Quaternary Environments and Humans 3 (2025) 100071

Contents lists available at ScienceDirect

Quaternary Environments and Humans

journal homepage: www.journals.elsevier.com/quaternary-environments-and-humans

Climate change and the spread of the Transeurasian languages

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ARTICLE INFO

Handling Editor: Dr Iizuka Fumie

Keywords:
Human-environment interaction
Language dispersal
Climate change
Early agriculture
Transeurasian languages

ABSTRACT

The term "Transeurasian" refers to a proposed language family stretching across Europe and northern Asia, which includes five well-established branches: Japonic, Koreanic, Tungusic, Mongolic and Turkic. The complex range of interacting factors that drove the spread of these languages from their homeland in Northeast Asia to their present-day locations is yet to be understood. Here, we investigate the potential impacts of climate change on the spread of the Transeurasian languages across mid-latitude East Asia during the Holocene, beginning from the initial break-up of the Transeurasian language family about 9200 years ago. Comparison of palaeoclimate records and linguistic developments demonstrates that global- to regional-scale climate trends may have been factors that promoted the spread of these languages.

1. Introduction

The great acceleration of climate change over the last decades has encouraged us to rethink the relationship between humans and their environment and to adapt in a way that reduces harm and fosters sustainable development. However, whereas much of the debate is centred around the loss of biological diversity and seeks to prevent the depletion of natural resources, less attention is paid to the loss of linguistic diversity and the preservation of languages for future generations. Notwithstanding the realization that the humanities have an important role to play in raising questions and developing potential responses with regard to climate change, linguists have been relatively slow to engage with the topic.

But how can linguistics help to solve the climate crisis? Language is not only a means to communicate climate change and motivate people to act, it is also an issue. Beyond instructing how language can be used to persuade, we need linguists to identify climate-induced threats faced by languages and their speakers, understand the underlying mechanism and work out sustainable solutions for the future. This requires a solid understanding of the interconnection between language dynamics and environmental change in the past. Linguists are able to trace reconstructed languages and their dispersals back to around 10,000 years ago (Comrie, 2000). This cut-off point provides us with a time frame to explore how climate change may have impacted language dynamics during most of the Holocene (11,650 cal BP to present).

Our study will focus on the association between language dispersal and climate change for the "Transeurasian" language family in mid-latitude East Asia (ca. 30°–50°N; Fig. 1). This region, comprising north-eastern China, the southern Russian Far East, the Korean Peninsula and Japan, serves as an interesting test-case, not only because it is home to a variety of language families, but also because it is known for its various landscapes with heterogeneous climate and environmental conditions, which experienced substantial change since Mesolithic times. The study region is primarily influenced by the East Asian monsoon system, a major atmospheric circulation system, which defines the regional climates and local vegetation composition. It is characterised by a seasonal reversal of atmospheric circulation and associated precipitation. This mechanism is due to the seasonal reversals in temperature and air pressure gradients between the Asian continent and the Pacific Ocean, which results in a "wet" and "dry" season in mainland Northeast Asia (Domrös and Peng, 1988; Webster et al., 1998). In general, the further a place on the mainland is located from the ocean, the less precipitation falls there, although topographic and latitudinal effects further complicate the spatial precipitation distribution. Forests are

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https://doi.org/10.1016/j.qeh.2025.100071
Received 1 February 2025; Received in revised form 9 May 2025; Accepted 22 May 2025
Available online 23 May 2025
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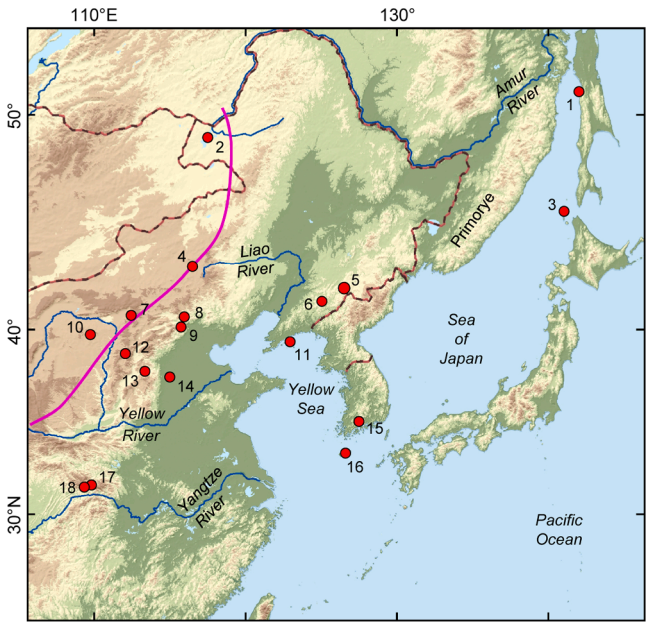


Fig. 1. The study region of mid-latitude East Asia and sites of palaeoclimate proxy records (see Table 1 for further details and references) used to discuss climate changes during the Holocene, including: 1 – Khoe Peat; 2 – Hulun Lake; 3 – Kushu Lake; 4 – Dali Lake; 5 – Sihailongwan Maar Lake; 6 – Nuanhe Cave; 7 – Daihai Lake; 8 – Taishizhuang Peat; 9 – Kulishu Cave; 10 – Qigai Nuur; 11 – B-Y14 sediment section, Yellow Sea; 12 – Gonghai Lake; 13 – Lianhua Cave, 14 – Ningjinpo Palaeolake; 15 – Seomjin River, 16 – Dongsuak Swamp; 17 – Sanbao Cave; and 18 – Dajiuhu Basin. Magenta line marks the modern boundary between steppe-dominated (in the northwest) and forest-steppe-dominated (in the southeast) areas in northern China (after Song, 1983).

the dominant natural vegetation type in the maritime parts of the study region. As trees and shrubs (i.e. arboreal plants) have a relatively high moisture requirement (Prentice et al., 1992), forests become more open towards the northwest and west. Along this moisture gradient the forest belt turns into a forest-steppe belt, a steppe belt and a desert-steppe belt (Song, 1983, Fig. 1). The transitional zone between the forest-steppe and steppe vegetation zone is regarded as a particularly suitable area for studying past climate changes by reconstructing vegetation distribution, as trees and shrubs react sensitively to changes in precipitation.

As shown in Fig. 2, the term "Transeurasian" refers to a large group of geographically adjacent languages, stretching across Europe and northern Asia and including five well-established linguistic families: Japonic, Koreanic, Tungusic, Mongolic and Turkic. In spite of the controversy with regard to the genealogical relatedness of these languages, we accept that there is a small core of reliable evidence in support of their common origin (Robbeets et al., 2021).

Modelling the break-up and dispersal of the Transeurasian languages, we will examine whether long-term climatic trends and archaeobotanical records in mid-latitude East Asia can be aligned with the linguistic evidence in time and space. To this end, we will review Holocene palaeoclimate proxy records from that region, covering moisture and temperature trends since the initial break-up of the Transeurasian family around 9200 cal BP. Although language dispersal has been partially associated with climatic factors for other language families in Eurasia (Grünthal et al., 2022; Fortescue and Vajda, 2022; Bradley et al., 2025; Sidwell and Blench, 2011), we are not aware of other attempts to connect climate and language in our focus region.

2. Material and methods

2.1. Historical comparative reconstruction in linguistics

The historical comparative method is a linguist's main tool for uncovering deep language history, also in areas of the world without longstanding written traditions. It is a technique for establishing that genealogically related languages descend from a most recent common ancestor and for reconstructing this ancestral state on the evidence of

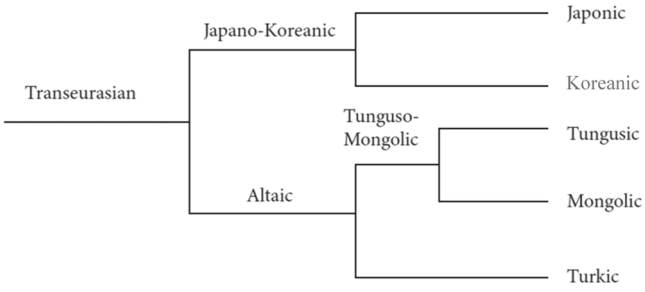


Fig. 3. Classification of the Transeurasian languages based on classical as well as computational approaches.

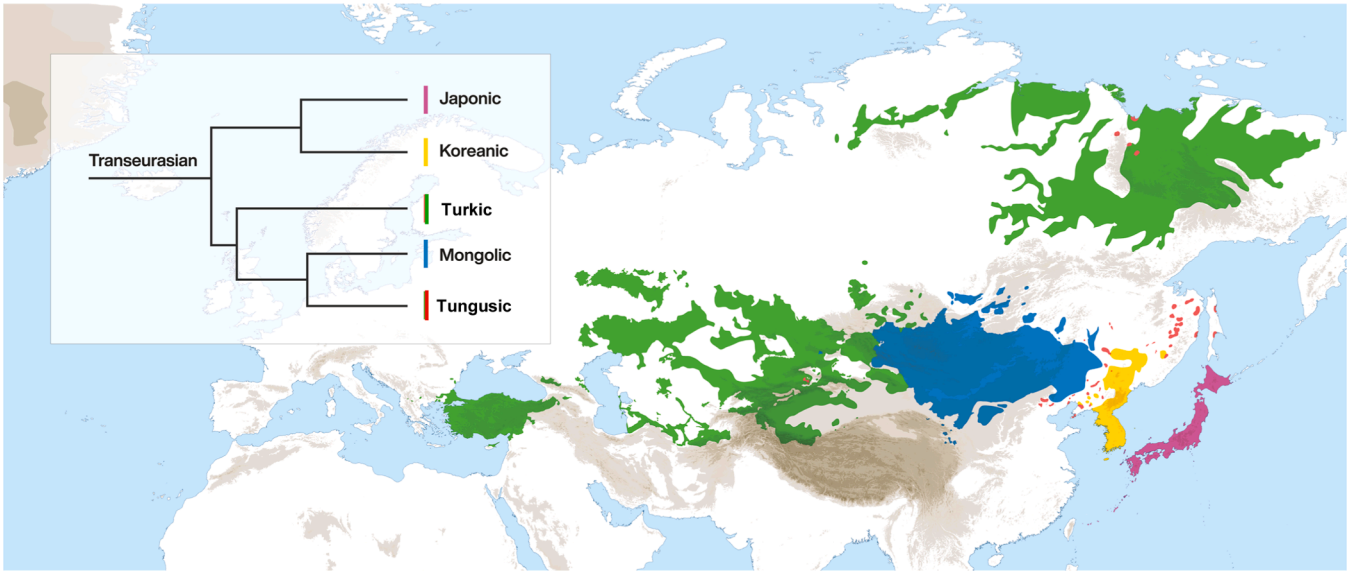


Fig. 2. The classification and current distribution of the Transeurasian languages across Asia.

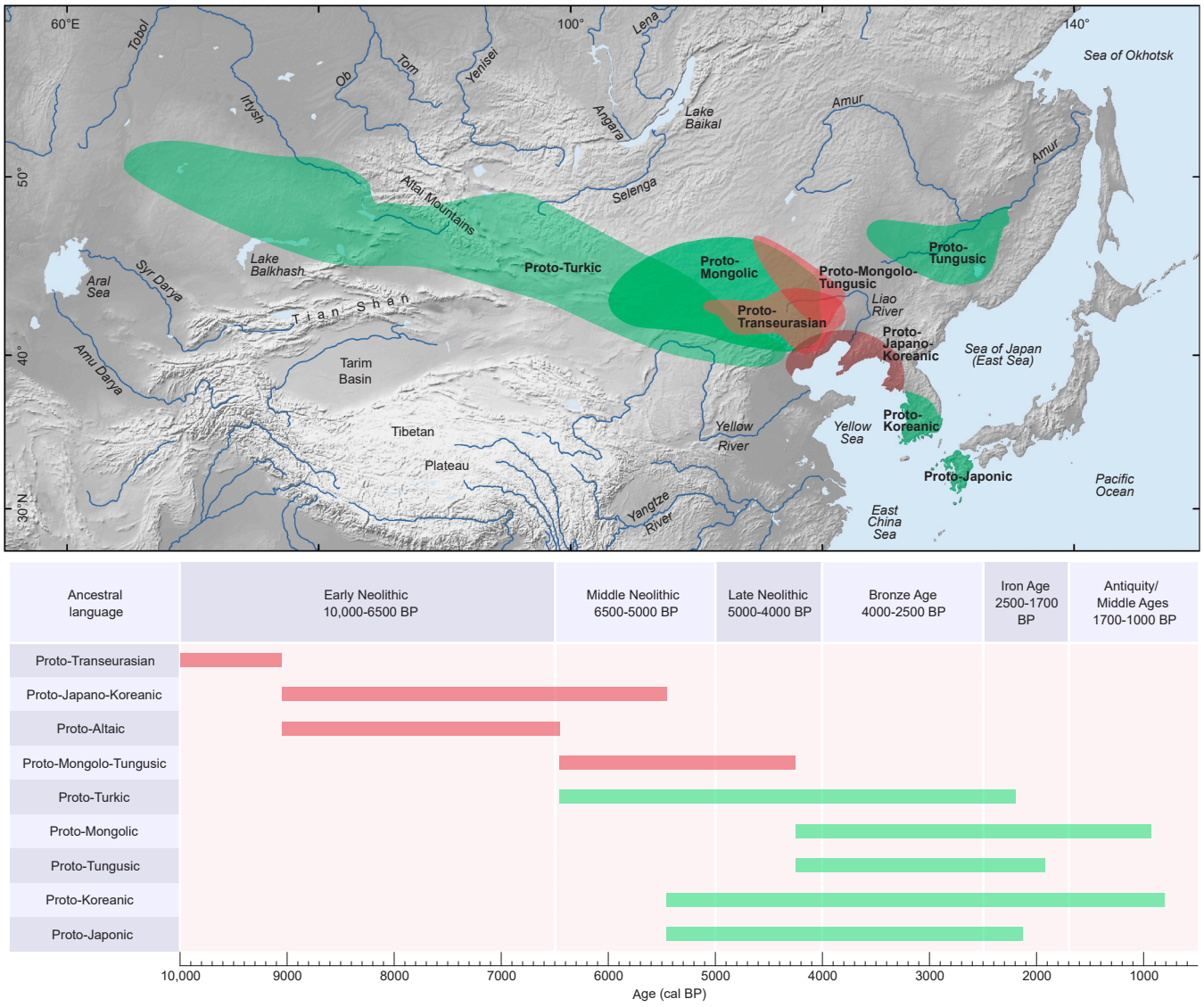


Fig. 4. Locations estimated for the Transeurasian homelands in time and space. Distinction is made between ancestral languages spoken during Neolithic times (red) and those spoken in the Bronze Age and later (green) (Robbeets et al., 2021).

data that are available from a later period (Bostoen and Robbeets, 2025; Barlow and Campbell, 2025). The convention is to call the unattested ancestral state of a group of related languages, "proto-language".

Linguists can infer language movement from building language trees that visualize how speech communities split into subgroups and dispersed (Heggarty and Powell, 2025). There are different methods for doing this but our study relies on the Maximum Parsimony approach and Bayesian phylolinguistics, which are considered to be most efficient. Both methods take sets of regularly corresponding cognates in related languages as their basic data, paying particular attention to basic vocabulary items.

We rely on Bayesian statistics to date the nodes in the trees and thus estimate the time depth of language dispersals (Dunn, 2025). The Bayesian approach calibrates the divergence time against known cases of language divergence over attested timespans and quantifies how likely it is that the inferred time depth falls within a certain density interval. In this paper, ages are given in 'cal BP', which refers to calendar ages before present, where 'present' equals 1950 Common Era.

In addition, linguists can locate the homeland where a proto-language was once spoken and from where the daughter languages dispersed. To this end, our research integrates various methods such as cultural reconstruction, the diversity hotspot principle and Bayesian phylogeography (Wichmann and Rama, 2021; Neureiter et al., 2021; Wichmann, 2025; Robbeets, 2025). Cultural reconstruction delimits an area in which certain reconstructed cultural items, plant and animal names converge to the exclusion of other regions. The diversity hotspot principle is based on the assumption that the homeland is closest to where one finds the greatest diversity with regard to the deepest subgroups of the language family. Bayesian phylogeography models how speech communities may have moved using a phylogenetic tree as a guideline, by using the diffusion rate at which languages change their location.

To model the spread of the Transeurasian languages in time and space, this study builds on Robbeets et al. (2021), which applies Bayesian phylolinguistics to build a dated Transeurasian tree and converges the three homeland detection methods mentioned above. Here, we complement previous study by proposing etymologies for agricultural vocabulary. These cognate sets shed additional light on the direction and timing of the proposed language spreads and enable us to integrate our linguistic inferences with archaeobotanical information in the final phase of our study.

2.2. Palaeoclimate reconstructions

Palaeoenvironmental reconstructions are based on records of indicators or so-called proxies, which are indirect measures of past climates, vegetation cover, biomes or other environmental characteristics and are preserved in natural archives, such as marine and terrestrial sediments, trees, speleothems and ice cores. The palaeoenvironmental proxies represent lithological/mineralogical, geochemical and palaeontological data that are sensitive to climatic or environmental parameters, such as solar variability, ocean surface temperature and productivity, atmospheric temperature and precipitation, lake water depth, seasonality and wind strength (Gornitz, 2009), as well as to human impact.

For the discussion of climate trends during key dispersal events of the Transeurasian languages across the study region, we selected twelve key proxy records from ten different locations within or near the study region (Table 1, Fig. 1). The records were selected by location, represented period of time and robustness of their chronologies and are considered representative of climate and environmental changes in the study region. Of all examined and discussed climate proxy records (Fig. 1) we selected twelve to visualise the main trends (Figs. 5–11).

The pollen-based records comprise different indicator taxa or indices. From the fossil pollen record from Kushu Lake in northern Japan, Leipe et al. (2018) used the percentages of oak pollen as a proxy for thermal conditions, as this temperate deciduous tree in the study area of northern Japan is sensitive to climate cooling. Similarly, Park et al. (2023) used the ratios of evergreen broadleaf tree (*Q.* subgen. *Cyclobalanopsis* and *Castanopsis*) pollen to the total major tree pollen as "tree pollen index of temperature" (TPIT) to infer changes in winter temperatures from the palynological record from Dongsuak Swamp on Jeju Island in the Korea Strait. The percentages of arboreal pollen (AP), which basically describes the ratio of arboreal/non-arboreal (herbaceous) pollen (often expressed as AP/NAP), is commonly used as an indicator of moisture and temperature variability in the semi-arid regions of northern and western China (Herzschuh, 2007). A similar measure is the pollen-based landscape openness (Tarasov et al., 2013), which was calculated for the Sihailongwan Lake record (Stebich et al., 2015). The landscape openness calculation is based on the major vegetation type (i.e. biome) reconstruction technique (Prentice et al., 1996) and expresses the difference between the maximum forest biome score and the maximum open biome score (Tarasov et al., 2013). A second proxy of moisture and temperature changes based on the pollen record from Sihailongwan Lake (Stebich et al., 2015) is the summed pollen percentages of temperate summergreen (i.e. deciduous) arboreal plants, a plant functional type (PFT) used in the biome reconstruction technique. PFTs are groups of pollen-producing plants defined by their stature, leaf form, phenology and bioclimatic tolerance (Prentice et al., 1992, 1996). For the selection of pollen types for percentage calculation, we followed PFT-taxa matrices successfully tested in the study region (Gotanda et al., 2002; Leipe et al., 2013; Mokhova et al., 2009).

For the lakes Dali (Xiao et al., 2015), Daihai (Xu et al., 2010), Gonghai (Chen et al., 2015) and Qigai Nuur (Sun and Feng, 2013) and the Taishizhuang Peat (Tarasov et al., 2006) pollen-based quantitative reconstructions of annual precipitation are available. The records from Daihai and Qigai Nuur were derived by applying the quantitative method known as Modern Analogue Technique (MAT) or Best Modern Analogue (BMA) approach (Guiot, 1990; Overpeck et al., 1985). The method relies on a large set of modern surface pollen spectra from the greater study region and values of modern climate parameters from long-term observations assigned to each of the surface pollen spectra sites. The best modern analogues (usually 8–10) are found by statistical comparison of each fossil spectrum to the entire dataset of modern pollen spectra. The modern climate values associated with the identified best modern analogues are then assigned to the respective fossil spectrum (see Tarasov et al., 2011 for a summary and example of the method). The records from Dali Lake, Gonghai Lake and Taishizhuang Peat were derived by applying different transfer functions, which is a common method to reconstruct climate parameters from microfossil data and may be summarized as a two-step approach. In terms of pollen, first, the relationship between the reference modern surface pollen spectra and their assigned modern climate parameter of interest are modelled by regression analysis. Second, the modelled relationships are used to infer values of the climate parameter in the past from the composition of the fossil pollen spectra (Birks, 2012; Ter Braak, Prentice, 1988).

In addition to pollen-based records, our selection comprises two speleothem $\delta^{18}O$ records from Sanbao Cave (Dong et al., 2010) and Nuanhe Cave (Wu et al., 2011). Speleothem stable isotopes are one of the most important proxies to reconstruct precipitation and temperature changes in terrestrial environments and have been widely used in monsoonal East Asia (Liu et al., 2020). The advantage of speleothems is that they can be dated very precisely and provide very high-resolution palaeoclimate records. The $\delta^{18}O$ in speleothems is mainly controlled by temperature and relative humidity (Lachniet, 2009). However, there are other factors, which influence $\delta^{18}O$ values and thus may complicate their interpretation (Liu et al., 2020).

Table 1
Palaeoclimate proxy records visualized (Figs. 5–11) and discussed in the text. See map in Fig. 1 for location of study sites. Metres above sea level is abbreviated as m a.s.l.

Environmental archive	Proxy	Location	Reference
Sanbao Cave	$\delta^{18}O$ (speleothem SB43) $\delta^{18}O$ (speleothem SB10)	31°40'N, 110°26'E; 1900 m a.s.l.	Dong et al. (2010) Wang et al. (2008)
Dongsuak Swamp	Pollen	33°22'N, 126°38'E; 650 m a.s.l.	Park et al. (2023)
Gonghai Lake	Pollen	38°54'N, 112°14'E; 1860 m a.s.l.	Chen et al. (2015)
Qigai Nuur	Pollen	39°19'N, 109°16'E; 1280 m a.s.l.	Sun and Feng (2013)
Taishizhuang Peat	Pollen	40°22'N, 115°50'E; 485 m a.s.l.	Tarasov et al. (2006)
Daihai Lake	Pollen	40°33'N, 112°40'E; 1225 m a.s.l.	Xu et al. (2010)
Nuanhe Cave	$\delta^{18}O$ (speleothem NH5)	41°20'N, 124°55'E; 500 m a.s.l.	Wu et al. (2011)
Sihailongwan Lake	Pollen	42°17'N, 126°36'E; 797 m a.s.l.	Stebich et al. (2015)
Dali Lake	Pollen	43°18'N, 116°37'E; 1226 m a.s.l.	Xiao et al. (2015)
Kushu Lake	Pollen	45°26'N, 141°02'E; 3 m a.s.l.	Leipe et al. (2018)

2.3. Archaeobotany

Archaeobotany may be defined as the study of the interrelationships between ancient peoples and plants based on the identification and interpretation of plant remains recovered from cultural layers of archaeological sites (D'Andrea, 2020; Ford, 1979). It has been a key method to examine prehistoric and early historic human subsistence economies and the domestication of plants and their dispersal. In the current study we discuss available archaeobotanical records consisting of charred remains (seeds) of cultivated plants and their chronologies based on direct ^{14}C dating to reconstruct migrations of agricultural populations and shifts in crop packages that may possibly be related to climate change and the dispersal of Transeurasian languages. All archaeobotanical records and dating results referred to are outlined and referenced in the Discussion section.

2.4. Triangulation

In this study, linguistics is the anchoring discipline to be combined

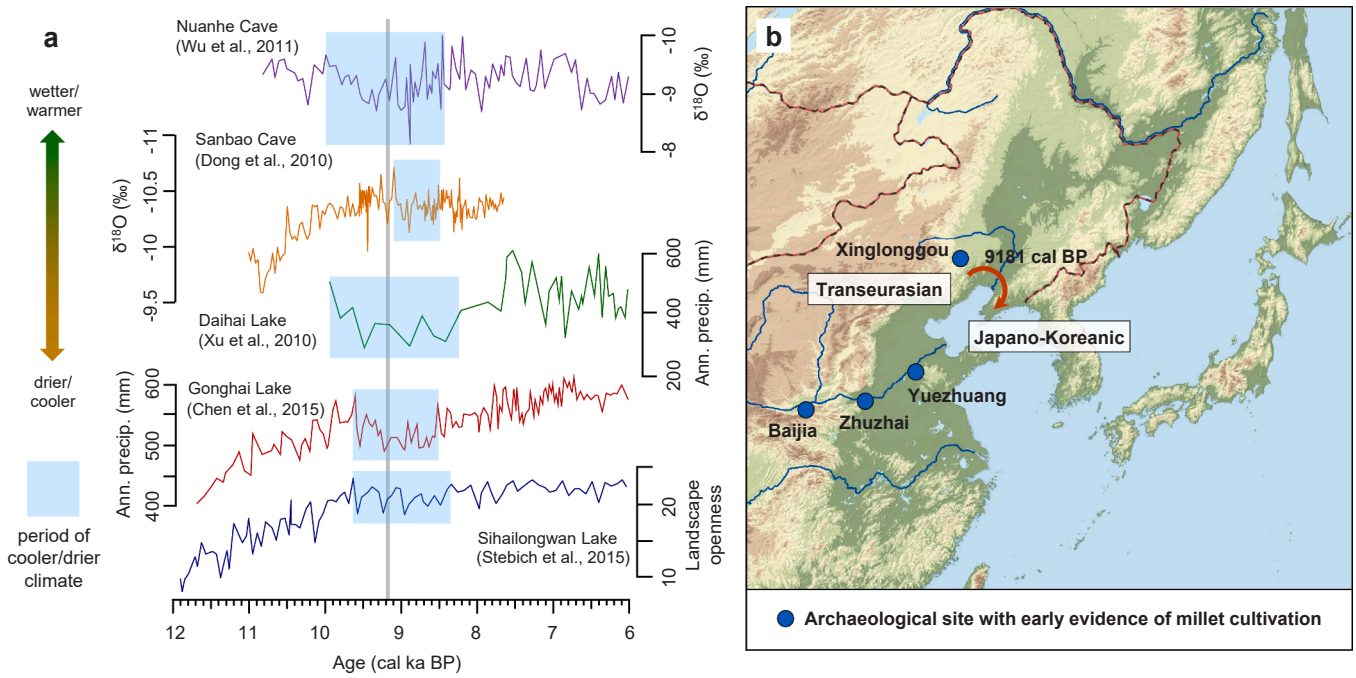


Fig. 5. (a) Selected palaeoclimate records (Table 1, Fig. 1) from the study region showing a period of cooler/drier climate conditions (blue bars) during the Early Holocene; (b) the separation of the Japano-Koreanic branch from Proto-Transeurasian and its dispersal estimated at 9181 cal BP and archaeological sites with earliest evidence of millet cultivation (ca. 8000–7500 cal BP) from the greater study region (see Stevens et al., 2021 for details and references). The vertical grey line in (a) marks the model-estimated break-up of Japano-Koreanic from Proto-Transeurasian.

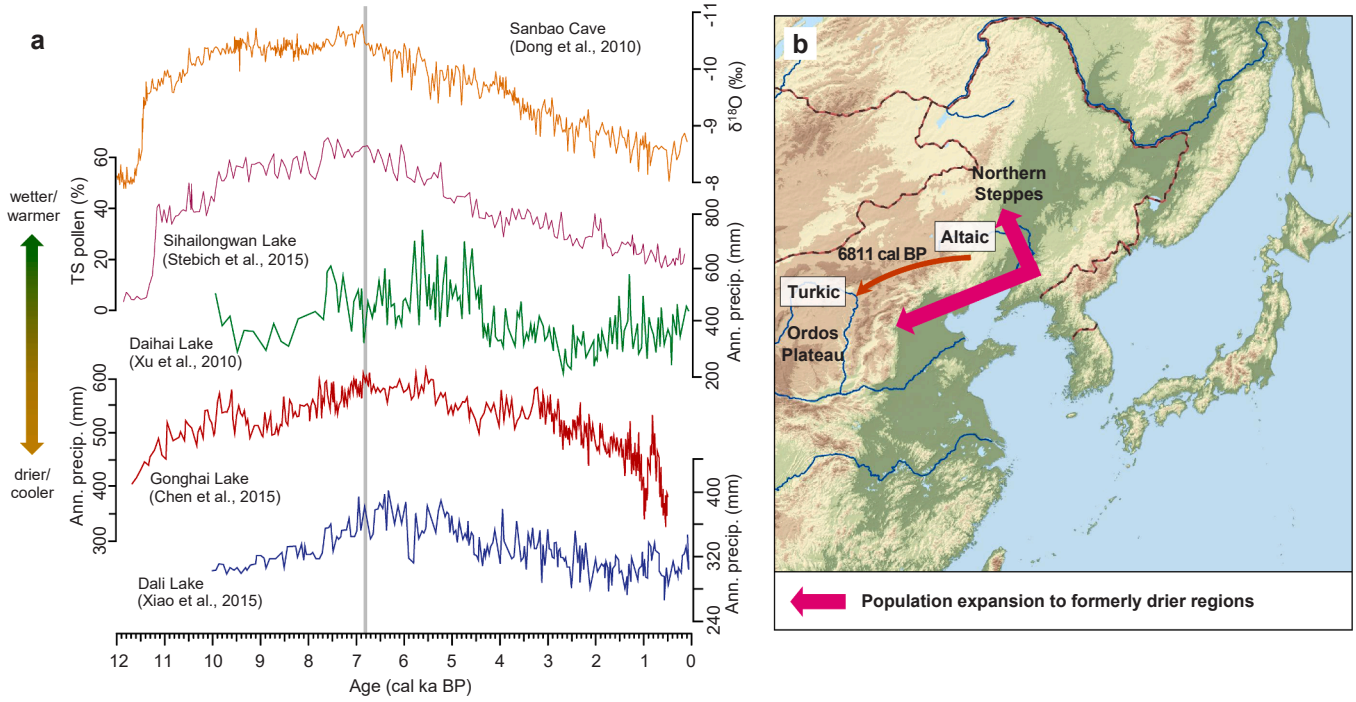


Fig. 6. (a) Selected palaeoclimate records (Table 1, Fig. 1) from the study region showing the Holocene temperature/precipitation maximum (ca. 8000–5000 cal BP) in northern China; (b) the separation of the Turkic branch from the Altaic branch and its dispersal estimated at 6811 BP. The vertical grey line in (a) marks the model-estimated break-up between Turkic and Altaic. Abbreviations in (a): Ann. precip. – annual precipitation, TS – temperature summergreen arboreal plants.

with evidence from archaeobotany and palaeoclimatology. Science today puts a lot of weight on the reproducibility of empirical results. However, the ongoing debates about the "replication crisis" (Fidler and Wilcox, 2018) make one wonder whether it is really useful to repeat one selected approach over and over again. Consistent findings can take the status of confirmed truths, even when they reflect failings in the study design, the methods or analytical tools (Munafò and Smith, 2018). Verifying results requires disparate lines of evidence, an approach which is called "Triangulation" (Kirch and Green, 2001, Robbeets et al., 2021). By making strategic use of multiple disciplines, methods, datasets and

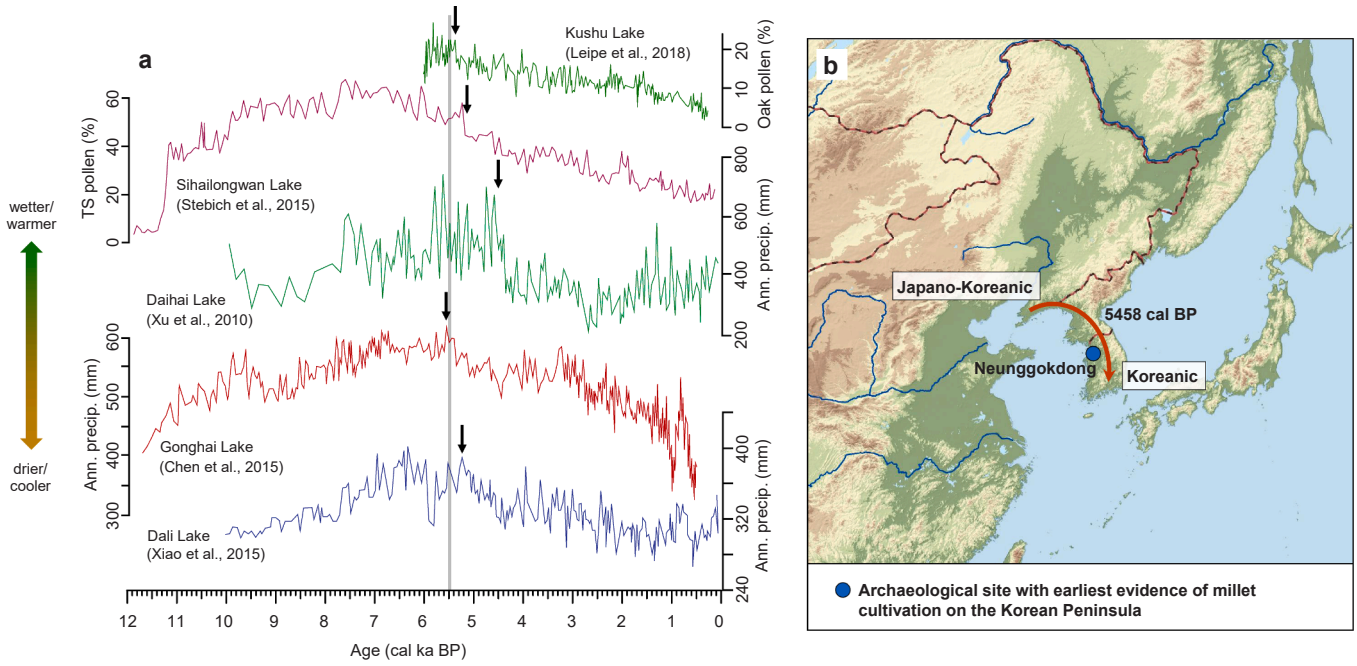


Fig. 7. (a) The onset of the Neoglaciation (black arrows) in the study region as indicated by selected palaeoclimate records (Table 1, Fig. 1) from northern China and northern Japan; (b) the separation of the Koreanic branch from the Japano-Koreanic branch and its dispersal, estimated at 5458 BP. Oldest millet remains from the Korean Peninsula from the Neunggokdong site directly ^{14}C-dated to 5594–5331 cal BP (95 % confidence interval) (Ahn et al., 2015). The vertical grey line in (a) marks the model-estimated break-up of Japonic from Japano-Koreanic. Abbreviations in (a): Ann. precip. – annual precipitation, TS – temperature summergreen arboreal plants.

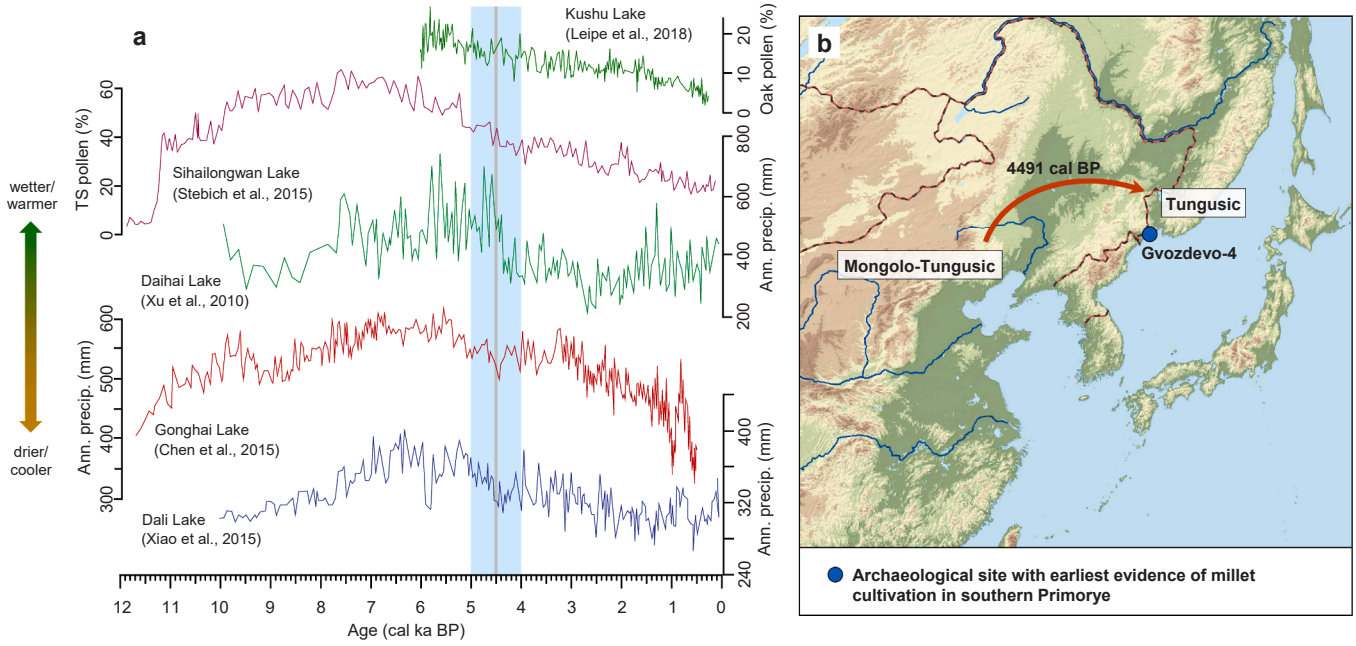


Fig. 8. (a) Early Neoglacial cooling/drying during the 5th millennium BP (blue bar) in the study region as indicated by selected palaeoclimate records (Table 1, Fig. 1) from northern China and northern Japan; (b) the separation of the Tungusic branch from the Mongolo-Tungusic branch and its dispersal estimated at 4491 cal BP and the Gvozdevo-4 archaeological site with the oldest directly ^{14}C-dated millet grain (4822–4530 cal BP, 95 % confidence interval) in southern Primorye (Sergusheva et al., 2022). The vertical grey line in (a) marks the model-estimated break-up of Tungusic from Mongolo-Tungusic. Abbreviations in (a): Ann. precip. – annual precipitation, TS – temperature summergreen arboreal plants.

researchers to address a single research question, this approach increases the validity and credibility of the research results.

Each discipline involved in this study is seriously challenged by its incomplete scientific record: palaeoclimate is derived from proxies, not from direct measurements; archaeobotanical records may be lost or poorly preserved; written sources may have disappeared and certain languages may have gone extinct. However, finding correlations between the three disciplines, that agree on a certain scenario, reduces eventual uncertainties and increases the credibility of the results. Integrating archaeobotanical and palaeoclimatological findings, can provide

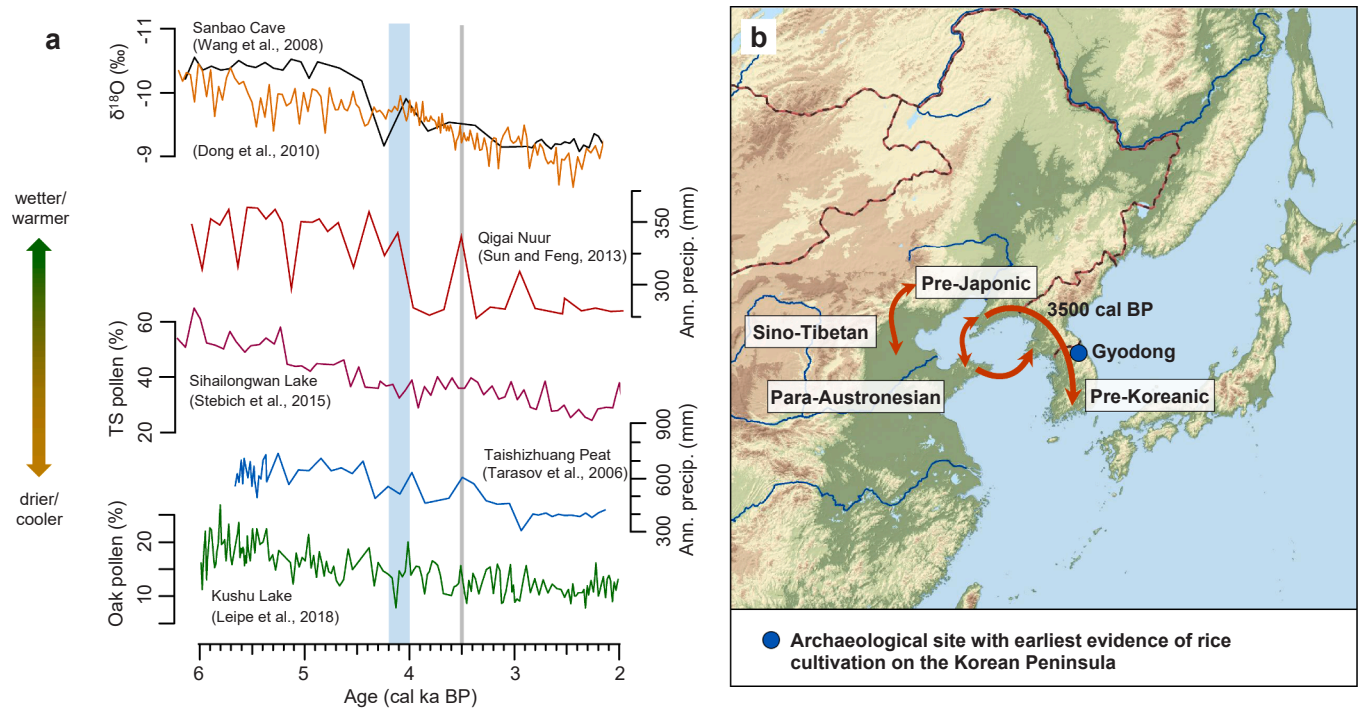


Fig. 9. (a) The Meghalayan Drought (4200–4000 cal BP, blue bar) and the following enhanced cooling/drying in the study region as indicated by selected palaeoclimate records (Table 1, Fig. 1) from northern China and northern Japan; (b) the dispersal of the pre-Japonic language to the Korean Peninsula, estimated at 3500 cal BP, and the Gyodong archaeological site with the oldest directly ^{14}C-dated rice grain (3385–3065 cal BP, 95 % confidence interval) from the Korean Peninsula (Ahn, 2010). The vertical grey line in (a) marks the model-estimated beginning of the dispersal of pre-Japonic to the Korean Peninsula. Abbreviations in (a): Ann. precip. – annual precipitation, TS – temperature summergreen arboreal plants.

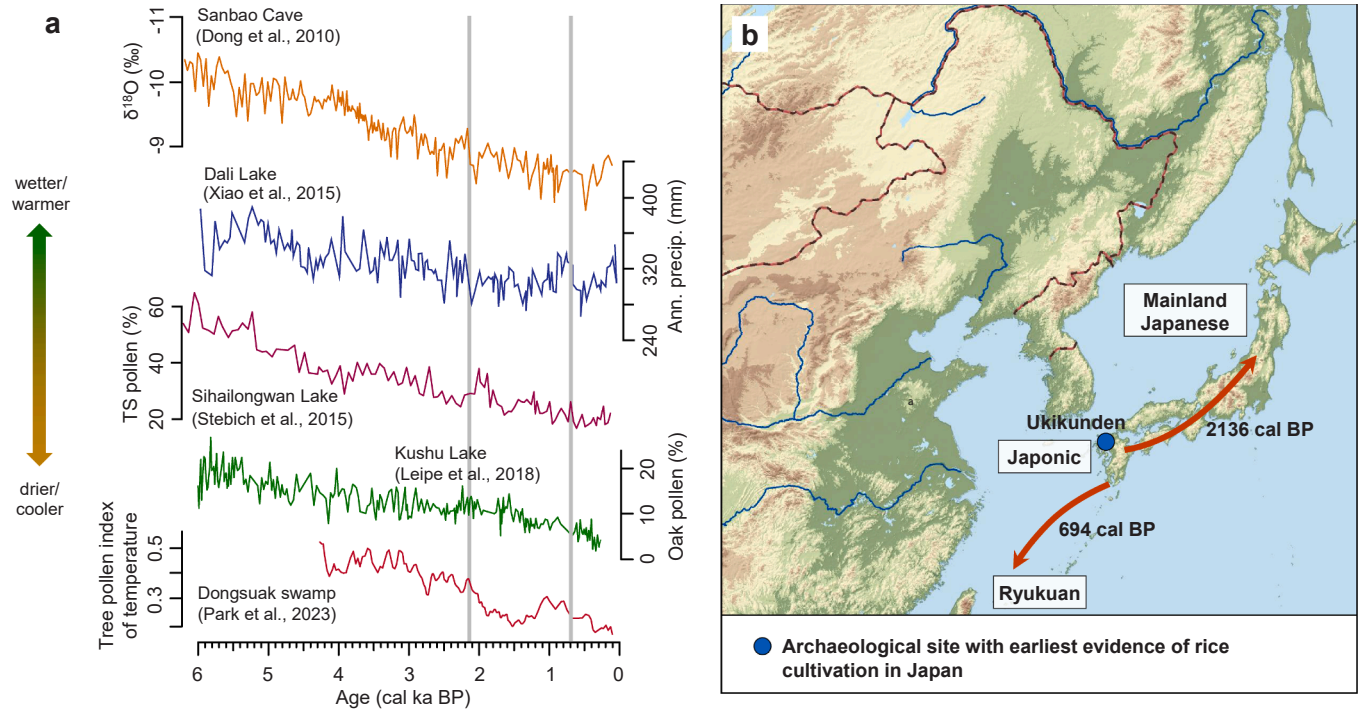


Fig. 10. (a) Progressive enhanced Late Holocene cooling/drying in the study region as indicated by selected palaeoclimate records (Table 1, Fig. 1) from northern China and northern Japan; (b) the break-up and dispersal of the Japonic language across Japan and the Ukikunden archaeological site with the oldest directly ^{14}C-dated rice grain (2849–2756 cal BP, 95 % confidence interval) from Japan (Miyamoto, 2018). The vertical grey lines in (a) marks the model-estimated break-ups of Japonic. Abbreviations in (a): Ann. precip. – annual precipitation, TS – temperature summergreen arboreal plants.

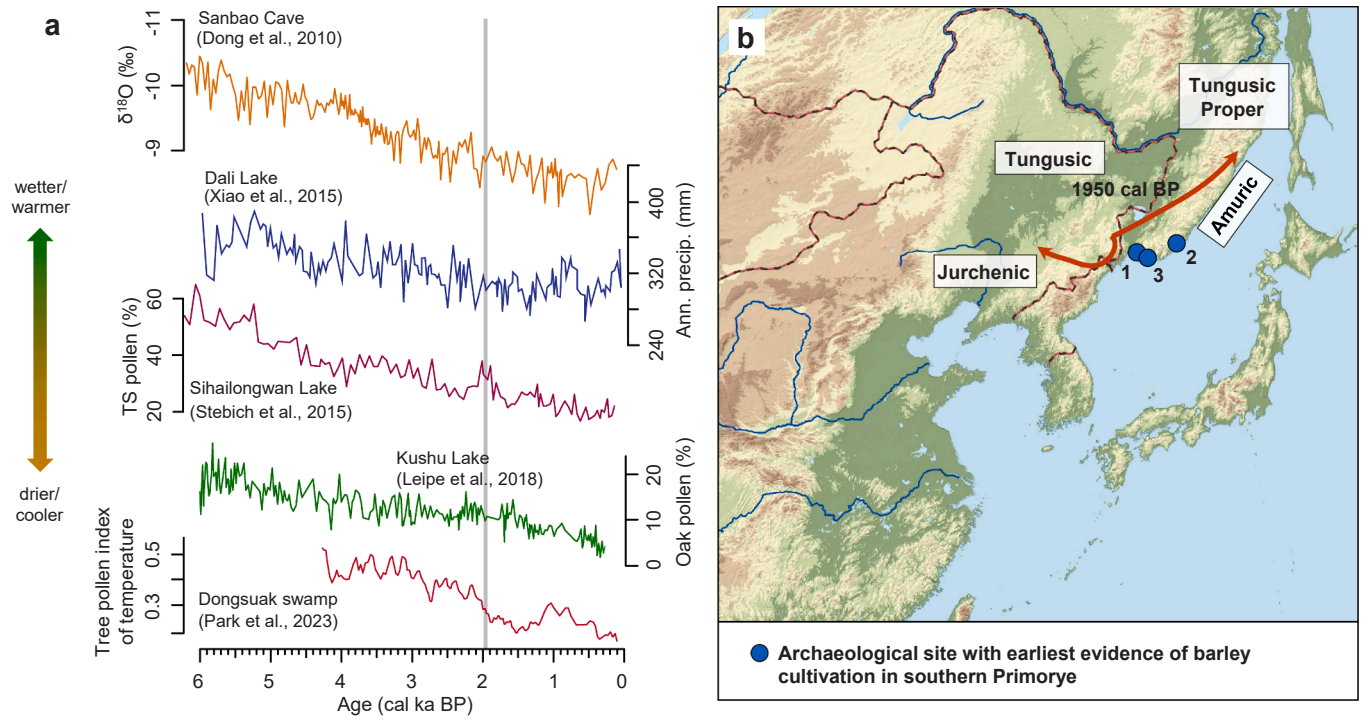


Fig. 11. (a) Progressive enhanced Late Holocene cooling/drying in the study region as indicated by selected palaeoclimate records (Table 1, Fig. 1) from northern China and northern Japan; (b) the break-up and dispersal of the Tungusic language family and archaeological sites (Malaya Podushechka – 1, Sinie Skaly – 2, Zolotaya Dolina – 3) with the oldest directly ^{14}C-dated barley grains (ca. 2300–2000 cal BP, 95 % confidence interval) in southern Primorye (unpublished data). The vertical grey line in (a) marks the model-estimated internal break-up of proto-Tungusic. Abbreviations in (a): Ann. precip. – annual precipitation, TS – temperature summergreen arboreal plants.

us with a more balanced insight into language dynamics of the past, than can offer only a single discipline.

Although the term "Triangulation" is borrowed from a navigational or surveying technique that determines a single point in space with the convergence of measurements taken from two other points, triangulation is not necessarily restricted to a "three-fields" approach. In addition to the three disciplines — palaeoclimatology, archaeobotany and linguistics — integrated in this article, triangulation may involve additional fields, such as genetics, archaeology, cultural anthropology, ecology, geography, etc. (Robbeets, 2025).

Even if palaeogenetic studies (Ning et al., 2020; Robbeets et al., 2021) support the chronology and trajectory of the Transeurasian farming/language dispersals addressed in this article, we did not revisit these studies here. Genetics is often thought to have leapfrogged archaeology and linguistics to become the best source of knowledge on human prehistory. However, whereas it can provide us with detailed descriptions of *where and when* people moved, it cannot tell us *why* these people moved. The integration of palaeoclimatology, archaeobotany and linguistics, however, can provide us with a better understanding of causalities in human prehistory, as they shed light on the impact of the natural environment on ancient populations.

The protocol for Triangulation applied in this study involves four steps: independent analysis; alignment of quantitative variables; alignment of qualitative variables; and cause-effect determination. To avoid circularity in the argumentation, we first carry out data collection and analyses independently within each discipline, before bringing the different lines of evidence together.

In the second step, we determine and align quantitative variables such as time depth, spatial distribution and —if applicable— direction of expansion for the objects of our independent analyses, i.e. languages, crops and climate types.

In the third step, we determine the agricultural context for the speakers of the proto-languages. Reconstructing the vocabulary of the proto-languages involved, we will examine whether it reveals words for crops. If the ancestral speakers had words for certain crops, the assumption is that they were familiar with the actual crops referred to. In the archaeobotanical part of our study, we analyse ancient plant remains recovered at the time and space in which the ancestral speakers are situated. In the palaeoclimatological part, we study climatological factors such as temperature, precipitation and photoperiod at the time and space of the proto-speakers and how they are expected to affect crop growth. Subsequently, we align the qualitative information yielded by the three disciplines to evaluate to which extent the languages, crops and climates under investigation reflect a consistent agricultural context. Results that agree across the three disciplines are less likely to be artefacts.

The final step opens the way for integrating the different lines of evidence, independently accumulated by each discipline and mapped onto each other, into a more holistic view of the human past. This step includes inferring the most parsimonious cause-effect relationship, e.g., from climate change to agricultural expansion to language dispersal, as well as specifying the nature of the connection between climate change and the spread of the Transeurasian languages across Northeast Asia.

3. Independent results

3.1. Holocene language dispersal

Our inferences about linguistic prehistory are based on the application of various methods for tree classification, linguistic dating, homeland detection and the reconstruction of agricultural vocabulary, discussed in Section 3.1. For the classification of Transeurasian, most classical (Poppe, 1965: 147, Street, 1962: 95, Tekin, 1994: 82, Robbeets, 2015: 506) and computational analyses (Robbeets et al., 2021) seem to converge on the tree model in Fig. 3, a point of contention being the position of the Tungusic branch in the tree.

Table 2
Time depth of Proto-Transeurasian and its major subbranches according to Bayesian dating methods (Robbeets et al., 2021).

Node	Time depth, cal BP	95 % Highest Posterior Density Interval (HDP), cal BP
Proto-Transeurasian	9181	12,793–5595
Proto-Altaic	6811	10,166–4404
Proto-Japono-Koreanic	5458	8024–3335
Proto-Tunguso-Mongolic	4491	6373–2599
Proto-Japonic	2136	2412–1499
Proto-Koreanic	975	1560–528
Proto-Tungusic	1950	2412–1499
Proto-Mongolic	939	1011–871
Proto-Turkic	2195	2493–1882

The time depth of the root and nodes in this tree have been estimated using Bayesian statistics. Table 2 shows the results of applying this method to the Transeurasian family for the primary break-ups in the language tree.

Combining the three homeland detection methods described in Section 3.1, Robbeets et al. (2021) suggested the homelands indicated in Fig. 4.

Reconstructing the vocabulary of proto-Transeurasian and its primary daughter languages, we examined the subsistence vocabulary revealed in the reconstructions. The results for proto-Transeurasian are shown in Table 2. They include words for 'field for cultivation', 'uncultivated field', 'to grow, ripen (of plants)', 'seed, seedling', 'components that are removed from the millet harvest, barnyard grass (*Echinochloa crus-galli*)', 'cooked cereal, (millet) gruel', 'spade, hoe', 'to ferment', 'to reduce/preserve food by fermentation' and 'to cut (cloth)'.

Reconstructions that are restricted to the proto-Japano-Koreanic branch are presented in Table 3, including maritime vocabulary, such as 'sea', 'boat', 'swellfish, *Takifugu chinensis*', 'crab, *Portunus trituberculatus*' as well as agricultural vocabulary, such as '(wet) field for cultivation', 'delimited plot for cultivation', 'hemp' and 'ramie (cloth)'. Agricultural

Table 4
Maritime and agricultural vocabulary reconstructable to Proto-Japano-Koreanic only.

No	Gloss	Proto-Japono-Koreanic	Proto-Japonic	Proto-Koreanic
3.1	'sea'	*pata	*wata 'sea'	*pata-k 'sea'
3.2	'boat'	*pʊnə	*puna 'boat'	*pʌ(n)i 'boat'
3.3	'swellfish, *Takifugu chinensis*'	*poko	*puku 'swellfish, *Takifugu chinensis*'	*pok 'swellfish, *Takifugu chinensis*'
3.4	'crab, *Portunus trituberculatus*'	*keni	*kani 'crab, *Portunus trituberculatus*'	*keni 'crab, *Portunus trituberculatus*'
3.5	'(wet) field for cultivation'	*non	*no 'field'	*non 'irrigated field, rice paddy field'
3.6	'delimited plot for cultivation'	*mati	*mati 'delimited plot for cultivation'	*mat(i)-k 'delimited plot for cultivation'
3.7	'hemp'	*ʌsa	*asa 'hemp'	*ʌsa-ma 'hemp'
3.8	'ramie (cloth)'	*mosi	*mosi 'ramie (cloth)'	*mosi 'ramie cloth'

Table 3
Agricultural vocabulary reconstructable to Proto-Transeurasian.

No	Gloss	Proto-TEA	Proto-Japonic	Proto-Koreanic	Proto-Tungusic	Proto-Mongolic	Proto-Turkic
2.1	'field for cultivation'	*pata	*pata '(dry) field'	*patʌ-k '(dry) field'			*(p)ata 'delimited field irrigated for cultivation'
2.2	'uncultivated field'	*muda	*muta 'marshland'	*mutʌ-k 'dry land'	*muda 'plain, open field'		
2.3	'to grow, ripen (of plants)'	*urə-	*ura- 'to mature, ripen (of plants)'		*ure- 'to grow, ripen (of plants)'	*ur-ga- 'to grow (of plants)'	*ur 'growth, excrescence'
2.4	'seed, seedling'	*pisi		*pisi 'seed; lineage'	*pisi-n 'seed' *pisi-ke 'broomcorn millet (*Panicum miliaceum*)'	*pisi ~ *pesi 'origin or base of a plant'	
2.5	'components that are removed from the millet harvest, barnyard grass (*Echinochloa crus-galli*)'	*kipi ~ kipe	*kinpi ~ *kimi ~ *kipi 'millets for human consumption such as barnyard or broomcorn millet'	*kipi 'barnyard millet (*Echinochloa esculenta*)'	*kipe 'components that need to be removed from the grain harvest, barnyard grass (*Echinochloa crus-galli*)'		
2.6	'cooked cereal, (millet) gruel'	*amʊ		*amʌ 'cooked cereal'		*amu-n 'cooked cereals; millet'	
2.7	'spade, hoe'	*sarpa		*salp(V) 'spade'			*sarpan 'wooden plough (breast), spade'
2.8	'to ferment'	*saga-	*saka- 'to ferment, be in heat, bloom'	*sak- 'to ferment, rot'		*saga- 'to ferment, reduce (food); to milk'	*sag- 'to milk; to extract'
2.9	'to reduce/ preserve food by fermentation'	*sü:-	*su- 'to be sour, fermented in vinegar'	*su- 'to be sour'		*sü- 'to strain, filter, skim off, reduce (food)'	*sü:- 'to filter, strain (milk or soup), reduce (food)'
2.10	'to cut (cloth)'	*giri-	*kira- 'to cut (e.g., cloth)'		*giri- 'to cut out (e.g., cloth, paper, pelt)'		*kïr- 'to cut, scrape, strip (hair), pluck out (hair), shave'

vocabulary restricted to Proto-Altaic is listed in Table 4 and includes words, such as 'to plant, grow (plants)', 'to prepare soil for cultivation, cultivate' and 'young male pig'. The full datasets underlying these etymologies are presented in the Supplementary Material (SI 1) attached to this article.

3.2. Holocene climate evolution

The climate in East Asia has considerably changed during the Holocene, which has been primarily driven by changes in the Asian monsoon circulation. However, the climate evolution has not been uniform throughout the Asian monsoon domain, which is divided into the South Asian and East Asian monsoon domains. For instance, the timing of the Holocene precipitation maximum varies between the southern and northern parts of the East Asian monsoon domain (An et al., 2000; Feng et al., 2006; He et al., 2004; Herzschuh et al., 2019). In addition, a seesaw in summer monsoon precipitation variations exists on interannual time-scales under modern climate conditions in East Asia. In years with relatively high monsoon rainfall in northern China, rainfall in southern China is relatively low (Domrös and Peng, 1988). Therefore, it is necessary to examine past climate changes within the Asian monsoon domain on region scale. The study region overlaps with the northern East Asian monsoon domain, which went through the following long- and short-term climate changes according to the existing palaeoclimate records.

During the Early Holocene or Greenlandian stage (ca. 11,650–8200 cal BP), the study region experienced a general long-term, although interrupted, increase in temperature and precipitation (Chen et al., 2015; Dong et al., 2010; Stebich et al., 2015). During the global centennial-scale 9.2 and 8.2 kiloyear (ka) cold climate events, which occurred around 9200 and 8200 cal BP, respectively, the study region also experienced considerable cooling and reduced monsoon precipitation (Park et al., 2018, 2019; Zhang et al., 2018). The Middle Holocene or Northgrippian stage (ca. 8200–4200 cal BP) is marked by the highest levels of temperature and precipitation since the end of the last glacial period (Jin et al., 2014; Stebich et al., 2015; Zhao et al., 2011). Towards the end of the Middle Holocene, temperature and moisture levels began to decrease, which was a long-term development called the Neoglaciation that generally persisted until the end of the stage and throughout the Late Holocene (ca. 4200 cal BP–present). The available palaeoclimate proxy records from the study region do not show a uniform beginning of this global-scale long-term cooling trend, which marks the end of the Holocene thermal maximum. However, two climate records from well-dated environmental archives suggest that considerable long-term cooling began around 5400 cal BP (Leipe et al., 2018; Stebich et al., 2015). The Late Holocene, which is marked by generally lower temperatures and precipitation levels in the study region (Chen et al., 2015; Dong et al., 2010; Stebich et al., 2015) begins with a phase of abrupt precipitation reduction, which has been registered in many palaeoclimate records from different regions across the middle and low latitudes of both hemispheres (Walker et al., 2019). This climate shift, which lasted between a few decades to two centuries (4200–4000 cal BP) is called the Meghalayan Drought or the 4.2 ka event (Walker et al., 2019). The Meghalayan Drought has been discussed as the main cause of the demise of Neolithic societies in the Yellow and Yangtze River regions (Guo et al., 2018; Liu and Feng, 2012; Yasuda et al., 2004) and as an accelerator for the adaptation of *japonica*-type rice in northern China to a temperate environment, which allowed the later north-eastward spread of the crop (Gutaker et al., 2020).

3.3. Development and spread of agriculture

During the last two decades the number of archaeobotanical investigations in the study region has substantially increased, which has greatly improved knowledge about the beginning of agriculture, the spread of crops and farmers and how agricultural practices and subsistence economies have changed over time (e.g. Endo and Leipe, 2022; Fuller et al., 2016; Leipe et al., 2019; Li et al., 2020; Liu et al., 2017; Long et al., 2018, 2022; Sergusheva et al., 2022; Stevens and Fuller, 2017; Stevens et al., 2016; Zhao, 2011). The emergence of early agriculture is linked to the domestication of broomcorn millet (*Panicum miliaceum*) and foxtail millet (*Setaria italica*), which occurred in the lower Yellow River, Wei River and Liao River regions around 9000 cal BP, although the long-term shift from foraging to farming may have begun as early as 11,000 cal BP (Stevens and Fuller, 2017; Stevens et al., 2021). The development of agricultural societies primarily based on millet cultivation during the following millennia led to population growth and the spread of farming, mainly to the west and east (Leipe et al., 2019).

From around 8000–7000 cal BP there is evidence of low-scale rice (*Oryza sativa*) cultivation in the lower Yellow River region (d'Alpoim Guedes et al., 2015; Long et al., 2022). The crop only became more important for food production in the Late Neolithic (ca. 4600–3900 cal BP) and after its climatic adaptation and development into the temperate *japonica*-type around 4000 cal BP (d'Alpoim Guedes et al., 2015; Fuller et al., 2016). During the intensification of rice cultivation in the lower Yellow River region, mixed millet-rice farming spread eastwards to the Liaodong Peninsula (Miyamoto, 2019) and arrived on the Korean Peninsula in the middle of the 3rd millennium BP and on the Japanese Archipelago at the end of the 3rd millennium BP (Crema et al., 2022; Leipe et al., 2020).

The most important West Asian crops in the study region in premodern times were bread wheat (*Triticum aestivum*) and barley (*Hordeum vulgare*). Wheat was likely first introduced in Shandong as a prestige and 'exotic' crop reserved for social elites in the middle of the 5th millennium BP (Long et al., 2018) and did not become a staple crop in northern China probably until the second half of the 2nd millennium BP (Zhou and Garvie-Lok, 2015). While wheat and barley appear together in many archaeobotanical records from eastern Eurasia (Lister et al., 2018), suggesting that both crops were introduced more or less simultaneously, the earliest robust evidence of barley cultivation in the lower Yellow River region from the early 3rd millennium BP (Liu et al., 2017) considerably postdates that of wheat. Knowledge of the chronology and spread of barley and wheat cultivation in the study region remains incomplete, but appears to be partly related to crop diversification in response to the continuous Neoglacial drying trend and territorial expansion policies of early dynastic China (unpublished data).

4. Discussion: Aligning the evidence

4.1. Early Holocene climate reversal and the break-up of Transeurasian

The Early Holocene in the study region is generally marked by increasing temperature and moisture levels (Stebich et al., 2015), which may have favoured human food resources and led to population growth and dispersal. However, spatiotemporal variability in the reconstructions of temperature and precipitation (Fig. 5a) for different locations in the greater study region indicate a centennial- to millennial-scale reversal of the long-term moisture trend during the second half of the Early Holocene. This phase of cooler/drier conditions stretches over different periods between ca. 10,000 and 8500 cal BP, which may be due to uncertainties in the chronologies of the different records and/or local environmental factors. However, all records show maximum cooling and drying around 9000 cal BP. This climate trend is also evident in the pollen records from Hulun Lake (Wen et al., 2010) on the Barga Plateau and from Ningjinpo Palaeolake (Zhang et al., 2024) on the North China Plain and by higher $\delta^{18}O$ values in speleothems from the Lianhua (Dong et al., 2018) and Kulishu (Duan et al., 2021) caves. A specifically strong cooling around 9000 cal BP is suggested by pollen records from a peat section in the Dajiuhu Basin (Zhang et al., 2018) and from a floodplain of the Seomjin River on the southern Korean Peninsula (Park et al., 2019). In addition, a pronounced cooling around this time is

also shown by a surface temperature record from the Yellow Sea (Nan et al., 2017) and the $\delta^{18}O$ record of the sb10 stalagmite from the Sanbao Cave (Dong et al., 2010) (see Fig. 1 for site locations).

The maximum cooling/drying shown in the different proxy records from the study region coincide with phases of colder climate conditions in the North Atlantic region at the end of the 10th millennium BP referred to as Bond event 6 around 9350 cal BP (Bond et al., 1997, 2001) and around 9200 cal BP (Fleitmann et al., 2008), which were likely induced by large-scale meltwater outbursts from the Laurentide ice sheet. Available palaeoclimate records show that these events had an impact on the climate of the entire Northern Hemisphere. While meltwater-induced cold conditions in the North Atlantic may have been the main driver of the recorded climate reversal in the study region, other forcing factors, such as reduced solar irradiance (Zhang et al., 2018), may have also played a role. Zhang et al. (2018) posit that this cooling event marks the strongest weakening of the Asian monsoon system during the entire Holocene.

The reversal of increasing moisture levels in northern China coincides with the beginning of the domestication of broomcorn millet in this region, dated to around 9000 cal BP (Stevens et al., 2021). However, it is likely that the domestication was probably preceded by a long period of millet harvesting and small-scale management (Stevens and Fuller, 2017; Stevens et al., 2021). The period of cooler and drier climatic conditions around 9000 cal BP was possibly one of the factors that initiated or intensify the cultivation of broomcorn millet to diversify the food spectrum and compensate for the reduced wild food resources under less favourable climatic conditions. This scenario essentially follows the mechanism suggested by Abe et al. (2016), which explains the growth of Middle Jomon (5000–4000 cal BP) populations in northern Japan despite long-term Neoglacial climate cooling. The authors postulate that in response to less favourable climate conditions, Jomon subsistence underwent a process of diversification and intensification. A main factor was probably the intensification in the exploitation of wild plant food resources (Crawford, 1997). One weedy plant that was used more intensively is barnyard grass (*Echinochloa crus-galli*). There is evidence that the plant was cultivated and probably underwent domestication to form the crop Japanese barnyard millet (*Echinochloa esculenta*) (Crawford, 2011).

Independently, the linguistic results in Table 1 suggest a primary break-up for the Transeurasian family at 9181 cal BP (12,793–5595 cal BP, 95 % confidence interval, Fig. 5b). The less favourable drier conditions may have pushed part of the Proto-Transeurasian language speakers towards the coastal environments of the Bohai Sea, the area corresponding to the Japano-Koreanic homeland in Fig. 4, in order to secure/supplement their diet by marine food resources.

As shown in Table 2, Proto-Transeurasian shares vocabulary related to agriculture, such as 'field for cultivation', 'to plant, grow (plants)' and 'seed, seedling', whereby etymologies (2.5) 'components that are removed from the millet harvest' and (2.6) 'cooked cereal, millet gruel' are suggestive of millet cultivation. However, it is not possible to reconstruct common marine vocabulary. By contrast, Table 3 shows that Proto-Japano-Koreanic had marine vocabulary in addition to agricultural vocabulary, including terms for 'ocean, sea' (3.1) and 'boat' (3.2) as well as species which are prevalent in the Bohai Sea, such as 'crab, *Portunus trituberculatus*' (3.3) and 'swellfish, *Takifugu chinensis*' (3.4). This indicates that Japano-Koreanic speakers moved towards the sea and supplemented their diet with marine resources. This coastal trend and the beginning or intensification of millet cultivation may have been responses to more challenging environmental conditions related to the cooling and drying at the end of the 10th millennium BP. So far, there is no evidence in the archaeological records from Liaodong for the use of millet as early as 9000 cal BP. One explanation for this could be that the sites of the Japano-Koreanic speakers were situated close to the former coastline, which would be submerged today as the global sea level has risen by about 30 m since 9000 cal BP (Lambeck et al., 2014).

4.2. Middle Holocene Thermal Maximum and the break-up of Altaic

The period of maximum temperature and precipitation (Holocene Thermal Maximum) during the current interglacial in northern China occurred during the Middle Holocene. The selected palaeoclimate records representative of the study region suggest that it began in the first half of the 8th millennium BP and ended with the onset of the Neoglaciation roughly around 5000 cal BP (Fig. 6a). While the pollen-based annual precipitation record from Daihai Lake shows highest values after 6000 cal BP, the remaining records in Fig. 6a and the speleothem $\delta^{18}O$ records from Lianhua Cave (Dong et al., 2018) demonstrate peak moisture levels before this date. The increased precipitation levels likely promoted the cultivation of millet in regions located further away from the ocean and thus receive less summer monsoon precipitation than coastal regions, such as the Liao River region. This may have favoured an expansion of agricultural population towards the north and west, including the Ordos Plateau and the northern Yellow River region (Fig. 6b).

Proto-Turkic separated from Proto-Altaic around 6811 cal BP (10,166–4404 cal BP, 95 % confidence interval), at the peak of humidity (Table 1). As shown in Fig. 4, linguists situate the original homeland of Proto-Turkic on the Ordos Plateau, from where it dispersed to the Sayan-Altai Mountain region from the Bronze Age onwards (Tenišev Edhjam et al., 2006; Janhunen, 1996: 26, 2015: 293; Robbeets et al., 2021). The increased moisture levels led to development of the landscape of the Ordos plateau to sparse forest grass-land as well as to the expansion of farming in the Middle and Late Neolithic. This is reflected by a Bayesian analysis of ^{14}C dates on archaeological millet grains from East Asia, which suggests that millet cultivation spread to the Middle Yellow River region during the first half of the 7th millennium BP (Leipe et al., 2019). However, it was not until 4000–3500 cal BP, at the time of the Meghalayan drought, that a pastoral way of living developed there (Wen et al., 2023). As shown in Tables 2 and 4, this development is paralleled by a gradual shift from agricultural subsistence mainly based on crop cultivation to nomadic agropastoralism in the subsistence vocabulary between Altaic and Turkic, such as (2.8) 'to ferment' to 'to milk; to extract'; (2.9) 'to reduce/ preserve food by fermentation' to 'to filter, strain (milk or soup); (2.10) 'to cut (cloth)' to 'to cut, scrape, strip (hair), pluck out (hair), shave' (4.1) 'to plant, grow (plants)' to 'to grow (of plants and animals)' and (4.3) 'young male pig' to 'young cattle/camel/horse'.

4.3. Onset of Neoglaciation and the break-up of Japano-Koreanic

The late Middle Holocene marks the beginning of a long-term drying trend in northern China, which is related to long-term cooling that persisted throughout the Late Holocene and is referred to as the Neoglaciation. The available palaeoclimate proxy records do not show a consistent beginning of this period and date it to between ca. 5400–4600 cal BP (Fig. 7a). While the pollen-based precipitation reconstructions from Daihai (Xu et al., 2010) and the AP percentages from Hulun Lake (Wen et al., 2017) show a decline in annual temperature from about 4600 cal BP, the palaeoprecipitation records from Gonghai Lake (Chen et al., 2015) and Dali Lake (Xiao et al., 2015) suggest that this occurred already in the middle of the 6th millennium BP (Fig. 7a). The results of the biomization (Stebich et al., 2015) and the temperate summergreen pollen taxa percentages (Stebich et al., 2015, Fig. 7 a) from the robustly dated Sihailongwan pollen record also date the beginning of more pronounced cooling to ca. 5400–5200 cal BP. Similarly, the well-dated pollen record from Kushu Lake in northern Japan dates the end of the Holocene Thermal Maximum to ca. 5400 cal BP (Leipe et al., 2018, Fig. 7 a). A contemporaneous climate transition towards cooler and drier conditions is also visible in the pollen-based temperature and precipitation reconstruction from the Khoe Peat section on northern Sakhalin Island (Leipe et al., 2015). Interestingly, the speleothem $\delta^{18}O$ records from Sanbao Cave (Dong et al., 2010) and

Lianhua Cave (Dong et al., 2018) indicate a continuous drying trend that began as early as ca. 7000 cal BP.

The oldest directly ^{14}C-dated millet grain from the Korean Peninsula dates to the beginning of the Neoglaciation, as suggested by most of the palaeoclimate records from the study region. This foxtail millet (*Setaria italica*) grain comes from the Neunggokdong archaeological site and dates to 5594–5331 cal BP (95 % confidence interval) with a median calibrated age of 5516 cal BP (Ahn et al., 2015). Therefore, it is not unlikely that in addition to socioeconomic and demographic factors, climate deterioration was one of the driving factors behind the expansion of millet farmers from northern China to the Korean Peninsula.

The Bayesian-modelled time span (5900–5450 cal BP, 68 % confidence interval) for the arrival of the first millet farmers based on all available directly dated archaeological millet grains from the southern Korean Peninsula (Leipe et al., 2019) is consistent with the modelled linguistic break-up between Japonic and Koreanic and the subsequent dispersal of Koreanic into the Korean Peninsula, estimated at 5458 cal BP (8024–3335 cal BP, 95 % confidence interval) as shown in Table 1 and Fig. 7b. The credible intervals for both the archaeological and linguistic modelling include the possibility for an earlier timing. An even earlier appearance of millet has been discussed based on millet grain impressions on pottery, which were dated to the Initial Neolithic (ca. 8000–7000/6500 cal BP), however no direct dates are yet available for these sherds or associated materials (Lee, 2017).

Our linguistic results in Tables 2 and 3 show that although Japonic and Koreanic share a substantial amount of agricultural vocabulary, such as (2.5) 'barnyard millet', (3.5) '(wet) field for cultivation', (3.6) 'delimited plot for cultivation', (3.7) 'hemp' and (3.8) 'ramie', they lack common rice terminology (Whitman, 2011, Francis-Ratte, 2017, Robbeets et al., 2021). This traces their common ancestry to a period before the adoption of rice agriculture, which is dated to the middle of the 4th millennium BP and the early 3rd millennium BP on the Korean Peninsula and Japan, respectively (see Leipe et al., 2020 and references therein).

4.4. Neoglaciation and the break-up of Tunguso-Mongolic

Most of the selected palaeoclimate records from the study region show a persistent trend of decreasing humidity during the 5th millennium BP (Fig. 8a) after the onset of the Neoglaciation (see discussion in previous section). An exception is the pollen-based annual precipitation reconstruction from Daihai Lake, which suggests that humidity remained on comparatively high levels until the middle of the 5th millennium BP. By contrast, a record of tree pollen percentages from the same lake suggests a pronounced drying trend during the entire 5th millennium BP (Wen et al., 2017; Xiao et al., 2004). A period of decreasing temperature and precipitation ca. 5300–4000 cal BP is also evident in available pollen records from the southern part of Russian Primorye (Lyashchevskaya et al., 2022).

The earliest undisputed evidence of millet use in the region is associated with a directly ^{14}C-dated (4822–4530 cal BP, 95 % confidence interval) grain of broomcorn millet (Sergusheva et al., 2022). Bayesian modelling of available millet ^{14}C dates from southern Primorye suggests that millet cultivation was most likely introduced during the first half of the 5th millennium BP (Leipe et al., 2019; Sergusheva et al., 2022). The migration of millet farmers to southern Primorye may have been partly motivated by deteriorating climate conditions for crop cultivation. Although the region was also marked by long-term cooling and drying (Lyashchevskaya et al., 2022), precipitation levels in maritime southern Primorye were likely still higher and more favourable for millet farming than in the West Liao River region.

The migration of the ancestors of Tungusic speakers from the West Liao River region to the Amur–Ussuri–Khanka region is estimated at 4491 cal BP (2599–6373 cal BP, 95 % confidence interval) as shown in Table 1 and Fig. 8 b. As such, it took place during a period of progressive cooling and drying, simultaneous with the dispersal of millet agriculture. It is therefore sensible to assume that millet was introduced to Primorye by farmers who spoke Proto-Tungusic.

Table 5
Agricultural vocabulary reconstructable to Proto-Altaic only.

No	Gloss	Proto-Altaic	Proto-Tungusic	Proto-Mongolic	Proto-Turkic
4.1	'to plant, grow (plants)'	*iuse	*üse- ~ üsi- 'to plant, grow'	*ös- 'to grow (of plants/animals)'	*ös- 'to grow (of plants/animals)'
4.2	'to prepare soil for cultivation, cultivate'	*tari-	*tari- 'to sow, plant, cultivate'	*tari- 'to prepare the soil for cultivation; to sow, plant'	*tari- 'to cultivate, prepare the soil for cultivation; to sow, disperse'
4.3	'young male pig'	*toru	*toro 'male pig'	*toru 'young male pig'	*to:ru 'young cattle/camel/horse'

Table 5 presents some etymologies suggesting that the speakers of Proto-Tungusic were familiar with millet agriculture. Among others, it includes a common word for 'broomcorn millet' (5.1), which is a non-native crop imported from the West Liao River region by the people who introduced the Late Neolithic Zaisanovskaya culture to Primorye (Sergusheva and Vostretsov, 2009, Leipe et al., 2019). Although the wild variant of foxtail millet is native to the Russian Far East, the wild variant of broomcorn millet is not. Nevertheless, the early Zaisanovskaya populations cultivated broomcorn millet, which was supplemented by foxtail millet only during the late Zaisanovskaya period (ca. 4000–3500 cal BP), as suggested by available archaeobotanical records (Sergusheva, 2013). This is in line with the etymology of the word (2.4), listed in Table 2, which traces its origins back to the Proto-Transeurasian language in the West Liao River area. Another word that can be traced back to the ancestral language is (5.4) 'to sow, plant, cultivate', see etymology (4.2) in Table 4.

4.5. The Meghalayan Drought and the spread of Japonic to the Korean Peninsula

The adoption of rice cultivation in Shandong was a long-term process, which resulted in the development of temperate *japonica*-type rice by 4000 cal BP (Fuller et al., 2016). Limited archaeobotanical evidence from the southern part of the Shandong Peninsula dating to the first phase (ca. 7000–4600 cal BP) of rice cultivation suggest only small-scale cultivation, which intensified during the Longshan period (ca. 4600–3900 cal BP) (d'Alpoim Guedes et al., 2015). It seems plausible that the long-term decline in monsoon precipitation since the beginning of the Neoglaciation (Fig. 9 a) was one factor that forced farmers to diversify their crop package by introducing rice, which was originally not well adapted to the region's climate.

Linguistic phylogeography places pre-Proto-Japonic in the area between the Shandong and Liaodong Peninsulas after its separation from Koreanic, estimated at 5458 cal BP (3335–8024 cal BP, 95 % confidence interval) as shown in Table 1 and Fig. 9 b. There are some indications that rice terminology was borrowed at an early stage into pre-Proto-Japonic. Continental neighbours in the Shandong area may have included among others, speakers of Sino-Tibetan languages, associated with the Yangshao culture (7000–4800 cal BP) and Para-Austronesian languages, i.e., sister languages of proto-Austronesian, associated with the Dawenkou culture (6100–4600 cal BP). Pre-Proto-Japonic probably borrowed terms such as **kəmai* 'dehusked rice' and **usu* '(rice and grain) mortar' from Para-Austronesian **semay* 'cooked rice' and **lusuŋ* '(rice) mortar' (Robbeets, 2017). Numerous attempts to relate Japonic to the Austronesian languages (e.g., Kawamoto, 1985; Benedict, 1990; Kumar, 2009) may reflect an early layer of prehistoric borrowing, dating back to a time when pre-Proto-Japonic was still spoken on the continent.

The long-term cooling and drying trend, which began with the

Neoglaciation in the late Middle Holocene, was superimposed in many regions of the Northern Hemisphere by the Meghalayan Drought (4200–4000 cal BP), also known as the 4.2 ka event (Walker et al., 2019). While the available palaeoclimate reconstructions in sum show that this decadal- to centennial-scale climate event did not occur in large, coherent spatial regions (McKay et al., 2024), it represents the Middle–Late Holocene (i.e. Northgrippian–Meghalayan) boundary (Walker et al., 2019), which marks the beginning of enhanced cooling in the Northern Hemisphere (e.g. Paasche and Bakke, 2009; Paasche et al., 2004; Peck et al., 2015). A substantial weakening of the South and East Asian summer monsoon circulations from 4200 cal BP is indicated by speleothem $\delta^{18}O$ records (Dong et al., 2010, Fig. 9a; Kathayat et al., 2017; Wang et al., 2005). Other palaeoclimate records from the study region support this trend or at least show a persistent drying from 4200 cal BP (Fig. 9a). Different studies have proposed a causal relationship between the Meghalayan Drought and the demise of Neolithic societies in the Yellow and Yangtze River regions (Guo et al., 2018; Liu and Feng, 2012; Yasuda et al., 2004). While socio-political factors related to expansion policies of early dynastic China may have played a primary role in the spread of rice-millet farmers from the Shandong Peninsula to the Korea Peninsula around 3500 cal BP, these processes may have been partly triggered by enhanced precipitation decline in the Asian steppes and northern China (Leipe et al., 2020). With generally higher amounts of monsoon rainfall, the Korean Peninsula was more favourable for agriculture, especially for wet-field cultivation (Shoda et al., 2021) of the relatively newly adopted temperate *japonica*-type rice.

Today linguists would agree that at least two different language families, i.e., pre-Koreanic and pre-Japonic, coexisted on the Korean Peninsula from the 3rd to 2nd millennium BP (Hudson and Robbeets, 2020). Linguistic evidence suggests that speakers of pre-Proto-Koreanic were originally millet farmers, who adopted rice agriculture from the pre-Proto-Japonic immigrants. The repurposing of Korean cereal vocabulary as rice vocabulary (Robbeets, 2017, Francis-Ratte, 2017) is illustrated in Table 6. The original meanings of (6.1) Proto-Koreanic **pap* 'any boiled cereal' and (6.2.) Proto-Koreanic **pʌsal* 'hulled (of any grain); hulled corn of grain' are fossilized in certain compounds, such as e.g., Korean *ssal poli* 'hulled barley'; *poli ssal* 'a grain of barley, a barley corn' (with *poli* 'barley') and *copssal* 'millet grain' (with *co* 'millet'). In the course of the history of Proto-Korean, the meanings specialized as 'boiled rice' and 'hulled rice', reflected in contemporary Korean.

In addition, Some Koreanic rice terms may also be borrowed from Japonic at an early stage in prehistory. As suggested in Table 7, Proto-Koreanic terms such as **pye* '(unhusked) rice', and **pʌsal* 'hulled (of any grain); hulled grain of any cereal; hulled rice' may be borrowings from the ancestor of Proto-Japonic **ip-i* 'cooked millet, steamed rice' and **wasa-ra* 'early ripening (of any grain)'. Both words are morphologically complex in Japanese: Proto-Japonic **ip-i* 'cooked millet, steamed rice' is derived as a deverbal noun from a verb **ip-* 'to eat', while **wasa-ra* is derived from OJ *wasa-* 'early ripening variety' and a suffix **-ra* deriving property nouns. The complex nature of these words suggests that the correspondence set is the result of borrowing rather than inheritance and that the direction of the borrowing is from the morphologically complex language, *in casu* Japonic, into the unsegmentable language, *in casu* Koreanic. These borrowed words suggest that pre-Proto-Koreanic speakers added rice technology to a pre-existing agricultural package through borrowing from pre-Proto-Japonic speakers. The full datasets underlying Table 7 are presented in the Supplementary Material (SI 1) attached to this article.

Table 6
Agricultural vocabulary reconstructable to Proto-Tungusic on the basis of cognates in the Jurchenic, Southern and Northern branches of Tungusic.

	Gloss	Proto-Tungusic	Jurchenic	South Tungusic	North Tungusic
5.1	'broomcorn millet (*Panicum miliaceum*)'	*pisi-ke	Manchu fisihe ~ fisike 'glutinous millet, broomcorn millet (*Panicum miliaceum*)',	Nanai pikse 'millet'	
5.2	'foxtail millet (*Setaria italica*)'	*jiya-kta	Manchu je 'foxtail millet (*Setaria italica*); grain'	Nanai jiekte 'foxtail millet (*Setaria italica*)'	Negidal ja: kta 'foxtail millet (*Setaria italica*), small millet,; cleaned grain; oats flour'
5.3	'to plant'	*üse- ~ üsi-	Manchu use- 'to plant, seed (tr.)'	Udehe uhi- 'to sow, to plant a garden'	Even isu:- ~ esu:- 'to sprout, come out (of plants), blossom, grow'
5.4	'to sow, plant, cultivate'	*tari-	Manchu tari- 'to cultivate, farm; to plow'	Nanai tari- 'to sow seeds'	Solon tari- 'to sow seeds; to plant; to cultivate; to grow; to disseminate'

4.6. *Advanced Late Holocene cooling and the spread of Japonic to and across Japan*

During the 3rd millennium BP at a time of Late Holocene cooling and drying (Fig. 10 a), rice-millet farming spread from the Korean Peninsula to Kyushu on Japan, leading to the birth of the Yayoi culture (ca. 3000–1700 cal BP). From there, rice-millet farming had spread to almost all parts of the Japanese Islands between southern Kyushu and northern Honshu by the turn of our era (Leipe et al., 2020; Crema et al., 2022). It is not until the beginning of the 1st millennium BP, however, that rice and millet together with wheat and barley spread to the Northern and Central Ryukyus (Takamiya et al., 2016).

Miyamoto (2009, 2016) proposed that phases of climate cooling (2850–2620 cal BP) inferred from increased concentrations of atmospheric ^{14}C triggered the spread of rice-millet farmers from the Korean Peninsula to Kyushu around 3000 cal BP. Increased ^{14}C production is linked to weak solar irradiance due to weak sunspot activity and has been used to explain phases of cooler climate conditions in palaeoclimate research (Shindell et al., 2001). A period of decreased total solar irradiance has been reconstructed for the early 3rd millennium BP, dating to ca. 2780–2680 cal BP (Steinhilber et al., 2009), which has been discusses as the main cause of simultaneous climate cooling in the North Atlantic region (Kromer and Friedrich, 2007) and strong flooding events in Central Europe at the beginning of the Iron Age (Sirocko, 2013). There is a temporal relationship between this phase of decreased total solar irradiance and the introduction of rice-millet farming in Kyushu, but the oldest directly ^{14}C-dated rice grain (2849–2756 cal BP, 95 % confidence

Table 7
The repurposing of cereal vocabulary as rice vocabulary in Proto-Koreanic.

	Proto-Koreanic form	Proto-Koreanic meaning 1	Proto-Koreanic meaning 2
6.1	**pap*	'any boiled cereal'	'boiled rice'
6.2	**pʌsal*	'hulled (of any grain or cereal); hulled grain of any cereal, hulled variety of any cereal'	'hulled rice'

interval) from Japan (Miyamoto, 2018) suggests that farmers began to migrate to Japan already before. Except for cooler winter temperatures 2800–2700 cal BP indicated by low proportions of evergreen broadleaf pollen in the palynological record from Jeju Island in the Korea Strait (Park et al., 2023), a centennial-scale phase of pronounced cooling/drying during this interval is not visible in other palaeoclimate records from the region (Fig. 10a). Thus, the phase of weaker solar irradiance ca. 2780–2680 cal BP was probably not the trigger of the initial spread of farmers from the Korean Peninsula to Kyushu, but may have further enhanced the long-term Late Holocene cooling in the study region (Fig. 10a), which may have fostered later migrations from the continent to Kyushu during the Yusu I (2850–2650 cal BP) and Yusu II (2650–2450 cal BP) pottery typological periods (Miyamoto, 2019). Leipe et al. (2020) hypothesized that the progressive long-term Late Holocene cooling and weakening of the Asian summer monsoon circulation was one factor that led to an expansion of agropastoralists from the Asian steppes to the south and east and the eastward expansion of the Shang and Zhou dynasties and the establishment of satellite states east of their homelands. These population shifts and expansion policies may have been the immediate factors that led to the initial migration of rice-millet farmers to the Korean Peninsula and ultimately to Kyushu.

As shown in Fig. 4, various homeland detection methods converge on identifying Kyushu as the homeland of Proto-Japonic. Table 1 estimates the internal break-up of Proto-Japonic at 2136 cal BP (2412–1499 cal BP, 95 % confidence interval), after which Japonic languages started to spread across western Japan (Fig. 10b). Associated with the farming dispersals, the Ryukyuan languages spread to the Ryukyu Islands as late as the medieval period. Table 8 illustrates the reconstruction of agricultural vocabulary, including words for 'barley/wheat', 'rice', 'foxtail millet', 'broomcorn millet' and 'barnyard millet' to Proto-Japonic. As indicated in the final column, most items have potential cognates on the continent, be it through prehistoric borrowing or inheritance.

Records of archaeological materials, archaeobotanical remains and palynological indicators of human activities from central Japan may provide evidence for the spread of Japonic languages across western Japan and related population pressure in the late 3rd millennium BP. Archaeological records show a new phase of early agriculture in central Japan's Kanto region marked by increased cultural influence from western Japan (Barnes, 2019) and the establishment of full-sale agriculture, which was focused on rice cultivation, from the middle Middle Yayoi period (Leipe et al., 2024). This development was associated with increased human activity (Leipe et al., 2024) and population numbers (Wakasa, 2022) dated to ca. 2250–2150 cal BP (see Leipe et al., 2024 and references therein), which is consistent with the estimated timing of the internal break-up of Proto-Japonic.

4.7. Advanced Late Holocene cooling and the internal break-up of proto-Tungusic

A review of palaeoclimate records from Primorye shows a period of enhanced cooling of the climate and coastal waters between ca. 2700 and 1800 cal BP (Lyashchevskaya et al., 2022). Colder temperatures and further reduced summer monsoon precipitation during this period are also indicated by proxy records from the wider region (Fig. 11a). This climate trend was likely accompanied by less favourable conditions for food procurement, which posed an increasing challenge for local populations in southern Primorye, who practiced a mixed farming-foraging subsistence economy. Diversification of crop packages and shifts in preferred settlement locations and food preferences (Vostretsov, 2013) were probably strategies to adapt to the deteriorating environmental conditions. The former response comprises the introduction of barley, soybean, hemp and likely wheat in addition to the existing cultivation of foxtail and broomcorn millet in the second half of the 3rd millennium BP (Sergusheva and Moreva, 2017; Sergusheva et al., 2022). Part of the population that had settled inland began to move to the coast. The migrations within southern Primorye probably led to increased competition for land and food resources as well as cultural assimilation and population decline at the end of the 3rd millennium BP (Sergusheva and Vostretsov, 2009; Vostretsov, 1999, 2005).

Bayesian dating in Table 1 estimates that the internal break-up of proto-Tungusic did not happen until 1950 cal BP (2412–1499 cal BP, 95 % confidence interval) in the Iron Age. This is supported by the fact that all Tungusic languages share a common word for 'iron', see etymology (9.1) in Table 9. The ancestral speakers also borrowed the word for 'barley' (9.2) from Old Chinese before their separation, which is consistent with the introduction of barley from regions further south or west (Sergusheva and Vostretsov, 2009). Moreover, they borrowed maritime vocabulary, such as words for (9.3) 'sea' and (9.4/9.5) 'whale' from Amuric speakers along the coast, the ancestors of the contemporary speakers of Nivkh (Robbeets and Wang and Robbeets, 2020; Knapen, 2023). This is consistent with the greater focus on marine resources and the migration along the coast, observed in the archaeological record. If the Late Holocene cooling can be associated with the primary break-up between Jurchenic and Tungusic Proper, as illustrated in Fig. 11b, it would explain why southern Tungusic populations on the Lower Amur reverted to hunting, gathering and fishing: Nanai, Oroch and Udehe people were traditionally predominantly fishers and gatherers, rather than farmers.

Table 8
Potential borrowings of rice vocabulary from pre-Proto-Japonic into pre-Proto-Koreanic.

	Proto-Japonic	Proto-Koreanic
7.1	*ip-i 'cooked millet, steamed rice'	*ipi > pi > pye '(unhusked) rice'
7.2	*wasa-ra 'early ripening (of any grain)	*pʌsal 'hulled (of any grain)'

5. Conclusions

Comparison of palaeoclimate records and linguistic developments demonstrates that global, hemispheric-scale and regional climate trends may have been factors that triggered or promoted the spread of the Transeurasian languages, which include an Early Holocene climate reversal at the root of the family; the Holocene precipitation maximum facilitating the migration of Turkic speakers to the Ordos Plateau; the onset of the Neoglaciation (i.e. long-term cooling/drying) leading to the migration of Koreanic speakers to the Korean Peninsula and Tungusic speakers to southern Primorye; the Meghalayan drought and the following enhanced Late Holocene cooling/drying pushing the Japonic language to the Korean Peninsula and the Turkic language towards the Sayan-Altai Mountains; and the further advanced Late Holocene cooling/drying leading to the dispersal of Japonic out of Korea and to the internal break-up of the Tungusic languages.

As such, the Transeurasian case makes it clear that climate trends of different spatial and temporal scales can yield local linguistic responses. This impact is obviously not restricted to the spread of Japanese and the Transeurasian languages, but also surfaces in other language families across the world. The Meghalayan drought, for instance, has also been correlated to the spread of Uralic (Grünthal et al., 2022), Austroasiatic (Sidwell and Blench, 2011) and Bantu (Bostoen et al., 2025).

As becomes clear from the Transeurasian test-case, the connection between climate change and language mobility is an indirect one, often going over subsistence, but, as shown by other cases, not restricted to agriculture. Even if agricultural societies are generally less resilient to climate change, climate may also impact subsistence in other ways, for instance by affecting the migration routes of hunted or herded animals such as reindeer or marine mammals, relevant for the spread of Eskimo-Aleut (Berge, 2018).

Depending on the subsistence strategy of the speakers, climate may have a weaker or stronger impact on language dispersal. As soon as the

Table 9
Agricultural vocabulary reconstructable to Proto-Japonic on the basis of cognates in Mainland Japanese and the Ryukyuan languages. Bracketed words do not represent cognates of the listed forms although they express the meaning indicated in the first column.

Gloss	Proto-Japonic	Old Japanese	Yamatoma (Amami)	Old Shuri	Hirara (Miyako)	Ishigaki (Yaeyama)	Yonaguni	External cognates
'barley/ wheat'	*munki	$mugi_1$	mugi	muzi	mugzɨ	muŋ	muŋ	borrowed
'rice'	*kəmai	ko_2me_2	khumï	'kumi	kumi	kumi	kumi	borrowed
'foxtail millet'	*apa	apa	ʔoo	ʔawa	a:	a:	a:	borrowed
'broomcorn millet'	*kimi	ki_1mi_1	thonokiN	(ma:zin)/ to:ʒimi	ksɨm	kĭŋ	c'iNti	inherited
'barnyard millet'	*kimi	ki_1mi_1	(hwei)	(ma:zin)	tsïm ~ kĭm	(pi:) ~kĭŋ	c'iNti	inherited
'field for cultivation'	*pata-ka-i	$patake_2$	hat^he	hataki	pataki	patagi	hatagi	inherited
'rice paddy'	*ta	ta	t^ha	'ta:	ta:	ta:	ta:	inherited?
'field'	*no	no_1	—	mo:	nu:	nu:	nu:	inherited

Table 10
Cultural and maritime vocabulary reconstructable to Proto-Tungusic on the basis of cognates in the Jurchenic, Southern and Northern branches of Tungusic. Potential sources of ancient borrowing are given in the last column.

	Gloss	Proto-Tungusic	Jurchenic	South Tungusic	North Tungusic	Borrowed from
9.1	'iron'	**sele*	Manchu *sele* 'iron'	Nanai *sele* 'iron'	Negidal *sele* 'iron'	
9.2	'barley (*Hordeum vulgare*)'	**murgi*	Manchu *muji* 'barley (*Hordeum vulgare*)'	Oroch *mujɨ* 'barley'	Solon *mụrgil* 'spring crops, spring-sown field'	Old Chinese 來*mə.rˤək > *mə.rˤə 'a kind of wheat'
9.3	'sea'	**lāmu*	Manchu *namu* 'sea'	Orok *namụ* 'sea', *lamu* 'wave'	Evenki *lāmu* 'sea'	Amuric **lam* 'small wave'
9.4	'whale'	**kalimu*	Manchu *kalimu* 'whale'	Udehe *kalima* 'whale'	Evenki *kalim* 'whale; walrus'	Amuric **qʰalm* 'whale of small size'
9.5	'whale'	**kiaŋa*		Orok *keŋa, kena, kiaŋa* 'whale'	Evenki *kēŋas* 'dolphin skin'	Amuric **keŋ* 'whale of intermediate size'

Japonic farmers integrated rice in their agricultural package, the climate became an even more determining factor for the spread of their language, because rice reacts more sensitively to cooler and drier conditions than millet. The susceptibility of a speech community's subsistence strategy to climate change may thus be one of the factors that determines how far the language in question will spread away from its original homeland.

In this study we focused on the identification of possible impacts of climate change on the spread of the Transeurasian languages. However, climate is obviously not the only factor that drives people and their languages. There is also a whole range of interacting social, cultural, political and demographic factors that should be considered. In other cases, climate change may kick off a chain of domino effects associated with changes in subsistence economies and migrations. During the period of advanced Late Holocene cooling and drying that began with the Meghalayan drought, for instance, agropastoral populations moved south and east from the Asian steppes to environments that received more monsoon precipitation, which in turn probably led to the eastward expansion/migration of agricultural societies that relied primarily on crop cultivation. We believe that a more holistic analysis of the different forcing factors and their interactions should be addressed in a future study.

In short, the interface between Historical Comparative Linguistics and palaeoclimate studies raises compelling questions. Adding linguistics to the wide range of disciplines, which are currently involved in the debate may be useful not only to raise new questions, but also to re-address some of the old ones, from a different perspective.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This study was conceptualized and carried out as a project of the "Language and the Anthropocene" Independent Research Group at the Max Planck Institute of Geoanthropology, Jena. In addition, it is a contribution to the "Japanscapes" project as part of the Domestication and Anthropogenic Evolution Independent Research Group at the Max Planck Institute of Geoanthropology, Jena. The work of C. Leipe was financially supported though a DFG Research Grant (TA 540/10–1) and the European Research Council Starting Grant (no. 851102) Fruits of Eurasia: Domestication and Dispersal (FEDD). We would like to thank Pavel Tarasov (Freie Universität Berlin) for his valuable comments and suggestions on an earlier version of the manuscript.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.qeh.2025.100071.

Data availability

Full linguistic datasets underlying the etymologies presented in Tables 2–4 are added as online supplementary material. All palaeoclimate records shown in the figures have been retrieved from datasets provided along the original publications. If no data was provided, records were digitised from the figures in the original publications.

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