

Contributions to the QR Forum

A critical assessment of claims that human footprints in the Lake Otero basin, New Mexico date to the Last Glacial Maximum

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Abstract

The ancient human footprints in valley-bottom sediments in Tularosa Valley, New Mexico, are fascinating and potentially important because they suggest interactions between Pleistocene megafauna as well as great antiquity. The dating of those footprints is crucial in interpretations of when humans first came to North America from Asia, but the ages have larger uncertainties than has been reported. Some of that uncertainty is related to the possibility of a radiocarbon reservoir in the water in which the dated propagules of *Ruppia cirrhosa* grew. As a test of that possibility, *Ruppia* specimens collected in 1947 from nearby Malpais Spring returned a radiocarbon age of ca. 7400 cal yr BP. We think it would be appropriate to devise and implement independent means for dating the footprints, thus lowering the uncertainty in the proposed age of the footprints and leading to a better understanding of when humans first arrived in the Americas.

Keywords: Radiocarbon reservoir, *Ruppia*, Early peopling of the Americas

INTRODUCTION

Recent reporting of human footprints in the muds of a New Mexican playa apparently dating to 23,000–21,000 cal yr BP at White Sands National Park (WNSA; Bennett et al., 2021a, b) has generated keen interest among both the scientific community and the public at large. Age estimates based on radiocarbon dating of “seeds” (technically, drupelets; see Kantrud 1991, p. 6) of a submerged aquatic plant (*Ruppia cirrhosa*) stratigraphically bracketing the footprint trackways seem to show that people entered the Americas much earlier than is commonly accepted, thus opening a wide range of new possibilities as to how, where, and when this initial emigration occurred. However, as pointed out by Bennett et al. (2021a, b), *Ruppia cirrhosa* obtains its carbon for photosynthesis from the water in which it grows rather than directly from the atmosphere. The water used by the plant may contain dissolved inorganic carbon (DIC) that is depleted in radioactive carbon (¹⁴C) relative to the carbon in atmospheric CO₂, resulting in radiocarbon-based age estimates of the plant tissues that can be much older than the plants themselves (e.g., Deevey et al., 1954; Marty and Myrbo, 2014). Bennett et al. (2021a, b) recognized this potential problem but did not adequately account for it. We suggested (Madsen et al., 2022) that these age estimates needed independent confirmation through other dating methods or sources. Unfortunately, space limitations imposed on Technical Comments for *Science* precluded an expanded discussion, so here we take the opportunity to provide a more detailed explanation as to why we think such confirmation is necessary.

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If the ages of *Ruppia* drupelets are only several thousand years older than the true age of the footprints, what difference does it make if the footprints are only, for instance, 18,000–17,000 cal yr BP, rather than 23,000–21,000 cal yr BP? That would still mean the footprint site in the Tularosa Valley could well be one of the oldest, if not the oldest, well-dated archaeological site in the Americas. But a difference of only a few thousand years can be crucial for informing our understanding of how, and from where, ancient Native Americans first moved into the New World. Bennett et al. (2021a, p. 1531) initially held that their footprint chronology “confirms that humans were present in North America before the glacial advances of the LGM closed the Ice-Free Corridor and the Pacific Coastal Route and prevented human migration from Asia,” and argued that any radiocarbon reservoir is expected to be “insignificant” and “less than a few hundred years” (Bennett et al., 2021a, b). Now, however, in a response to our Technical Comment for *Science*, they indicated only that “we stand behind our conclusion that humans were present in southwestern North America during the Last Glacial Maximum” (Pigati et al., 2022a, p. 1). We think there is a crucial difference between these two conclusions. If an adjustment of a few thousand years is applied to their measured *Ruppia* drupelet ages, the timing of human presence in the lake basin could shift into the age range of other pre-Clovis North American sites. While we agree that people were likely in the Americas during the latter part of the local last glacial maximum (LLGM; Clark et al., 2009), whether or not they had arrived before the ice free corridor (IFC) closed or the Pacific coastal route became available is a more controversial conclusion and needs to be confirmed by more accurate dating.

The age of opening of the IFC between the Laurentide and Cordilleran ice sheets after the last glacial maximum is now well known—a slew of cosmogenic ¹⁰Be exposure ages, combined

with geomorphic mapping and high-quality minimum-limiting ^{14}C ages indicate it opened sometime after ca. 13,500 cal yr BP, possibly ca. 13,200 cal yr BP (Heintzman et al., 2016; Norris et al., 2021). The age of ca. 13,500 to 13,200 cal yr BP for the opening of the IFC is too late for even proponents of a “Clovis First” model to postulate an initial entry via a land route from Beringia through the IFC, because sites with Clovis technology appear to be widespread throughout southeastern North America by at least ca. 13,350 cal yr BP (Haynes et al., 1984; Haynes, 1992; Waters and Stafford, 2007; Waters et al., 2020). However, when the IFC first closed at the beginning of the LLGM is less well known due to data limitations, with mapping of the ice sheet margins suggesting the route was closed sometime between ca. 30,000–25,000 cal yr BP (Dalton et al., 2022). But if the pre-LLGM closing of the IFC occurred prior to the oldest ^{14}C ages from the Lake Otero footprint site, as Bennett et al. (2021a) suggested, humans may well have entered the Americas via an interior IFC route before the LLGM. This is one major reason why the *Ruppia* dates from the Tularosa basin need to be confirmed.

Another major reason why confirmation of the footprint *Ruppia* ages is important is that those ages conflict with a variety of other data that suggest humans first entered the Americas during the LLGM rather than prior to its beginning. Many of these data are derived from age estimates provided by paleogenetics, with molecular clocks indicating that initial occupation of the Americas south of the ice sheets occurred sometime after ca. 20,000 yr BP (e.g., Raghavan et al., 2015; Llamas et al., 2016; Moreno-Mayar et al., 2018; Pinotti et al., 2019; Roca-Rada et al., 2021; Willerslev and Meltzer, 2021; Colombo et al., 2022). If the Lake Otero footprint ages are valid, then as Pigati et al. (2022a, p. 2) suggested, “researchers in archaeology and allied fields may need to reexamine existing hypotheses and the underlying data related to the peopling of the Americas in light of these discoveries.” It is certainly possible the *Ruppia* ages from a single site in a New Mexico lake basin are valid and that age estimates from a variety of other fields are invalid, but we think the *Ruppia* ^{14}C ages should be confirmed with results from other dating methods.

RUPPIA PLANT GROWTH AND FRUIT PRODUCTION

An assessment of the validity of ^{14}C age estimates based on *R. cirrhosa* must take into account how and where these plants grow, as well as the nature of seed production and dispersal. The genus *Ruppia*, commonly called widgeongrass (aka wigeongrass) or spiral ditchweed, consists of several species of submerged rooted aquatic vascular plants that inhabit shallow saline to alkaline lagoons, estuaries, lakes, and ponds worldwide, mainly along coastlines, but with scattered inland populations as well. *Ruppia* often forms large monospecific beds that serve as productive substrates for many aquatic organisms and ecosystems under conditions unfavorable to other aquatic plants, and it is widely regarded as a key ecological engineer (Verhoeven, 1980). A wide range of waterfowl and shorebirds favor the plants and their fruits as a considerable part of their diet (Martin et al., 1961).

Ruppia predominates in well-lit saline or alkaline waters from ~0.5–2 m depth, although it can tolerate even deeper waters (to ~4.5 m) and wide variation in water levels (Kantrud, 1991). *Ruppia* tolerates a wider range of water salinity than any other aquatic vascular plant (Brock, 1981; Murphy et al., 2003; Triest et al., 2018); it does poorly in fresh, soft, or slightly acidic waters.

Water transparency and availability of sunlight are also critical growth factors; it performs well in clear, still, or slowly moving waters, but not turbid, shaded, or turbulent conditions (possibly caused by wind and waves). *Ruppia* can survive periodic exposure to air in wetlands subject to tidal fluctuations, but not persistent drought or desiccation, and *Ruppia* does not grow in permanently subaerial terrestrial habitats.

Ruppia plants are simple, often nearly threadlike, with reduced vegetative and reproductive structures. Growth forms and life histories vary greatly depending on environmental conditions and phenotypic plasticity (Kantrud, 1991; Mannino et al., 2015; Triest et al., 2018). In North America, two forms are recognized as distinct end members of one or more broad species complexes, with *R. maritima* considered mainly coastal and *R. cirrhosa* mainly inland (Setchell, 1946; Mason, 1957; Kantrud, 1991; Thorne, 1993; Haynes, 2000). *Ruppia cirrhosa* is distinguished primarily by having long flowering tendrils (peduncles) with spiral coils up to 10 dm long and small non-fleshy fruits (drupelets, sometimes called “seeds”), while the *R. maritima* form has shorter peduncles, few to no coils, and smaller fruits.

The flexuous spiraling peduncle serves an important function in *R. cirrhosa*'s reproductive ecology, which depends on hydrophilous pollination on the water surface of its submerged aquatic habit (Les, 1988; Cox and Knox, 1989). Bearing two tiny naked flowers at its tip, the peduncle elongates to place the flowers' stigmas at the water surface to be fertilized by rafts of floating pollen; after pollination, the peduncle may recoil and draw the floral structures back under water during fruit development (Taylor et al., 2020). Underwater self-pollination of the smaller *R. maritima* occurs via pollen attached to tiny gas bubbles (Verhoeven, 1979; Richardson, 1983; Kaul, 1993; Lacroix and Kemp, 1997; Triest and Sierens, 2015; Triest et al., 2018). Because pollination cannot happen in a terrestrial setting, such as an alluvial mudflat, no drupelets form (no drupelets = no radiocarbon dates at WHSA).

Drupelets are produced in large quantities within two weeks after first flowering (Kantrud, 1991). These may drop to the bottom to lie dormant until the next growing season, either submerged or exposed to the air. The drupelets are very drought-resistant (and can persist as sub-fossils in sediments for millennia). They are often transported for considerable distances on floating mats, or via the guts of fish and waterfowl. Kantrud (1991, p. 7) noted that “widgeongrass drupelets mix with small amounts of other plant material, forming compact balls up to the size of small watermelons—these are often found along the beaches of saline lakes in windy locations. Such balls presumably form by wave action.” Germination requires at least 5–10 cm of water depth and is affected by water and sediment chemistry, salinity, oxygen content, temperature, water permeability, and depth.

Depositional environments

This basic *Ruppia* biology is important in the Lake Otero context because the dated *Ruppia* drupelets are said to occur in “distinct seed layers” in alluvial deposits above lake level (Pigati et al., 2022a, p. 1). *Ruppia* would not germinate, grow, or persist in a subaerial environment, and the drupelets must have developed in water, not on land. How, then, did layers of them become deposited in subaerial alluvium? Three possibilities come to mind. (1) The *Ruppia* drupelet layers could represent windrow strandlines of *Ruppia* detritus floated by wind and wave action

to the lake's shoreline from nearshore *Ruppia* growth beds. Such detrital strandlines are common around lagoons, estuaries, bays and lakes where *Ruppia* is plentiful (Verhoeven, 1979). (2) The layers could represent old-growth *Ruppia* beds from a time when the lake had been higher, that subsequently were left dry and exposed as the lake dropped. The presence of *Ruppia* drupelet layers in several bedding planes in the stratigraphic profile may suggest an alternating rising and falling lake, with repeated re-establishment of *Ruppia* beds followed by subaerial exposure. (3) *Ruppia* drupelets and other detritus might have been washed down from upslope by fluvial processes if upstream water sources were deep enough to support *Ruppia* growth and reproduction. One of the streams that flowed toward Lake Otero (Lost River, east of the WHSA footprint locality) could have been a source, and *Ruppia* has been reported growing elsewhere in the Tularosa basin (Turner, 1987). How such a stream source could have deposited the dense *Ruppia* drupelet beds illustrated by Bennett et al. (2021a, b) without containing a mixture of other terrestrial plant remains is difficult to imagine, though (in addition, see the exchange between Haynes, 2022, and Pigati et al., 2022b).

Assimilation of old carbon by *Ruppia*

Ruppia routinely assimilates carbon via epidermal photosynthesis using dissolved inorganic carbon (DIC) in the water, including aqueous carbon dioxide (CO_2), bicarbonate (HCO_3^-) (Lucas, 1983; Sand-Jensen and Gordon, 1984; Hellblom and Axelsson, 2003), and/or carbonate (CO_3^{2-}). CO_2 dissolves in water to form carbonic acid, and HCO_3^- and CO_3^{2-} are produced during the dissolution of CaCO_3 by carbonic acid (Drever, 1988; Falkowski and Raven, 1997). Ancient ^{14}C -depleted CaCO_3 is abundant in sediments and bedrock of the Tularosa Valley and surrounding mountains (e.g., Herrick, 1900, 1904; Meinzer and Hare, 1915; Leuth et al., 2002; Lucas and Hawley, 2002).

Ruppia readily uses carbon in the form dissolved CO_2 in the water, but the concentration of carbon from that source is typically low even in air-saturated water, and *Ruppia* plant growth is strongly limited using that source alone (Sand-Jensen, 1983; Fontana, 2007). As with many submerged aquatic plants, *Ruppia* uses various carbon-concentrating mechanisms to extract

bicarbonate from the water to overcome the dissolved CO_2 carbon limitation (Sand-Jensen and Gordon, 1984; Madsen and Sand-Jensen, 1991; Marty and Myrbo, 2014; Larkum et al., 2017). The use of dissolved carbonates by *Ruppia* growing in Lake Otero is likely to have been substantial even if its shallow waters were well-mixed and in CO_2 equilibrium with the atmosphere.

Dissolved carbonate in the water column is the primary source of the hard-water or reservoir effect on radiocarbon-based age estimates (Olsson, 1980). Dissolved carbonate has a substantially different $\delta^{13}\text{C}$ signature than aqueous CO_2 , so the $\delta^{13}\text{C}$ of the dated *Ruppia* drupelets may provide a useful indicator of the relative proportion of the atmospheric versus carbonate sources used by *Ruppia* in the Lake Otero sediments (e.g., Smith and Walker, 1980; Marcenko et al., 1989; Larkum et al., 2017). Unfortunately, Bennett et al. (2021a, b) did not give $\delta^{13}\text{C}$ values, which would help determine whether, and to what extent, dissolved carbonate was a source of carbon in the dated *Ruppia* drupelets (we hope that those $\delta^{13}\text{C}$ values will be made available).

Instead, one of the arguments used by Bennett et al. (2021a, p. 1530) was that “the geologic and hydrologic settings along the shallow lake margin that hosts the human trackways make it unlikely that stands of emergent aquatic plants would harbor prominent hard-water effects.” It is true that emergent aquatic plants (such as bulrush or cattail) are not expected to display prominent hard-water effects because their aerial leaves obtain their carbon from the atmosphere above the waterline, not the water; only very limited carbon assimilation takes place via submerged roots. For that reason, the fruits or other remains from those emergent aquatic plants would be an ideal dating alternative to the *Ruppia* drupelets (such remains unfortunately do not appear to be present in the WHSA locality sediments). In contrast to Bennett et al.'s (2021a) assertion, submerged aquatic plants such as *Ruppia* that obtain their carbon from the water column and not directly from the atmosphere should be expected to exhibit hard-water effects.

A search of the literature for reported radiocarbon ages of *Ruppia* samples shows that *Ruppia* very commonly yields radiocarbon ages that exhibit prominent radiocarbon reservoir effects (Table 1). Thus it seems that radiocarbon dates of *Ruppia* samples should be assumed to show a radiocarbon reservoir effect, and

Table 1. Examples of reservoir ages (^{14}C yr) from lacustrine deposits based on *Ruppia* propagules.

Location	Estimated Reservoir Age (^{14}C yr)	Reference
Lago Cardiel, Argentina	ca. 0 (living, post-bomb)	Markgraf et al., 2003
Sarlieve, France	ca. 85 ± 42	Hatté et al., 2013
La Olla, Argentina	ca. 800	Fontana, 2007
Qinghai Lake, China	ca. 1100	Colman et al., 2007; Kelts et al., 1989 (cf., Jull et al., 2014)
Laguna Miscanti, Chile	1230 ± 250 (living, ca. 2200–2500 accounting for bomb effect)	Geyh et al., 1999; Grosjean et al., 2001
Laguna Lejia, Chile	ca. 1900	Geyh et al., 1999
Laguna del Negro Francisco, Chile	ca. 2500	Geyh et al., 1999
Sugan Lake, China	ca. 2600–3800	Zhou et al., 2009
Hurleg Lake, China	ca. 2758	Zhao et al., 2010
Chatyr Kol, Kyrgyz Republic	ca. 4360 max	Kalanke et al., 2020
Juke Box trench, UT, USA	ca. 9300	Oviatt et al., 2018

substantial efforts are required to demonstrate that the Lake Otero *Ruppia* did not utilize DIC derived from dissolution of limestone in photosynthesis, which resulted in a significant reservoir offset of its radiocarbon content. $\delta^{13}\text{C}$ values may provide a useful test of that hypothesis.

DATING OF MODERN *RUPPIA*

To assess the magnitude of a potential hard-water reservoir effect on radiocarbon dates from the WHSA *Ruppia* samples, we sought to date plants of known age from a natural system within the Tularosa basin. On June 3, 1947, Edward F. Castetter and W.J. Koster visited Malpais Spring, a large spring/salt marsh/shallow lake ecosystem on the southwest end of the Carrizozo Malpais lava flow (Myers and Naus, 2004), in the watershed of Pleistocene Lake Otero and ~45 km north of the WHSA footprint site. There they collected *Ruppia cirrhosa* specimens as well as a specimen of chairmaker's bulrush (*Schoenoplectus americanus*), a common emergent aquatic plant in the wetland. We obtained samples from these collections from the University of New Mexico Herbarium for radiocarbon dating and ^{13}C isotopic analysis. We expected that the *Ruppia* should utilize dissolved carbonate in the water and would exhibit a significant hard-water reservoir effect by having a radiocarbon date significantly older than modern and high $\delta^{13}\text{C}$ consistent with its carbonate assimilation physiology. Water quality analysis of Malpais Spring by Cruz (1983) indicated that it had a measured pH = 7.8, specific conductance = 6050, dissolved CO_2 = 0.2 mg/l, dissolved organic C = 0.6 mg/l, dissolved inorganic C = 7.0 mg/l, with a $^{13}\text{C}/^{12}\text{C}$ ratio = -8.6‰. Measured alkalinity (CaCO_3) = 44–49 mg/l, and bicarbonate (HCO_3^-) = 54–60 mg/l. Cruz (1983) reported an age of the water from Malpais Spring of >27,900 ^{14}C BP with <3.1% modern ^{14}C , but Myers and Naus (2004, p. 1) cautioned that “this age may not be accurate because the aquifer system is not a closed system.” In contrast, we expected that the *Schoenoplectus* would have assimilated its carbon from the atmosphere and exhibit little to no hard-water offset, having a modern or near-modern radiocarbon age and a low $\delta^{13}\text{C}$ value typical of C3 plants.

The *Ruppia* specimen (UNM 0109200) yielded an age estimate of 6420 ± 30 ^{14}C BP, with $\delta^{13}\text{C} = -13.6$. The age estimate results in a median Calib8.20 (Intcal20) calibration of ca. 7353 cal yr BP (7274–7422 cal yr BP, 2σ range). The *Schoenoplectus* specimen (UNM 0066467) yielded an age estimate of 310 ± 30 ^{14}C BP (median 389 cal yr BP, 301–460 cal yr BP, 2σ range), with $\delta^{13}\text{C} = -23.9$. These values confirmed our expectations. *Ruppia*, growing in spring-fed wetlands within the Lake Otero watershed, appears to utilize the abundant dissolved carbonate and exhibits a large hard-water effect (on the order of ca. 7350 years in this instance), whereas emergent aquatic vegetation inhabiting the same water does not exhibit such a large effect (although it may exhibit some smaller effect).

Due to unmeasured variables, such as possible differences in sources and amounts of waters supplying paleolake Otero, as Pigati et al. (2022a) noted, the strong hard-water reservoir value exhibited by this date on modern *Ruppia* cannot be directly applied to the WHSA specimens. However, if this value were consistent with the postulated hard-water effect of Lake Otero waters on the *Ruppia* at the WHSA footprint site, then the dates reported by Bennett et al. (2021a, b) would be on the order of ca. 15,500–13,500 cal yr BP, which is similar in age to those for a number of other dated 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). Because Lake Otero is known to have similar carbonate-rich waters, it would make sense that *Ruppia* growing in its waters would exhibit a similar reservoir effect.

PROBLEMS WITH THE VALIDITY OF *RUPPIA CIRRHOSA* RADIOCARBON DATES IN THE TULAROSA VALLEY

Despite the well-known problems with dating *Ruppia* drupelets due to their incorporation of DIC in its photosynthesis, Bennett et al. (2021a) provided several reasons why they think the *Ruppia* age estimates from WSHA Locality 2 are “robust.” Madsen et al. (2022) suggested this reasoning is more problematic than Bennett et al. (2021a) implied. Here, we expand on this discussion and examine other problematic issues raised by Pigati et al. (2022a).

Alluvial/Aeolian sedimentation

Bennett et al. (2021b, p. 9), in arguing that the stratigraphic context of the radiocarbon-dated *Ruppia* drupelets gives reason to suspect a radiocarbon reservoir did not affect the plants, stated that “...the hydrologic conditions at WSHA Locality 2 are not conducive for perpetuating significant age offsets through hard-water effects because water levels must have been quite shallow if humans and megafauna were walking on the plants during or shortly after the plants were alive. This interpretation is based on our observations that well-preserved *R. cirrhosa* [drupelets] were often found embedded in human footprints at WSHA Locality 2. Therefore, long-term stratification and isolation from the atmosphere could not have taken place in this setting.” This statement contrasts with the statement of Pigati et al. (2022a, p. 1) that “Although aquatic plants such as *Ruppia* living in lakes that are this deep may indeed be subject to hard-water effects, the [drupelets] chosen for dating at WSHA Locality 2, as well as the footprints they stratigraphically constrain, were not present in lake deposits.”

This clarification, including the phrase “the largely gypsiferous and calcareous sediments contain both alluvial and aeolian components” (Pigati et al., 2022a, p. 2), changes possible interpretations of the *R. cirrhosa* ^{14}C ages. By definition, alluvial and aeolian sediments are redeposited, the former by water and the latter by wind. If the drupelets contained in the sediments studied by Bennett et al. (2021a) were redeposited in terrestrial beds, then they are older, by some unknown amount, than the footprints found in these beds. Exactly how much older is unknown. They may be relatively contemporaneous, as Bennett et al. (2021a) and Pigati et al. (2022a) assumed, or they could easily be hundreds to thousands of years older. Unless the origin of the dated *R. cirrhosa* drupelets is known, it isn't possible to know which of these interpretations is correct.

Atmospheric mixing in shallow lakes

Bennett et al. (2021a) thought that the dates on *R. cirrhosa* drupelets were robust partly based on the reasoning that the radiocarbon reservoir effect in a shallow lake would be minimal because of atmospheric mixing. But, as we have noted, dating of modern *Ruppia* from shallow lakes in different locations around the world in many cases produce age estimates that are thousands of years older than their correct age (Table 1). However, an extended discussion of these alternate interpretations is complicated because of the possibility that the dated *R. cirrhosa* drupelets at the

WSHA site were redeposited. Since it is impossible to know the depth of the water in which the *Ruppia* plants originally grew, debate about whether or not atmospheric mixing in shallow lakes eliminates problems with a radiocarbon reservoir is pointless, at least in the case of the WSHA Locality 2 age estimates.

Age and effects of groundwater in the Tularosa Valley

Pigati et al. (2022a, p. 1) contended that "...the consistency of our calibrated ages argues against contamination by groundwater with hardwater effects on the order of many thousands of years." One of the reasons we question this conclusion is based on the geology of Tularosa Valley, which is well understood (e.g., Herrick, 1900, 1904; Meinzer and Hare, 1915; Leuth et al., 2002; Lucas and Hawley, 2002). The hydrology of the basin is similar to that of other hydrographically closed basins in western North America and elsewhere in the world (e.g., Langbein, 1961; Rosen, 1994). The Tularosa Valley is surrounded by mountain ranges that include a glaciated mountain (Sierra Blanca) and other high mountains (the Sacramento Mountains) on the east, and the San Andres Mountains on the west, which are lower in elevation and were not glaciated. In both bounding mountain ranges, and in other high-elevation terrain within the drainage basin of Tularosa Valley, groundwater is recharged. In the closed Tularosa basin (closed to surface water), some groundwater seeps southward into another closed basin (Love et al., 2014, p. 135). Closed-basin lakes are known for their frequent and rapid water-level changes (Bohacs et al., 2000), which in some cases might lead to shallow lakes appearing and disappearing on seasonal, decadal, or centennial time scales. It seems likely that the behavior of shallow Lake Otero would have been similar to that of other closed-basin lakes.

The water table on the floor of the basin is relatively high (typically within a few meters of the ground surface), and there is an upward component of groundwater flow (Meinzer and Hare, 1915), so that the basin floor is a large groundwater discharge area (capillary rise above the water table and evaporation at the surface). Several studies in Tularosa Valley have documented ages for groundwater in wells and springs of hundreds to thousands of years (Cruz, 1983; Huff, 2002; Mamer et al., 2014). Therefore, the discharge of old groundwater into Pleistocene lakes on the basin floor is more likely than not to have occurred. If it were postulated that groundwater did not discharge into Pleistocene lakes in this basin, that groundwater would have to be disposed of in some way.

Newton and Allen (2014, p. 3) noted that the "...regional groundwater component [in the Tularosa basin] has a distinct geochemical signature and is greater than 10,000 years old"; they also said (p. 17) "This water likely represents regional groundwater that originated as precipitation in the Sacramento Mountains thousands of years ago." These statements only partially align with the comment by Pigati et al. (2022a, p. 1), that "The age of shallow groundwater in the White Sands area ranges from a few hundred to a few thousand years [Newton and Allen (2014)], which is in stark contrast to groundwater emerging from deep-seated, regional-scale aquifers that are known to impart exceptionally large hard-water effects [in other valleys, specifically in southern Nevada]." Considering that old groundwater is making its way to the surface in Tularosa Valley, it seems reasonable to assume, although it does not prove, that the radiocarbon ages of the remains of aquatic organisms that lived in Tularosa Valley are likely to be older than carbon-bearing materials (organic and

inorganic compounds) derived from organisms that received their carbon directly from the contemporaneous atmosphere.

Pigati et al. (2022a) pointed out correctly that groundwater ages could be spatially and temporally variable. WSHA Locality 2 is a single location, so spatial variability is not in question in this case. Taken at face value, the radiocarbon dates of Bennett et al. (2021a, b) span a range of about 2000 years. However, considering the uncertainty in those ages, as discussed here, the apparent 2000-year period may not be correct—the length of the period is unknown, but easily could be larger or smaller than 2000 years. Pigati et al. (2022a) cited a study in a lake basin in China (Zhou et al., 2009) where the reservoir effect during the late Holocene varied from ca. 4300 yr to ca. 2700 yr (a range of ca. 1600 yr) during a period of ca. 2100 yr. Each groundwater-discharge setting is different, however, and the details of the situation in Tularosa Valley are not currently known. We regard temporal variability in the radiocarbon reservoir at the WSHA site as a possible, but undocumented, complicating factor in determining the true age of the footprints.

Stratigraphic order and validity of radiocarbon ages

Bennett et al. (2021a, p. 1530) stated "...our calibrated ^{14}C ages maintained stratigraphic order even when samples were separated by a few centimeters, which would not be the case if hard-water effects were large and variable." We agree that correct stratigraphic order is necessary if the sequence of ages is to be interpreted as valid, but correct stratigraphic order is not sufficient by itself to indicate validity because the ages could be in stratigraphic order but not representative of the age of sediment deposition.

An example of correct stratigraphic order of radiocarbon ages, but incorrect individual ages, is provided by Thompson et al. (2016), where >50 radiocarbon ages (not of *Ruppia*, but other organic materials) in a core of sediments from Great Salt Lake, Utah, are in stratigraphic order (with few exceptions). However, all of the ages had to be adjusted by some amount, as shown by comparison with independently determined ages at five stratigraphic levels. Thompson et al. (2016) chose 1800 yr as an appropriate average for adjustment based on the available evidence (i.e., the unadjusted radiocarbon ages of bulk organic matter in small samples from the Great Salt Lake core are 1800 radiocarbon years too old), but the exact amount required at each stratigraphic level is not known. The important observation in the context of the ages of the White Sands footprints is that it is possible for ages to be in proper stratigraphic order, but individually incorrect (i.e., "reliable," but not "valid").

If, in contrast to the assumption of Pigati et al. (2022a), there were no variability in the reservoir effect during the ca. 2000-yr dated interval in this case, a sequence of radiocarbon dates from that time interval might be in correct stratigraphic order, even if samples were separated by only a few centimeters, but the entire sequence could be shifted toward an older age by an amount proportional to the radiocarbon reservoir. Therefore, it would be important to determine independently whether a radiocarbon reservoir existed at the time the dated samples were forming. As discussed below, the age of redeposited charcoal fragments in combination with ages of aquatic organisms in Tularosa Valley, as reported by Allen et al. (2009), does not adequately provide an independent test of the absence of a radiocarbon reservoir at the time humans created the footprints at WSHA locality 2.

The scattered pattern in the chronostratigraphic record reported from the western edge of Alkali Flat by Bustos et al.

(2018, fig. S1; in a plot of those ages versus depth, ~48% of the variance is explained by a linear regression) suggests that the radiocarbon samples of “palustrine mud” they dated from a nearby section may have had unresolved problems, such as variable incorporation of carbon-bearing clastic debris in the mud samples, reworking and mixing as the muds were deposited, or a variable radiocarbon reservoir effect in that area. If reworking and/or radiocarbon reservoir effects are a problem on the west side of Alkali Flat, they may also be problematic on the east side of the flats where the *Ruppia* drupelets were found in association with the human footprints (Bennett et al., 2021a).

Confirmation of the footprint chronology using other Tularosa Basin sections

Bennett et al. (2021b) created a Bayesian model for radiocarbon ages from a stratigraphic section in the northern Tularosa basin (locality 8 of Allen et al., 2009) to support their notion that a possible long-term reservoir effect amounted to a few hundred years at most. However, we find their use of radiocarbon ages of charcoal fragments, “macrophytes,” and ostracodes, to be problematic. Bennett et al. (2021b, fig. S14) referred to the charcoal fragments as “terrestrial material.” However, the charcoal fragments presumably were transported to the site of deposition and are not necessarily the same age as the deposition at that site. Allen et al. (2009, p. 17–18) stated “...charcoal fragments were probably transported to depositional sites by alluvial processes, and uncertainty in the duration of transport and the antiquity of the plants when they died also suggests a maximum-age interpretation for those samples.”

The charcoal that ended up as fragments that were dated by Allen et al. (2009) formed from stems of some plant that was receiving its carbon from the atmosphere and therefore would yield a radiocarbon age not influenced by a radiocarbon reservoir, but the chances that the plant that ultimately yielded the charcoal fragments was living at the site of deposition, and at the same time as sediment deposition, are slim. The transport mechanism(s), the history of potential temporary storage and re-entrainment, the location where the plant was growing, and the species of plant are not known. This means that the charcoal age should be regarded as a limiting age (that is, the age of deposition is equal to or younger than the charcoal age), not as a direct age of deposition of the sediment (as presumably the “macrophyte” and ostracode ages are, if they were not affected by radiocarbon reservoirs). The statement “...that terrestrial and aquatic material yielded concordant ^{14}C ages between ~44 and 25 ka [44,000 and 25,000 cal yr BP]” (Bennett et al., 2021a, p. 1531) is based on assumptions that are unlikely to be correct.

Pluvial Lake Otero and climatic implications of the footprint ages

Bennett et al. (2021a, p. 1531) suggested that pluvial Lake Otero reached levels higher than the footprint site before ca. 23,300 cal yr BP: “The depositional sequence reported here exhibits a potential paleoclimate signal in which lacustrine conditions were succeeded by alluvial sedimentation that occurred in temporal correspondence with abrupt warming during Dansgaard-Oeschger event 2, beginning at ~23.3 ka (Svensson et al., 2008). This drying event resembles sequences observed in other paleohydrological records in the southwestern US (Menking et al., 2018; Springer et al., 2015).”

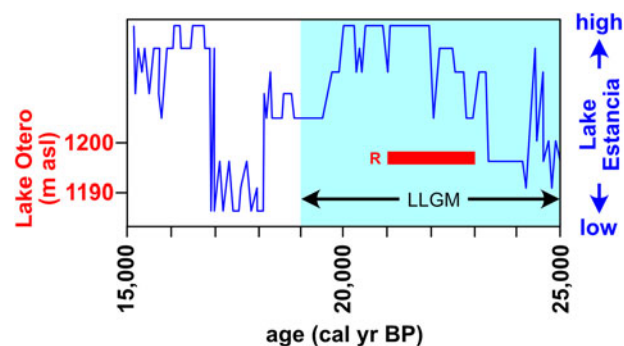


Figure 1. Diagram showing the relationship between *Ruppia* ages for the human footprints in the Lake Otero basin (red bar labeled “R” in the figure; the elevation scale on the left is for the red bar, as dated by Bennett et al. (2021a, b) compared with the history of Pleistocene Lake Estancia. The Lake Estancia record shown in the blue line (using the scale on the right side of the diagram, relatively wetter [high] or dryer [low]) is simplified from Menking et al. (2018, fig. 4; see also Allen and Anderson, 2000, fig. 12). According to Bennett et al. (2021a), Lake Otero dropped from an indetermined elevation to below the elevation of the footprint site after ca. 23,000 cal yr BP. The approximate duration of the part of the LLGM shown on the figure is marked with the light blue rectangle (the full duration of the LLGM is 26,500–19,000 cal yr BP; Clark et al., 2009).

Despite this claim, the three records (from Otero, Estancia, and southern Nevada) resemble one another only in that they all exhibit a number of wet and dry episodes. The geologic record of fluctuations of Lake Estancia (Menking et al., 2018), ~200 km north of Lake Otero, shows evidence of increased moisture at the same time that, according to the dating of the WHSA footprint record by Bennett et al. (2021a), Lake Otero was dry enough for humans to leave footprints on the exposed lake floor (Fig. 1). The geologic record of wet periods in groundwater-discharge deposits near Las Vegas, Nevada (Springer et al., 2015) shows both wet and dry episodes at the time human footprints were being formed in Tularosa Valley (using the ages reported by Bennett et al., 2021a). While it is possible these other records are incorrect due to dating issues, it is also quite possible that the Lake Otero record, as reported by Bennett et al. (2021a), is incorrect.

Ages reported for the LLGM highstands of nearby Pleistocene lakes provide useful comparisons with Lake Otero. Lake Estancia highstands were between ca. 24,000 and 18,300 cal yr BP according to Allen and Anderson (2000, fig. 12) and Allen (2005; note the use of radiocarbon years rather than calibrated years in older publications—we have calibrated those ages for this paper), or between ca. 22,000 and 20,000 cal yr BP (Menking et al., 2018; see also Fig. 1). In Pleistocene Lake King, ~180 km southeast of Tularosa Valley, four highstands occurred between ca. 27,000 and 19,000 cal yr BP (Wilkins and Currey, 1997). On a larger scale, the Devils Hole speleothem climate proxy record from southern Nevada shows that groundwater was at a relatively high level at ca. 19,850 cal yr BP, and that it was ~1.5 m lower between ca. 30,000 and 20,000 cal yr BP (Wendt et al., 2018, fig. 4). At Lake Otero, the Late Pleistocene highstand was between ca. 18,900 and 18,700 cal yr BP (Allen et al., 2009).

POTENTIAL RESOLUTION

For the reasons outlined above, we think the footprint ^{14}C ages on *Ruppia* drupelets need to be confirmed using other chronometric methods. As we noted previously, propagules or other suitable remains from terrestrial or emergent aquatic plants would not

be expected to have the same hard-water issues. If available (and keeping in mind possible re-deposition of older materials), they could constitute a useful validity test of the *Ruppia* dates. To our knowledge, though, such remains are not available.

Madsen et al. (2022) suggested that optically stimulated luminescence (OSL) methods might be a useful way to validate the ^{14}C ages. Pigati et al. (2022a, p. 2) were less hopeful, saying that OSL methods "...may not yield robust ages at WHSA Locality 2 because the largely gypsiferous and calcareous sediments contain both alluvial and aeolian components. Multigenetic deposits like these often violate the underlying assumption of total bleaching prior to deposition [Rhodes, 2011]." We agree that when single/multiple aliquot methods are used, which involve averaging the luminescence of thousands to millions of individual grains, alluvial sediments may produce inaccurate OSL ages due to poor resetting or partial bleaching of some of the sediments as they are transported and redeposited. In newer single-grain methods, on the other hand, the luminescence signals of a series of separate grains (typically 100) are read individually. Poorly reset outliers producing aberrant older ages, as well as aberrant younger ages for grains introduced through bioturbation, can then be removed using statistical methods (e.g., Gilbraith and Green, 1990).

Gypsiferous and calcareous sediments are poor candidates for OSL dating, but the aeolian components of the WHSA Locality 2 sediments very likely contain quartz grains suitable for OSL dating methods. Bustos et al. (2018, Table S1) reported two OSL ages ($26,130 \pm 1920$ cal yr BP and $41,350 \pm 2650$ cal yr BP) from Lake Otero basin deposits, which shows this method will work in these sediments. While OSL age estimates do not have the precision of ^{14}C ages, they do have typical errors of only 5–10%. Therefore, single-grain age estimates could help provide a useful test of the robustness of the *Ruppia* ^{14}C ages.

Allen et al. (2009, p. 19) stated that "Kocurek et al. (2007) report optically stimulated luminescence (OSL) ages on core samples obtained within the crescentic dunes of White Sands National Monument, with basal clay sediment at a depth of 9 m below the land surface yielding an age of 7.3 ± 0.5 ka and gypsum sand at a depth of 6 m yielding an age of 5.2 ± 0.4 ka." This demonstrates that OSL does work on the gypsum-rich sediments of the basin and that the errors are likely to be small enough to test ^{14}C age estimates of *Ruppia* drupelets.

CONCLUSIONS

We are open to the idea that humans could have entered the Americas during or prior to the LLGM. However, for the following reasons, we remain unconvinced that the evidence put forth by Bennett et al. (2021a, b) and the response provided by Pigati et al. (2022a) represent secure evidence of such an event for many reasons. (1) The dated *Ruppia* drupelets are said to occur as discrete bedding layers in alluvial and aeolian deposits above lake level and "...were not present in lake deposits" (Pigati et al., 2022a, p. 1). *Ruppia* does not grow in terrestrial environments, although it may survive in tidal mudflats for a limited time. *Ruppia* inhabits ponds, lakes, bays, and slow-moving streams with water depths ranging from ~0.5–2.5 m (it is more likely to be found in stream channels rather than in water spread thinly over flat terrain, such as is typical of Alkali Flat in Tularosa Valley). (2) Because the alluvial and aeolian deposits consist of redeposited sediments, the drupelets they contain must be redeposited as well and therefore older by some unknown amount than the human footprints they bracket. (3) The use of DIC by

Ruppia growing in Pleistocene Lake Otero is likely to have been substantial, even if its shallow waters were well mixed with the atmosphere. It seems likely that Lake Otero's DIC contained a large component derived from dissolved carbonates that were not in equilibrium with the contemporaneous atmosphere, resulting in a hard-water reservoir effect that cannot be lightly dismissed. (4) Regional groundwater in the Tularosa Valley is >10,000 years old. The proportion of groundwater versus surface water in Lake Otero may have varied temporally and spatially, but possibly not. Either way, this has not been adequately investigated. (5) Dated modern *R. cirrhosa* plant material from Malpais Springs in the Lake Otero watershed shows a significant hard-water reservoir effect, with a date of ca. 7400 cal yr BP. *Ruppia* plants growing in the saline, carbonate-rich waters of Lake Otero also are expected to have had a significantly high reservoir effect. (6) The stratigraphic consistency of the *Ruppia* ^{14}C ages does not provide definitive evidence of their accuracy because the persistent use of the same water source (in the absence of temporal variability) also would provide stratigraphic consistency. (7) Bennett et al. (2021a) used a Bayesian model from a stratigraphic section in the northern Tularosa basin to support their claim that their footprint chronology is "robust," yet charcoal fragments from that section were redeposited and yield a maximum-limiting age. (8) The lake history for pluvial Lake Otero, as reconstructed from the *Ruppia* age estimates, is out of phase with that of other regional lakes, although the chronologies from other regional lakes are not in total agreement with each other. (9) A radiocarbon reservoir of less than a few hundred years was expected by Bennett et al. (2021a); however, the radiocarbon age of groundwater in the Tularosa basin was reported by the same authors (Pigati et al., 2022a) to range from a few hundred to a few thousand years. If the *Ruppia* drupelet ages are a few thousand years too old (i.e., if old groundwater was influencing the *Ruppia* ages), then the ages of the human footprints in the Tularosa basin are within the age range of other pre-Clovis North American sites and do not confirm "...that humans were present in North America before the glacial advances of the LLGM closed the Ice-Free Corridor" (Bennett et al., 2021a, p. 1531).

Given what we know about the hydrology of the Lake Otero (Tularosa) basin, and lacking an independent chronometric evaluation of the footprint-bearing deposits, we cannot know the ages of the *Ruppia* drupelets with certainty. If the *Ruppia* radiocarbon ages can be confirmed, the stratified Tularosa Valley footprints remain extremely important because that would overturn current conventional wisdom in a number of scientific fields and force us to rethink both our analytic approaches and the conclusions we have derived from them. However, until independent age controls are established for the footprint-bearing stratigraphic sequence, we can only say for sure that humans were present at Lake Otero sometime after the radiocarbon age of the *Ruppia* drupelets and before the extinction of mammoths in the Southwest (Faith and Surovell, 2009) (i.e., sometime between ca. 21,000–12,500 cal yr BP).

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