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ORIGINAL ARTICLE

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The effect of bark decortication for *hiwada* production on xylem and phloem formation in *Chamaecyparis obtusa*

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Abstract Of all plant materials used to cover the roofs of traditional Japanese buildings, Japanese cypress (*Chamaecyparis obtusa*) bark, *hiwada*, has the longest service life and has been used from ancient times. However, wood and bark properties after *hiwada* harvest have not been evaluated in detail. We studied whether decortication for *hiwada* production in winter affected xylem and phloem formation. Decorticated trees still preserved all inner bark and part of the outer bark, and both decorticated and control trees had similar annual ring structures at all stem heights in the xylem and phloem. In both xylem and inner bark, no significant difference in ring width at any stem height was found between annual rings before and after decortication. Thus, this study revealed that the decortication of bark for *hiwada* production does not affect the formation of xylem and the inner and outer bark if decortication is carried out by highly skilled workers in winter.

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Introduction

In Japan, many plant materials for roofing (e.g., split boards of *Cryptomeria japonica*, *Chamaecyparis pisifera*, the bark of *C. japonica*, and some thatches) have been used since ancient times. Among these plant materials, Japanese cypress (*Chamaecyparis obtusa* Endl.) bark shingles, *hiwada*, have the longest service life (more than 50 years) and have been used on many historic buildings.[1]

The highly skilled workers who harvest *hiwada*, called *motokawashi*, decorticate standing *C. obtusa* trees that are more than 70 years old. In general, decortication is undertaken from mid-August to the following April and is repeated every 8–10 years.[2] The decortication procedure is as follows. A wooden spatula made from *Photinia glabra* is inserted into the bark and the piece of bark is exfoliated from the stem. Subsequently, the bark is decorticated from the base to the crown by hand without removing the inner part of the bark, which is called *amakawa*. The first decorticated bark is called *arakawa* and the following decorticated bark is called *kurokawa*. *Kurokawa* has a higher quality and process yield than *arakawa*.[3]

Hiwada has been used to cover the shrines and palaces of aristocrats since the seventh century in Japan. About 700 buildings roofed with *hiwada* are designated as national treasures and nationally important cultural assets. To maintain these buildings, 3500 m^2 of *hiwada* is needed annually.[2] However, the number of *C. obtusa* trees that are more than 70 years old is decreasing. Moreover, the number of forest owners who permit *hiwada* harvest has been decreasing drastically because of the opinion that decortication for *hiwada* production might cause deterioration in growth and wood quality. Thus, a stable supply of *hiwada* to maintain traditional buildings in Japan had become a major concern.[2,4]

Despite *hiwada* being an integral material for the preservation and restoration of historic buildings as previously mentioned, the effects of decortication for *hiwada* production on the xylem or phloem have not been evaluated in detail. For example, the position of decortication in the bark or the factors that cause differences in quality between *arakawa* and *kurokawa* have not been considered. In this study, we revealed the effect of decortication for *hiwada* production on xylem and phloem formation and anatomically determined the position of decortication in the bark.

Materials and methods

As shown in Fig. 1, the materials for this study were obtained from the following experimental sites: the Kasuya Research Forest of Kyushu University (33° 38′N, 130° 31′E), the Tokuyama Experimental Station of Kyoto University (34° 04′N, 131° 50′E), the Wakayama Experimental Forest of Hokkaido University (33° 38′N, 135° 41′E), and the University Forest in Chiba of The University of Tokyo (35° 07′N, 140° 09′E). Each experimental site was established in a 69- to 88-year-old *Chamaecyparis obtusa* stand in 1998. Ten pairs of trees at each site were selected, and 10 trees were treated while others remained untreated and were used as control trees. In February 1998, the bark of trees selected as treated trees were decorticated up to a stem height of 8.2 m from the base by the *motokawashi*.

Four years after decortication, one treated tree and one control tree from each experimental site were felled. Xylem and phloem samples were collected from both the north and south sides at stem heights of 1.2 m and 9.2 m from all sample trees felled. Samples were fixed in formalin acetic acid alcohol (FAA), dehydrated with ethanol, placed in *n*-butyl glicidyl ether overnight, and embedded in the mixture of Epok 812 (Okenshoji, Tokyo, Japan), methyl nadic anhydride (Okenshoji), dodecenylsuccinic anhydride (Okenshoji), and tri-dimethyl aminomethyl phenol (Okenshoji) (31: 20: 16: 1, v/v). The resin was polymerized at 60°C for 48 h. The embedded samples were then sectioned at 15-μm thickness with a disposable steel blade (S35-L; As One, Osaka, Japan) of a sliding microtome (LS-113; Yamatokoki, Tokyo, Japan), stained with safranine aqueous solution, and mounted in Bioleit (Okenshoji). The eight annual rings from the cambium in the xylem, all annual rings from the cambium in the inner bark, and several annual rings in the outer bark were observed by light microscopy (Eclipse E600; Nikon, Tokyo, Japan). The width of each annual ring was also measured, and averages taken for the south and north sides of the same ring.

Results

Xylem

Sample trees were decorticated in February 1998 and cut down in February 2002. As a result, the first to fourth annual rings from the cambium were defined as the xylem produced after decortication, and the fifth to eighth annual rings from the cambium was the xylem produced before decortication. The mean of all annual ring widths was 1.62 mm. Table 1 shows the annual ring width in the xylem before and after decortication at each site. The averaged ring width varied with treatment, sampling site, and sampling position. No significant difference in the averaged ring width at the stem heights of 1.2 m and 9.2 m was found between the xylem before and after decortication by *t*-test and Mann-Whitney U test. Drastic change in annual ring width was not found in the tree rings after decortication (Fig. 2). At the stem heights of 1.2 m and 9.2 m in the decorticated trees, no xylem including the first annual ring

Fig. 1. Locations of the experimental sites studied

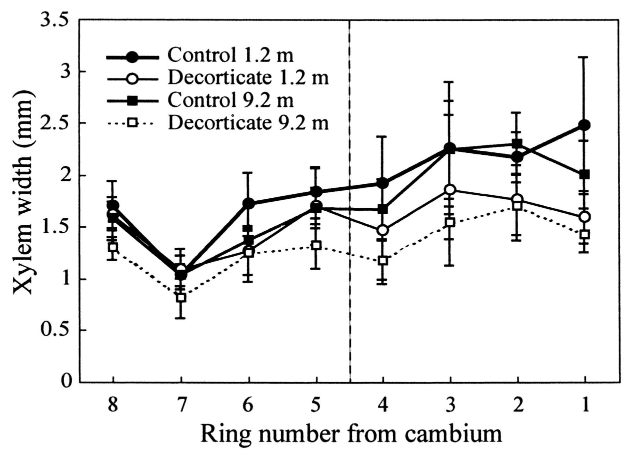

Fig. 2. Variations in annual ring width in the xylem formed before and after decortication. *Closed circles*, variation at the stem height of 1.2 m in the control tree; *open circles*, variation at the stem height of 1.2 m in the decorticated tree; *closed squares*, variation at the stem height of 9.2 m in the control tree; *open squares*, variation at the stem height of 9.2 m in the decorticated tree; *vertical dashed line*, decortication

Table 1. Xylem ring width before and after decortication

Site	Annual rings	Control (1.2 m)	Control (9.2 m)	Decorticate (1.2 m)	Decorticate (9.2 m)
Kasuya	1–4	2.96 ± 0.94	1.99 ± 0.68	0.98 ± 0.16	1.13 ± 0.43
	5–8	2.13 ± 0.95	1.33 ± 0.58	1.04 ± 0.45	0.74 ± 0.33
Tokuyama	1–4	3.13 ± 1.76	2.66 ± 0.74	2.76 ± 0.96	1.99 ± 0.52
	5–8	1.42 ± 0.58	1.48 ± 0.68	1.68 ± 0.95	1.50 ± 0.79
Wakayama	1–4	1.21 ± 0.39	1.33 ± 0.22	0.96 ± 0.41	1.43 ± 0.33
	5–8	1.31 ± 0.24	1.21 ± 0.21	1.45 ± 0.38	1.09 ± 0.15
Chiba	1–4	1.55 ± 0.56	1.90 ± 0.56	1.99 ± 0.42	1.32 ± 0.56
	5–8	1.45 ± 0.49	1.67 ± 0.45	1.51 ± 0.40	1.35 ± 0.45

Each number represents the mean ± SE of each treatment. All data given in millimeters

Table 2. Phloem ring width before and after decortication

Site	Annual rings	Control (1.2 m)	Control (9.2 m)	Decorticate (1.2 m)	Decorticate (9.2 m)
Kasuya	1–6	0.29 ± 0.04	0.32 ± 0.04	0.17 ± 0.06	0.20 ± 0.02
	7–10	0.33 ± 0.16	0.32 ± 0.11	0.24 ± 0.05	0.17 ± 0.05
Tokuyama	1–6	0.32 ± 0.06	0.39 ± 0.07	0.33 ± 0.05	0.33 ± 0.05
	7–10	0.25 ± 0.07	0.33 ± 0.09	0.24 ± 0.04	0.27 ± 0.04
Wakayama	1–6	0.14 ± 0.02	0.18 ± 0.02	0.20 ± 0.04	0.23 ± 0.03
	7–10	0.14 ± 0.04	0.18 ± 0.03	0.20 ± 0.06	0.24 ± 0.03
Chiba	1–6	0.28 ± 0.08	0.24 ± 0.04	0.25 ± 0.05	0.24 ± 0.06
	7–10	0.21 ± 0.02	0.25 ± 0.04	0.18 ± 0.03	0.18 ± 0.02

Each number represents the mean ± SE of each treatment. All data given in millimeters

formed immediately after decortication had traumatic tissue (Fig. 3a). Other than samples from Wakayama, some of the decorticated and control trees had false rings.

Phloem

Chamaecyparis obtusa has an annual ring structure consisting of sieve cells, phloem parenchyma, and phloem fiber.[5] All samples in this study had both inner bark (Fig. 3b) and outer bark (Fig. 3b), and the annual ring structure was observed clearly (Fig. 3c, d). The inner bark was distinguished from the outer bark by the presence of the innermost periderm. The outer bark of control trees had 11 to 19 annual rings and the decorticated trees had 5 to 10 annual rings at the stem height of 1.2 m (Fig. 3c). The means of annual ring numbers in control trees and decorticated trees were 14.4 and 6.9, respectively.

The inner bark of all sample trees in this study had 10 to 15 annual rings. *Chamaecyparis obtusa* has traumatic resin canals in the inner bark,[6] and the traumatic resin canal is formed in the innermost two annual rings from the cambium when the cambium is wounded.[7] We determined that the first to sixth annual rings from the cambium were the phloem formed after decortication, and the seventh or older annual rings were the phloem formed before the decortication in this study. The mean of annual ring width in the inner bark based on all samples was 0.23 mm. Table 2 shows the annual ring width in the phloem before and after decortication at each site. No significant difference in the averaged ring width at both the stem heights of 1.2 m and 9.2 m was found between the phloem before and after decortication by *t*-test and Mann-Whitney U test. No drastic change in annual ring width was found between the rings before and after decortication in all samples (Fig. 4). At the stem height of 1.2 m of decorticated tree, no significant difference was found between the relationship of phloem and xylem ring width before and after decortication by analysis of covariance. The coefficient of correlation between phloem and xylem ring width of all samples was 0.61 and was significant ($P < 0.01$).

In the fifth and sixth annual rings of the decorticated trees, no apparent structural difference (Fig. 3d) or drastic ring width change (Fig. 4) was found when compared with other annual rings. Traumatic resin canals were present in both the decorticated and control trees (Fig. 3e). However, there was no traumatic resin canal in the first annual ring from the cambium in all samples. No apparent structural difference between the decorticated and control trees was found in the outer bark (Fig. 3f) and periderm (Fig. 3f). In the periderm, the cells that contained nuclei (Fig. 3g) were oriented tangentially.

Discussion

The decortication of a standing tree has the potential to directly affect the formation of xylem. Four annual rings in the xylem were formed after decortication in this study. However, in each annual ring, the intertree variation of ring

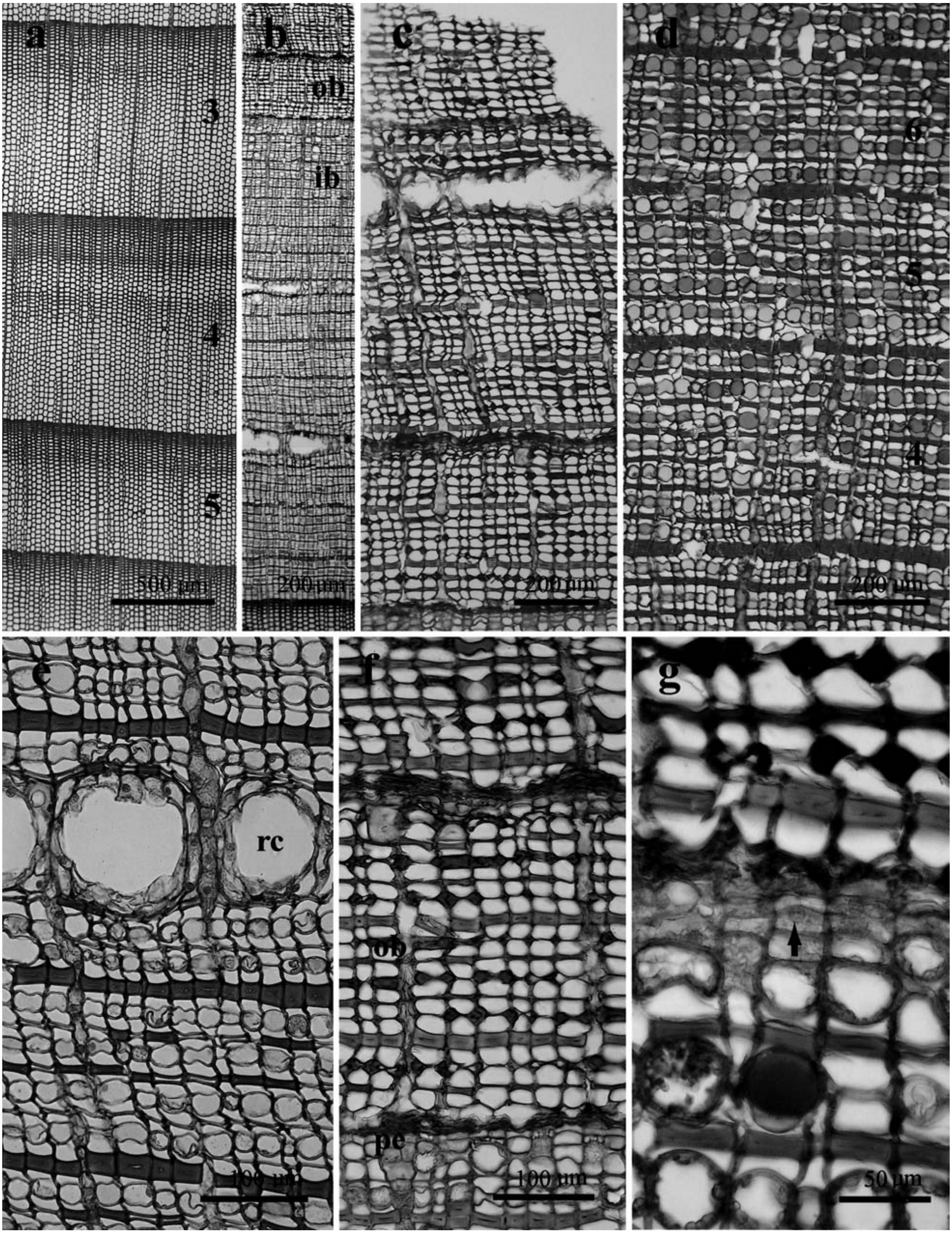

Fig. 3a–g. Transverse sections of the xylem and phloem. **a** Xylem of the third to fifth annual rings from the cambium at the stem height of 1.2 m in the decorticated tree from Wakayama. *Numbers* indicate the annual ring from the cambium. **b** Inner and outer bark at the stem height of 1.2 m in the decorticated tree from Chiba. *ob*, Outer bark; *ib*, inner bark. **c** Outer bark at the stem height of 1.2 m in the decorticated tree from Chiba. **d** Inner bark at the stem height of 1.2 m in the decorticated tree from Wakayama. *Numbers* indicate the annual ring from the cambium. **e** Resin canal (*rc*) in the inner bark at the stem height of 9.2 m in the control tree from Chiba. **f** Outer and inner bark at the stem height of 1.2 m in the decorticated tree from Chiba. *ob*, Outer bark; *pe*, periderm. **g** Periderm at the stem height of 1.2 m in the decorticated tree from Kasuya. *Arrow* indicates a cell nucleus

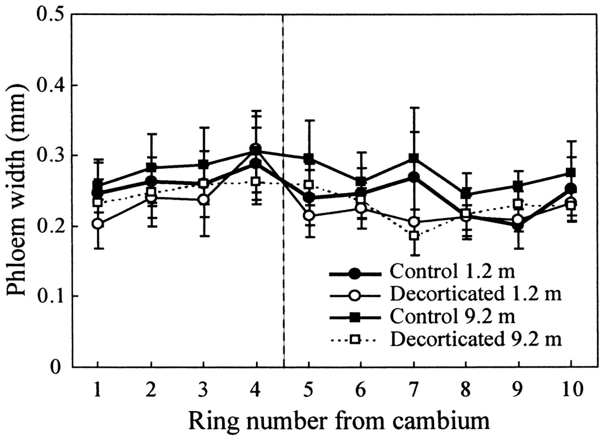

Fig. 4. Variation in annual ring width in the phloem before and after decortication. See Fig. 2 for definition of symbols

width was large (Fig. 2), and the averaged ring width in the xylem before and after decortication varied (Table 1). The growth character of each tree or environmental factors such as temperature and precipitation would more greatly affect the ring width than the decortication effect on xylem formation in *Chamaecyparis obtusa*.

The inner bark had a clear annual ring structure (Fig. 3d). In many species, the phloem has no discernible annual ring.[8] Only some species have an annual ring structure in the phloem,[9–11] and the ring width in such species changes with climatic conditions.[12,13] However, results from our study indicated that ring width in the inner bark showed only a small variation, and there was no apparent change throughout all the inner bark (Fig. 4). Even in the fifth and sixth annual rings that may have been influenced by the decortication, ring width was similar to that of the other rings. Therefore, decortication for *hiwada* production in *C. obtusa* would have little effect on the growth of phloem both directly and indirectly.

It is known that abnormally growing *C. obtusa* trees have traumatic tissue in the xylem.[14] Kuroda and Shimaji[15] reported in *Tsuga sieboldii* that mechanical damage in the cambial zone caused the formation of traumatic tissue in the xylem. In this study, decortication appeared to have the potential to affect the xylem formation by its mechanical stress. However, we did not observe traumatic tissue in the xylem after decortication (Fig. 3a), or any structural changes, even in the xylem at the insertion point of the wooden spatula. It is also known in some species that the mechanical damage to the inner bark causes the formation of callus and traumatic tissue,[16–19] as well as ethylene generation in the phloem.[20,21] However, we did not observe any callus formation or traumatic tissue in the phloem after decortication (Fig. 3d). The outer bark decortication in this study would less affect the formation of traumatic tissue in the inner bark even that might cause dehydration in the radial direction. In addition, decortication at the beginning of February, which is the dormant season of cambial activity at all experimental sites, would minimize any negative effect on new cell formation. It appears that *hiwada* harvest in the dormant season of cambial activity does not injure the cambial zone, and does not form any abnormal tissue.

All decorticated trees had five to ten annual rings in the outer bark (Fig. 3c), and ten or more in the inner bark (Fig. 3d). This result indicates that decortication for *hiwada* production would preserve all inner bark and one to six annual rings of outer bark in this study. Because the *motokawashi* in general remove the bark without removing *amakawa* from the trees, this operation is indicative of a treatment that would maintain the periderm and the thin layer of outer bark. *Amakawa* includes the inner bark and periderm. In the periderm, the cell arrangement (Fig. 3f) and the form of individual cells containing a nucleus (Fig. 3g) were not different between the decorticated and control trees, suggesting that decortication for *hiwada* production by the *motokawashi* does not inhibit the formation of outer bark.

The mean of outer bark annual ring number in decorticated trees was smaller than for the control trees. *Kurokawa* consists of the mostly newly formed outer bark after the previous decortication and *arakawa* contains the older part of the outer bark. Bark is potentially vulnerable to fungal and insect attack, and to mechanical damage.[21,22] Particularly older outer bark would increase the possibility of damage by such attacks. *Arakawa* that contains particularly old outer bark might suffer age degradation and decreased process yield.

All over the world, bark has been used in various ways, mainly the inner bark.[23,24] Periodic outer bark decortication without tree cutting is limited to a few cases such as the commercial cork production from *Quercus suber*[25,26] and the harvest of *hiwada*. Sustained *hiwada* production is required not only from the aspect of the preservation of traditional culture, but also for the cyclical use of forest resources. In conclusion, this study revealed that one reason *hiwada* has been able to be harvested repeatedly and used for traditional buildings in Japan for more than 1000 years is that *hiwada* production in winter has no effect on the growth and wood quality of *C. obtusa*. As such, the sawn timber should still be of high quality. However, the degree of damage at *hiwada* harvest depends on the skill of the *motokawashi*. The relation of their skill to traumatic tissue formation in the xylem and phloem should be considered in future studies.

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