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Large-Scale Data Synthesis

A Way Forward for Stable Isotope Analysis in Zooarchaeology

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Stable isotope analysis in zooarchaeology has increasingly become *de rigeur* for dietary reconstruction, for interpreting mobility and migration of both people and animals, and as a valuable proxy for environmental change and landscape reconstruction (Makarewicz and Sealy 2015; Pilaar Birch 2013; Zangrando et al. 2014). This chapter will focus primarily on the use of stable isotope values from faunal remains—bones, teeth, and shell—as paleoenvironmental proxy data with the potential to inform on a variety of variables related to climate and landscape. However, the same characteristics that make these data so versatile are also what makes them a challenge to work with: they are influenced by multiple spatially and temporally variable factors. This challenge is one that zooarchaeologists are uniquely equipped to confront in diverse taxa, as they can apply their knowledge of physiology, osteology, ethology, and ecology in their interpretations.

Stable Isotopes from Fauna as Paleoenvironmental Indicators

In other contexts, stable isotope values have been used for mapping "isoscapes" that inform on predicted, modern, and past environments. For instance, global $\delta^{18}O$ in leaf water has been empirically modeled based on ground-truthing and interpolation (West et al. 2008) and $\delta^{13}C$ distribution in Africa has been theoretically modeled based on distribution of C_3/C_4 plants (Still and Powell 2010). These are modern examples with the ability to test real-time values. When reconstructing the past, proxy indicators must be used to calculate environmental stable isotope values. This is

possible using values derived from faunal specimens, because stable isotope ratios vary predictably in time and space and are incorporated into bones, teeth, and shells as they grow and remodel. For instance, though the archaeologist or paleoecologist does not have immediate access to meteoric $\delta^{18}O$ data from 5,000 years ago, herbivore teeth and bone bioapatite record provide a useful proxy in that $\delta^{18}O$ from ingested water and in nonobligate drinkers may be equated with leaf water and therefore with meteoric $\delta^{18}O$ (for example, Cormie et al. 1994; Rivera-Araya and Pilaar Birch 2018). Likewise, comprehensive subfossil plant assemblages for evaluation of $\delta^{13}C$ distributions on continental scales currently do not exist, but paired with pollen records and modeled vegetative communities, $\delta^{13}C$ values derived from herbivore bones and teeth may be a valuable way to evaluate the paleo distribution of C_3 and C_4 plants, "ground-truthing" pollen-derived vegetation models alongside geochemical data from cores and other proxies.

In any paleoenvironmental reconstruction, it is important to consider more than one proxy type, including more than one stable isotope system when at all possible, to avoid narrow interpretations. Due to the time-intensive and cost-intensive nature of sampling, preparing, and analyzing faunal remains for stable isotope analysis from archaeological and paleontological contexts, stable isotope values from faunal remains may remain a supplemental, rather than primary, paleoenvironmental proxy. However, they can still serve to broaden and deepen our understanding of what climate conditions were like, how land cover changed, and, through combination with other types of analyses, how faunal communities responded to these factors, on both short and long temporal scales. Currently, many paleo-stable isotope data that are being collected from archaeological human and animal remains are used to address archaeologically-focused questions. At a single-site and multi-site level, this is, of course, desirable for making interpretations about human and animal behavior. Relatively small sample sizes are acceptable and often necessary. However, these stable isotope data also have the potential to be harnessed and used for larger-scale interpolation, toward regional and continental paleoenvironmental synthesis through time. This requires the ability to access and manipulate large numbers of stable isotope datasets which may not be readily available, even if published as supplemental information in articles; databases and tools for downloading data are imperative in achieving this goal, as discussed below.

Data Challenges in Zooarchaeological Stable Isotopes

Currently, much stable isotope data from faunal remains are published on a site by site basis, or if they are summarized on a regional basis, they tend to address archaeological questions more so than environmental ones (but see Gil et al. 2016 as a good example of the latter). Even if one were to collate multiple records, this leaves us with the issue of nowhere to deposit the physical results of such an effort, even if an article or chapter may be published with data. Though stable isotope specific databases and data resources are growing (for example, IsoBank: Pauli et al. 2015a, 2015b, 2017; IsoArch and IsoMemo: Salesse et al. 2018), if we want to assess isotopic data from faunal remains with particular reference to paleoclimate and paleoenvironmental variables, the Neotoma Paleoecological Database emerges as an ideal repository for data storage, retrieval, and most importantly, integration with other paleo data types (Pilaar Birch and Graham 2015). If we want to link the stable isotope data archive with other types of paleodata (including stable isotope values from other materials such as sediment and vegetation) to create archaeologically-linked, informed paleoenvironmental reconstructions on local and regional scales, the use of a comparative database such as Neotoma is a must. In addition, radiocarbon dates and direct dating of archaeological material when possible are essential components for integrating archaeological specimens with other paleodata, on either isotopically analyzed bone or teeth.

Neotoma and the Faunal Isotope Database

Neotoma

The NSF-supported Neotoma Paleoecology Database (www.neotomadb. org) is a nexus for paleoenvironmental research, exploration, and education (Williams et al. 2018). It serves data from multiple constituent databases that represent different proxy types that include pollen, ostracods, diatoms, and faunal remains. Data derived from peer reviewed/in press publications are uploaded by trained data stewards and can be accessed by anyone for free. Some databases are accessible through individual web portals, while others exist within the framework of Neotoma itself. Data are entered through the software program Tilia (www.tiliaIT.com), which is designed for managing stratigraphically organized paleoenvironmental proxy data. Data are discoverable and accessible via the browser-based

Neotoma Explorer. This interface allows for searches using a wide range of potential variables. Among others, one can look up information by taxon, age range, depositional setting, database, site name, or researcher name.

Development of the Faunal Isotope Database

The Faunal Isotope Database is the most recent addition to Neotoma and was created in part through the efforts of the Stable Isotopes in Zooarchaeology Working Group (SIZWG; zooarchisotopes.com) of the International Council for Zooarchaeology (ICAZ). The initial development of the data entry infrastructure was completed in 2018, and stable isotope data from individual vertebrate specimens (both archaeological and paleontological) can be uploaded and retrieved using a combination of the Tilia data entry software and the Neotoma Explorer.

The effort first began in 2013, with the official formation of the SIZWG as part of ICAZ. At the working group meetup during the ICAZ meeting in Argentina in 2014, there was consensus that there was a need for a stable isotope database, and author Pilaar Birch initiated contact with the growing Neotoma Paleoecology Database on behalf of the group. Following a meeting at Pennsylvania State University in 2015 to discuss initial needs and functionality, development of data structure occurred via email circulation with zooarchaeologists, paleontologists, and isotope geochemists. In 2016, the first formal SIZWG meeting was held at the University of Georgia (UGA). This meeting included a Neotoma data input workshop with Eric Grimm, which also allowed for some discussion of needs and flexibility. By 2017, it became possible to input data into Tilia in beta form, and the first dataset was entered. In 2018, Pilaar Birch's lab group, consisting of coauthor Veres and three undergraduate research assistants at UGA, compiled approximately two hundred peer reviewed journal articles, all papers containing stable isotope data related to archaeological research in North America. In 2020, a virtual workshop on data entry was attended by over sixty participants. As of 2021, thirty-five sites have been entered and uploaded (Figure 10.1).

Prior to the addition of the stable isotope data infrastructure, only presence/absence, MNI, or NISP of faunal taxa by stratigraphic context at the site level was available, which did not provide a high enough level of detail for use of the database by zooarchaeologists. Now, the user can input skeletal element, side, and portion information for each specimen, facilitating interpretation of stable isotope data and aiding in the development of a forthcoming taphonomy database. The current iteration of Tilia allows for

Figure 10.1. Data points representing faunal stable isotope datasets entered into Tilia and Neotoma as part of the Faunal Isotope Database. Some points represent multiple sites in close proximity and become visible when zoomed in on a given area. Map is from the Neotoma Paleoecology Database, Faunal Isotopes Database. CC BY 4.0. https://www.neotomadb.org/.

the input of data and metadata for $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, δD (δ^2H), $\delta^{34}S$, and $^{87}Sr/^{86}Sr$ stable isotopes from bulk collected samples. The ability to create files with serially sampled isotope values, such as those from teeth and shell, is in development at the time of writing.

Data Entry Process

Tilia (tiliaIT.com) is a custom data entry program that works in tandem with the Neotoma database. This software was originally designed to manage stratigraphically organized paleoenvironmental proxy data, specifically pollen. The current iteration allows for counts of pollen, diatom, ostracod, and faunal taxa to be assigned to stratigraphic layers with an associated chronological description. Specimen-level data can then be entered for each faunal taxon, including stable isotope values.

Data entry is segregated by data and metadata types. Metadata include information regarding the site, collection unit, chronologies, and isotopes to be entered. This is also where the individual entering the data can associate it with the relevant publications and authors. Depending on the section, some data is manually entered, while others default to drop-down menus with a list of terms.

The order in which data is entered in Tilia matters, because some data tables require prior data to be in place. For example, the individual specimen-level data, such as skeletal element and isotopic value, cannot be entered until the taxon and stratigraphic affiliation are present, as in Figure 10.2. Additional data, including stable isotope data, can then be entered by navigating to the metadata tab (Figure 10.3).

Under the metadata tab shown in Figure 10.2, there is a "site" tab (see Figure 10.3), which includes information on the common name for the site, governmental or archaeological designations, and latitude and longitude. As a feature, the Tilia interface shows the pin within Google Maps, and also allows the option of making points "fuzzy" by randomly moving the point within a minimum distance of 1 km and a maximum distance of 5 km, given the potential sensitivity of revealing exact site locations. From drop-down menus, users can select the country, state, county, and administrative units, and can enter altitude, area of the site in hectares, a brief site description, and any additional site notes.

The "collection unit" tab (far left tab, Figure 10.3) provides more specific information about the site. This can be as broad as an assemblage or a particular unit at the site. You can note the depositional environment from a drop-down menu that includes "archaeological," "biological," "fluvial,"

Code	Name	Element	Units	Context	Group	Layer 11	Layer 13	Layer 14.1	Layer 14.2	Layer 14.3	Layer 16.1	Layer 16.2	Layer 18	Base
#Chron1...	Layer 11 Younger					6409								
#Chron1...	Layer 11 Older					6538								
#Chron2...	Layer 13 Younger						1823							
#Chron2...	Layer 13 Older						1931							
#Chron3...	Layer 14.1 Younger							3211						
#Chron3...	Layer 14.1 Older							3364						
#Chron4...	Layer 14.2 Younger								6645					
#Chron4...	Layer 14.2 Older								6787					
#Chron5...	Layer 14.3 Younger									6799				
#Chron5...	Layer 14.3 Older									6976				
#Chron6...	Layer 16.1 Younger										7422			
#Chron6...	Layer 16.1 Older										8773			
#Chron7...	Layer 16.2 Younger											8774		
#Chron7...	Layer 16.2 Older											8998		
#Chron8...	Layer 18 Younger												9549	
#Chron8...	Layer 18 Older												9680	
#Chron9...	Base Younger													9917
	Base Older													10177
Tho.ta	Thomomys talpoides	mandible	present/...		RODE	1	1	1	1	1	1	1	1	1
Bra.id	Brachylagus idahoensis	mandible	present/...		LAGO	1	1	1	1	1	1	1	1	1
Sprto	Spermophilus townsendii	mandible	present/...		RODE		1			1				

Figure 10.2. Data entry screen in Tilia showing chronological boundaries of stratigraphic layers, taxon name, skeletal element, defined unit (in this case, presence/absence), and presence in respective layers. Neotoma Paleoecology Database, Faunal Isotopes Database. Data is from Commendador and Finney (2016). CC BY 4.0. https://www.neotomadb.org/.

	Depth	Unit	Taxon	Element	Spec ID	δ13C	SD	Scale	Reps	C:N Ratio	Material	Substrate	Pretreatme	Analyst	Lab	Lab Nr	Mass (mg)	Weight %	Atomic %	δ15N	SD	Scale
1		Layer 11	Thomomys talpoides	mandible	3359.PG.1	-19		VPDB		3.3	bone	collagen								7.2		Air N
2		Layer 11	Thomomys talpoides	mandible	3359.PG.2	-18		VPDB			bone	collagen								8.5		Air N
3		Layer 11	Thomomys talpoides	mandible	3502.PG.1	-21.4		VPDB		3.4	bone	collagen								6.6		Air N
4		Layer 11	Thomomys talpoides	mandible	3565.PG.1	-21.4		VPDB		3.3	bone	collagen								8.2		Air N
5		Layer 11	Thomomys talpoides	mandible	3865.PG.1	-21.3		VPDB		3.3	bone	collagen								8.1		Air N
6		Layer 11	Thomomys talpoides	mandible	3419.PG.1	-21.7		VPDB		3.3	bone	collagen								8.1		Air N
7		Layer 11	Thomomys talpoides	mandible	3419.PG.2	-21.1		VPDB		3.2	bone	collagen								7.8		Air N
8		Layer 11	Thomomys talpoides	mandible	3505.PG.1	-19.5		VPDB		3.3	bone	collagen								6		Air N
9		Layer 11	Thomomys talpoides	mandible	3552.PG.1	-17.9		VPDB		3.3	bone	collagen								8.7		Air N
10		Layer 11	Brachylagus idahoensis	mandible	3359.PR.1	-21.9		VPDB		3.4	bone	collagen								6.8		Air N
11		Layer 11	Brachylagus idahoensis	mandible	3359.PR.2	-19.4		VPDB		3.4	bone	collagen								8.5		Air N
12		Layer 11	Brachylagus idahoensis	mandible	3359.PR.3	-21.2		VPDB		3.4	bone	collagen								6.6		Air N
13		Layer 11	Brachylagus idahoensis	mandible	3565.PR.1	-20.7		VPDB		3.3	bone	collagen								7.5		Air N
14		Layer 11	Brachylagus idahoensis	mandible	3565.PR.2	-21.2		VPDB		3.4	bone	collagen								5.5		Air N
15		Layer 11	Brachylagus idahoensis	mandible	3565.PR.3	-19.8		VPDB		3.4	bone	collagen								8.2		Air N
16		Layer 11	Brachylagus idahoensis	mandible	3419.PR.1	-20.2		VPDB		3.4	bone	collagen								6.2		Air N
17		Layer 11	Brachylagus idahoensis	mandible	3419.PR.2	-20		VPDB		3.5	bone	collagen								10.2		Air N
18		Layer 11	Brachylagus idahoensis	mandible	3505.PR.1	-21.8		VPDB		3.3	bone	collagen								7.5		Air N
19		Layer 11	Brachylagus idahoensis	mandible	3552.PR.1	-22.1		VPDB		3.3	bone	collagen								7.9		Air N
20		Layer 13	Thomomys talpoides	mandible	3515.PG.1	-19.5		VPDB		3.4	bone	collagen								10.5		Air N
21		Layer 13	Thomomys talpoides	mandible	3515.PG.2	-22.3		VPDB		3.3	bone	collagen								7.1		Air N
22		Layer 13	Thomomys talpoides	mandible	TT13-1	-21.1		VPDB		3.3	bone	collagen								6.8		Air N
23		Layer 13	Thomomys talpoides	mandible	TT13-2	-20.4		VPDB		3.6	bone	collagen								7.7		Air N
24		Layer 13	Thomomys talpoides	mandible	TT13-4	-22.1		VPDB		3.4	bone	collagen								7		Air N
25		Layer 13	Thomomys talpoides	mandible	TT13-5	-14.1		VPDB		3.3	bone	collagen								8.3		Air N
26		Layer 13	Thomomys talpoides	mandible	TT13-6	-20.6		VPDB		3.4	bone	collagen								8.7		Air N

Figure 10.3. Metadata tab in Tilia showing the "Isotopes" tab, where specimen-level stable isotope data is entered for $\delta^{13}C$ and $\delta^{15}N$. Neotoma Paleoecology Database, Faunal Isotopes Database. Data is from Commendador and Finney (2016). CC BY 4.0. https://www.neotomadb.org/.

"estuarine," etc. Within each of the broad categories, more specific options are often available. For example, under "archaeological" you can select "burial," "midden," or "mound," among others. Because data uploaded into Neotoma must have an associated publication, the metadata also includes entry of researcher contact information and publication citations (far right tabs, Figure 10.3). Any work from which data has been derived should be added, as well as contact information for the authors. Roles such as "faunal analyst" or "isotope analyst" can be defined.

The example data in Figure 10.2 presented each taxon found at the site, with its presence/absence noted for each stratigraphic layer. While this could also be presented as NISP or MNI, the lack of specimen-level information means, ultimately, that this resolution is not sufficient for the input of stable isotope data. Thus, after entering either presence/absence or counts on the data tab, the user must navigate to enter additional metadata.

To enter specimen-level data regarding sampled individuals, the user must click on the appropriate cell for the desired taxon and stratigraphic unit in order to access a new table (in Figure 10.2, these are shown as pink cells). The taxon is selected from a drop-down menu, which can be amended if necessary. This is particularly useful if the taxon on the data tab is listed only at the genus level, but species-level identification is only possible for some specimens and not for others. Across the row, the user then selects the types of units (MNI, NISP, or individual specimen). When describing the skeletal element, one can select specific terms (such as "mandible" or "femur"), but broader terms such as bone, tooth, or skeleton may also be chosen if necessary. This is an important distinction for those who may be entering legacy data where the desired level of detail may not be available, in contrast to an investigator entering their own data. Next, the context can be selected from another drop-down menu, with options like "articulated," "burial," "midden," or "mound." Other categories that can be filled for each individual specimen include: a unique specimen ID, symmetry, portion, maturity, sex, and physical repository, among others. Most of these options are drop-down menus for ease of entry and consistency within the databases. This allows for as much detailed information about the individual samples as possible to be associated with the unique ID, yet retains flexibility by allowing blank spaces in cases in which the data is unknown.

Once specimen-level data is entered, the unique IDs and accompanying data can be imported to the "isotopes" tab, as shown in Figure 10.3. The user can check $\delta^{13}C$, $\delta^{15}N$, $\delta^{18}O$, δD (δ^2H), $\delta^{34}S$, and $^{87}Sr/^{86}Sr$ at the

top of the sheet in order to add columns for each stable isotope type. Both bulk and serially sampled isotope values can be entered for each specimen. Two critical categories include "material" and "substrate." Material refers to the physical specimen, and can be entered as "bone," "tooth," or "hair," for example, while substrate refers to the compound that is being sampled: "collagen," "bioapatite," or "keratin." Other data categories include instrumentation, pretreatment chemicals and concentrations, lab ID numbers, International Standard used during IRMS analysis (that is, VPDB, AIR), sample mass, weight %, repetitions and standard deviations, and C:N ratio.

While stratigraphic layer information is defined in the initial tab, the chronology that each stratigraphy is tied to must also be specified. Within the metadata, there is a "chronologies" tab. Here, it is possible to enter dates for each sampled context, matching the columns that were entered with the individual specimens on the primary data tab. Users can also note the preparers, the associated publication, age unit, age model, and older bound and younger bound for the chronology used. Within each chronology, an age basis can be selected from a drop-down menu, including historical documentation or North American archaeological time scale, the calibration curve, and calibration program used. These selections can be imported back to the main data tab in order to associate dates with each context, so that even if specimens included in the study have not been directly dated, they are tied to a chronological time scale.

Once data entry is complete, the user can submit the data to be uploaded to the database, which is completed by a data steward. The Tilia program automatically runs a validation that checks the file for all required and recommended entries before uploading it to the selected Neotoma constituent database (in this case, the Faunal Isotope Database). The new data point becomes searchable through the online Neotoma Explorer function and will be visible on the map (Figure 10.1).

Use Cases and Applications

Multiple Sites and Data Types

The online Neotoma Explorer interface allows for searches within a wide range of potential variables and offers an interactive map. Through the advanced search, it is possible to query by taxon, age range, depositional setting, database, site name, or researcher name. When a search is run, dots will appear on the map indicating sites that meet the set parameters.
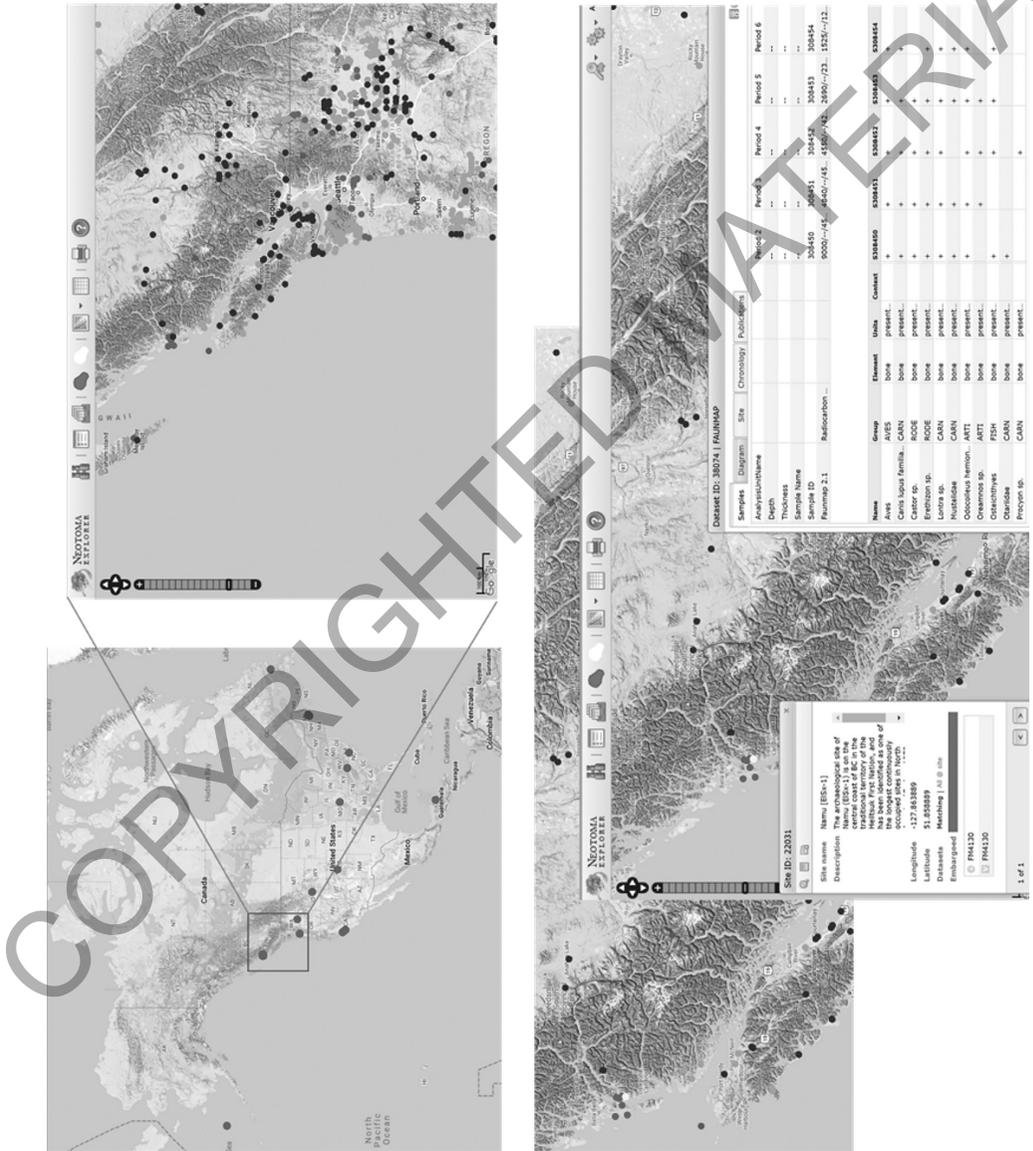
Figure 10.4. Sites with paleoenvironmental data, including stable isotope data for the Pacific Northwest, and display tables. Neotoma Paleoecology Database, Faunal Isotopes Database. Data is from Commendador and Finney (2016). CC BY 4.0. https://www.neotomadb.org/.

Multiple searches can be run, and each search will appear as a uniquely colored set of dots. In Figure 10.1, the dots (colored red in the program) have been returned by searching for the "Faunal Isotope Database" through the advanced search.

The top panel of Figure 10.4 shows sites that have been entered into the Faunal Isotope Database in the Pacific Northwest, specifically coastal British Columbia and Washington (shown in red in the program), alongside sites with pollen (green), plant macrofossil (maroon), and faunal remains (blue). This demonstrates the potential of integrating multiple different kinds of macroscopic and microscopic paleoenvironmental proxy data with the stable isotope proxy data at the regional scale, especially as additional datasets are added through time. Depending on the focus of research, this functionality allows users to assess the availability of data and possible sites of interest for future sampling.

The lower panel of Figure 10.4 shows five mainland sites with faunal stable isotope data located north of Vancouver Island, British Columbia. The site of Namu (shown in yellow in the program) has been selected and site location, name, and additional details are displayed. Associated tables that are connected with the site display the radiocarbon date chronology and vertebrate faunal data at the presence/absence level. In this case, though there are multiple vertebrate data records at Namu, all faunal isotope data are derived from the mollusk *Saxidomus giganteus,* the butter clam, found in several surrounding area shell middens, providing marine $\delta^{18}O$ values that can be interpreted as reflecting sea surface temperatures (SST; bulk values) as well as seasonal fluctuations (serial samples) relevant to Namu (see Burchell et al. 2013). Possible opportunities for expansion of research in this region relevant to the database are either the addition of vertebrate faunal datasets from surrounding sites with accompanying stable isotope data, stable isotope values for vertebrate fauna from Namu, or additional molluscan stable isotope data. These data can easily be compared and cross-referenced to address questions regarding changes in SST through time or along a transect, or evaluate differences between marine and terrestrial proxy reconstructions.

Single Species Stable Isotopes

Researchers may also be interested in species-level variation in stable isotope values that may be related to regional distributions and available food sources. While the number of sites with faunal stable isotope data is limited

Table 10.1. List of sites with stable isotope values for dogs, *Canis lupus familiaris,* in the Faunal Isotope Database

Site ID	Site Name	Lat.	Long.	Dataset ID	Age Oldest	Age Youngest
24231	Port au Choix Site [EeBi-2]	50.70	-57.35	42640	4720	3950
23802	Cathlapotle [41CL1]	45.83	-122.74	41239		
24592	Josey Farm Site [22OK793]	33.48	-88.85	43298		
25894	22OK904	33.49	-88.84	44726		
3653	Turner Farm [29.9]	44.14	-68.84	42642	4500	3800
24239	Nevin [40.1]	44.37	-68.55	42666	4500	3800
23764	Yerba Buena Island [CA-SFR-4/H]	37.81	-122.36	41144	685	430
23774	Kaphan Umux (Three Wolves) Site [CA-SCL-732]	37.24	-121.77	41168	685	180

at the time of this writing, there is potential to use this much insofar as the vertebrate faunal data stored in FaunMap and the pollen data in the NAPD are used for understanding past species distributions, ranges, and change through time to evaluate species-level "isoscapes" and how these may have changed on regional and continental scales in response to vegetation and climate shifts. Herbivore taxa would be preferred for this type of analysis, but for the sake of sample size in this example, we present data for omnivores—dogs—as an example. Using the advanced search functionality, it is possible to select a taxon (*Canis lupus familiaris*) and then select the "Faunal Isotope Database" to narrow the search. Map view makes it possible to visualize site distribution, while the user can also export a data table with a list of sites. In this instance, there are eight sites with stable isotope values from dog remains currently available (Table 10.1). The search returns site names, location in latitude and longitude, and date ranges. With additional sites, this feature has the potential to be a robust way to evaluate trends within taxa across space and time, as well as identify gaps in the research record. Although the search table does not return information such as number of records, the user can navigate to each site using Neotoma Explorer to evaluate individual dataset quality.

Discussion

The Faunal Isotope Database represents part of the beginning of a larger movement to make stable isotope data more accessible, promoting large-scale data analysis, data re-use, and collaborative publication. Zooarchaeology is at a watershed moment when it comes to "big data," with discussion on synthesis and re-use (Open Context; Lau and Kansa 2018), digitization and databases (ZooArchNet; LeFebvre et al. 2019), and best practices (Kansa et al. 2019).

Though the current iteration of the Faunal Isotope Database represents over three years of development and implementation, it should still be considered as being in the early stages of development and growth. Its success as a platform for data sharing and synthesis depends on the continued efforts of legacy data entry alongside new data added by PIs as they are generated. Neotoma is an open access database, but allows data embargoes to exist prior to publication. It also provides DOIs for datasets, providing a recognized and stable mechanism for data citation, which in turn can be seen as an incentive for data sharing (see also Marwick and Pilaar Birch 2018 and references therein). As funding agencies increasingly require primary data publication alongside articles, accessible and stable data archiving is becoming standard across disciplines. In an ideal workflow, data generators would enter their faunal and stable isotope data under an embargo during the analysis stage, and the data would be released upon publication of an accompanying article.

As the Faunal Isotope Database continues to grow, it is important to consider the legacy of the vertebrate faunal database FaunMap, with over 4,400 sites and 6,800 datasets entered (Graham 1994). It continues to be an active database, and the entry of primary zooarchaeological and paleontological data prior to the entry of derived data based on that material, such as stable isotope values, is essential to retain the integrity of the data record. For example, a faunal analyst may have identified 1,000 specimens from a given site, but may have only carried out stable isotope analysis on 10% of the bones, producing 100 possible entries for the Faunal Isotope Database. Though it may be tempting to simply enter specimen-level data for the 100 specimens of use for the FID, we recommend a comprehensive approach, first entering specimen-level data for the entire faunal dataset and then adding the stable isotope data for the sampled specimens. This may be difficult or impossible for legacy datasets where the stable isotope data is published separately from the faunal data, or in unfortunate cases,

in which isotope analysis was carried out without previous zooarchaeological analysis. By ensuring that the data entry process is as thorough as possible at first pass, this improves the quality of data synthesis and cross-referencing, helps to avoid data duplication, and increases the ease of future use and expansion of the dataset. For example, if further isotope analysis is done, an existing dataset can be modified and supplemented, instead of piecemeal additions made by the user. If the capacity to enter taphonomic or measurement data is developed, either within the structure of Neotoma or externally, having the complete specimen-level faunal data available at the site level will allow for the addition of those derived data and for the possible linking and export of relevant data to other databases. It also helps to identify "real" gaps in research as opposed to perceived or erroneous gaps due to extant data that has not been entered into the database.

Conclusions

Interdisciplinary collaboration and access to large, multiproxy datasets are important for addressing a range of research questions targeting global climate and environmental change. Pulling these data together into a central location by using the Neotoma Paleoecology Database (www.neotomadb.org) provides an unparalleled opportunity for knowledge creation and the ability to assess trends across a variety of spatial and temporal scales. The new functionality of storing and serving specimen-level stable isotope data through the Faunal Isotope Database will support large-scale syntheses and further advances in this area of research, but its success ultimately depends on adoption by members of the zooarchaeological, paleontological, and biogeochemical research communities at the intersection of these fields.

References

Burchell, Meghan, Aubrey Cannon, Nadine Hallmann, Henry P. Schwarcz, and Bernd R. Schöne
2013 Inter-site Variability in the Season of Shellfish Collection on the Central Coast of British Columbia. *Journal of Archaeological Science* 40(1):626–36.
Commendador, Amy S., and Bruce P. Finney
2016 Holocene Environmental Change in the Eastern Snake River Plain of Idaho, USA, as Inferred from Stable Isotope Analyses of Small Mammals. *Quaternary Research* 85(03):358–70.
Cormie, A. B., B. Luz, and H. P. Schwarcz
1994 Relationship between the Hydrogen and Oxygen Isotopes of Deer Bone and

Their Use in the Estimation of Relative Humidity. *Geochimica et Cosmochimica Acta* 58(16):3439–49.

Gil, Adolfo F., Andrew Ugan, Clara Otaola, Gustavo Neme, Miguel Giardina, and Lumila Menéndez

2016   Variation in Camelid δ¹³C and δ¹⁵N Values in Relation to Geography and Climate: Holocene Patterns and Archaeological Implications in Central Western Argentina. *Journal of Archaeological Science* 66:7–20.

Graham, Russell W.

1994   *FAUNMAP: A Database Documenting Late Quaternary Distributions of Mammal Species in the United States.* Vol. 25. Illinois State Museum, Springfield.

Kansa, Sarah W., Levent Atici, Eric C. Kansa, and Richard H. Meadow

2019   Archaeological Analysis in the Information Age: Guidelines for Maximizing the Reach, Comprehensiveness, and Longevity of Data. *Advances in Archaeological Practice* 8(1):40–52.

Lau, Hannah, and Sarah Whitcher Kansa

2018   Zooarchaeology in the Era of Big Data: Contending with Interanalyst Variation and Best Practices for Contextualizing Data for Informed Reuse. *Journal of Archaeological Science* 95:33–39.

LeFebvre, Michelle J., Laura Brenskelle, John Wieczorek, Sarah Whitcher Kansa, Eric C. Kansa, Neill J. Wallis, Jessica N. King, Kitty F. Emery, and Robert Guralnick

2019   ZooArchNet: Connecting Zooarchaeological Specimens to the Biodiversity and Archaeology Data Networks. *PLOS ONE* 14(4):e0215369.

Makarewicz, Cheryl A., and Judith Sealy

2015   Dietary Reconstruction, Mobility, and the Analysis of Ancient Skeletal Tissues: Expanding the Prospects of Stable Isotope Research in Archaeology. *Journal of Archaeological Science* 56:146–58.

Marwick, Ben, and Suzanne E. Pilaar Birch

2018   A Standard for the Scholarly Citation of Archaeological Data as an Incentive to Data Sharing. *Advances in Archaeological Practice* 6(2):125–43.

Pauli, Jonathan N., Seth D. Newsome, Joseph A. Cook, Chris Harrod, Shawn A. Steffan, Christopher J. O. Baker, Merav Ben-David, David Bloom, Gabriel J. Bowen, Thure E. Cerling, Carla Cicero, Craig Cook, Michelle Dohm, Prarthana S. Dharampal, Gary Graves, Robert Gropp, Keith A. Hobson, Chris Jordan, Bruce MacFadden, Suzanne Pilaar Birch, Jorrit Poelen, Sujeevan Ratnasingham, Laura Russell, Craig A. Stricker, Mark D. Uhen, Christopher T. Yarnes, and Brian Hayden

2017   Opinion: Why We Need a Centralized Repository for Isotopic Data. *Proceedings of the National Academy of Sciences* 114(12):2997–3001.

Pauli, Jonathan N., Shawn A. Steffan, and Seth D. Newsome

2015a   It Is Time for IsoBank. *BioScience* 65(3):229–30.

2015b   Response to Pilaar Birch and Graham. *BioScience* 65(10):953–54.

Pilaar Birch, Suzanne E.

2013   Stable Isotopes in Zooarchaeology: An Introduction. *Archaeological and Anthropological Sciences* 5(2):81–83.

Pilaar Birch, Suzanne E., and Russell W. Graham

2015   A Stable Isotope Data Repository as Part of Neotoma, a Paleoecological Database. *BioScience* 65(10):953.

Rivera-Araya, Maria, and Suzanne Pilaar Birch

2018   Stable Isotope Signatures in White-Tailed Deer as a Seasonal Paleoenvironmental Proxy: A Case Study from Georgia, United States. *Palaeogeography, Palaeoclimatology, Palaeoecology* 505:53–62.

Salesse, Kevin, Ricardo Fernandes, Xavier de Rochefort, Jaroslav Brůžek, Dominique Castex, and Elise Dufour

2018   IsoArcH.eu: An Open-Access and Collaborative Isotope Database for Bioarchaeological Samples from the Graeco-Roman World and Its Margins. *Journal of Archaeological Science: Reports* 19:1050–55.

Still, Christopher J., and Rebecca L. Powell

2010   Continental-Scale Distributions of Vegetation Stable Carbon Isotope Ratios. In *Isoscapes: Understanding Movement, Pattern, and Process on Earth through Isotope Mapping,* edited by Jason B. West, Gabriel J. Bowen, Todd E. Dawson, and Kevin P. Tu, pp. 179–93. Springer Netherlands, Dordrecht.

West, Jason B., Adam Sobek, and James R. Ehleringer

2008   A Simplified GIS Approach to Modeling Global Leaf Water Isoscapes. *PLOS ONE* 3(6):e2447.

Williams, John W., Eric C. Grimm, Jessica L. Blois, Donald F. Charles, Edward B. Davis, Simon J. Goring, Russell W. Graham, Alison J. Smith, Michael Anderson, Joaquin Arroyo-Cabrales, Allan C. Ashworth, Julio L. Betancourt, Brian W. Bills, Robert K. Booth, Philip I. Buckland, B. Brandon Curry, Thomas Giesecke, Stephen T. Jackson, Claudio Latorre, Jonathan Nichols, Timshel Purdum, Robert E. Roth, Michael Stryker, and Hikaru Takahara

2018   The Neotoma Paleoecology Database, a Multiproxy, International, Community-Curated Data Resource. *Quaternary Research* 89(1):156–77.

Zangrando, A. F., A. Tessone, A. Ugan, and M. A. Gutiérrez

2014   Applications of Stable Isotope Analysis in Zooarchaeology: An Introduction. *International Journal of Osteoarchaeology* 24(2):127–33.