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Emerging strontium isoscapes of Anatolia (Türkiye): new datasets and perspectives in bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ baseline studies

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Introduction: The use of strontium isotope ratio ($^{87}\text{Sr}/^{86}\text{Sr}$) analysis in ancient mobility studies in the archaeology of Anatolia (modern Türkiye) has steadily grown since the early 2010s. However, a coherent map of the isotopic variability of bioavailable Sr (isoscape) does not exist for the region and the paucity of baseline data that is necessary for the interpretation of archaeological data significantly constrains the heuristic power of this methodology in Anatolian archaeology. Baseline and “local range” determination in previous studies have relied on geology maps or various sample types from very limited areas in site-centered mobility studies, and the use of predictive modeling for isoscape reconstruction at regional scales has just begun in Türkiye.

Methods: In this study, we discuss current methodologies in Sr isoscape reconstruction including the recent open-access R-script and global database developed for modeling bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ isoscapes and we present a review of extant $^{87}\text{Sr}/^{86}\text{Sr}$ analyses and baseline studies in Anatolian archaeology. We combine all published baseline $^{87}\text{Sr}/^{86}\text{Sr}$ data from Türkiye with our unpublished $^{87}\text{Sr}/^{86}\text{Sr}$ data from proxy samples (plants and snail shells) from central Anatolia, and by incorporating this data ($n = 688$) into the global database (where data from Türkiye is currently lacking), we create a modeled $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape of Türkiye utilizing the R-script and we calculate the predicted standard error for this isoscape.

Results and discussion: This study demonstrates how additional empirical data serves to improve the Türkiye section of the global model using kriging and random forest regression (RFR) techniques and it discusses how the uneven distribution of data impacts the resultant isoscape map. In closing, we comment on beneficial avenues for mobility studies in under-researched periods and regions in Anatolia.

KEYWORDS

$^{87}\text{Sr}/^{86}\text{Sr}$ analysis, bioavailable strontium isotopes, isoscapes, mobility, random forest regression (RFR), kriging, Anatolia, Türkiye

1 Introduction

Following a few decades of theoretical debate and skepticism on archaeology’s disciplinary capability for documenting migrations in the ancient past, we are now equipped with high-precision toolsets, including aDNA, strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) and multiple stable isotope ratio analysis, that allow for a nuanced understanding of individual

life histories and sociohistorical entanglements (Müller et al., 2025). However, as Britton et al. (2022) herald in “A golden age for strontium isotope research?”, although the use of Sr isotope ratio analyses in archaeological research has increased exponentially in recent years, advances in our understanding of Sr cycling has also led to new methodological concerns. Boosted by the rapid growth of open-access, regional, and global isotopic databases in the last few years, meta-analysis has also emerged as a recent trend in the field. While meta-analyses are inarguably valuable, inferences based on pan-regional data compilations may be problematic due to different baseline determination methods employed in individual studies and statistical methods selected for the determination of non-local individuals (e.g., Leppard et al., 2020; cf. Perry et al., 2022). Our current understanding of bioavailable Sr isoscapes urges us to continue to improve our methodological toolkits and to develop nuanced interpretative frameworks beyond the concept of “local range” and the “local/non-local” binary adopted in the interpretation of archaeological human data in earlier studies. In archaeological mobility studies, the key to accurate interpretation of $^{87}\text{Sr}/^{86}\text{Sr}$ data from bioarchaeological samples is the establishment of a robust environmental baseline of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ in the research region. Accordingly, the primary objective of this study is to contribute to the field a ground-truthed baseline map of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ isoscapes in Türkiye (ancient Anatolia) derived from various biological substrates and utilizing the R-script developed for a global model by Bataille et al. (2020). Toward this goal, we combined the authors’ unpublished baseline data from central Anatolia with all available $^{87}\text{Sr}/^{86}\text{Sr}$ data from archaeological research projects conducted to date in Türkiye (Table 1, Supplementary material 2), and we integrated this data in the computation of a modeled $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape for Anatolia. In doing so, not only do we demonstrate a methodological approach that enhances the power and utility of current methods for isoscape modeling, but we also bring Sr isotope ratio analysis and mobility studies in Anatolian archaeology into dialogue with the new advances in the field. After evaluating our resultant isoscape map for the region, in our concluding discussion, we highlight significant episodes of human mobility in the archaeological (and textual) record of ancient Anatolia, which would benefit from further isotopic analyses.

2 Principles of strontium isotope ratio analysis

2.1 Bedrock geology and strontium isotopes in the geosphere

Strontium is a heavy alkaline earth metal with four naturally occurring isotopes: ^{84}Sr (~0.56%), ^{86}Sr (~9.87%), ^{87}Sr (~7.04%) and ^{88}Sr (~82.53%). While three of these isotopes are stable, strontium-87 (^{87}Sr) is radiogenic and is produced by the radioactive

decay of rubidium-87 (^{87}Rb) with a half-life of $\sim 4.88 \times 10^{10}$ years (Bentley, 2006). Due to this process, the abundance of ^{87}Sr in the geosphere is gradually increasing through time, thus altering the ratio of ^{87}Sr to the stable isotopes of strontium. The isotopic evolution of strontium in the geosphere began about $4.5 \pm 0.1 \times 10$ (four and a half billion) years ago with a primordial $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of about 0.699 (Faure, 1986). The isotopic composition of strontium in a rock or mineral that contains rubidium is dependent on the age and the initial Rb/Sr ratio of that rock or mineral, and the utility of the isotopic variation of Sr for age determination of bedrock and provenance of minerals and sediments has long been recognized in geology (Nebel et al., 2011). Because of the utility of Rb-Sr decay systems in the estimation of geological age, the variation of Sr concentrations and Rb/Sr ratios in rock types are well studied in many parts of the world (Capo et al., 1998). As a corollary, Sr isotope ratios of geological formations have also been extensively studied, expressed using the ratio of ^{87}Sr relative to ^{86}Sr corrected for any mass-dependent fractionation by normalization to a fixed $^{86}\text{Sr}/^{88}\text{Sr}$ (0.1194) (Bataille et al., 2020). Accordingly, as a general principle, older bedrock typically has a higher $^{87}\text{Sr}/^{86}\text{Sr}$. Very old rocks (>100 Ma) with original high Rb/Sr have higher $^{87}\text{Sr}/^{86}\text{Sr}$ (>0.710), while recently formed rocks (<1–10 Ma) with low Rb/Sr ratios have lower $^{87}\text{Sr}/^{86}\text{Sr}$ (<0.706) (Bentley, 2006). Rocks enriched in alkali metals, alumina, and silica (e.g., clay and shale), which are the oldest rocks on the Earth’s crust, have high initial Rb/Sr and tend to have high $^{87}\text{Sr}/^{86}\text{Sr}$, as well. Likewise, certain granitic rocks with high initial Rb/Sr, which were formed very early during our planet’s formation have high $^{87}\text{Sr}/^{86}\text{Sr}$, although the isotopic ratios of igneous granites may be highly variable. Oceans have a homogenous $^{87}\text{Sr}/^{86}\text{Sr}$ (0.7092) at present, which has varied between ~0.707–0.709 over geological time (McArthur et al., 2001). Carbonates, which have precipitated from seawater, reflect the seawater $^{87}\text{Sr}/^{86}\text{Sr}$ at the time of their formation and approximate the ocean water $^{87}\text{Sr}/^{86}\text{Sr}$ (Farkaš et al., 2025).

A geological map of bedrock types in a region can be used as a preliminary guide to produce a coarse map of expected $^{87}\text{Sr}/^{86}\text{Sr}$ of the basement rock, but the $^{87}\text{Sr}/^{86}\text{Sr}$ in bedrock is rarely the same as the $^{87}\text{Sr}/^{86}\text{Sr}$ in topsoil (Maurer et al., 2012; Bataille et al., 2020). Besides geological age and the initial Rb/Sr, a variety of geological processes related to igneous activity, metamorphism, weathering, and sedimentation play a significant role on the transfer of Sr from the Earth’s crust to the surface (White, 2023). These factors influence the isotopic ratios of geological formations and cause their $^{87}\text{Sr}/^{86}\text{Sr}$ to be significantly different than the expected ratios based on Rb-decay. For example, as a general principle, the $^{87}\text{Sr}/^{86}\text{Sr}$ of basalts, which are young volcanic rocks with very low Rb/Sr, can go as low as 0.702; however, because the basaltic magmas thrust out onto the surface may interact extensively with old sialic rocks, volcanic rocks may exhibit very high $^{87}\text{Sr}/^{86}\text{Sr}$ (Köksal et al., 2004). Research on various volcanic regions around the world has shown that the chemical and isotopic compositions of igneous rocks differ greatly in oceanic vs. continental regions, reflecting a unique set of circumstances and processes (e.g., multiple eruptions in stratovolcanoes, contamination by old sialic rocks, and blending of magmas) in each volcanic province (Prytulak and König, 2025).

Abbreviations: PPNA, Pre-Pottery Neolithic A (10000–8800 BCE); PPNB, Pre-Pottery Neolithic B (8800–6500 BCE); EBA, Early Bronze Age (3rd millennium BCE); MBA, Middle Bronze Age (early 2nd millennium BCE); LBA, Late Bronze Age (late 2nd millennium BCE); EIA, Early Iron Age (ca. 1200–900 BCE); MIA, Middle Iron Age (9th–6th centuries BCE).

TABLE 1 Summary of bioarchaeological strontium isotope ratio ($^{87}\text{Sr}/^{86}\text{Sr}$) studies conducted to date in Türkiye.

Archaeological site and research region	Bibliographic references	Archaeological period and research question
A. Published research		
Körtik Tepe and Diyarbakır region	Benz et al., 2016a,b	PPNA (Younger Dryas/Early Holocene) human mobility
Göbekli Tepe and Nevalı Çori	Lang et al., 2013; Wang et al., 2023	PPNA gazelle mobility and PPNA-PPNB human mobility patterns
Gritille and Adıyaman/Urfa region	Meiggs, 2009	PPNB herding practices; south-eastern Anatolia isoscapes
Pınarbaşı, Boncuklu, Çatalhöyük	Pearson et al., 2023	Pre-Pottery and Early Neolithic human mobility and kinship
Çatalhöyük and Konya Plain	Bogaard et al., 2014; Larsen et al., 2019 (review article)	Early Neolithic land management (herding and agriculture)
Domuztepe	Lau, 2016; Lau et al., 2021	Late Neolithic (Halaf) herding practices
Köşk Höyük and south-central Anatolia	Meiggs et al., 2018	Chalcolithic herding practices; south-central Anatolia isoscapes
İkiztepe and central Black Sea region	Welton, 2010, 2015	Early Bronze Age human mobility; Black Sea region baseline
Tell Atchana/ <i>Alalakh</i> and Amuq Plain	Meiggs, 2011	Middle Bronze Age and Late Bronze Age herding practices
Tell Atchana/ <i>Alalakh</i> and Amuq Plain	Ingman, 2020; Ingman et al., 2021	Middle Bronze Age and Late Bronze Age human mobility
Kültepe/ <i>Kanesh</i> and central Anatolia	Yazıcıoğlu Santamaria, 2015; Yazıcıoğlu Santamaria, 2017	Middle Bronze Age human mobility; Central Anatolia isoscapes
Ortaköy/ <i>Shapinuwa</i> and north-central Anatolia	Pişkin et al., 2023	Late Bronze Age (Hittite) land management and herding practices
Uluburun shipwreck and Antalya forests	Rich et al., 2015, 2016	Late Bronze Age timber provenance; Mediterranean forest isoscapes
Hierapolis and south-western Anatolia	Wong et al., 2017, 2018, 2021	Roman/Byzantine human mobility; south-western Anatolia isoscapes
Hierapolis and Ephesos	Wong et al., 2019	Roman/Byzantine human mobility
Sagalassos	Degryse et al., 2006	Byzantine glass provenance/recycling
Sagalassos and Lakes District	Dufour et al., 2007	Byzantine fish provenance and aquatic resource management
Review of $^{87}\text{Sr}/^{86}\text{Sr}$ analyses in Türkiye	Irvine and Özdemir, 2020; Yazıcıoğlu and Irvine, 2025	Sr isotope ratio ($^{87}\text{Sr}/^{86}\text{Sr}$) analysis research history in Türkiye
Archaeological site and research region	Research group	Archaeological period and research question
B. Ongoing research projects		
Başur Höyük	S. Pilaar Birch, Brenna Hassett	Early Bronze Age human mobility; joint aDNA analysis
Kaman-Kalehöyük	G. B. Yazıcıoğlu, S. Pilaar Birch, Cheryl Anderson, Levent Atıcı	Middle Bronze Age and Hellenistic human mobility
Boğazköy/ <i>Hattusha</i>	Catherine Mikeska (dissertation), Benjamin Arbuckle, et al.	Late Bronze Age (Hittite) herding practices
Gordion	D. Meiggs, John Marston	Iron Age herding practices, crop management; north-western Anatolia Sr isoscapes
Kızılırmak watershed and North-central plateau	G. B. Yazıcıoğlu, S. Pilaar Birch, D. Meiggs	North-central Anatolia $^{87}\text{Sr}/^{86}\text{Sr}$ baseline (snail shells and plants)
Alişar Höyük and Yozgat region	G. B. Yazıcıoğlu, S. Pilaar Birch with Yilmaz S. Erdal, Füsun Özer et al. and Maanasa Raghavan, Hannah Moots, John Novembre et al.	Late Bronze Age, Iron Age, Byzantine human mobility; joint project with Hacettepe U (Ankara) and U of Chicago aDNA working groups

Sites in first column are ordered chronologically; references in brackets (...) in second column indicate unpublished dissertations and conference papers (listed in [Supplementary material 1](#)).

2.2 Strontium-cycling in the hydrosphere and bioavailable strontium

Although bedrock (“parent rock”) is the primary source of Sr in soils, many natural processes like weathering, erosion, alluviation, and the mixing effect of rivers contribute to and alter the Sr

isotopic ratio of the Earth’s surface in each location (Probst et al., 2000). While differential weathering rates of various rocks and minerals result in an uneven contribution from the constituents of parent rock to the Sr budget of surface soils, atmospheric factors like sea-spray, rainfall, and aeolian dust also alter the $^{87}\text{Sr}/^{86}\text{Sr}$ in topsoil (Whipkey et al., 2000; Evans et al., 2010; Hartman and

Richards, 2014). Rivers and streams have a high concentration of Sr (~110 ppm), which is derived from both the atmosphere and the weathering of rocks into solution in fluvial basins (Bentley, 2006). There are major factors that cause stream water $^{87}\text{Sr}/^{86}\text{Sr}$ to be different than the underlying bedrock including differential precipitation rates due to climatic and seasonal conditions and differential weathering rates of rocks (Bataille and Bowen, 2012; Bataille et al., 2020) (e.g., rapidly dissolving carbonates and evaporites contribute disproportionately high amounts of Sr). Most importantly, erosion and sedimentation by rivers are crucial for an accurate understanding of $^{87}\text{Sr}/^{86}\text{Sr}$ distribution in surface soils (Bentley, 2006): at higher elevations, there is a stronger correlation between stream water $^{87}\text{Sr}/^{86}\text{Sr}$ and bedrock, because elevated regions erode faster, generate more surface soil, and contribute more to river sediments than the soils at lower elevations. At lower elevations, on the other hand, the correlation between local bedrock and river $^{87}\text{Sr}/^{86}\text{Sr}$ is blurred due to the mixing of sediments along the course of rivers as they flow from higher elevations to the floodplains.

Considering all the processes that contribute to the Sr budget in an ecological zone, an important distinction has emerged between geological $^{87}\text{Sr}/^{86}\text{Sr}$ and *bioavailable* $^{87}\text{Sr}/^{86}\text{Sr}$ in the utilization of Sr isotope ratio analysis in archaeology in recent years. Accordingly, bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ is the term that is used for the isotopic ratio of the strontium in the ecosystem that can be absorbed by biological organisms (plants, animals, humans) in their natural habitat (Hartman and Richards, 2014). For an accurate understanding of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$, it is necessary to understand the pathways that Sr follows from the Earth to the living organisms (Maurer et al., 2012). Due to its properties as a divalent (+2 valence) element and its similar atomic size, strontium replaces calcium in living organisms (Montgomery, 2010). Sr enters the food chain through plants first and it is then transferred into animals and humans who consume plants (and animals). Unlike the fractionation rate of light stable isotopes across the trophic levels of the food chain, which constitutes the main principle for paleodietary reconstruction in bioarchaeology, the radiogenic ^{87}Sr does not fractionate across trophic levels (Flockhart et al., 2015; for mass-dependent fractionation in stable isotope ^{88}Sr , see Knudson et al., 2010; Lewis et al., 2017). Plants absorb the atmospheric Sr through their leaves and the Sr in soil minerals (sourced from bedrock and surface soils) by root uptake, which implies that plants with different root depths absorb Sr from different substrata (Poszwa et al., 2004). The main source of Sr in terrestrial animals is plants, and $^{87}\text{Sr}/^{86}\text{Sr}$ in animal tissues is expected to reflect that of the local plants in their food catchment area but stream and lake water $^{87}\text{Sr}/^{86}\text{Sr}$ may contribute and skew (especially in carbonate-rich environments) the $^{87}\text{Sr}/^{86}\text{Sr}$ in animal tissues (Lewis et al., 2017; Bataille et al., 2020). $^{87}\text{Sr}/^{86}\text{Sr}$ in human tissues is also sourced from dietary intake (including plants, animals, and water), and in theory the $^{87}\text{Sr}/^{86}\text{Sr}$ in various parts of the human skeleton that develop over the lifetime of an individual reflects the averaged $^{87}\text{Sr}/^{86}\text{Sr}$ of the constituents of human diet at the time of the development of the sampled skeletal/dental tissue, which is the foundational premise for the utility of $^{87}\text{Sr}/^{86}\text{Sr}$ as a mobility tracer in archaeology (Montgomery, 2010).

2.3 $^{87}\text{Sr}/^{86}\text{Sr}$ as a mobility tracer and “local range”

The use of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ as a mobility tracer in archeological animal and human populations is founded upon two theoretical principles. As reviewed above, the first principle is that the primary source of $^{87}\text{Sr}/^{86}\text{Sr}$ for a biological organism is the bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ in its food catchment area (see reviews in Price et al., 2002; Bentley, 2006). Accordingly, $^{87}\text{Sr}/^{86}\text{Sr}$ in the tissues of sedentary fauna that have a local feeding range (e.g., rodents and other small mammals) incorporate the bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ of the locality where they feed. Larger mammals and migratory taxa with a wider feeding range, on the other hand, incorporate $^{87}\text{Sr}/^{86}\text{Sr}$ from multiple localities (Toncala et al., 2020). For domesticated species, socio-economic factors and cultural choices further complicate the picture as animals may be grazed intentionally at different localities, varying altitudes, and may even be traded across long distances (Hammer and Arbuckle, 2017). In the case of human populations from hunter-gatherers to complex societies, multiple cultural and economic factors contribute to dietary intake including the proportion of plants and domesticated and hunted animals in diet, imported foods, and locations of available freshwater resources (for an Sr mixing model in human diet, see Montgomery et al., 2007). Therefore, in human mobility studies, it is among best practices to sample a variety of archaeological plants and animals, as well as stream water and groundwater, to assess the numerical range of $^{87}\text{Sr}/^{86}\text{Sr}$ for the local food catchment area (“local range”) as part of baseline determination (see discussion in Lengfelder et al., 2019; Snoeck et al., 2020; Frank et al., 2021a).

The second principle in mobility studies utilizing $^{87}\text{Sr}/^{86}\text{Sr}$ hinges on the chronological development of skeletal tissues and dental enamel across the lifetime of animal and human individuals (Müller et al., 2025). In humans, enamel formation of permanent molars begins in gestation stage and is completed in adolescence (Hillson, 1996; AlQahtani et al., 2010). Because the crown of each molar completes formation in about 3–4 years in succession and enamel does not undergo turnover in later life (unlike bone), the enamel of each tooth preserves a record of the $^{87}\text{Sr}/^{86}\text{Sr}$ at the geographical location where the human individual was present during the crown formation of that specific tooth (Montgomery, 2010). With this understanding, a series of enamel samples from the first, second, and third molars of a human individual can reveal their lifetime mobility from the time of birth to the beginning of adulthood. When the $^{87}\text{Sr}/^{86}\text{Sr}$ of enamel samples are compared with the “local range” $^{87}\text{Sr}/^{86}\text{Sr}$ at the burial location of the sampled individual and/or when compared with bone samples from the same individual, which reveal an averaged $^{87}\text{Sr}/^{86}\text{Sr}$ of their food catchment area in the last decade of life before death, migrant and mobile individuals can be identified with confidence (e.g., Haverkort et al., 2008; Giblin et al., 2013). In animal management studies, incremental enamel samples from the tall crowns of herbivores yield the $^{87}\text{Sr}/^{86}\text{Sr}$ at the location where the animal was feeding during the period the sampled teeth were developing, thus revealing seasonal grazing patterns (e.g., Balasse et al., 2002; Chazin et al., 2019) or imported animals (Arnold et al., 2016). In any case, the key to a correct interpretation of $^{87}\text{Sr}/^{86}\text{Sr}$ data and

archaeological/historical inferences drawn from isotopic analysis is a robust baseline map of $^{87}\text{Sr}/^{86}\text{Sr}$ signatures for the geographies pertinent to the research questions being pursued.

3 Methods in mapping and modeling strontium isoscapes

In earlier decades, geological $^{87}\text{Sr}/^{86}\text{Sr}$ distribution in a research area was used directly as a reference map for mobility studies, and the “local range” of an archaeological site was determined by the statistical majority of its sampled population within two standard deviations (Price et al., 2002). While bedrock geology is still a major contributing source to the bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ at a given geographical location, for the reasons outlined above, analyzing archaeological or modern plants, snail shells, and small fauna, and water, soil, or soil leachate samples to act as proxy for the bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ at a given location has become a common strategy in bioarchaeological mobility studies; however, there is no consensus on which sample types serve best as proxies (Britton et al., 2020; Holt et al., 2021). Accumulating knowledge of $^{87}\text{Sr}/^{86}\text{Sr}$ distribution at a global scale has also demonstrated that the impact of industrial contaminants (e.g., fertilizers, limes, toxic waste) on modern proxy samples (Böhlke and Horan, 2000; Andreassen and Thomsen, 2021) and diagenesis from the soil matrix in bone samples (Nelson et al., 1986; Budd et al., 2000) are also factors that contribute to the skewing of $^{87}\text{Sr}/^{86}\text{Sr}$ in analytical results.

A major issue in $^{87}\text{Sr}/^{86}\text{Sr}$ baseline determination is that the analysis of a large set of proxy samples necessary for intensive coverage is costly. In the last several years, alternative cost-effective methodologies have been developed for creating a baseline map of $^{87}\text{Sr}/^{86}\text{Sr}$ isoscapes that can be utilized in environmental sciences, provenance studies, and forensics, as well as archaeology (Holt et al., 2021). The term *isotope landscape* (isotopic landscape) refers to a geospatial distribution of isotope ratio variation that can be modeled and predicted at scales relevant to the research questions (Bowen and West, 2008; Bowen, 2010). Isoscape predictions can be based on empirical data utilizing geostatistical algorithms (kriging) or they can be generated by mechanistic mixing models based on the principles of isotope geochemistry (Bataille and Bowen, 2012). An intermediary approach that has developed in recent years to overcome the constraints of the two alternative approaches is “process-based statistical isoscapes”, which relies on the integration of empirical data and mechanistic models with covariates and regression techniques (Bataille et al., 2020). For the purposes of this study that aims at generating an improved $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape of Türkiye based on the global model developed by Bataille et al., we will briefly describe the first and the third approaches.

3.1 Isoscape mapping using kriging

The first approach, kriging, is a geostatistical algorithm that uses a limited set of empirical data from sampled regions (“cells” or polygons) to interpolate the value of a variable over a continuous spatial field within a geographically constrained area (e.g., Willmes et al., 2018; Lugli et al., 2022; Tarrant et al., 2024). Where datasets are geographically scattered, a continuous surface of predicted

values can be created with this method, i.e., geographical areas where no empirical data exists for the bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ can be assigned estimated $^{87}\text{Sr}/^{86}\text{Sr}$ values. The presence of high-resolution geological $^{87}\text{Sr}/^{86}\text{Sr}$ values and the density of empirical bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ data points increase the accuracy of the kriging method in a study region. Kriging utilizes either deterministic interpolation, in which the similarity of nearby cells is determined by a mathematical formula, or geostatistical interpolation, in which this formula is enhanced by an element of probability built into the model (Wheatley and Gillings, 2002). The most common method in archaeological studies is Inverse Distance Weight (IDW) method, a deterministic interpolation. This method was effectively used to create an $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape of southwest Anatolia based on 283 shallow-, medium-, and long-rooted plant and snail-shell samples from 87 locations (Wong et al., 2021; see Table 2). However, as observed by Bataille et al. (2018) in their work on West European $^{87}\text{Sr}/^{86}\text{Sr}$ isoscapes, “the accuracy of these empirical interpolation methods is generally low due to the non-normal distribution of $^{87}\text{Sr}/^{86}\text{Sr}$ data and the non-continuous scalar patterning of $^{87}\text{Sr}/^{86}\text{Sr}$ variability”. In other words, when modeling predicted isoscapes of strontium for the purposes of bioarchaeological investigations of mobility, it is necessary to account for the multiple variables that cause the bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ to diverge from the geological $^{87}\text{Sr}/^{86}\text{Sr}$.

3.2 Isoscape modeling using machine learning

To overcome the lack of quantitative understanding of controls in bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ variability, Bataille et al. (2018) developed a machine learning algorithm combining process-based models and regression techniques to predictively model $^{87}\text{Sr}/^{86}\text{Sr}$ isoscapes at various scales. For the basis of this model, interpolation of empirical $^{87}\text{Sr}/^{86}\text{Sr}$ data (as explained above) was combined with a mechanistic bedrock $^{87}\text{Sr}/^{86}\text{Sr}$ model, which hinges on the radiogenic equation accounting for the decay of ^{87}Rb into ^{87}Sr . Distinct from empirical models that rely on deterministic or geostatistical formulas, however, multiple covariates that impact bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ variability were incorporated into the model and the predictive model was trained by testing various regression techniques to evaluate and optimize its predictions. In the developing stages of the model (Bataille et al., 2018), researchers first computed the covariates “parent rock, aerosols, biological processes, relief, climate, and water dynamics” (following Capo et al., 1998), and the later version of the model was improved by inclusion of additional covariates like “global nitrogen and phosphorus fertilization, surficial deposits, global mean annual temperature, and an updated raster of global sea salt aerosol deposition” (Bataille et al., 2020). By testing the model utilizing multiple regression techniques, it was noted that random forest regression (RFR) yielded results with the highest precision (see below for details). The R-script for this global $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape is made available open-access and it can be regenerated and updated by uploading new data, which is a great service to many disciplines including our research community. Machine learning approaches to bioavailable Sr isoscape reconstruction in world regions where

TABLE 2 Summary of bioarchaeological and bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ datasets from Türkiye.

Site	Reference	Archaeological samples	Baseline samples
Körtik Tepe	Benz et al., 2016a,b	PPNA human enamel $N = 89$; PPNA human bone $N = 5$; Early modern human enamel $N = 2$	Water $N = 4$; Modern plants $N = 6$
Göbekli Tepe	Lang et al., 2013	PPNA fauna (gazelle) enamel $N = 21$; PPNA fauna (gazelle) jawbone $N = 17$	Archaeological small fauna (rodents) $N = 6$
Nevalı Çori	Wang et al., 2023	PPNB and Late Neolithic human enamel $N = 15$ [$n = 26$]; EBA, Iron Age, Roman human enamel $N = 13$ [$n = 19$]; PPNB fauna (gazelle, deer, bovid, caprine) enamel $N = 20$	Archaeological sedentary fauna (pig and fox) $N = 6$
Gritille and Urfa-Diyarbakır region	Meiggs, 2009	PPNB fauna (caprine) $N = 14$; For regional baseline in same study: Göbekli PPNA (3), Çayönü PPN (3), Titriş EBA (5) fauna (bovid and equid) $N = 11$	Archaeological sedentary fauna (pig) $N = 1$
Pınarbaşı	Pearson et al., 2023	Epipaleolithic (1) and PPN (3) human enamel $N = 4$	Soil (archaeological) $N = 2$
Boncuklu	Pearson et al., 2023	Early Neolithic human enamel $N = 18$	
Çatalhöyük and Konya Plain	Pearson et al., 2023 , Bogaard et al., 2014 this study (Meiggs data)	Neolithic human enamel $N = 77$; Neolithic plants (nuts, grains) $N = 5$	Modern plants (cereals) $N = 16$; Soil and salt $N = 2$; Archaeological sedentary fauna (fox) $N = 6$; Modern fauna (fox, souslik, equid) $N = 11$; Konya and Taurus modern snail shells $N = 12$
Domuztepe	Lau, 2016 ; Lau et al., 2021	Late Neolithic fauna (caprine) enamel $N = 7$ [$n = 21$]; Late Neolithic fauna (caprine, bovid, pig) enamel $N = 148$; Late Neolithic human enamel $N = 7$	Archaeological small fauna (rodents) $N = 10$
Köşk Höyük and Cappadocia (Niğde, Aksaray)	Meiggs et al., 2018 , this study (Meiggs data)	Chalcolithic fauna (caprine, equid) enamel $N = 18$ [$n = 79$]	Niğde modern plants (grasses) $N = 29$; Aksaray modern plants (9) and dung (4) $N = 13$; Aksaray soil (3) and rock (11) $N = 14$; Aksaray modern small fauna (misc.) $N = 8$; Aksaray modern snail shells $N = 2$
İkiztepe	Welton, 2010, 2015	EBA human enamel $N = 72$; EBA human bone $N = 18$	Archaeological fauna (pig) $N = 8$; Geological zones (not geo-referenced) $N = 59$
Kültepe/Kanesh and Kızılırmak and Yeşilırmak watersheds	Yazıcıoğlu Santamaria, 2015 ; Yazıcıoğlu Santamaria, 2017 ; this study (Yazıcıoğlu and Meiggs data)	MBA human enamel $N = 25$	Modern plants (grass, grains) $N = 31$; Modern snail shells $N = 36$
Tell Atchana/Alalakh and the Amuq Plain	Meiggs, 2011 ; Ingman, 2020 ; Ingman et al., 2021	MBA/LBA fauna (caprine, deer) enamel $N = 10$ [$n = 28$]; MBA/LBA human enamel $N = 3$; MBA/LBA human enamel $N = 94$	Modern plants $N = 6$; Modern snail shells $N = 6$; Modern snail shells $N = 9$; Archaeological small fauna and mollusk $N = 7$
Ortaköy/Shapinuwa and Çorum region	Pişkin et al., 2023	LBA fauna (caprine, bovid) enamel $N = 53$ [$n = 87$]	Bedrock samples $N = 42$; Modern snail shells $N = 30$; Archaeological plants (cereals) $N = 11$
Uluburun and Mediterranean	Rich et al., 2015, 2016	Late Bronze Age wood $N = 4$	Modern plants (trees) $N = 15$
Hierapolis and Southwest Anatolia	Wong et al., 2017, 2018, 2021	Roman (11) and Byzantine (37) human enamel $N = 47$	Modern plants (grass, shrub, tree) $N = 188$; Modern snail shells $N = 61$
Ephesos	Wong et al., 2019	Roman (11) and Byzantine (18) human enamel $N = 29$	
Sagalassos and Lakes District	Degryse et al., 2006 , Dufour et al., 2007	Byzantine (recycled) glass $N = 11$ Byzantine fish $N = 14$	Modern fish $N = 16$; Water $N = 3$

First column: sites are ordered chronologically; second column: brackets (...) indicate unpublished dissertations and conference papers (listed in [Supplementary material 1](#)); third column: N indicates number of analyzed individuals [n] indicates number of sequentially sampled enamel values from one tooth or number of multiple tooth sample values from one individual; fourth column: represents baseline samples included in this study (for metadata and $^{87}\text{Sr}/^{86}\text{Sr}$ values, see [Supplementary material 2](#)).

proxy baseline data is scarce is rapidly developing (e.g., [Janzen et al., 2020](#); [Barberena et al., 2021](#); [Gigante et al., 2023](#)).

It is of utmost importance for the purposes of this study to emphasize that the global model performs best in world

regions where abundant $^{87}\text{Sr}/^{86}\text{Sr}$ data from various substrates is available (e.g., Europe), while in regions lacking bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ data (e.g., Madagascar) predictions do not characterize the isotopic heterogeneity accurately ([Bataille et al., 2020](#)). Because

Türkiye is among relatively data-poor regions for bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$, the global model would be expected to perform with low accuracy in this region relative to other world regions. In fact, the previously published global model did not include any datapoints from Türkiye. Including empirical $^{87}\text{Sr}/^{86}\text{Sr}$ data from Anatolian sites into the global model would optimize the regional model for Türkiye. Furthermore, the inclusion of this dataset could also aid in increasing the resolution of the model at a global scale. Before focusing on the state of strontium isotope ratio research in the archaeology of Türkiye and the compilation of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ data, we will briefly review available isotopic data compilation initiatives in neighboring regions to contextualize this effort.

3.3 Global and regional isotope ratio databases

With the rise of open data movement, scientific communities around the world have begun to embrace FAIR data principles (Findability, Accessibility, Interoperability, and Reusability, after Wilkinson et al., 2016). In addition to the long-standing open-access database platforms in (paleo)environmental research (e.g., Neotoma) and radiocarbon dating (e.g., CARD), global databases of stable isotope ratios (e.g., waterisotopes.org, IsoBank, Faunal Isotopes Database) and open-access platforms hosting regional isotope ratio repositories (e.g., IsoMemo network via Pandora) have developed in the last 20 years. In the last decade, there has been an upswing in the development of regional, open-access databases for bioarchaeological isotope ratio data in the circum-Mediterranean, as well. The IsoArch database, which incorporates bioarchaeological isotopic data from the Greek and Roman world (Salesse et al., 2018), AfriArch repository that integrates bioarchaeological isotopic measurements from African archaeological sites (Goldstein et al., 2022), IsoMedIta: A stable isotope database for medieval Italy (Mantile et al., 2023), and SrIsoMed: An open access strontium isotopes database for the Mediterranean (Nikita et al., 2022) are notable recent initiatives in the regions just west and south of Anatolia (Türkiye). However, the “Greater Ancient Near East” from the Balkans to the south Caucasus, and from northern Sudan to the Persian Gulf and Iran, remains on the margin of these geographies covered by the compilation of isotopic data (also see Nafplioti, 2011, 2021; Frank et al., 2021a,b). This is mainly due to the historical divides between disciplinary fields of European, Graeco-Roman and Near Eastern archaeology, language barriers that set research communities apart, and the much-delayed arrival of isotopic analyses to the archaeology of southwest Asia.

To address this lacuna and to move the field of isotopic analysis forward in the greater ancient Near East, the project “BioIsoANE: An open-access repository of bioarchaeological isotopic analysis in the greater ancient Near East” was initiated in recent years (Irvine and Yazıcıoğlu Santamaria, 2021). Once completed, the BioIsoANE website will host a comprehensive bibliography of published bioarchaeological isotopic analyses and a database of all published bioarchaeological isotopic data georeferenced to an interactive map of the Greater Ancient Near East (as defined above), which can be

queried by regions, site names, cultural and chronological periods, sample types, isotopes reported, and research themes. Additionally, the website will contain information about the theory, principles, and methodologies of isotope chemistry, isotopic analyses, and their applications, as well as guidelines for best practices in project development, sample collection and preparation, data analysis, interpretation, and presentation, to serve not only specialized researchers but also students as a pedagogic resource on the utility, power, and limitations of isotopic analysis in bioarchaeology (Yazıcıoğlu and Irvine, 2025). The review of bioarchaeological $^{87}\text{Sr}/^{86}\text{Sr}$ analysis conducted to date in Türkiye, presented below, and the compilation of data sourced from published research, which we have incorporated into the global map of $^{87}\text{Sr}/^{86}\text{Sr}$ isoscapes in this study, are made possible by the efforts in compiling the BioIsoANE database.

4 Mobility studies and $^{87}\text{Sr}/^{86}\text{Sr}$ analysis in Anatolian archaeology

Ever since the earliest decades of archaeological research in southwest Asia, human mobility and interregional connections in and through Anatolia (modern Türkiye) have been hot topics of scholarly discussion. Due to its geographical location between Mesopotamia and Greece, Anatolia has often been perceived as a bridge that has facilitated the transmission of technological know-how, cultural traits, and languages across the ages (e.g., Neolithization, proto-Indo-European dispersals, dark ages), notwithstanding theoretical problems in how ancient human mobilities were conceptualized (Yazıcıoğlu, 2007). In tandem with theoretical shifts in anthropological archaeology, meta-narratives of large-scale migration and static conceptualizations of societal change stemming from a culture-area approach have given way to a nuanced understanding of human interactions in the ancient world, which has inevitably required new methodologies and high-precision toolkits. Albeit with much delay, the utility of strontium isotope ratio ($^{87}\text{Sr}/^{86}\text{Sr}$) analysis for empirically documenting mobility at the individual and community scales not only for wide-scale residential mobility but also for research on pastoralism, herding strategies, kinship- and marriage-based mobilities, and merchant communities is now well-recognized in Anatolian archaeology.

4.1 Overview of $^{87}\text{Sr}/^{86}\text{Sr}$ analysis in Türkiye

$^{87}\text{Sr}/^{86}\text{Sr}$ analysis in Türkiye only began in the 2010s and has progressed slowly but steadily in recent years. Table 1 presents (A) a list of seventeen archaeological sites (ordered chronologically from distant to recent past), where $^{87}\text{Sr}/^{86}\text{Sr}$ analysis was conducted to investigate various research questions, followed by (B) a list of additional five sites where bioarchaeological $^{87}\text{Sr}/^{86}\text{Sr}$ analysis is ongoing. Among sites with published data, research themes pursued by $^{87}\text{Sr}/^{86}\text{Sr}$ analysis include human mobility (eleven sites), animal management and herding practices (seven sites), management of aquatic resources (one), timber provenance in shipwrecks (one), and glass provenance/recycling (one). Research into $^{87}\text{Sr}/^{86}\text{Sr}$ isoscapes is a relatively novel field in the region,



FIGURE 1

Map of Türkiye showing the location of archaeological sites where strontium isotope ratio ($^{87}\text{Sr}/^{86}\text{Sr}$) analysis has been conducted to date as detailed in Table 1.

pursued by the authors of this paper in central Anatolia and the study by Wong et al. (mentioned above) in southwestern Anatolia. Pioneering work in isotopic analysis in Anatolian archaeology is to be credited to excavation projects with a vision of long-term, multi-disciplinary landscape archaeology like Neolithic Çatalhöyük in central Anatolia and Classical period Sagalassos in the southwest (Figure 1). Early prehistoric sites of southeastern Anatolia and south-central Anatolia constitute hot spots for multi-isotopic analyses, including strontium. The impetus for the use of $^{87}\text{Sr}/^{86}\text{Sr}$ analysis in early prehistory is a fine-resolution understanding of human-environment interactions across the transition to sedentism and the incipient and advanced stages of domestication of plants and animals.

Beginning with the Bronze Ages, the rationale for the use of $^{87}\text{Sr}/^{86}\text{Sr}$ analysis shifts from human-environment interaction to the investigation of long-distance human mobility to shed light on the multi-ethnic composition of protohistoric Anatolian communities. Notably, in each case, $^{87}\text{Sr}/^{86}\text{Sr}$ data has revealed that human mobility in proto-urban and urban societies are far more complex than what is implied by the textual record. For example, at the coastal EBA cemetery of İkiztepe, where the site's excavators had hypothesized long-distance migrations via the Black Sea to explain the early dispersal of proto-Indo-European speakers into Anatolia, $^{87}\text{Sr}/^{86}\text{Sr}$ data revealed individuals engaged with transhumant pastoralism in addition to possible emigrants from distant regions (Welton, 2015). At Kültepe (ancient Kanesh) in south-central Anatolia, which is renowned for its large corpus of

cuneiform texts belonging to an enclave of resident merchants from the city of Assur in northern Iraq, $^{87}\text{Sr}/^{86}\text{Sr}$ data helped identify immigrants from multiple other locations including north-central Anatolia and possibly the upper Euphrates or other Bronze Age cities in south-central Anatolia (Yazıcıoğlu Santamaria, 2017). At another cosmopolitan MBA-LBA city, Tell Atchana (ancient Alalakh), combined $^{87}\text{Sr}/^{86}\text{Sr}$ and aDNA analysis shed particularly interesting light on the period of societal collapse between the levels characterized by palaces with administrative archives (Ingman et al., 2021). And finally at Hierapolis and Ephesos, $^{87}\text{Sr}/^{86}\text{Sr}$ was used for identifying pilgrims (potentially from Europe) in the early Christian era (Wong et al., 2018). These examples demonstrate that $^{87}\text{Sr}/^{86}\text{Sr}$ analysis of human remains is a particularly relevant methodology in text-aided archaeology because it provides contextualized empirical data that help us conceptualize human mobility and ethnicity beyond the straightjacketing culture-area paradigm and “the tyranny of the text”.

4.2 Geographical distribution of datasets and sample types

The map of Anatolia in Figure 1 shows that the geographical distribution of sites with analyzed remains is far from even. The number of archaeological samples and baseline reference samples

analyzed in each study according to sample type are summarized in Table 2, which demonstrates this uneven distribution across sites and regions in further detail. For example, currently there are tooth enamel samples from 495 human individuals buried at Anatolian sites across the periods, and of this total, 76 are from southwestern Anatolia, 124 are from south-central Anatolia, and 223 are from southeastern Anatolia, while only 72 samples are from north-central Anatolia. To a certain extent, this trend reflects the geographical distribution of archaeological sites with well-preserved and curated human remains unearthed by modern excavation methods. Archaeological fauna analyzed for documenting animal management and herding practices show a somewhat similar distribution: of the total 302 sampled terrestrial animals, 231 are from sites in southeastern Anatolia, 18 are from south-central Anatolia and 53 are from north-central Anatolia, while in southwestern Anatolia faunal samples are represented only by fish (14 samples). Analyzed archaeobotanical samples are minimally represented (5 Neolithic plant samples and 4 LBA wood samples). Reference samples analyzed for $^{87}\text{Sr}/^{86}\text{Sr}$ baseline determination in each study are diverse (Table 2). Sample types include archaeological and modern plants, small fauna, snail shells, fish, water, soil, rock, salt, and dung. In terms of sample type distribution, modern plants constitute the largest dataset (298 samples) with an additional 16 samples from archaeological plants, followed by 64 samples from modern and archaeological small fauna, 62 samples from modern and archaeological snail shells, 60 soil/rock samples, 30 modern and archaeological fish samples, and 13 water samples (Supplementary material 2).

To reiterate, while the temporal span of $^{87}\text{Sr}/^{86}\text{Sr}$ data is quite impressive, there remain significant geographical gaps in the northern half of the country. For the purposes of this study, the uneven distribution of analyzed baseline samples is significant because the number of georeferenced empirical datapoints will add to the weighted probability in the isoscape interpolation and it will influence the accuracy of the resultant $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape map.

4.3 Previous strategies for $^{87}\text{Sr}/^{86}\text{Sr}$ baseline determination in Türkiye

In archaeological mobility studies utilizing $^{87}\text{Sr}/^{86}\text{Sr}$ analysis at prehistoric Anatolian sites (e.g., Göbekli, Nevalı Çori, Çatalhöyük, Domuztepe, İkiztepe), researchers have typically used small and sedentary archaeological fauna (rodents, fox, pig) from the researched site as proxy samples for the determination of the site's local food catchment area, while in more recent studies (e.g., Körtik Tepe), a broader local catchment area has been characterized by water and modern plant samples (Table 2). Because land-snail shells are relatively easy to collect and have a high concentration of Sr, this sample type has also been frequently used in research typically at Bronze Age and Classical period sites (e.g., Kültepe, Tell Atchana, Ortaköy, Hierapolis, Ephesos), where the food catchment area is expected to be wider than the immediate vicinity due to food provisioning strategies of state societies. At Tell Atchana and Kültepe, for example, baseline determination for the site's catchment area was carried out at the scale of the settlement plain and sampling spots were selected by targeting geologically distinct

units using bedrock geology maps as reference.¹ At the highland site of Ortaköy, where the research question was concerned with the use of pasturelands for herding strategies, snail shells and rock samples were collected from distinct geological units for baseline determination within a much broader radius around the site (Pişkin et al., 2023). Baseline determination for the human mobility study at Kültepe was extended to a regional scale in accordance with its research questions concerning inter-site mobility between MBA cities involved in a trade network. To this end, snail shells and plant samples were collected with regular intervals along the watersheds of two major rivers (Kızılıрма and Yeşilirmak) in central Anatolia with the objective of understanding the mixing effect of these rivers. Analysis of samples nearby known Bronze Age sites were prioritized given budget constraints (Yazıcıoğlu Santamaria, 2017); samples analyzed in later years are included in this study (Supplementary material 2) and analyses are ongoing.

The first systematic study for creating a local isoscape, which enables the $^{87}\text{Sr}/^{86}\text{Sr}$ characterization of a continuous surface rather than scattered spots on the map, was carried out around the prehistoric site of Köşk Höyük in south-central Anatolia (Meiggs et al., 2018). Modern grasses were collected from sampling areas that were chosen not only based on bedrock composition but also different geomorphological contexts where alluvial and colluvial processes contribute to the mixing of sediments. Using kernel smoothing and spline features in ArcGIS, a local $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape with contour lines was interpolated, which was then used for mapping the grazing grounds of Chalcolithic sheep/goats based on results from incrementally sampled enamel. In recent years, a larger-scale systematic study was conducted for regional baseline determination in southwestern Anatolia, in which modern snail shells and short-, medium-, and long-rooted plant samples were collected from each sampling spot using a hand-held GPS, and an estimated $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape was created using the inverse distance weight method (Wong et al., 2021), as described above.

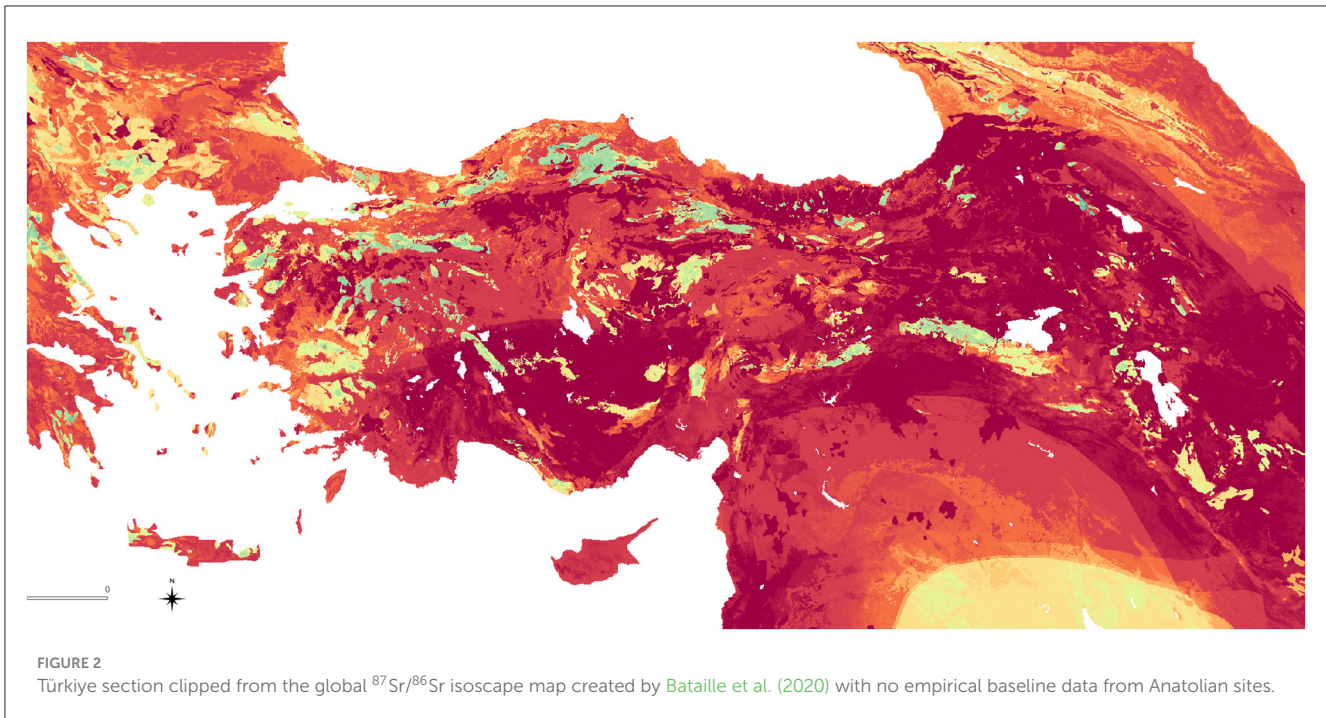
5 Methods and materials

5.1 Data harvesting strategy and screening of baseline data

Reviewing the empirical data layer included with the publication of the R-script made available open-access by Bataille et al., we realized that $^{87}\text{Sr}/^{86}\text{Sr}$ data generated by archaeological research projects conducted in Türkiye were not present in this dataset (Figure 2). Likewise, bioarchaeological and baseline $^{87}\text{Sr}/^{86}\text{Sr}$ data from Anatolian sites were largely absent from the SrIsoMed database online, in which predominantly geological $^{87}\text{Sr}/^{86}\text{Sr}$ data is compiled from Türkiye.² We compiled all available publications of archaeological mobility and provenance studies and dissertations utilizing $^{87}\text{Sr}/^{86}\text{Sr}$ in Anatolia from the BioIsoANE database (see above) and added unpublished baseline data from the authors' ongoing analyses. First, all $^{87}\text{Sr}/^{86}\text{Sr}$ data

1 Geological maps of Türkiye prepared by the MTA (General Directorate of Mineral Research and Exploration) are available online at <https://www.mta.gov.tr/en/maps/geological-500000>.

2 <https://srisomed.emmebioarch.com/>



from archaeological and baseline samples were compiled into an excel sheet for comprehensive coverage (summarized in Table 2), and then this data was sorted and screened according to sample type to assess their relevance and applicability to the purposes of this study. Datapoints that were reported by authors as not having passed the quality control checks (e.g., $^{88}\text{Sr}/^{85}\text{Rb}$ or $^{84}\text{Sr}/^{86}\text{Sr}$ QC) and datapoints from replicate runs were eliminated. Next, all data was georeferenced by recording latitude and longitude information from original publications. In cases where coordinates were not presented in the original publication, latitude and longitude information was inferred from published maps showing the sampling locations, and accuracy level for the coordinates of each sample was recorded in the datasheet (Supplementary material 2). Data reported only in graphs and with no map for sampling location were not included in this study. After this data cleaning process was completed, further exclusion criteria were introduced to the dataset. Because the purpose of this study is to increase the accuracy of the existing predictive $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape model by incorporating empirical and *in situ* bioavailable data, a conservative strategy was followed: all human $^{87}\text{Sr}/^{86}\text{Sr}$ data and $^{87}\text{Sr}/^{86}\text{Sr}$ data from all domesticated species that are grazed and herded were excluded from the dataset so as to eliminate any possibility of skewing the resulting map by data that may be influenced by anthropogenic factors. This resulted in an empirical dataset of 688 $^{87}\text{Sr}/^{86}\text{Sr}$ values from archaeological and modern flora, wild fauna, mollusk (snail shell), and soil samples that could be incorporated into the global $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape model.

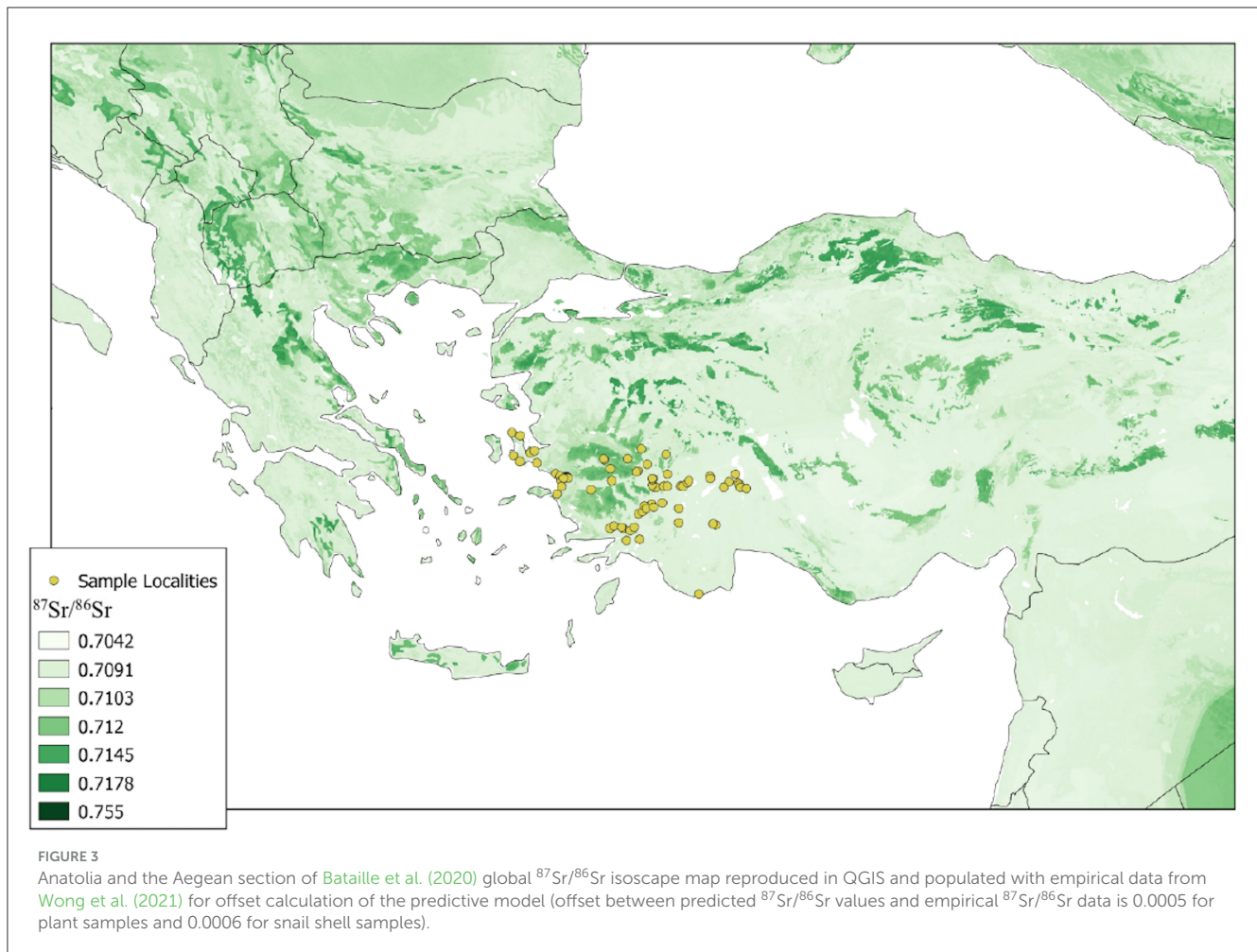
5.2 Assessing the accuracy of the existing global isoscape model

Prior to generating the random forest model for Türkiye, we assessed the extent to which the existing global model was accurate

for Türkiye without integrating additional data, so that we could later evaluate its improvement. To test this, we reproduced Bataille's Sr isoscape for Türkiye in QGIS and populated it with measured sample data from the systematic study by Wong et al. (2021) to calculate an offset between the measured $^{87}\text{Sr}/^{86}\text{Sr}$ values at a given point as compared to the predicted $^{87}\text{Sr}/^{86}\text{Sr}$ value for that same GPS coordinate (Figure 3). We found that agreement was generally good, with plant remains performing slightly better than those for snails (cf. Britton et al., 2020). Both data types were only precise to the fourth decimal point, or ten-thousandths. A higher precision model (to five decimals) would allow for stronger interpretive power, as is desirable for interpretation of mobility in the archaeological record. Considering that no $^{87}\text{Sr}/^{86}\text{Sr}$ data from Türkiye were used in the generation of the original global model, the performance of the model in predicting values was encouraging and suggested that adding empirical data from Türkiye to the model should notably improve the predictive power of the model.

5.3 Modeling by random forest regression (RFR) decision tree method

After identifying offsets between predicted and empirical $^{87}\text{Sr}/^{86}\text{Sr}$ measurements in Türkiye based on the general global model, we used the existing R-script and modified the global dataset including 688 new analytical values from baseline samples at and around Anatolian sites to create a new isoscape model for Türkiye (Figure 4). This model used a random forest decision tree based on a priori relationships between variables and multiple iterations to generate a robust model that can then be tested and validated with additional measured data. In order to create a raster of predicted strontium ratios, we began by obtaining geolocated data of Sr isotope analysis samples from the global model (Bataille et al., 2020) in addition to covariate rasters. This spreadsheet included

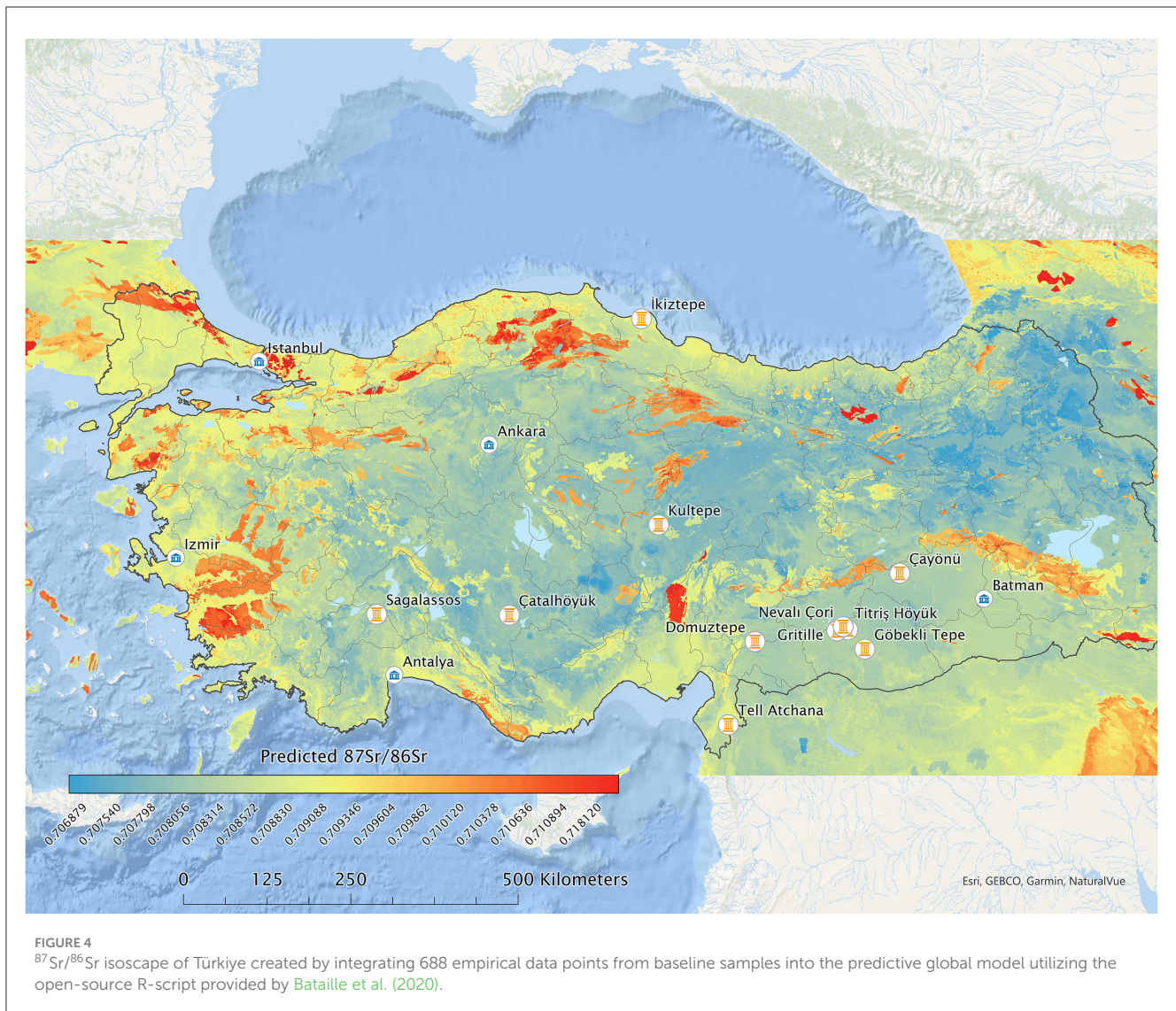


more than 16,000 entries, while the rasters included geologic and climatic data related to the ratio of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$. The original script was then trimmed and altered to only include code necessary to generate a raster of predicted $^{87}\text{Sr}/^{86}\text{Sr}$ for the region. After trimming the code, we ran the model several times with adjusted parameters. The final model cropped the extent of the model to the area surrounding Türkiye, before running the random forest regression on a dataset of 8,000+ georeferenced samples. This created a model with a relatively small range of $^{87}\text{Sr}/^{86}\text{Sr}$ values ($\sim 0.705\text{--}0.719$), in which the predicted strontium isotope ratios matched the regional trends in $^{87}\text{Sr}/^{86}\text{Sr}$ identified by previous research. For example, mountainous areas in the northeastern parts of Anatolia had significantly higher $^{87}\text{Sr}/^{86}\text{Sr}$ ratios than other areas, consistent with the findings by Bentley and Knipper (2005) on horst formations of Palaeozoic granites and metamorphic rocks in Europe. After creating our raster of predicted $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for Türkiye and surrounding areas and our accompanying raster of standard errors, we imported the prediction raster into ArcGIS to conduct geospatial analysis and create graphics. We symbolized the raster using a percent clip stretch symbology in order to best display the continuous nature of $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. We then overlaid prominent archaeological sites, cities, and national borders over our raster in order to provide important contextual information to assist us in our later analysis.

We constructed buffer zones around our archaeological sites of interest and conducted zonal statistics over these buffers to find the mean predicted $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for each site, so as to compare the means to our established values for these sites to check for model accuracy.

5.4 Calculation of the predicted standard error

To assess the accuracy of the model within Türkiye, we also computed the predicted standard error across the landscape. This entailed using additional code in order to create a second raster to represent the standard error for each cell of predicted $^{87}\text{Sr}/^{86}\text{Sr}$. The code paralleled the original random forest regression, but it was adapted to predict standard error instead of $^{87}\text{Sr}/^{86}\text{Sr}$ using the same predictors to best match each cell. On the map presented in Figure 5, colors proceed from cooler to warmer as the standard error progresses from smaller to larger. As we would expect, standard error is relatively smaller in areas represented by a higher number of analyzed reference samples, for example, around Hierapolis, where the systematic isoscape study by Wong et al. (2021) was conducted.



6 Geological $^{87}\text{Sr}/^{86}\text{Sr}$ variability in Türkiye and observations on the resultant map

The peninsular landmass of Anatolia (Figure 6) was formed with the closing of the Tethys Ocean during the late Cretaceous, and it is geologically divided into three tectonic units: the Pontides, the Anatolides-Taurides and the Arabian Platform (Okay, 2008): The Pontides, an amalgamation of three terrains that show markedly different geological evolutions, were faulted during the Alpidic orogeny but were not metamorphosed. To the contrary, Anatolide-Tauride terrain was intensely deformed and partly metamorphosed during the Alpidic orogeny, leading to its subdivision into several zones based on the type and age of metamorphism. Southeastern Anatolia constitutes the northern extension of the Arabian Platform, and it shows a similar stratigraphy to the Taurus range, consisting of a clastic-carbonate dominated Palaeozoic and a carbonate dominated Mesozoic succession. Geological $^{87}\text{Sr}/^{86}\text{Sr}$ variability is well-documented

especially in volcanic regions of Anatolia (Robertson and Dixon, 1996; Köksal and Göncüoğlu, 2008).

In comparing our modeled bioavailable Sr isoscape map for Türkiye (Figure 4) with the Sr isoscape of Türkiye clipped from Bataille's global model (Figure 2), we do see a finer resolution variability at the local level in areas where there are robust datasets of analyzed samples like southwestern Anatolia and the Konya Plain. Notably, bedrock type still manifests as the dominant factor in predicting expected values. When using a modeled Sr isoscape to address questions of mobility in the archaeological record, it will be essential to approach the question as a matter of scale. Higher-resolution isoscapes generated at local and regional levels will be more useful for addressing site-level questions, whereas country- and continental-scale models should be reserved for large scale, broad interpretations.

At sub-regional scales, we found that the addition of the new dataset increased the predictive strength of the model when compared to empirical $^{87}\text{Sr}/^{86}\text{Sr}$ values from archaeological sites, with accuracy in some areas up to the fifth decimal point (e.g., for Çatalhöyük, Göbekli Tepe, Kültüpe), or at least better predictive

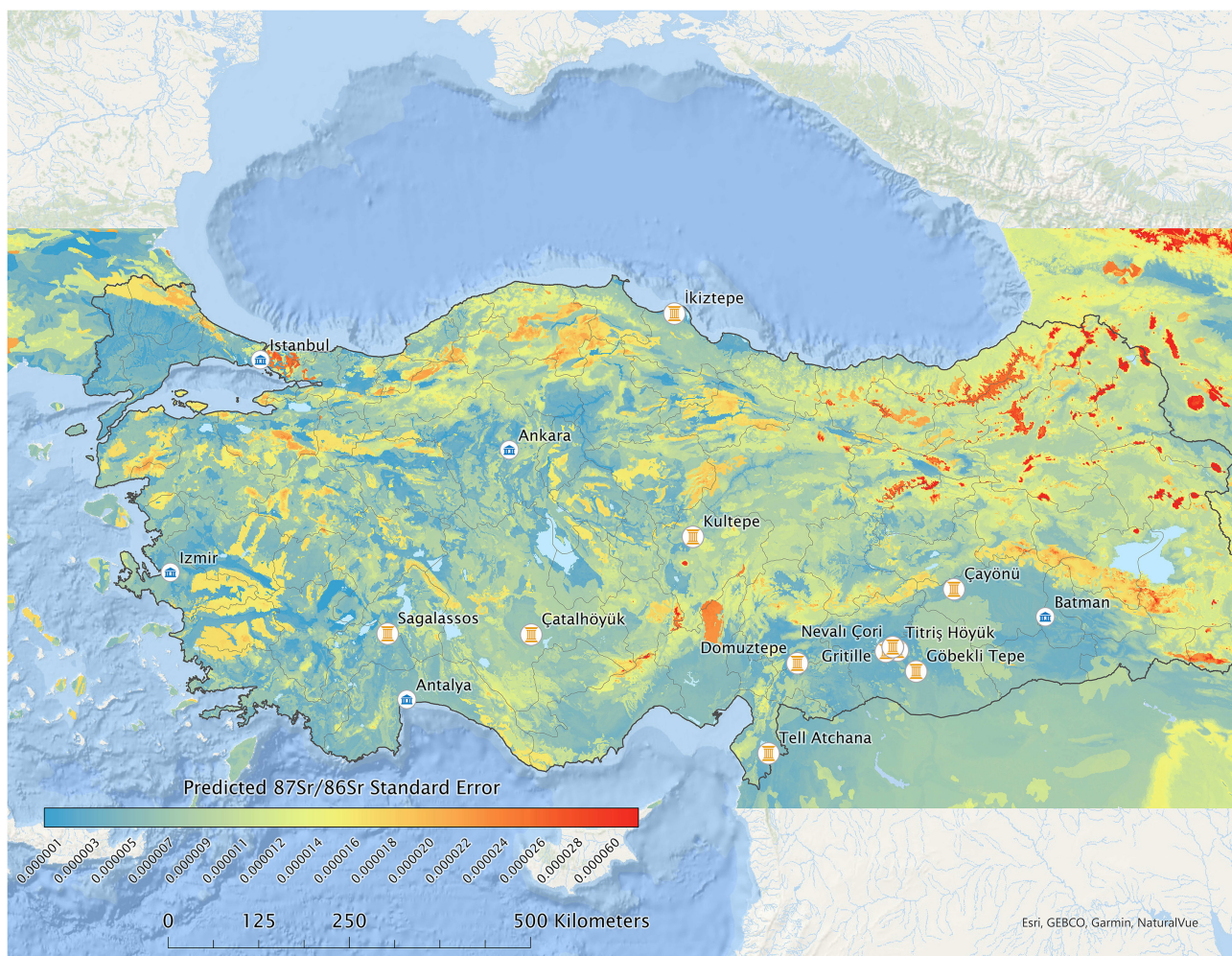


FIGURE 5

Map of Türkiye showing the predicted standard error in the $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape model across the Anatolian landscape.

performance than Bataille et al.'s global model in other areas (e.g., for Hierapolis and southwest Anatolia, Tell Atchana and the Amuq, and Domuztepe vicinity). However, our model performed less accurately than Bataille et al.' model at two sites (İkiztepe and Köşk Höyük), demonstrating the need for higher-resolution sampling and modeling when addressing site-level questions. In the case of İkiztepe, this can be explained by the lack of biological baseline data from the vicinity of the site. Köşk Höyük is centered within ample comparative data points, and therefore, this result could be attributed to local bedrock variability in this volcanic region with a complex geology. This could also be due to the resolution of the input geological map of Türkiye, in which some of the smaller geological units, despite their differences, are aggregated into fewer categories.

7 Human mobility in ancient Anatolia

In the archaeological and historical record of southwest Asia, there are several significant episodes of broad-scale human mobility

across the Anatolian peninsula, which have become specialized topics of investigation in and of themselves. Most notably, the westward spread of early farming populations in the Neolithic from Anatolia to Europe ("Neolithization", see review in [Düring, 2011](#)) and the spread of proto-Indo-European-speaking populations in protohistory (sometime before mid-3rd millennium BCE), who later formed the Hittite kingdom and the Luwian confederacy in Anatolia, have spurred much debate in scholarship over the decades and will remain significant research topics. Additionally, Early Iron Age (ca. 1200–900 BCE) that is marked by the supra-regional collapse of centralized, territorial states and lack of textual evidence (i.e., "Dark Ages") is characterized by the movement of new populations into Anatolia by land and by sea from the west and the east. The textual record of the following period shows that Indo-European-speaking tribes (e.g., Mushki/Phrygians), Semitic-speaking populations (e.g., Aramaeans) and others (e.g., Bianili/Urartu) had moved into various subregions of Anatolia in this obscure period. Due to the scarcity of permanent settlements, lack of texts, and paucity of human skeletal material (cremation being common practice in the Iron Age), the details



Bioarchaeological remains from early prehistoric sites of Anatolia, as discussed above, have received much greater attention from an analytical perspective, as opposed to later periods. Multi-isotopic investigations at the pre-pottery and early Neolithic sites of southeastern and south-central Anatolia constitute a large portion of isotopic analyses carried out to date in Anatolia, followed by Bronze Age sites (Irvine and Özdemir, 2020). To increase our insight into the experienced human mobilities in more recent state societies and their cycles of territorial expansion and disintegration, $^{87}\text{Sr}/^{86}\text{Sr}$ ratio analysis would be an apt strategy especially at sites where the historical transitions are documented by stratified sequences and in multi-period cemeteries. There are other cases of local and regional mobilities in and into Anatolia, which have not been investigated isotopically. Among these, the southward expansion of the Early Transcaucasian cultural sphere in eastern/southeastern Anatolia across the EBA, the impact of EBA urbanization along the upper Euphrates, the influx and dispersal of populations in western and eastern Anatolia in the EIA, forced deportations by the Urartian kingdom and the

Seasonal human mobility in tandem with nomadic and transhumant pastoralism, which has until recently been a strong component of rural subsistence economy in Anatolia, is another important research topic that can be tackled with strontium (and oxygen) isotope ratio analysis of animal and human remains. Although herding and grazing strategies have been investigated at several Anatolia sites, considering the pastoralist basis of many tribal states in Anatolia beginning with the Iron Age, further systematic investigations of seasonal mobility patterns, aided by ethnographic research, would greatly benefit our understanding of not only subsistence economy and human mobility in the past but also political organization in significant periods of social transformation. An interesting question that has not yet been investigated by isotopic analysis in Anatolian archaeology is the mobility of animals by trade, exchange, and conquest/conflict. In this regard, horses taken as tribute from neighboring lands by the Urartian army in eastern Anatolia, donkeys brought to central Anatolia from Iraq by the (Old) Assyrian trade caravans and traded in Anatolia, and horses trained for the armies of the Hittite Empire in south-central Anatolia are distinct cases of long-distance animal

mobility that can be empirically documented by $^{87}\text{Sr}/^{86}\text{Sr}$ analysis. Wood/timber provisioning/trade is also a promising subject to explore at Anatolian sites with good wood preservation (e.g., Gordion and its tumuli) and in underwater archaeology.

Importantly, ancient human mobility studies have been increasingly adapting interdisciplinary research strategies, utilizing strontium isotope ratio analysis in conjunction with anthropological biodistance studies and aDNA analysis (e.g., Çatalhöyük, Nevalı Çori, Tell Atchana; Başur Höyük, Alişar, Table 1). This research strategy is particularly powerful in providing at once an isotopic, high-resolution perspective into short-term human mobility (human lifetime and within one or two generations) and a genetic, long-term perspective on the movement of populations through the generations across broader landscapes. The pairing of isotopic and genetic datasets from the same population bears a higher potential to reveal the nature of case-specific mobilities than either of the methods employed alone (Haak et al., 2008).

8 Discussion

The basic premise of this study is that the analytical power, utility, and accuracy of strontium isotope ratio analysis increase manifold when $^{87}\text{Sr}/^{86}\text{Sr}$ of archaeological samples can be referenced to a robust baseline of the geographical distribution of bioavailable Sr isotope ratios. This is valid for various scales of analysis including big questions like the spread of early humans, the “Neolithic package”, or proto-Indo-European languages as well as regional-to-local scale questions regarding hunting, herding strategies, exogamy, and kinship-based mobilities. Whether we are studying human mobility, the migration of animal species, or socioeconomic trade in animal and plant commodities, a robust bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape is imperative for realizing the full potential of this biogeochemical method and accurate interpretation of $^{87}\text{Sr}/^{86}\text{Sr}$ data from bioarchaeological remains. Isoscapes covering broad geographical areas allow enhanced assessment of the nature of variability in isotopic values from bioarchaeological remains. Predictively modeled isoscapes utilize machine learning algorithms to account for multiple variables that influence the geographical variation in bioavailable strontium isotopes and allow us to visualize isotopic variation as a continuous surface across the landscape (Meiggs et al., 2018). This mapping tool is particularly helpful in showing the spatial distribution of isotopic values in areas where variation in regional geology has units that mix different source areas (e.g., fluvial areas) or units whose composition produce strontium isotope values that overlap with the site-centered baseline. Bioavailable strontium isoscapes are more refined in areas that have an intensive coverage of empirical data procured from systematically collected baseline samples representing distinct geological units (e.g., Wong et al., 2021). Small-scale variation in geology, as is present in many areas of Anatolia, may cause potential over interpretation of “non-local” vs. “local” individuals, if “local range” has been defined by geographically narrow environmental samples. This becomes especially important where the geology immediately surrounding a site may be different than the agricultural and pastoral land

utilized for the dietary input of that site’s population. Therefore, it is important to design sampling strategies for baseline determination that best fit the research question pursued, and it is necessary to base archaeological interpretations not solely on the numerical correspondence between $^{87}\text{Sr}/^{86}\text{Sr}$ values from bioarchaeological samples and geographical areas but on a contextualized evaluation of isotopic data together with multiple lines of bioarchaeological and associated material culture evidence (cf. Nafplioti, 2021). Furthermore, broadscale isoscapes facilitate answering specific research questions that explicitly hypothesize large-scale mobility, such as the Early Iron Age/Archaic Period migrations in the Aegean. Current bioavailable data from western Anatolia show some similar values to those in the greater Aegean, creating a need for broader consideration of mobility in regard to overlapping $^{87}\text{Sr}/^{86}\text{Sr}$ ratios in different regions (cf. discussion in Nafplioti, 2021). Recent initiatives in generating broadscale, open access $^{87}\text{Sr}/^{86}\text{Sr}$ databases for the Mediterranean basin (e.g., SrIsoMed, Nikita et al., 2022) corroborate the fact that this need is recognized by the scholarly community, and yet $^{87}\text{Sr}/^{86}\text{Sr}$ isoscapes of Anatolia remains a *terra incognita* at large.

In site-scale mobility studies worldwide, researchers have previously defined the “local range” by the statistical majority of analyzed bioarchaeological samples (within 2 s.d.); they have extrapolated expected $^{87}\text{Sr}/^{86}\text{Sr}$ values for the local environment based on bedrock geology; or they have analyzed a relatively small number of samples (archaeological and modern small fauna, snail shells, plants) to serve as geographical reference for local baseline determination. All three of these approaches have been used in archaeological research across Anatolia, making it a challenging task to gain a cohesive picture of the extent of bioavailable $^{87}\text{Sr}/^{86}\text{Sr}$ variability in relation to bedrock values. Ultimately, these approaches address different scales of variation, and the extent to which each provides the ability to interpret mobility more accurately depends on the particular circumstances of the site and research question. For example, high variability in local bedrock $^{87}\text{Sr}/^{86}\text{Sr}$ values may result in highly variable $^{87}\text{Sr}/^{86}\text{Sr}$ values within sampled individuals. This variability may be misinterpreted as a non-local or highly mobile signature despite this not being the case. This issue is not unique to Anatolia and remains a limiting factor more broadly in geologically complex regions. The reverse is also true: lack of variability in $^{87}\text{Sr}/^{86}\text{Sr}$ values across wide geographical units (e.g., the limestone lithology of the circum-Mediterranean), which would result in a restricted range of $^{87}\text{Sr}/^{86}\text{Sr}$ values from bioarchaeological samples, may be masking distinct geographical origins and mobility patterns of the sampled individuals. At the scale of meta-analysis, the cumulative evaluation of the high percentages of individuals identified as “locals” in separate studies may lead to broad claims about the lack of mobility in the ancient world, albeit debatable (e.g., Leppard et al., 2020 vs. Perry et al., 2022). In fact, the presence of broad regions with overlapping $^{87}\text{Sr}/^{86}\text{Sr}$ values in the Mediterranean isoscape suggests that the high percentages of “local” individuals in the archaeological record is a manifestation of the methodological limitations of Sr isotopic analysis in detecting mobile individuals, rather than being indicative of a broad historical pattern. This methodological shortcoming of Sr isotopic analysis can be overcome by conducting multi-isotopic analyses for assessing mobility (oxygen, sulfur)

and dietary (carbon, nitrogen) patterns, creating isoscapes for other isotopes (Nafplioti, 2021), and using the entire gamut of bioarchaeological methods in assessing biodistance (Gregoricka, 2021).

The application of $^{87}\text{Sr}/^{86}\text{Sr}$ analysis to archaeological studies of mobility remains limited in part by the cost of obtaining *bioavailable* $^{87}\text{Sr}/^{86}\text{Sr}$ values from large numbers of samples needed for establishing a local “baseline” empirically, which in turn restricts our ability to derive interpretations from the isotopic analysis of bioarchaeological remains. Further, depending on the types of environmental samples used in a given study, different scales of strontium variation may be represented, and integrating these data into a coherent picture presents a challenge in ascertaining broadscale variation. The lack of adequate baseline data also remains problematic in many regions, especially those which remain less accessible to researchers due to remoteness or political unrest. Advances in the field in recent years led to the development of alternative methodologies that combine available empirical data with multi-variate statistics and machine learning algorithms to create *isoscapes* (isotopic landscapes), which allow us to visualize a spatially continuous distribution of predicted $^{87}\text{Sr}/^{86}\text{Sr}$ values across the landscape rather than a spotty distribution of empirical $^{87}\text{Sr}/^{86}\text{Sr}$ values, providing a broader coverage at a much lower cost. A recent advance in this direction is the global model of $^{87}\text{Sr}/^{86}\text{Sr}$ isoscapes, created by Bataille et al. (2020), which incorporates geological $^{87}\text{Sr}/^{86}\text{Sr}$ data from Türkiye but does not include any empirical $^{87}\text{Sr}/^{86}\text{Sr}$ data from archaeological studies at ancient Anatolian sites (Figure 2).

9 Conclusions

In this study, we demonstrated that, as expected, the accuracy of this global model for Türkiye increases with the incorporation of empirical $^{87}\text{Sr}/^{86}\text{Sr}$ data from archaeological studies. To this end, we combined our unpublished $^{87}\text{Sr}/^{86}\text{Sr}$ data from baseline samples with all available $^{87}\text{Sr}/^{86}\text{Sr}$ data from published research and unpublished dissertations on Anatolian sites (Tables 1, 2; Supplementary materials 1, 2). After compiling the data from all sample types, we systematically eliminated data from human and domesticated animal species, and we reduced this dataset to only include $^{87}\text{Sr}/^{86}\text{Sr}$ data from *in situ*, georeferenced samples (archaeological and modern flora, wild fauna, mollusk/snail shell, and soil) that can serve as empirical baseline data. Following the analytical steps described in this study, we incorporated the resultant 688 datapoints into Bataille et al.’s global database of $^{87}\text{Sr}/^{86}\text{Sr}$ values and re-generated the Türkiye portion of the $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape map (Figure 4), as well as a map of standard error distribution (Figure 5), using the R-script provided by Bataille et al. (2020). The resulting ground-truthed isoscape introduced more nuanced $^{87}\text{Sr}/^{86}\text{Sr}$ variability to the modeled map, increased its accuracy, and led to three major observations. First and foremost, as Figure 1 clearly demonstrates, the geographical distribution of $^{87}\text{Sr}/^{86}\text{Sr}$ datasets in Anatolia is very uneven, with sampled sites clustering in the southern half of the peninsula and no analyses in vast areas of the northern and eastern portions of the country. Second, because of this uneven distribution, when statistically tested against analytical results from archaeological samples, the

predictive isoscape model performs with higher accuracy in regions represented by larger empirical datasets, as opposed to northern sites not covered by extensive baseline sampling (e.g., İkizepe). And third, the relatively poor performance of the model in Cappadocia despite the presence of ample baseline data at and around prehistoric Köşk Höyük suggests that, in regions with a particularly complex geology (e.g., volcanism) where the resolution of geology maps may not be optimal, more intensive coverage by site-scale, empirical baseline studies is necessary.

In the future stages of this project, we hope to expand the spatial boundaries of our research objective to include neighboring regions of the “Greater Ancient Near East” (Balkans and the Aegean, the Caucasus, Iran, and Syro-Mesopotamia), where we have already completed data-harvesting within the framework of the BioIsoANE Project (Irvine and Yazıcıoğlu Santamaria, 2021). It is worth noting that global and pan-regional isoscapes are useful and relevant for archaeological research (and environmental sciences, geology, and forensics), but generating high-resolution isoscapes at local and regional levels will likely be the most effective strategy for addressing the relevant spatiotemporal scales of research questions related to ancient human and animal mobility. It is our hope that a higher resolution ground-truthed *bioavailable* $^{87}\text{Sr}/^{86}\text{Sr}$ isoscape map for all Türkiye will allow for the eventual use of statistical packages to model what is known as “individual assignment” for people and animals, used for probabilistically pinpointing the most likely geographical origin(s) of mobile individuals (cf. Bowen et al., 2014). Generating additional local datasets and more robust models will also allow us to reassess the power or perhaps the limitations of Sr isotope analysis in provenancing bioarchaeological individuals in our research region. This may in turn lay the groundwork for advocating the pairing of Sr isotope analysis with isotopic analyses of oxygen, sulfur, and/or lead for finer-resolution interpretations of ancient mobility.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

GBY: Conceptualization, Data curation, Investigation, Methodology, Project administration, Validation, Writing – original draft, Writing – review & editing. DCM: Conceptualization, Formal analysis, Investigation, Methodology, Writing – review & editing. MD: Investigation, Methodology, Software, Validation, Visualization, Writing – review & editing. SPB: Conceptualization, Funding acquisition, Investigation, Methodology, Software, Supervision, Writing – original draft, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

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Supplementary material

The Supplementary Material for this article can be found online at: <https://www.frontiersin.org/articles/10.3389/fearc.2025.1520345/full#supplementary-material>

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