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NOTE

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# Intra-ring radial cracks in Sakhalin spruce (*Picea glehnii*) from artificial forest

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**Abstract**

The occurrence of radial cracks in Sakhalin spruce (*Picea glehnii*), differences in the degree of cracking among five habitats, and the relationship between cracks and wood density were investigated in a total of 79 logs collected from five sites in Hokkaido, Japan. The cracks were divided into two types: intra-ring radial cracks that were restricted to cracks within an annual ring and larger radial cracks that extended beyond a single annual ring. The number and the longitudinal length of cracks in log varied depending on habitat, and it was considered that the cold temperature conditions in winter might affect the incidence and length of cracks. The results of soft X-ray densitometry showed that the annual ring density with cracks was lower than the annual ring density without cracks. It is considered that this low wood density affected the occurrence of cracks.

## Introduction

Sakhalin spruce (*Picea glehnii*) occurs naturally on the islands of Hokkaido, Honshu (Iwate Prefecture), southern Kuril and Sakhalin [1]. In Hokkaido, planting of Sakhalin spruce started at the beginning of the twentieth century and the plantations of this species now occupy the third largest area (167,526 ha) after Sakhalin fir (*Abies sachalinensis*) and Japanese larch (*Larix kaempferi*) in Hokkaido.

In Japan, Sakhalin spruce has been planted only in Hokkaido. Since Sakhalin spruce has strong resistance against frost damage, disease, and insect attack, it is still planted in sites where Sakhalin fir and Japanese larch are difficult to grow due to environmental/biological stresses. Thinning operations for Sakhalin spruce are typically conducted when the trees are approximately 40 years old or when diameter at breast height is 20–30 cm. The timber from these thinned trees is economically important and used for small-dimension construction lumber or for producing glulam.

Since the late 2000s, it becomes apparent that a major problem with the logs of Sakhalin spruce that are harvested from thinned plantations in Hokkaido is that they are highly susceptible to break during sawing. Investigation revealed that internal cracks were frequently found in logs of Sakhalin spruce [2]. Further, it was confirmed that these cracks in Sakhalin spruce formed in standing trees, and that they were not caused by frost crack damage, as seen in Sakhalin fir [3, 4] or timber drying after cutting. The morphological characteristics of these cracks in Sakhalin spruce resembled that of the cracks commonly found in Alaskan white spruce [5] and European spruce [6–9]. In several studies conducted in Europe, similar cracks were described as "stem cracks" [6, 7]. For example, Persson [6] reported that the stem cracks in logs from artificial forest of European spruce have been observed in northern Europe since the 1980s. Further, Persson reported that the cracks in European spruce tended to occur in low-density logs with wide annual rings that were grown on poor soil. Cherubini et al. [8] reported that the cracks were caused by water imbalances during the early spring, primarily due to transpiration losses and inadequate moisture supply from cold roots. Grabner et al. [9] reported that the earlywood

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density was low in annual rings with cracks in European spruce.

The purpose of this study was therefore to investigate the difference in the degree of cracking in Sakhalin fir due to differences in habitat and to clarify the causes and consequences of the cracking. A total of 79 logs were obtained from five sites, and the presence or absence of internal cracks and their size were investigated. In addition, the relationship between the occurrence of the cracks and the wood density was also clarified.

## Materials and methods

Seventy-nine logs were sampled at five sites in Hokkaido. Logs measuring 3.65 m long were cut from the bottom basal parts of the tree trunks, excluding any crooked portions. Details of the studied sites and logs are described in Table 1. The meteorological data at each site are 10-year averages from 2005 to 2015, and were calculated using Agro-Meteorological Grid Square Data provided by the National Agriculture and Food Research Organization [10].

The logs were cut longitudinally into quarters along the pith with a band saw, and then these quarter logs were cut transversely at 50-mm intervals, as shown in Fig. 1.

Every cross section was scanned with a conventional image scanner (GT-F730, Epson, Tokyo, Japan) at 600 dpi. The wood samples were processed as quickly as possible after harvesting, and image scanning was performed when the logs were green. From a continuous series of digital images taken at 50-mm intervals along the axis, the years when the cracks were initiated were identified and the longitudinal length of each crack was determined.

Wood density analysis was performed based on soft X-ray densitometry. Briefly, 2-mm-thick cross sections were cut from parts near the upper ends of the logs. The wood samples were soaked in an ethanol and benzene solution (1:2 in volume ratio) for a week to remove resin and placed in a temperature- and humidity-controlled chamber (i.e., at 20 °C and a relative humidity of 65 %) until a moisture content of 12 % was achieved. The X-ray films (XFR, Fujifilm Inc., Tokyo, Japan) on which specimens were placed were irradiated in a soft X-ray machine (CMB-2, Softex Co., 1986, Tokyo, Japan) using an irradiation distance of 760 mm, a voltage of 19 kVp, a current of 2.5 mA, and an exposure time of 39 s. The X-ray films were then scanned at 1600 dpi (DS-G20000, Epson, Tokyo, Japan), and the annual ring width and wood density were measured based on the scanned images. WinDENDRO 2019a (Regent Instruments Inc., Quebec, Canada) was then used to analyze the annual ring width and wood density in the images. Earlywood and latewood density were separated using boundary of 550 kg/m$^3$.

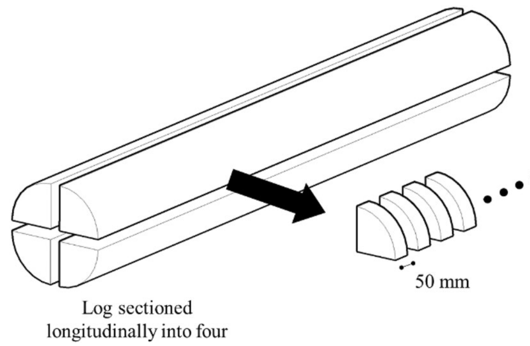


**Fig. 1** Preparation of logs to assess cracks

## Results and discussion

Small cracks (hereinafter referred to as intra-ring radial cracks) were observed, as shown in Fig. 2a. The inside of the cracks was typically filled with resin and the cracks were lentoid in cross section with bulges in the centers of the annual rings. Occasionally, cracks extended radially beyond the annual ring (Fig. 2b) and these cracks are referred to as larger radial cracks.

Longitudinal continuity of intra-ring radial cracks was observed in series of cross sections that were collected at 50-mm intervals as shown in Fig. 3. Continuous cracks in the longitudinal direction were counted as the same intra-ring radial crack.

**Table 1** Details of the logs and study sites in this study

| Site | Age | Number of logs | Top end diameter of logs (cm) | Average temperature (℃) | Minimum temperature (℃) | Annual precipitation (mm) |
|---|---|---|---|---|---|---|
| A | 38 | 18 | 19.7 ± 2.2 | 7.1 ± 0.3 | − 26.1 ± 1.8 | 956 ± 210 |
| B | 42 | 21 | 21.3 ± 5.1 | 6.2 ± 0.3 | − 17.6 ± 1.8 | 1159 ± 224 |
| C | 39 | 12 | 15.7 ± 2.6 | 6.6 ± 0.3 | − 15.7 ± 2.3 | 2331 ± 310 |
| D | 39 | 18 | 18.7 ± 2.1 | 7.6 ± 0.3 | − 19.1 ± 2.0 | 1138 ± 159 |
| E | 33 | 10 | 20.7 ± 3.2 | 5.3 ± 0.3 | − 21.5 ± 1.7 | 1318 ± 220 |

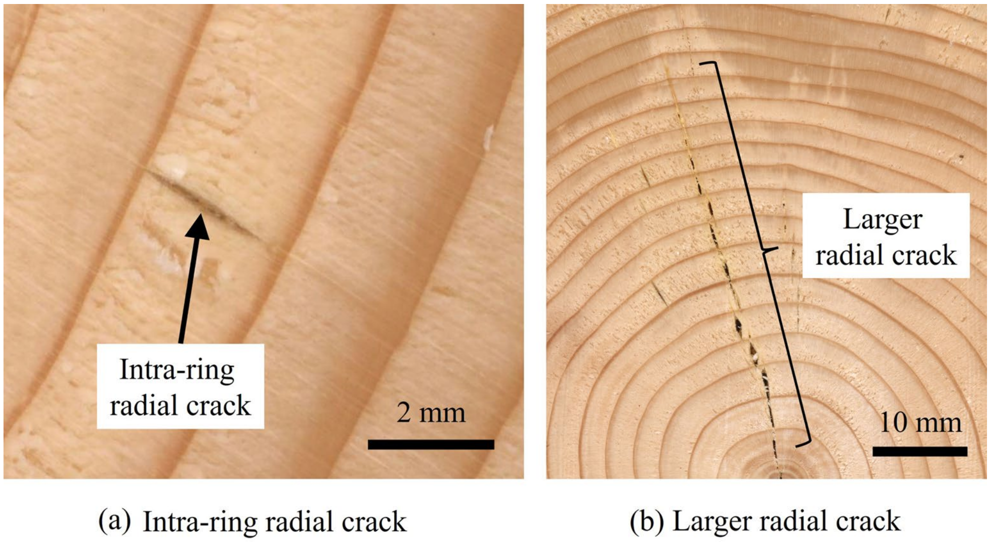


**Fig. 2** Intra-ring radial crack and larger radial crack

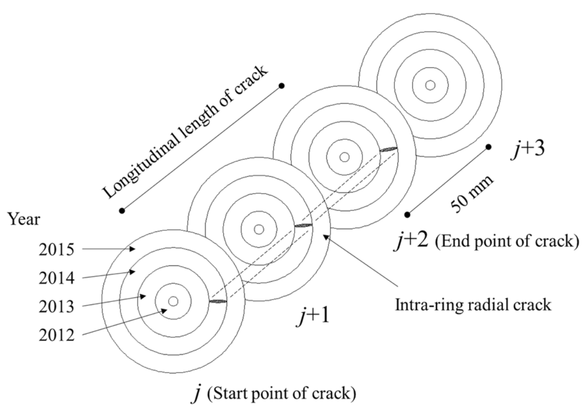


**Fig. 3** Outline of intra-ring radial crack

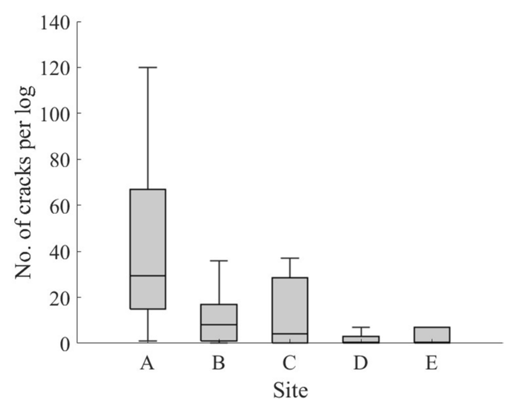


**Fig. 4** Number of cracks per log at each site. (The line inside each box is the sample median. The whisker connects the upper quartile to the non-outlier maximum.)

Since the fracture lines for these larger radial cracks were not homogeneously thick and always narrowed at the ring boundaries, the larger radial cracks were composed of a series of radially contiguous intra-ring radial cracks. The number of larger radial cracks was counted using the same procedure that was used for the intra-ring cracks.

Figure 4 shows a boxplot of the number of cracks per log at each site. Site A, which experienced the lowest minimum winter temperatures (Table 1), had the largest number of cracks. The results of Kruskal–Wallis test revealed that the number of cracks differed among sites (Kruskal–Wallis test, $df=4$, $\chi^2=25.1$, $p<0.01$). In the multiple comparison test by Dunn–Šidák correction, the number of cracks at site A was significantly higher than that at sites D and E (Table 2).

**Table 2** *p* values for multiple comparisons of number of cracks per log at each site

| | | Site | | | |
|---|---|---|---|---|---|
| | | **B** | **C** | **D** | **E** |
| Site | A | 0.08 | 0.06 | < 0.01 | < 0.01 |
| | B | – | 1.00 | 0.22 | 0.88 |
| | C | – | – | 0.77 | 1.00 |
| | D | – | – | – | 1.00 |

Figure 5 shows a boxplot of the longitudinal length of the cracks in the logs harvested at each site. The average length of cracks at each site was in the range 0.2–0.5 m, which corresponds to the findings for European spruce

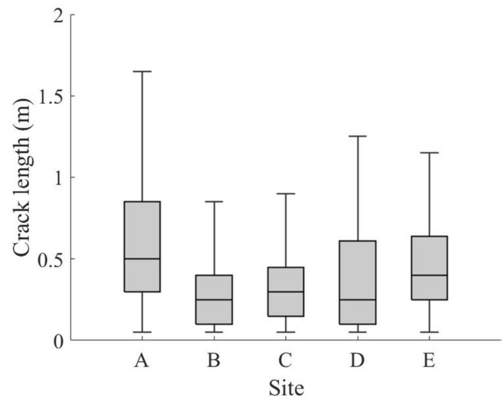


**Fig. 5** Longitudinal length of cracks in logs harvested at each site. (The line inside each box is the sample median. The whisker connects the upper quartile to the non-outlier maximum.)

**Table 3** p values for multiple comparisons of length of cracks at each site

| | | Site | | | |
|---|---|---|---|---|---|
| | | B | C | D | E |
| Site | A | < 0.01 | < 0.01 | < 0.01 | 0.17 |
| | B | – | 0.12 | 0.99 | < 0.01 |
| | C | – | – | 1.00 | < 0.01 |
| | D | – | – | – | 0.08 |

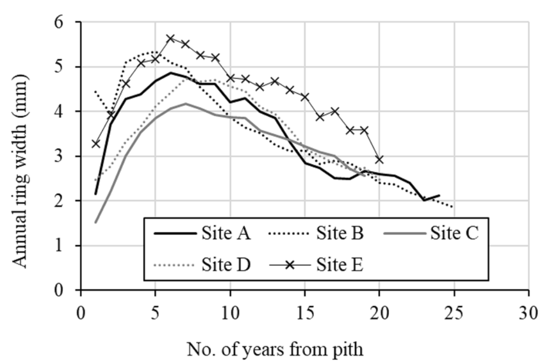


**Fig. 6** Variations in annual ring width at each site

[6]. It was found that the length of cracks differs among sites (Kruskal–Wallis test, d$f$ = 4, $\chi^2$ = 189.0, $p < 0.01$), and that the length of cracks was significantly higher at site A than at sites B, C, and D in the multiple comparison test performed using Dunn–Šidák correction (Table 3).

Figure 6 shows the variations in annual ring width at each site. The annual ring width increased from the 1st to 5th or 7th years and then gradually decreased. Site E had the largest annual ring width.

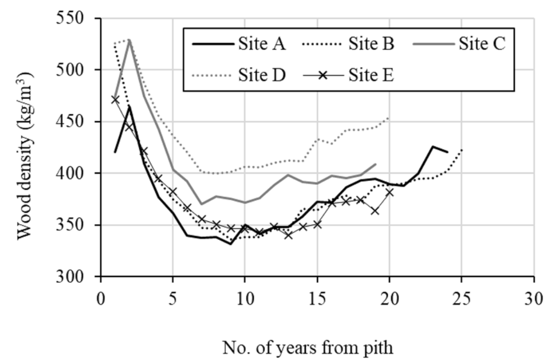


**Fig. 7** Variations in the mean wood density at each site

Figure 7 shows the variations in the mean wood density at each site. The mean wood density decreased from the 1st to 7th or 8th years and then gradually increased outward. Site D, which had the highest mean wood density, had the fewest cracks (Fig. 4).

Table 4 shows the annual ring width, mean wood density, earlywood density, latewood density, and proportion of latewood at each site; the values of each 10-year average are shown in the table.

The wood density was compared between annual rings without cracks and annual rings with cracks, as shown Fig. 8. The mean wood density of annual rings with cracks was significantly lower than that of annual rings without cracks (Student's $t$-test, d$f$ = 1056, $t$ = 18.7, $p < 0.01$). Furthermore, the earlywood (Student's $t$-test, d$f$ = 854, $t$ = 15.2, $p < 0.01$) and latewood densities (Student's $t$-test, d$f$ = 667, $t$ = 6.3, $p < 0.01$) of annual rings with cracks were lower than those of annual rings without cracks.

Figure 9 shows the mean wood densities of annual rings with intra-ring radial cracks and those with larger cracks. The earlywood density of annual rings with larger cracks was lower than that of annual rings with intra-ring radial cracks (Student's $t$-test, d$f$ = 181, $t$ = 5.31, $p < 0.01$). Furthermore, the latewood density of annual rings with larger radial cracks was comparable to that of annual rings with intra-ring radial cracks (Student's $t$-test, d$f$ = 78, $t$ = 0.98, $p$ = 0.33).

## Conclusions

In Sakhalin spruce, the degree of crack formation in logs depends on the habitat. Site A, which experienced the lowest minimum winter temperatures, had the highest number and length of the cracks.

Since the early- and latewood densities of annual rings with cracks were lower than those of annual rings without cracks, it was considered that the cracks may have developed after the formation of low-density annual rings in Sakhalin spruce due to the influence of

**Table 4** Annual ring width and wood density at each site

| Site | Number of year | Annual ring width (mm) | | Mean wood density (kg/m$^3$) | | Earlywood density (kg/m$^3$) | | Latewood density (kg/m$^3$) | | Proportion of latewood (%) | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Ave | S. D | Ave | S. D | Ave | S. D | Ave | S. D | Ave | S. D |
| A | 1–10 | 4.94 | 1.18 | 443 | 65 | 382 | 66 | 685 | 64 | 22.1 | 18.9 |
| | 11–20 | 4.04 | 1.01 | 386 | 35 | 327 | 28 | 723 | 66 | 15.4 | 6.9 |
| B | 1–10 | 4.68 | 1.07 | 390 | 69 | 347 | 45 | 668 | 58 | 16.2 | 22.1 |
| | 11–20 | 3.03 | 1.03 | 366 | 40 | 327 | 30 | 683 | 88 | 11.2 | 5.3 |
| C | 1–10 | 3.43 | 1.15 | 421 | 73 | 367 | 61 | 685 | 61 | 18.9 | 16.9 |
| | 11–20 | 3.18 | 0.96 | 393 | 57 | 341 | 37 | 726 | 123 | 13.8 | 10.5 |
| D | 1–10 | 3.95 | 1.14 | 446 | 75 | 368 | 64 | 728 | 64 | 23.4 | 18.7 |
| | 11–20 | 3.31 | 1.06 | 428 | 56 | 350 | 35 | 759 | 69 | 20.3 | 10.5 |
| E | 1–10 | 4.85 | 1.12 | 388 | 52 | 352 | 43 | 662 | 52 | 13.8 | 17.6 |
| | 11–20 | 4.08 | 1.10 | 359 | 36 | 319 | 26 | 706 | 46 | 10.7 | 5.2 |

Ave. and S. D. represent average and standard deviation, respectively

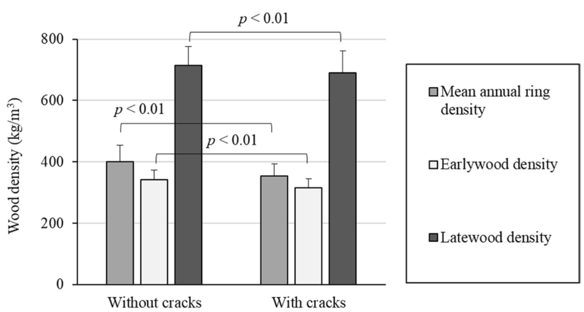


**Fig. 8** Comparison of annual ring density in logs with and without cracks

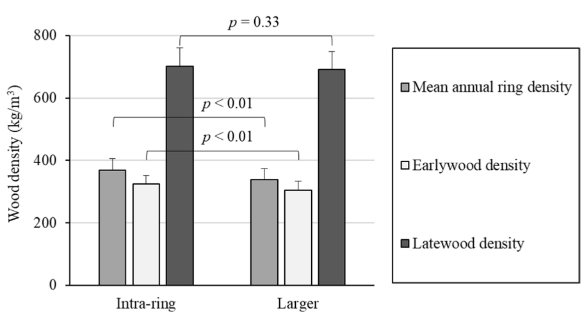


**Fig. 9** Comparison of annual ring density in logs with intra-ring radial cracks and larger radial cracks

the external environment. Furthermore, the earlywood density of annual rings with larger cracks was lower than that of annual rings with intra-ring radial cracks.


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**Author contributions**

Murakami designed the study, was responsible for the data collection, and wrote the manuscript; Ohsaki and Sato helped collect the samples and data; Sano supervised the conduct of the study. All the authors have read and approved the final manuscript.


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**Availability of data and materials**

The samples, test methods, and data are described in this manuscript. A more detailed explanation of the test methods and data are available from the corresponding author upon reasonable request.

## Declarations

**Competing interests**

The authors declare that they have no competing interests regarding the publication of this manuscript.


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## Publisher's Note