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Direct isotopic evidence for human millet consumption in the Middle Mumun period: Implication and importance of millets in early agriculture on the Korean Peninsula

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ABSTRACT

It is generally believed that early agriculture on the Korean Peninsula was established during the Mumun period (1500–100 BC). While previous studies on agriculture in prehistoric Korea have relied on cultivated plant remains from archaeological sites, only a few isotopic studies have been conducted on Mumun individuals due to poor bone preservation during this period. Here, we measured bulk carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) stable isotope ratios as well as individual amino acid $\delta^{13}C$ results ($\delta^{13}C_{AA}$) of collagen from human ($n = 7$) and animal ($n = 4$) bones from three Mumun sites (Hwangsok-ri, Jungdo, Maedun Cave) in the central inland portion of South Korea. The aims of this study were to explore the contribution of plant foods to the human diet and to examine the type and extent of agriculture in the Mumun period. In contrast to the surrounding C_3 vegetation, all the Mumun humans in this study had significantly ^{13}C-enriched results, evidence for the consumption of C_4 plants (foxtail and broomcorn millet). The $\delta^{13}C_{AA}$ data show that there was no consumption of freshwater or marine resources in the diet of the Mumun. These data indicate that C_4 plants (millets) were the main dietary sources in central inland South Korea and that millet agriculture was fully established during the Middle Mumun period. This finding highlights the importance of millet cultivation during the Mumun period and provides a revaluation for the significance of millets in the development of early agriculture on the Korean Peninsula.

1. Introduction

The origins, cultivation, and consumption of domesticated plants on the Korean Peninsula in prehistory is debated due to the paucity of direct dietary evidence (Ahn, 2005; 2006; 2010; Bale, 2001; Crawford and Lee 2003; 2011; Kim, 2015; Kwak et al., 2017; Kim and Park, 2020). Most previous studies focused on the development of early agriculture on the Korean Peninsula were based on the analyses of plant and animal remains from excavated sites (Lee, 2001, 2003, Lee, 2011; Crawford and Lee, 2003). Based on the archaeobotanical evidence, it is assumed that early agriculture was intensified during the Bronze Age in Korean prehistory or the Mumun period (1500–100 BC) (Ahn, 2010; 2011; Kwak et al., 2017). Although the earliest evidence for cultivated plants is reported from the Middle Chulmun period (3500–2000 BC), it is believed that domesticated crops started to be important from the Early Mumun period (1500–800 BC) (Lee, 2011; Bale, 2001; Lee and Bale, 2016). The Mumun people cultivated various domesticated plants such as rice (*Oryza sativa*), foxtail millet (*Setaria italica*), broomcorn millet (*Panicum miliaceum*), six-rowed barley (*Hordeum vulgare*), naked bread wheat (*Triticum aestivum*), soybean (*Glycine max*), and adzuki bean (*Vigna angularis*) (Lee, 2003; Ahn, 2010). Despite abundant evidence for the cultivation of multiple crops during the Mumun period, most previous studies were mainly focused on the importance of rice agriculture (Kim, B–C., 2005; 2006; Cho, 2008; Ahn, 2010; Kim, M., 2015). Along with rice, other crops also are believed to be important foods for the Mumun people (Ahn, 2010; Lee, 2011). However, previous archaeobotanical research on domesticated crops has been limited in its ability to directly determine the relative contribution of these crops to the whole diet. In addition, recent studies on organic residues in pottery also have provided evidence of the presence rather than the dietary significance, of

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different food resources in the Mumun diets (Kwak and Marwick, 2015; Shoda et al., 2017; Kwak et al., 2017). Until now, little research has been conducted on the direct dietary significance of each cultivated crop to the whole Mumun diet. Hence, it is necessary to investigate the relative contribution of each crop (e.g. *rice vs. millet*) in terms of the Mumun diet in order to better understand the nature and type of agriculture that the Mumun engaged in on the Korean Peninsula.

While archaeobotanical analysis of cultivated cereals provides valuable information about the dietary resources of past populations (Ahn, 2010; Kim, 2015), the presence of plant remains in excavated sites does not imply direct human consumption of these plant remains because they can be encountered as artifacts or as natural deposits in archaeological sites (Kusaka et al., 2010). In order to bridge these disparities between the preservation and direct consumption of plant remains, stable isotope ratio analysis of human bone collagen is applied here. This approach is an established method in bioarchaeology used to reconstruct direct dietary patterns of ancient individuals or population (Lee-Thorp, 2008; Richards, 2020). Isotopic measurements of bone collagen provide direct evidence of the long-term dietary record of an individual related to the average foods consumed over their lifetime (Katzenberg, 2000; Richards, 2020). Specifically, carbon stable isotope ratios (δ^{13}C) distinguish diets based on the consumption of plants that use different photosynthetic pathways (C_3 vs. C_4 plants) (Wang et al., 2019) and between the consumption of terrestrial and marine foods (Richards and Hedges, 1999; Lee-Thorp, 2008). In Asia, the main C_4 domestic plants, broomcorn and foxtail millet, are significantly ^{13}C-enriched, which results in measurable differences in the bone collagen of consumers of these foods (Chen et al., 2016; Lu et al., 2009; Dai et al., 2016; Ma et al., 2016a, 2016b, 2016c; Wang et al., 2016, 2018, 2019).

Bulk nitrogen stable isotope ratio measurements (δ^{15}N) provide information about the trophic level of a consumer in a food chain, with human and animal bone collagen ^{15}N-enriched by ~3–5‰ compared to dietary sources (Minagawa and Wada, 1984; Bocherens and Drucker, 2003; Hedges and Reynard, 2007). Thus, human δ^{15}N values higher than associated faunal δ^{15}N values are interpreted as indicating a diet with significant quantities of these animals, whereas δ^{15}N values close to the associated herbivore values are interpreted as indicating a diet based mainly on plant proteins (Lee-Thorp, 2008).

In addition, compound specific stable isotope ratio analysis of individual amino acids (CSIA-AA) is used to overcome limitations associated with bulk carbon and nitrogen isotopic measurements and provide more detailed dietary reconstructions (Hare et al., 1991; Fogel and Tuross, 2003; Smith et al., 2009; Jaouen et al., 2019). In particular, carbon amino acid measurements ($\delta^{13}C_{AA}$) can better distinguish between C_3 vs. freshwater consumers as well as C_4 vs. marine consumers in environmental settings with diverse dietary resources (Corr et al., 2005; Choy et al., 2010a; Honch et al., 2012; Webb et al., 2015, 2018; Ma et al., 2021). Further, nitrogen amino acid measurements ($\delta^{15}N_{AA}$) can provide more accurate trophic level determinations without direct comparisons of associated faunal specimens (Fuller and Petzke, 2017; Ohkouchi et al., 2017; Jaouen et al., 2019). An in-depth discussion of bulk and CSIA-AA is beyond the scope of this work, and the following reviews should be consulted for additional details (Lee-Thorp, 2008; Reitsema, 2015; McMahon and Newsome, 2019; Richards, 2020).

In Korean archaeology, the application of bulk and CSIA-AA analysis to palaeodiet reconstruction has provided important information about subsistence practices in prehistoric populations (Choy and Richards, 2009, 2010b; Choy et al., 2010a, 2012; Shin and Lee, 2009; Kim, H–S., 2010). In particular, isotopic results revealed that the Chulmun (8000–1500 BC) people were mainly dependent on marine food resources before the introduction of domesticated crops (Choy et al., 2012). However, after the arrival of domesticated crops on the Korean Peninsula, during the Mumun period (1500–100 BC) there are few applications of stable isotope analysis to human bone collagen largely due to the lack of human remains from this time. Most previous studies on dietary patterns during the Mumun period are based on the analysis of charred plant remains (Lee, 2001; Lee, 2003; Crawford and Lee, 2003; Ahn, 2010; Kim, M., 2015). In this study, we were fortunate to obtain access to human (n = 7) and animal bones (n = 4) from three Mumun sites (Hwangsok-ri, Jungdo, Maedun Cave), which are all located in the inland portion of central South Korea (Fig. 1). Bulk and $\delta^{13}C_{AA}$ analyses were applied to these specimens to directly reconstruct the dietary patterns of the Mumun people. Direct radiocarbon measurements were also conducted on three of these humans to firmly anchor these isotopic measurements in time. In addition, the contribution of each food source to the entire human diet is investigated and the importance of agriculture crops in terms of human consumption patterns, is examined during the Mumun period in South Korea.

2. The Korean Bronze Age: Mumun culture

Korean archaeologists refer to the Mumun period (1500–100 BC) as the Bronze Age in Korean prehistory. The beginning of the Mumun period is marked by the first appearance of an undecorated plain pottery style, called “Mumun” pottery (Fig. 2A) (Kim, 2015). On the basis of distinct characteristics of artifacts and features, this period can be subdivided into several periods: Early Mumun (1500-800 B.C.), Middle Mumun (800–400 BC), and Late Mumun (400–100 BC) (Bale, 2001; Bale and Ko, 2006; Lee and Bale, 2016). The Mumun culture is characterized by intensive agriculture with large dry-field remains, settlements with ditch enclosures, pit-houses, and evidence for the presence of incipient elites (Lee and Bale, 2016; Bale, 2017). In the Middle Mumun period, a number of megalithic burials (*Goindol*) (Fig. 2B) with prestige artifacts such as bronze daggers, jade, and red-burnished pottery were built in the vicinity of the southern coast (Lee and Bale, 2016). Burials from the Middle Mumun period contain a few high-status mortuary offerings such as bronze artifacts, which result in the Mumun period being called the Bronze Age in Korea. It is believed that bronze production probably began around the Middle Mumun in southern Korea. High status burials and large raised-floor buildings provide further evidence of the growth of social inequality and the existence of polities. Based on archaeological investigations (Kim, J., 2003; Bale and Ko, 2006; Kim, 2015), Mumun society seems to have been more culturally complex than the previous Chulmun period (8000–1500 BC) because of the presence of prestige artifacts in mortuary and settlement contexts (Bale, 2001; Bale and Ko, 2006).

The Mumun period is characterized by an early agriculture economy in which the social and economic complexities appear and coincide with new house features and pottery styles (Ahn, 2008; Kim and Park, 2020). Archaeological investigations on flora remains suggest that the subsistence activities in Mumun period were largely dependent on crop production. The Mumun people cultivated multiple crops, but rice was believed to be the most important (Ahn, 2008; Lee 2003). The Mumun period is considered as the beginning of the long-term tradition of rice farming on the Korean Peninsula which links the Mumun culture to the present-day Korean culture (Kim, B–C., 2005; 2006; Kim, M., 2015; Lee and Bale, 2016; Kwak et al., 2017). In addition to rice, the Mumun also cultivated millets, barley, wheat, legumes, and continued to hunt and fish (Crawford and Lee, 2003; Ahn, 2010). Millet was likely an especially important crop for the Mumun people in the northeast region where cold and dry soils were not suitable for rice cultivation. In the Middle Mumun (800–400 BC), the early agriculture was intensified and a large number of agricultural settlements emerged along the river banks and low-lying hillsides, and diverse agricultural tools, such as stone-harvesting knives (*Ban-dal dol-kal*) (Fig. 2C), wooden tillage and pounding tools are found (Lee, 2003; Ahn, 2008, 2010). Dry fields in the form of ridges and furrows also started to appear along river banks during this period.

3. Archaeological context

A total of 7 human and 4 animal bone specimens were available for

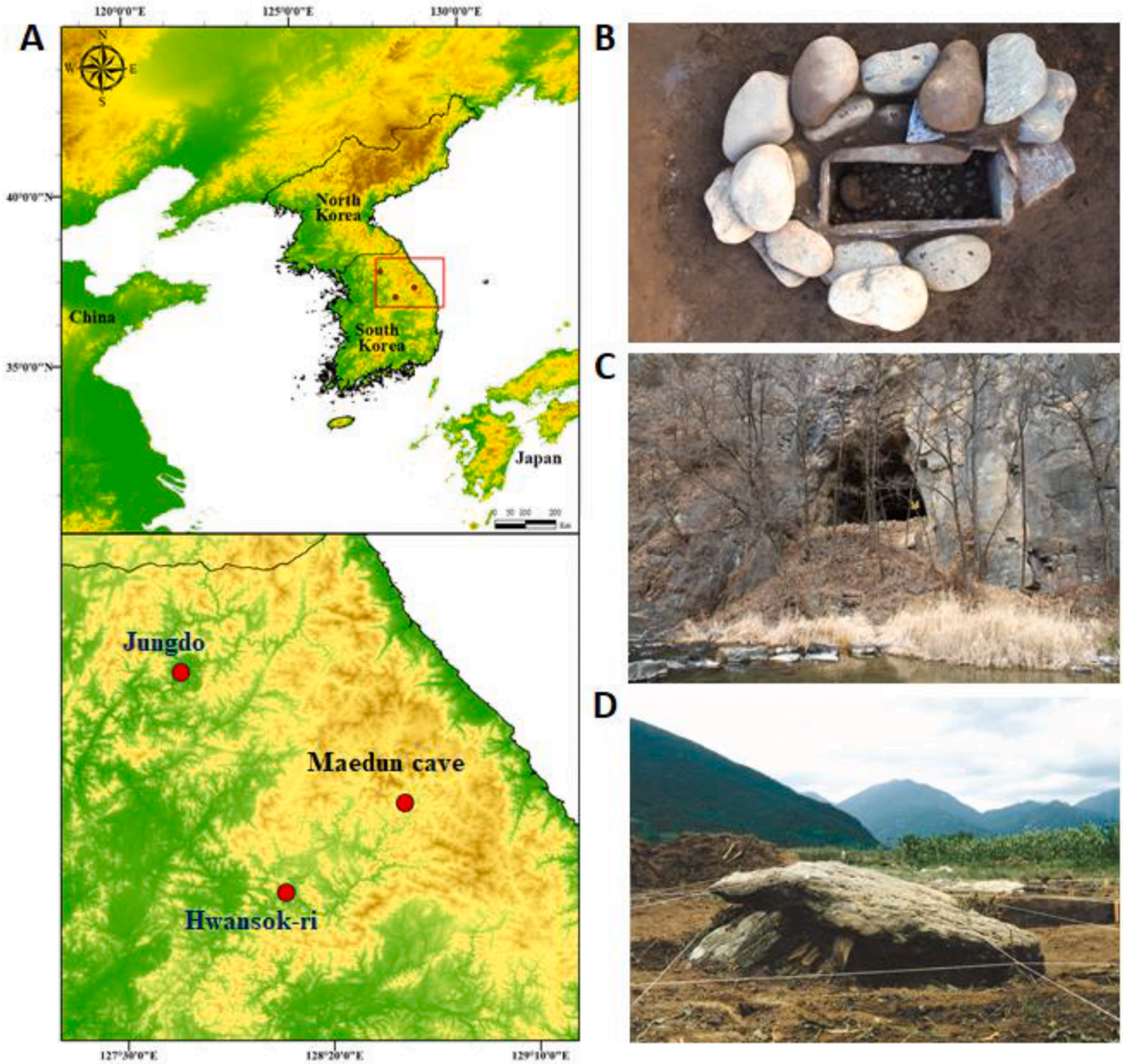

Fig. 1. (A): Map of the Korean Peninsula showing the detailed location of the three Mumun sites studied in this paper. (B): Chuncheon Jungdo (C): Jeongseon Maedun Cave, (D): Jecheon Hwangsok-ri, (Photo courtesy of CNUM, KICH, and YUM).

isotopic analyses from the three Mumun sites described below (see Fig. 1). There are an extremely limited number of human and animal specimens dating to the Mumun period in South Korea due to the poor bone perseveration compared with the previous Chulmun period. This is the reason for the small number of Mumun specimens analyzed and presented in this study.

4. Jecheon Hwangsok-ri

The Hwangsok-ri site lies on a low alluvial deposit floodplain that was formed by a stream meandering on the South Han River in the middle of North Chungchung Province, South Korea, (37° 1′ E, 128° 8’ N). The site is situated 103 m above sea level and is surrounded by high mountains ranging from 500 to 700 m. This site was investigated by the Korean National Museum (KNM) in 1962 and was later investigated by Chungbuk National University Museum (CNUM) in 1982 and 1983 because of the construction of the Chungju Dam on the South Han River near Jecheon City (Chungbuk National University Chungbuk University Museum, 1983). The site contained 46 megalithic burials from the Mumun period but only 26 of these burials were excavated. During the excavation in 1962, a complete male skeleton was found in the megalithic burial (13 ho) dated to 2450 BP (Kim and Yoon, 1967). Later archaeological study by CNU in the 1980s investigated about 20 megalithic burials. Among these 20 megalithic burials, 4 burials (6, 7, 13, 17 ho) had human remains. The age and sex assessments of the human skeletons determined that three of these individuals were adult males aged ~20–30 years old and one was an adult female aged ~40 years old. The megalithic burials also yielded artifacts such as semi-lunar blades, stone axes, Mumun pottery and bead ornaments (Chungbuk National University Chungbuk University Museum, 1983). Burials containing males were accompanied by stone blades, stone axes, and female burials were associated with bead ornaments. In addition to the human skeletons, a few faunal specimens (*Cervidae, Bovidae*, and *Suidae*) were recovered from the same megalithic burials. In this study, we analyzed only three well-preserved individuals (6, 7, 17 ho) for isotopic analysis.

5. Chuncheon Jungdo

The Jungdo site lies on a small alluvial island in the middle of the

Fig. 2. Undecorated plain Mumun pottery (A), human remains recovered from megalithic burials (*Goindol*) at the Jecheon Hwangsok-ri site (B), and stone-harvesting knives (*Ban-dal dol-kal*) from the other Mumun site (C). The stone knives were used to harvest crops during the Mumun period. The two holes at the upper side of the stone knife were tied with leather strings. The blade was ground a bit askew to give it a sharper edge (Photo courtesy of CNUM and National Museum of Korea).

confluence of the North Han River and Soyang River near Chuncheon City in Kangwon Province, South Korea (37° 41′ E, 127° 30’ N). This site was investigated by several institutes supervised by the Cultural Heritage Administration (CHA) from 2013 to 2017 because of the construction of Legoland Korea (Korea Institute of Cultural Heritage , 2017). This island site was occupied from the Mumun (1500–100 BC) to Proto-Three Kingdom period (1–300 AD). It contained a Mumun period ditch-enclosed settlement with 1266 house structures and 133 megalithic burials. The square-shaped settlement is one of the largest Mumun settlements discovered in South Korea to date. This site also has well preserved dry-field features that are identified by ridges and furrows characteristic of cultivation during the Mumun period. In addition, nine megalithic burials with artifacts such as stone daggers, stone arrowheads, bronze arrowheads and Mumun pottery were excavated (Korea Institute of Cultural Heritage , 2017). One small megalithic burial (5 ho) contained juvenile remains (6–8 years old), and this single individual was selected for isotopic analysis.

6. Jeongseon Maedun Cave

The Maedun Cave site is located at the bottom of a limestone cliff in Jeongseon County, Kangwon Province, South Korea (37° 19′ E, 128° 41’ N). This cave site is situated 330 m above sea level and is 29 m long and 7 m high and the entrance of the cave is located at the bottom of a slope next to the Chijang River, a tributary to the South Han River. The Maedun Cave is a karstic limestone cave that was periodically occupied. This site was systematically excavated four times by the Yeonsei University Museum (YUM) from 2016 to 2018 (Yeonsei University Museum, 2017). The excavations yielded rich finds that provided valuable information about the occupation of the cave. The cave occupations took place from the Paleolithic to Mumun period. Most of the Chulmun and Mumun culture layers are located at the entrance of the cave. Chulmun artifacts such as pottery and stone tools were excavated and terrestrial animal bones (*Cervidae, Suidae*) and freshwater fish were found from the same layers. In the Mumun layers, four human remains were recovered with Mumun pottery and stone arrowheads. In this study, two individuals (1 ho and 2 ho) from the Mumun period and four animals were available for isotopic analysis.

7. Methods

7.1. Radiocarbon dating

Three human bones (ER-HW1, ER-KO8, ER-JE9) were selected for radiocarbon dating because the collagen extracts from these individuals met the quality control criteria for well-preserved collagen (%C, % N, and C: N) (DeNiro, 1985; van Klinken, 1999). The collagen was dated at BETA Analytic in Florida, USA.

7.2. Collagen extraction

The humans and animals from the three Mumun sites were prepared for collagen extraction using the protocol outlined in Richards and Hedges (1999) with the addition of an ultrafiltration step (Brown et al., 1988) at the Moesgaard Archaeo-Science Laboratory, Aarhus University in Denmark. In brief, bone samples were cleaned and demineralized in 0.5 M HCl at 4 °C. Demineralized bones were then rinsed in deionized water and gelatinzed at 70 °C in a pH 3 solution for 48 h. The insoluble fraction was then filtered, first with 5 mm Ezee filters and then the remaining solution was filtered to collect purified collagen using >30 kDa filters. The purified solution was then frozen and freeze dried for 48 h.

7.3. Bulk isotopic analysis

The purified collagen was placed in tin capsules and analyzed for bulk carbon and nitrogen isotope ratios at the Alaska Stable Isotope Facility at the University of Alaska, Fairbanks, USA using a continuousflow isotope ratio mass spectrometer. A Costech ECS4010 Elemental Analyzer (Costech Scientific Inc, Valencia, CA) combusted samples to carbon dioxide and nitrogen gas, which were carried in a constant flow of helium to a Finnigan Delta Plus XP isotope ratio mass spectrometer via the Conflo III interface (Thermo-Finnigan Inc, Bremen, Germany). Data are presented in the accepted delta notation as δX = (R sample –R standard)/(R standard) x 1000‰, where R is the ratio of heavy to light isotope. In addition, multiple peptone standards (n = 5) were run with the unknowns ($\delta^{13}C = -15.8‰$, $\delta^{15}N = 7.0‰$) to assess analytical accuracy and precision. The carbon and nitrogen isotope ratios were calculated relative to Vienna Pee Dee Belemnite (VPDB) for $\delta^{13}C$ and atmospheric N_2 (AIR) for $\delta^{15}N$, respectively. Replicate measurement errors on known standards were less than ±0.2‰ for both $\delta^{13}C$ and $\delta^{15}N$.

7.4. *$\delta^{13}C_{AA}$ hydrolysis and derivatization*

CSIA-AA $\delta^{13}C_{AA}$ analysis was performed on collagen from the Mumun humans and animals. Derivatization was performed according to a modified protocol of Honch et al. (2012). Briefly, collagen (~1–1.5 mg) was hydrolyzed with 1 mL 6 M HCl (110 °C, 20 h). Standard mixtures of 12 amino acids in roughly the same amounts as found in bone collagen: alanine (Ala), aspartic acid/asparagine (Asx), glutamic acids/glutamine (Glx), glycine (Gly), hydroxyproline (Hyp), proline (Pro), serine (Ser), threonine (Thr), isoleucine (Ile), leucine (Leu), phenylalanine (Phe), valine (Val) (Sigma-Aldrich Chemie; Fluka Chemie) were prepared with the unknowns and underwent all steps including hydrolysis. During acid hydrolysis, the amide groups of glutamine (Gln) and asparagine (Asn) are converted to carboxylic acid groups or the amino acids glutamic acid (Glu) and aspartic acid (Asp), respectively (Fountoulakis and Lahm, 1998). Thus, the combined values of Gln and Glu are denoted as Glx and the combined values of Asn and Asp are denoted as Glx. The hydrolysates were evaporated to dryness at 60 °C in a heating block under a gentle stream of N_2. After evaporation, samples were stored at 4 °C for <2 wk. Standard amino acid mixtures and isolated collagen amino acids were derivatized to N-acetyl methyl esters as described in Corr et al. (2007). Each sample was propylated in a 0.63-mL solution of acidified methanol (anhydrous methanol: acetyl chloride, 6:1) for 1 h at 75 °C, then dried under a gentle stream of N_2. Acetylation was performed by adding 0.75 mL acetic anhydride: triethylamine: acetone (1:2:5, v: v: v, 10 min at 60 °C). Following each reaction, reagents were evaporated under N_2 and the amino acid derivatives were dissolved in 2 mL of ethyl acetate. Then, 1 mL of saturated NaCl were added to remove any precipitates. The samples were then transferred to a gas chromatography vial for analysis.

7.5. *$\delta^{13}C_{AA}$ analysis*

The $\delta^{13}C_{AA}$ values of the derivatized standards and collagen were determined with a Hewlett Packard 7890 N series gas chromatograph (Agilent Technologies) coupled via a combustion interface (glass tube packed with CuO/NiO/Pt, operated at 950 °C) to an isotope ratio mass spectrometer (visION, Isoprime) (GC-C-IRMS). A mid-polar column (VF-35 ms, 30 m length, 0.32 mm i. d., and 1 μm film thickness) was used with He as a carrier gas (at a constant 1.3 mL/min flow rate). The temperature program utilized was 80 °C (1min), 135 °C at 20 °C min^{-1}, 160 °C (2 min) at 5 °C min^{-1} and 300 °C (10 min) at 8 °C min^{-1} °C. To enhance peak separation of Hyp and Phe, a polar column (VF-23 ms, 30 m length, 0.25 mm i. d., and 0.25 m film thickness) was also utilized. The temperature program applied was 80 °C (1min), 135 °C at 20 °C min^{-1}, 160 °C (2 min) at 5 °C min^{-1} and 250 °C (20 min) at 4 °C min^{-1} °C. Each reported $\delta^{13}C_{AA}$ value is a mean of triplicate measurement. A mixture of standard AAs was analyzed every 9 runs of samples and standard deviations of the $\delta^{13}C$ measurements in the standard AAs were approximately ±0.4‰ during our overall analysis. To account for the non-analyte carbon added to AA-NACMEs during derivatization, measured sample $\delta^{13}C_{AA}$ values were corrected to underivatized $\delta^{13}C_{AA}$ values using a stoichiometric mass balance, which is based on the relation between measured, derivatized standard AA-NAMCE $\delta^{13}C_{AA}$ values and known, underivatized $\delta^{13}C_{AA}$ values (Silfer et al., 1991).

8. Results

8.1. *Radiocarbon dating*

The radiocarbon dates for the three Mumun humans are listed in Table 1. The dates were calibrated by the CALIB REV8.2 program (Stuiver et al., 2020). The Mumun humans date from approximately 770 to 410 cal BC (2σ) with the median probability dates occurring at 625 cal BC for ER-HW1, 535 cal BC for ER-KO8, and 635 cal BC for ER-JE9. Thus, the three humans from each of these sites belong approximately to the Middle Mumun period (800–400 BC) in Korean prehistory.

8.2. *Bulk isotopic results*

The bulk isotopic results for the Mumun humans and fauna are presented in Table 2. In general, the collagen from the human and animal bones at the three Mumun sites is well preserved, with nearly all collagen yields more than 1% and C:N ranging from 2.9 to 3.4 (DeNiro, 1985). One human (ER-HW2) from the Jaecheon Hwangsok-ri site had a collagen yield of 0.8%, but as the collagen was ultrafiltered and all of the other quality control indicators (%C, %N, C: N) were indicative of well-preserved collagen, this specimen was retained for discussion. However, one of the humans (ER-JE10) from the Jeongseon Maedun Cave site failed to yield sufficient collagen for isotopic analysis.

The bulk $\delta^{13}C$ and $\delta^{15}N$ values for the Mumun humans and animals are plotted in Fig. 3. In addition, to the Mumun data, previously published fauna from South Korean prehistoric sites (Dongsamdong, Ando and Nukdo) are included to expand the faunal isotopic baseline for interpretation (Choy and Richards, 2009, 2010b; Choy et al., 2012). The Mumun deer have isotopic results within the range of C_3 plant consumers with mean ± SD values for $\delta^{13}C = -20.7 \pm 0.8‰$ and $\delta^{15}N = 3.3 \pm 0.4‰$. The single wild boar also has isotopic results indicative of C_3 plant consumers ($\delta^{13}C = -19.6‰$ and $\delta^{15}N = 3.3‰$). The isotopic data of the terrestrial animals from the Jeongseon Maedun Cave are similar to those of terrestrial animals from previously published faunal data (Fig. 3) (Choy and Richards, 2010b; Kim, H–S., 2010). Thus, these isotopic results from the terrestrial herbivores indicate a predominance of C_3 vegetation in this region during the Mumun period.

The humans had mean ± SD isotopic results of −11.2 ± 0.8‰ for $\delta^{13}C$ and 7.0 ± 0.5‰ for $\delta^{15}N$, with a narrow range of $\delta^{13}C$ (−12‰ to −9‰), and $\delta^{15}N$ values (6.3‰–7.6‰) (Table 2). As seen in Fig. 3, the Mumun human bulk $\delta^{13}C$ values are nearly ~10‰ higher than those of the terrestrial herbivores. These ^{13}C-enriched values appear to reflect the consumption of C_4 plants, most likely millets (Wang et al., 2019). Furthermore, the narrow range of $\delta^{13}C$ results in the Mumun humans indicate that millets were the dominant dietary resources consumed. The $\delta^{15}N$ values (7.0‰) of the Mumun humans are at least one trophic level higher than those of the terrestrial herbivores (3.3‰), this suggests that wild game such as the deer and boar for animal proteins were consumed by the Mumun.

8.3. *$\delta^{13}C_{AA}$ results*

The $\delta^{13}C_{AA}$ results of 12 bone collagen amino acids, five essential (Ile, Leu, Phe, Thr, Val) and seven non-essential (Ala, Asx, Glx, Gly, Hyp, Pro, Ser), from the Mumun human and faunal samples are listed in Table 3. A regression line of the $\delta^{13}C_{Hyp}$ vs. $\delta^{13}C_{Pro}$ values is used as a quality control check of the amino acid derivatization and instrument performance (Roberts et al., 2018; Ma et al., 2021), and the 1:1 line of our results demonstrates the good quality of the data ($R^2 = 0.976$; Fig. 4).

As no lysine (lys) $\delta^{13}C$ results are reported here, it is impossible to use

Table 1
AMS radiocarbon dates on bone collagen of humans from Mumun sites in this study.

Sample ID	Site	Species	Element	C:N	^{14}C Date (BP)	Calendar Age Cal BC (2σ)	Median Age Cal BC	Period
ER-HW1	Jecheon Hwangsok-ri	*Homo Sapiens*	Femur	3.4	2470 ± 30 BP	765–420	625 BC	Middle Mumun
ER-KO8	Chuncheon Jungdo	*Homo Sapiens*	Cranium	3.2	2440 ± 30 BP	750–410	535 BC	Middle Mumun
ER-JE9	Jeongseon Maedun Cave	*Homo Sapiens*	Rib	3.2	2480 ± 30 BP	770–430	635 BC	Middle Mumun

Table 2
List of human and fauna bone samples for bulk stable carbon and nitrogen isotope analyses in this study.

Sample ID	Site	Location	Species	Element	% yield	$\delta^{13}C_{Bulk}$ (‰)	$\delta^{15}N_{Bulk}$ (‰)	%C	%N	C:N
ER-HW1	Jecheon Hwangsok-ri	Chung 6 ho	*Homo Sapiens*	Femur	2.5	−9.9	6.9	43.8	15.8	3.2
ER-HW2	Jecheon Hwangsok-ri	Chung 7 ho	*Homo Sapiens*	Cranium	0.8	−11.4	6.9	43.1	15.1	3.3
ER-HW3	Jecheon Hwangsok-ri	Chung17 ho	*Homo Sapiens*	Cranium	1.9	−12.0	7.6	44.6	15.3	3.4
ER-HW6	Jecheon Hwangsok-ri	Unknown	*Homo Sapiens*	Femur	1.5	−11.0	6.8	44.4	15.5	3.3
ER-KO8	Chuncheon Jungdo	Dolmen 5 ho	*Homo Sapiens*	Cranium	2.5	−12.0	7.4	42.4	15.9	3.1
ER-JE9	Jeongseon Maedun Cave	1ho	*Homo Sapiens*	Rib	11.5	−11.1	6.3	41.8	15.8	3.1
ER-JE10	Jeongseon Maedun Cave	2ho	*Homo Sapiens*	Cranium	0.1	NA	NA	NA	NA	NA
ER-JE11	Jeongseon Maedun Cave	G8	*Cervus Nippon*	Tibia	4.2	−21.5	3.4	40.0	15.5	3.0
ER-JE12	Jeongseon Maedun Cave	F8	*Cervus Nippon*	Tibia	4.6	−20.7	2.9	40.5	15.7	3.0
ER-JE13	Jeongseon Maedun Cave	G6	*Cervus Nippon*	Tibia	8.7	−20.0	3.7	39.2	15.4	3.0
ER-JE14	Jeongseon Maedun Cave	G8	*Sus Scrofa*	Tibia	6.2	−19.6	3.3	39.7	15.7	2.9

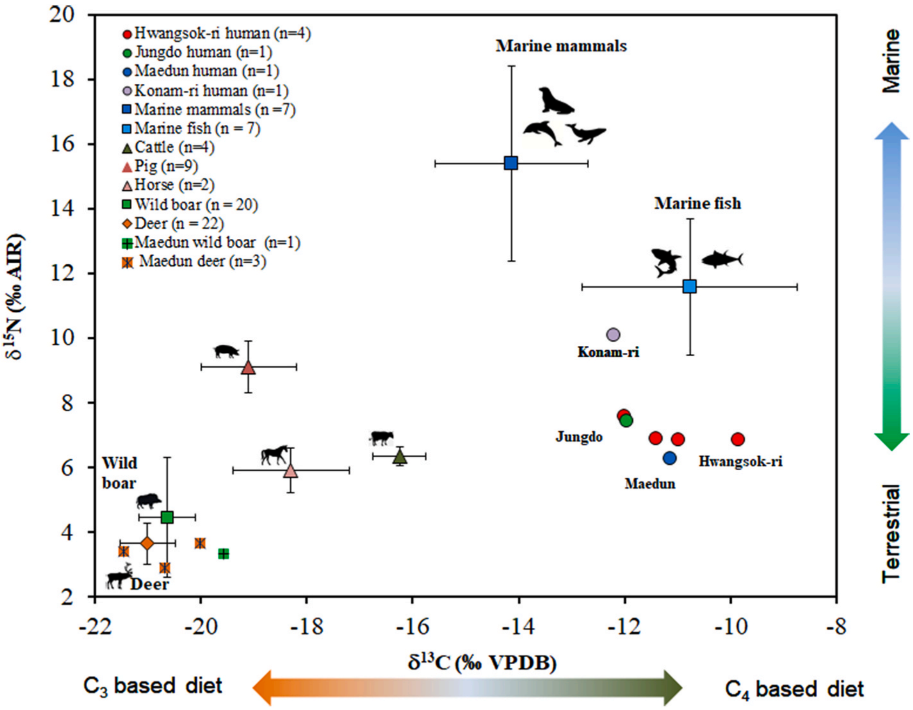

Fig. 3. Carbon and nitrogen isotope values of bone collagen from humans and fauna recovered at the three Mumun sites (Hwangsok-ri, Jungdo, and Maedun) and a previously published Konam-ri human (An, 2006). Isotopic data of wild and domesticated animals come from the published Dongsamdong, Ando, Nukdo, and Dongnae sites (Choy and Richards, 2009; 2010b; Choy et al., 2012; Kim, 2015).

the $\delta^{13}C_{Lys}$ vs. $\Delta^{13}C_{Gly\text{-}Phe}$ and $\delta^{13}C_{Lys}$ vs. $\Delta^{13}C_{Val\text{-}Phe}$ proxies that were developed by Webb et al. (2015; 2018). However, bivariate plots of $\delta^{13}C_{Phe}$ and $\delta^{13}C_{Val}$ values can distinguish between C_3, C_4, freshwater and marine consumers (Honch et al., 2012). The $\delta^{13}C_{Phe}$ and $\delta^{13}C_{Val}$ results of the Mumun animals and humans are plotted in Fig. 5a and the Mumun humans in relation to known consumers of C_3, C_4, freshwater and marine diets from Honch et al. (2012) and known consumers of millet from Ma et al. (2021) in Fig. 5b. All six of the Mumun humans plot along the x = y line and with the C_4 Mesoamerican results of Honch et al. (2012). As maize is not found in Korean Peninsula, the C_4 signal represents millet, which was a common crop in the north of China, maritime Russia and northeastern Korea (Kang, 2009; Wang et al., 2019). The Mumun humans are also graphed in relation to the data from Honch et al. (2012) and Ma et al. (2021) using machine learning assisted principal component analysis (MLA-PCA) (Fig. 6). All the Mumun humans plot with the “world C_4 group” indicating that their diet was comprised largely of millet. However, it is interesting to note that they do not plot directly with the near exclusive millet consumers from the Nancheng site of China (Ma et al., 2021). This could suggest that their diet was not exclusively based on millet and that a small component of C_3 dietary resources were consumed in Mumun humans.

Table 3
Collagen $\delta^{13}C_{AA}$ values for human and fauna bone samples from the Mumun sites. All samples were measured in triplicate.

Sample Code	Species	Ala	±SD	Gly	±SD	Val	±SD	Leu	±SD	Ile	±SD	Thr	±SD	Ser	±SD	Asx	±SD	Pro	±SD	Glx	±SD	Hyp	±SD	Phe	±SD
ERI-HW1	*Homo Sapiens*	−10.0	0.1	−7.3	0.0	−18.8	0.1	−21.7	0.0	−12.6	0.1	−4.3	0.4	0.0	1.2	−9.1	0.0	−9.8	0.6	−8.9	0.8	−10.4	0.0	−18.9	0.2
ERI-HW2	*Homo Sapiens*	−10.0	0.2	−8.6	0.0	−19.3	0.5	−25.1	1.0	−12.8	0.5	−6.3	0.5	−5.6	0.2	−9.1	0.1	−10.0	0.5	−8.8	0.2	−12.0	0.1	−19.6	0.3
ERI-HW3	*Homo Sapiens*	−11.0	0.6	−8.0	0.4	−20.1	0.2	−23.3	0.3	−12.7	2.2	−6.3	1.9	−2.4	1.5	−10.7	0.1	−10.9	0.2	−9.8	0.1	−12.5	0.0	−19.9	0.0
ERI-HW6	*Homo Sapiens*	−8.8	0.1	−6.8	0.8	−20.8	0.3	−22.0	0.4	−11.1	0.6	−6.3	0.1	0.3	0.7	−11.8	0.9	−9.8	0.3	−10.1	0.2	−10.7	0.4	−22.2	0.3
ERI-KO8	*Homo Sapiens*	−13.8	0.3	−8.7	0.8	−22.1	0.4	−24.4	0.3	−11.7	0.7	−6.7	1.5	−4.7	0.0	−12.4	0.6	−13.2	0.3	−9.9	0.7	−12.9	0.2	−22.9	0.2
ERI-JE9	*Homo Sapiens*	−10.5	1.0	−7.9	0.3	−21.1	0.7	−23.0	0.0	−10.9	0.5	−5.8	0.8	−4.3	0.7	−12.7	0.3	−11.6	0.2	−8.7	1.0	−11.9	0.4	−19.6	0.0
ERI-JE11	*Cervus Nippon*	−27.0	1.0	−18.2	0.8	−28.8	1.0	−32.0	0.5	−23.5	1.7	−16.7	0.3	−15.0	1.0	−20.7	0.9	−20.8	0.8	−21.1	0.3	−19.8	0.3	−27.8	0.6
ERI-JE12	*Cervus Nippon*	−25.4	0.1	−20.5	0.7	−30.1	0.0	−33.2	0.5	−22.8	1.1	−14.2	1.1	−13.7	0.2	−20.7	0.6	−21.0	0.0	−21.8	0.1	−21.0	0.3	−27.5	0.4
ERI-JE13	*Cervus Nippon*	−25.4	0.4	−21.4	0.7	−29.5	0.3	−31.9	0.1	−21.7	0.6	−12.0	0.1	−16.2	0.4	−22.0	0.3	−20.5	0.3	−22.2	0.1	−20.2	0.7	−28.9	0.6
ERI-JE14	*Sus Scrofa*	−24.3	0.3	−18.8	0.2	−29.0	0.9	−30.5	0.1	−20.7	0.4	−11.5	1.0	−15.6	0.5	−21.8	1.2	−19.9	0.0	−21.3	0.1	−18.5	0.8	−28.4	0.1

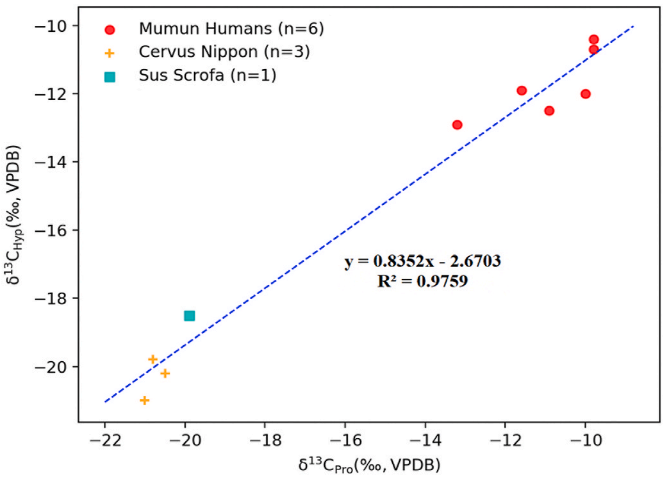

Fig. 4. Bivariate quality control plot of $\delta^{13}C_{Pro}$ vs. $\delta^{13}C_{Hyp}$ values for the Mumun humans and fauna.

9. Discussion

9.1. Evidence for millet consumption in the mumun period

The bulk isotopic data show that all 6 individuals from the three Mumun sites have high $\delta^{13}C$ and low $\delta^{15}N$ values, suggesting that C_4 plants were consumed. Given the absence of wild C_4 plants on the Korean Peninsula, the isotopic results indicate that these Mumun inhabitants in the inland central region of South Korea cultivated millets (foxtail and broomcorn millets) as a major component of their diet. In addition, the CSIA-AA results, in particular the $\delta^{13}C_{Phe}$ and $\delta^{13}C_{Val}$ values also indicate that these Mumun humans consumed significant amounts of millets. Further, the $\Delta^{13}C_{Gly\text{-}Phe}$ and $\Delta^{13}C_{Val\text{-}Phe}$ proxies show that there was no contribution of marine or freshwater sources to the diets of the Mumun. The $\delta^{13}C_{Ala}$ results, which are suggestive of the intake of carbohydrates (Choy et al., 2013), also indicate that C_4 plants were important food sources in the diets of the Mumun. Overall, the MLA-PCA analysis clearly shows that the Mumun humans are clustered with the world C_4 group, indicating a diet mainly based on C_4 plants. Thus, our study confirms that millets were the main dietary inputs for these inland individuals during the Middle Mumun period (800–400 BC).

In terms of animal protein consumption, the low Mumun human $\delta^{15}N$ values (7.0 ± 0.5‰), suggest that the millets may have been eaten directly rather than by the consumption of millet-consuming animals. While no domestic animals were isotopically analyzed from these Mumun sites, comparison of the human data can be made to other sites in South Korea. For example, a single cow from the Late Mumun site of Nukdo has a $\delta^{15}N = 6.8‰$ (Choy and Richards, 2009) and livestock from the Proto-Three Kingdoms site of Dongnae, Busan City, have $\delta^{15}N = 5.9 \pm 0.3‰$ for cattle, $\delta^{15}N = 5.9 \pm 0.7‰$ for horses, and $= 9.1 \pm 0.8‰$ for pigs (Kim, H–S., 2015) (Fig. 3). If significant quantities of domestic animal protein were consumed during the Mumun period, a ~3–5‰ ^{15}N-enrichment would be expected in the humans over the animals (Bocherens and Drucker, 2003; Hedges and Reynard, 2007). However, these similar or only slightly elevated $\delta^{15}N$ results of the Mumun humans over the domestic animals suggests that they may not have consumed these animals in large amounts. Animal protein may have been acquired from wild herbivores such as the wild boar and deer measured here ($\delta^{15}N = 3.3 \pm 0.4‰$). Nonetheless, the contribution of wild boar and deer appears to have been relatively small compared with the millets due to the ^{13}C-enriched values of the Mumun humans. This could suggest that the Middle Mumun people in the central regions of the Korean Peninsula relied on the hunting wild animals to meet their protein needs, but not on domesticated animals, and that there might

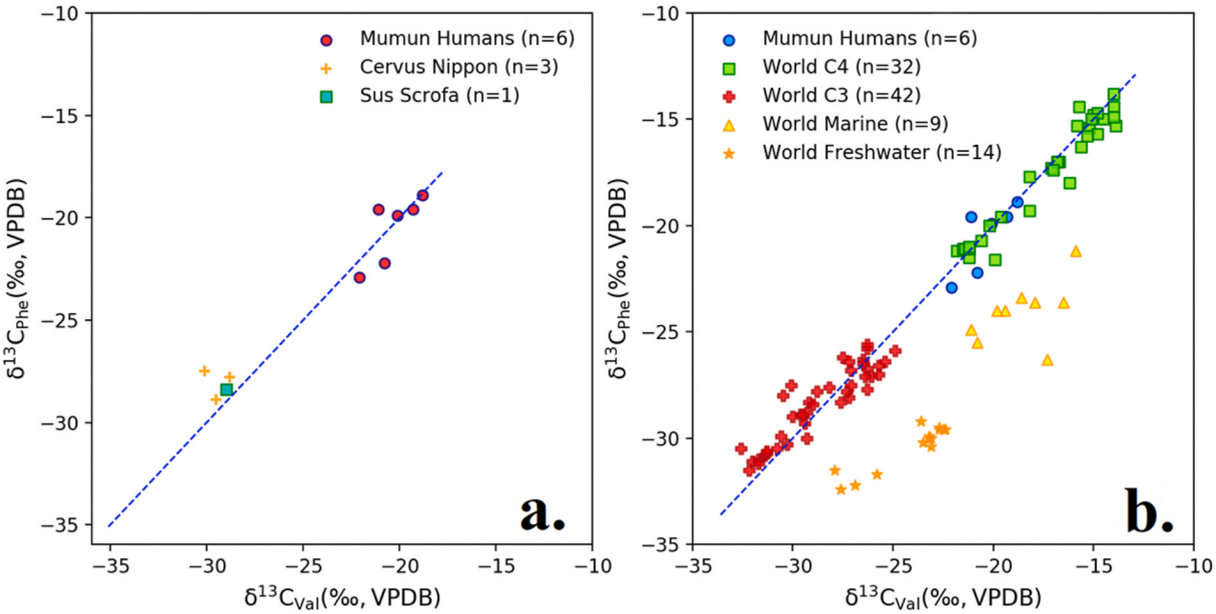

Fig. 5. a, b. Bivariate plots of $\delta^{13}C_{Phe}$ vs. $\delta^{13}C_{Val}$ results for the Mumun humans and fauna (a) and the Mumun $\delta^{13}C_{Phe}$ and $\delta^{13}C_{Val}$ results (b) by dietary classification with known types of dietary consumers (C_3, C_4 freshwater, marine) from Honch et al. (2012) and Ma et al. (2021).

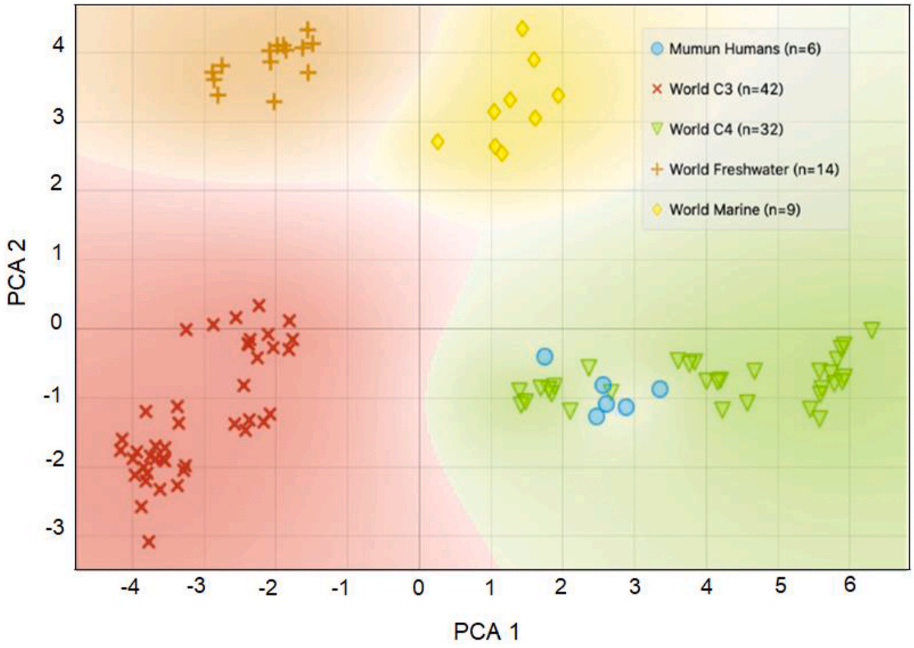

Fig. 6. MLA-PCA plot of $\delta^{13}C_{AA}$ results for the Mumun humans from South Korea and the datasets of Honch et al. (2012) and Ma et al. (2021).

have been a time lag between the domestication of plants and animals during this period. To confirm or refute this possibility, a large number of domestic and wild animals as well as millet grains from Mumun sites need to be isotopically analyzed in the future.

Our findings are consistent with a previously published isotopic study of a single Mumun human from the Konam-ri shell midden site, Taean County, on the western coast of South Korea (An, 2006) (Fig. 3). This study found that this individual had a high $\delta^{13}C$ value (−12.2‰), which was interpreted as reflecting the consumption of C_4 plants. However, the Konam-ri human has a higher $\delta^{15}N$ value (10.1‰) than the individuals studied here, suggesting the possible consumption of high nitrogen marine resources. Given the bulk isotopic overlap between marine and C_4 diets (Honch et al., 2012; Ma et al., 2021), it is difficult to determine if this individual consumed marine foods or millets or a mixture of both. Nonetheless, archaeological and isotopic evidence between the two regions suggests that there were similarities in plant consumption between the coastal and inland Mumun people (An, 2006), although the coastal Mumun likely also exploited marine foods. A possible explanation for these regional similarities might be the intensification of millet agriculture during the Mumun period. It is assumed that millet agriculture was fully adopted and spread to the coastal region of Korean Peninsula. Recent research on charred organic residues in pottery from the Majeon-ri site, Nonsan City, confirmed that broomcorn millet was regularly processed during the Mumun period (Heron et al., 2017). Thus, the Majeon-ri humans from the western inland regions cooked and ate millets for foods. Along with our results, the previous isotopic data from different regions also indicate that millet was of major significance and was used as a stable crop during the Mumun period.

9.2. Millet and early agriculture on the Korean Peninsula

Archaeological and archaeobotanical evidence support our isotopic results for the consumption of millets during the Mumun period. In East Asia, millets were a key crop in prehistory along with rice (Crawford, 2009; Lu et al., 2009; Wang et al., 2019). There is abundant archaeobotanical remains which attest to the presence of millets on the Korean Peninsula (Ahn, 2010; Lee, 2011; Kwak et al., 2020). Based on the remains of charred grains, millets were first introduced into Korea as a result of interactions with the Chulmun populations from north-eastern China and the maritime region of the Russian Far East (Crawford, 2009; Lee, 2011). In southern Korea, the earliest appearance of domesticated broomcorn and foxtail millet was dated to the Middle Chulmun period (3500 BC) (Ahn, 2005). Later, millet was represented as a major crop of the Early Mumun (1500–800 BC) in the southwestern regions (Ahn, 2010) and stores of broomcorn and foxtail millets were recovered from the Middle Mumun period (800–400 BC) (Crawford and Lee, 2003; Ahn, 2008, 2010). In addition to archaeobotanical data, archaeological excavations have found abundant evidence of agricultural activities such as agricultural tools and fields from the Middle Mumun period (Kim, S–O., 2015; Kwak et al., 2017). Middle Mumun people resided on hilltops, hillsides, terraces, and floodplains of tributary inland rivers, and constructed massive dry fields and irrigated wet fields for growing multiple crops (Bale and Ko, 2006; Lee and Bale, 2016). A large amount of potteries for storage were manufactured and agricultural tools such as stone-harvesting blades, querns and digging tools were utilized during this period.

The investigation of changing subsistence patterns from hunting and gathering to agriculture are an important topic of research in Korean archaeology. It is assumed that the Korean Peninsula witnessed drastic changes in subsistence practices during the Chulmun-Mumun transition period (Crawford and Lee, 2003; Ahn, 2010; Lee, 2011). Along with archaeobotanical data, recently, the isotopic analysis of human and animal remains from South Korea has provided important information about the development of early agriculture on Korean Peninsula. Despite the discovery of domesticated plants and a large amount of terrestrial and marine animal bones, isotopic analysis of fauna and humans from the Incipient, Early to Middle Chulmun sites (Ando, Tongsamdong, Janghang, and Daepo) have revealed that marine animals were the main dietary components of humans (Choy and Richards, 2010b; Choy et al., 2012; Shin et al., 2013, Kim, H–S., 2010). In the Late Chulmun (2500–1500 BC), isotopic results of humans from western coastal sites (Daejuk-ri, Konam-ri) have shown that both C_3 plants and terrestrial animals were important food sources (An, 2006; Choy et al., 2012). The new isotopic data from the Middle Mumun (800–400 BC) sites presented here (Jungdo, Maedun Cave, Hwangsok-ri) have discovered that millet was a main dietary source. Thus, based on the current isotopic dataset available for Korea, it appears that millet cultivation and consumption was not significant until the Middle Chulmun period and became important in the Middle Mumun period. However, there are still gaps in our knowledge regarding subsistence changes due to the lack of human isotopic data from the Late Chulmun (2500–1500 BC) to Early Mumun (1500–800 BC) periods. Future isotopic studies from the Late Chulmun and Early Mumun periods are necessary to refine and clarify dietary patterns during these key transitional timeframes in Korean prehistory.

Finally, one of the most debated topics during the Mumun period is the role of rice cultivation and how this led to the drastic changes in the subsistence economy and social hierarchy of the Mumun (Kim B–C., 2005, 2006; Kim, M., 2015; Kwak et al., 2017; Kim and Park, 2020). Most previous studies on Mumun agriculture were often mainly focused on rice farming and considered rice cultivation as the main impetus for the dietary transition from hunting-gathering to agriculture (Kim, 2003; Kim, 2006; Kim and Park, 2020). It is believed that rice was a main staple crop in the Mumun period and the spread of rice agriculture triggered social and economic complexities in the Mumun society (Ahn, 2010; Kim, B–C., 2015; Kim and Park, 2020). However, an overly simplified emphasis on rice agriculture by many Korean archaeologists has appeared to ignore the real complexity of the Mumun agricultural practices (Kim, 2003; Lee, 2011; Kwak et al., 2017). Our isotopic data presented here show that reliance on rice during the Mumun period was much lower than previously thought. Rather, millet could have been a much more important crop in the central areas of the Korean Peninsula than rice. The Mumun people living near the hillsides or river plains needed time to adjust to local environmental conditions, particularly for rice, which required water irrigation techniques. Crops such as millet, which were introduced earlier from the Middle Chulmun period, may have been more suitable in the inland areas. Compared with rice, millet also is known for its adaptability to a wide range of climates and soils without requiring a lot of water or irrigation (Mann, 1946; Wang et al., 2018, 2019). Therefore, millet may have been a more suitable crop in the central inland area of the Korean Peninsula where the environmental and soil conditions are not suitable for cultivation of other less tolerant species, such as rice and barely (Mann, 1946; Ahn, 2010). This may have provided the inland Mumun people the impetus for embracing millet agriculture. Thus, the isotopic evidence presented here for significant millet consumption during the Mumun period calls for a reassessment of agriculture practices of the Mumun and we look forward to additional research at other Mumun sites on the Korean Peninsula.

10. Conclusions

Here bulk and $\delta^{13}C_{AA}$ isotopic analysis of bone collagen provided direct evidence for the diet of humans and animals from three Middle Mumun sites in central inland South Korea. The isotopic data found that the Mumun humans consumed diets mainly from C_4 plants such as broomcorn and foxtail millet. This work represents direct evidence for human millet consumption in the Middle Mumun period. This isotopic evidence is in contrast with the current emphasis on the importance of rice farming during the Mumun period. As a result of this work, it can now be better understood that Mumun agriculture was more diverse and complex than previous thought, and this may have been based on local climate and soil conditions. However, the findings of this study are only based on a small number of individuals due to the extreme difficulty of finding well preserved human remains from the Mumun period. Thus, more Mumun sites need to be found, excavated, and studied to investigate larger-scale dietary patterns during this time period. Further, data from a wider geographical range of sites may be useful for elucidating the spread of millet on the Korean Peninsula.

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.

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References

Ahn, S.-M., 2005. Review of the neolithic agriculture in southern Korea. Journal of the Korean Neolithic study (Hankuk Shinsukki Yeongu) 10, 7–25 (in Korean with English abstract).

Ahn, S.-M., 2006. Beginning of agriculture and sedentary settlement in East Asia. Journal of the Korean Neolithic study (Hankuk Shinsukki Yeongu) 11, 25–54 (in Korean with English abstract).

Ahn, S.-M., 2008. Crop assemblage of Korean bronze age. Journal of the Honam Archaeological Society 28, 5–50 (in Korean).

Ahn, S.-M., 2010. The emergence of rice agriculture in Korea: archeobotanical perspectives. Archaeological and Anthropological Sciences 2, 89–98.

An, D.-I., 2006. Dietary reconstruction by stable isotopic analysis: the Konam-r shell midden in Korea. Journal of the Korean Ancient Historical Society 54, 5–20 (In Korean).

Bale, M.T., 2001. Archaeology of early agriculture in Korea: an update on recent developments. Bulletin of the Indo-pacific Prehistory Association 21, 77–84.

Bale, M.T., 2017. An examination of surplus and storage in prehistoric complex societies using two settlements of the Korean peninsula. World Archaeol. 49, 90–104.

Bale, M.T., Ko, M.-J., 2006. Craft production and social change in Mumun pottery Period Korea. Asian Perspect. 45, 159–187.

Bocherens, H., Drucker, D., 2003. Trophic level isotopic enrichment of carbo and nitrogen in bone collagen: case studies from recent and ancient terrestrial ecosystems. Int. J. Osteoarchaeol. 13, 46–53.

Brown, T.A., Nelson, D.E., Vogel, J.S., Southon, J.R., 1988. Improved collagen extraction by modified Longin method. Radiocarbon 30, 171–177.

Chen, X., Fang, Y., Hu, Y., Hou, P., Lü, J., Yuan, G., Song, G., Fuller, B.T., Richards, M.P., 2016. Isotopic reconstruction of the late Longshan period (ca. 4200-3900 BP) dietary complexity before the onset of state-level societies at the wadian site in the ying river valley, central plains, China. Int. J. Osteoarchaeol. 26, 808–817.

Cho, H.-J., 2008. The Archaeology of Early Rice Cultivation in Korean Peninsula. Unpublished Ph.D. dissertation, Chonnam National University, Korea (in Korean).

Choy, K., Richards, M.P., 2009. Stable isotope evidence of human diet at the Nukdo shell midden site, South Korea. J. Archaeol. Sci. 36, 1312–1318.

Choy, K., Smith, C.I., Fuller, B.T., Richards, M.P., 2010. Investigation of amino acid δ^{13}C signatures in bone collagen to reconstruct human palaeodiets using liquid chromatography-isotope ratio mass spectrometry. Geochem. Cosmochim. Acta 74, 6093–6111.

Choy, K., Richards, M.P., 2010. Isotopic evidence for diet in the middle Chulmun period: a case study from the Tongsamdong shell midden, Korea. Archaeological and Anthropological Sciences 2, 1–10.

Choy, K., An, D., Richards, M.P., 2012. 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.

Choy, K., Nash, S.H., Kristal, A.R., Hopkins, S., Boyer, B.B., O'Brien, D.M., 2013. The carbon isotope ratio of alanine in red blood cells is a new candidate biomarker of sugar-sweetened beverage intake. J. Nutr. 143, 878–884.

Chungbuk University Museum, 1983. Excavation Report of Chewon Hwangsok-Ri District B, Archaeological Investigation of Cultural Properties in Chungju Dam Area. Chungbuk National University Museum, pp. 109–133 (in Korean).

Corr, L.T., Sealy, J.C., Horton, M.C., Evershed, R.P., 2005. A novel marine dietary indicator utilizing compound-specific bone collagen amino acid d13C values of ancient humans. J. Archaeol. Sci. 32, 321–330.

Corr, L.T., Berstan, R., Evershed, R.P., 2007. Development of N-acetyl methyl ester derivatives for the determination of δ^{13}C values of amino acids using gas chromatography-combustion- isotope ratio mass spectrometry. Anal. Chem. 79, 9082–9090.

Crawford, G.W., Lee, G.-A., 2003. Agricultural origins in the Korean peninsula. Antiquity 77, 87–95.

Crawford, G.W., 2009. Agricultural origins in North China pushed back to the Pleistocene-Holocene boundary. Proc. Natl. Acad. Sci. Unit. States Am. 106, 7271–7272.

Dai, L., Li, Z., Zhao, C., Yuan, J., Hou, L., Wang, C., Fuller, B.T., Hu, Y., 2016. An isotopic perspective on animal husbandry at the Xinzhai site during the initial stage of the Xia Dynasty (2,070 – 1,600 BC). International Journal of Osteoarcaheology 26, 885–896.

DeNiro, M.J., 1985. Postmortem preservation and alteration of in vivo bone collagen isotope ratios in relation to palaeodietary reconstruction. Nature 317, 806–809.

Fogel, M.L., Tuross, N., 2003. Extending the limits of palaeodietary studies of humans with compound specific carbon isotope analysis of amino acids. J. Archaeol. Sci. 30, 535–545.

Fountoulakis, M., Lahm, J.W., 1998. Hydrolysis and amino acid composition analysis of proteins. J. Chromatogr. A 826, 109–134.

Fuller, B.T., Petzke, K.J., 2017. The dietary protein paradox and threonine ^{15}N-depletion: pyridoxal-5'-phosphate enzyme activity as a mechanism for the δ^{15}N trophic level effect. Rapid Commun. Mass Spectrom. 31, 705–718.

Hare, P.E., Fogel, M.L., Stafford Jr., T.W., Mitchell, A.D., Hoering, T.C., 1991. The isotopic composition of carbon and nitrogen in individual amino acids isolated from modern and fossil proteins. J. Archaeol. Sci. 18, 277–292.

Hedges, R.E.M., Reynard, L.M., 2007. Nitrogen isotopes and the trophic level of humans in archaeology. J. Archaeol. Sci. 34, 1240–1251.

Heron, C., Shoda, S., Barcons, A.B., Czebreszuk, J., Eley, Y., Gorton, M., Kirleis, W., Kneisel, J., Lucquin, A., Mueller, J., Nishida, Y., Son, J.-H., Craig, O.E., 2017. First molecular and isotopic evidence of millet processing in prehistoric pottery vessels. Sci. Rep. 6, 38767. https://doi.org/10.1038/srep38767.

Honch, N.V., McCullagh, J.S.O., Hedges, R.E.M., 2012. Variation of bone collagen amino acid δ^{13}C values in archaeological humans and fauna with different dietary regimes: developing frameworks of dietary discrimination. Am. J. Phys. Anthropol. 148, 495–511.

Jaouen, K., Richards, M.P., Cabec, A.L., Welker, F., Rendu, W., Hublin, J.-J., Soressi, M., Talamo, S., 2019. Exceptionally high δ^{15}N values in collagen single amino acids confirm Neandertals as high-trophic level carnivores. Proc. Natl. Acad. Sci. Unit. States Am. 116, 4928–4933.

Kang, I.-U., 2009. The appearance and spread of agriculture in the Zaisanovka Neolithic Culture, Primorie, Russia in New approaches to prehistoric agriculture. In: Ahn, S.-M., Lee, J.-J. (Eds.), Seoul. Sahoi Pyoungnon, pp. 372–425 (In Korean).

Katzenberg, M.A., 2000. Stable isotope analysis: a tool for studying past diet, demography and life history. In: Katzenberg, M.A., Saunders, S.R. (Eds.), Biological Anthropology of the Human Skeleton. Wiley-Liss, New York, pp. 305–327.

Kim, B.-C., 2005. Rice Agricultural Intensification and Sociopolitical Development in the Bronze Age, Central Western Korean Peninsula. PhD Thesis. University of Pittsburgh.

Kim, B.-C., 2006. Political economy of wet rice cultivation in the Bronze period in central western Korea. Journal of the Korean Archaeological Society (Hanguk kogo-Hakbo) 58, 40–65 (in Korean with English abstract).

Kim, H.-S., 2010. The carbon dating and dietary analysis of human remains from Daepo shell midden. Journal of Korean Neolithic Research (Hankuk Shinsukki Yeongu) 20, 89–111 (in Korean with English Abstract).

Kim, H.-S., 2015. The diet and breeding system of Dongnae people by isotope analysis at Korea. Kogo Kwangchang) 20, 89–111 (in Korean with English Abstract).

Kim, J., 2003. Land-use conflict and the rate of the transition to agricultural economy: a comparative study of southern scandinavia and central-western Korea. J. Archaeol. Method Theor 10, 277–320.

Kim, J., Park, J., 2020. Millet vs rice: an evaluation of the farming/language dispersal hypothesis in the Korean context. Evolutionary Human Sciences 2, 1–18.

Kim, J.-W., Yoon, M.-B., 1967. Study of Korean dolmen (hankuk jisuk-myo yeongu). Archaeological excavation reports of Korean National Museum 6, 99–135 (in Korean).

Kim, M., 2015. Rice in ancient Korea: status symbol or community food? Antiquity 89, 838–853, 346.

Kim, S.-O., 2015. Recent developments and debates in Korean prehistoric archaeology. Asian Perspect. 54, 11–30.

Korea Institute of Cultural Heritage (KICH), 2017. Short Excavation Report of D District in Chuncheon Jungdo Legoland Korea Project. Korea Institute of Cultural Heritage (in Korean).

Kusaka, S., Hyodo, F., Yumoto, T., Nakatsukasa, M., 2010. Carbon and nitrogen stable isotope analysis on the diet of Jomon populations from two coastal regions of Japan. J. Archaeol. Sci. 37, 1968–1977.

Kwak, S., Kim, G., Lee, G.-A., 2017. Beyond rice farming: evidence from central Korea reveals wide resource utilization in the Songgukri culture during the Late-Holocene. Holocene 27, 1092–1102.

Kwak, S., Marwick, B., 2015. What did they cook? A preliminary investigation into culinary practices and pottery use in the central part of the Korean Peninsula during the mid to late Holocene. Journal of Indo-Pacific Archaeology 37, 25–43.

Kwak, S., Obata, H., Lee, G.-A., 2020. Broad-spectrum foodways in southern coastal Korea in the Holocene: isotopic and archaeobotanical signatures in Neolithic shell midden. J. I. Coast Archaeol. https://doi.org/10.1080/15564894.2020.1776427.

Lee, J.-J., 2001. From Shellfish Gathering to Agriculture in Prehistoric Korea: the Chulmun to Mumun Transition. Ph.D. dissertation, University of Wisconsin, Madison.

Lee, G.-A., 2003. Changes in Subsistence Patterns from the Chulmun to Mumun Periods: Archeobotanical Investigation. Ph.D. Dissertation, Department of Anthropology, University of Toronto.

Lee, G.-A., 2011. The transition from foraging to farming in Prehistoric Korea. Curr. Anthropol. 52, 307–329.

Lee, R.J., Bale, M.T., 2016. Social change and household geography in Mumun period South Korea. J. Anthropol. Res. 72, 178–198.

Lee-Thorp, J.A., 2008. On isotopes and old bones. Archaeometry 50, 925–950.

Lu, H., Zhang, J., Liu, K.-B., Wu, N., Li, Y., Zhou, K., Ye, M., 2009. Earlies domestication of common millet (*Panicum miliaceum*) in East Asia extended to 10,000 years ago. Proc. Natl. Acad. Sci. Unit. States Am. 106, 7367–7372.

Ma, Y., Fuller, B.T., Sun, W., Hu, S., Chen, L., Hu, Y., Richards, M.P., 2016a. Tracing the locality of prisoners and workers at the mausoleum of qin shi huang: first emperor of China (259-210 BC). Sci. Rep. 6, 26731. https://doi.org/10.1038/srep26731.

Ma, Y., Fuller, B.T., Chen, L., Zhao, C., Hu, Y., Richards, M.P., 2016b. Reconstructing the diet of the early qin (ca. 700 – 400 BC) at xishan, gansu Province, China. International Journal of Osteoarcaheology 26, 959–973.

Ma, Y., Fuller, B.T., Wei, D., Shi, L., Zhang, X., Hu, Y., Richards, M.P., 2016c. Isotopic perspectives (δ13C, δ15N, δ34S) of diet, social complexity, and animal husbandry during the proto-shang period (ca. 2000–1600 BC) of China. Am. J. Phys. Anthropol. 160, 433–445.

Ma, Y., Grimes, V., Van Biesen, G., Shi, L., Chen, K., Mannino, M.A., Fuller, B.T., 2021. Aminoisoscapes and palaeodiet reconstruction: new perspectives on millet-based diets in China using amino acid δ^{13}C values. J. Archaeol. Sci. 125, 105289.

Mann, H.H., 1946. Millets in the Middle East. Emp. J. Exp. Agric. 14, 208–221.

McMahon, K.W., Newsome, S.D., 2019. Amino acid isotope analysis: a new frontier in studies of animal migration and foraging ecology. In: Hobson, K., Wassenaar, L.

(Eds.), Tracking Animal Migration with Stable Isotopes. Academic Press, London, pp. 173–190.

Minagawa, M., Wada, E., 1984. Stepwise enrichment of δ^{15}N along food chains: further evidence and the relation between δ^{15}N and animal age. Geochem. Cosmochim. Acta 48, 1135–1140.

Ohkouchi, N., Chikaraishi, Y., Close, H.G., Fry, B., Larsen, T., Madigan, D.J., McCarthy, M.D., McMahon, K.W., Nagata, T., Naito, Y.I., Ogawa, N.O., Popp, B.N., Seffan, S., Takano, Y., Tayasu, I., Wyatt, A.S.J., Yamaguchi, Y.T., Yokoyama, Y., 2017. Advances in the application of amino acid nitrogen isotopic analysis in ecological and biogeochemical studies. Org. Geochem. 113, 150–174.

Reitsema, L.J., 2015. Laboratory and field methods for stable isotope analysis in human biology. Am. J. Hum. Biol. 27, 593–604.

Richards, M.P., 2020. Isotope analysis for diet studies. In: Richards, M.P., Britton, K. (Eds.), Archaeological Science: an Introduction. Cambridge University Press, Cambridge, pp. 125–145.

Richards, M.P., Hedges, R.E.M., 1999. 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.

Roberts, P., Fernandes, R., Craig, O.E., Larsen, T., Lucquin, A., Swift, J., Zech, J., 2018. Calling all archaeologists: guidelines for terminology, methodology, data handling, and reporting when undertaking and reviewing stable isotope applications in archaeology. Rapid Commun. Mass Spectrom. 32, 361–372.

Shin, J.Y., Lee, J.J., 2009. Dietary reconstruction of human remains from the Kyungsan Imdang burials using stable carbon and nitrogen isotope analysis. Journal of Korean Archaeology 70, 84–108 (in Korean with English Abstract).

Shin, J.Y., Kang, D.Y., Kim, S.H., Jung, E.D., 2013. Isotopic dietary history of neolithic people from Janghang site at gadeok island. Busan. Analytical Science and Technology 26, 387–394.

Silfer, J.A., Engel, M.H., Macko, S.A., Jumeau, E.L., 1991. Stable carbon isotope analysis of amino acid enantiomers by conventional isotope ratio mass spectrometry and combined gas chromatography/isotope ratio mass spectrometry. Anal. Chem. 63, 370–374.

Smith, C.I., Fuller, B.T., Choy, K., Richards, M.P., 2009. A three-phase liquid chromatographic method for δ^{13}C analysis of amino acids from biological protein hydrolysates using liquid chromatography-isotope ratio mass spectrometry. Anal. Biochem. 390, 165–172.

Stuiver, M., Reimer, P.J., Reimer, R.W., 2020. CALIB 8.2 [WWW program] at. http://calib.org. (Accessed 11 December 2020).

van Klinken, G.J., 1999. Bone collagen quality indicators for palaeodietary and radiocarbon measurements. J. Archaeol. Sci. 26, 687–695.

Wang, T., Fuller, B.T., Wei, D., Chang, X., Hu, Y., 2016. Investigating dietary patterns with stable isotope ratios of collagen and starch grain analysis of dental calculus at the Iron Age cemetery site of Heigouliang, Xinjiang, China. International Journal of Osteoarcaheology 26, 693–704.

Wang, X., Fuller, B.T., Zhang, P., Hu, S., Wang, W., Hu, Y., Shang, X., 2018. Millet manuring as a driving force for the Late Neolithic agricultural expansion of north China. Sci. Rep. 8, 5552.

Wang, T., Wei, D., Chang, X., Yu, Z., Zhang, X., Wang, C., Hu, Y., Fuller, B.T., 2019. Tianshanbeilu and the isotopic millet road: reviewing the late neolithic/bronze age radiation of human millet consumption from north China to europe. National Science Review 6, 1024–1039.

Webb, E.C., Honch, N.V., Dunn, P.J.H., Eriksson, G., Liden, K., Evershed, R.P., 2015. Compound-specific amino acid isotopic proxies for detecting freshwater resource consumption. J. Archaeol. Sci. 63, 104–114.

Webb, E.C., Honch, N.V., Dunn, P.J.H., Linderholm, A., Eriksson, G., Liden, K., Evershed, R.P., 2018. Compound-specific amino acid isotopic proxies for distinguishing between terrestrial and aquatic resource consumption. Archaeological and Anthropological Sciences 10, 1–18. https://doi.org/10.1007/s12520-015-0309-5.

Yeonsei University Museum, 2017. Short Excavation Report on Maedun Cave in Jeongseon, Korea. Yeonsei University Museum (in Korean).