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ORIGINAL PAPER

Resource risk and stability in the zooarchaeological record: the case of Pueblo fishing in the Middle Rio Grande, New Mexico

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Abstract
Disarticulated fish remains are frequently recovered from late preHispanic and early historic archaeological sites in the Middle Rio Grande basin of central New Mexico, but they are rare during earlier time periods. Increased aquatic habitat quality brought on by wetter climatic conditions may have impacted Ancestral Pueblo foraging goals related to risk minimization, leading to an uptick in fish exploitation. Wetter stream conditions can increase the number of different energy channels that help support fish populations and increase ecological stability, which makes fish less risky to pursue for human foragers. Here, we illustrate how to identify stable ecological communities in the archaeological record using stable carbon and nitrogen isotope values of fish bones recovered from archaeological sites in the Middle Rio Grande. We find that energy derived from terrestrial C_4 plants—a stabilizing "slow" allochthonous energy source—was important for the Middle Rio Grande aquatic food web during the late preHispanic/early historic period. This result suggests that fish populations were supported by a broader resource base and were thus more stable and less risky to pursue for Ancestral Pueblo people.

Keywords Risk-sensitive foraging · Ecological stability · Stable isotope analysis · Ancestral Pueblo · Desert fishes

Introduction

Optimal foraging theory (OFT; Stephens and Krebs 1986) and energy maximization logic have been instrumental in examining the relationship between food acquisition and cultural change in the zooarchaeological record across the globe (Broughton 1994; Broughton and Cannon 2010; Jones 2004; Stiner Mary et al. 2000). One of the main ways that zooarchaeologists have used energy maximization logic is to identify resource depression, a topic at the center of the OFT literature in zooarchaeology from 1997 to 2013 (Jones and Hurley 2017). There are different types of resource depression (Charnov et al. 1976; Wolverton et al. 2012), but the one most often examined by archaeologists is exploitation depression or the decline in food availability due to overhunting. Exploitation depression is identified by comparing the amount of high-ranked to low-ranked prey in archaeofaunal assemblages through time, where prey rank is frequently assumed to positively covary with prey body size (Badenhorst and Driver 2009; Broughton 1994; Broughton et al. 2011; Nagaoka 2002). Exploitation depression relies on energy maximization logic because it occurs when humans cannot obtain enough large-bodied food items.

Many zooarchaeologists have been quick to point out that thinking about prey rank strictly in terms of body size is potentially misleading. On the surface, this might seem to indicate advances in zooarchaeological thought are pulling away from energy maximization logic. Cooperative hunting or technology can make the mass collection of smaller taxa more

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profitable (Codding et al. 2010; Jones 2006; Lupo and Schmitt 2005; Rick and Erlandson 2000), and manipulating prey habitat can change pursuit costs associated with certain prey items (Badenhorst and Driver 2009; Linares 1976; Muir and Driver 2002; Neusius 2008). However, the underlying assumption of what matters most to human foragers does not change when thinking about how foragers might collect smaller-bodied prey *en masse* or closer to settlements. Abundance in terms of body size or the number of individuals captured (or both) is assumed to guide foragers at all costs (Lubinski 2013, but see Byers and Ugan 2005). However, foragers do not select food in only this way.

Another way to think about the process of food selection is through risk minimization (Caraco 1981, 1982; Caraco et al. 1980; Stephens 1981, 1990; Stephens and Charnov 1982), which differs from energy maximization in that food items are selected based on the probability of successful acquisition. Risk-sensitive foraging models assume that foragers have incomplete knowledge of the environment and make decisions based on contingency. If energy demands are low, a forager will select food items that are predictably acquired. If energy demands are high, however, it may make sense to select resources that are highly variable in their return. Risky foraging decisions are made when high energy demands could be met in a single foraging bout (Fig. 1; Stephens 1981; Stephens and Charnov 1982).

The use of risk-sensitive foraging models in anthropological and archaeological research has largely focused on the domestication of plants and how engagement with agriculture can offset the failure of riskier foraging strategies (Gremillion 1996; Marston 2017; Winterhalder and Goland 1997). In contrast to plant domestication, the study of risk related to the procurement of wild animal resources has received far less attention in the archaeological literature (but see Cashdan 1990; Halstead and O'Shea 1989; O'Shea 1989). This may relate to the complicated nature of understanding what makes wild food resources risky and how it is measured in the archaeological record.

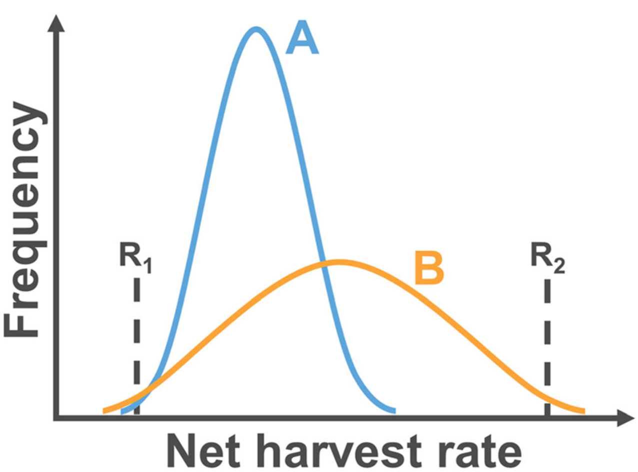

Fig. 1 The *Z*-score model for two resource types (A and B) with two different nutritional demands represented (R_1 and R_2) for a forager. Resource A is preferred when nutritional demands are lower (R_1), and resource B is preferred when nutritional demands are higher (R_2). (Simplified from Winterhalder and Goland 1997; Marston 2017)

In this article, we tackle the issue of how to measure and identify risky wild food resources through stable isotope analysis. We focus on archaeofaunal assemblages that have been recovered from the Middle Rio Grande (MRG) region of central New Mexico from late preHispanic and early historic contexts (ca. AD 1300–1680). This time period is characterized by major demographic and religious reconfigurations across what is now the American Southwest and Mexican Northwest. In the MRG specifically, there is major population aggregation within large multistory room blocks alongside environmental change, and the end of this period is marked by Spanish conquest (Barrett 2009; Cordell et al. 1994). Interestingly, fish remains are more commonly recovered in small quantities during the late preHispanic and early historic period than earlier in the archaeological record (Fig. 2; Akins 1987, 1995, 2004; Clark 2007; Cordero 2013; Dombrosky 2015; James 1986, 1987; Jones 2015; Snow 2002; Stiner 1986). The small quantity of fish remains, usually only considered on a site-by-site basis, has led to a stereotypical view among archaeologists that fishes were unimportant in Pueblo society (White 1947:240). Thinking about fish remains recovered from Pueblo sites on a regional scale, however, shifts this narrative and demands a more comprehensive view of how exactly fishing fit into Pueblo foodways and lifeways in general. While the prevalence of fish remains during the late preHispanic/early historic period could have several socioenvironmental causes, we ask one specific question: under what environmental conditions can a small amount of a small-bodied resource become optimal for human foragers? Optimality is a multifaceted concept and understanding how the food selection strategies of past peoples incorporated factors beyond the number or size of available prey is critical.

Foraging risk, ecological stability, and stable isotope analysis

The successful pursuit of a prey type is partially dependent on how organisms within an ecological community (Clements 1936; Elton 1927; Gleason 1926) or paleocommunity (Damuth 1982; Fagerstrom 1964; Hoffman 1979; Louys et al. 2012) interact, and is thus inherently tied to the concept of ecological stability (Donohue et al. 2016). In its most general sense, stability refers to how well ecosystems or ecological communities can persist after a disturbance (Holling 1973). Stable ecological communities are better able to maintain their function and structure after continual perturbations that impact mortality of community members (e.g., via predation or harvest). By extension, a resource that is part of a stable

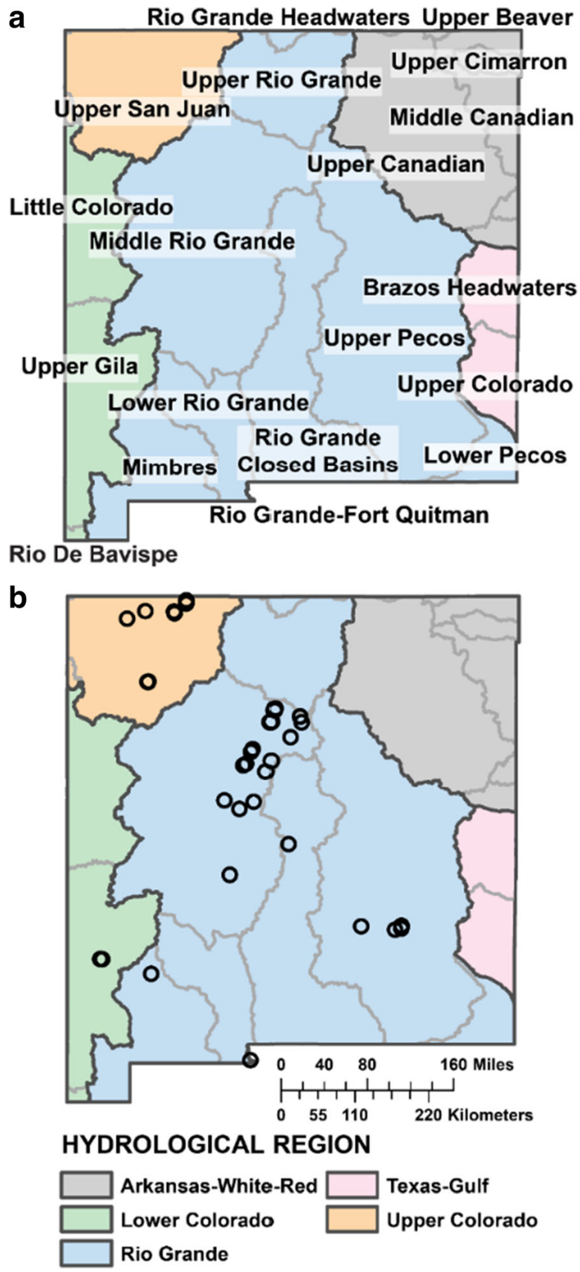

Fig. 2 **a** Hydrological basins present in New Mexico. **b** Location of archaeological sites where fish remains have been recovered in New Mexico from Snow (2002). Roughly 51% of sites where fishes have been recovered and reported in the state of New Mexico occur in the Middle Rio Grande hydrological basin, and of these sites, 85% were occupied from ca. AD 1300 and onward

ecological community is less risky to exploit for humans because foraging returns are less variable.

The degree of stability exhibited by an ecological community is determined by local food web diversity, structure, and resource partitioning (Rooney and McCann 2012). Researchers initially assumed that species diversity alone was the most important attribute of stability (Elton 1927; Hutchinson 1959; MacArthur 1955); however, some argued that species diversity actually destabilizes food webs (Gardner and Ashby 1970; May 1971, 1972). This argument precipitated a new view about the nature of ecological stability: the total amount of species richness is not as important as where in a food web it occurs. The structure of species richness helps enhance stability (Yodzis 1981), but how those species use resources (*sensu* Paine 1966; Schoener 1974) and what those resources are might be even more important (Moore and William Hunt 1988).

Consumers relying on prey that derive their energy from different energy channels likely provides the most stability to food webs (Kondoh 2003; McCann and Rooney 2009; Post et al. 2000; Rooney et al. 2006). An energy channel represents the flow of a specific production source (e.g., aquatic algae or terrestrial plants) through a food web (Zhao et al. 2018), and there are two general types of energy channels cogent to ecological stability. Fast energy channels are those where energy is depleted and replaced quickly such that the biomasses of primary producers and the primary consumers that rely on them have high rates of turnover. In contrast, slow energy channels have low rates of biomass turnover. One of the most important slow energy sources is derived from the decomposition of organic detritus (Hagen et al. 2012; Steffan et al. 2017; Wolkovich et al. 2014; Zou et al. 2016). Fast energy channels allow predators to rapidly recover after disturbance, but since fast channel predators maximize efficiency by relying on a single source of energy with high rates of turnover, overconsumption and eventual collapse may result. Instead, linking a slow channel to a fast one allows for predators to take advantage of completely different resources that rely on their own separate resource pools and allows for asynchronous resource depletion in the food web as a whole. There are also characteristics of ecological stability tied to long-term environmental stochasticity and how different measures of environmental change are aligned with one another in time (Yang et al. 2019). When ecological communities are continuously exposed to favorable environmental conditions, their recovery time from a disturbance is decreased because the community has the resources it needs to bounce back. In contrast, consistently unfavorable environmental conditions cause recovery time to increase as the resources needed to return to some baseline condition are low.

Stable isotopes offer a way to measure the stability of past ecological communities. Carbon isotope ($\delta^{13}C$) values are useful for tracing the energy channels supporting food webs because $\delta^{13}C$ values of primary producers vary systematically across functional groups. Plants that use the C_3 photosynthetic pathway (e.g., riparian trees, such as *Populus* spp. and *Salix* spp.) have average $\delta^{13}C$ values around − 26 to − 28‰, while those that use the C_4 pathway (e.g., many aridland grasses, such as *Sporobolus* spp. and *Bouteloua* spp.) typically have values around − 12 to − 14‰ (Fry 2007) and aquatic algae

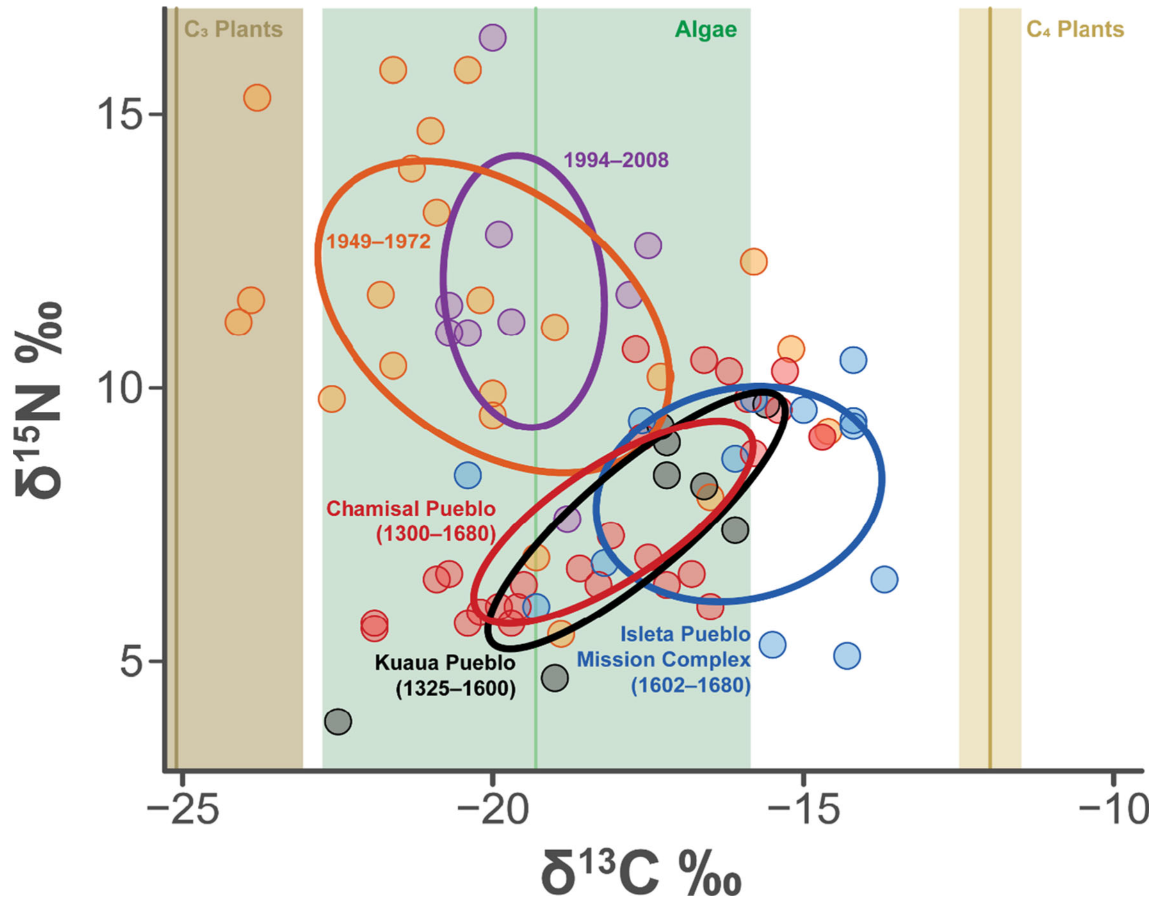

Fig. 3 $\delta^{13}C$ and $\delta^{15}N$ values of bone collagen from fishes recovered from three large preHispanic/early historic archaeological sites near the Middle Rio Grande: Isleta Pueblo Mission Complex, Chamisal Pueblo, and Kuaua Pueblo (ca. AD 1300–1680). Archaeological fishes are compared to museum specimens collected before (1949–1972) and after (1994–2008) the construction of Cochiti Dam. All dates provided are AD calendar dates. $\delta^{13}C$ values of modern samples are Suess corrected using the model presented in Dombrosky (2020). Standard ellipse areas corrected for small sample size (SEA_c) are used as a measure of isotopic niche width. SEA_c overlap between archaeological and late twentieth century (1949–1972) is minimal ($\leq 0.2‰^2$) Primary producers sampled from the Middle Rio Grande are shown in the background; solid lines denote mean $\delta^{13}C$ values and the shading represents $\pm$ 1σ. (Raw data available in Supplemental File 1)

have $\delta^{13}C$ values intermediate to these terrestrial end-members (Supplementary File 1; Figure 3). Stability can be inferred from $\delta^{13}C$ data alone if consumers show that they use primary production from both slow and fast energy channels. Another indicator of increased stability is food chain length, which is the total number of trophic levels in a given food web. More trophic levels serve to increase the probability that different consumers thoroughly incorporate both fast and slow energy channels within the food chain (MacArthur 1955; Pimm 1984; Rooney et al. 2006). Nitrogen isotope ($\delta^{15}N$) values measure food chain length because they steadily increase by ~ 2–4‰ per each trophic step (Post 2002; Vanderklift and Ponsard 2003).

Community-wide metrics of isotopic niche width are useful for inferring stability because they can define the structure and variation of ecological communities in delta space (or δ-space; Layman and Post 2008; Turner et al. 2015). The term δ-space, here, refers to the two-dimensional area defined by axes of $\delta^{13}C$ and $\delta^{15}N$ values (Newsome et al. 2012). Stability can be inferred from whole communities if the overall niche width spans multiple energy channels and/or shows substantial trophic complexity. Such metrics simultaneously incorporate $\delta^{13}C$ and $\delta^{15}N$ measurements of multiple individuals from within or across communities and are resistant to outlier effects. For instance, the use of Bayesian-based standard ellipse areas has allowed for niche width estimates that account for sample size effects (Jackson et al. 2011), which often plague paleozoological data. However, it is key to draw specimens from contexts where fast and slow energy channels have distinct isotopic values. Certain environmental contexts, like aridland rivers, are better suited for inferring ecological stability using stable isotopes because different sources of fast (e.g., aquatic algae) and slow (e.g., terrestrial plants) energy are isotopically distinct with little overlap.

Aridland river food web dynamics, the Middle Rio Grande, and Ancestral Pueblo fishing

Reviewing some foundational concepts in stream ecology is necessary before assessing stability in the late preHispanic/early historic Middle Rio Grande (see Allan and Castillo 2009 for further discussion). Organic carbon in freshwater aquatic ecosystems—and by extension in consumers, like fishes—can originate from autochthonous or allochthonous production. Autochthonous sources of organic carbon are supplied by aquatic primary producers such as filamentous algae or phytoplankton, which have high rates of biomass turnover and are considered labile sources of fast energy (Thorp et al. 1998; Rooney et al. 2006). In contrast, allochthonous sources of organic carbon come from the surrounding landscape, usually from the vegetated riparian zone (Zeug and Winemiller 2008). Rivers and streams obtain allochthonous energy through downstream transport and/or lateral exchange with their floodplains (Tank et al. 2010). Allochthonous inputs are considered to be a slow energy channel since their incorporation into food webs is dependent on decomposition rates and the conversion of recalcitrant biomolecules (e.g., cellulose) into compounds that are more easily assimilated by aquatic consumers (e.g., fatty and amino acids); this process is mediated by microorganisms (e.g., bacteria and fungi) in the form of biofilms and macroinvertebrates (Arce Funck et al. 2015; Marks 2019; Tank et al. 2010). The relative importance of autochthonous and allochthonous sources (e.g., fast and slow energy channels) for large river food webs is a fundamental topic of considerable debate in stream ecology, and there have been a number of models proposed to explain how stream ecosystems function to incorporate these different energy sources (Humphries et al. 2014; Junk et al. 1989; Vannote et al. 1980; Thorp and Bowes 2017; Thorp and Delong 2002; Thorp et al. 2006, 2008).

Autochthonous inputs (fast energy) are commonly thought to be the main form of energy in aridland rivers like the Middle Rio Grande since sunlight is abundant and facilitates high rates of biomass turnover (Busch and Fisher 1981). Further, it is typically assumed that riparian vegetation in desert environments is not productive enough to provide sufficient allochthonous inputs to the food web because the production (biomass) of vegetation along aridland rivers is typically lower than that along temperate rivers (Webster and Meyer 1997). Some have even suggested that streams do not process allochthonous carbon from C_4 grasses at all (Clapcott and Bunn 2003; Lewis et al. 2001) because this functional group exhibits high cellulose concentrations and does not easily decompose (Ross et al. 2002; Throop and Archer 2009; Vanderbilt et al. 2008). Contrary to these suggestions, allochthonous energy sources could be important in aridland aquatic ecosystems for several reasons. Solar radiation—while abundant in desert environments—cannot penetrate far into the turbid main channels of aridland rivers and streams, limiting the overall potential of autochthonous production. Riparian ecosystems are also some of the most productive terrestrial biomes in deserts and could provide sufficient allochthonous inputs given the right environmental conditions. Finally, river systems with strong seasonal pulses of snowmelt—which characterizes many aridland river systems in the Western USA—have a strong connection with their floodplain, thus enhancing the availability of allochthonous energy to aquatic consumers.

In the case of Ancestral Pueblo fishing activity in the MRG, there is also important environmental context linked to stability that could relate to increased fishing by humans. The North American Southwest experienced persistent aridity between approximately AD 900 and 1300, which is generally referred to as the Medieval Warm Period (Cook et al. 2016; Woodhouse and Overpeck 1998). This climatic event impacted human populations across North America (Benson et al. 2007; Douglass 1929; Hodell et al. 2001; Kintisch 2016). It caused intermittent connectivity between different stretches of river systems in the American Southwest, including the Rio Grande headwaters (Meko et al. 2007; Routson et al. 2011; Woodhouse et al. 2010). Increased aridity also results in the fragmentation of stream ecosystems, which can cause instability for freshwater fish communities in several ways. Stream fragmentation cuts off genetic diversity for fishes, reduces habitat size, increases variation in physiochemical conditions, and reduces prey diversity (Lynch et al. 2016). Increasing stream fragmentation is also shown to result in isotopic niche width collapse of freshwater fish communities (Layman et al. 2007). The release from arid conditions at the end of the Medieval Warm Period coincides with the beginning of the late preHispanic period (ca. AD 1300) in the American Southwest, which is when fishing activity became more prevalent in the MRG. It follows that more precipitation would increase seasonal snowmelt and flooding in the MRG. Wetter stream conditions would enhance connectivity with the floodplain, increase the accessibility of multiple channels of (auto- and allochthonous) energy that resulted in the availability of more diverse resources for fish communities, and would have improved overall stability of the aquatic ecosystem (Reese 2016). This climatic shift would have essentially rewired the MRG food web (*sensu* Bartley et al. 2019; Blanchard 2015)

A foraging goal of risk minimization paired with changing aquatic habitat conditions and improved ecological stability during the late preHispanic/early historic period in the MRG could have helped make fishes a more attractive resource to pursue in small quantities. Ancestral Pueblo people clearly used a different and somewhat novel resource patch—an aquatic patch—on the MRG landscape more frequently, but are there traces of stability directly measurable from fish remains during this time? To explore this question, we asked a more specific one: what energy channels fueled the late preHispanic/early historic MRG food web? We hypothesize that both slow (allochthonous terrestrial) and fast (autochthonous algal) energy channels were important in fueling the food web during this period, that this duality led to increased ecological stability, and thus increased exploitation of aquatic taxa.

We measured the bone collagen $\delta^{13}C$ and $\delta^{15}N$ values of MRG fishes (n = 79) recovered from historical and archaeological contexts to test this hypothesis (Supplemental File 1). We sampled multiple taxa including carps/minnows (Cyprinidae), suckers (Catostomidae), smallmouth buffalo (*Ictiobus bubalus*), catfishes (Ictaluridae), gar (*Lepisosteus* spp.), and shovelnose sturgeon (*Scaphirhynchus platorynchus*). The archaeological specimens were recovered from three major late preHispanic/early historic MRG sites: Isleta Pueblo Mission Complex (LA 724), Chamisal (LA 22765), and Kuaua (LA 187) Pueblos. We also sampled fishes historically collected in the MRG that are curated in the Museum of Southwestern Biology (MSB). The historical samples are split into two categories: before (1949–1972) and after (1994–2008) the construction of the Cochiti Dam, which greatly impacted ecosystem functioning in the historical MRG (Turner et al. 2015). The historical samples provide a reference for limited river channel/floodplain connectivity due to the construction of large impoundments that drastically changed flow regimes along the MRG. We would ideally compare the isotope values of fishes from the late preHispanic/early historic period to previous time periods. However, fishes are much rarer during earlier time periods, and an adequate sample does not yet exist. Fishes from the historic period are derived from a qualitatively similar setting to earlier preHispanic archaeological fishes in that both drought conditions and impoundments limit nutrient exchange between the main channel of the Middle Rio Grande and its floodplain. In theory, isotopic data of modern specimens should indicate they are overwhelmingly composed of fast energy derived from autochthonous production (similar to fishes in drought contexts, like preAD 1300 fishes), while archaeological fishes from the late preHispanic/early historic period should reflect a more equable mixture of autochthonous and allochthonous production if they were part of stable communities. We used small sample size corrected Standard Ellipse Areas (SEAc) to estimate community wide isotopic niche width (Jackson et al. 2011).

Our results indicate that many fishes recovered from late preHispanic/early historic archaeological sites consistently have higher $\delta^{13}C$ but lower $\delta^{15}N$ values compared with late twentieth century fish communities collected in the same area (Fig. 3). The increase in $\delta^{15}N$ values over time likely reflects anthropogenic nitrogen loading, where the incorporation of human effluent from the Albuquerque, NM, water treatment facility and runoff from fertilizer into the MRG has increased baseline $\delta^{15}N$ values that cascades up to primary and secondary consumers like fish (Turner et al. 2015). While inferences about historical shifts in trophic complexity such as food chain length are likely confounded by anthropogenic nutrient inputs, the significant shift in $\delta^{13}C$ values we observe through time is interesting in the context of ecological stability. These data suggest that C_4 riparian plants (e.g., aridland grasses) helped fuel the protohistoric MRG aquatic food web. Such a $\delta^{13}C$ signature measured from protohistoric fish communities indicates that a notably slow allochthonous energy source helped bolster MRG fish communities. The coupling of both slow and fast energy channels likely led to increased stability of the MRG food web. Thus, fishes could have represented a stable and low risk resource for Ancestral Pueblo fishers to rely on in small quantities.

While fishes could have represented a low risk food resource because of the stability of aquatic communities, it is also possible that fishes fit into the risk management strategies of Ancestral Pueblo people in a slightly more specific way. The season of death of a small sample of late preHispanic catfish remains recovered from Henderson Pueblo (LA 1549) near the Pecos River in New Mexico shows that most of the catfishes were captured during that late summer or early fall, which coincides with a major precipitation pulse from summer monsoonal rains (Arntzen and Speth 2004; Speth et al. 2004). This result highlights that monsoons might have been an extremely important factor in why Ancestral Pueblo people fished. Additionally, fishes captured during monsoon season could also represent a type of famine food. Prior to agricultural harvest in the late fall, stored resources are known to dwindle among small-scale farming societies (Arntzen and Speth 2004:324), and foraging becomes an important subsistence strategy to fall back on (Strawhacker et al. 2020). The coupling of fast and slow energy channels—largely influenced by the influx of allochthonous resources during spring snowmelt-induced overbank flooding—likely led to stable fish populations that could be exploited later in the year to buffer the risks associated with stored resource shortfall. River flow during monsoon season is dynamic. Monsoon events cause intense short-term increases in flow, but most of the time the flow is low near baseline. These low flows could have helped increase access to fishes and could have been seasonally predictable (*sensu* Smith 1974). It could be useful, in the future, to pair isotopic analyses with estimates of season of death to test the association more rigorously between season, ecological stability, accessibility/predictability, and Ancestral Pueblo need for a reliable resource buffer. The analysis of otoliths might be especially helpful to address this question (Higham and Horn 2000; Hufthammer et al. 2010; Wurster and Patterson 2001, 2003).

Another important factor to consider is whether Ancestral Pueblo land use practices could have enhanced aquatic ecological stability. Floodplain farming and irrigation networks are known to have been used by Ancestral Pueblo people along the Rio Grande (Doolittle 2000; Eiselt et al. 2017; Worman 2013). Detritus from staple crops such as corn (*Zea mays*) could be partially responsible for the C_4 signature measured from MRG fishes. While differentiating among C_4 primary producer sources is almost impossible using bulk tissue isotope analyses, analyzing the $\delta^{13}C$ values of essential amino acids found in bone collagen of late preHispanic/early historic MRG fishes could be a fruitful area for future research. Essential amino acids move up food chains virtually unmodified because animals cannot synthesize them de novo and instead must acquire them directly from their food (Howland et al. 2003). Different functional groups of producers (plants, algae, bacteria, and fungi) use discrete biochemical pathways to synthesize essential amino acids, which leads to distinctive patterns or "fingerprints" among $\delta^{13}C$ values of essential amino acids in these producers (Larsen et al. 2009, 2013; Elliott Smith et al. 2018; Whiteman et al. 2019). This allows for higher-resolution identification, and possible quantification, of the relative importance of autochthonous versus allochthonous primary producers in aquatic food webs.

Analyzing $\delta^{15}N$ values of individual amino acids from fish bone collagen could be used to separate baseline from trophic level shifts. Separating these two effects is impossible to do with bulk tissue $\delta^{15}N$ analysis without samples of primary producers or consumers (invertebrates), which are rare in the archaeological record. For $\delta^{15}N$ analysis, amino acids are categorized into two main groups: (1) source amino acids that are minimally altered by consumers and thus reflect baseline $\delta^{15}N$ values and (2) trophic amino acids that significantly increase in $\delta^{15}N$ with each trophic step (Chikaraishi et al. 2014; McMahon and McCarthy 2016). By comparing source and trophic amino acid $\delta^{15}N$ values, and estimating a few other physiological parameters, one can differentiate between baseline $\delta^{15}N$ shifts and changes in trophic position from a single sample (McMahon and McCarthy 2016). Pairing these amino acid $\delta^{13}C$ and $\delta^{15}N$ approaches with direct AMS radiocarbon dates from archaeological MRG fish remains could provide a powerful way to reconstruct environmental conditions in the MRG over time and to better understand the context of past Pueblo fishing strategies in relation to stability, agricultural intensification, and trophic complexity.

Conclusion

The trouble in identifying risky wild food resources from zooarchaeological material is one reason why OFT models that use energy maximization dominate the literature. There is certainly value in these models, but we maintain that human foragers use both energy maximization and risk minimization logic when selecting resources. We have established one proxy for identifying low risk prey items with stable isotope analysis. The identification of both fast and slow energy sources in aquatic consumers that constitute prey items for human foragers is a strong biomarker for increased ecological stability. Prey items drawn from more stable populations are less risky to pursue, because they are resistant to harvest pressure and can provide reduced variation in foraging return. To help illustrate this point, we have provided data from the late preHispanic/early historic period from fish remains sourced from the MRG in central New Mexico. How fishes have played into the food getting strategies of Ancestral Pueblo people is an understudied topic, but the theoretical framework and the data we present suggests that increased ecological stability might have played an important role in the fishing strategies of Ancestral Pueblo people during this time. Ultimately, we believe this represents a productive way to frame important future research that incorporates fishes recovered before AD 1300 and to test more specific ways that fishing and ecological stability fit into Pueblo lifeways.

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Availability of data and material See Supplemental File 1.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

Code availability The R package SIBER is available at https://cran.r-project.org/web/packages/SIBER/index.html, and the corresponding author can provide code upon request.

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