

<https://doi.org/10.1038/s40494-026-02357-2>

Isotopic insights into han period coastal agriculture on the liaodong peninsula in northeast China

Check for updates

Yuan Lin^{1,2}, Ru Yu^{1,2}, Qi Dai³, Weiwei Si⁴, Quanchao Zhang^{1,2}✉ & Liangliang Hou⁵✉

During the Han Dynasty's (202 BCE–220 CE) territorial and economic expansion, the subsistence strategies of coastal populations in Northeast China remain ambiguous. In this study, we conducted carbon and nitrogen stable isotope analysis on 74 human skeletal remains from the Han-period Shagangzi Cemetery. The results revealed a C₄-based diet and high $\delta^{15}\text{N}$ values. We attribute this $\delta^{15}\text{N}$ enrichment not to marine foods, but to intensive manuring that elevated the local baseline of the food web. This interpretation, supported by archaeological and historical evidence, suggests the transplantation of a Central Plains agricultural tradition (millet-based agriculture and pig husbandry) to the coast. Despite their coastal location, these Han communities prioritized land-based agriculture, a practice stemming from an imperial policy of military-agricultural colonization. This study highlights the primacy of imperial policy over local ecology in shaping subsistence strategies on the northeastern frontier of Han China.

The Han Dynasty (202 BCE–220 CE) established China's first enduring centralised imperial state^{1,2}. During the reign of Emperor Wu (141–87 BCE), the empire achieved unprecedented territorial expansion, systematically consolidating the Central Plain while strategically integrating peripheral regions³. Historical analyses indicate that political stability, coupled with moderate fiscal policies, fostered significant demographic growth⁴. By the late Western Han period, census records estimated that the population was approaching 60 million, which placed considerable pressure on agricultural production and resource management systems⁵.

Agriculture formed the foundation of the Han economy. Historical research suggests that the Han Dynasty was a period of significant advancement in agriculture⁶. This perspective is increasingly supported by archaeological research. Stable isotope analysis of millet from the Guanzhong Basin, the political centre of the Western Han, reveals a significant increase in $\delta^{15}\text{N}$ values compared to the Neolithic period. This increase indicates that farmers adopted more intensive fertilisation strategies to maintain soil fertility and productivity, which may represent a response to changing climatic conditions⁷. This intensification of agriculture was not only the result of technological innovation, but was also driven by state organisation and evolving social structures. During the Western Han period (early Han), the state promoted peasant-based agriculture by investing in large-scale irrigation, encouraging the use of iron tools and ox-ploughs, and spreading new cultivation methods^{2,8}. Subsequently, during the Eastern

Han, as landholding patterns shifted towards large estates, these state-provided technologies facilitated the development of a rationalised, market-oriented “manorial economy” that advanced northern Chinese agriculture⁹.

The state aimed to facilitate this development process, guided by the traditional doctrine of “prioritising agriculture and restraining commerce” (重农抑商). This principle held that agriculture was the “fundamental pursuit” (本业), while commerce was treated as the “secondary” or “non-essential pursuit” (末业). Historical texts describe its implementations through fiscal incentives like reduced taxation and large-scale frontier development programs^{8,10}. The impact of these policies was complemented by technological innovations, such as the widespread use of iron tools and ox-drawn ploughs, which increased agricultural productivity and enabled regional development on a large scale⁸.

The capacity of the state for such large-scale development relied on the synergy between two key institutions: the prefecture–county (Junxian, 郡县) system and the military-agricultural colony (Tuntian, 屯田) policy. The Junxian system provided an institutional framework, extending imperial authority into newly acquired territories and enabling the state to implement the Tuntian policy^{3,8,11}.

This policy settled soldiers and civilian migrants in strategic frontier zones, such as the Hexi Corridor, to achieve the dual goals of military self-sufficiency and agricultural production¹². This integrated model of combining administrative control and state-led colonization was designed to

¹Bioarchaeology Laboratory in School of Archaeology, Jilin University, Changchun, China. ²College of Archaeology, Jilin University, Changchun, China.

³Department of Archaeology and Museology, Faculty of History, Nankai University, Tianjin, China. ⁴Liaoning Provincial Institute of Cultural Relics and Archaeology, Shenyang, China. ⁵College of Archaeology and Museology, Shanxi University, Taiyuan, China. ✉e-mail: py2000sdqy@sina.com; llhou@sxu.edu.cn

play an important role in transforming peripheral territories into productive agricultural regions, thereby securing the frontiers and integrating them into the Han economic system. During the Western Han Dynasty, incursions by the Xiongnu (匈奴) posed a persistent threat to imperial stability. In response, Emperor Wen (r. 180–157 BCE) initiated Tuntian policies in 169 BCE as a strategy for settling civilians on the frontier, and under Emperor Wu (r. 141–87 BCE) these schemes were greatly expanded, becoming a core mechanism for consolidating border defences^{4,12}. Although most scholarship has focused on the northwest, these policies also extended to the northeast, which faced comparable defensive pressures. Accounts in the *Hanshu* (Book of Han), particularly the “Annals of Emperor Zhao” (昭帝传) and the “Account of the Xiongnu” (匈奴传), record the establishment of Tuntian colonies in the Liaoxi and Liaodong regions¹². Archaeological discoveries of Han official seals along sections of the Great Wall in these areas further attest to the presence of garrisoned agricultural communities and the exercise of administrative control¹³.

In addition to the northwest frontier, the northeast also held dual strategic importance, fulfilling both military and agricultural roles. Administrative innovations, such as the establishment of the Liaodong Commandery and the promotion of the Tuntian system, were key instruments through which the Han government aimed to integrate the region into the imperial administration while simultaneously securing its borders¹³. This dual strategy was portrayed as strengthening the empire’s territorial control and contributing to its stability and prosperity^{13,14}.

However, there was a complex and dynamic interaction between state policy goals and on-the-ground practices in the political economy of the Han Dynasty, which evolved over time². In practice, state policies were not always implemented uniformly across the vast empire. Instead, local responses in frontier zones emerged from a dialectic between top-down imperial agendas and adaptations to local environmental conditions and social contexts. Therefore, the study of how core agricultural practices were adopted or modified in frontier zones is critical to achieving a more nuanced understanding of imperial integration.

Past research has significantly advanced our understanding of the diverse subsistence economies during China’s Han Dynasty, which range from mixed wheat and millet agriculture in the northwest to specialised wet-rice systems in the southeast^{15–25}. However, a pronounced geographical bias remains, with northeastern coastal communities receiving comparatively limited attention. As a strategically significant frontier, China’s northeast coast comprises both fertile alluvial plains suitable for agriculture and abundant marine resources, providing unique ecological and economic opportunities²⁶. Despite systematic agricultural development facilitated by Han administrative innovations, most notably the establishment of the Liaodong Commandery and the implementation of the Tuntian system^{3,27}, academic research has focused on the Central Plains and other inland regions, leaving the northeastern coastal frontier regions relatively underexplored.

The paucity of stable isotope research on dietary patterns and subsistence economies among populations inhabiting China’s northeastern coastal zone is particularly striking. To date, only three published studies have examined this region, with only a single study focusing on a Han-period site: isotopic analysis of human and faunal remains from shell tombs at the Bayuquan Cemetery²⁸. This research gap is especially striking because of the significant Han frontier expansion strategies and the region’s exceptional ecological configuration, in which fertile alluvial plains conducive to agriculture are combined with rich marine resource availability¹³. Bridging this research gap is essential for developing a more nuanced understanding of the regional adaptive strategies and subsistence diversification across the territorial sphere of the Han Dynasty.

To address this lacuna, this study focuses on the subsistence economy of a Han-period population on the Liaodong Peninsula in Northeast China. Several fundamental questions require further investigation: What was the foundational subsistence strategy of this northeastern coastal community? How did this community manage its agricultural ecosystem? Specifically, what agricultural and animal husbandry practices were adopted, and how

might these practices have influenced the isotopic signatures of the local food chain, thus complicating the distinction between terrestrial and marine dietary inputs? What were the potential drivers of their subsistence economy? Finally, do these dietary patterns indicate a pragmatic, local choice for resource utilisation, or do they represent the successful implementation of a state-driven policy aimed at establishing an agricultural frontier to serve broader imperial objectives?

Within this context, the Liaodong Peninsula, located in the southern part of Liaoning Province between the Yellow Sea and the Bohai Sea (Fig. 1), offers an ideal case study. As the southernmost extension of the Qianshan Range within the expansive Changbai Mountain system, the Liaodong Peninsula is characterised by its favourable hydrogeological and geomorphological conditions. These include abundant groundwater resources, a well-developed river network, and diverse topographic features^{29–31}. The central highlands gradually transition through terraced terrain to coastal plains, forming a heterogeneous landscape that has historically supported human habitation and various subsistence strategies³².

The Junxian (郡县) administrative system originated during China’s Warring States period (480–221 BCE). It was formally extended to Liaodong when the Qin Dynasty (221–206 BCE) first established the Liaodong Commandery; following the Qin, the Han Dynasty inherited this administrative structure and further implemented the Tuntian system to solidify control¹³. Dalian, located in the southern part of the Liaodong Peninsula, has long been regarded as a regionally significant archaeological centre at least since the Warring States period¹⁴. By the Han period, the region had been incorporated into Youzhou Province. Han imperial rule fostered unprecedented political stability, which in turn drove significant advancements in agricultural and artisanal production, elevating Dalian as a key socio-economic hub in Northeast China^{13,14}. Furthermore, archaeological surveys have also documented dense Han-period settlement networks radiating from coastal hubs, highlighting its pivotal role in the region³³.

The agricultural potential of this region stems from its long history of local development. *Hanshu Dilizhi* records Youzhou Province, encompassing present-day Dalian, cultivating the “three principal grains” during the Han period⁵. In his commentary on *Hanshu*, the Tang Dynasty scholar Yan Shigu (581–645 CE) identified these grains as broomcorn millet (*Panicum miliaceum*), foxtail millet (*Setaria italica*), and rice (*Oryza sativa*), while archaeological evidence indicates an even more diverse system incorporating sorghum (*Sorghum bicolor*) and wheat (*Triticum aestivum*)¹⁴.

Notably, the agricultural foundations of this region can be traced to the late Neolithic (3000–2000 BCE), when millet macroremains were systematically recovered at the Wangjiacun and Xiaozhushan Phase V sites. In subsequent centuries, legumes, wheat, and rice were progressively integrated into the agricultural repertoire, indicating systematic crop diversification amid expanding husbandry strategies³⁴.

By the Middle Bronze Age (1500–1000 BCE), excavation at the Dazuizi site in Dalian Bay revealed large quantities of carbonised rice and millet associated with faunal assemblages dominated by domesticated species, including domestic pigs (*Sus scrofa domestica*), chickens (*Gallus gallus domesticus*), dogs (*Canis lupus familiaris*), and sheep (*Ovis aries*)³⁴. Collectively, these findings point to increasingly sophisticated mixed farming and herding systems in prehistoric Dalian, which laid the foundations for later agricultural and economic trajectories in Northeast China.

During the Han period, Dalian maintained robust socioeconomic interaction with the Central Plain, with connections institutionalised under Emperor Wu through Liaodong Commandery. This administrative institution aimed to consolidate imperial control via integrated military and civil governance, most prominently with the Tuntian policy. This initiative, which was implemented as a strategic countermeasure to address frontier pressures (particularly from the Xiongnu nomadic confederation), precipitated state-directed population transfers from Shandong Province and Hebei Province^{4,14,35}. According to historical records, such activities aimed to alter the agricultural landscape of the Dalian region. Reclamation and intensified cultivation



Fig. 1 | Geographic location of Shagangzi Cemetery. The inset map (top left) shows the general location of this study area in China, highlighted by a red rectangle. The main map illustrates the topographic setting of the Liaodong Peninsula. The red triangle marks the specific location of Shagangzi Cemetery. The colour gradient represents elevation in meters (m), with green indicating low and orange indicating high elevation (Maps were generated in ArcGIS Pro 3.4 by Yuan Lin).

practices were promoted to reshape the agrarian economy of the region, laying the foundation for sustained agricultural productivity.

Archaeological evidence from Dalian points to substantial cultural connections with both Shandong Province and the Central Plain. Typical artefacts include heating stoves (陶方炉), cosmetic cases (陶奩), waist eaved tripods (带腰檐陶鼎), and distinctive pottery jars, all of which exhibit clear typological affinities with ceramic assemblages from the Weihai region in Shandong^{36,37}. Particularly notable are owl-shaped pottery vessels (陶鸱壶) from the Huaershan Han Tomb M2, which closely resemble early examples from Xinxiang, Henan Province, a core region of the Central Plain. Within the context of Han agricultural policy, these vessels underscore the importance of agriculture through their association with rodent control³⁸. Together with finds such as silk textiles preserved on bronze mirrors from the Yingchengzi Tomb, these materials provide concrete evidence for the transmission of Central Plain material culture and agricultural traditions to the Liaodong frontier and for state-supported population movements and migrant subsistence practices³⁷.

The migration of populations from the Central Plains also introduced advanced iron agricultural tools and cultivation techniques to the Liaodong Peninsula, helping to transform local agricultural practices. Systematic archaeological evidence confirms the widespread use of diverse iron tools throughout the Han period in Dalian^{14,33,35}. These technological innovations reveal both improved metallurgical capability and intensified farming practices, marking a pivotal transformation in agricultural production systems and fostering greater productivity and efficiency^{14,39}. Concurrently, complementary developments in husbandry, which included the raising of pigs, cattle, dogs, and chickens, revealed the consolidation of an integrated agriculture and husbandry economy¹⁴.

Past archaeological investigations in Dalian have uncovered remarkably well-preserved Han-period tombs and settlement sites³³. Shagangzi Cemetery is located on the Liaodong Peninsula (Fig. 1). Specifically, it is strategically situated within the Yingchengzi–Shagangzi (营城子-沙岗子) settlement cluster, which provides critical insights into local subsistence economies. Moreover, this context is an ideal case study for investigating the subsistence economy among coastal populations in Northeast China during the Han period.

Shagangzi Cemetery is located in Yingchengzi Subdistrict, Ganjingzi District, Dalian. Between June 2021 and December 2021, excavations were carried out under the direction of the Liaoning Provincial Institute of Cultural Relics and Archaeology in preparation for the development of the Ganjingzi Industrial Park. Figure 2a presents a detailed plan of the excavated area, illustrating the spatial arrangement of the tombs. The cemetery, which dates to the Han Dynasty (202 BCE–220 CE), is part of the larger Yingchengzi–Shagangzi burial complex³³. Since the early 20th century, this complex has been the site of extensive archaeological investigation, documenting more than 300 Han-period tombs of various types and recovering thousands of artefacts. The cemetery comprises three primary tomb types: shell-constructed tombs (the most common), earthen pit tombs, and brick-chamber tombs (Fig. 2b, c and Fig. 3). Burial assemblages consist of ceramic vessels, supplemented by smaller quantities of bronze implements, bone tools, lacquerware, and jade ornaments.

Although no definitive Han-era settlements have been identified in the immediate vicinity, the wide spatial distribution of tombs; the abundance of burial goods, including valuable nonceramic items such as bronze, lacquer, and jade; and the architectural diversity of the tombs strongly indicate that this area was densely populated and economically

Fig. 2 | Shagangzi Cemetery landscape and burial practices. **a** Overview of Shagangzi Cemetery excavation site; **b** Shell tomb M33 containing skeletal remains of a male individual aged 30 – 35 years; **c** Shell tomb M14, a double burial containing a pottery assemblage (Images of tombs are provided by Weiwei Si; The final layout was created using Adobe Photoshop CC 64 Bit).



prosperous during the Han period. This region is likely associated with the southern part of historical Tashi County. Documentation of additional excavated materials remains ongoing as part of comprehensive post-excavation analysis.

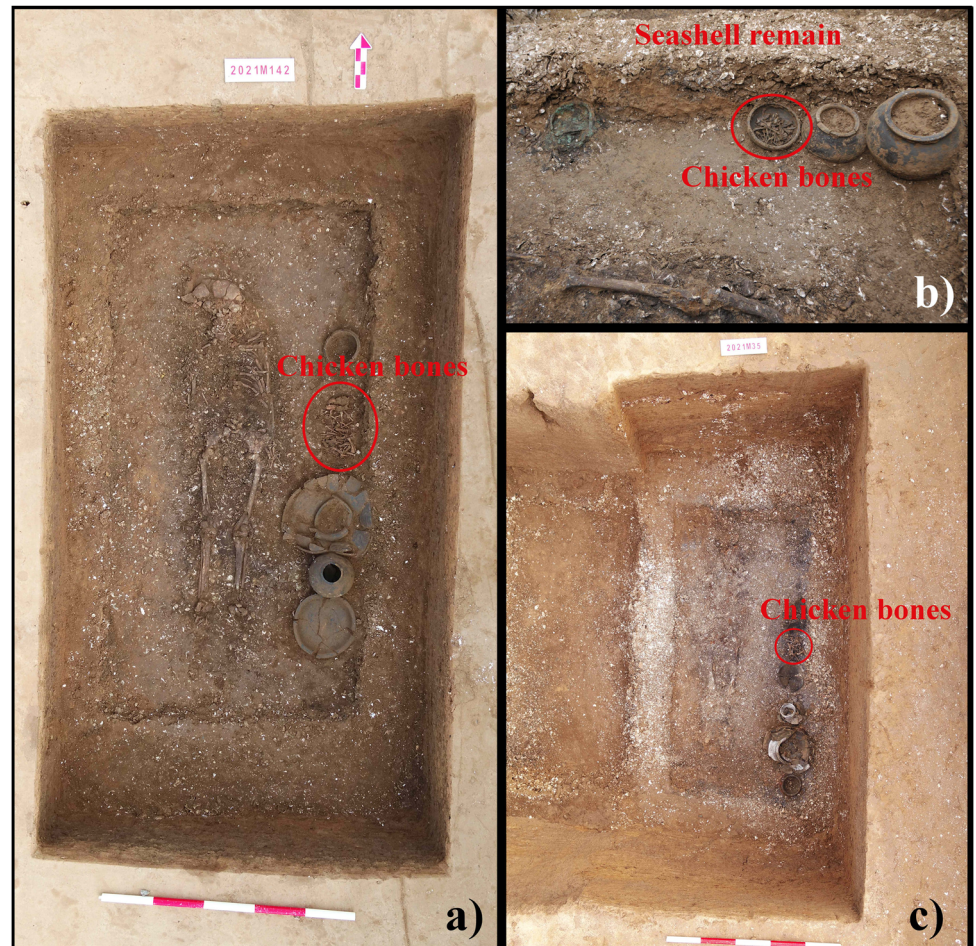
This study analyses human skeletal ($n = 74$) and faunal ($n = 10$) remains from Shagangzi Cemetery. By integrating carbon and nitrogen stable isotope analysis with historical documents and archaeological contexts, this study aims to reconstruct dietary patterns and subsistence economies among coastal populations in northeastern China. These findings address critical gaps in the understanding of political-economic systems within Han frontier zones. Through this analysis, this research provides empirical data on the dynamics between state-driven agricultural expansion and local human-environment adaptations in the frontier regions of the Western Han Empire.

Carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) stable isotope analysis is now indispensable in archaeology for reconstructing ancient diets and subsistence economies^{40–42}. This technique offers particular utility for investigating the origins, development, and diffusion of agriculture across diverse spatiotemporal contexts^{43–45}. On the basis of these broad applications, stable

isotope analysis has emerged as a pivotal methodology for specifically examining dietary patterns and subsistence strategies among coastal populations worldwide^{46–49}.

Building on its wide application in archaeological research, carbon and nitrogen stable isotope analysis provides a robust framework for investigating diet and subsistence, particularly in coastal settings where terrestrial and aquatic resources may be intertwined. In Han-period China, such studies have revealed pronounced regional diversity in farming and protein acquisition, spanning mixed C_3/C_4 crop systems in the arid northwest^{15–18}, wheat-dominated or wheat–millet consumption in parts of the Yellow River basin^{19–22,24}, and rice-based or rice–wheat systems in the south and southeast^{23,25}. These datasets collectively highlight how subsistence strategies responded to local ecologies and broader political-economic contexts across the empire. However, isotopic evidence from the northeastern coastal frontier remains limited, which constrains our understanding of how coastal communities in Liaodong integrated agriculture, husbandry, and marine resources under frontier administration. Addressing this gap is essential for evaluating regional adaptive strategies and the heterogeneity of imperial integration.

Fig. 3 | Shell, faunal remains and funerary objects unearthed in the tombs at Shagangzi Cemetery. **a** Shell tomb M142, containing skeletal remains of a young adult female (25 – 30 years old); **b** A shell tomb with faunal remains preserved in ceramic vessels; **c** Shell tomb M35, which yielded the skeletal remains of an adult individual (Images of tombs are provided by Weiwei Si; The final layout was created using Adobe Photoshop CC 64 Bit).



Hence, stable isotope analysis of bone collagen provides a rigorous methodological framework for investigating subsistence economies among coastal populations in Northeast China during the Han period, decoding human–environment adaptations in marginal ecologies and the dialectic between cultural traditions and state agricultural policies. These dual investigations establish empirical foundations for modelling frontier economic frameworks under imperial consolidation.

Methods

Sampling strategy

This study analysed 74 human samples and 10 faunal skeletal samples excavated from Shagangzi Cemetery. Faunal species identification and pig age categories (piglet, middle/sub-adult and big/adult) were determined using standard zooarchaeological methods, and human sex and age-at-death were assessed using standard osteological methods. To minimise contamination, samples were selected on the basis of strict preservation criteria³⁰, and comprehensive sample data are presented in Supplementary Tables 1 and 2.

Shagangzi Cemetery is part of a large burial group. According to decades of archaeological research on burial types and associated artefacts, the cemetery is generally believed to be of Han Dynasty origin³³. In order to determine the chronology for our study population, accelerator mass spectrometry (AMS) radiocarbon dating was performed on a well-preserved adult male skeleton (Tomb M206, western sector) at Beta Analytic Inc. (Miami, Florida). The sample was selected on the basis of its excellent preservation ability, ensuring the reliability and precision of the radiocarbon analysis.

In order to contextualise the dietary patterns and subsistence economy of the Shagangzi population within the broader framework of Han China,

we compared our isotopic results with published data from 18 contemporaneous sites, primarily dating to the Western Han period. These comparative sites, which include details on their locations, sample sizes, and full citations, are detailed in Supplementary Table 3.

Collagen preparation

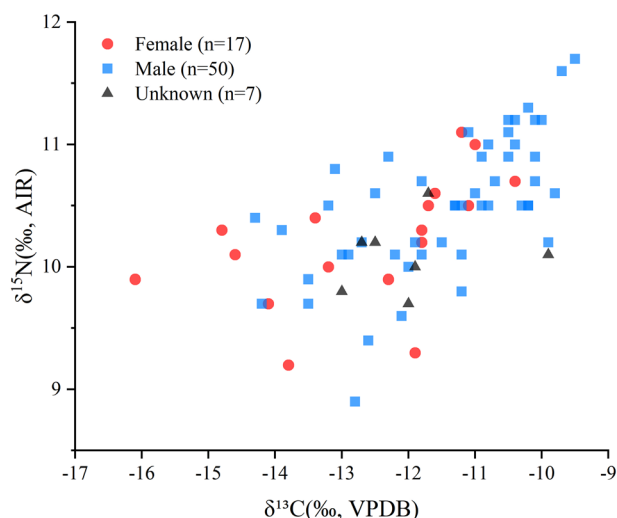
All bone samples were processed at the Stable Isotope Laboratory of Jilin University following established collagen extraction protocols⁴⁸. Bone fragments were sectioned and surfaces abraded to remove any contaminants. Aliquots of 2.00 g were weighed for each sample. Samples were demineralised in 0.5 mol/L HCl at 4 °C, with the acid replaced every 48 hours until the bones became texturally softened, indicating completion. The demineralised samples were then neutralised to pH 7.0 ± 0.5 and treated with 0.125 mol/L NaOH at 4 °C for 20 hours to remove humic substances, followed by repeated rinsing with deionised water. Gelatinisation was conducted in 0.001 mol/L HCl at 70 ± 1 °C for 48 hours, and the resulting solution was hot-filtered through glass fibre filters. Finally, the solution was lyophilised to obtain purified collagen, which was weighed to calculate yield.

Isotopic measurements

Collagen isotopic compositions were measured using an IsoPrime-100 isotope ratio mass spectrometer (IRMS) coupled with an Elementar PyroCube elemental analyser at the Testing Center, Institute of Environment and Sustainable Development in Agriculture, Chinese Academy of Agricultural Sciences. Elemental concentrations were calibrated against sulfanilamide standards. The $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values are reported relative to V-PDB and AIR standards, respectively. For quality assurance, an in-house collagen standard ($\delta^{13}\text{C} = -14.7 \pm 0.1\text{‰}$; $\delta^{15}\text{N} = 6.9 \pm 0.2\text{‰}$) was analysed in duplicate every 12 samples. All six procedural replicates exhibited

Table 1 | AMS-¹⁴C dating data of human bones

Lab no.	Sample no.	Sample information	¹⁴ C dating	¹⁴ C dating (95.4% confidence interval)
Beta-673883	SG04	Human: Femur	2120 ± 30 BP	2150–1998 cal BP (89.4%) 2292–2271 cal BP (6.0%)

**Fig. 4 | Scatter plot.** Distribution of stable isotope values for Shagangzi population in Dalian (the plot was generated in Origin 2021 by Yuan Lin).

deviations within $\pm 0.2\%$ of certified values, confirming measurement accuracy.

Statistical analyses were conducted using SPSS 26.0, with data visualisation performed in Origin 2021.

Results

Bone contamination identification

Collagen preservation in the analysed samples was excellent. Of the 74 human samples processed, extracted collagen exhibited carbon contents (C%) ranging from 14.5% to 62.5% and nitrogen contents (N%) from 5.1% to 22.8%. All samples had atomic C:N ratios between 3.2 and 3.3, meeting established criteria for well-preserved collagen. Based on strict quality control protocols (C:N ratios of 2.9–3.6 and collagen yield $>1\%$)^{51,52}, all human samples were deemed suitable for stable isotope analysis (see Supplementary Table 1).

The same rigorous quality assessment was applied to faunal samples, with 9 out of 10 (90%) meeting the preservation criteria and were included in isotopic analyses. The high preservation rates observed for both human (100%) and faunal (90%) samples indicate favourable taphonomic conditions at Shagangzi Cemetery, ensuring the reliability of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values for reconstructing trophic relationships and dietary practices.

AMS-¹⁴C dating

Radiocarbon dating yielded an uncalibrated age of 2120 ± 30 BP for the analysed sample (Table 1). Calibration yielded two probable intervals: a primary range of 2150–1998 cal. BP (89.4% probability) and a secondary range of 2292–2271 cal. BP (6.0% probability). Given the significant difference in probability, the primary interval of 2150–1998 cal. BP was adopted for a chronological interpretation. These results collectively date Shagangzi Cemetery to 200–48 BCE, directly overlapping with the Western Han Dynasty (202 BCE–8 CE).

Carbon and nitrogen stable isotope results

Figure 4 presents the distribution of stable isotope values ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$) in human bone collagen from Shagangzi Cemetery. The $\delta^{13}\text{C}$ values indicate

marked variation (range: -16.1% to -9.5% ; mean $\pm 1\sigma = -11.8\% \pm 1.4\%$), reflecting differential consumption of C_4 and C_3 food resources. While the average $\delta^{13}\text{C}$ value at the population level suggests a predominantly C_4 -based diet, the lower $\delta^{13}\text{C}$ values observed in certain individuals (e.g., SG20: -16.1%) indicate dietary variability, including mixed C_3/C_4 consumption patterns. In contrast, $\delta^{15}\text{N}$ values are more consistent (8.9% to 11.7% ; mean $\pm 1\sigma = 10.4\% \pm 0.6\%$), suggesting stable protein sourcing at a similar trophic level across the population.

The isotopic data further reveal dietary differentiation between the sexes within the Shagangzi population. Normality was assessed using the Shapiro-Wilk test. $\delta^{13}\text{C}$ data did not follow a normal distribution ($p = 0.03$), whereas the $\delta^{15}\text{N}$ data were consistent with a normal distribution ($p = 0.9$). Males ($n = 50$) exhibit significantly higher mean $\delta^{13}\text{C}$ values ($-11.4\% \pm 1.3\%$, 1σ) compared to females ($n = 17$, $-12.6\% \pm 1.6\%$; Mann-Whitney U, $p = 0.005$), indicating greater reliance on C_4 plants. Similarly, males show elevated $\delta^{15}\text{N}$ values ($10.5\% \pm 0.6\%$ vs. $10.2\% \pm 0.5\%$; Independent samples t-test, $p = 0.045$), suggesting higher consumption of animal protein. These statistically significant differences indicate: (1) sex-based divergence in plant food consumption, and (2) unequal access to animal products. Collectively, these results provide robust evidence for sex-based dietary differences within the population.

Discussion

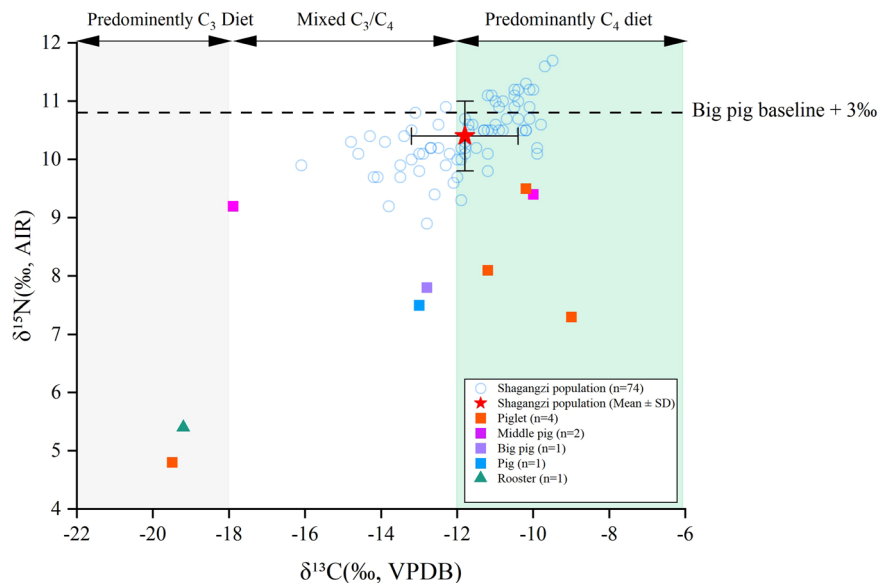
The $\delta^{13}\text{C}$ values of bone collagen primarily reflect the isotopic signature of dietary protein sources^{53–55}. The Shagangzi population exhibits a significant range of $\delta^{13}\text{C}$ values (-16.1% to -9.5% , mean $\pm 1\sigma = -11.8\% \pm 1.4\%$), which indicates a mixed diet. The overall enriched nature of these values points to a significant dietary contribution from high- $\delta^{13}\text{C}$ resources. One explanation is a strong reliance on C_4 resources; another is the consumption of marine protein, which typically exhibits enriched $\delta^{13}\text{C}$ values compared with terrestrial fauna at equivalent trophic levels^{56–58}. At this stage, these results establish a baseline understanding of the Shagangzi community as one sustained by a mixed subsistence economy.

Historical and archaeobotanical evidence from the Liaodong Peninsula, summarised in the Introduction, indicates that wheat and millet were the dominant Han period cereals⁵. Millet, a traditional staple crop in northern China, likely served as the primary C_4 dietary source³⁴. For C_3 dietary components, although wild C_3 plants may have been consumed as supplementary foods, their overall contribution to bone-collagen $\delta^{13}\text{C}$ values was probably limited. Cultivated C_3 crops, particularly wheat, with additional inputs from legumes and locally adapted japonica rice (*Oryza sativa* subsp. *japonica* Kato) also contributed to the diet in Dalian's temperate microclimate³⁵. Wheat likely served as the principal C_3 source, consistent with historical records of state-promoted cultivation of dryland crops (millets, wheat, legumes and hemp) over rice²⁴.

The faunal isotope data help to contextualise this agricultural background. Domestic animals fall into two distinct feeding groups based on their $\delta^{13}\text{C}$ values. Most pigs exhibit higher $\delta^{13}\text{C}$ values (from -13% to -9%), indicating diets dominated by C_4 resources, a pattern particularly clear in piglets; even considering the effect of lactation^{59,60}, their values primarily indicate the C_4 -rich (millet-based) diet of sows. This finding suggests that C_4 fodder was an important part of the feeding management strategy, particularly for breeding groups.

In contrast, a small group of animals, including a pig (SG75), a piglet (SG83) and a rooster (SG84), shows significantly lower $\delta^{13}\text{C}$ values, from -19.5% to -17.9% . These values indicate a diet based almost exclusively on C_3 resources. These contrasts suggest that both C_4 (millet) and C_3 (wheat)

Fig. 5 | Bivariate plot of carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) stable isotope values for human and faunal bone collagen from Shagangzi Cemetery. Individual data from Shagangzi Cemetery ($n = 74$) are shown as open circles, with the population mean and standard deviation indicated by the red star. Data for fauna include piglet ($n = 4$), middle pig ($n = 2$), big pig ($n = 1$), pig ($n = 1$) and rooster ($n = 1$). The shaded vertical zones represent dietary categories based on $\delta^{13}\text{C}$ values: predominantly C_3 diet ($< -18\text{‰}$), mixed C_3/C_4 diet (-18‰ to -12‰), and predominantly C_4 diet ($> -12\text{‰}$)⁷⁰. The horizontal dashed line represents the trophic level threshold, calculated as $\delta^{15}\text{N}$ value of the big pig (Big pig baseline = 7.8‰) plus a 3‰ trophic enrichment, to distinguish between diets with low versus high levels of animal protein consumption. (The plot was generated in Origin 2021 by Yuan Lin).



crops and their by-products were used not only for human consumption, but also as livestock fodder, suggesting potential variation in fodder management strategies. This pattern indicates close integration between crop agriculture and animal management and supports the view that agriculture formed the backbone of the Shagangzi subsistence economy.

Considering the coastal location of Shagangzi Cemetery, the possibility of marine resource consumption must be considered. Since marine organisms typically exhibit higher $\delta^{13}\text{C}$ values compared with terrestrial fauna at equivalent trophic levels^{56–58}, marine protein could theoretically contribute to the elevated $\delta^{13}\text{C}$ values in some individuals. However, the terrestrial agricultural system previously described appears sufficient to account for the isotopic data. This suggests that marine resources, while potentially exploited, made only a minor contribution to the overall diet and did not constitute a staple food source. Instead, the Shagangzi economy was fundamentally based on terrestrial agriculture. Through $\delta^{15}\text{N}$ analysis, the precise role of marine resources will be explored further below.

To differentiate between a diet based primarily on C_4 terrestrial plants and one incorporating substantial marine resources, $\delta^{15}\text{N}$ analysis is essential. Habitual consumers of marine resources typically display $\delta^{15}\text{N}$ values $> 14\text{‰}$, which is consistent with local marine mammals^{48,61,62}. In contrast, the human $\delta^{15}\text{N}$ values at Shagangzi (mean = 10.4‰) are not sufficiently elevated to suggest major reliance on marine resources, a dietary pattern that typically results in significantly higher $\delta^{15}\text{N}$ values. Hence, this finding provides strong corroborating evidence that the subsistence economy was predominantly terrestrial, consistent with the interpretation derived from the $\delta^{13}\text{C}$ data.

After establishing a predominantly terrestrial diet, we now use $\delta^{15}\text{N}$ to evaluate the trophic position of the Shagangzi population. This analysis requires a reliable local faunal baseline. Adult pig ($\delta^{15}\text{N} = 7.8\text{‰}$), which is presumed to have consumed local agricultural products, serves as an appropriate proxy. The selection of adult individuals is critical because the Shagangzi porcine assemblage is dominated by piglets, likely in the lactation stage. Experimental studies have indicated that nursing animals consistently exhibit elevated $\delta^{15}\text{N}$ values (typically $+ 1\text{--}2\text{‰}$ higher than those of adult conspecifics) due to trophic effects^{63–66}. The abundance of piglets therefore both necessitates careful selection of an adult baseline and is consistent with on-site breeding and local animal husbandry.

The mean $\delta^{15}\text{N}$ value of humans (10.4‰) is enriched by only an average of 2.6‰ relative to the adult pig baseline (7.8‰) (Fig. 5). This trophic spacing falls below the conventional $3\text{--}5\text{‰}$ $\delta^{15}\text{N}$ enrichment expected for a full trophic level shift in terrestrial ecosystems^{67,68}. To

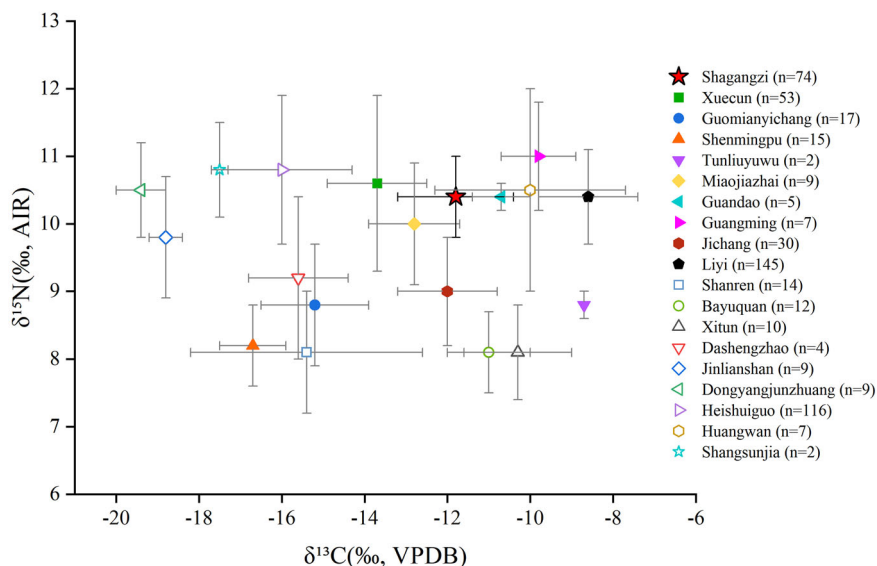
avoid overestimating meat consumption, this study adopts the lower boundary of this range (3‰), as a threshold for inferring significant animal protein⁵⁰. Notably, only 18% of individuals exceeded the adult pig baseline by $\geq 3\text{‰}$, a level consistent with a single trophic-level enrichment. These isotopic results reveal two key dietary patterns: for most individuals, diets were predominantly plant-based with minimal terrestrial animal protein intake and significant variation in meat consumption frequency within the population. However, stable isotope analyses typically indicate $\delta^{15}\text{N}$ ranges of 9‰ – 12‰ for carnivores and 7‰ – 9‰ for omnivores^{69,70}. In contrast, the $\delta^{15}\text{N}$ values for all Shagangzi individuals but one exceeded 9‰ (9.2‰ to 11.7‰). This raises an important question: why does a largely plant-based population exhibit $\delta^{15}\text{N}$ values comparable to those of carnivores?

Analysis of the faunal stable isotope data suggests that the answer lies in an enriched baseline rather than in unusually high animal or marine protein intake. The adult pig baseline at Shagangzi (7.8‰) is elevated relative to herbivorous cattle from the nearby Han period Bayuquan Cemetery (6.5‰) and to domestic pigs from the contemporaneous Wanfabozi site (4.7‰)^{28,71}. Non-adult pigs at Shagangzi also show high $\delta^{15}\text{N}$ values, with sub-adult individuals (SG75, SG78) reaching 9.4‰ and one piglet (SG77) peaking at 9.5‰ . These values reflect a combination of lactation effects and fodder enriched in $\delta^{15}\text{N}$. Together, these observations are most parsimoniously explained by a generally high $\delta^{15}\text{N}$ baseline in the local food web, consistent with crops grown on manured fields. This pattern is widely recognised in both modern experiments and archaeological case studies as a classic isotopic signature of intensive manuring^{72–75}.

Within this framework, the relatively high human $\delta^{15}\text{N}$ values at Shagangzi can be explained without invoking heavy consumption of animal protein or marine foods. Instead, they reflect a high-input agricultural system in which organic fertilisers, principally animal dung and domestic waste, were closely integrated into crop production. Intensive manuring is well documented in historical texts and regional archaeological evidence for the Western Han^{76–80}. Taken together, this isotopic, historical, and archaeological evidence provides a parsimonious explanation for both the enriched faunal baseline and the strong positive correlation observed between human $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values (Spearman's $r = 0.6$, $p < 0.001$): millet (a C_4 plant) inherently produces high $\delta^{13}\text{C}$ values, while manuring would simultaneously elevate its $\delta^{15}\text{N}$ values.

Another hypothesis can now be directly tested, that is the assumption of significant consumption of marine resources. Owing to the lack of contemporaneous isotopic data for Han-period fish species from the Yellow Sea

Fig. 6 | Comparison of mean $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values (\pm SD) for the Shagangzi population with other contemporaneous populations from Han Dynasty China. A comprehensive list of the comparative sites, including their specific locations, sample sizes, and full citations, is provided in Supplementary Table 3 (the plot was generated in Origin 2021 by Yuan Lin).



and Bohai Sea near Dalian, alternative datasets are needed. Two key references were employed: (1) Neolithic fish remains from Dalian Guanglu Island’s Xiaozhushan site ($\delta^{15}\text{N} = 12.5\text{‰} \pm 1.1\text{‰}$, $n = 3$) and (2) modern fish samples from the Yellow Sea and the northern East China Sea ($\delta^{15}\text{N} = 11.7\text{‰} \pm 1.4\text{‰}$)^{81,82}. Both datasets present $\delta^{15}\text{N}$ values that significantly exceed those of the Shagangzi individuals. There is a significant isotopic difference between the human and marine fish (1.2‰ to 2.0‰), which makes it unlikely that marine fish constituted a dietary staple. Instead, any contribution from marine resources was likely minimal and supplementary, rather than the primary driver of the observed isotopic signatures. This result is further supported by the remarkably low coefficient of variation (CV) for human $\delta^{15}\text{N}$ values (0.06), which points to a highly uniform protein base across the population⁸³, a pattern more consistent with a standardised agricultural diet than with the more variable returns of diversified marine foraging.

A prominent archaeological feature of Shagangzi Cemetery is the presence of numerous shell tombs and the abundant marine shell remains in the burials, which appear at first glance to contradict the isotope data indicating limited contribution of marine resources. Historical records highlight this discrepancy. For tomb construction (Fig. 2b, c and Fig. 3), coastal shells were layered directly to reinforce burial pits and stabilize coffins, serving primarily as functional architectural materials that provided moisture resistance and structural support⁸⁴. Therefore, burial shells should not be misinterpreted as dietary evidence. Instead, isotopic analysis emphasizes plant-based subsistence dominance, revealing how cultural practices, such as burial traditions, may not invariably indicate dietary behaviour.

The terrestrial, agriculture-based subsistence strategy of the Shagangzi population becomes clearer when their isotopic data are placed within the broader archaeological context of Han Dynasty China. As shown in Fig. 6, comparison of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ data from the Shagangzi population with those from 18 contemporaneous communities across diverse geographical and economic contexts reveals a clear pattern. Despite its coastal location, the Shagangzi population clusters closely with representative C_4 -based agriculturalist sites from the Central Plains (such as Xuecun, Guomianyichang, and Liyi). This convergence provides strong evidence that the Shagangzi community practiced a millet-based agricultural economy, similar to the Yellow River region, rather than a maritime one.

This interpretation is further supported when Shagangzi is considered within a wider Northeast Asian context. Notably, contemporaneous coastal populations in Japan and Korea that heavily exploited marine resources consistently exhibit significantly higher $\delta^{15}\text{N}$ values^{85,86}. The distinct isotopic difference between Shagangzi and these typical marine-foraging groups

provides compelling evidence against a marine-based diet, thereby underscoring the community’s fundamental reliance on terrestrial agriculture.

Stable isotope analyses reveal that the coastal Shagangzi community maintained a dietary pattern closely resembling that of contemporaneous agricultural groups in China’s Central Plains, with a predominantly plant-based subsistence strategy. The isotopic data strongly indicate that millet cultivation formed the foundation of their subsistence economy. This implies a low intake of animal protein, particularly in light of the presence of piglets in burial contexts. These faunal remains should be interpreted through historical documents, rather than representing a large amount of daily meat consumption. Our AMS-¹⁴C radiocarbon dating confirms that Shagangzi Cemetery was active during the early and middle periods of the Western Han Dynasty. Historical documents from this period suggest that the consumption of meat by commoners was largely restricted to ceremonial or ritual use, with regular meat consumption among peasants not appearing until the Eastern Han period (25–220 CE)⁸. This alignment between the archaeological timeline and historical records strongly supports the interpretation of the isotopic data from Shagangzi. Therefore, the Shagangzi community can be seen as one whose dietary norms mirrored those of inland agriculturalists of the Western Han, for whom animals held significant ritual value but were not a dietary staple.

This pronounced orientation towards terrestrial agriculture is particularly noteworthy given the coastal location of Shagangzi Cemetery in Dalian. It represents a clear departure from earlier coastal subsistence models, in which mixed economies combining millet farming with marine resource exploitation were common, as at the Neolithic Fujia site in Shandong^{87,88}. However, the predominant reliance on agriculture by the Shagangzi community during the Han Dynasty indicates a more profound economic transformation.

We suggest that this transformation was not driven by a single factor but by the combined effects of demographic pressure, state policy, and favourable local conditions. Historical records provide the foundational context for this argument. According to the *Hanshu Dili zhi*⁵, Liaodong Commandery had a registered population of 272,539 individuals in 2 CE. For a frontier zone, this figure of over a quarter of a million people represented substantial demographic pressure. Such a population, likely concentrated in and around administrative centres (Dalian) and military garrisons, would have created intense population-level demand for a reliable, high-yield food supply, making intensive agriculture a practical necessity.

This shift cannot be solely attributed to environmental constraints, because fish remains in numerous Western Han tombs in Dalian reveal that marine resources continued to be exploited^{128,89,90}. Instead, the agricultural

focus at Shagangzi must be understood as the outcome of a complex interplay between inherent advantages of agriculture, key interventions at the state level, and the specific socio-political context of the Western Han frontier expansion. This interpretation is consistent with isotopic evidence from the Guanzhong Basin, the Han political centre, where intensive fertilisation has also been documented⁷, suggesting that high-input agriculture was an empire-wide trend rather than a purely local phenomenon. Our findings from the Liaodong frontier are consistent with the wider trend, suggesting a systematic, state-driven agricultural agenda. Hence, the emergence of an agriculture-dominated economy at Shagangzi can be seen as the joint result of the high productivity achievable in the local environment and the sustained promotion of farming by the Han imperial state for strategic purposes.

The predominance of agriculture at Shagangzi must also be understood in light of the local climatic and environmental setting. This predominance is supported by favourable local climatic and geomorphological conditions^{29–31,91}. These favourable conditions supported a diverse cropping system centred on millet and supplemented by wheat and rice, greatly enhancing the reliability and productivity of dry-land farming. Compared to the potential risks and seasonal limitations of marine subsistence, the capacity of agriculture for stable, high yields and storable surplus offered a strong incentive for local communities to prioritize it as their primary subsistence strategy⁹².

As outlined in the Introduction, Han frontier governance in Liaodong combined civilian administration with the Tuntian system of state-led agricultural colonisation under an overarching policy of prioritising agriculture. Our isotopic evidence from Shagangzi is consistent with this framework: even at a coastal frontier site, subsistence was strongly agriculture-dominated, with millet-based farming and intensive manuring underpinning both human diets and livestock management. This pattern supports the view that imperial agricultural policies shaped local subsistence organisation and were implemented through locally adapted farming regimes in the Liaodong Peninsula.

While our research provides a coherent model for the Shagangzi community, several limitations should be acknowledged. First, this analysis is based on the data from a single cemetery. Future research incorporating isotopic data from additional coastal and inland sites across the Liaodong Peninsula will be essential for testing the wider applicability of this state-driven agricultural model and assessing potential regional variations. Second, the present study focuses on community-level dietary patterns; intra-group differences related to social status or other factors, potentially reflected in Shagangzi's diverse burial types, remain to be explored. Such analyses will depend on the availability of more detailed contextual data for individual burials. Third, the faunal baseline, particularly for the adult pig and the rooster, is derived from a limited sample size, which constrains the precision of our reconstructions of human dietary inputs and limits the strength of any inferences about fodder management or husbandry regimes; expanding the faunal sample will be a priority for future work. Finally, our marine baseline relies on proxy data from different periods, a necessary compromise that introduces some uncertainty, as marine reservoir effects can vary through time. These limitations do not undermine our main conclusion regarding the predominance of a land-based, state-influenced agricultural economy, but they do highlight specific and promising directions for future research.

The agricultural subsistence economy at Shagangzi was thus not an isolated anomaly, but the result of powerful forces shaping the Han frontier. It emerged at the intersection of the region's inherent agricultural potential and a state strategy that pragmatically combined administrative control, population settlement, and technological transfer to achieve economic self-sufficiency and military consolidation. At the same time, local communities on the Liaodong coast actively engaged with these processes, adapting imperial agricultural models to their own environmental and social circumstances. Ultimately, the case of Shagangzi illustrates how, in this coastal frontier context, the Western Han agrarian policies could be projected onto local communities and interact with existing environmental and social

conditions, contributing to a shift towards an agriculture-dominated subsistence regime aligned with imperial priorities.

This study improves our understanding of Han Dynasty coastal subsistence economies in Northeast China by providing systematic isotopic data for the region, thereby addressing a critical research void. Stable isotope analysis reveals how imperial agrarian policies could override or reconfigure environmental opportunities in shaping ancient dietary patterns, revising the traditional “live off the land/sea” subsistence model. Our results suggest how the Han state's agrarian policies were projected onto its coastal frontiers, substantially shaping their development and providing an empirical foundation for future cross-cultural comparisons of imperial resource management. These findings reveal the need for a multidisciplinary approach in future isotopic research that integrates political, economic, and cultural dimensions to fully reconstruct the ancient diet and subsistence economy.

Data availability

All data generated or analysed during this study are included in this manuscript and its supplementary material files.

Received: 10 August 2025; Accepted: 27 January 2026;

Published online: 13 February 2026

References

1. Fang, H., Feinman, G. M. & Nicholas, L. M. Imperial expansion, public investment, and the long path of history: China's initial political unification and its aftermath. *Proc. Natl. Acad. Sci.* **112**, 9224–9229 (2015).
2. Peach, T. & Wang, F. (eds). *The Political Economy of the Han Dynasty and Its Legacy*. (Routledge, 2019).
3. Leung, V. S. The Former Han empire. In *Routledge Handbook of Early Chinese History*, 160–179. (Routledge, 2018).
4. Shelach-Lavi, G. *The archaeology of early China: From prehistory to the Han Dynasty*, 308–311. (Cambridge University Press, 2015).
5. Ban, G. *History of The Han Dynasty* (Zhonghua Book Company, 1962).
6. Von Glahn, R. *An Economic History of China: From Antiquity to the Nineteenth Century*. (Cambridge University Press, 2016).
7. Liao, J. et al. Millet stable isotopes reveal the advance of agricultural practices in the core political regions of early imperial China. *Catena* **257**, 109148 (2025).
8. Xu, Z. *Han Agriculture: The Formation of Early Chinese Agrarian Economy, 206 BC–AD 220*. Vol. 2 (University of Washington Press, 1980).
9. Bray, F. Agricultural technology and agrarian change in Han China. *Early China* **5**, 3–13 (1979).
10. Jaffe, Y. *Food in Ancient China* (Cambridge University Press, 2023).
11. Sanft, C. The Qin dynasty. In *Routledge Handbook of Early Chinese History*. 146–159. (Routledge, 2018).
12. Kong, Z. Learning from Tuntian of Western Han. In *The Making of a Maritime Power: China's Challenges and Policy Responses*. 117–143. (Springer Singapore, 2016).
13. Wang, M. *History of Northeast China during the Qin and Han Dynasties* (Liaoning People's Publishing House, 1994).
14. Dalian Historical Compilation Committee. *General History of Dalian: Ancient Volume* (People's Publishing House, 2007).
15. Xiong, J. et al. Sex-biased population admixture mediated subsistence strategy transition of Heishuiguo people in Han Dynasty Hexi Corridor. *Front. Genet.* **13**, 827277 (2022).
16. Wang, X. et al. Diet along the eastern Silk Roads: an isotopic case study of ancient humans and livestock from the Han-Jin Dynasties in the Lop Nur region, northwest China. *Archaeol. Anthropol. Sci.* **16**, 145 (2024).
17. Wan, W., Duan, F., Zhang, J., Nie, Y. & An, C. Gender differences in millet consumption in arid Inner Asia during the Iron Age documented

- by stable isotopes: a case study from Shihuyao, Xinjiang. *Quat. Sci. Rev.* **312**, 108187 (2023).
18. Su, A. et al. Stable carbon and nitrogen isotope analysis of human bones during the Warring States and Qin-Han periods in the Chuanzhang Cemetery, Inner Mongolia, China. *J. Archaeol. Sci. Rep.* **50**, 104150 (2023).
 19. Tao, D., Zou, H., Chen, Q., Zhang, G. & Guo, Y. Staple food and possible famine food in Han Dynasty Guanzhong: archeobotanical and stable isotopic perspectives. *Archaeometry* **66**, 683–695 (2024).
 20. Hou, L., He, X. & Zhang, G. Wheat contribution to the dietary pattern of the past populations (c. 2000 BC–220 AD) in the Yellow. *Agric. Hist. China* **43**, 87–100 (2024).
 21. Zhou, L., Garvie-Lok, S. J., Fan, W. & Chu, X. Human diets during the social transition from territorial states to empire: stable isotope analysis of human and animal remains from 770 BCE to 220 CE on the Central Plains of China. *J. Archaeol. Sci. Rep.* **11**, 211–223 (2017).
 22. Hou, L. et al. Transition of human diets and agricultural economy in Shenmingpu Site, Henan, from the Warring States to Han Dynasties. *Sci. China Earth Sci.* **55**, 975–982 (2012).
 23. Wang, T. et al. Microfossil analysis of dental calculus and isotopic measurements reveal the complexity of human-plant dietary relationships in Late Bronze Age Yunnan. *Archaeol. Anthropol. Sci.* **14**, 94 (2022).
 24. Zhou, L. & Garvie-Lok, S. J. Isotopic evidence for the expansion of wheat consumption in northern China. *Archaeol. Res. Asia* **4**, 25–35 (2015).
 25. Guo, Y., Zhou, S., Chen, G. & Li, Z. Stable isotope analysis of human bones unearthed from the Han tombs at the Junzhuang site located in Dongyang, Xuyi, Jiangsu Province. *Southeast Cult.* **6**, 68–75 (2016).
 26. Ma, H. et al. Spatial distribution and driving factors of soil organic carbon in the Northeast China Plain: Insights from latest monitoring data. *Sci. Total Environ.* **911**, 168602 (2024).
 27. Sterckx, R. Food and agriculture. In *Routledge Handbook of Early Chinese History* 300–318. (Routledge, 2018).
 28. Zhang, Q., Tao, H., Qun, Z. & Zhi, S. Stable isotope analysis of human bones from shell tombs of Han Dynasty in Bayuquan, Yingkou, Liaoning. *Res. China's. Front. Archaeol.* **2**, 341–347 (2018).
 29. Zhu, S., Zhou, Z., Guo, Q. & Ma, J. A study on the cause of layered seawater intrusion in the Daqing River Estuary of Liaodong Bay, China. *Sustainability* **12**, 2842 (2020).
 30. Liu, J., Liu, F. X., Li, S. H. & Lai, C. K. Genesis of the Xiaotongjiapuzi gold deposit of the Liaodong gold province, Northeast China: Fluid inclusion thermometry and S–Pb–H–O–He isotope constraints. *Geol. J.* **55**, 1023–1040 (2020).
 31. Zhang, P., Kou, L. & Zhao, Y. Three periods of gold mineralization in the Liaodong Peninsula, North China Craton. *Int. Geol. Rev.* **64**, 2922–2940 (2022).
 32. Ren, Z. et al. Middle Jurassic intracontinental evolution of East Asia: insights from the Tianshifu-Dongyingfang basin of the Liaodong Peninsula, NE China. *Bulletin* **135**, 915–936 (2023).
 33. Han, J. (ed.) *Collected Papers on Dalian Archaeology, Volume 1* (Science Press, 2011).
 34. Xu, Z., Han, Y. & Zhao, M. The formation and propagation of agricultural diversification in the south of Liaodong Peninsula. *Agric. Hist. China* **42**, 3–10 (2023).
 35. Xu, M. Overview of ancient agricultural archaeology in the Dalian region. *Agric. Archaeol.* **3**, 87–95 (1992).
 36. Dalian Institute of Cultural Relics and Archaeology. *Collected Papers on Dalian Archaeology, Volume 1* (ed. Han, J.), **358**. (Science Press, 2011).
 37. Song, W. & Wang, H. A study of shell midden tombs in the Bohai Rim region: with a discussion on the development of Han Dynasty maritime routes around the Bohai Sea. *Sichuan Cult. Relics* **3**, 66–74 (2020).
 38. Li, C. The owl in Han Dynasty: investigating from art, agricultural and belief history, religious beliefs, and agricultural practices. *Agric. Hist. China* **41**, 11–28 (2022).
 39. Zhu, H. *Research on the Regional Agriculture Development During the Period of Qin and Han Dynasties* (Northwest A&F University, 2006).
 40. Lee-Thorp, J. A. On isotopes and old bones. *Archaeometry* **50**, 925–950 (2008).
 41. Hu, Y. Thirty-four years of stable isotopic analyses of ancient skeletons in China: an overview, progress and prospects. *Archaeometry* **60**, 144–156 (2018).
 42. Defant, S. et al. Isotopic data reveal a localist Roman population in late Roman Albintimilium, Liguria. *Sci. Rep.* **15**, 12097 (2025).
 43. Richards, M. P. A brief review of the archaeological evidence for Palaeolithic and Neolithic subsistence. *Eur. J. Clin. Nutr.* **56**, 1021–1029 (2002).
 44. Wang, J. et al. Relationship between C₄ biomass and C₄ agriculture during the Holocene and its implications for millet domestication in Northeast China. *Geophys. Res. Lett.* **48**, e2020GL089566 (2021).
 45. Hou, L. et al. Dietary shift and the development of millet agriculture in Haidai region of China during the early and middle Neolithic periods (c. 8300 BP–c. 6000 BP): evidence from stable isotopes. *J. Archaeol. Sci. Rep.* **43**, 103456 (2022).
 46. Schoeninger, M. J. & DeNiro, M. J. Nitrogen and carbon isotopic composition of bone collagen from marine and terrestrial animals. *Geochim. Cosmochim. Acta* **48**, 625–639 (1984).
 47. Chisholm, B. S., Nelson, D. E. & Schwarcz, H. P. Stable-carbon isotope ratios as a measure of marine versus terrestrial protein in ancient diets. *Science* **216**, 1131–1132 (1982).
 48. Richards, M. P. & Hedges, R. E. M. Stable isotope evidence for similarities in the types of marine foods used by late Mesolithic humans at sites along the Atlantic coast of Europe. *J. Archaeol. Sci.* **26**, 717–722 (1999).
 49. Kelly, J. F. Stable isotopes of carbon and nitrogen in the study of avian and mammalian trophic ecology. *Can. J. Zool.* **78**, 1–27 (2000).
 50. Hedges, R. E. M. & Reynard, L. M. Nitrogen isotopes and the trophic level of humans in archaeology. *J. Archaeol. Sci.* **34**, 1240–1251 (2007).
 51. DeNiro, M. J. Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. *Nature* **317**, 806–809 (1985).
 52. Ambrose, S. H. Preparation and characterization of bone and tooth collagen for isotopic analysis. *J. Archaeol. Sci.* **17**, 431–451 (1990).
 53. Cheung, C., Zhang, H., Hepburn, J. C., Yang, D. & Richards, M. P. Stable isotope and dental caries data reveal abrupt changes in subsistence economy in ancient China in response to global climate change. *PLoS ONE* **14**, e0218943 (2020).
 54. Nikitin, A. G. et al. Interactions between earliest Linearbandkeramik farmers and central European hunter-gatherers at the dawn of European Neolithization. *Sci. Rep.* **9**, 313 (2019).
 55. Hermes, T. R. et al. Early integration of pastoralism and millet cultivation in Bronze Age Eurasia. *Proc. R. Soc. B* **286**, 20191273 (2019).
 56. Lorrain, A. et al. Nitrogen isotopic baselines and implications for estimating foraging habitat and trophic position of yellowfin tuna in the Indian and Pacific Oceans. *Deep-Sea Res.* **113**, 188–198 (2015).
 57. Jaouen, K., Szpak, P. & Richards, M. P. Zinc isotope ratios as indicators of diet and trophic level in Arctic marine mammals. *PLoS ONE* **11**, e0152299 (2016).
 58. Guiry, E. Complexities of stable carbon and nitrogen isotope biogeochemistry in ancient freshwater ecosystems: implications for the study of past subsistence and environmental change. *Front. Ecol. Evol.* **7**, 313 (2019).
 59. Fuller, B. T., Richards, M. P. & Mays, S. A. Stable carbon and nitrogen isotope variations in tooth dentine serial sections from Wharram Percy. *J. Archaeol. Sci.* **30**, 1673–1684 (2003).

60. Richards, M. P., Mays, S. & Fuller, B. T. Stable carbon and nitrogen isotope values of bone and teeth reflect weaning age at the Medieval Wharram Percy site, Yorkshire, UK. *Am. J. Phys. Anthropol.* **119**, 205–210 (2002).
61. Zhang, G., Hou, X., Li, S., Zhou, Y. & Richards, M. P. Agriculturalization of the Nomad-Dominated Empires of the Northern Wei Dynasty in Pingcheng City (398–494 AD): a stable isotopic study on animal and human bones from the Jinmaoyong Cemetery, China. *Int. J. Osteoarchaeol.* **30**, 632–643 (2020).
62. Madigan, D. J., Snodgrass, O. E., Hyde, J. R. & Dewar, H. Stable isotope turnover rates and fractionation in captive California yellowtail (*Seriola dorsalis*): insights for application to field studies. *Sci. Rep.* **11**, 4466 (2021).
63. Balasse, M. Potential biases in sampling design and interpretation of intra-tooth isotope analysis. *Int. J. Osteoarchaeol.* **13**, 3–10 (2003).
64. Makarewicz, C. & Tuross, N. Foddering by Mongolian pastoralists is recorded in the stable carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotopes of caprine dentinal collagen. *J. Archaeol. Sci.* **33**, 862–870 (2006).
65. Tsugawa, T. et al. Palaeoproteomic identification of breast milk protein residues from the archaeological skeletal remains of a neonatal dog. *Sci. Rep.* **9**, 128 (2019).
66. Tsutaya, T. & Yoneda, M. Reconstruction of breastfeeding and weaning practices using stable isotope and trace element analyses: a review. *Am. J. Phys. Anthropol.* **156**, 2–21 (2015).
67. Bocherens, H., Fizet, M. & Mariotti, A. Diet, physiology and ecology of fossil mammals as inferred from stable carbon and nitrogen isotope biogeochemistry: implications for Pleistocene bears. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* **107**, 213–225 (1994).
68. Ebert, C. E. et al. Sulfur isotopes as a proxy for human diet and mobility from the Preclassic through Colonial periods in the Eastern Maya Lowlands. *PLoS ONE* **16**, e0254992 (2021).
69. Yi, B. et al. Fishing or farming? Isotopic evidence of human subsistence strategies at the Dashuitian site during the middle Neolithic in the Three Gorges of the Yangtze River, China. *Archaeol. Res. Asia.* **40**, 100564 (2024).
70. Wang, T. et al. Tianshanbeilu and the Isotopic Millet Road: reviewing the late Neolithic/Bronze Age radiation of human millet consumption from north China to Europe. *Natl. Sci. Rev.* **6**, 1024–1039 (2019).
71. Guan, L. et al. Stable carbon and nitrogen isotope analysis of pig bones from the Wanfabozi site, Tonghua. *Chin. Sci. Bull.* **52**, 1679–1681 (2007).
72. Wang, X. et al. Millet manuring as a driving force for the Late Neolithic agricultural expansion of North China. *Sci. Rep.* **8**, 5552 (2018).
73. Wang, X. et al. Manuring and land exploitation in the Central Plains of late Longshan (2200–1900 BCE) China: implications of stable isotopes of archaeobotanical remains. *J. Archaeol. Sci.* **148**, 105691 (2022).
74. Yang, J., Yang, X., You, T. & Chen, F. The $\delta^{15}\text{N}$ values of foxtail millet (*Setaria italica*) and common millet (*Panicum miliaceum*) are reliable indicators of manuring practices. *Sci. China Earth Sci.* **67**, 2910–2923 (2024).
75. Dong, Y. et al. The potential of stable carbon and nitrogen isotope analysis of foxtail and broomcorn millets for investigating ancient farming systems. *Front. Plant Sci.* **13**, 1018312 (2022).
76. Sheng, P., Storzum, M., Tian, X. & Wu, Y. Foodways on the Han dynasty's western frontier: archeobotanical and isotopic investigations at Shichengzi, Xinjiang, China. *Holocene* **30**, 1174–1185 (2020).
77. Ouyang, H. & Shang, X. The manuring principles in ancient China from the perspective of the San Cai theory. *Humanit. Soc. Sci. Commun.* **12**, 1–14 (2025).
78. Wu, R. & Guo, Y. A preliminary study on the application of nitrogen stable isotope analysis in the study of prehistoric fertilisation. *Agric Archaeol.* **2017**, 7–12 (2017).
79. Choi, W. J., Chang, S. X., Allen, H. L., Kelting, D. L. & Ro, H. M. Irrigation and fertilisation effects on foliar and soil carbon and nitrogen isotope ratios in a loblolly pine stand. *Ecol. Manag.* **213**, 90–101 (2005).
80. Szpak, P., Millaire, J. F., White, C. D. & Longstaffe, F. J. Influence of seabird guano and camelid dung fertilisation on the nitrogen isotopic composition of field-grown maize (*Zea mays*). *J. Archaeol. Sci.* **39**, 3721–3740 (2012).
81. Chen, X. et al. From foraging to food production: stable isotopic evidence for animal domestication at the Xiaozhushan site, Guanglu Island, Dalian. *Cult. Relics South. China* **1**, 180–192 (2017).
82. Bai, H. et al. Determination of trophic levels of marine fish in the Yellow Sea and northern East China Sea using nitrogen stable isotope ($\delta^{15}\text{N}$) analysis of otoliths. *J. Oceanol. Limnol.* **40**, 634–642 (2022).
83. Wu, M., Ge, W. & Chen, Z. Diets of a late Neolithic maritime settlement: carbon and nitrogen stable isotope analysis of human bones from the Tanshishan site. *Acta Anthropol. Sin.* **35**, 246–258 (2016).
84. Han, X. A comparative study of the tombs of Dalian and the Central Plains region in Han Dynasty. *J. Liaoning Norm. Univ. (Soc. Sci. Ed.)* **5**, 712–718 (2013).
85. Tsutaya, T., Sawada, J., Dodo, Y., Mukai, H. & Yoneda, M. Isotopic evidence of dietary variability in subadults at the Usu-moshiri site of the Epi-Jomon culture, Japan. *J. Archaeol. Sci.* **40**, 3914–3925 (2013).
86. Choy, K., An, D. & Richards, M. P. Stable isotopic analysis of human and faunal remains from the Incipient Chulmun (Neolithic) shell midden site of Ando Island, Korea. *J. Archaeol. Sci.* **39**, 2091–2097 (2012).
87. Dong, Y. et al. Social and environmental factors influencing dietary choices among Dawenkou culture sites, Late Neolithic China. *Holocene* **31**, 271–284 (2021).
88. Wang, J. et al. Ancient DNA reveals a two-clanned matrilineal community in Neolithic China. *Nature*. **1–8** (2025).
89. Cao, J. *Research on Han Dynasty Burials in Southern Liaoning* (Cultural Relics Publishing House, 2008).
90. Yu, L. The Yingchengzi shell tomb. *Acta Archaeol. Sin.* **25** (1958).
91. Qin, C. et al. Persistent humid climate favored the Qin and Western Han Dynasties in China around 2,200 years ago. *Proc. Natl. Acad. Sci.* **122**, e2415294121 (2025).
92. Lu, X. & Song, X. The "Benefits of Fish and Salt" in coastal regions and the livelihood of coastal populations during the medieval period. *J. East China Norm. Univ. (Humanit. Soc. Sci.)* **4**, 14–23 (2016).

Acknowledgements

This study was supported by the National Social Science Fund of China Major Historical Issues Research Project of History Research of China 2023 Major Bidding Project-A bioarcheological perspective on early cross-cultural exchange in the Eurasian steppe (Grant No.23VLS007), the National Social Science Fund of China Project-A comprehensive physical anthropological analysis of Bronze to Early Iron Age populations in the eastern Eurasian steppe (Grant No. 23VRC034), and The Jilin University "Chinese Modernization and New Form of Human Civilization" Philosophy and Social Science innovation team project (Grant No.2023ONTD12).

Author contributions

Conceptualization: Y.L., L.H. and Q.Z. Methodology and investigation: Y.L., R.Y. Data organization: Y.L., R.Y. and Q.D. Image sorting: W.S. Writing-original draft preparation: Y.L. Writing-review and editing: L.H. and Q.Z. All authors have read and agreed to the published version of the manuscript.

Competing interests

The authors declare no competing interests.

Additional information

Supplementary information The online version contains supplementary material available at <https://doi.org/10.1038/s40494-026-02357-2>.

Correspondence and requests for materials should be addressed to Quanchao Zhang or Liangliang Hou.

Reprints and permissions information is available at <http://www.nature.com/reprints>

Publisher's note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

© The Author(s) 2026