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ORIGINAL ARTICLE

Motonari Ohyama · Megumi Ohwada · Mitsuo Suzuki

Chronology development of Hiba arbor-vitae (*Thujopsis dolabrata* var. *hondae*) and dating of timbers from an old building

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Abstract Two site chronologies of the ring widths of Hiba arbor-vitae (*Thujopsis dolabrata* var. *hondae*) were developed for the northern-most part of Honshu Island, Japan (AOTK: 1715–2001, AOSO: 1753–2000). These are highly coherent, satisfactorily indicating high values of expressed population signal and mean correlation between trees. The two series were merged into a single composite chronology, spanning a period of 287 years from 1715 to 2001, because they correlated significantly with each other. The developed chronology is the first quality-controlled tree-ring chronology for this region extending back to the eighteenth century. Using the master chronologies, we successfully crossdated three historical timbers from an old building near the sampling sites. The tree-ring dates strongly supported the documented construction date of the building. It is revealed that Hiba arbor-vitae has sufficient potential to contribute to future dendrochronological study in this region by extending the chronologies back into the past.

Key words Dendrochronology · Chronology development · Hiba arbor-vitae · Tree-ring dating · Construction date

Introduction

Dendrochronology is a discipline which uses growth rings of trees for determining calendar years of antique wood. The method has been widely applied in archaeology, paleoclimatology, and other historical sciences.[1] Much remarkable research has been carried out so far, especially in Europe and North America. However, in spite of the recent increase in the number of works in dendrochronology in Japan,[2–6] tree-ring chronologies have been published very sparsely. Above all, in the Tohoku district, the northern-most part of Honshu (the main island of Japan), such studies have been less often achieved,[7,8] although there are several promising, long-lived tree species such as *Fagus crenata*,[9] *Cryptomeria japonica*, and *Abies firma*. It is important to improve the coverage of long-term tree-ring records in this region.

Thujopsis dolabrata Sieb. et Zucc. var. *hondae* Makino (Hiba arbor-vitae) is a member of the family Cupressaceae and is one of the most important tree species in the forestry of Japan because of its high durability to chemical and biological degradation and its fine-grained wood. The species is naturally distributed across northern Japan from the northern-most parts of the Kanto district (south of the Tohoku district) to the Oshima Peninsula of Hokkaido Island.[10] Natural forests dominated by Hiba arbor-vitae are located on the Tsugaru and the Shimokita Peninsulas in Aomori Prefecture (Fig. 1). Mature adults of this species can reach heights of 30 m and often live for more than 300 years.

Because Hiba arbor-vitae has long been the most important wood resource in this region, we have the possibility to obtain tree-ring samples from not only mature living trees but also from many archaeological wooden remains of this species.[11,12] In fact, several archaeological reports referring to wooden remains of Hiba arbor-vitae have been published and the time span of the archaeological sites roughly covers the last millennium.[11,12] Additionally, buried forests of Hiba arbor-vitae are often found in this region. For example, wood samples of Hiba arbor-vitae from the Sarugamori buried forest showed radiocarbon dates of up to 2600 cal BP (before present).[13] Thus, Hiba arbor-vitae should have potential for building a millennium-scale chronology that would greatly contribute to dendrochronology (*sensu lato*), although dendrochronological investigations on Hiba arbor-vitae have been relatively few. Earlier works implied good synchronization of the ring-width series between trees and even between sites for this species in northern Tohoku.[7,8]

This article examines the dendrochronological potential of Hiba arbor-vitae by developing ring-width chronologies in the Tohoku district. A number of antique timbers from an old building were dated to examine the ability of the constructed chronologies to date archaeological samples.

M. Ohyama (✉) · M. Ohwada · M. Suzuki
Botanical Gardens, Tohoku University, Sendai 980-0862, Japan
Tel. +81-22-795-6761; Fax +81-22-795-6788
e-mail: motonari@mail.tains.tohoku.ac.jp

Materials and methods

Living tree samples

Living tree samples of Hiba arbor-vitae were taken from two mature natural stands in Aomori Prefecture. One site is located on the Tsugaru Peninsula (AOTK), the other on the Shimokita Peninsula (AOSO) (Fig. 1). Ten transversal disks were sampled from each site at heights of 50–100 cm of the stems in the summers of 2002 (for AOTK) and 2001 (for AOSO). The altitude of the sites ranges from 100 to 400 m asl (Table 1). These two sites are situated in a cool-temperate zone, where annual mean temperature and annual total precipitation from 1971 to 2002 are 10.1°C and 1290 mm, respectively, as reported by the Aomori meteorological station, which is the nearest to the forest sites. Most of the precipitation during winter is due to snowfall.

Chronology development

We observed that false rings and extremely narrow rings frequently occurred in the samples. In order to avoid errors in identifying and counting the annual rings, we employed soft X-ray densitometry.[14] This method enabled us to identify annual ring boundaries more precisely, because we could recognize them not only by changes in color between earlywood and latewood but also by profiles of the density curves (peculiar density fluctuations from one ring to another).

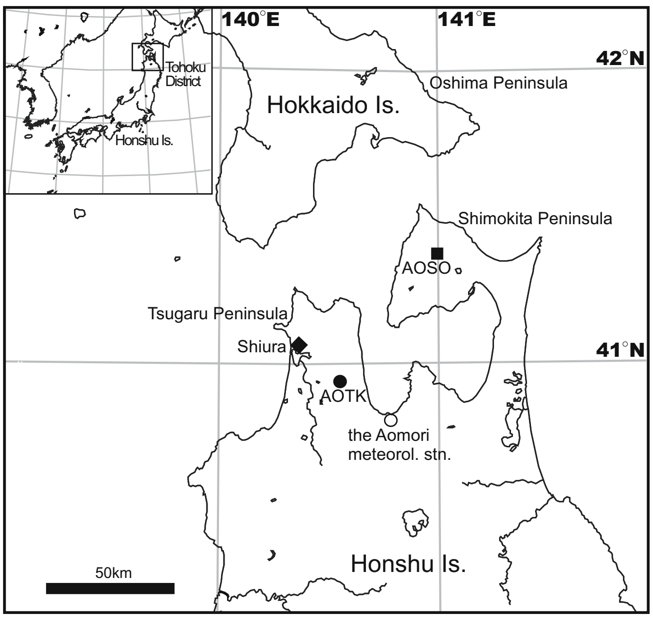


Fig. 1. Locations of the sampling sites. AOTK, *black circle*; AOSO, *black square*; Shiura, *black diamond*; Aomori meteorological station, *white circle*

Four to six radii per disk were prepared for densitometric analysis. These were cut transversely into 1.2-mm-thick strips. After moisture control of the strips, X-ray negatives were taken in an air-conditioned room (20°C, 60% relative humidity), where the strips were irradiated at 18 kV and 14 mA for 4 min. The distance between the X-ray source and the film was 2.4 m. The negatives were scanned to obtain density profiles using Dendro 2003 (Walesch Electronic) and ring widths were measured with an accuracy of 0.01 mm.

The raw ring-width series were then crossdated visually and statistically using the programs COFECHA[15] and PAST4[16] (SCIEM) to check possible measurement errors. The former is a quality-control program used to check the crossdating and the latter is a program used for visual and statistical cross-matching. Flagged 50-year segments suggested by the program COFECHA were visually checked against the strips, the X-ray negatives, and the densitometric diagrams until all tree-ring boundaries were consistently confirmed.

Standardized chronologies were obtained using the program ARSTAN.[17] The ring-width measurements were standardized by fitting cubic smoothing splines[18] to remove the long-term growth trend, possibly reflected by aging, root-hold, and stand dynamics (e.g., suppression and release). In order to select the most appropriate fitting curves and thus maximize the common signals contained in the resulting chronologies, we examined different stiffness of the smoothing splines by changing the 50% frequency cutoff at 10, 20, 40, 80, and 120 years. The shorter the spline filter length, the greater the spline curve flexibility; as a result, the more flexible the spline curve, the greater the range of low-frequency signals that were eliminated. We assessed the effect of the spline filter length in removing noise using the mean correlation coefficient among radii calculated for the common interval of 1860–1999.

After the tree-ring series were standardized, the chronology for each site was calculated using a biweight robust mean.[19] We analyzed mean correlation within trees and mean correlation between trees for the common interval of 1860–1999. The two site chronologies were crossmatched by calculating *t*-values using the program PAST4 (SCIEM).

Crossdating of historical timbers

The office building of the old Shiura Regional Forest Office was located at Shiura on the Tsugaru Peninsula (Fig. 1). The construction date of the building was documented to be

Table 1. Summary of the sites and the samples used in the study

Site	Latitude	Longitude	Altitude (m asl)	Span	No. of trees	No. of radii
AOSO	140° 59′ E	41° 23′ N	180–400	1753–2000	10	46
AOTK	140° 32′ E	40° 56′ N	100–400	1715–2001	10	44

AOSO, Shimokita Peninsula, Aomori Prefecture; AOTK, Tsugaru Peninsula, Aomori Prefecture

November of 1933.[20] The building was demolished in March of 2003 due to the structural reform of the national forest services in the Tohoku district. We collected ten beams from the building. The timbers were cut with a chain saw and the transverse surfaces were finished with a retractable knife along the radii. Although no abrupt release and depression were observed for all the samples, they contained juvenile wood with or without the pith. Because their ring widths were generally greater than those of living tree samples, we could easily identify tree-ring boundaries. The ring widths were measured with an accuracy of 0.01 mm. In addition, we investigated the outermost rings of the samples to estimate felling dates and seasons.

A standard practice of dendroarchaeological dating was employed.[21–23] Crossdating was undertaken in order to determine the dates of the historical samples using the reference chronology. In this study, standardization was performed using a 10-year cubic smoothing spline. The lag correlations between a reference chronology and a sample were computed for the standardized series. The correlation coefficients were transferred to Student's *t*-values. Candidates of tree-ring dates were suggested by *t*-values higher than 3.5. The *t*-value of 3.5 is an arbitrary criterion proposed by Baillie[22] for oaks in Europe and widely used with other tree species. For all historical samples that were crossdatable, this statistical process greatly assisted the subsequent visual crossdating by reducing the number of possible tree-ring dates. The tree-ring dates of the historical samples were finally determined among the candidates by finding the best visual matches between a reference and a sample. The visual crossdating was carried out using a raw ring-width curve of the samples, compared with a reference (the so-called mean curve) plotted on a semilogarithmic graph. The processes mentioned above were performed on the program PAST4 (SCIEM).

Results and discussion

Crossdating and standardization of living samples

We measured 44 radii from ten trees of AOTK and 46 radii from ten trees of AOSO. As is usual, crossdating was difficult for the parts of the cross sections in which false rings, extremely narrow rings, and, in a few cases, missing rings were detected in some radii. However, careful and repeated checks of tree-ring boundaries eventually allowed us to successfully crossdate all the radii. It is well known that growth irregularities such as missing rings in a stem occur more frequently at the trunk base than at breast height.[24] Frequent occurrences of false and extremely narrow rings would be partly due to sampling at the lower sampling height of 50–100 cm.

Raw ring-width series mostly show low-frequency variability (interdecadal or higher in time domain) that is not synchronized with those in other individual series. Such low-frequency variations of each tree-ring series are usually radii-specific, as shown in Fig. 2. Hiba arbor-vitae grows in closed canopy forests and is subject to competitive pressures over its life span. Therefore, growth suppression or release may happen in any time period for an individual tree. Additionally, it is likely that the low-frequency variability in raw ring-width series is a consequence of anomalous radial growths by roothold. These facts indicate that the low-frequency variability is usually radius-specific and/or tree-specific, indicative of competition or growth peculiarity rather than variable climate changes, while climatic signals would be mainly expressed in high-frequency (annual to interannual) variability.

For the reasons mentioned above, we can expect that a more flexible spline curve, which eliminates low frequency variations, is most appropriate for standardizing raw ring-width series of Hiba arbor-vitae. Table 2 shows the mean correlation coefficients between trees of standardized series by fitting smoothing splines of different stiffness (50% frequency cutoff at 10, 20, 40, 80, and 120 years) for the interval of 1860–1999. It is apparent in the result that the mean correlation between trees is higher with a shorter spline filter length. The highest values are 0.256 for AOTK and 0.284 for AOSO in the case of fitting a spline with a 10-year filter length. Therefore, we decided to use the spline curves of 10-year filter length to detrend tree-ring series of our Hiba arbor-vitae chronologies.

Chronology development

Ring-width chronologies were developed at the two sites, AOTK and AOSO (Fig. 3). The chronologies span 1715–2001 (287 years) for AOTK and 1753–2000 (248 years) for AOSO. The ring-width data of the outermost ring (AOTK: 2002, AOSO: 2001) were eliminated, because their latewood was not completely formed.

The chronology statistics are presented in Table 3. Mean correlation between trees, which indicates an expression of the strength of common signals among trees, increased considerably after the standardization (Table 3). These values (0.258 for AOTK and 0.284 for AOSO) of the chronologies are similar compared with the mean correlation of other Japanese coniferous species, for example 0.24–0.27 for *Abies mariesii*,[4] 0.323–0.338 for *Cryptomeria japonica*,[25] and 0.24–0.33 for *Picea glehnii*.[2]

Expressed population signal (EPS)[26] is used to evaluate the confidence of a chronology. An EPS value greater than

Table 2. Mean correlations between trees for the standardized chronologies (AOTK and AOSO), using 50% frequency cutoff splines of different stiffness

Spline 50% frequency cutoff (years)	Mean correlation between trees	
	AOTK	AOSO
10	0.258	0.284
20	0.247	0.280
40	0.207	0.237
80	0.153	0.188
120	0.128	0.163

The correlation coefficients are calculated for the common interval of 1860–1999

Fig. 2. Raw tree-ring series of Hiba arbor-vitae (*Thujopsis dolabrata* var. *hondae*) from the Tsugaru Peninsula (AOTK01, AOTK07, and AOTK08). *Lowercase letters* of sample names indicate radii

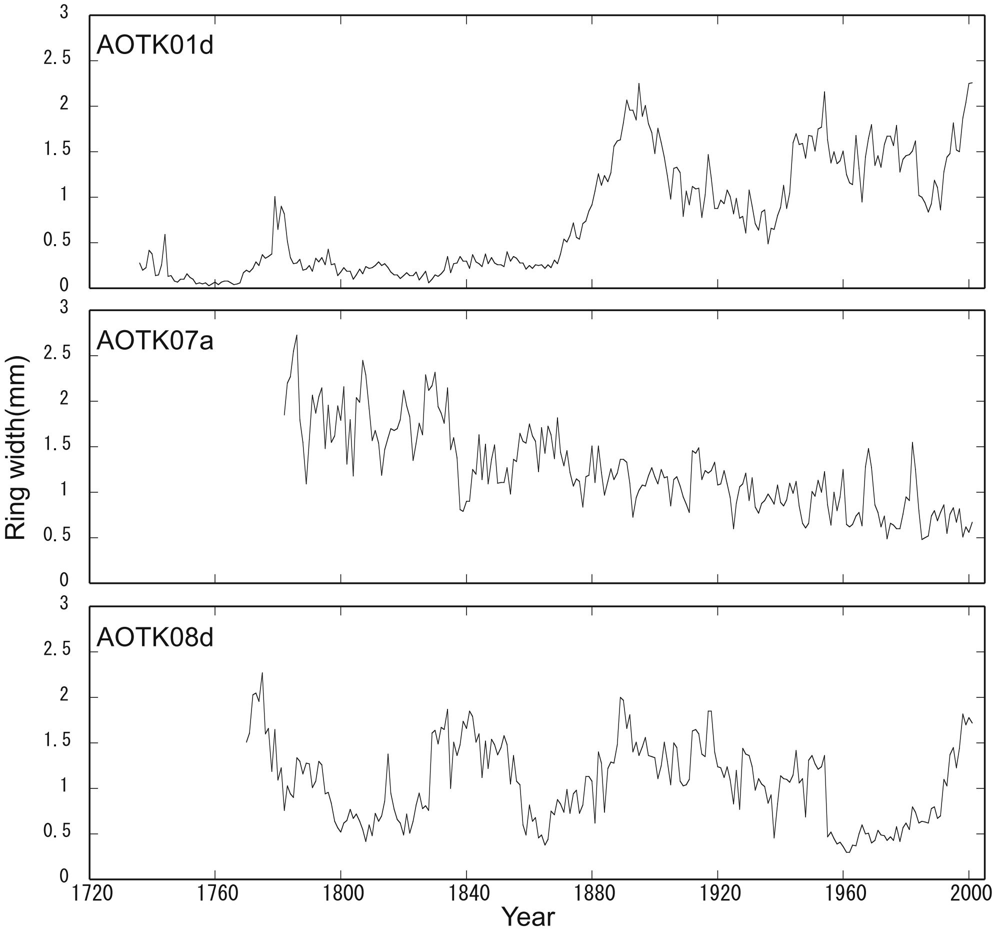
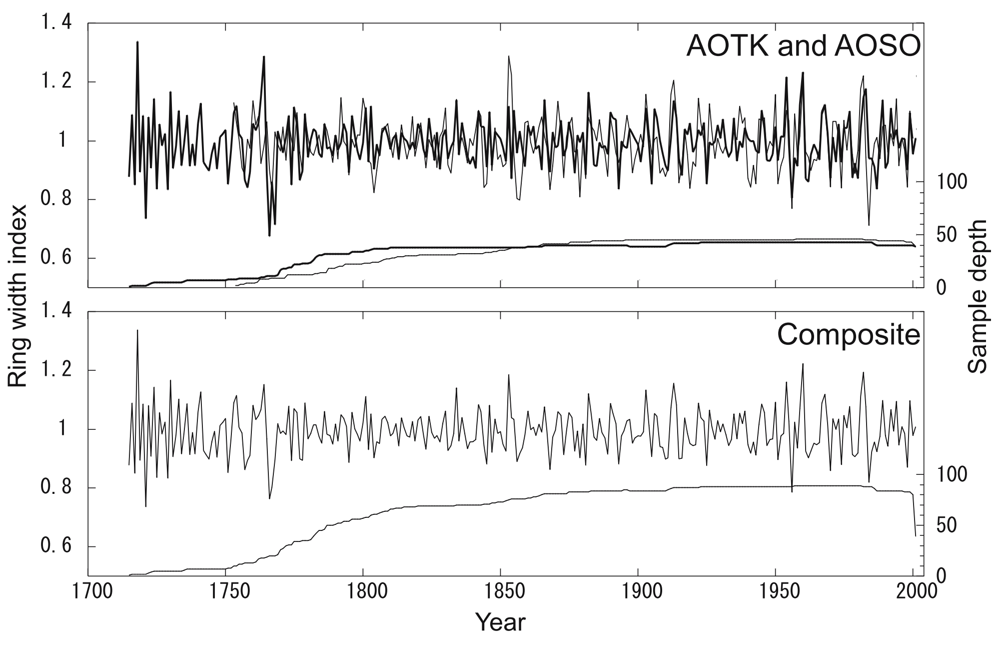


Fig. 3. Standardized ring-width chronologies of Hiba arbor-vitae (*Thujopsis dolabrata* var. *hondae*). In the upper graph, *thick lines* represent AOTK chronology and sample depth, while *thin lines* show AOSO chronology and sample depth



0.85 is considered to be a good compromise to assure the reliability of a tree-ring chronology.[26] Both of our chronologies showed high EPS values, at 0.933 for AOTK and 0.940 for AOSO. An acceptable chronology confidence based on the EPS >0.85 was achieved from A.D. 1769 onward for AOTK and from A.D. 1782 onward for AOSO.

Mean sensitivities, a measure of year-to-year variability,[27] were 0.099 for AOTK and 0.092 for AOSO. These low values are probably due both to sampling at a low height and the use of short (10-year) length of spline fits. In this standardization, the spline curves remove not only low-frequency variations but also a certain extent of higher frequency variations. A drastic decrease of the first-order autocorrelation from high values (0.849 and 0.821) in the raw series to extremely low values (–0.014 and 0.146) in the standardized series is due to the standardization by the highly flexible spline fits. The statistical characteristics mentioned above revealed that Hiba arbor-vitae has good potential for performing dendrochronological analysis.

The two site chronologies were crossdated statistically and visually. They correlate significantly with each other and demonstrate a very good visual matching (Fig. 3). The correlation coefficient between the two chronologies also shows a high value of 0.374 ($t = 6.32$) over the period 1753–2000. The good synchronization indicates that Hiba arbor-vitae growing on both peninsulas would respond to wide-area climatic changes.

The previous studies also described the regional similarity of ring-width patterns for this species growing in the northern Tohoku district.[7,8] Mitsutani[7] built six mean curves consisting of four to ten samples collected from three sites on the Tsugaru Peninsula and three sites on the Shimokita Peninsula. The t value between a site on the Tsugaru Peninsula and a site on the Shimokita Peninsula ranged from 3.5 to 8.1 and the mean was 6.3. Our result is consistent with that in Mitsutani's previous study.[7] Consequently, we conclude that the radial growths of Hiba arbor-vitae show good synchronization in the northern-most part of the Tohoku district. Further studies are necessary in order to clarify the regional extent of the synchronicity in growth and the interspecies similarity of tree-ring series.

The similarity between the two chronologies justified merging the series into a single chronology. Thus, we built a composite chronology, spanning a period of 287 years from 1715 to 2001 (Fig. 3). An acceptable reliability of the chronology based on the EPS (>0.85) was achieved from A.D. 1765 onward for this chronology. The composite chronology is considered a regional ring-width chronology of Hiba arbor-vitae for the northern-most part of the Tohoku district. This study developed the first quality-controlled and fully crossdated tree-ring chronology for the northern Tohoku district extending back to the eighteenth century.

Table 3. Statistics of the tree-ring series

	AOTK	AOSO	Composite
Measurements			
Mean (mm)	1.11	1.30	1.21
MS	0.119	0.119	0.103
$\bar{r}_{wt}$	0.619	0.593	0.607
$\bar{r}_{bt}$	0.098	0.073	0.063
AC(1)	0.849	0.821	0.834
Standardized chronologies			
No. of trees (radii)	10 (44)	10 (46)	20 (90)
Time span	1715–2001	1753–2000	1715–2001
Mean	0.994	0.992	0.992
Standard deviation	0.087	0.088	0.079
MS	0.099	0.092	0.088
$\bar{r}_{wt}$ [a]	0.503	0.542	0.522
$\bar{r}_{bt}$ [a]	0.258	0.284	0.214
AC(1)	–0.104	0.146	–0.108
EPS	0.933	0.940	0.954

MS, Mean sensitivity; SD, standard deviation; $\bar{r}_{wt}$, mean correlation within tree; $\bar{r}_{bt}$, mean correlation between trees; AC(1), first-order autocorrelation; EPS, expressed population signal

[a] Calculated for the common interval of 1860–1999

Crossdating of the historical timbers

We measured the ring widths of ten historical timbers (AOSE) from the office building of the old Shiura Regional Forest Office located at Shiura on the Tsugaru Peninsula (Fig. 1). The numbers of annual rings ranged from 75 to 180 for the samples. Five samples had waney edges, showing curved cambial surfaces underneath the bark. Three samples were successfully crossdated with the AOTK and the composite chronologies (Table 4). For all dated samples, only a single candidate year was detected, even by statistical crossdating, in which a t-value was sufficiently higher than 5. A final decision of the tree-ring dates was made by visual crossdating. Good visual matches were demonstrated between the reference and the sample series, as shown in Fig. 4.

Table 4. List of the samples from the office building of the old Shiura Regional Forest Office and the results of tree-ring dating

Reference chronology			Waney edge	AOTK				AOSO				Composite			
Sample no.	NR	ARW (mm)		Period	Overlap	t-value	r	Period	Overlap	t value	r	Period	Overlap	t-value	r
AOSE05	75	3.62	LW	–	–	–	–	–	–	–	–	–	–	–	–
AOSE08	126	1.08	–	1776–1901	126	5.40	0.405	–	–	–	–	–	–	–	–
AOSE10	180	0.90	C	1752–1931	180	6.29	0.397	–	–	–	–	1752–1931	180	5.07	0.337
AOSE12	109	1.44	–	–	–	–	–	–	–	–	–	–	–	–	–
AOSE14	84	2.03	LW	–	–	–	–	–	–	–	–	–	–	–	–
AOSE15	174	1.27	EW	–	–	–	–	–	–	–	–	–	–	–	–
AOSE16	108	1.31	LW	1825–1932	108	6.33	0.476	–	–	–	–	1825–1932	108	5.02	0.407
AOSE17	91	3.56	–	–	–	–	–	–	–	–	–	–	–	–	–
AOSE19	94	1.72	EW	–	–	–	–	–	–	–	–	–	–	–	–
AOSE20	94	1.86	–	–	–	–	–	–	–	–	–	–	–	–	–

Three chronologies are used for reference chronologies

NR, Number of tree rings; ARW, average ring width; r, correlation coefficient; EW, waney edge with an incomplete earlywood; LW, waney edge with an incomplete latewood; C, waney edge with a complete ring

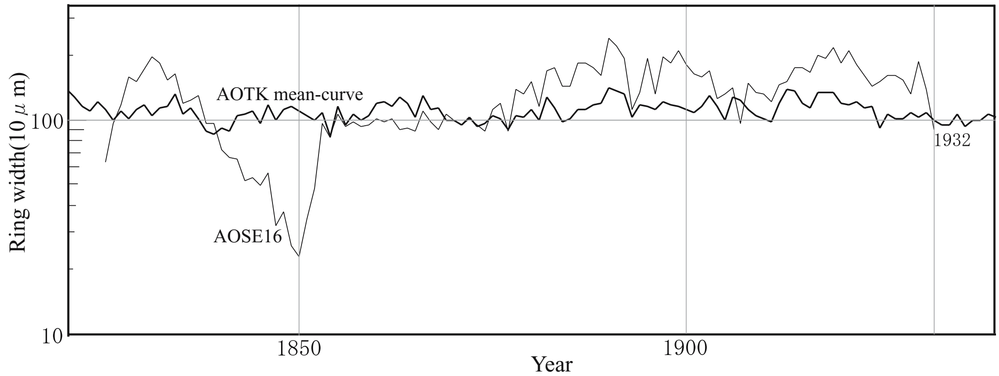


Fig. 4. Comparison of the tree-ring pattern of AOSE16 with the AOTK mean-curve chronology. A visual matching was performed by comparing an undated series with a mean-curve chronology on the program PAST4

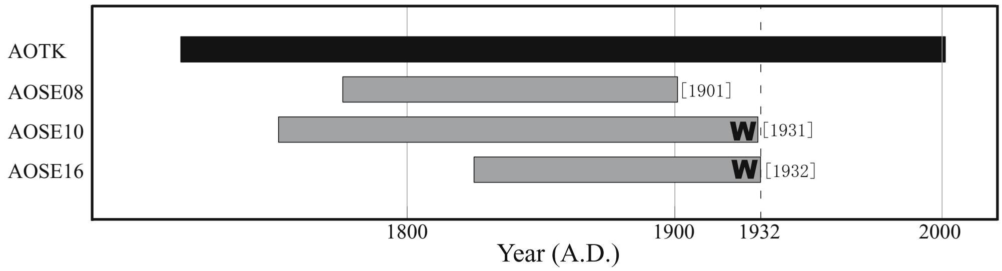


Fig. 5. Bar diagram showing all dated samples from the office building of the old Shiura Regional Forest Office. *Black bar,* AOTK chronology; *gray bars*, samples. AOSE10 and 16 have sapwood rings and waney edges (*W*)

The dates of the outermost rings are 1901 for AOSE08, 1931 for AOSE10, and 1932 for AOSE16 (Table 4, Fig. 5). We estimate that AOSE10 was cut down in the winter or early spring of 1931/1932, because a complete terminal ring was observed. AOSE16 was cut down in the late summer or fall of 1932, showing a terminal ring with incomplete latewood. The estimation of the felling date for AOSE08 was not possible, because the outer rings were scraped and the sapwood was not distinguished from the heartwood. These tree-ring dates strongly support the documented construction date (November of 1933) for the office building of the old Shiura Regional Forest Office.[20] It is important and should be noted that in this study an independent, critical check was successfully made on the correctness of the description of the construction dates in the historical document. It is highly likely that the Hiba arbor-vitae trees were cut down in 1931–1932 and used to construct the building after seasoning.

Seven timbers out of the ten did not show good matches both statistically and visually, with any of the references. It is known that ring-width patterns of an inner part of xylem containing juvenile wood show poorer agreement than those of the outer part of xylem.[28,29] Because all the samples contain juvenile wood with or without the pith, our result would be partly attributable to irregular radial growth of juvenile wood in the samples. In fact, the numbers of tree-rings in the three dated samples are relatively greater, that is, the samples have a smaller proportion of inner xylem (Table 4). Our dating result is consistent with the previous studies.[28,29]

Finally, the three samples were crossdated successfully with the AOTK chronology, but not with the AOSO chronology. It is likely that the timbers for the office building would have been derived from a forest on the Tsugaru Peninsula, which was within the jurisdiction of the old Shiura Regional Forest Office. Successful results of crossdating only with the AOTK chronology from the Tsugaru Peninsula might imply the possibility of dendro-provenancing, which is the use of dendrochronology to estimate origins of timbers, for Hiba arbor-vitae in the northern-most part of the Tohoku district. Future efforts should concentrate on building more site chronologies and their extension using archaeological wood for this region. The ring-width data of the present study will be available on the Web site of the Botanical Gardens, Tohoku University.

Conclusions

Two tree-ring width chronologies of Hiba arbor-vitae were developed for the northern part of Japan's main island (AOTK: 1715–2001, AOSO: 1753–2000). Because these chronologies were highly correlated with each other, a composite chronology was also built using the two site chronologies. These chronologies demonstrated high reliability by indicating significantly high chronology statistics. These are the first quality-controlled tree-ring chronologies in this region. Moreover, we successfully crossdated historical timbers from an old building with the chronologies; the tree-ring dates strongly supported the documented construction date of the building. To conclude, Hiba arbor-vitae has good potential for performing dendrochronological analysis; the tree-ring growth of this species shows good synchronization in the northern-most part of the Tohoku district; and the constructed chronologies have sufficient ability to date historical samples.

Further studies on developing more site chronologies and their extensions are necessary in order to date archaeological samples in this region and to clarify the regional extent of the synchronicity in tree-ring growth.

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