the different spatial distributions of local sediments and bedrock geology within a given catchment can influence the HWE. The discharge rate and water chemistry of associated surface and groundwater inputs can also differentially influence the HWE (Fontes et al., 1996). Whether a lake is closed, drains into a river, or has a river flowing into it can influence the residence time of the DIC in the water column, which could also impact the HWE (Liu et al., 2017). Temporal changes in spring discharge, runoff from storms, or precipitation can cause the DIC in the water column to fluctuate or can even dilute the mineral concentration of the lake (Zhou et al., 2009). Changes in salinity, water depth, water flow, and other ecological factors can influence the plant's ability to efficiently pull in the DIC from the water (Osmond et al., 1981). This can lead to site- and time-specific $^{14}$C age offsets (differences between actual age and radiocarbon age) within a lake system that, in turn, can result in a range of artificial aging of hundreds to thousands of years.

The accurate radiocarbon dating of *Ruppia* seed layers at the human trackway site (Locality-2) near paleo-Lake Otero requires knowing the order of magnitude of the HWE in the paleo-Lake Otero basin. Our approach for estimating the HWE in the basin begins with determining the $\delta^{13}$C values and radiocarbon ages of modern *Ruppia* plants that still grow in the spring-fed wetlands along the Tularosa Basin's Salt Creek, a major tributary of paleo-Lake Otero. We then compare the radiocarbon date of each of the plant samples to its actual modern age to gauge the age offset caused by the HWE. Due to environmental variables that could influence the HWE, we did not expect to arrive at a single age correction based on one radiocarbon date that could be applied to the *Ruppia* seed layers (Oviatt et al., 2022). In the design of this study, we chose to sample different hydrological settings to find the ranges of, and variability in, $\delta^{13}$C isotopic values and radiocarbon age offsets that could be expected when dating *Ruppia* seeds from the past. This study was conducted by sampling two *Ruppia* meadows along Salt Creek to better understand the variability of the HWE. We hypothesized that the radiocarbon ages for modern plant samples would be highly variable in the drainage and that the more enriched (closer to 0) their $\delta^{13}$C values, the greater the age offset or discrepancy between their radiocarbon ages and their actual ages. If this relationship were correct, then it would be possible to use the $\delta^{13}$C values of the buried ancient *Ruppia* seed layers to determine their respective radiocarbon date offsets and thereby provide a maximum limiting (no older than) age range for the human footprints in the Tularosa Basin.

## STUDY AREA

Salt Creek is a 38-km-long stream in the northern Tularosa Basin (Figure 1A). The watershed of Salt Creek includes parts of the northern San Andres and Oscura Mountains. The 5000-yr-old Carrizozo lava flow is located to the east of the drainage (Dunbar, 1999). In addition to surface water from the mountains, perennial flow in Salt Creek is supplemented by groundwater discharge from a series of springs and seeps that are fed by an alluvial aquifer (Weir, 1965). These springs occur throughout the northern portion of Salt Creek. Groundwater input decreases in the middle portion of the stream, resulting in spatially intermittent surface flows (Myers and Naus, 2004). Eventually, Salt Creek becomes even more sporadic and can sometimes completely dry at the end of the drainage in a Holocene-age deflationary playa

named Big Salt Lake. This playa is in proximity to Salt Creek's Pleistocene fan delta at the north end of paleo-Lake Otero.

The annual stream flow for Salt Creek is highly variable. For water years 1995 to 2008, the average annual stream flow and total stream flow for Salt Creek were 0.038 cubic meters per second (m$^3$/s) and 121 hectare meter (983 acre-feet,) respectively (Naus et al., 2014). From water years 1997 to 2020, the average annual stream flow and total stream flow for Salt Creek were 0.033 m$^3$/s and 106 hectare meter (861 acre-feet), respectively (http://waterdata.usgs.gov/nwis, accessed September 14, 2023). Unfortunately, the gauge was not operational for the 2022 sampling year, so flow measurements for Salt Creek during that time period are unknown. It is worth mentioning that 2002 through 2006 were years during which the creek experienced zero flow. Rainfall runoff events typically associated with the summer monsoon can cause short-term increases in stream flow in Salt Creek. In May 2007, one such event resulted in a peak flow of 10.6 m$^3$/s (Naus et al., 2014). Rainfall runoff events provide the main source of surface water flow in the lower Salt Creek in the summer monsoon months. Without this rainfall runoff, the lower reaches of Salt Creek will not flow, and it will remain dry during much of the summer. However, continual groundwater inputs from springs and seeps allow the upper section of Salt Creek to hold water year-round.

Salinity values for paleo-Lake Otero tributaries are important to consider as well. Salinity in Salt Creek is also highly variable throughout the length of the stream channel. However, there is a general trend of increasing salinity with increasing distance from its headwaters (Myers and Naus, 2004). Salt Creek also has a higher salinity than the Malpais Spring Figure 1A). However, the Lost River, which is the drainage that Locality-2 is nearby, is located at the eastern edge of the paleo-Lake Otero basin and has the highest salinity of any modern drainage in the Tularosa Basin (Myers and Naus, 2004; Figure 1A). Regardless, water salinity concentrations of the streams range from 2290 to 66,700 mg/L. Water quality is typically considered saline (defined for this study as 10,000–100,000 mg/L total dissolved solids [TDS]), but during periods of higher and lower precipitation, it can vary from slightly to strongly brackish (defined for this study as 1000–10,000 mg/L TDS) to saline.

Finally, Salt Creek should be considered an ancestral waterway and an integral component of the paleo-Lake Otero hydraulic system, because it flowed into paleo-Lake Otero during the local last glacial maximum (LLGM; Clark et al., 2009). The modern creek is inset into a large relict terminal Pleistocene wetland complex that held water between 11,000 and 10,000 yr ago (Love et al., 2014). The aforementioned time period was determined by the radiocarbon dating of macrophytes (possibly reeds) (Love, D., personal communication, May 18, 2022), but without accounting for any HWE. The wetland complex was a refugium during post-LLGM times for the submerged *Ruppia* plant. It is likely that this rooted plant once occupied the deep-water spring-fed salty embayments of paleo-Lake Otero during the LLGM (Rachal et al., 2022), and it still grows in underwater meadows in the northern, perennial portion of Salt Creek (Figure 1B and 1C). There is also a small population of *Ruppia* growing in the lower intermittent flow portion of the drainage (Figure 1A). In this area, the plant grows in a relatively short section of perennial surface water sustained largely by groundwater input. The soil/sediment substrate in which the plant grows is massive (without layering), structureless, bluish-gray or dark black calcareous muds (Figure 1B and C).
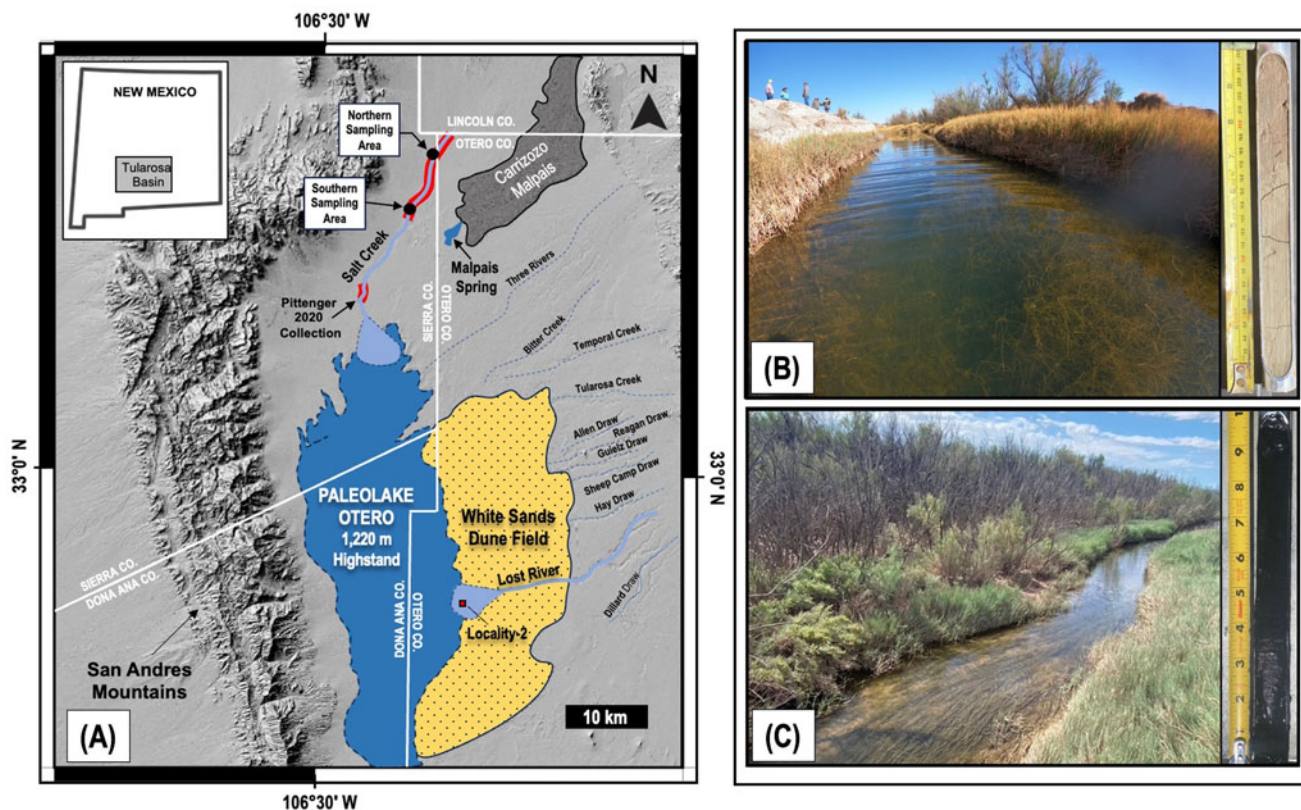
**Figure 1.** (**A**) Map showing perennial (solid line) and ephemeral (dashed line) stream reaches in the northern Tularosa Basin, with the red line outlining *Ruppia* distribution along Salt Creek. It also shows the location of Locality-2 in relation to the Salt Creek. Our *Ruppia* plant samples were collected from two locations in the northern and southern perennial sections of Salt Creek. (**B**) A photo of a *Ruppia* meadow in the north reach of Salt Creek. The water depth is ~90 cm. Note push probe sample of the underlying reduced aqueous soil/sediment. (**C**) A photo of a submerged *Ruppia* meadow in the south reach of Salt Creek. The water depth is ~40 cm. Note push probe sample of the massive, structureless organic rich sediment in which plant is growing.

## MATERIALS AND METHODS

### Field collection of plant specimens

The *Ruppia* plant samples in our study were obtained from two locations in the southern and northern perennial portions of Salt Creek (Figure 1A). Bulk samples of submerged *Ruppia* plants were collected from the soft sediment by wading through the water and gathering samples with a large, 101.6-cm Extended Reach Grappler tool. Individual plants were then separated from the bulk sample and air-dried overnight in a food dehydrator. We also collected a water-depth measurement and a water sample during the field collection. Each water sample was analyzed for electrical conductivity (EC) and bicarbonate content ($HCO_{3-}$). These analyses were conducted at the Brigham Young University Environmental Analytical Laboratory in Provo, Utah.

### Carbon isotope (δ¹³C) analysis

Once dried, one *Ruppia* stem from an individual plant was divided into two halves. One half of the plant stem was collected for $\delta^{13}C$ analysis. To make a direct comparison between the $\delta^{13}C$ values of modern plants and those of the seed layers on the eastern shoreline, stems and seeds were also collected from one *Ruppia* seed ball. As previously mentioned, such seed balls are formed when wind pushes floating *Ruppia* mats into the lake's littoral zone, where they are rolled into vegetative balls by wave action (see Olson et al., 2005). This sampled seed ball had been previously found partially buried in the same stratigraphic level

as the human trackway. *Ruppia* seeds and stems collected from the ball yielded several radiocarbon dates that ranged from 22,411 to 20,834 cal yr BP (Rachal et al., 2022). It has been hypothesized that this range in radiocarbon dates is an indication of the mixing of seeds with differing degrees of the HWE. All *Ruppia* stem and seed samples were sent to the University of Kansas for independent $\delta^{13}C$ isotopic analysis. Each sample underwent an acid wash before analysis. The samples' isotopic ratios are reported in δ-notation as follows: $\delta^{13}C$ (‰) = $[(R_{SAMPLE} - R_{STANDARD})/R_{STANDARD}] \times 1000$. These results are presented with respect to the Vienna Pee Dee Belemnite standard (VPDB; Craig, 1957).

### Radiocarbon dating

The other half of the *Ruppia* stem was sent to the Arizona Climate and Ecosystem Isotope Laboratory at Northern Arizona University for radiocarbon dating. The dating employed a graphite approach using a mini radiocarbon dating system from Ionplus. Each sample underwent an acid–base–acid wash pretreatment (acid = 1 M HCl; base = 1 M NaOH; process at 70°C; Santos and Ormsby, 2013). The calibration of each radiocarbon date was completed using Calib 8.2 software (Stuiver et al., 2021) and the IntCal20 data set. Our conventional radiocarbon ages have been corrected for isotope fractionation by normalizing to VPDB (Wacker et al., 2010) and are then reported with 2σ error ranges and as median calibrated years before the present (see Table 1). A complication of the calibration process is that

**Table 1.** Summary of radiocarbon and calibrated ages along with $\delta^{13}C$ values.

| Lab no. | Location[a] | Collection month | Water depth (cm) | *Ruppia* material dated[b] | $^{14}C$ age | $\delta^{13}C$ ‰[c] | 2σ-calibrated age range[d] | Median calibrated age[e] |
|---|---|---|---|---|---|---|---|---|
| 1766.1.2 | USC | March | 90 | Stems | 2085 ± 15 | −19.02 | 2107–1995 | 2041 |
| 1767.1.2 | USC | March | 90 | Stems | 1832 ± 15 | −19.26 | 1649–1647 | 1728 |
| | | | | | | | 1750–1703 | |
| | | | | | | | 1792–1758 | |
| | | | | | | | 1818–1810 | |
| 1768.1.2 | USC | March | 90 | Stems | 2482 ± 16 | −18.73 | 2604–2490 | 2588 |
| | | | | | | | 2660–2609 | |
| | | | | | | | 2711–2665 | |
| 1769.1.2 | USC | March | 120 | Stems | 2599 ± 16 | −18.28 | 2753–2727 | 2743 |
| 1770.1.2 | USC | March | 120 | Stems | 2469 ± 16 | −17.85 | 2451–2432 | 2600 |
| | | | | | | | 2547–2462 | |
| | | | | | | | 2620–2553 | |
| | | | | | | | 2705–2628 | |
| 1771.1.2 | USC | March | 120 | Stems | 2530 ± 16 | −17.47 | 2592–2515 | 2624 |
| | | | | | | | 2636–2614 | |
| | | | | | | | 2736–2697 | |
| 1906.1.1 | LSC | May | 36 | Stems | 3555 ± 24 | −17.04 | 3752–3725 | 3853 |
| | | | | | | | 3795–3766 | |
| | | | | | | | 3922–3822 | |
| | | | | | | | 3960–3950 | |
| 1907.1.1 | LSC | May | 41 | Stems | 3534 ± 35 | −16.72 | 3906–3695 | 3803 |
| 2510.1.1 | LSC | August | 31 | Stems | 2486 ± 14 | −17.98 | 2602–2492 | 2584 |
| | | | | | | | 2622–2611 | |
| | | | | | | | 2657–2626 | |
| | | | | | | | 2709–2668 | |
| 2511.1.1 | LSC | August | 38 | Stems | 2520 ± 15 | −17.92 | 2506–2499 | 2589 |
| | | | | | | | 2593–2512 | |
| | | | | | | | 2638–2614 | |
| | | | | | | | 2725–2696 | |
| 3208.1.1 | LSC | October | 42 | Stems | 7991 ± 17 | −8.52 | 8733–8729 | 8878 |
| | | | | | | | 8995–8770 | |

[a]USC, northern perennial portion of the Salt Creek; LSC, southern perennial portion of the Salt Creek.
[b]Plant materials were subjected to standard acid–base–acid pretreatment.
[c]Carbon isotopic ratios in delta notation (relative to the VPDB standard); used to correct for isotopic fractionation.
[d]Calibrations were calculated using the Calib tool 8.2 (Stuiver et al., 2021).
[e]Median calibrated dates listed are those occupying the largest percentage of area under the calibration curve (when multiple intercept ranges apply).

the resulting model for the calibrated $^{14}C$ age can be multimodal and asymmetric. This produces a degree of uncertainty that is larger than that of the original $^{14}C$ age and must be represented in the form of a range. Because both the 1σ and 2σ error ranges of the calibrated ages were very small and difficult to represent graphically, we chose to simply plot the median values of the calibrated ages.

These radiocarbon ages have not been corrected for the increases in $^{14}C$ content caused by the atomic bomb $^{14}C$ effect (de Vries, 1958). It should be noted that there is currently no universally accepted correction for it or for its inherent local variability. We argue that this of little importance, because most of the bomb carbon has, by now, been absorbed into oceans and has been diluted back to very near pre-bomb levels by $^{14}C$-free carbon dioxide produced by the burning of fossil fuels (i.e., Suess effect) (Graven, 2015). If it is present, it will most likely make the radiocarbon ages older by a couple hundred years (see Philippsen, 2013).

## RESULTS AND ANALYSIS

### $\delta^{13}C$ values and $^{14}C$ age offsets of modern Ruppia

*Ruppia* utilizes a $C_3$ photosynthetic pathway (TRY Plant Trait Database, https://www.try-db.org/TryWeb/Home.php, accessed September 11, 2023) and is efficient in using DIC, such as bicarbonate ($HCO_{3-}$), from the water column during photosynthesis (Sand-Jensen and Gordon, 1984). Aquatic plants can use other carbon sources (i.e., carbon dioxide) from the air or the water column, but the concentrations of these types of carbon are often very low in an aqueous or submerged setting (Hemminga and Mateo, 1996). *Ruppia* plants that have grown in a submerged setting with elevated concentrations of DIC are more enriched in $^{13}C$ relative to a plant growing aboveground in the normal atmospheric setting (Boutton, 1991; Keeley and Sandquist, 1992; Oviatt et al., 2022). The assimilation of DIC during photosynthesis can lead to relatively high $\delta^{13}C$ values for the plant (Marcenko et al., 2016). Such plants have $\delta^{13}C$ values similar to those found with $C_4$ plants (−10 to −15‰) (Chappuis et al., 2017). However, depending on the environmental setting, the $\delta^{13}C$ values of *Ruppia* can be more depleted and can overlap with local terrestrial CAM (crassulacean acid metabolism) plants (−15 to −20‰) and even other $C_3$ plants (−20 to −35‰) (Gallegos, 1999).

The $\delta^{13}C$ values of the modern *Ruppia* growing in Salt Creek were highly variable and ranged from around −19.26 to −8.52‰. As previously mentioned, the assimilation of DIC not only affects $\delta^{13}C$ values, but also affects the $^{14}C$ age offsets of the plant. For instance, the $^{14}C$ age offset (difference between actual age and radiocarbon age) of the modern *Ruppia* plants ranged from 8878 to 1728 cal yr BP. However, there are differences in both age offsets and isotope values when comparing the *Ruppia* plant samples from upper and lower reaches of the drainage. Plant samples collected from the upper reach provided more-depleted $\delta^{13}C$ isotope values ranging from −19.26 to −17.47‰. The radiocarbon age offsets of these plant samples were also smaller and ranged from around 2743 to 1728 cal yr BP. On the other hand, plant samples collected from the lower reach were more enriched, with $\delta^{13}C$ isotope values ranging from −17.98 to −8.52‰. The radiocarbon age offsets of these plant samples were also larger and ranged from around 8878 to 2584 cal yr BP (Figure 2). These wide ranges of $^{14}C$ age offsets and $\delta^{13}C$ values coincide with differences in water quality.

At the time of sampling in the northern reach, the water had an EC of 5100 micro-deci-siemens per meter (µdS/m) and a bicarbonate content ranging from 138 to 223 ppm. The springs that feed the area were located tens of meters to the north of the sampling site. As noted earlier, these water-quality measurements coincide with smaller age offsets and more-depleted $\delta^{13}C$ values. We collected plant samples in the vicinity of the lower reach throughout the year and documented that the samples in that reach had an EC ranging from 15,500 to 27,000 µdS/m. The bicarbonate content in the general area ranged from 224 to 1500 ppm. The springs feeding this area were located a few meters from the sampling site, and water could be seen emanating along the margins of the drainage. These higher salinity and bicarbonate values coincide with more-enriched $\delta^{13}C$ values and larger age offsets.

There is also a lot of variation in $^{14}C$ age offsets among individual plants over a very short geographic distance. *Ruppia* plants collected from one meadow in the upper reach yielded radiocarbon age offsets of 2743 to 1728 cal yr BP. That is a range of ~1000 yr among individual *Ruppia* plants from the same general location. Naus et al. (2014) reported a percent modern $^{14}C$ value
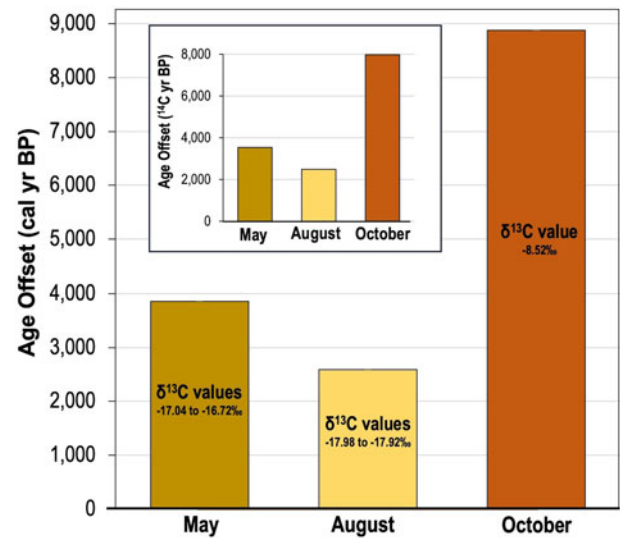


**Figure 2.** Graph depicting $\delta^{13}C$ and both calibrated and $^{14}C$ (inset graph) age changes in modern *Ruppia* during May, August, and October, indicating mixotrophic behavior in this aquatic plant across its annual life cycle. These samples were gathered from the southern perennial part of Salt Creek.

of 87.73%, which yields an age of ~1100 $^{14}C$ yr BP for the water at this collection site. Interestingly, the *Ruppia* plant material in this area is 600 to 1600 yr older than the $^{14}C$ content of the water.

There is also a lot of variation in $^{14}C$ age offsets over time. *Ruppia* plants collected from one area in May yielded age offsets of 3853 to 3803 cal yr BP. At the end of the summer, in August, *Ruppia* plants collected in the same general area yielded age offsets of 2589 to 2584 cal yr BP. That is a range of ~1200 yr among individual *Ruppia* plants over a 3 month period. Surprisingly, a *Ruppia* plant collected in the same general area in October, which is at the end of the growing season, yielded an age offset of 8878 cal yr BP. That is a range of ~6200 yr among individual *Ruppia* plants over a 6 month period within one *Ruppia* meadow.

### Water chemistry and the HWE of modern Ruppia in paleo-Lake Otero tributaries

The water chemistry in Salt Creek varies both spatially (as noted earlier) and temporally throughout the length of the drainage. Differences in this water chemistry can cause large variations in the $\delta^{13}C$ values of submerged plants (Boyce et al., 2001). Intra-annual variations in the water quality can result in seasonal changes in the $\delta^{13}C$ values of submerged plants (Anderson and Fourqurean, 2003). Even the $\delta^{13}C$ values of the parts (leaf, rhizome, etc.) of submerged plants can change seasonally (Vizzini et al., 2003). Changes in the $\delta^{13}C$ values suggest that the plant exhibits mixotrophic behavior, utilizing various carbon sources during photosynthesis, which may include changes in the concentrations of $^{14}C$-deficient carbonate, $CO_2$ derived from decaying vegetation, or dissolved organic carbon from plant residues (Firmin et al., 2022). The type of carbon source determines the magnitude of the HWE. Unfortunately, we did not differentiate between the uptake of dissolved organic and inorganic carbon by *Ruppia* over time; nonetheless, we did record variations in water chemistry that correlated with changes in the age offset of the plant. Thus, regarding Salt Creek, changes in both water quality and the physical functioning of the plant over its yearly

phenological life cycle cause wide fluctuations in $\delta^{13}C$ values and $^{14}C$ age offsets for the aquatic plant over space and time (Figure 2). Although Bennett et al. (2021a) claim that fresh, well-aerated water at Locality-2 minimized or eliminated the HWE, they do not consider how plant physiology can influence the HWE. This can happen whether or not the plant is growing near a spring and could add additional uncertainty to the seed dates.

However, it is still unclear whether the shallow water at Locality-2 was as fresh as Bennett et al. (2021a) claim. *Ruppia* can tolerate the widest range of salinities of any aquatic angiosperm, but it characteristically prefers extreme saline conditions (Mannino et al., 2015). This is because the plant cannot survive in fresh water and lacks the ability to compete with freshwater aquatic plants (Verhoeven, 1979; Menéndez and Penuelas, 1993). Typically, aquatic plant biodiversity and competition will increase as the water freshens (Hammer 1986; Bailey et al., 2006). For instance, a noticeable decrease in the prevalence of *Ruppia* was observed in the inland lakes and wetlands of the Northern Great Plains/Prairie Pothole Region, especially in saline lakes that have gradually become less salty and fresher over time (Swanson et al., 1988). *Ruppia*, which lacks the ability to compete in these conditions, will die back and only regrow when harsher saline conditions return (Kantrud, 1991). The pH and EC measurements show alkaline conditions (pH > 8.0), high sodicity (sodium absorption ratio > 81%,), and high salinity (EC > 57 mS/m$^{-1}$) within the trackway stratum at Locality-2 (https://data.nal.usda.gov/dataset/soilweb, accessed September 11, 2023). These findings suggest a salt-affected depositional lake environment that could only have supported aquatic halophytic plants. Typically, *Ruppia* will grow as monospecific or single-species meadows in high-salinity environments (Verhoeven, 1980). The monotypic seed layers that washed into the Locality-2 site suggest that the water quality of paleo-Lake Otero was most likely brackish, and possibly saline, making it too salty for other freshwater plants to colonize and grow in embayments around the lake.

Furthermore, Holliday (2022) hypothesized that the Lost River could have supplied Locality-2 with fresh water. This alluvial stream setting would have minimized or eliminated the HWE in the site. The fact that ground water in the basin is of high salinity is another reason why the Lost River was not likely to have been a freshwater source. Substantial volumes of fresh water do exist in the basin, but they are confined to narrow zones next to the Sacramento Mountains (Land, 2016). Runoff from the mountains would have been fresher, but the salinity of the local ground water and surface water would have increased toward the center of the basin (Fryberger, 2023). This is because the Lost River cuts through ~25 km of some of the most salt-affected sediment and soils in the basin. During the LLGM, the water table would have been higher and the localized discharge of brackish ground water into the river channel would likely have resulted in the salinization of the Lost River long before it poured into paleo-Lake Otero at Locality-2. Today, the high-salinity ground water from sedimentary brine sources leaks into the Rio Grande and significantly increases the salinity levels of the river as it traverses New Mexico (Hogan et al., 2007). Langford et al. (2009) have documented a similar trend in groundwater salinity at White Sands National Park.

Therefore, the same scenario could have occurred with the Lost River during the LLGM. While it is possible for the mountain runoff to have been great enough during the LLGM to have diluted some of the salt content, the substantial volume of the geologic salinity source coupled with the large reserve of brackish to brine ground water in the basin suggests that it would have been very unlikely for Lost River water to have been fresh when it arrived at Locality-2.

## Water depth and $^{14}C$ age offsets of modern Ruppia

Pigati et al. (2022a, 2022b) argued that *Ruppia* plants grew within Locality-2 in a shallow-water setting that was probably no more than a few centimeters deep. They also argue that, in this setting, the water would have been well-mixed and near or close to $CO_2$ equilibrium with the atmosphere. This scenario would have, according to Pigati et al. (2022a, 2022b) reduced, or even eliminated, the HWE. To date, we have not found *Ruppia* plants growing in extremely shallow, 1- to 3-cm-deep water in Salt Creek. Instead, *Ruppia* is typically found in the lowest and deepest portions of the channel in water that is around 90 to 120 cm deep, although it can still grow in somewhat shallower water around 31 to 40 cm deep. Also, we could find no evidence of a relationship between water depth and the $^{14}C$ age offset of the modern plants (Figure 3; the linear regression indicates that only ~18% of the variance in age offsets is explained by the variance in depth). In fact, the largest age offsets typically came from shallower water in the lower reach of Salt Creek. These findings indicate that use of DIC is substantial even in relatively shallow waters (>30 cm deep) that are well mixed and in equilibrium with the atmosphere.

## $\delta^{13}C$ values of Ruppia seed ball aliquots

To directly compare the $\delta^{13}C$ values of modern plants, reported earlier, with the seed layers on the eastern shoreline of paleo-Lake Otero, a collection was made that included stems and seeds from one *Ruppia* seed ball. The seeds from the ball yielded several radiocarbon dates, which ranged from 22,411 to 20,834 cal yr BP (see Rachal et al., 2022). The youngest and oldest dates in this age range differ significantly at a 95% confidence level ($t = 6.366141$; $\chi^2$ (0.05) = 3.84; df = 1). This difference of more than 1500 yr may indicate the mixing of seeds with varying degrees of HWE (Rachal et al., 2022), particularly when considering the documented 1000 yr range among individual modern
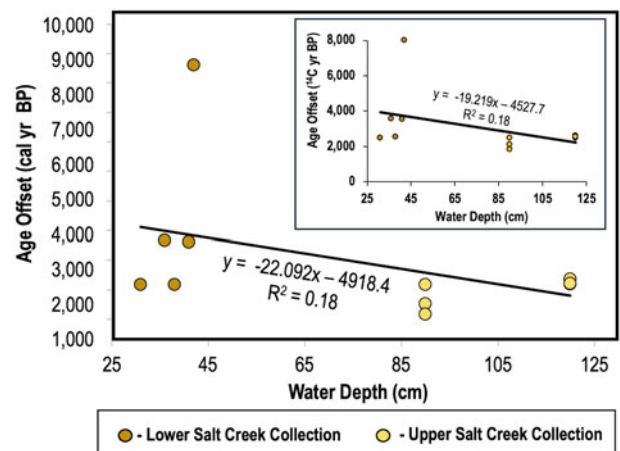


**Figure 3.** Linear regression demonstrating a weak correlation ($r^2 = 0.18$) between water depth and both calibrated and $^{14}C$ age (inset graph) offsets of modern *Ruppia* in the Salt Creek. These results suggest that even in shallow, well-mixed waters in atmospheric equilibrium, the utilization of DIC by *Ruppia* is significant.

*Ruppia* plants in a single meadow documented by this study and a 1000 yr range across seed dates in Trackway Horizon 6 (Bennett et al., 2021b). Interestingly, the $\delta^{13}C$ values of the seeds and stems from the same ball were also highly variable and also appear to have been mixed. The $\delta^{13}C$ values of the seeds ranged from −10.21 to −5.37‰, with an average value of −8.1‰ (Figure 4). The $\delta^{13}C$ values of the stems were roughly similar to the seed isotopic values and ranged from −9.59 to −6.13‰, with an average value of −7.9‰ (Figure 4).

Unfortunately, Bennett et al. (2021a) did not report the $\delta^{13}C$ values with their radiocarbon dates, so a direct comparison cannot be made between the *Ruppia* seed balls and the buried seed layers in the trackways site on the eastern shoreline (Locality-2). However, Allen et al. (2014) did radiocarbon date two *Ruppia* seed layers sampled from the lake margin outcrop within the site boundary of Localty-2. The $\delta^{13}C$ values associated with those radiocarbon dates ranged from −11.7 to −10.0‰. Allen et al. (2009) also reported the $\delta^{13}C$ values associated with probable *Ruppia* radiocarbon dates at Locality-8 as ranging from −14.0 to −12.0‰. It should be noted that Allen et al. (2009) described the samples as "macrophytes." It is possible that these samples may have included a variety of aquatic plants that incorporate various amounts of carbon from different sources and may have different $\delta^{13}C$ values. Bennett et al. (2021a), on the other hand,

referred to these samples as *Ruppia*. It is possible that Bennett et al. (2021a) obtained additional information through consultation with Allen et al. (2009) regarding the dated samples, which were potentially identified as *Ruppia* seeds. If such consultation did occur, Bennett et al. (2021b) did not explicitly report this detail in their supplementary materials. Regardless, Oviatt et al. (2022) radiocarbon dated a modern *Ruppia* plant collected in 1947 from the Malpais Spring (see Figure 1A) and reported a similar $\delta^{13}C$ value of −13.6‰ for the plant. Interestingly, the $\delta^{13}C$ values of the seed ball and seed layers closest to Locality-2 are more enriched when compared with the modern-day isotopic baseline for *Ruppia* growing in the Salt Creek and Malpais Spring areas. These more-enriched $\delta^{13}C$ values are also greater (more enriched) than the $\delta^{13}C$ values reported at Locality-8.

## DISCUSSION

### A "no-analog" approach and a problematic age–depth model

Because the HWE can cause large chronological uncertainties, many researchers who develop age models from lake sediments typically try to correct for it. When reviewing the purported dates for the Locality-2 tracks, critics of Bennett et al. (2021a, 2021b) suggested that the *Ruppia*-based radiocarbon dates
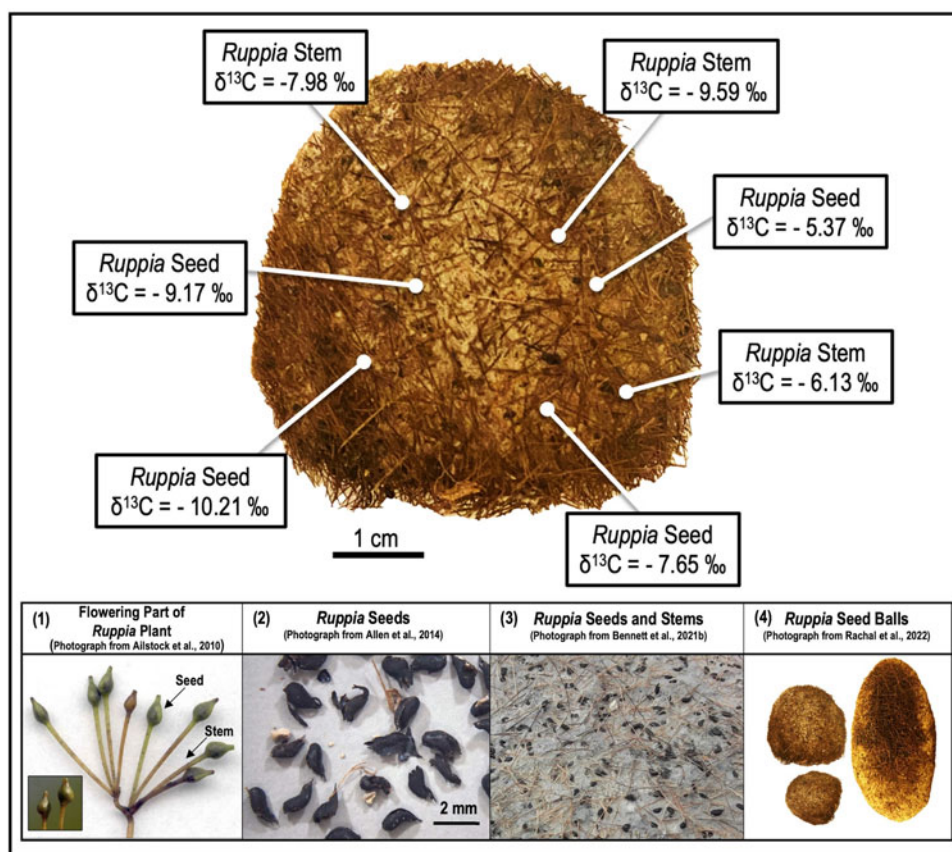


**Figure 4.** $\delta^{13}C$ values of a *Ruppia* seed ball. This seed ball was collected from a partially buried seed layer on the eastern paleo-Lake Otero shoreline. The seeds from the ball yielded several radiocarbon dates, which span a ~1500-yr period, that ranged from 22,411 and 20,834 cal yr BP (see Rachal et al., 2022). Inset photographs (1 through 4) located at the base of the illustration shows the various components of a *Ruppia* seed ball. Inset Photo 1: *Ruppia* Seed balls are composed of reproductive shoots (seeds and stems) from the plant's flower part. *Ruppia* seed balls are composed of detached reproductive shoots (seeds and stems) from the flowering part of the plant. Inset Photo 2: Seeds are beaked and black, 1.5 to 2 mm long and 1 to 1.5 mm wide. Inset Photo 3: Stems can be 1 to 2 cm long and are often still attached to the seed. They can be found as seed layers at Locality-2. Inset Photo 4: These seeds and stems can float and are often rolled into a vegetative ball by wave action in the littoral zone of a lake (Olson et al., 2005).

utilized to date the trackways were impacted by the HWE and could thus be too old and that modern *Ruppia* could help address the problem (Oviatt et al., 2022; Rachal et al., 2022). Bennett et al. (2021a) and Pigati et al. (2022b) argued that any *Ruppia* plants growing in the Tularosa Basin were not comparable to those that would have grown in the paleo-Lake Otero setting and that, as a result, the modern *Ruppia* vegetation could not be used to determine how much error had been introduced into Pleistocene seed dates by the HWE. Their position, which suggests that the prehistoric *Ruppia* community at Locality-2 was a vegetational population in a setting that is no longer observed in contemporary ecosystems, can be described as a "no-analog" (Williams and Jackson, 2007) approach to ecology.

However, the researchers at the Locality-2 trackway site were aware that modern *Ruppia* grows within the paleo-Lake Otero hydraulic system. Approximately 15 km south of our southern sampling location in the lower reaches of Salt Creek, J. Pittenger (at the request of White Sands National Park) collected a modern *Ruppia* sample in 2020 and submitted it to personnel at the Park (Pittenger, J., personal communication, March 31, 2022; Figure 1A). However, no ^{14}C dating results from this *Ruppia* sample have yet been published. By avoiding the use of the potential modern analog *Ruppia* growing in Salt Creek, and because they were unable to date any terrestrial vegetation fossils in the trackway horizons, Bennett et al. (2021a, 2021b) chose to rely completely on the *Ruppia* seeds found buried in the same sediments as the trackways. They dated large seed aliquots, each containing 40–60 seeds or more, and employed an uneven sampling design that effectively eliminated or minimized any potential age variations caused by the HWE that are commonly associated with *Ruppia.* Their large seed aliquots averaged the age ranges of the individual seeds and thus minimized the possibility of detecting age reversals caused by variations in the HWE (Rachal et al., 2022).

Bennett et al. (2021b) also generated an age–depth model based on *Ruppia* seeds, ostracods, and charcoal ages from a stratigraphic section in the northern Tularosa Basin (Locality-8; Allen et al., 2009) to support their hypothesis that the HWE, if present, was very minimal during the LLGM. We argue that this age–depth model might be unreliable, because it is based on the dating of materials with debatable chronometric utility or that were recovered from questionable contexts. That is, the radiocarbon dating of ostracod valves can be hundreds to several thousands of years too old, because they obtain their carbon from the water, not from the atmosphere (Gouramanis et al., 2010; Junginger et al., 2014). They can also be affected by the absorption of ^{14}C-enriched carbon during diagenesis, making the ages appear too young (Hajdas et al., 2004; Zimmerman et al., 2012). Thus, they are an unreliable material to radiocarbon date. The charcoal, on the other hand, could have been redeposited in the stratigraphic section by alluvial processes and not necessarily be of the same age as the deposit from which it was recovered (Allen et al., 2009; Madsen et al., 2022; Oviatt et al., 2022). Therefore, it is unclear which dated samples in the age–depth model are actually correct, if any.

Another issue with the age–depth model employed by Bennett et al. (2021b) is that the sedimentation rates for the lake most likely varied over time. For instance, Allen et al. (2009) documented several different stratigraphic units at Locality-8 that reflect alternating marsh–shallow perennial lake–alluvial plain depositional environments. Some of these geologic units contain cut and fill channels and root traces, suggesting punctuated periods of shoreline stability and instability. If so, the linear extrapolation of the ^{14}C-based age–depth model might not serve as an accurate representative standard with which to refute the impacts of the HWE during the Pleistocene.

## A simplified modern analog approach

We believe that *Ruppia* presently growing in the Tularosa Basin can help gauge the degree to which the HWE might have affected the Locality-2 trackway ages. As such, in this study, we employ a modern analog approach using $\delta^{13}C$ values and radiocarbon dates from modern *Ruppia* plants growing in Salt Creek to establish, and correct for, the age offset that could have been introduced into seed dates by the HWE. Our sample *Ruppia* plants were collected from two different areas in the drainage to estimate how water quality could influence the age offset caused by the HWE. Our study demonstrates a strong positive linear relationship between the $\delta^{13}C$ values and the age offsets (measured in both uncalibrated and calibrated radiocarbon years in Figure 5A–D) of our modern *Ruppia* plants (Figure 5A and B; the linear regression indicates that ~94–95% of the variance in age offsets is explained by the variance in $\delta^{13}C$ values). In this relationship, lower $\delta^{13}C$ values suggest that the *Ruppia* plant took in less DIC from the water column, resulting in a smaller HWE and a smaller age offset. Higher $\delta^{13}C$ values, on the other hand, suggest that the *Ruppia* plant took in more DIC from the water column, resulting in a greater HWE and a larger age offset. Although this linear regression is based on only 12 modern observations, it does demonstrate a promising positive and direct association between $\delta^{13}C$ values and potential age offsets caused by the HWE.

Our simple regression model can be used to estimate HWE-induced errors in paleo-Lake Otero's seed dates by plotting *Ruppia* radiocarbon $\delta^{13}C$ values on the regression line. However, its applicability beyond the Tularosa Basin is uncertain. The *Ruppia* stems and seeds along the eastern paleo-Lake Otero shoreline have $\delta^{13}C$ values ranging from −11.7 to −5.37‰, sourced from Allen et al. (2009, 2014) and Rachal et al. (2022). According to our model, *Ruppia* stems and seeds that have a $\delta^{13}C$ value of −11.7‰ could have a minimum age offset of 7500 cal yr BP, while a $\delta^{13}C$ value of −8.5‰ could have a minimum age offset of 8800 cal yr BP. While we can extrapolate the line of the relationship beyond the $\delta^{13}C$ value of −8.5‰, our model loses some predictive power past that point. Nevertheless, the higher $\delta^{13}C$ values of *Ruppia* stems and seeds from the *Ruppia* ball, such as −7.98‰, −6.13‰, and −5.37‰, further underscore the likelihood of the mixing and/or reworking of seeds with differing degrees of HWE. When these higher $\delta^{13}C$ values are placed on the extrapolated regression line (Figure 5D), they correspond with age offsets from 10,000, 11,200, and 11,800 cal yr BP, respectively. This finding aligns, in order of magnitude, with a study by Oviatt et al. (2018), which suggested that the actual ages of *Ruppia* seeds in a buried context could be up to 9300 yr younger than indicated by their radiocarbon dates.

As previously mentioned, Bennett et al. (2021a) generated an age–depth model based on *Ruppia* seeds, ostracods, and charcoal ages from Locality-8 to support their hypothesis that the HWE was very minimal during the LLGM. Bennett et al. (2021b, p. 10) also stated that the similarity of the aquatic and terrestrial ages and the nearly linear slope of the age–depth curve proved that the HWE in paleo-Lake Otero was negligible between ~44,000 and ~25,000 cal yr BP. The two dates for aquatic plants, which are presumed to have been derived from *Ruppia* plant material, and utilized in their model (Bennett et al. 2021, p. 10), exhibit $\delta^{13}C$ values ranging from −14.0 to −12.0‰.
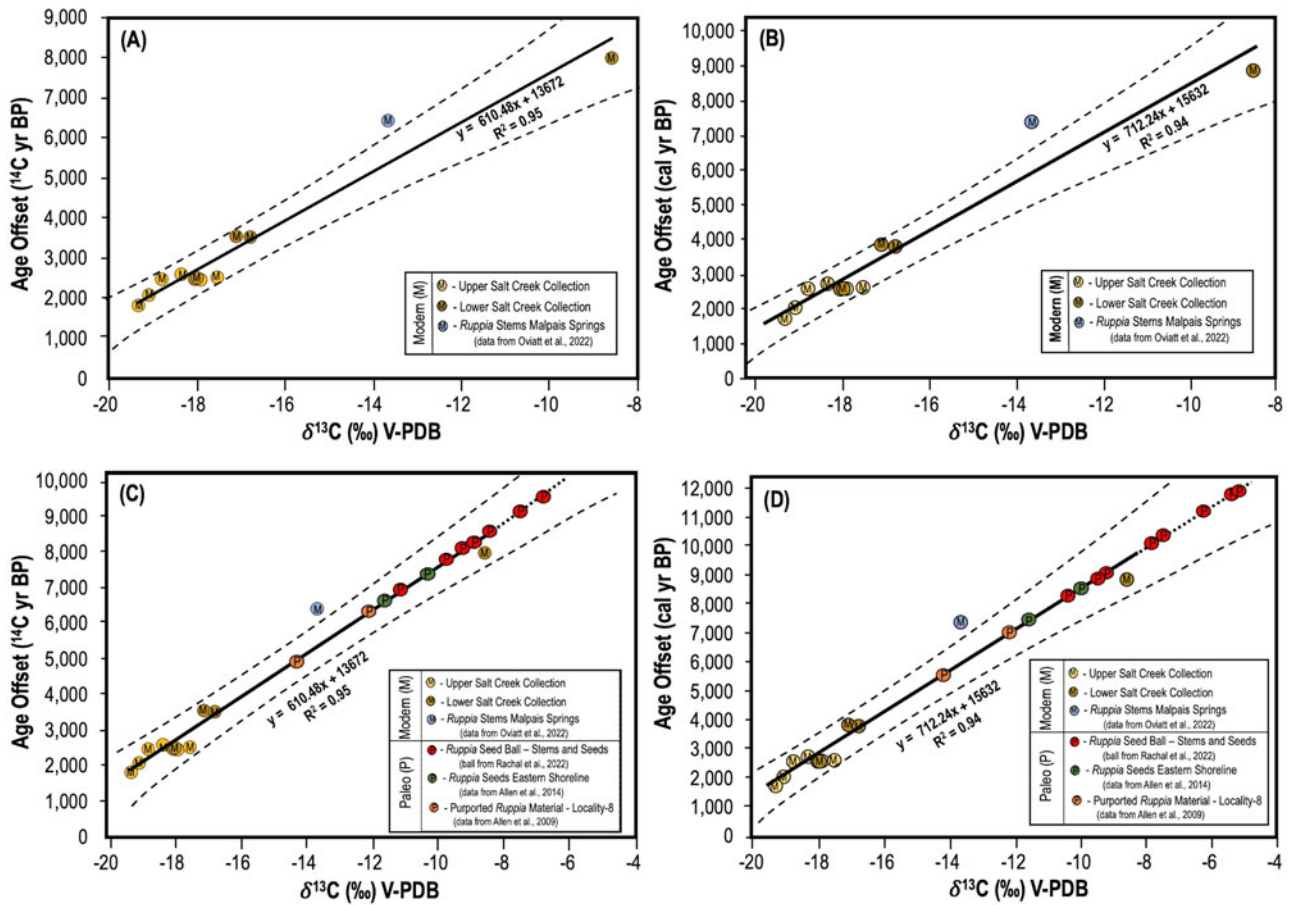
Figure 5. (**A and B**) Linear regression of the relationship between $\delta^{13}C$ values and both $^{14}C$ and calibrated age offsets of modern *Ruppia* in the Tularosa Basin. (**C and D**) $\delta^{13}C$ values and both $^{14}C$ and calibrated age offsets with *Ruppia* samples superimposed on the linear regression. The model's 95% probability intervals are indicated by the dashed line. Because both the 1σ and 2σ error ranges of the calibrated ages were very small and were difficult to represent graphically, we chose to simply plot the median values of the calibrated ages.

When these values are placed on our extrapolated regression line (Figure 5D), they are found to correspond with age offsets from 6800 to 5500 cal yr BP, respectively, for the radiocarbon dates used in their model (Bennett et al. 2021, p. 10). This would change their radiocarbon dates from 35,397 and 32,356 cal yr BP to 29,897 and 25,556 cal yr BP. Although this correction does not affect the stratigraphic ordering of the dates, it does demonstrate that both dates are individually incorrect and not congruent with the charcoal age. As a result, it is highly likely that the HWE was present and substantial in paleo-Lake Otero during the LLGM.

### Salt Creek $^{14}C$ age offsets and the eastern shoreline

In this study, we used $\delta^{13}C$ isotopic values and radiocarbon age offsets from modern Salt Creek *Ruppia* plants to correct *Ruppia* radiocarbon dates on the eastern shoreline of paleo-Lake Otero, where the HWE could impact dating accuracy. The HWE can vary in magnitude both spatially and temporally (Hou et al., 2012), raising questions about the transferability of our age offsets from Salt Creek to the eastern shoreline. Key concerns include whether Salt Creek had a hydrologic connection with paleo-Lake Otero during the LLGM, whether the lake's water salinity resembled that of modern Salt Creek, and whether distant, severely impacted HWE *Ruppia* habitats in the lake basin were connected to the eastern shoreline. We address these issues in this section.

Salt Creek was the largest tributary to paleo-Lake Otero during the LLGM (Weir, 1965; Hawley, 1993). During this wet period, it emptied into the northern margin of the lake, creating a fluvial fan delta complex with wetlands (Allen et al., 2005). This fan delta depositional setting would have been similar to the Lost River fan delta near Locality-2. Pittenger and Springer (1999) stated that the endangered White Sands pupfish (*Cyprinodon tularosa*) inhabited paleo-Lake Otero and extended into Salt Creek. However, during the Holocene, paleo-Lake Otero dried out, and a small population of pupfish became isolated in the wetlands of Salt Creek (Pittenger, 2015). The isolated native Salt Creek pupfish population has always been regarded as evidence of a hydrologic connection between the lake and Salt Creek. The absence of pupfish in Lost River hints at isolation during the LLGM due to dunes blocking the drainage.

Salt Creek is primarily groundwater-fed (Naus et al., 2014), but does receive some contributions from surface water as well. Paleo-Lake Otero also received water from various sources, including enhanced surface runoff (Allen et al., 2009). Despite this runoff potentially freshening the lake, evidence from ostracods and foraminifera in paleo-Lake Otero sediments indicates brackish water conditions (~1000–100,000 mg/L), akin to today's Salt Creek (Allen et al., 2009; Rachal et al., 2020, 2021). Further support for this is provided by Bennett et al. (2021a), who argue for lower lake levels and reduced surface runoff when the

seeds were deposited on the eastern shoreline. Springs, which respond slowly to warming events, likely maintained the low lake levels, with older ground water as the primary water source. $\delta^{13}C$ values of ancient *Ruppia* seed layers along the eastern shoreline resemble or exceed those of modern Salt Creek and Malpais Spring, suggesting similar conditions in terms of water salinity, alkalinity, and groundwater hydrology between the prehistoric lake and modern Salt Creek.

*Ruppia* spp., a highly mobile, opportunistic, aquatic plant with rapid colonization abilities, relies on waves and currents for long-distance seed dispersal (Kantrud, 1991; Lopez-Calderon et al., 2010). Storms or floods can detach buoyant reproductive shoots (stems and seeds), which then form drifting mats that can float from one side of a body of water to the other (Källström et al., 2008; Triest et al., 2018). Wind pushes these mats ashore, where waves roll the material into *Ruppia* seed balls (Olson et al., 2005). This process transfers HWE-affected *Ruppia* plants and seeds (without roots) from the western lake margin, depositing them on the eastern shoreline (Rachal et al., 2022). *Ruppia* seed balls provide evidence of rapid, long-distance, direct seed dispersal, linking the eastern shoreline to various severely HWE-impacted, Pleistocene-age *Ruppia* habitats around the lake margin, including Salt Creek.

Salt Creek is the sole surviving remnant of paleo-Lake Otero and, being a modern analog of the lake, assumes a pivotal role as a crucial reference point. Based on the connections listed earlier, Salt Creek is a unique benchmark that can be used to better understand the spatial and temporal variations in $\delta^{13}C$ values and radiocarbon age offsets in the lake basin. Consequently, it enables us to apply our regression model for estimating age offsets to the trackway *Ruppia* dates on the eastern shoreline.

## CONCLUSION AND CHRONOLOGICAL IMPLICATIONS

In the Salt Creek samples, the HWE is large and highly variable over spatial and short, temporal scales. Correspondingly, the $\delta^{13}C$ values for the *Ruppia* plant tissue ranged from $-19.26$ to $-8.52‰$, while the $^{14}C$ age offset of the plants ranged from 8878 to 1728 cal yr BP. These variations are most likely caused by changes in the differential contributions of inorganic and organic carbon sources in Salt Creek. Thus, the more enriched the $\delta^{13}C$ values, the larger the age offset.

Based on these findings and our modern analog model, we propose that the *Ruppia* seed dates used to constrain the age of the human footprints at White Sands National Park to around 23,000–21,000 cal yr BP could be at least ~7500 yr too old. Given this, the ages reported by Bennett et al. (2021a) would be, at a maximum, on the order of 15,500–13,500 cal yr BP. This corrected, maximum limiting age range falls roughly in line with the ages of other older archaeological sites in North America (e.g., Jenkins et al., 2012; Halligan et al., 2016; Waters et al., 2018; Williams et al., 2018; Davis et al., 2019) and is also consistent with the apparent co-occurrence of human and mammoth tracks in the stratigraphic record at Locality-2. In the latter situation, the human footprints must be at least as old as 12,700 cal yr BP, as the final mammoth population appears to have declined around the onset of the Younger Dryas in the southwestern United States (Stewart et al., 2021). While human footprints of this revised age would still be a significant discovery, Bennett et al. (2021a) have, unfortunately, not reported their $\delta^{13}C$ values, so a precise evaluation of their *Ruppia* dates is not possible at this time. We hope that those $\delta^{13}C$ values can soon be made publicly available and their chronological claims can be assessed with our modern analog model.

## POSTSCRIPT

During the review of our manuscript, Pigati et al. (2023) published pollen dates that appear to strongly agree with their previously published *Ruppia* seed dates, raising questions about how two research teams could reach contrasting conclusions regarding the likely ages of the human tracks in Locality-2. This disparity stems from conflicting interpretations of the stratigraphic and geomorphic contexts of the seed layers.

Bennett et al. (2021a, 2021b) and Pigati et al. (2022a, 2022b, 2023) perceive the shoreline of paleo-Lake Otero as a stable geomorphic setting where *Ruppia* plants grew in situ in shallow, fresh water with no potential for the HWE. Our interpretation, presented in our current paper and by Rachal et al. (2022), considers the site to have been an unstable, dynamic environment where HWE-affected *Ruppia* seeds had been introduced from an ex situ location and were subsequently subjected to cycles of redeposition and mixing. This is evidenced by the presence, within the thinly bedded alluvial sediments at Locality-2, of aggregated *Ruppia* seed balls and unaggregated seed layers composed of buoyant plant parts and reproductive shoots (stems and seeds, absent any roots). Therefore, because the *Ruppia* seeds had, in our opinion, been redeposited, it is likely that any pollen deposits introduced to the site had also undergone redeposition and mixing.

The influence of older pollen within $^{14}C$-dated pollen samples can thus result in significant age discrepancies, potentially spanning hundreds or even thousands of years (Neulieb et al., 2013). The magnitude of these discrepancies depends on the interplay between the continuous production and deposition of contemporary pollen and the erosion and redeposition of ancient pollen that has been preserved in the landscape (Zimmerman et al., 2019). If reworked older pollen is present in the samples, it introduces chronometric uncertainty and the potential for data distortion, resulting in dates that do not accurately represent the true ages of the deposit from which the pollen samples were recovered. Resolving the stratigraphic and geomorphic context issues for pollen is crucial before the radiocarbon ages of such samples can be accepted as representing the age of the deposit.

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