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A strontium isotope analysis on the relationship between ritual tooth ablation and migration among the Jomon people in Japan

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Abstract

Distinct patterns can be discerned in the extensive ritual tooth ablation found among the human skeletal remains of the Late-Final Jomon period (ca. 3200–2800 cal BP) in Japan. Based on comparative observations of sex and grave patterns in the skeletal remains, two major patterns in ritual tooth ablation, termed type 4I and type 2C, have been assigned to locals and immigrants, respectively. In order to test this hypothesis, strontium (Sr) isotope ($^{87}Sr/^{86}Sr$) analyses were performed on human skeletal remains from the Yoshigo shell mound in Aichi Prefecture, central Japan. Plants in the surrounding area were also examined to illustrate the geographic $^{87}Sr/^{86}Sr$ distribution. The Sr isotopic variation in human tooth enamel ($^{87}Sr/^{86}Sr$ = 0.70868–0.71028) was greater than that in human bones ($^{87}Sr/^{86}Sr$ = 0.70871–0.70943). Individuals with higher Sr isotope ratios in their tooth enamel than seawater Sr values of 0.7092 can be identified as immigrants (36% of population). The presence of these isotopically identified immigrants among both type 2C and type 4I individuals does not support the previous hypothesis. The intra-population $^{87}Sr/^{86}Sr$ distribution of tooth enamel of type 2C individuals showed a significantly higher mean ratio than that of type 4I individuals, suggesting a higher proportion of immigrants among the former.

Keywords: Jomon period; hunter-gatherers; strontium isotopes; mobility; ritual tooth ablation

1. Introduction

The period of Jomon culture in the Japanese Archipelago lasted from 13000 to 2300 years BP. The Jomon people were hunter-gatherers who are well known for their cord-marked pottery. A brief description of the Jomon culture is presented in Table 1 (for details, see Habu, 2004; Harunari, 1986; Imamura, 1996). The Jomon people in general led a sedentary life, effectively exploiting marine and/or terrestrial resources. As their numbers declined during the Late-Final Jomon period (ca. 4000–2300 BP), ritual practices and artifacts developed and changed (Imamura, 1996).

A widely debated question in Japanese archaeology concerns ritual tooth ablation among the Jomon people, which was characterized by a variety of forms and widely practiced during the Late-Final Jomon period (e.g., Watanabe, 1966; Harunari, 1979, 1986). Patterns in tooth ablation provide an invaluable source of information on the social structure of the Jomon people. Several interpretations have been proposed, such as a coming-of-age ceremony (Funahashi, 2003; Harunari, 1979; Hasebe, 1919), mourning for a deceased family member (Funahashi, 2003; Harunari, 1979), representation of descent group (Yamada, 2008), and representation of moiety group (Tanaka, 1998).

The most influential interpretation of variation in ritual tooth ablation is that proposed by Harunari (1979). Comparisons of sex and grave patterns of Jomon skeletal remains have led this author to hypothesize that ritual tooth ablation was performed at a coming-of-age ceremony and at marriage, and that different types of ablation can distinguish locals from immigrants. The proposed five types of ritual tooth ablation and their interpretations are (Fig. 1): (1) type 0 individuals, with two maxillary incisors removed, representing the coming-of-age tooth ablation; (2) type 4I individuals, with additional four mandibular incisors removed, whose burial with personal offerings (such as hip accessories and earrings) led Harunari (1979) to conclude that they were locals of high prestige; (3) type 2C individuals, who lacked all canines and who were immigrants married to type 4I individuals; (4) type 4I2C, with all canines and four mandibular incisors removed; and (5) type 2C2I, with all canines and two mandibular central incisors removed, which characterize people married more than once. Harunari (1979) extended this interpretation to propose the ambilocal system for the rule of residence after marriage in Jomon society, because type 2C individuals, who were immigrants, include both males and females.

Harunari's (1979) hypothesis has been assessed through the methods of physical anthropology. A cranial nonmetric trait study of migration patterns (Mouri and Oku, 1998) supported this hypothesis. In contrast, Funahashi's (2003) comparison of the age of human skeletons and the timing of ritual tooth ablation showed that ablation also occurred before marriage and childbirth. It is not clear whether the hypothesis is valid. Thus, Harunari's (1979) hypothesis needs to be tested by independent lines of evidence.

The purpose of the present study was to provide a strontium (Sr) isotopic ($^{87}Sr/^{86}Sr$) test for Harunari's (1979) hypothesis that tooth ablation types and migration were closely related during the Jomon period. Strontium isotopes have been widely used in archaeological science as tracers of prehistoric residential mobility (e.g., Bentley et al., 2002, 2005, 2007; Ezzo et al., 1997; Haak et al., 2008; Knudson and Buikstra, 2007; Montgomery et al., 2007; Price et al., 2002). Application of this method to reveal mobility among hunter-gatherers is still developing (Haverkort et al., 2008; Tafuri et al., 2006). The rationale is that Sr isotope composition in plants and animals faithfully reflects that of their geological background, because biologically available Sr originating from rocks and soil is incorporated into biosynthetic processes with no isotope fractionation along a food chain (Blum et al., 2000). Thus, if human migration did occur between geologically contrasting residential areas, the Sr isotopic signatures in the tooth enamel of immigrants, an excellent archive of Sr in their childhood, would differ from those in other adult human bones as well as those in soil, plants, and other regional animals (Bentley, 2006).

This study is the first to apply Sr isotope analysis to Jomon skeletal remains. In addition to detailed $^{87}Sr/^{86}Sr$ measurements of human skeletal remains, extensive mapping of Sr isotopes in plants was completed to estimate the geographical origin of immigrants (e.g., Hodell et al., 2004; Wright, 2005). We then examined the relationship between Sr isotope-based immigrants and tooth ablation types in light of tests on Harunari's (1979) hypothesis.

2. Materials and Methods

The Yoshigo shell mound is located on the northern coast of the Atsumi Peninsula, Aichi Prefecture (Fig. 2). The mound was excavated in 1922 (Kiyono, 1969). About 300 human skeletons were recovered. This collection of skeletal remains was one of the main types of material to provide the basis for research by Harunari (1979). The site is dated as extending from the later part of the Late Jomon period to the Final Jomon period (ca. 3500–2300 BP) based on the chronology of pottery types (Yamanouchi, 1952). Essentially consistent ages (ca. 3200–2800 cal BP) have been newly established by radiocarbon dating of human bone collagen (see Appendix 1).

For this study, 39 third molars and 37 rib samples were selected from individuals with definite ritual tooth ablation in the collection of the Laboratory of Physical Anthropology, Department of Zoology, Graduate School of Science, Kyoto University (Appendix 2). We assumed that tooth enamel in the third molar retains Sr acquired from the diet during childhood (9–13 years old [Hillson, 1996]). Bone retains averaged Sr isotope ratios for about the previous 10 years of one's lifetime, because the turnover time of bone is about 10 years (Stenhouse and Baxter, 1979). This dietary signature in bone, however, cannot be completely retained because of the effect of diagenetic alteration, as discussed later. Plant samples (tree leaves, e.g., Chinese hackberry) were collected from 40 locations in the surrounding area of Mikawa Bay and along the Pacific coast (Appendix 3).

Human tooth and bone samples were ultrasonically cleaned in ultrapure water and then dried. Human tooth samples were embedded in resin and cut longitudinally with a Minitom diamond cutter (Marumoto Struers K.K.). A dental drill equipped with a diamond burr was used to abrade tooth enamel and bone samples. After abrading the surface area to remove soil-derived substances, enamel samples (5 mg) were collected. Human bone samples (5 mg) were also obtained from the compact bone of ribs.

Strontium isotope analysis was performed at the Research Institute for Humanity and Nature (RIHN), including the pretreatment steps in a clean laboratory. Buffered acetic acid solution (0.1 M, pH = 4.5, 1 ml) was used to eliminate diagenetic contaminants from enamel and bone samples (Hoppe et al., 2003; Sillen, 1986; Trickett et al., 2003). The samples were agitated for 10 minutes in the acetic acid solution, and after centrifugation, the solution was discarded. After performing this procedure twice, a further 10-minute leach solution was obtained as supernatant. Each plant sample (0.5 g; ashed in a muffle furnace at 650°C for 24 hours) was placed in a centrifuge tube, to which ultrapure water (10 ml) was added, and left overnight. After centrifugation, sample solution was obtained as supernatant.

All solution samples were dried down in Teflon® vials on a hotplate. Then HNO_3 (14M) was added and the vials were placed on a hotplate at 200°C to decompose organic matter. Samples were dissolved in HCl (2M), and Sr was separated chromatographically by using cation exchange resin (DOWEX, 50 × 8, 200–400 mesh). Strontium isotope ratios were measured on degassed tungsten filament with a TRITON thermal ionization mass spectrometer (Thermo Fisher Scientific K.K.). Normalization of sample $^{87}Sr/^{86}Sr$ data was based on the difference between the within-run average of NIST SRM 987 and its recommended value, for which we accepted 0.710250 (Faure and Mensing, 2005). Internal precision based on 100 times of ion counting was ± 0.000003–0.000010 (= 1 standard error). External precision determined by repeated measurements (n = 104) of NIST SRM 987 was ± 0.000007 (= 1 standard deviation [s.d.]) with the mean of 0.710256 throughout all measurements over 6 months. All $^{87}Sr/^{86}Sr$ data are listed in Appendices 2 and 3.

3. Results

3.1. Strontium isotopes in skeletal remains from the Yoshigo site

Strontium isotope ratios in human tooth enamel were 0.70925 ± 0.00036 (mean ± 1 s.d.) with a range of 0.70868–0.71028. Human bone had $^{87}Sr/^{86}Sr$ ratios of 0.70895 ± 0.00018 with a range of 0.70871–0.70943. The mean value of tooth enamel was higher than that of bone, and the standard deviation of tooth enamel was larger than that of bone. The minimum $^{87}Sr/^{86}Sr$ ratios were almost the same for both tooth enamel and bone, but the maximum $^{87}Sr/^{86}Sr$ ratio of human tooth enamel was higher than that of bone.

It should be noted that Sr isotopic records in bone hydroxyapatite are generally susceptible to diagenetic alteration because of the relatively porous crystal structure of bone hydroxyapatite (Hoppe et al., 2003; Sillen, 1986; Trickett et al., 2003). Specifically, compact bone of ribs that we studied would be more porous than the compact bone of long bones. Diagenesis would narrow the primary $^{87}Sr/^{86}Sr$ variation in bone samples, and lower the $^{87}Sr/^{86}Sr$ ratios. The $^{87}Sr/^{86}Sr$ ratios in bones could be equilibrated with those of the ground water (Bentley, 2006). Two of the sources of Sr in ground water are weathered minerals and soil, which have lower $^{87}Sr/^{86}Sr$ ratios (<0.709) that would be expected from the local geology of the site. Another source of Sr is seawater, which has a ratio of 0.7092 because in coastal areas the $^{87}Sr/^{86}Sr$ ratios can be dominated by sea-spray or rainwater derived from evaporated seawater (Bentley, 2006, Whipkey et al., 2000). Furthermore, modern precipitation in Japan shows mean $^{87}Sr/^{86}Sr$ ratios of 0.7089 and ranges of 0.7065–0.7100 (Nakano et al., 2006). The mixing of those sources constitutes diagenetic Sr. Diagenesis would result in bone $^{87}Sr/^{86}Sr$ ratios of 0.7086–0.7092 in most individuals. Thus, we assumed that bone $^{87}Sr/^{86}Sr$ ratios are characterized by diagenesis as well as the diet of the Yoshigo population. Some exceptional individuals had higher bone Sr isotope ratios, with values greater than 0.7092, because they had died several years after immigration but before their bones could fully match local Sr isotope ratios.

3.2. Geographic $^{87}Sr/^{86}Sr$ distribution of plants

Fig. 3A shows the geographic $^{87}Sr/^{86}Sr$ distribution of plants in the surrounding area of the Yoshigo site. A wide range of $^{87}Sr/^{86}Sr$ variation can be recognized, with high $^{87}Sr/^{86}Sr$ ratios (up to 0.7142) dominating the north of the study area, and low $^{87}Sr/^{86}Sr$

ratios (as low as 0.7070) occurring in the east of the study area (Appendix 3). Strontium isotope ratios in plants in the Atsumi Peninsula represent the intermediate values of these two end members.

The observed $^{87}Sr/^{86}Sr$ variation in plants correlates very well with the surface geology (Fig. 3B). In the north of the study area, where $^{87}Sr/^{86}Sr$ ratios in plants are distinctively high, granitic rocks of the Ryoke Belt are extensively exposed. In contrast, low $^{87}Sr/^{86}Sr$ ratios in the east of the study area overlap with the distribution of the limestone and chert of the Chichibu Belt. Similarly, relatively low $^{87}Sr/^{86}Sr$ ratios in the Atsumi Peninsula appear to correspond with the distribution of the Chichibu Belt. It is noteworthy that the observed relationship between $^{87}Sr/^{86}Sr$ ratios and rock type is predictable in light of the empirically known $^{87}Sr/^{86}Sr$ range in the earth's lithosphere (i.e., $^{87}Sr/^{86}Sr > 0.712$ for granitic continental crust; $^{87}Sr/^{86}Sr = 0.707–0.709$ for minerals of marine origin, e.g., Bentley, 2006).

Sea-spray effect was observed in the $^{87}Sr/^{86}Sr$ ratios of coastal areas (Fig. 3A). Even in the north of the study area, plants from coastal areas showed lower $^{87}Sr/^{86}Sr$ values than those from inland areas. The lowest $^{87}Sr/^{86}Sr$ ratios were present in the inland region of the east of the study area. The Atsumi Peninsula is likely to be affected by sea-spray; therefore, most of the plant $^{87}Sr/^{86}Sr$ ratios equilibrate toward seawater ratios and exhibit small variation.

We subdivided the study area into four regions based on the location of the Yoshigo shell mound, geographic $^{87}Sr/^{86}Sr$ distribution in plants, and geology (Fig. 3A). This subdivision enabled us to estimate the geographical origin of immigrants. First the "Yoshigo area" was defined as being within a radius of 10 km of the Yoshigo shell mound ($^{87}Sr/^{86}Sr = 0.70907 \pm 0.00037$ [mean ± 1 s.d.]), because the foraging radius of hunter-gatherers is generally within 10 km from a settlement, although this radius varies (Binford, 2001). Next, the "north area" was defined as the northern coastal area of Mikawa Bay (to the west of the Toyo River), comprising the Ryoke Belt ($^{87}Sr/^{86}Sr = 0.71140 \pm 0.00192$). The "east area" lies to the east of the Yoshigo area and to the south of the Toyo River, and consists mainly of the Chichibu Belt ($^{87}Sr/^{86}Sr = 0.70859 \pm 0.00090$). Finally, we defined the remainder of the study area, to the point of the Atsumi Peninsula, as the "west area" ($^{87}Sr/^{86}Sr = 0.70910 \pm 0.00019$).

The mean plant $^{87}Sr/^{86}Sr$ ratios in the four regions differ from each other (one-way analysis of variance, $P < 0.0001$). Student's t-test (Table 2) shows that the mean $^{87}Sr/^{86}Sr$ ratio in plants in the north area is significantly higher than that in the Yoshigo area, east area, or west area ($P < 0.0011$). This result suggests that Sr isotope analysis of the Yoshigo population can be used to identify immigrants from the north area.

It should be noted that agricultural fertilizers could have affected plant $^{87}Sr/^{86}Sr$ ratios (Bentley, 2006). On the Atsumi Peninsula, Paleozoic limestone and chert have nonradiogenic $^{87}Sr/^{86}Sr$ ratios of <0.709. Theoretically, plant $^{87}Sr/^{86}Sr$ ratios comprising a two-component mix of weathered minerals and a marine input would be between 0.7080 and 0.7092. Some plant Sr isotope values in the Atsumi Peninsula, however, show values above 0.7092. These values may result from agricultural fertilizers with relatively radiogenic Sr isotope ratios. Because we collected only plants growing naturally on flat land or hillside terraces, we expected minimal levels of Sr sourced from agricultural fertilizers in these samples. Despite such artificial sources of Sr, local geology still has a significant effect on $^{87}Sr/^{86}Sr$ ratios in the regions. Therefore, plant $^{87}Sr/^{86}Sr$ ratios show clear regional differences associated with local geology.

3.3. Identifying immigrants in the Yoshigo population

By determining the “local” $^{87}Sr/^{86}Sr$ range for this dataset, immigrants can be distinguished from locals. To identify biologically available Sr in the Yoshigo population, assessing two major sources of Sr, marine and terrestrial, was important. According to the carbon and nitrogen isotope analysis on the Yoshigo skeletal remains, these people consumed considerable amounts of marine food, although the proportion in the diet differed among individuals (Kusaka et al., 2008). In Appendix 1, the three radiocarbon dates also show a range in marine food consumption of 20–88%. A high proportion of seafood consumption makes human bone Sr ratios equilibrate toward the seawater value of 0.7092. As discussed above, the $^{87}Sr/^{86}Sr$ ratios of terrestrial sources would be about 0.7086, inferred from the Sr isotope values of plants in the Yoshigo area and the local geology. Interestingly, mixing these two components resulted in a continuous gradation observed between 0.7086 and 0.7092, and extensively between 0.7088 and 0.7092 (Fig. 4). The gradation appears to indicate different proportions of dietary dependence on marine foods. Thus, we assumed the local, biologically available Sr isotope ratios to be 0.7086–0.7092, and that 25 individuals out of 39 are locals. On the other hand 14 individuals whose enamel showed $^{87}Sr/^{86}Sr$ ratios of above 0.7092 consumed marine foods and terrestrial foods with higher Sr isotope values. Because high Sr isotope ratios in enamel (>0.7092) are not likely to be recorded from the Atsumi Peninsula, those individuals would be immigrant members of the Yoshigo population.

There is a clear break in the continuous gradation at 0.7087, particularly among females (Fig. 4). One male and one female may be immigrants, possibly from inland in the eastern area. However, we did not identify them as immigrants because the lowest values can also be explained by the fully terrestrial food consumption at the Yoshigo site.

In Fig. 4, most of the bone $^{87}Sr/^{86}Sr$ values are within the local $^{87}Sr/^{86}Sr$ range. Since bone Sr isotope values are a mixed signature of the diet of individuals and diagenesis, this association enhances the feasibility of setting the local $^{87}Sr/^{86}Sr$ range.

In Fig. 5, all measured $^{87}Sr/^{86}Sr$ ratios in tooth enamel and bone of each individual are arranged according to each tooth ablation type. Table 3 shows the number and proportion of immigrants, and their classification according to sex, ritual tooth ablation types, and the presence of offerings in burials. These results are significant for testing Harunari’s hypothesis (see later discussion).

4. Discussion

4.1. Testing Harunari’s (1979) hypothesis

Application of Sr isotope analysis to the Yoshigo skeletal remains with definite ritual tooth ablation does not support Harunari’s (1979) hypothesis that type 4I individuals are locals and type 2C individuals are immigrants. According to the criterion of the local $^{87}Sr/^{86}Sr$ range of 0.7086–0.7092, four (24%) out of 17 individuals were identified as immigrants among type 4I individuals, and five (56%) out of nine individuals were identified as immigrants among type 2C individuals (Fig. 5, Table 3). Not all type 2C individuals were immigrants, however, and type 4I individuals also include immigrants. Furthermore, one of the two type 0 individuals, who were regarded as unmarried local individuals by Harunari (1979), was an immigrant.

Harunari (1979) further hypothesized that type 4I individuals were more prestigious than type 2C individuals, and that type 4I individuals were locals, because type 4I individuals were more frequently buried with offerings than type 2C individuals.

However, both patterns of burial, with and without offerings, include immigrants (Table 3). Thus no clear relationship exists between the possession of offerings and immigrants, as Harunari (1979) argued.

Our results clearly show that tooth ablation types do not necessarily match representation of locals and immigrants. We speculate that tooth ablation types represent kin-based descent groups (Kusaka et al., 2008; Yamada, 2008). Stable carbon and nitrogen isotope analysis on the Inariyama skeletal remains revealed that the diet of these subjects was associated with ritual tooth ablation types; i.e., type 4I individuals consumed terrestrial foods, and type 2C individuals consumed marine foods (Kusaka et al., 2008). This finding suggests that each food procurement group shared the same tooth ablation type, and we assume that these groups possibly correspond to descent groups. This possibility should be explored in other archaeological or anthropological research.

4.2. Proportion of immigrants among type 4I and 2C individuals

Type 2C individuals have appreciably higher $^{87}Sr/^{86}Sr$ ratios than type 4I individuals in enamel (Mann-Whitney test: enamel, $P = 0.019$). This result suggests that type 2C individuals generally consumed foods with higher $^{87}Sr/^{86}Sr$ ratios at least during their childhood and, further, that type 2C individuals appear to include more immigrants than type 4I individuals. Four (24%) out of 17 individuals in type 4I and five (56%) out of nine individuals in type 2C were identified as immigrants. Although the number of type 2C individuals is relatively small, the mobility of these individuals might have been higher than that of 4I individuals. This tendency also applies to type 2C2I and 4I2C individuals: type 2C2I individuals include more immigrants (57%) than type 4I2C individuals (0%). Mouri and Oku (1998) investigated cranial nonmetric variants of the Yoshigo people, and presented greater similarities among type 4I crania than among type 2C crania. Their cranial nonmetric variant study and the present study suggest the same possibility; that is, that type 2C individuals include more immigrants than type 4I individuals.

4.3. Geographical origin of immigrants

Some clusters can be found among the enamel $^{87}Sr/^{86}Sr$ ratios of immigrants. One cluster, between 0.7094 and 0.7097, includes four males and three females (Fig. 4). Another cluster, between 0.7099 and 0.7100, includes three males. These results indicate several places of origin for the immigrants. We predict that the immigrants with high Sr isotope values originated from inland sites which are less affected by seawater Sr.

Marked inter-regional contrasts in geographic $^{87}Sr/^{86}Sr$ distribution in the study area (Fig. 3A) are particularly advantageous for elucidating the geographical origin of immigrants to the Yoshigo site. Specifically, immigrants identified through this study may have originated in the north area, where the mean $^{87}Sr/^{86}Sr$ ratio in plants is significantly high. Indeed, another famous site of the Final Jomon period exists in the north area (at the north of the mouth of the Toyo River; Fig. 2), namely, the Inariyama shell mound, from which about 50 human skeletal remains have been excavated (Kiyono, 1969). Future application of the Sr isotopic technique to the Inariyama skeletal remains will help establish the human interaction between the Yoshigo and Inariyama populations.

There are also several Jomon shell mounds of the Late-Final Jomon period in the west area, such as the Kawaji, Hobi, and Ikawazu sites (Fig. 2). Because no clear differences can be discerned in the geology and Sr isotope ratios of plants in the west area and the Yoshigo area, immigrants from these areas to the Yoshigo population, if any, cannot be identified through Sr isotope analysis. Thus, the number of immigrants in the Yoshigo site may be the minimum estimate.

4.4. Mobility of the Yoshigo population

Our study indicates a high proportion (36%) of immigrants among the Yoshigo population. Kondo (1994) argued that the heterogeneities of the intra-regional variation of cranial morphology are as large as those of inter-regional variation among the Jomon population from two regions: northern Chiba and the Atsumi Peninsula. Morphological similarity between the regions is also found in tooth metric and nonmetric studies (Matsumura, 1989, 2007). The morphological similarity among the Jomon population could be the result of the high mobility inferred from this study.

Some hunter-gatherer social units have a fluid composition, with individuals and families moving at different times. Thus, the size of each group can be highly variable in annual cycles (Binford, 2001). Various reasons can be suggested for migration among the Jomon people, as described in many ethnographic records of hunter-gatherers (e.g., Kelly, 1995). Hunter-gatherers may migrate as a result of resource depletion, to decrease social stress, or for marriage. Some migrants possibly joined the Yoshigo population as individuals for marriage, and others may have joined as family groups. We cannot elucidate clear reasons from our limited data. Future application of Sr isotopic techniques at multiple sites could enable a more comprehensive understanding of prehistoric human mobility in Japan.

5. Conclusions

(1) Strontium isotope data from human skeletal remains of the Jomon people from the Yoshigo shell mound show that the $^{87}Sr/^{86}Sr$ variation in tooth enamel (0.70925 ± 0.00036 [mean ± 1 s.d.]) is greater than that in bone (0.70895 ± 0.00018). Tooth enamel Sr values from these remains show a continuous gradation between 0.7086 and 0.7092, suggesting that they belong to locals. This conclusion is supported by the plant Sr isotope values collected from the surrounding area of the site, and the local geology. Thus, 36% of the population with enamel values above 0.7092 appear to be immigrants.

(2) Strontium isotope ratios in plants in the north area (= the northern coast of Mikawa Bay) are significantly higher than those around the Yoshigo shell mound, and conform well to tooth enamel $^{87}Sr/^{86}Sr$ ratios found among immigrants. The north area is presumably the geographical origin of immigrants.

(3) The most influential hypothesis on the significance of ritual tooth ablation types is that of Harunari (1979), who regarded type 4I individuals as locals and type 2C individuals as immigrants. The present study does not support this hypothesis because both type 2C and type 4I individuals include immigrants.

(4) The mean $^{87}Sr/^{86}Sr$ ratios in tooth enamel of type 2C individuals in the Yoshigo population are significantly higher than those of type 4I individuals, which suggests that type 2C individuals include many immigrants compared with type 4I individuals.

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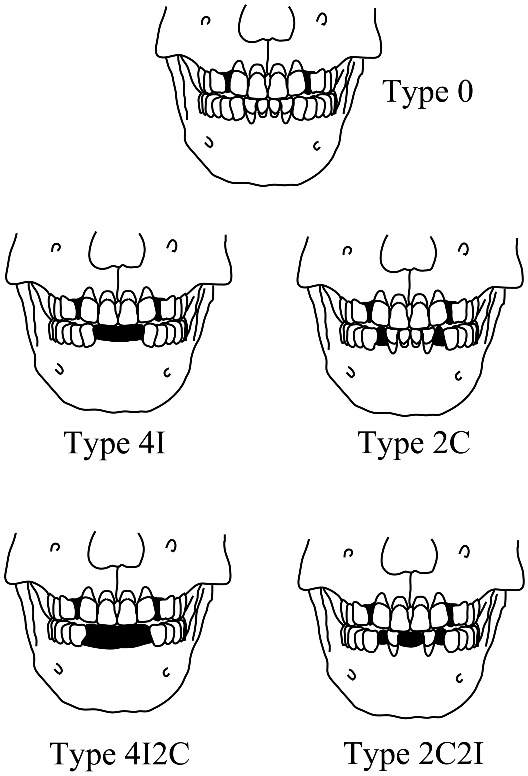

Figure 1: Types of ritual tooth ablation based on Harunari (1979).

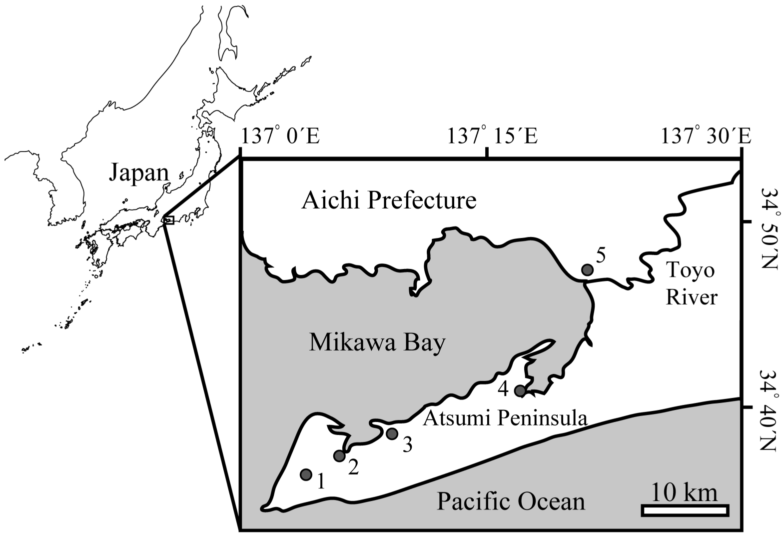

Figure 2: Plan map of study area in Aichi Prefecture, Japan, showing the location of the Yoshigo shell mound in the Late-Final Jomon period and other contemporary shell mounds discussed in the text. Numbered gray circles are locations of the shell mounds: 1, Kawaji; 2, Hobi; 3, Ikawazu; 4, Yoshigo; 5, Inariyama.

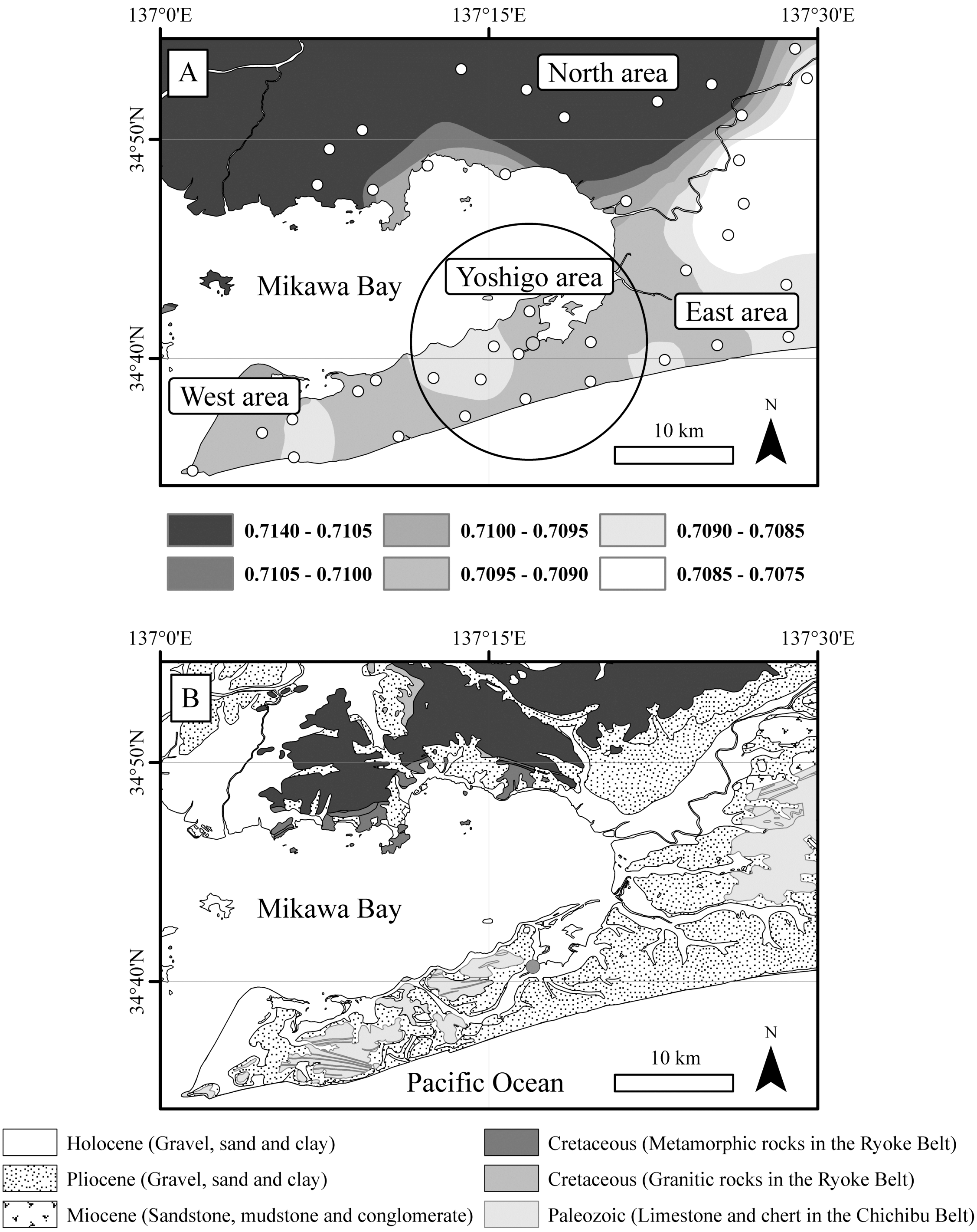

Figure 3: (A) Map of geographic distribution of Sr isotope ratios in plants in study area surrounding Mikawa Bay. Graphic representation is based on ArcGIS (ESRI, Inc.) software through the calculation method of kriging. Open circles are the locations where plant samples were collected. The gray circle is the location of the Yoshigo shell mound. (B) The geological map of the study area was modified from the 1:200,000 geological map "Toyohashi and Irago Misaki" (Makimoto et al., 2004).

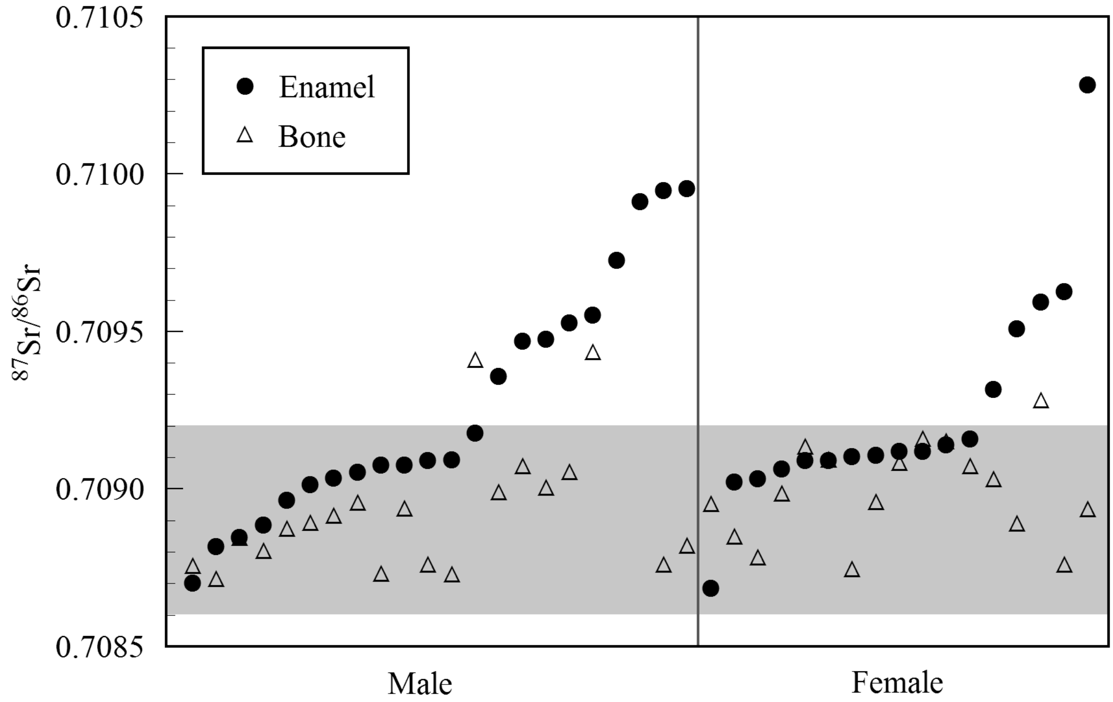

Figure 4: Strontium isotope ratios in human tooth enamel and bone of the Yoshigo skeletal remains. A pair of the $^{87}Sr/^{86}Sr$ ratios of tooth enamel and bone on the same transverse axis is generated from the same individual, and these individuals are categorized by sex. The gray horizontal bar indicates the local $^{87}Sr/^{86}Sr$ range of 0.7086–0.7092.

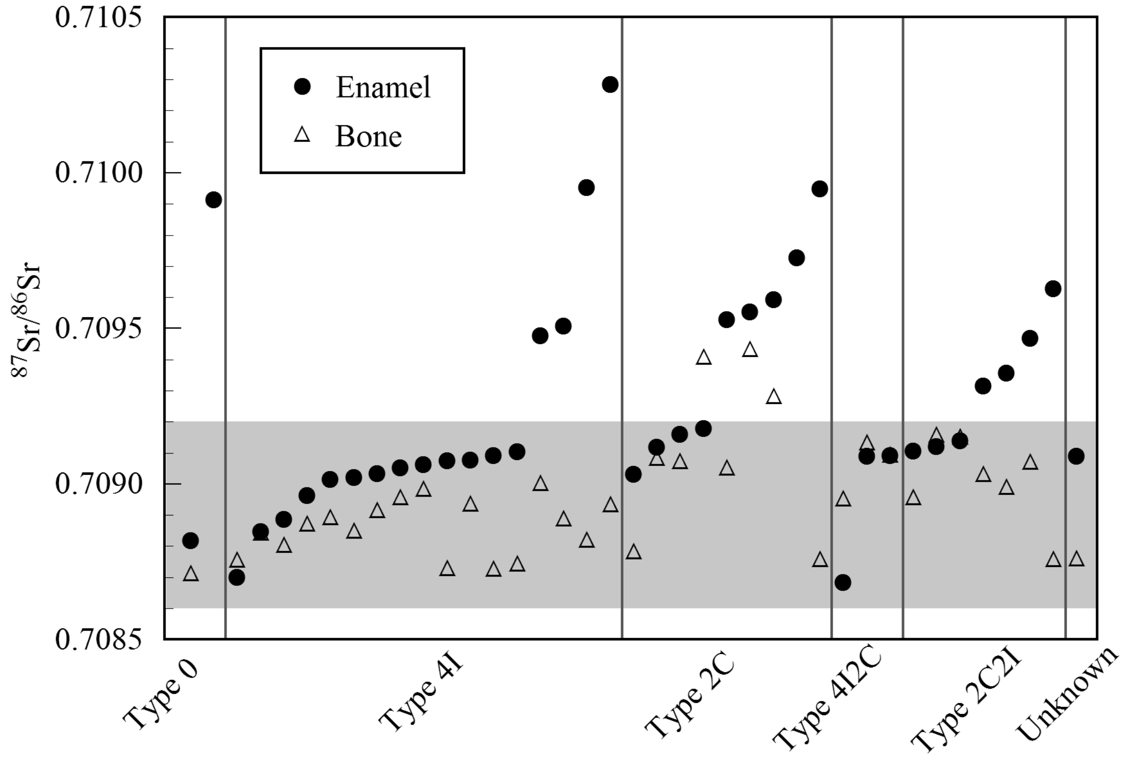

Figure 5: Strontium isotope ratios in human tooth enamel and bone of the Yoshigo skeletal remains categorized by ritual tooth ablation types.

Table 1. Cultural history of Jomon period.

Period	Uncalibrated BP	General description	Mortuary tradition	Ritual tooth ablation
Incipient-Initial Jomon	13000–6000	Pottery, large settlements	Flexed	Absent
Early-Middle Jomon	6000–4000	Increasing population, large shell mounds	Flexed, extended	Upper lateral incisors
Late-Final Jomon	4000–2300	Decreasing population, ritual artifacts	Flexed, extended, second burial, offerings	Canines, incisors

Table 2. Difference in mean Sr isotope ratios in plants among four regions in the study area and results of Student's *t*-test (unpaired data with unequal variance).

	West area	East area	North area
Yoshigo area	0.00030	–0.00048	0.00234*
	P=0.8297	*P*=0.1483	*P*=0.0009
West area		–0.00051	0.00231*
		P=0.1156	*P*=0.0010
East area			0.00281*
			P=0.0002

*$P<0.01$

Table 3. Number and proportion of immigrants in the Yoshigo skeletal remains categorized by selected archaeological characteristics.

Characters		Total	Locals	Immigrants (%)
All samples		39	25	14 (36)
Sex				
	Male	22	13	9 (41)
	Female	17	12	5 (29)
Ritual tooth ablation				
	Type 0	2	1	1 (50)
	Type 4I	17	13	4 (24)
	Type 2C	9	4	5 (56)
	Type 4I2C	3	3	0 (0)
	Type 2C2I	7	3	4 (57)
	Unknown	1	1	0 (0)
Offerings				
	Present	9	4	5 (56)
	Absent	30	21	9 (30)

Appendix 1. Results of radiocarbon dating.

Radiocarbon ages of three randomly selected Yoshigo human skeletons were measured by accelerator mass spectrometer at National Institute for Environmental Studies (Yoneda et al., 2004). Extraction of bone collagen and purification of graphite were carried out at RIHN following the methods of Kusaka et al. (2008) and Hyodo et al. (2008), respectively. The results of carbon isotope measurements of the bone collagen have already been described by Kusaka et al. (2008).

In order to properly estimate radiocarbon ages of human skeletons, the marine reservoir effect needs to be calibrated. The percentage of marine food of the human bone collagen (Marine %) was estimated using a linear mixing of $\delta^{13}C$ values between –21.0‰ and –12.5‰, which are the representative values for pure terrestrial (C3) and pure marine consumers, respectively (Yoneda et al., 2005). Calibrated ^{14}C ages were calculated from conventional ^{14}C ages by the Calib program version 5.0 (Stuiver and Reimer, 1993). A calibration curve mixing the atmospheric (INTCAL04; Reimer et al., 2004) and the marine datasets (MARINE04; Hughen et al., 2004) should be used for each sample, depending on the estimated percentage of marine carbon in each sample's collagen.

The results are listed in Table A1. New radiocarbon ages of Yoshigo skeletal remains are ca. 3200–2800 cal BP, essentially conforming to previous chronology of the site based on the pottery types (ca. 3500–2300 BP).

Table A1. Radiocarbon ages for Yoshigo human skeletal remains.

Lab. Code	Sample No.	Conventional radiocarbon age (BP)	C/N	$\delta^{13}C$	Marine %	2σ ranges of calibrated age (cal BP)	Probability (%)
TERRA – 080707b29	281	2900 ± 45	3.4	−19.3	20	2801–2824	1.5
						2839–3079	98
						3096–3103	0.5
TERRA – 080707b15	295	2770 ± 50	3.3	−16.6	52	2838–3163	100
TERRA – 080707b30	341	3190 ± 40	3.3	−13.5	88	2909–3193	100

Appendix 2. Characters and $^{87}Sr/^{86}Sr$ data of Yoshigo human skeletal remains.

Sample No.	Sex	Age at death	Tooth ablation type	Offering[a]	$^{87}Sr/^{86}Sr$ in enamel	$^{87}Sr/^{86}Sr$ in bone	Local vs. immigrant
273	male	young adult	4I	–	0.708958	0.708868	local
280	male	adolescent	4I	–	0.709047	0.708951	local
287	female	middle adult	2C2I	–	0.709311	0.709026	immigrant
292	male	young adult	Unknown	–	0.709085	0.708755	local
302	female	young adult	2C	–	0.709114	0.709078	local
310	female	young adult	2C2I	–	0.709135	0.709146	local
316	male	young adult	2C	–	0.709548	0.709429	immigrant
322	female	young adult	4I2C	–	0.709086	0.709088	local
333	male	young adult	2C	–	0.709722	–	immigrant
335	female	adolescent	2C2I	–	0.709115	0.709153	local
341	male	adolescent	0	–	0.709908	–	immigrant
342	female	middle adult	4I	–	0.709017	0.708844	local
345	male	middle adult	4I	H	0.708696	0.708750	local
349	male	young adult	4I	–	0.709471	0.708998	immigrant
352	female	adolescent	4I	H	0.709058	0.708979	local
357	female	middle adult	2C	–	0.709154	0.709067	local
363	male	middle adult	2C	H	0.709523	0.709048	immigrant
366	male	middle adult	4I	H	0.709948	0.708815	immigrant
375	male	young adult	4I	H	0.709029	0.708910	local
383	male	middle adult	2C	H, E	0.709943	0.708753	immigrant
386	male	young adult	4I	–	0.709071	0.708932	local
388	male	young adult	4I	–	0.709009	0.708887	local
396	male	young adult	4I	–	0.709070	0.708724	local
404	female	adolescent	2C	–	0.709027	0.708777	local
408	female	adult	4I	–	0.710279	0.708930	immigrant
419	male	young adult	2C2I	H	0.709352	0.708984	immigrant
435	male	young adult	2C	–	0.709173	0.709404	local
436	male	young adult	2C2I	–	0.709464	0.709066	immigrant
460	female	young adult	2C2I	–	0.709622	0.708753	immigrant
461	male	middle adult	0	–	0.708813	0.708708	local
481	male	middle adult	4I	–	0.709087	0.708723	local
488	female	middle adult	4I	–	0.709503	0.708884	immigrant
500	female	middle adult	2C	E	0.709588	0.709276	immigrant
509	male	middle adult	4I	H	0.708881	0.708798	local
522	female	young adult	4I	–	0.709098	0.708739	local
523	female	young adult	4I2C	–	0.709085	0.709128	local
534	male	middle adult	4I	–	0.708842	0.708838	local
540	female	middle adult	4I2C	–	0.708679	0.708947	local
541	female	young adult	2C2I	–	0.709102	0.708952	local

[a] H—hip accessory; E—earring.

Appendix 3. Strontium isotope ratios in plant samples.

Sample No.	Common name	Specific name	$^{87}Sr/^{86}Sr$	Latitude	Longitude	Region[a]
AP1	Kakuremino	*Dendropanax trifidus*	0.709002	34.6703	137.2724	Y
AP2	Chinese hackberry	*Celtis sinensis*	0.709284	34.6783	137.2834	Y
AP3	Inugashi	*Neolitsea aciculata*	0.709158	34.7027	137.2808	Y
AP4	Japanese mallotus	*Mallotus japonicus*	0.708967	34.6761	137.2537	Y
AP5	Isunoki	*Distylium racemosum*	0.708227	34.6510	137.2438	Y
AP6	Horutonoki	*Elaeocarpus sylvestris*	0.708857	34.6521	137.2078	Y
AP7	Isunoki	*Distylium racemosum*	0.709310	34.6502	137.1640	W
AP8	Tabunoki	*Machilus thunbergii*	0.709099	34.6419	137.1505	W
AP9	Japanese knotweed	*Polygonum cuspidatum*	0.708849	34.6205	137.1005	W
AP10	Japanese mallotus	*Mallotus japonicus*	0.709311	34.6103	137.0775	W
AP11	Japanese cheesewood	*Pittosporum Tobira*	0.709038	34.5780	137.0246	W
AP12	Inugashi	*Neolitsea aciculata*	0.708882	34.5916	137.1017	W
AP13	Tabunoki	*Machilus thunbergii*	0.709179	34.6075	137.1813	W
AP14	Round leaf holly	*Ilex rotunda*	0.709559	34.6229	137.2319	Y
AP15	Kuroki	*Symplocos kuroki*	0.709451	34.6360	137.2777	Y
AP16	Tabunoki	*Machilus thunbergii*	0.709147	34.6493	137.3270	Y
AP17	Tabunoki	*Machilus thunbergii*	0.709004	34.6793	137.3273	Y
AP18	Chinese hackberry	*Celtis sinensis*	0.708843	34.6659	137.3837	E
AP19	Kakuremino	*Dendropanax trifidus*	0.709216	34.6770	137.4237	E
AP20	Kakuremino	*Dendropanax trifidus*	0.708790	34.6833	137.4776	E
AP21	Japanese mallotus	*Mallotus japonicus*	0.709118	34.7229	137.4761	E
AP22	Chinese hackberry	*Celtis sinensis*	0.709260	34.7339	137.3999	E
AP23	Chinese hackberry	*Celtis sinensis*	0.707303	34.7606	137.4319	E
AP24	Chinese hackberry	*Celtis sinensis*	0.708515	34.7846	137.4437	E
AP25	Japanese mallotus	*Mallotus japonicus*	0.707000	34.8176	137.4401	E
AP26	Chinese hackberry	*Celtis sinensis*	0.709845	34.8517	137.4422	E
AP27	Chinese hackberry	*Celtis sinensis*	0.708000	34.8800	137.4917	E
AP28	Japanese mallotus	*Mallotus japonicus*	0.709260	34.9023	137.4827	N
AP29	Chinese hackberry	*Celtis sinensis*	0.713235	34.8753	137.4193	N
AP30	Chinese hackberry	*Celtis sinensis*	0.712677	34.8621	137.3781	N
AP31	Japanese mallotus	*Mallotus japonicus*	0.713539	34.8503	137.3074	N
AP32	Chinese hackberry	*Celtis sinensis*	0.714209	34.8714	137.2787	N
AP33	Chinese hackberry	*Celtis sinensis*	0.710465	34.8869	137.2289	N
AP34	Japanese mallotus	*Mallotus japonicus*	0.712506	34.8406	137.1536	N
AP35	Japanese knotweed	*Polygonum cuspidatum*	0.710829	34.8261	137.1286	N
AP36	Japanese mallotus	*Mallotus japonicus*	0.713536	34.7988	137.1196	N
AP37	Tabunoki	*Machilus thunbergii*	0.709769	34.7952	137.1618	N
AP38	Japanese mallotus	*Mallotus japonicus*	0.709732	34.8136	137.2032	N
AP39	Tabunoki	*Machilus thunbergii*	0.708805	34.8070	137.2625	N
AP40	Chinese hackberry	*Celtis sinensis*	0.709679	34.7865	137.3541	N

[a] Y, Yoshigo area; W, west area; E, east area; N, north area.