

## A RECENT NORTHERN ORIGIN FOR THE UTO-AZTECAN FAMILY

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The Uto-Aztecan language family is one of the largest language families in the Americas. However, there has been considerable debate about its origin and how it spread. Here we use Bayesian phylogenetic methods to analyze lexical data from thirty-four Uto-Aztecan varieties and two Kiowa-Tanoan languages. We infer the age of Proto-Uto-Aztecan to be around 4,100 years (3,258–5,025 years) and identify the most likely homeland to be near what is now Southern California. We reconstruct the most probable subsistence strategy in the ancestral Uto-Aztecan society and infer no casual or intensive cultivation, an absence of cereal crops, and a primary subsistence mode of gathering (rather than agriculture). Our results therefore support the timing, geography, and cultural practices of a northern origin and are inconsistent with alternative scenarios.

*Keywords:* Uto-Aztecan languages, historical linguistics, language phylogeny, human prehistory, agriculture

### 1. INTRODUCTION.

#### 1.1. UTO-AZTECAN EXPANSION AND MECHANISMS OF LANGUAGE FAMILY DISPERSAL.

The spatial scale and diversity of language families around the world varies immensely, from small regional families containing a handful of languages to much larger families containing hundreds of languages spoken across large areas (Greenhill 2014). The FARMING/LANGUAGE DISPERSAL HYPOTHESIS (Diamond & Bellwood 2003) proposes that the distribution of large language families throughout the world is the outcome of languages spreading across vast geographic areas in conjunction with the spread of cultivation systems and their practitioners from centers of agricultural innovation (Diamond & Bellwood 2003, Bellwood 2005). As a global explanation for linguistic and cultural diversity patterns, this mechanism for the dispersal of language in concert with agriculture has been hypothesized to occur in all parts of the world in which agriculture has independently arisen. The hypothesis is controversial, however, with scholars pointing out exceptions where language spreads have occurred in the absence of agriculture, indicating that farming is, at best, a partial but incomplete explanation (Campbell 2002, Ross 2006, Campbell & Poser 2008b, Hammarström 2010). Here we examine the history, geography, and subsistence patterns of the North American language family that has been proposed to exemplify the farming/language dispersal

\* The asterisk on author names indicates equal first authors. We are particularly grateful to Jane H. Hill for generously aiding in correcting the lexical data and performing cognate judgments, and answering numerous questions about Uto-Aztecan linguistics and prehistory. We thank Gabriela Garcia Salido for providing lexical data from Southeastern Tepehuan, and Chiara Barbieri for discussion, Hans Sell for graphical assistance with the maps, and the referees and editors for their comments.

hypothesis: Uto-Aztecan. By constructing phylogenetic trees, inferring the geography of protolanguages, and reconstructing the ancestral states of subsistence variables within this family, we uncover evidence that challenges the characterization of Uto-Aztecan expansion as an agriculture-driven language spread.

**1.2. PROPOSED SCENARIOS FOR UTO-AZTECAN ORIGINS.** The Uto-Aztecan language family is one of the largest in North America in terms of the number of individual languages, the number of speakers of those languages before European colonization, and the extent of its attested spatial range (Campbell 2002). However, its origins and dispersal have remained contested, with three contrasting scenarios, each of which places differing emphasis on the role of agriculture (Figure 1).

The **NORTHERN ORIGIN** scenario places the original Proto-Uto-Aztecan community in the area between Southern California's Mojave Desert and the Sonoran and Chihuahuan Desert regions of Arizona and northern Mexico, between 3,000 and 5,000 years before present (BP) (Lamb 1958, Fowler 1983, Campbell 1997, 2002). This northern hypothesis is supported by the reconstruction of flora and fauna terms to this biogeographic region in this time frame, and it argues that the Proto-Uto-Aztecs were primarily foragers and hunters. In this scenario, agriculture was adopted only after the Northern and Southern subfamilies of Uto-Aztecan diverged and the Southern languages migrated down into Mexico, acquiring agriculture on the way. This expansion was potentially caused by mid-Holocene Altithermal climate change between 7,000 and 4,500 BP, leading to desertification in the Sonoran Desert area (Carpenter Slaven & Sánchez 2013). This desertification may have led to the split between Northern Uto-Aztecan groups, who took refuge in the Great Basin, and Southern Uto-Aztecan groups, who went south to the area between the Mayo and Sinaloa Rivers (Carpenter Slaven & Sánchez 2013). The occurrence of agriculture in the Northern Uto-Aztecan Hopi culture is explained in the northern origin scenario by cultural diffusion of the maize cultivar across northern Mexico and into the American Southwest—a possibility that is consistent with migrations from the south into the Hopi community that feature in Hopi ethnohistory (Shaul 2014).

The second scenario, the **SOUTHERN ORIGIN**, recruits Uto-Aztecan as an exemplar of a farming-driven expansion (Bellwood 2001a, Hill 2001). In this scenario, the Proto-Uto-Aztecan community originated on the northern edge of Mesoamerica approximately 5,000 BP. The primary cultivation of maize, originally domesticated approximately 9,000 years ago in the Balsas River Valley of Southern Mexico (Piperno et al. 2009), enabled this Proto-Uto-Aztecan population to grow rapidly (Hill 2001). Geographically constrained by agricultural Otomanguean and Purépecha (Tarascan) populations to the south, population pressure fueled by sedentary cultivation forced a northward population movement, bringing both maize agriculture and Uto-Aztecan languages northward. Proponents of this scenario have argued that the ancestral Uto-Aztecan society was agriculturalist—a view supported by what they take to be the reconstruction of some agricultural terms to Proto-Uto-Aztecan (Hill 2001, 2002, 2007, 2011). The absence of agriculture in Uto-Aztecan communities of the Great Basin and California is explained in this southern origin scenario as the abandonment of cultivation upon entering climates incompatible with inherited cultivation techniques and the adoption of more locally efficient foraging techniques (Bellwood 2001b, Hill 2001).

More recently, a third **ANCIENT ORIGIN** scenario has proposed a much older origin of the Uto-Aztecan language family in the Great Basin (Merrill et al. 2009, Merrill 2012, 2013). This scenario posits that Proto-Southern Uto-Aztecan people were the first prac-



FIGURE 1. Map of languages and proposed homeland regions for the three competing scenarios for Uto-Aztecan origins.

tioners of maize agriculture within the larger family. Evidence in favor of this hypothesis includes the probable arrival of maize agriculture in the American Southwest by approximately 4,000 years ago (da Fonseca et al. 2015) and the lack of human mitochondrial DNA (mtDNA) signatures of Uto-Aztecan migration to the Southwest from Mesoamerica (Malhi et al. 2003, Kemp et al. 2010). Sound change and semantic evidence also call into question the reconstruction of maize terminology to Proto-Uto-Aztecan (Campbell 2002, Campbell & Poser 2008b, Merrill 2012). As these Southern Uto-Aztecan people advanced southward from the Arizona-Mexico border area into Mesoamerica, the southernmost groups adopted agriculture and spread it northward by cultural diffusion through a chain of Uto-Aztecan-speaking communities. To allow maize agriculture to reach Arizona and New Mexico by roughly 4,000 years ago within a diversifying Southern Uto-Aztecan clade, the ancient origin scenario argues that the time depth of Proto-Uto-Aztecan must be older—approximately 8,900 BP. This date remains highly controversial (Brown 2010, Hill 2010). Revisiting the biogeography of reconstructed flora and fauna terms in the context of archaeology, paleoclimate reconstruction, and an ancient date for the protolanguage, this theory places the original Uto-Aztecan community on the western edge of the Great Basin (Merrill et al. 2009) and argues that agriculture was adopted by Southern Uto-Aztecan groups and the Hopi of

the Southwest, but not by other Northern Uto-Aztecan groups because of environmental conditions, alternative resource strategies, and cultural adaptations.

Resolving this debate about the origins of the Uto-Aztecs has major implications for understanding the linguistic history of Western North America and the Americas more generally (Campbell 1997, Shaul 2014). At the time of European colonization, the languages of the Uto-Aztecan language family were in contact with members of more than a dozen other language families, as well as several language isolates or unclassified languages (Campbell 1997). The timing and dynamics of Uto-Aztecan language expansion may thus provide clues for resolving larger questions about prehistoric language movements and contacts in some of the world's most linguistically diverse regions, California and Mesoamerica (Hua et al. 2019). Here we apply Bayesian phylogenetic methods to a data set of basic vocabulary in order to shed light on the origin and homeland of these languages and to evaluate whether their origins can be strongly linked to agriculture.

## 2. MATERIALS AND METHODS.

**2.1. LINGUISTIC DATA.** Lexical data and cognate judgments are drawn from a variety of sources (Miller 1984, K. Hill 2011, Stubbs 2011), with gaps filled in by consulting unpublished and published word lists and dictionaries. Two historical linguists with expertise in Uto-Aztecan languages (J. H. Hill and L. Campbell) revised cognate judgments. In all, the word list comprised 121 items of basic vocabulary (e.g. basic verbs, body parts, colors, numbers) from thirty-four Uto-Aztecan language varieties (thirty-two languages and two modern varieties of Nahuatl; see Fig. 1 and table S1 in the online supplementary materials, at <http://muse.jhu.edu/resolve/175>). This sample includes similar numbers of Northern and Southern Uto-Aztecan languages and represents approximately 60% of documented Uto-Aztecan varieties (Hammarström et al. 2020). We added two Kiowa-Tanoan languages as plausible outgroups for the family—Kiowa-Tanoan has been proposed to be a sister group to Uto-Aztecan (e.g. Aztec-Tanoan; Whorf & Trager 1937, Davis 1979); however, we use these languages purely to help root the tree and consolidate the inference about the age and homeland of Uto-Aztecan, and not to support or test any claims about Aztec-Tanoan. From these word lists, 1,125 binary cognate sets and a total of 3,997 cognates were identified. In order to check the consistency of the expert cognate judgments, a comparison with state-of-the-art methods for automated cognate judgments (LexStat; List et al. 2017) was carried out with the help of LingPy v. 2.6.9 (List & Forkel 2022a) and LingRex v. 1.3.0 (List & Forkel 2022b).

All linguistic data (lexemes, cognate sets, information on sources) are curated on GitHub (<https://github.com/lexibank/utoaztecan>) and archived with Zenodo (DOI: 10.5281/zenodo.6867616) in the formats proposed by the Cross Linguistic Data Format initiative (CLDF; Forkel et al. 2018) and the Lexibank project (List et al. 2022). CLDF is based on a series of comma-separated values (CSV) files, which are easily loaded and usable in all programming languages and in data-analysis tools like Microsoft Excel.

**2.2. PHYLOGENETIC ANALYSIS.** We estimated time-dated phylogenies from the lexical cognate data using a Bayesian phylogenetic framework with the MARKOV CHAIN MONTE CARLO (MCMC) method implemented in BEAST v. 2.4.1 (Drummond & Bouckaert 2013, Bouckaert et al. 2014). We fitted two different models: a CONTINUOUS TIME MARKOV CHAIN MONTE CARLO (CTMC) model and a COVARION model. The CTMC is a simple model that allows cognates to be gained and lost at the same rate across the phylogeny (Bouckaert et al. 2012). To allow cognate gains and losses to vary in rate, we allowed them to be sampled from a gamma distribution with the shape parameter  $\alpha$  being

estimated from the data (Yang 1993). The covarion model allows cognates to be gained and lost at different rates on different branches by switching into an ‘on’ or ‘off’ state, essentially modeling bursts of cognate change (Penny et al. 2001).

We modeled each word (i.e. each meaning slot, comprising a variable number of cognate sets) with a separate site model and ascertainment correction following suggestions that the CTMC and covarion models fit the data better under this scheme (Alekseyenko et al. 2008, Chang et al. 2015). Using separate site models for individual words allows parameters used to model evolutionary processes to vary from lexical item to lexical item. Ascertainment corrections are used to resolve sampling bias related to unobserved traits. In lexical data this sort of bias typically arises due to the encoding of only those cognate sets that are found in the data, and the exclusion of cognate sets that are not found in the particular set of languages under examination. The correction alters the likelihood calculation to adjust for these exclusions. Both of these modeling decisions help to account for word-to-word variability in lexical data sets (see Hoffmann et al. 2021 for more details).

As our data include Classical Nahuatl recorded around 1555 CE in the *Vocabulario* of Fray Alonso de Molina (de Molina 1571), we used the BIRTH-DEATH SKYLINE tree prior (Stadler et al. 2013), rather than the simpler tree prior based on a constant-rate branching process (a.k.a. Yule process; Yule 1925). The skyline is a flexible tree prior that requires few assumptions about the evolutionary process but can handle ancient lineages (Hoffman et al. 2021). We parameterized this skyline prior with a sampling proportion of 60% (i.e. we assumed we had observed data from about 60% of the modern languages, based on the attested diversity in Glottolog v. 4.3; Hammarström et al. 2020). As population-size changes were not our primary concern, we specified a single epoch rather than attempting to infer population-size changes and variation in birth and death rates over time.

Because rates of language change vary substantially across lineages, we modeled rate variation using both a strict and relaxed clock model (Drummond et al. 2006). The strict clock allows only a single rate of change for each feature in all subgroups and at all points in history, and this rate is estimated from the data and calibrations rather than specified a priori like glottochronology. In contrast, the relaxed clock allows rates of change to vary across branches on the tree. In our case these branch rates are drawn from a log-normal distribution with mean and standard deviation estimated from the data, given the calibrations (see Maurits et al. 2019, Greenhill et al. 2020, or Hoffman et al. 2021 for more details).

To calibrate these clocks and to estimate divergence times, we used archaeological evidence, reconstructed plant names, and dated plant distributions to calibrate the date ranges for five nodes and one ancient language (see §2.3 below). Each of these calibrations was implemented as a date range on one or more languages that enforces a monophyletic constraint.

We ran these analyses for 100 million generations, sampling from the posterior distribution every 10,000 generations after removing the initial 10% of the generations as burn-in, since exploratory analyses indicated that this was sufficient for all analyses to reach stationarity with EFFECTIVE SAMPLE SIZES (ESS) for all critical parameters greater than 500. In order to compare the model fit of these analyses to the data, we used path-sampling (Baele et al. 2013) to estimate the marginal likelihood estimates for each analysis. Each path-sample ran for 10 million generations over a total of thirty path steps, setting burn-in to 10%. All analyses are available on Zenodo (DOI: 10.5281/zenodo.4691957).

**2.3. CALIBRATIONS: NORTHERN UTO-AZTECAN.** Both Fowler (1983) and Hill (2015) argue that the dispersal of Proto-Northern Uto-Aztecan speakers is unlikely to have occurred before the earliest attested dates of mesquite (*Prosopis* spp.) in the area ~3,490 BP. We implemented this calibration as a log-normal distribution ( $\mu = 500$ ,  $\sigma = 0.5$ ) offset by 2,790 years, such that the median age was 3,230 years with a 95% range from 2,960–3,970 years.

**TAKIC.** While the origins of the Takic group are still under active debate, there were clear markers of a major population change around 3,000 BP (Sutton 2009). Kerr (2004) argues that Takic speakers arrived on the southern Channel Islands (California) somewhere between 3,000 BP and 2,500 BP. Further, Fowler (1983) links the Takic language group to the Colorado Desert of Southern California, as these languages share a cognate for fan palms, which do not appear in this region before 2,800 BP (Koehler & Anderson 1995). To capture these possibilities, we implemented this calibration as a log-normal distribution ( $\mu = 510$  years,  $\sigma = 0.50$ ) offset by 2,526 years, such that the median age was 2,980 years with a 95% range from 2,690–3,730 years.

**TÜBATULABAL.** Garfinkel (2005) argues that Tübatulabal peoples can be found in the Kern Plateau and Isabella Basin, with continuous occupation dating back 2,500 years or longer. We implemented this as a log-normal calibration ( $\mu = 120$ ,  $\sigma = 1$ ) offset by 2,380 years, such that the median age was 2,450 years with a 95% range from 2,390–2,900 years.

**NUMIC.** The Numic group is commonly linked to an archaeological transition from ‘traveling’ sites to ‘processing’ sites (Bettinger & Baumhoff 1982) in the southern Sierra Nevada and eastern California, possibly linked to the Haiwee Period around 600 BCE (Garfinkel 2005). This transition manifests as more continuous site occupation in the region, as well as shifts in rock art and projectile points (e.g. the desert side-notched and cottonwood types; Garfinkel 2005, Delacorte 2008) and mitochondrial haplogroups (Kaestle & Smith 2001). We implemented this as a log-normal calibration ( $\mu = 120$ ,  $\sigma = 1$ ) offset by 1,280 years, such that the median age was 1,350 years with a 95% range from 1,290–1,800 years.

**NAHUAN.** The Nahuatl languages are widely thought to have originated in northern Mexico before migrating southward into central Mexico (Suárez 1983, Kaufman 2001). These languages all share cognate terms for traditionally Mesoamerican cultural traits, but there is ongoing debate about the timing of their entry into the Valley of Mexico relative to the fall of Teotihuacan ~500 CE (Suárez 1983, Dakin & Wichmann 2000, Kaufman 2001, Macri &Looper 2004). Kaufman (2001) suggests that the origins of this group could date back to about 400 BCE (~2,400 BP) to explain the large quantity of loanwords and contact-induced change between Nahuatl and Mixe-Zoquean languages, as well as influences from Huastecan and Totonacan. We implemented this as a log-normal calibration ( $\mu = 290$ ,  $\sigma = 0.7$ ) offset by 1,510 years, such that the median age was 1,740 years with a 95% range from 1,570–2,410 years. We chose this wide range because of the uncertainty on the age; it places the median origin time shortly before the fall of Teotihuacan but significantly later than the rise of Teotihuacan.

**CLASSICAL NAHUATL.** As our data set included Classical Nahuatl originally sourced from the dictionary of Alonso de Molina (1571), we specified a tip date of 445 BP for Classical Nahuatl. This 445 year age was chosen to place an approximate twenty-year time frame around this date.

**2.4. PHYLOGEOGRAPHIC ANALYSIS.** To infer the homeland of the Uto-Aztecan language family we applied Bayesian phylogeographic methods to the best-fitting model

(covarian with relaxed clock) and simulated a RELAXED RANDOM WALK in geographic space (Lemey et al. 2010). We incorporated point estimates of the present-day language locations and allowed these to evolve along branches on the tree to infer the locations of ancestral nodes (Bouckaert et al. 2012). We used two alternative phylogeographic methods: (i) a standard DIFFUSION-BASED model, in which daughter lineages disperse at equal rates following a lineage split (Lemey et al. 2010, Bouckaert et al. 2012), and (ii) a founder-event dispersal, or BREAK-AWAY model, in which only one daughter lineage disperses following a lineage split (Bouckaert et al. 2018). These two phylogeographic methods essentially infer ancestral locations and phylogenetic relationships between a set of languages using both cognate and geographic location data. Runs for each model were set for 100 million iterations, with a thinning rate of 100,000. The first 50% of the iterations were subsequently discarded as burn-in.

For each method, we performed 100 runs, each time using a different set of coordinates for the location of present-day languages. These sets were obtained by sampling random points within the estimated range of tip languages, using time-of-contact language range maps (Haynie & Gavin 2019). As Classical Nahuatl was spoken much earlier than the other languages in our sample and is not included in available language range data sets, we encoded the location of this language as a single-point estimate as specified in Glottolog (Hammarström et al. 2020). For each model, we also ran iterations informed only by the prior. The analyses were implemented in the software BEAST v. 2.6.0 (Drummond & Bouckaert 2013, Bouckaert et al. 2014).

Recent work by Neureiter et al. (2021) suggests that Bayesian phylogeographic methods perform well when the language group of interest undergoes a grid-based region-growing process, where languages occupy cells in a geographical grid and randomly expand into neighboring cells. This process, labeled as EXPANSION by Neureiter et al., consists of small-scale movements and results in a slow but steady spread of the language family. However, scenarios of directional movement in which populations and/or their languages completely leave their homelands (labeled as MIGRATIONS in Neureiter et al. 2021) can cause problems when reconstructing the ancestral homeland. Neureiter et al. propose quantitative tests to help distinguish between these two processes. The sample size of our data set limits the application of these statistics. However, all three hypotheses about the diversification of Uto-Aztecan languages fit the scenario of expansions rather than migrations. Further, including an outgroup should also alleviate potential issues of homeland reconstruction (Neureiter et al. 2021).

**2.5. RECONSTRUCTING SUBSISTENCE IN PROTO-UTO-AZTECAN SOCIETY.** To evaluate whether Proto-Uto-Aztecan was or was not an agricultural society we used ancestral-state reconstruction, a phylogenetic approach to infer the most probable value of a variable at a given point on the phylogeny (Evans et al. 2021). We identified four cultural variables in the *Ethnographic atlas* (Murdock 1967) provided by D-PLACE (Kirby et al. 2016) that were relevant to the question of Proto-Uto-Aztecan subsistence. These variables represent characteristics of preindustrial societies that are of interest for cross-cultural comparison, and they are coded with information extracted from ethnographies. Of the thirty-six language varieties on our phylogeny, there was matching ethnographic information for twenty-two in D-PLACE. D-PLACE had data for fifteen of seventeen of the Northern languages, fewer Southern languages (six of seventeen), and one of the outgroup languages (Kiowa). The time reference for the ethnographic data we include ranges from 1550 to 1960 CE, with a majority of groups represented in the time period of 1860–1870.

To facilitate phylogenetic reconstruction, we recoded these variables to reduce the number of categories (character states). Where there were multiple states for a given

language, we coded these as polymorphic, allowing all specified alternatives to remain present. For example, two societies in D-PLACE are identified as speaking Southern Paiute. For variable EA028 (Intensity of cultivation), one society was coded as #2 (Casual agriculture) and #6 (Intensive cultivation); we kept both of these alternatives in the analysis. For variable EA042 (Dominant mode of subsistence), the Tongva society was originally coded as ‘two or more sources contribute equally’; we converted this to being either Gathering or Hunting or Agriculture.

- EA005: DEPENDENCE ON AGRICULTURE, RELATIVE TO OTHER SUBSISTENCE ACTIVITIES. This variable measures ‘dependence on agriculture, relative to other subsistence activities’ and was originally coded as an ordinal variable. As we did not have all states of the variable present in the Uto-Aztecan languages and the ordinalization of this variable was somewhat arbitrary, we recoded this variable to represent two alternatives: high or low dependence on agriculture (see table S2 in the supplementary materials).
- EA028: INTENSITY OF CULTIVATION. This variable, which measures the intensity of cultivation, was recoded to group any type of extensive or intensive cultivation into these two basic categories (supplementary table S3).
- EA029: PRINCIPAL TYPE OF CROP CULTIVATED. This variable identifies the principal type of crop cultivated and was recoded simply to denote presence or absence of cereal crops (supplementary table s4).
- EA042: DOMINANT MODE OF SUBSISTENCE. This variable, which identifies the mode of subsistence most important to the society’s typical diet, is derived from the other variables in the *Ethnographic atlas* on subsistence and type of agriculture. We recoded this variable to ignore the distinction between the types of agriculture: intensive, extensive, or ‘unknown’ (supplementary table S5). Dominance of a particular subsistence activity does not mean that no other activity contributes substantially to the diet. It is common for foraging societies to hunt for some components of the diet, for example. This variable simply reflects the activity that results in the majority of calories in a group’s typical diet.

To calculate the probability of each of the ethnographic traits in Proto-Uto-Aztecan we used ancestral-state reconstruction. We fitted each trait onto each tree in the posterior using the ‘rayDISC’ function of the ‘corHMM’ v. 1.22 package (Beaulieu et al. 2013) in R v. 4.01 (R Core Team 2020). We used two different models: an EQUAL-RATES model, where all transition rates between character states were equal, and an ALL-RATES-DIFFERENT model, where transition rates of gains and losses between states were allowed to vary. For the two traits with three states (EA029 and EA042), we also applied a SYMMETRICAL RATES model, where gains and losses of each state have the same rate, while changes between states have a different rate. Note that for the traits with two states (EA005 and EA028) the symmetrical model is identical to the equal-rates model. Using these models, we estimated the marginal probabilities at each node, and allowed polymorphic and missing states in the cultural data following the method in Felsenstein 2004. Ascertainment bias was corrected for following Lewis 2001, and we set the root state probabilities following Maddison et al. 2007 and FitzJohn et al. 2009. To identify the best-fitting rates model for each character we used the AKAIKE INFORMATION CRITERION, with a correction for small sample size (AICc; Akaike 1974).

One possible concern with the above models is that the relatively small size of the phylogeny might mean that it is hard to obtain accurate estimates of the transition rates between the states of the ethnographic traits. We therefore also fitted each trait onto the

posterior distribution using a reversible jump Markov chain Monte Carlo method (RJ-MCMC) implemented in ‘BayesTraits’ (v. 3.0; Pagel & Meade 2004). In this context, the RJ-MCMC is a Bayesian approach that allows very small rates to go to zero and to be removed from the model to simplify it. Here we analyzed each variable for 10 million generations, setting burn-in to the first 10%. State frequencies were set to empirical, and transition rates were drawn from an exponentially distributed hyperprior from the range 0 to 10.

### 3. RESULTS.

**3.1. COGNATE EVALUATION.** In order to check the consistency of the expert cognate judgments and to assess whether methods that involve no ‘intuition, guesswork, and arguments from authority’ are superior in identifying evidence of relationships (Wheeler & Whiteley 2014:114), a comparison with state-of-the-art methods for automated cognate judgments (LexStat; List et al. 2017) was carried out with the help of the LingPy software (List & Forkel 2022a). This analysis shows an overwhelming agreement between words grouped into cognate sets by the automated approach and the expert annotations on the one hand (B-cubed precision from expert cognates to automated cognates of 0.95; List et al. 2017), while showing that the automated method fails to group words into deeper cognate sets on the other hand (B-cubed recall of 0.58).

A closer inspection of the deeper cognate sets in which the automated method differs from the experts’ cognate judgments shows that the majority of cases are well-established cognate sets that have long since been identified in the literature. The automated method fails to identify these deeper cognates for three main reasons. First, sound-correspondence information may not be available to the algorithm due to the size of the word lists, while experts base their cognate judgments on their knowledge of the data. Second, compound word forms tend to confuse cognate-detection methods, and the conversion of partially cognate word forms to full cognates cannot be done in a straightforward, automatic way at the moment (Wu & List 2023). Third, automated cognate-detection methods tend to have problems with the identification of cognate sets consisting of words small in length. A thorough point-to-point comparison of expert cognates and automated cognates is provided as part of the supplementary materials accompanying this study.<sup>1</sup>

In addition, we carried out a detailed analysis of the correspondence patterns that can be derived from both analyses, using a recently proposed method for the automated inference of sound-correspondence patterns (List 2019) implemented as part of the LingRex software package (List & Forkel 2022b). This analysis showed that the expert cognate judgments lead to a slightly increased proportion of cognate sets, which can be shown to be formally regular in the data set when taking only internal information into account (15% vs. 10%). In addition, the regular cognates inferred by the expert analysis cover a much larger proportion of the words in the database (12% vs. 3%). All in all, this suggests that the expert analysis is superior to the purely automated analysis, which emphasizes the important role that expert cognate judgments play in the preparation of linguistic data for phylogenetic analyses. This provides evidence against previous claims which argue that fully automated analyses would result in more objective inferences (Wheeler & Whiteley 2014).

**3.2. PHYLOGENETIC ANALYSIS.** We evaluated all of the phylogenetic analyses using trace plots in the software package Tracer (Rambaut et al. 2018). These trace plots indi-

<sup>1</sup> The supplementary materials can be accessed at <http://muse.jhu.edu/resolve/175>.

cated that all analyses had converged and reached stability, and all parameters had ESS values greater than 500.

Model comparison via path-sampling indicated that the best-fitting model was the covarion with relaxed clock, with decisive support as measured by a BAYES FACTOR (BF; Kass & Raftery 1995) of 36 for this model over the next best-fitting model, the covarion with strict clock (Table 1).

| MODEL        | CLOCK   | MARGINAL LOG<br>LIKELIHOOD | BAYES<br>FACTOR |
|--------------|---------|----------------------------|-----------------|
| Covarion     | relaxed | −8856                      | —               |
| Covarion     | strict  | −8893                      | −36.25          |
| CTMC         | relaxed | −9162                      | −269.19         |
| CTMC + gamma | relaxed | −9179                      | −17.45          |
| CTMC         | strict  | −9199                      | −19.69          |
| CTMC + gamma | relaxed | −9207                      | −8.54           |

TABLE 1. Phylogenetic models and model comparison showing the marginal log likelihood and Bayes factor for each model compared to the best-fitting model.

To assess whether the addition of date information via node calibration affected the tree topology, we ran the best-fitting model (covarion with relaxed clock) without the dated nodes. Date calibrations are best handled in BEAST by requiring the dated node to occur in the tree as the common ancestor of a set of daughter languages (a.k.a. a monophyly constraint). However, if the data do not support the existence of a given node, then using it as a calibration is problematic. Fortunately, in this analysis each of the nodes that included a time calibration was well supported in the best-fitting model, with each having a posterior probability of  $p = 1.00$ . The sole exception was Proto-Northern Uto-Aztecan, which had a posterior probability of  $p = 0.82$ . This result indicates that the calibrations did not affect the tree topology.

**3.3. UTO-AZTECAN SUBGROUPING.** There is widespread agreement about the internal classification of Uto-Aztecan based on the linguistic comparative method’s ‘gold standard’ of shared phonological innovations for identifying subgroups (Campbell 1997, Hill 2012, Merrill 2013), as well as grammatical innovations (Langacker 1977). This agreement holds despite the fact that these classifications have been developed by defenders of the northern origin (Campbell 1997), southern origin (Hill 2001, 2012), and ancient origin homeland hypotheses (Merrill et al. 2009, Merrill 2013). We compared the inferred subgroups under the best-fitting model from our unconstrained analyses (i.e. the analyses that do not enforce monophyly on age-calibrated nodes) to these proposals (we do not discuss branches with posterior probabilities less than 0.50 because the evidence for these groupings is weak). We find a striking level of congruence between our results and the classifications proposed on the basis of widely endorsed shared phonological innovations.

**NORTHERN UTO-AZTECAN.** Phonological evidence for the Northern Uto-Aztecan group is good, with one strong and three plausible shared phonological innovations (Heath 1977, Hale & Harris 1979, Manaster Ramer 1992a, Hill 2012). Evidence of distinct Proto-Northern Uto-Aztecan and Proto-Southern Uto-Aztecan morphophonological processes and grammatical morphemes bolsters this phonological evidence (Heath 1977). However, quantitative studies have shown equivocal results for this group, with two studies that use distance-based methods contradicting each other (i.e. Cortina-Borja & Valiñas 1989 vs. Haugen et al. 2020). Our results, based on more powerful character-

based methods, find strong support for this grouping. Note that we enforce a calibration on this node in our main results (Figure 2) and therefore find a posterior probability of 1.0 for this subfamily in that analysis. However, Northern Uto-Aztecan is still present in the unconstrained analysis with a probability of 0.82, indicating that we find good support for this subgroup based on our lexical cognate data.

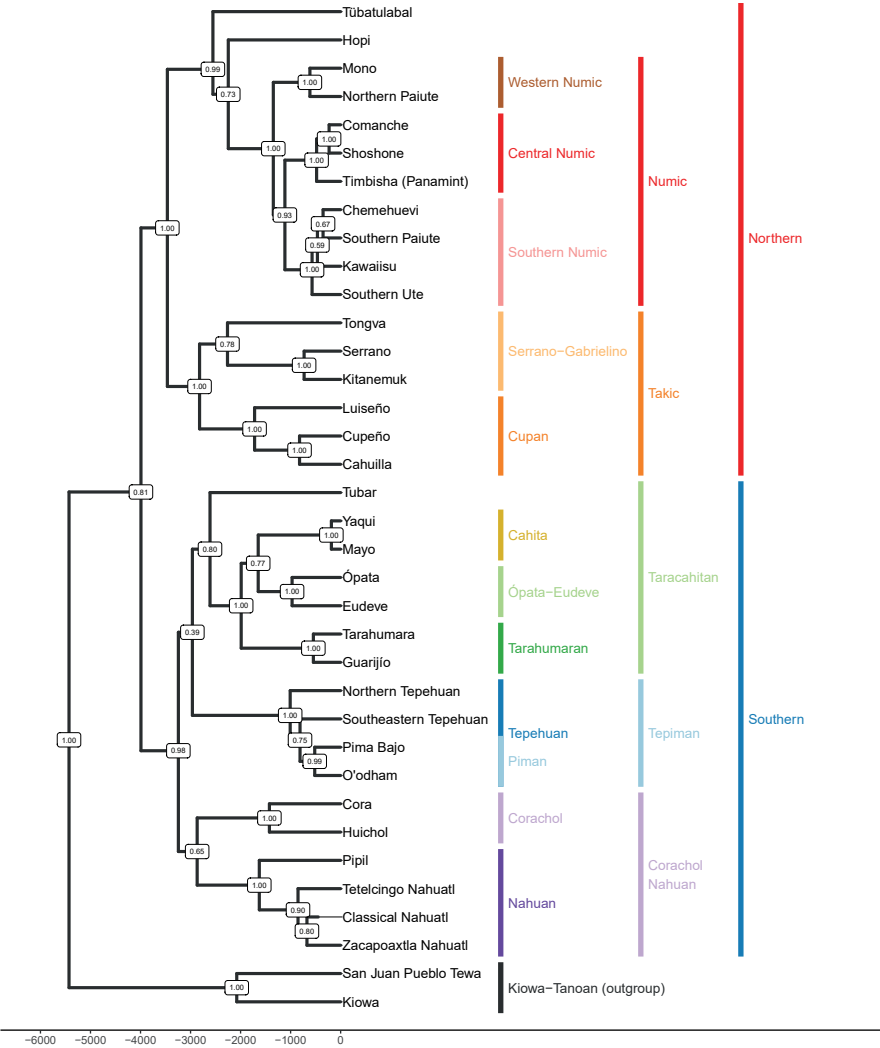


FIGURE 2. The maximum clade credibility tree of the Uto-Aztecan languages (and outgroup). Clades represented by vertical bars to the right of the tree are labeled according to language subgroup membership. This tree is a summary tree of the full posterior probability distribution, and the numbers on branching nodes indicate posterior probability support for each node. This probability varies from 0.00 to 1.00, with higher numbers indicating more support for the node in the full posterior distribution; values about 0.80 are considered well supported.

NUMIC. While there is little phonological evidence for a Numic subgroup, it is widely accepted (Campbell 1997, Hill 2012, Merrill 2013). We find strong support for this subgroup ( $p = 1.00$ ). It is also widely accepted that Numic itself comprises three sub-

groups: (i) Western Numic: Mono and Northern Paiute; (ii) Southern Numic: Southern Ute, Kawaiisu, Chemehuevi, and Southern Paiute; and (iii) Central Numic: Timbisha, Comanche, and Shoshone. We find strong evidence for all three of these groups: Western Numic ( $p = 1.00$ ), Southern Numic ( $p = 1.00$ ), and Central Numic ( $p = 1.00$ ). In addition, we find moderate support for a subgroup consisting of Central Numic and Southern Numic ( $p = 0.93$ ), which is consistent with suggestive evidence for this classification (Freeze & Iannucci 1979).

**TAKIC.** There is evidence for a Takic subgroup composed of Cupan and Serrano-Gabrielino (Campbell 1997, Hill 2012, Merrill 2013), despite there being no strong proposals for phonological innovations (Kenneth Hill, p.c. reported in Shaul 2014). We find strong support for this subgroup ( $p = 1.00$ ).

**CUPAN.** We find strong support ( $p = 1.00$ ) for a Cupan subgroup composed of Cahuilla, Cupeño, and Luiseño (Bright & Hill 1967, Munro 1990).

**TÜBATULABAL AND HOPI.** There is widespread agreement that Tübatulabal and Hopi are Northern Uto-Aztecan languages. Two contemporary classifications represent Tübatulabal and Hopi as separate clades within Northern Uto-Aztecan (Campbell 1997, Merrill 2013), and a third represents Hopi as a separate subgroup of its own and Tübatulabal as part of a proposed Californian subgroup comprising a Takic subgroup and Tübatulabal (Hill 2012). No single set of sound changes or innovations confirms the Californian subgroup (Hill 2012); nevertheless, there is tentative evidence of a shared reanalysis of the form *\*taka-ta* ‘man’ and a possible innovated word *\*cicacV* ‘one, only’ found in Tübatulabal and Serrano, though the latter may in fact constitute a Proto-Uto-Aztecan retention (Manaster Ramer 1992b, 1993, Stubbs 2011). Our analysis does not recover the Californian subgroup. Instead, we find surprisingly strong support ( $p = 0.99$ ) for a subgroup comprising Numic, Tübatulabal, and Hopi. Furthermore, within this subgroup we find moderate support ( $p = 0.73$ ) for a subgroup consisting of Numic and Hopi.

Although the placement of Tübatulabal and Hopi in our phylogeny is somewhat unexpected, two factors suggest that a subgroup composed of Numic, Tübatulabal, and Hopi could be genuine. First, Hopi must be placed nearer one subgroup than another (phylogenetic inference does not output polytomies, or nodes with more than two branches), so a placement nearer Numic than Takic is equally consistent with contemporary classifications as a placement nearer Takic than Numic. Second, the Californian subgroup proposal is not well established, and two out of three contemporary Uto-Aztecan classifications do not endorse it (Campbell 1997, Merrill 2013). Nevertheless, it is possible that unidentified lexical borrowings may have resulted in an incorrect placement of Tübatulabal.

In the absence of clear phonological evidence for the position of Hopi and Tübatulabal, we have reason to believe that the analysis presented here improves upon prior application of computational methods to infer the structure of Uto-Aztecan and Northern Uto-Aztecan in particular. Four earlier studies used distance-based methods to make inferences about Uto-Aztecan classification using cognate data (Miller 1984, Cortina-Borja & Valiñas 1989, Haugen et al. 2020) or lexical similarity data (Holman et al. 2011). These distance-based methods have been roundly critiqued for failing to handle variation in rates of language change (Bergsland & Vogt 1962, Greenhill & Gray 2009) and for an inability to tease apart common ancestry and contact when making inferences, which can result in serious errors in classification (Blust 2000, Campbell & Poser 2008a). Not only is the tree inferred by the present analysis much closer to those

proposed by specialists (Campbell 1997, Hill 2012, Merrill 2013) than the trees inferred by these distance-based methods, but the phylogenetic inference implemented here is also less susceptible to the biases that have prompted criticism of distance-based classifications of Northern Uto-Aztecan languages.

One particular problem for distance-based classifications of Northern Uto-Aztecan is the lexical diversity of Takic languages, which include in their basic vocabularies a greater number of items that cannot be traced to Uto-Aztecan origins or non-Uto-Aztecan neighbors than the Numic languages, possibly due to effects of language spread and shift (Hill 2015). This has prompted concerns that distance-based classifications may treat Takic as misleadingly divergent (Bright & Bright 1969, Hill & Hill 2019). While these same lexical characteristics may to some extent influence our finding that Hopi and Tübatulabal are placed nearer to Numic than to Takic, we expect a character-based method that allows rates of change across lineages and lexemes to have greater sensitivity than a distance-based approach to the signal that does exist in shared cognates (Greenhill & Gray 2009).

**SOUTHERN UTO-AZTECAN.** Traditionally, a Southern Uto-Aztecan grouping is established on the basis of both lexical innovations (Campbell & Langacker 1978a,b) and two phonological innovations (Heath 1977, Miller 1984, Merrill 2013). However, this classification was not accepted by Hill (2012), and a previous computational cladistic study (Wheeler & Whiteley 2014) did not find support for the unity of this grouping. Our results are in line with the traditional grouping in finding strong support for Southern Uto-Aztecan ( $p = 1.00$ ), as does a recent survey of non-Bayesian distance-based phylogenetic methods (Haugen et al. 2020).

**TARACAHITAN.** The proposed Taracahitan subgroup includes as its members the smaller subgroups of Cahitan, Eudeve-Ópata, Tarahumaran, and Tubar, with the primary evidence coming from lexical cognate density (Miller 1984). However, this subgroup has not been supported by shared phonological innovations (Hill 2012), and the placement of Tubar is uncertain because it is extinct and poorly documented. In fact, Tubar's affiliation has been described as 'enigmatic' (Stubbs 2011:7). Our results find moderate support for a Taracahitan subgroup ( $p = 0.80$ ), with Tubar being the first branch to diverge in this subgroup.

Within Taracahitan, there are suggestions that similarities in morphology indicate that Eudeve-Ópata and Cahitan form a subgroup (Shaul 1986); however, these similarities are retentions, not innovations, and therefore do not provide strong evidence (Hill 2012). Nevertheless, our results (based on lexical cognates) find moderate support ( $p = 0.77$ ) for this subgroup.

**TARAHUMARAN, CAHITAN, EUDEVE-ÓPATA.** Finally, we find strong support for the constitutive Tarahumaran (Guarijo, Tarahumara;  $p = 1.00$ ), Cahitan (Mayo, Yaqui;  $p = 1.00$ ), and Eudeve-Ópata (Eudeve, Ópata;  $p = 1.00$ ) subgroups, all of which are widely endorsed due to shared phonological innovations (Campbell 1997, Hill 2012, Merrill 2013).

**TEPIMAN.** Tepiman (Northern Tepehuan, O'odham, Pima Bajo, Southeastern Tepehuan) is an uncontroversial subgroup based on shared phonological innovations (Campbell 1997, Hill 2012, Merrill 2013). We find strong support for this subgroup ( $p = 1.00$ ).

**CORACHOL.** Corachol (Cora, Huichol) is a well-established subgroup supported by two shared phonological innovations (Campbell & Langacker 1978a,b). We find strong support for this subgroup ( $p = 1.00$ ).

NAHUAN. Nahuatl (Pipil, Tetelcingo Nahuatl, Zacapoaxtla Nahuatl, Classical Nahuatl, and Pochutec) is a well-established subgroup supported by shared phonological innovations (Campbell & Langacker 1978a,b). We find strong support for this subgroup ( $p = 1.00$ ). We recognize that there is some uncertainty regarding the categorization of Nahuatl varieties as distinct languages or sets of dialects. The close relationship between Nahuatl varieties is reflected in our finding that Classical Nahuatl, Tetelcingo Nahuatl, and Zacapoaxtla Nahuatl form a clade within the Nahuatl subgroup.

CORACHOL-NAHUAN. On the basis of evidence for four shared phonological innovations it has been argued that the Corachol and Nahuatl branches are linked in a more inclusive Corachol-Nahuatl subgroup (Campbell & Langacker 1978a,b). Though the similarities between these languages have been argued to result from contact (Dakin 1983, Kaufman 2001, Hill 2012), recent work provides additional support for the Corachol-Nahuatl subgroup (Pharao Hansen 2020). Our results find weak support for this subgroup ( $p = 0.65$ ), consistent with Campbell and Langacker (1978a,b) and Pharao Hansen (2020).

**3.4. AGE OF UTO-AZTECAN.** Under the best-fitting model (covarion with relaxed clock), Proto-Uto-Aztecan is estimated to have a mean age of 4,095 BP, with a 95% highest posterior density interval (HPD) between 3,258 and 5,025 years ago (Table 2). This age estimate of around 4,000 years is consistent across all of the phylogenetic models, including the phylogeography, averaging between 3,825 and 5,395 years (Table 2 and Figure 3). The oldest age range was estimated under the covarion model with a strict clock at 5,395 years (95% HPD = 4,641–6,185). Therefore none of the analyses find an age range consistent with the ancient origin scenario, but instead are consistent with the two younger scenarios (northern and southern origins).

| MODEL                               | CLOCK   | MEAN AGE | 95% HPD INTERVAL |         |
|-------------------------------------|---------|----------|------------------|---------|
|                                     |         |          | MINIMUM          | MAXIMUM |
| Covarion                            | relaxed | 4,095    | 3,258            | 5,025   |
| Covarion                            | strict  | 5,395    | 4,641            | 6,185   |
| CTMC + gamma                        | relaxed | 4,118    | 3,261            | 5,115   |
| CTMC + gamma                        | strict  | 5,387    | 4,584            | 6,183   |
| CTMC                                | relaxed | 4,044    | 3,240            | 5,020   |
| CTMC                                | strict  | 5,317    | 4,538            | 6,139   |
| Phylogeography (standard diffusion) | relaxed | 3,825    | 3,265            | 4,820   |
| Phylogeography (break-away)         | relaxed | 4,063    | 3,347            | 5,181   |

TABLE 2. Estimated age of Proto-Uto-Aztecan across all models of language evolution.

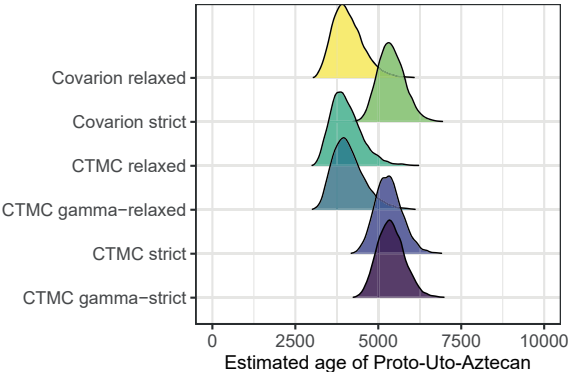


FIGURE 3. Estimated age of the Proto-Uto-Aztecan language family.

**3.5. PHYLOGEOGRAPHIC ANALYSIS.** For the two phylogeographic analyses, we assessed convergence of parameters using trace plots in the software package Tracer v. 1.7.1 (Rambaut et al. 2018), and all critical parameters had ESS values greater than 200, indicating that convergence was achieved. When summarizing the results for the standard diffusion model, we discarded iterations that inferred a nonterrestrial homeland for the group ( $n = 6954/50100$ , 13.8%). The standard diffusion-based model shows an estimated age of the breakup of Proto-Uto-Aztecan at a mean of 3,993 BP (95% HPD = 3,265–4,820 BP). This range comfortably overlaps with ages for the breakup proposed by the northern origin (3,000–5,000 BP) and southern origin (2,900–5,000 BP) hypotheses. However, this age range strongly rules out the ancient origin hypothesis (8,900 BP). Further, the most probable pair of coordinates for the homeland of the Proto-Uto-Aztecan linguistic community is represented by a latitude of 34.77 and a longitude of  $-116.67$  (Figure 4 and figure S1 in the supplementary materials). These coordinates place the Uto-Aztecan homeland within a region near those presented by the ancient origin and northern origin scenarios, but do not provide strong support for the location proposed by the southern origin scenario.

The break-away (founder-event dispersal) model showed an estimated age for the breakup of Proto-Uto-Aztecan at 4,063 BP (95% HPD = 3,347–5,181 BP). These results

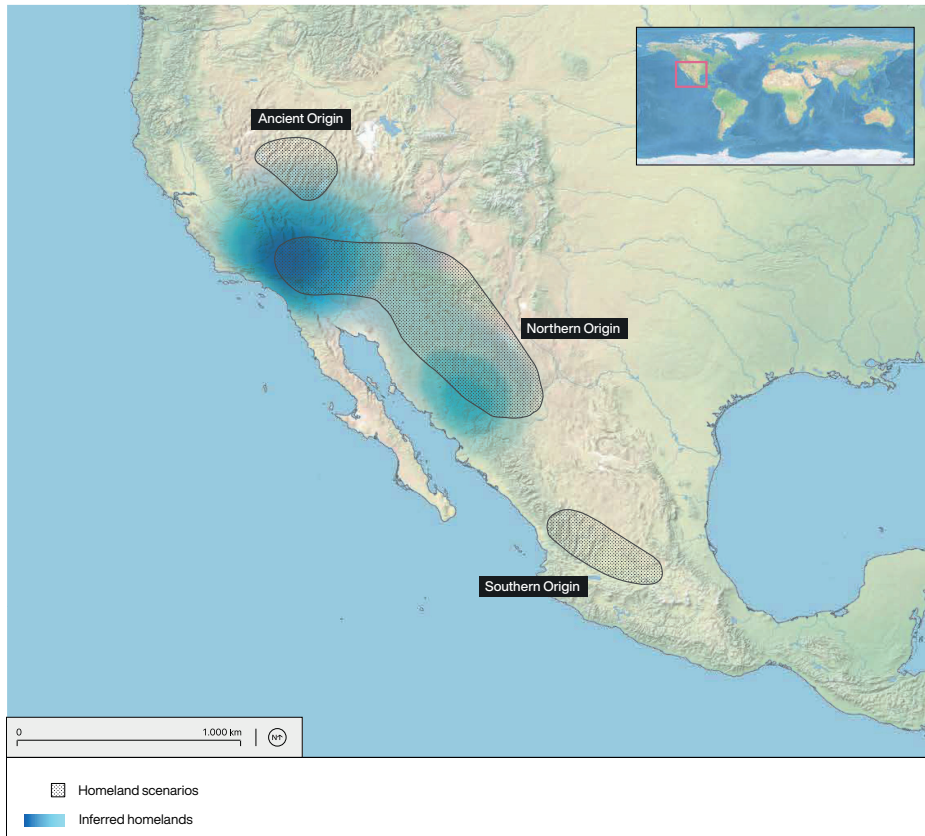


FIGURE 4. Map showing the inferred homeland of the Uto-Aztecan languages under the standard diffusion phylogeographic model. Gray regions indicate the proposed origins of the language family under the three homeland scenarios. The region of blue is the kernel density estimate of the inferred homeland.

are similar to the estimates of the standard diffusion model, and accordingly the estimated age interval is consistent with the northern and southern origin hypotheses, but does not provide support for the ancient origin hypothesis (supplementary figure S2). The break-away model, however, did not converge on a single best solution for the ancestral location of Uto-Aztecan. Rather, the density estimates for the latitude and longitude are bimodal and identify two potential homelands, defined by: (i) 27.65 latitude and -108.25 longitude, and (ii) 34.75 latitude and -118.15 longitude, similar to the solution inferred by the standard diffusion-based model. The highest density estimate based on the distribution of latitudes alone has a value of 27.65, whereas the highest density estimate based on the distribution of longitudes alone has a value of -118.15. However, under the break-away model, the universe of possible locations for the ancestral homeland is restricted to the locations of present-day languages. We note that none of these can be identified by a pair coordinate of 27.65 and -118.15, and thus it is likely that the constraints of the break-away model prevent it from identifying a single best solution for the ancestral homeland in our data set. Alleviating such limitations likely allows the standard diffusion-based model to converge on a single most probable solution.

**3.6. RECONSTRUCTING SUBSISTENCE IN PROTO-UTO-AZTECAN SOCIETY.** Fitting the ethnographic data onto the phylogeny using AICc indicated that the best-fitting model across the 1,000 trees in the posterior was almost always the equal-rates model (Table 3, Figures 5 and 6). For EA005 (Dependence on agriculture, relative to other subsistence activities), 1,000 of 1,000 trees preferred the equal-rates model (average AICc across 1,000 replicates = 17.7, *SD* = 0.90) over the all-rates-different model (average AICc = 18.4, *SD* = 0.97). For EA028 (Intensity of cultivation), 664 of 1,000 trees preferred the equal-rates model (average AICc = 32.2, *SD* = 2.34) over the symmetrical (average AICc = 32.3, *SD* = 1.81) and all-rates-different models (average AICc = 41.2, *SD* = 2.06). For EA029 (Principal type of crop cultivated), 991 of 1,000 trees preferred the equal-rates model (average AICc = 26.8, *SD* = 1.46) over the symmetrical (average AICc = 26.8, *SD* = 1.47) and all-rates-different models (average AICc = 27.8, *SD* = 1.73). For EA042 (Dominant mode of subsistence), 990 of 1,000 trees preferred the equal-rates model (average AICc = 33.0, *SD* = 1.82) over the symmetrical (average AICc = 36.4, *SD* = 1.37) and all-rates-different models (average AICc = 44.0, *SD* = 1.66).

| VARIABLE | LABEL  | MODEL | LIKELIHOOD | <i>SD</i> | AICc | <i>SD</i> |
|----------|--|-------|------------|-----------|------|-----------|
| EA005    | Dependence on agriculture,<br>relative to other subsistence activities | ER    | -7.73      | 0.448     | 17.7 | 0.897     |
|          |  | ARD   | -6.88      | 0.483     | 18.4 | 0.965     |
| EA028    | Intensity of cultivation   | ER    | -14.99     | 1.170     | 32.2 | 2.340     |
|          |  | SYM   | -12.48     | 0.905     | 32.3 | 1.810     |
|          |  | ARD   | -11.79     | 1.030     | 41.2 | 2.061     |
| EA029    | Principal type of crop cultivated                                      | ER    | -12.32     | 0.729     | 26.8 | 1.458     |
|          |  | SYM   | -12.32     | 0.735     | 26.8 | 1.470     |
|          |  | ARD   | -11.57     | 0.866     | 27.8 | 1.731     |
| EA042    | Dominant mode of subsistence   | ER    | -15.41     | 0.910     | 33.0 | 1.820     |
|          |  | SYM   | -14.55     | 0.685     | 36.4 | 1.370     |
|          |  | ARD   | -13.22     | 0.833     | 44.0 | 1.666     |

TABLE 3. Cultural character models showing, for each variable, the mean log likelihood and standard deviation (*SD*) and mean Akaike information criterion (corrected for small sample size, AICc) and standard deviation. Models are equal rates (ER), symmetrical (SYM, for characters with three states), and all rates different (ARD).

We therefore focus on the results for the equal-rates model here, as the model comparisons strongly support this model over the others. We also report the RJ-MCMC results,

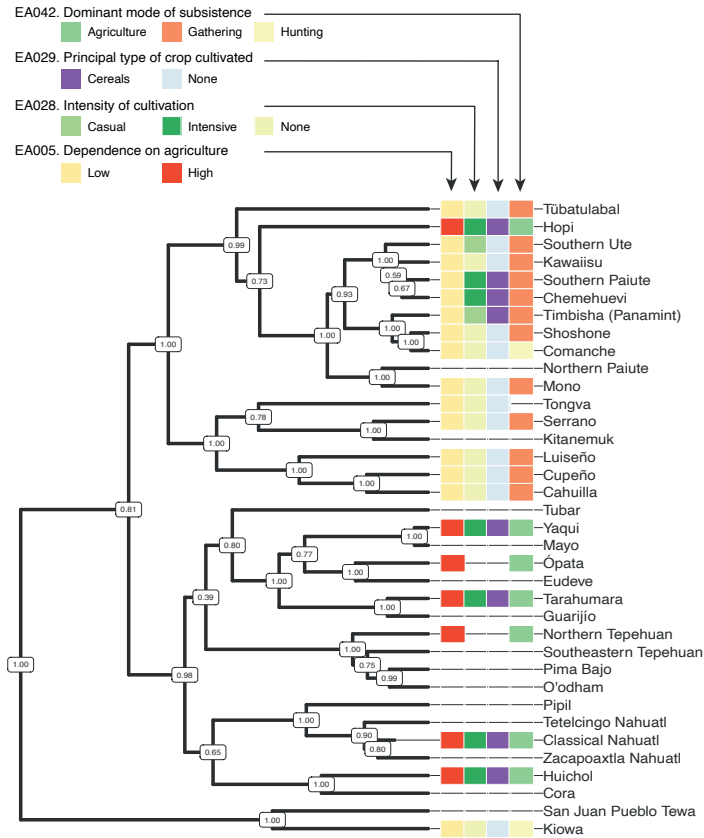


FIGURE 5. The maximum clade credibility summary tree showing the ethnographic data mapped onto the languages. Colored boxes indicate the value of the variable, where data is available, and numbers on the nodes of the tree indicate the posterior probability support for that particular grouping.

as they provide a useful comparison. However, the results for all models are presented in supplementary tables S6–S9 and are qualitatively the same. To summarize the results, we calculated the median probability (as the distributions are markedly asymmetric) and standard deviation across the entire posterior probability distribution.

In EA005 (Dependence on agriculture, relative to other subsistence activities), the most probable state for Proto-Uto-Aztecan was ‘Low dependence’ (median probability across the 1,000 trees in the posterior of 0.92,  $SD = 0.18$ ). The RJ-MCMC results were consistent with this, although with slightly weaker support for a low dependence on agriculture in Proto-Uto-Aztecan (median probability = 0.69,  $SD = 0.26$ ).

In EA028 (Intensity of cultivation), the most probable state for Proto-Uto-Aztecan was ‘None’ (median probability = 0.92,  $SD = 0.17$ ). This is supported by the RJ-MCMC results, which also estimated ‘None’ (median probability = 0.95,  $SD = 0.23$ ).

In EA029 (Principal type of crop cultivated), the most probable state for Uto-Aztecan was ‘None’ (median probability = 0.71,  $SD = 0.16$ ), followed by ‘Cereals’ (median probability = 0.29,  $SD = 0.16$ ). This is the most equivocal result, but the all-rates-different model actually strengthens the support for no cereal crops in Proto-Uto-Aztecan (median probability = 1.0,  $SD = 0.19$ ). Likewise, the RJ-MCMC results are more equivocal here, with the analysis finding ‘None’ to be only slightly more likely (median probability = 0.60,  $SD = 0.19$ ) than ‘Cereals’ (median probability = 0.40,  $SD = 0.19$ ).

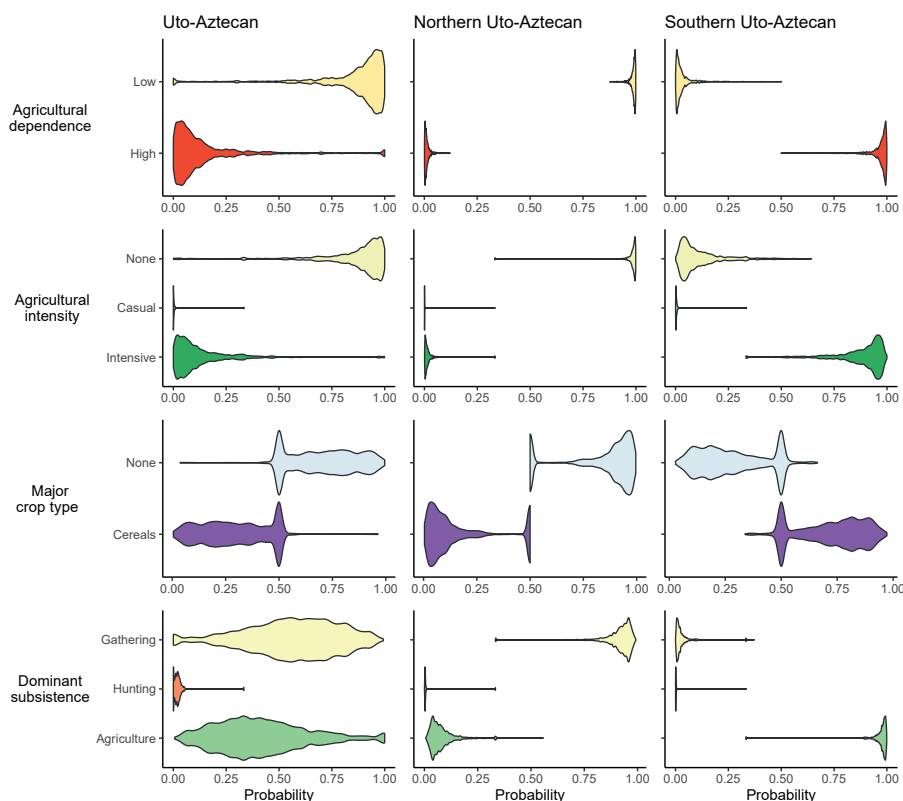


FIGURE 6. Probability of ethnographic traits in the ancestral Proto-Uto-Aztecan society as well as Proto-Northern and Proto-Southern Uto-Aztecan across the full posterior probability distribution. The ancestral Uto-Aztecan society very probably had low dependence on agriculture and no agricultural intensity, it was unlikely to have cereal crops, and the dominant subsistence strategy was most likely to be gathering. This pattern is likely to have held in the Northern Uto-Aztecan group, while the Southern Uto-Aztecan group is more likely to have had a dependence on intensive agriculture and cereal crops.

In EA042 (Dominant mode of subsistence), the most probable state for Proto-Uto-Aztecan was ‘Gathering’ (median probability = 0.58,  $SD = 0.22$ ), followed by ‘Agriculture’ (median probability = 0.39,  $SD = 0.22$ ). Again, this result in favor of a nonagricultural society is strengthened in the symmetrical and all-rates-different models (median probabilities of ‘Gathering’ = 0.91,  $SD = 0.19$ , and 1.00,  $SD = 0.21$ , respectively). The RJ-MCMC analyses concur and find overwhelming support for ‘Gathering’ (median probability = 0.97,  $SD = 0.31$ ).

**4. DISCUSSION.** To test the competing scenarios for Uto-Aztecan origins, we applied Bayesian phylogenetic methods (Bowerman 2018, Greenhill et al. 2020) to infer the sub-grouping, age, and homeland of the Uto-Aztecan language family. We collected lexical data for 121 items of basic vocabulary from thirty-two Uto-Aztecan languages (plus two additional Nahuatl varieties) and two languages from a neighboring group, Kiowa-Tanoan. These items were coded for cognacy following the linguistic comparative method (Durie & Ross 1996), in consultation with linguistic experts on these languages. We then fitted six different phylogenetic models of cognate evolution to these data to infer the sub-grouping and timing of Uto-Aztecan. The resulting tree topology

(Fig. 2 above) correctly recovers most of the major subfamilies found in the historical linguistic literature, suggesting that our results are consistent with our current understanding of the internal subgrouping. The best-fitting model inferred the age of Uto-Aztecan to be a mean of 4,095 BP with a 95% HPD interval of 3,258–5,025 BP (Fig. 3). All of the other models were broadly consistent with these ages (Table 2). The timing of this breakup of Proto-Uto-Aztecan is consistent with both the northern and southern origin scenarios, but the age is considerably younger than that suggested by the ancient origin scenario.

Using the best-fitting model—the covarion (Penny et al. 2001) with a relaxed clock (Drummond et al. 2006)—we then applied two phylogeographic models to these data by incorporating language area locations at approximately the time of contact with Europeans. Our results place the likely geographic origin for the Uto-Aztecan language family in or near what is now Southern California (Fig. 4), with the most probable coordinates being a latitude of 34.50 and a longitude of  $-116.96$ . These results place the homeland in a region that matches the northern origin scenario and extends with lower probability to parts of the region associated with the ancient origin, but provides little support for the southern origin.

The structure of our phylogenetic tree places Hopi within a clearly delineated Northern Uto-Aztecan clade. This finding would be consistent with proposals that certain agricultural terms in the Hopi lexicon reflect inheritance of agriculture from a Proto-Uto-Aztecan ancestor into an ancestral Northern Uto-Aztecan language (Hill 2001, 2007). However, the putative cognates for Hopi maize agriculture terms have been challenged on the basis of sound correspondence and semantic fit, casting doubt on the reconstruction of maize-related meanings in Proto-Uto-Aztecan (Campbell 2002, Merrill 2012).

The position of Hopi in our Uto-Aztecan phylogeny also complicates a scenario in which Proto-Uto-Aztecan agriculture would have been abandoned by Northern Uto-Aztecan people as a consequence of moving into environments less compatible with agriculture. Not only are Numic and Takic forager communities located near the Uto-Aztecan homeland throughout the family's history, but for Hopi to have retained agriculture from Proto-Uto-Aztecan, there would have to be two independent losses of agriculture in the two main branches of Northern Uto-Aztecan: Takic and Numic. Alternatively, Hopi could have obtained agriculture via borrowing from a non-Uto-Aztecan source after Hopi, Numic, and Takic had diverged from a nonagricultural Proto-Uto-Aztecan.

To formally test whether agriculture can be reconstructed to ancestral Uto-Aztecan society, we extracted ethnographic data from the D-PLACE database (Kirby et al. 2016) for four variables linked to subsistence type: intensity of agriculture, presence of cereal grain crops, dominant subsistence activity, and low-to-zero or high dependence on agriculture (Fig. 5). We fitted these data onto the posterior probability distribution of language trees to infer the most probable ancestral states (Fig. 6). Overwhelmingly, we found support in Proto-Uto-Aztecan for no casual or intensive cultivation (median probability of no intensity = 0.92,  $SD = 0.40$ ), an absence of cereal crops (median probability = 0.61,  $SD = 0.29$ ), the majority of the diet from gathering (median probability = 0.57,  $SD = 0.39$ ), and low-to-zero agricultural dependence (median probability of low agriculture = 0.92,  $SD = 0.44$ ). A similar pattern of agricultural absence is found in the Northern Uto-Aztecan group, indicating that this group was also nonagriculturalist (Fig. 4, supplementary tables S6–S9). We infer that these historical groups relied heavily on foraging, most likely augmented with hunting, for their subsistence. In stark contrast, however, the Southern Uto-Aztecan languages show a strong association with agriculture, with the

most probable configuration of traits indicating intensive cultivation (median probability = 0.92,  $SD = 0.12$ ), presence of cereal crops (median probability = 0.75,  $SD = 0.15$ ), the majority of the diet from agriculture (median probability = 0.98,  $SD = 0.07$ ), and high agricultural dependence (median probability = 0.98,  $SD = 0.05$ ).

Our results find strong evidence of a Southern Uto-Aztecan group ( $p = 1.00$ ), consistent with lexical and phonological innovations (Heath 1977, Campbell & Langacker 1978a,b, Miller 1984, Merrill 2013) and a recent survey of classifications done by non-Bayesian computational approaches (Haugen et al. 2020). In contrast, a recent cladistic study (Wheeler & Whiteley 2014) does not recover the Southern Uto-Aztecan group but places the Nahuatl languages outside the Southern subgroup, at the base of the tree. The authors therefore interpret their results as supporting the southern origin scenario. However, they model sound change within lexical data as a sequence alignment, and there are compelling reasons to believe their results are therefore problematic. First, this approach is likely to be heavily affected by the lexical morphology of the raw data, since not all words can be truly aligned (Schweikhard & List 2020). Our evaluation of our cognate-set data indicates that the lexical forms contain many partial cognates—that is, due to processes like prefixing and suffixing, different parts of a lexeme may or may not be cognate—which will heavily confound their alignment. Second, their analysis conflates cognate and noncognate forms in their sequence alignment and treats these as the same for indicating language relationships (List et al. 2018), which increases the risk of noise overwhelming the true relationships (Greenhill 2011). Finally, they do not infer dates, or attempt to infer the most likely homeland, so their inferences are based solely on the placement of a single branch on the tree rather than the temporal, spatial, and cultural data we bring to bear.

**5. CONCLUSION.** To summarize, neither the geography nor the timing of the ancient origin scenario is consistent with our results. We infer a probable location for Proto-Uto-Aztecan outside of the Great Basin region and a time depth for that ancestral language roughly 5,000 years more recent than that proposed in the ancient origin scenario (Merrill et al. 2009). While the timing of our results is not inconsistent with that proposed by the southern origin scenario, the identified homeland does not fit, nor does the lack of reconstructible farming cultural traits in Proto-Uto-Aztecan. Instead, our inferred geographic range for the probable homelands overlaps with the westernmost portion of the northern origin scenario, and in particular with the area west of the Colorado River that Fowler (1983) pinpoints on biogeographic grounds as a possible Proto-Uto-Aztecan homeland. Our geographic model is also partially compatible with an alternative Old California Uto-Aztecan hypothesis, which places Proto-Uto-Aztecan somewhere in California's Central Valley roughly 5,000–3,500 BP (Shaul 2014). Both of these compatible proposals assume that the Proto-Uto-Aztecan community subsisted on foraging and some hunting in a region north of the US-Mexico border in similar windows in time, consistent with our timing, geographical, and ancestral-state reconstruction results.

An agriculture-driven language expansion should, according to Hill (2001) and Bellwood (2001b), show (i) rake-like structures in the phylogeny as a result of rapid initial dispersal, (ii) homelands and time depths that correlate with evidence of agriculture in the archaeological record, and (iii) convincing reconstructions of agricultural terminology in the vocabulary of the protolanguage that can be correlated with the archaeological record. Our results contrast with all three of these predictions for Proto-Uto-Aztecan. Instead, we find, first, a clear initial branching into Northern and Southern clades rather than the five primary branches associated with the southern origin scenario (Hill 2007,

2012). Second, our results infer the origin of Proto-Uto-Aztecan in North America with a time depth roughly contemporary with the earliest archaeological evidence of maize in Arizona and Utah (Piperno et al. 2009), suggesting that the northward spread of the cultivar did not depend on migrations of Uto-Aztecan people. Third, evidence for agricultural terminology in Proto-Uto-Aztecan is lacking (Hill 2001, 2007, 2010, Campbell 2002, Merrill 2012, Shaul 2014), and our results indicate that speakers of Proto-Uto-Aztecan were unlikely to have been agriculturalists. Therefore, it seems the initial impetus for the expansion of Uto-Aztecan was not farming; farming may have been associated with Southern Uto-Aztecan and may have contributed to the subsequent expansion of that subfamily, though it is also possible that agriculture spread gradually to Southern Uto-Aztecan groups by acculturation after they had separated from one another. Our results show how a combined phylogenetic, linguistic, and cultural analysis can shed light on human prehistory by refining large-scale hypotheses about the drivers of linguistic and cultural diversity.

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[Received 22 March 2021;  
revision invited 7 November 2021;  
revision received 1 April 2022;  
accepted pending revisions 13 June 2022;  
revision received 14 July 2022;  
accepted 15 July 2022]