Bulletin of Glaciological Research 38 (2020) *25–38*
doi: 10.5331/bgr.20A01

Monitoring bending stress of trees during a snowy period using strain gauges

Ayana MIYASHITA[1,2]*, Ryoko MINAMINO[3], Koichiro SAWAKAMI[1], Takafumi KATSUSHIMA[4] and Masaki TATENO[1]

1 Nikko Botanical Gardens, Graduate School of Science, the University of Tokyo, 321–1435 Nikko, Japan
* ayanamiyashita@gmail.com
2 (present address) Center for Forest Damage and Risk Management, Forestry and Forest Products Research Institute (FFPRI), 305–8687 Tsukuba, Japan
3 Gifu University, River Basin Research Center, 501–1193 Gifu, Japan
4 Tohkamachi Experimental Station, Forestry and Forest Products Research Institute (FFPRI), 948–0013 Tohkamachi, Japan

(Received January 15, 2020; Revised manuscript accepted August 16, 2020)

Abstract

The load created by snow greatly affects forest trees; however, almost no studies have reported on the mechanical stress in tree trunks due to snow under field conditions. In this study, we monitored trunk bending stresses using strain gauges during the snowfall season at two sites, Tadami and Kaneyama, both in a cool-temperate forest in Japan. Measurements were made of the various sizes and trunk shapes of beech trees at Tadami, and of beech trees and Japanese cedars at Kaneyama. Young's modulus and bending strength were also measured. At Tadami, beech trees with substantially curved trunks often bent down to the ground surface soon after snowfall started. The strain no longer increased once a tree had lodged; however, individuals with larger diameters had stresses exceeding the proportional limit stress. By contrast, among beech trees with erect trunks, those with larger diameters had smaller maximum strain and estimated stress values. These results imply that in areas greatly affected by snow, beech trees struggle both to remain erect and to grow to diameters of 10 cm or more. At Kaneyama, large strain values exceeding 1 % were observed in trees with a diameter at breast height ≤7 cm, all of which were cedars. Among trees of the same diameter, strain values were lower in beech trees than in cedars, and Young's modulus was three times larger for beech trees. These results indicate that it is more difficult to grow erect cedars compared to erect beech trees in regions with deep snow.

Key words: biomechanics, beech forest, moduluds of elasticity, tree trunk, snow over

1. Introduction

Accumulated snow can mechanically stress trees in snow-covered regions, considerably affecting tree and forest growth, and it has been reported that the vegetation established in natural forests varies depending on accumulated snow depths, which are influenced by wind direction (Onodera, 1995). Avalanches can also affect forest regeneration in mountainous areas (Kajimoto *et al*., 2002). In planted and secondary forests in snowy regions, trees often suffer from problems such as broken trunks, buckling, and uprooting (Cremer *et al*., 1983; Curtis, 1936; Díaz-Yáñez *et al*., 2017; Hanewinkel *et al*., 2011; Hlásny *et al*., 2011; Martín-Alcón *et al*., 2010; Shidei, 1954; Valinger, 1997; Wallentin and Nilsson, 2014; Zhu *et al*., 2006). In addition, trees in deep-snow regions often have deformed roots and trunks because of pressure attributed to the movement of accumulated snow on slopes (Charles *et al*., 1972; Shidei, 1954). Bebi *et al*. (2009) reviewed the interactions between avalanches and forest vegetation and suggested a two-way interaction between forest structure and avalanches. Therefore, understanding the mechanical impact of snow cover on trees could elucidate snow cover dynamics on mountain slopes.

However, few studies have directly measured the mechanical stress in trees in a forest during a period of snow cover. To understand the mechanisms that impact the distribution of forest vegetation and tree growth due to snow, the magnitude of the external forces exerted by snow must be measured, and the extent of trunk damage by snow must be evaluated. Multiple methods have been used to calculate the pressure of snow on an object on a slope (*e.g.*, Haefeli, 1939; Margreth, 2007), and one study estimated the pressure on a single tree trunk using these methods (Viglietti *et al*., 2013). By contrast, other studies have assessed the strength of tree trunks and the extent of root spread under different snow loads and pressures (Cannell and Morgan, 1989; Höller *et al*., 2009; Päätalo *et al*., 1999; Peltola *et al*., 1997). However, few studies (*e.g.*, Takahashi *et al.*, 1968; Yamanoi 2006) have measured these factors in trees in a forest.

There are various devices for measuring the magnitude of such forces in the field, including displacement meters (*e.g.*, Milne, 1991), strain gauges (*e.g.*, Blackburn, 1997; Ennos, 1995), accelerometers (*e.g.*, White *et al.*, 1976), and inclinometers (*e.g.*, Flesch and Wilson, 1999). Among these, the strain gauge has two notable advantages: it is small and relatively inexpensive, and it enables direct measurement of tree deformation, which is easily converted into mechanical stress. Strain values can be used as a direct indicator of the damage caused to the trees measured. Ennos (1995) studied the magnitude of stress in trees in a forest using an artificial load against buttress roots. Other studies have measured dynamic bending moments during wind (Moore *et al.*, 2005; Minamino and Tateno, 2014) and quantified the risk of wind damage (Suzuki *et al.*, 2016). However, none of these studies used strain gauges in a snowy area to measure damage to tree trunks by snow in a forest setting.

In this study, we used strain gauges to measure the deformation of tree trunks during a snow-cover period to clarify the effects of snow on the trunks. We also measured the wood strength required to convert the strain values to stress values to assess the risk of trunk collapse. Our goal was to reveal patterns of stress due to snow in beech trees of different sizes and trunk shapes, and to compare stress patterns between sympatric beech and cedar trees.

2. Materials and Methods

2.1 Study site

The study was conducted at two forest sites, Tadami and Kaneyama, both of which are located in Fukushima Prefecture, Central Japan (Fig. 1). This region is in the cool-temperate zone and is characterized by heavy snowfall. Climate information was obtained from the nearest meteorological stations to Tadami (37°20.6′ N, 139° 18.8′ E, 377 m a.s.l., 1.5 km south-southeast of the experimental site) and Kaneyama (37°28.4′ N, 139°31.7′ E, 296 m a.s.l., 3.2 km south-southwest of the experimental site). The respective average daily mean temperature, maximum temperature, minimum temperature, precipitation, and maximum snow cover height of the snowfall season (December–April) were 1.3℃, 5.7℃, −2.5℃, 1107 mm, and 238 cm for Tadami in 2013–2014, and 1.2℃, 6.0℃, −2.4℃, 916 mm, and 316 cm for Tadami in 2014–2015; and 3.2℃, 7.9℃, −0.4℃, 809 mm, and 130 cm for Kaneyama in 2015–2016 (Japan Meteorological Agency). Note that ∼ 40% of the observed annual precipitation at both sites was from December to March, primarily falling as snow. The unique vegetation of this region is affected by snow, and deciduous tree species such as *Fagus crenata*, *Quercus crispula*, and *Acer* species are dominant on mountain ridges and gentle slopes. Evergreen coniferous species such as *Cryptomeria japonica*, which occurred only at the

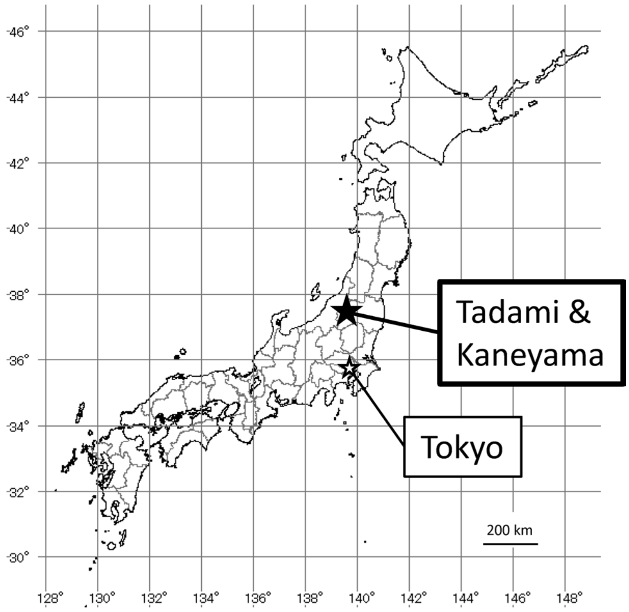

Fig. 1. Study sites. Map of Japan and the locations of the Tadami and Kaneyama sites. The base map was created using "MapMap6.0" [Kamada, T., http://www5b.biglobe.ne.jp/t-kamada/CBuilder/mapmap.htm].

Kaneyama site, *Pinus parviflora* var. *pentaphylla*, and *Thuja standishii* are also present, but they are only found on ridges. Only short-tree species such as *Hamamelis japonica*, *Weigela hortensis*, and *Camellia rusticana* are observed on steep slopes; there are few tall-tree species, and shrubs are mixed. Furthermore, the mountains in this region have some extreme slopes with herbaceous species and exposed bedrock. Until the 1960 s, these forests were used for anthropogenic activities such as logging for timber and fuelwood. Thereafter, they regenerated naturally.

In this study, we focused on Japanese beech (*Fagus crenata*), a species of deciduous broadleaved tree and a dominant species in snowy areas in Japan, and Japanese cedar (*Cryptomeria japonica*), an evergreen needle-leaved tree that grows with beech trees. The beech usually has an erect trunk and propagates seeds when it reaches maturity. However, in snowy areas, it has a dwarf phenotype with many branches as a result of the influences of slope inclination and snow depth (Homma, 1997; Tanimoto, 1993).

At the Tadami site, we set experimental plots along two mountain slopes facing northeast (NE) and southwest (SW) near the top of Mt. Yogaisan (37°21′23″ N, 139°18′ 31″E, 705 m a.s.l.) (Fig. 2). We chose the NE and SW slopes because they show clear environmental differences. Generally, accumulated snow is deeper on the NE slope than on the SW slope because of the direction of the seasonal wind. In particular, on the lower NE slope, avalanches frequently occur, resulting in a number of deformed slender trees and very few erect trees. A number of erect, adult beech trees grow in the upper area of the NE slope, and throughout the SW slope:

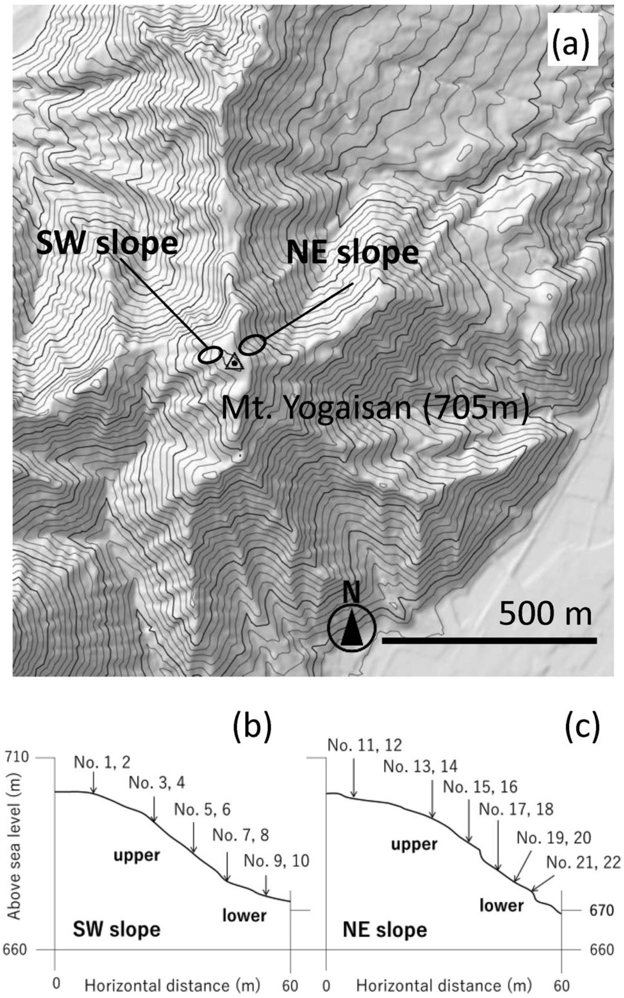

Fig. 2. Topographical map of the area around the Tadami site (a), and schema of the SW slope (b) and the NE slope (c). The numbers in panels (b) and (c) correspond to the numbers of individual trees that were measured (Table 1) and represent the measurement points. On both the SW and NE slopes, a number of erect beech trees were present in the upper parts (as seen in Fig. 4b), and many deformed individuals were located in the lower parts (as seen in Fig. 4c). The topographical map was created using 'Web Contour Maker' (Tani, 2015). The cross-sections of the slopes were created using "GSI Map" [Geospatial Information Authority of Japan (GSI), https://maps.gsi.go.jp/].

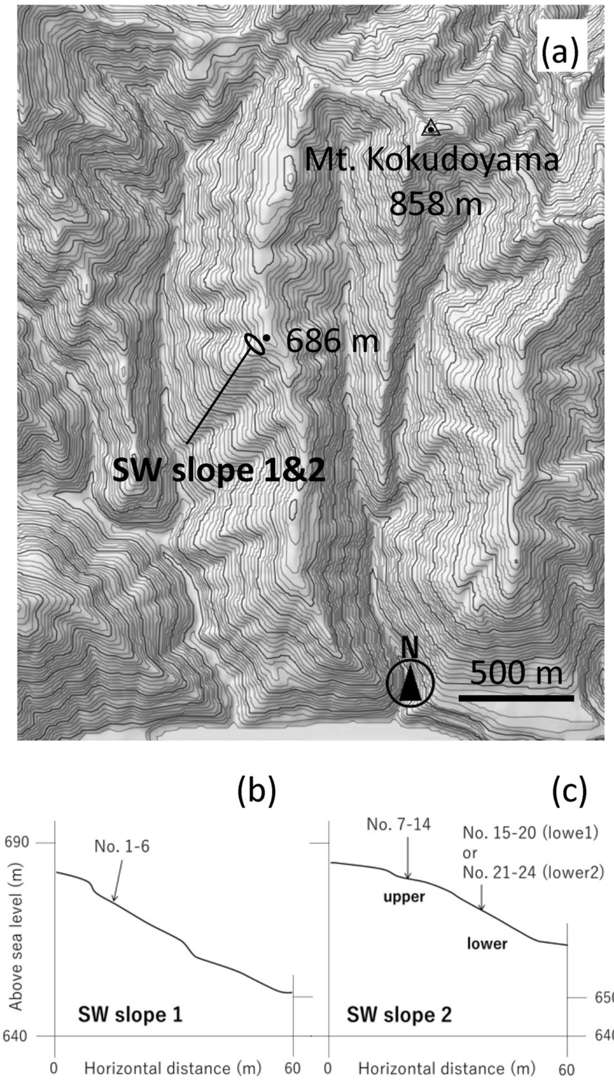

Fig. 3. Topographical map of the area around the Kaneyama site (a), and schema of the SW slope 1 (b) and the SW slope 2 (c). The lower 1 and lower 2 points on the SW slope 2 were different locations, but are shown together for convenience. The numbers in the diagram correspond to the numbers of individual trees measured (Table 2) and represent the measurement points. The topographical map was created using 'Web Contour Maker' (Tani, 2015). The cross-sections of slopes were created using "GSI Map."

however, both slopes also have some deformed trees that may be the result of local environments. At the Kaneyama site, measurements were taken at points on the SW slope, along the ridge (670 m a.s.l.; Fig. 3) leading to the summit of Kokudoyama (37° 30′ 28″ N, 139° 33′ 02″ E, 858 m a.s.l.). Individual erect beech trees and cedars are found at most of these points.

2.2 Data collection

2.2.1 Monitoring trunk bending

Trunk bending was measured using strain gauges. Two active gauge bridge circuits were used to measure bending strain; strain gauges attached to points facing the mountain and valley sides of a tree (Fig. 4). If the tree trunk fell towards the valley side (applying tensile force on the mountain side and compressive force on the valley side), both gauges produced positive output values. If the tree trunk bent towards the mountainside, they produced negative output values. These values were divided by two to yield a bending-strain value. A network-based measuring instrument (Tokyo Measuring Instruments Lab., Tokyo, Japan) was used (TML-NET) to record the measured values. The strain gauges on two trees were connected to one of the network modules (NSW-024C; Tokyo Measuring Instruments Lab.), each of which was connected to one data logger controller (MD-111; Tokyo Measuring Instruments Lab.). Using the data logger, instantaneous values were recorded at 30-min intervals (or 10-min intervals for measurements starting in 2013).

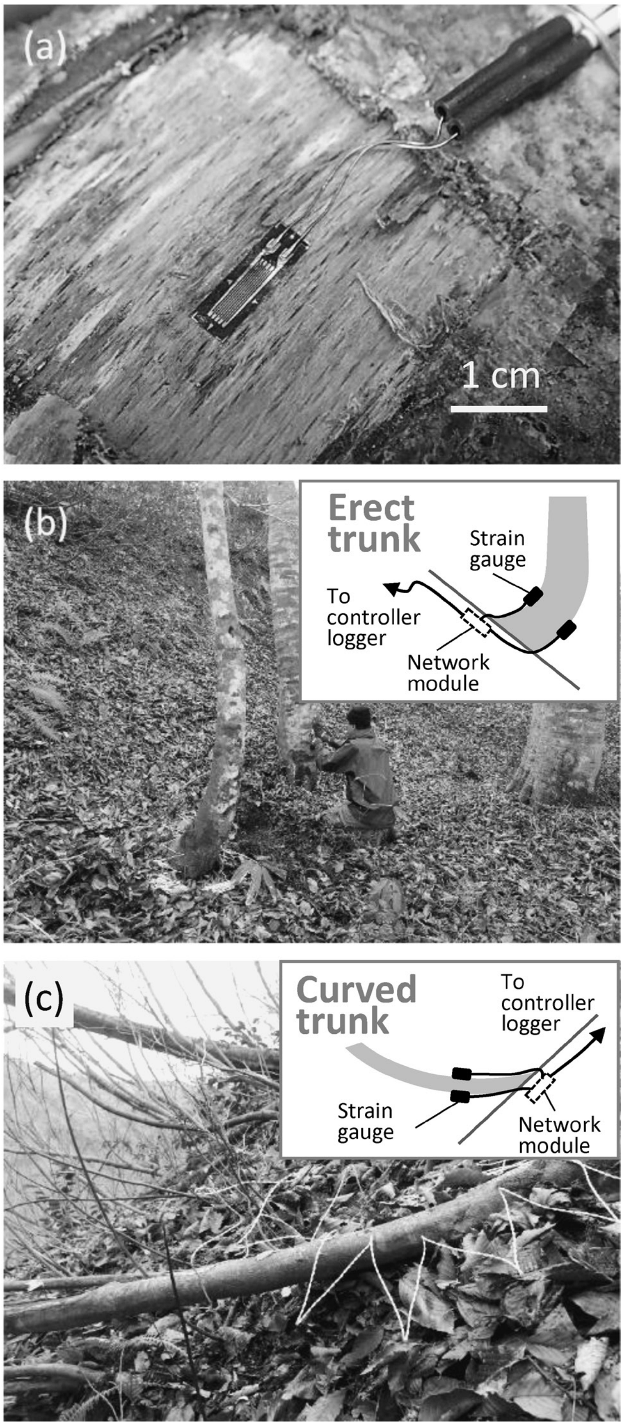

Fig. 4. Image of measuring set-up. (a) Strain gauges were attached to the trunks. (b) Trees with erect trunks among those to be measured (Nos. 11 and 12 at the Tadami site) and schema of strain-gauge attachment. (c) Trees with substantially curved trunks among those to be measured (No. 17 at Tadami site) and schema of strain-gauge attachment.

The upper limit for the measured values was ~30,000 $\mu\varepsilon$, the sum of the tensile and compressive side values. The network module was placed in a robust plastic case, waterproofed, and buried near the target tree. The logger controller was installed in a control facility operated by the Electric Power Development Co., Ltd. (J-power; Tokyo, Japan) at the Tadami site, from which power was supplied at 100 V. At the Kaneyama site, the logger controller was installed at the base of a large tree on the ridge, and then 40 AA batteries were connected (4 in series × 10 in parallel) to create a power source. Wires were placed along the slope and buried in the ground.

At the Tadami site, one large (diameter at breast height [DBH] > 30 cm) tree, and one small (DBH < 10 cm) tree were selected at each study point (22 individuals in total; Fig. 2a; Table 1). A strain gauge was attached to the point with the maximum curvature near the ground in the case of erect trunks (Fig. 4b), and to a point at which the trunk did not touch the ground, as near to the base as possible, for substantially curved trunks (Fig. 4c). These points were chosen because they were expected to provide the highest bending or mechanical stress values; on average, they were at points 50–100 cm from the tree base. To ensure firm attachment of the gauge, bark and the cambium layer were stripped from the target site (~3 cm in length × 2 cm in width) to expose the wood. Cyanoacrylate adhesive (CN; Tokyo Measuring Instruments Lab.) was applied to the rear of the strain gauge (FLA-3-11-5L; Tokyo Measuring Instruments Lab.), which was then held in place by hand for 1 min. The exposed wood with the attached gauge was covered with isobutylene-isoprene rubber tape, and then vinyl tape was wrapped around for waterproofing. Measurements were recorded during two periods: from 18 November 2013 to 16 April 2014, and from 11 November 2014 to 30 May 2015; however, tree Nos. 1 and 2 on the SW slope were measured only during the first period, and tree Nos. 11–22 on the NE slope were measured only during the second period. When the gauge was attached, we measured the DBH, the trunk diameter of the target individual at the gauge attachment site, and the slope inclination angle (mean inclination angle in a range of approximately 2 m in the direction of inclination at the tree base) (Table 1). Furthermore, the depth of accumulated snow near the base of the tree was measured using a probe on 26 February 2014 and on 3 March 2015. Based on the Automated Meteorological Data Acquisition System (AMeDAS; Japan Meteorological Agency), data for neighboring areas and the maximum depth of accumulated snow was recorded in late February.

At the Kaneyama site, strain measurements of two to four individuals were conducted at each study point, including 11 beech trees, and 13 cedars (Fig. 2b; Table 2). In November 2015, strain gauges were attached to the trees following the same procedure as at the Tadami site, and measurements were recorded from 13 November 2015 to 2 April 2016. On 13 March 2016, the depth and density of accumulated snow were measured using a probe and by observing a cross-section of accumulated snow, respectively, at each study point.

2.2.2 Mechanical properties of the tree trunks

The three-point bending test was conducted on

Table 1. Trees for the strain measurement at Tadami site.

experimental slope	experimental point		No.	diameter (cm) at Breast height	diameter (cm) at Strain gauge	Trunk form E: erect C: curved	slope angle from horizontal (°)	maximum snow cover depth * (m)
SW	upper	1	1	26.1	32.3	E	2	1.5
			2	3.5	3.6	E	2	1.5
		2	3	8.6	9.9	E	43	1.2
			4	46.3	57.0	E	43	1.2
		3	5	7.7	7.8	E	41	1.7
			6	33.1	38.5	E	41	1.7
	lower	1	7	5.5	7.4	C	32	2.6
			8	9.5	10.1	C	32	2.6
		2	9	6.7	7.8	C	22	1.5
			10	32.7	40.8	E	22	1.5
NE	upper	1	11	30.6	35.6	E	15	>3
			12	14.6	19.7	E	15	>3
		2	13	4.0	6.9	E	32	>3
			14	10.2	15.4	E	32	>3
		3	15	8.9	10.6	C	30	>3
			16	20.8	25.4	E	30	>3
	lower	1	17	6.0	5.9	C	40	>3
			18	4.6	5.8	C	52	>3
		2	19	10.0	10.0	C	47	>3
			20	7.3	8.8	C	47	>3
		3	21	6.4	8.6	C	48	>3
			22	3.2	4.8	C	48	>3

All listed individuals are *Fagus crenata*. *: measured on 26th February, 2014 (on the day AMeDAS presented the daily maximum snow depth of 181 cm), on the SW slope, and on 3rd March, 2015 (that of 235 cm), on the NE slope.

beech and cedar trees growing near the strain measurement site at Kaneyama to estimate Young's modulus, proportional limit stress (PLS), and fracture stress. We sampled 10 beech specimens with a length of 1 m and a diameter of 1.8–6.2 cm, and 7 cedar specimens with a length of 1 m and a diameter of 2.5–6.5 cm. Measurements were recorded at the Forest Products Research Institute in Tsukuba, Japan in early June 2016. We used a TCM-10000 (Minebea Inc.) to measure the specimens with diameters > 3 cm, which were measured at a loading rate of 10–20 mm min^{-1} using the concentrated load method; the distance between fulcrums was set to 800 mm. A displacement meter (DP-500E; Tokyo Measuring Instruments Lab.) was attached to the middle of the rear side of the specimen to measure the displacement. Specimens with a diameter < 3 cm were measured by the concentrated load method, with the distance between fulcrums set to 420 mm and using an Olsen material testing machine (Mori Testing Machine Corp.). The test was conducted in accordance with JIS Z 2101. Similarly, a displacement meter (CDP-50 M; Tokyo Measuring Instruments Lab.) was attached to specimens to measure the displacement. The maximum stress (bending strength) and PLS were calculated based on the maximum load obtained during testing or load under the proportional limit condition using the following formula:

$$\sigma = \frac{LP}{2Z} \quad (1)$$

where σ is the maximum stress or the PLS (N mm^{-2}), L is the distance between fulcrums (mm), P is the maximum load or load under the proportional limit condition (N), and Z is a section modulus (mm^3).

The load under the proportional limit condition was assumed to be the load obtained when displacement amplitudes with maximum loads of 10 % and 40 % (30 % for some specimens) were connected by a straight line, and 2 % deviation (3 % for some specimens) from this line was observed. Based on this inclination line, Young's modulus E (kN mm^{-2}) was calculated using the following

Table 2. Trees for the strain measurement at Kaneyama site.

experimental point		No.	species	diameter at (cm) Breast height	diameter at (cm) Strain gauge	slope angle from horizontal (°)	maximum snow cover depth* (m)
SW1		1	*C. japonica*	41.0	53.4	50	0.49
		2	*F. crenata*	26.5	29.4	50	0.55
		3	*C. japonica*	5.8	7.4	40	0.55
		4	*F. crenata*	4.2	5.3	46	0.59
		5	*C. japonica*	3.1	3.1	50	0.55
		6	*F. crenata*	4.4	4.4	50	0.55
SW2	Upper	7	*C. japonica*	10.6	13.1	21	0.64
		8	*F. crenata*	5.1	6.4	21	0.64
		9	*C. japonica*	9.3	10.4	15	1.00
		10	*F. crenata*	6.2	7.8	14	1.00
		11	*C. japonica*	9.9	11.7	12	0.63
		12	*F. crenata*	13.3	12.3	12	0.63
		13	*C. japonica*	10.2	11.6	20	0.95
		14	*F. crenata*	7.0	9.2	20	0.95
	Lower 1	15	*F. crenata*	13.0	14.0	42	0.10
		16	*F. crenata*	17.4	17.4	42	0.10
		17	*C. japonica*	2.5	3.5	48	0.10
		18	*C. japonica*	11.7	13.6	47	0.10
		19	*C. japonica*	9.6	11.8	47	0.10
		20	*C. japonica*	14.9	17.4	46	0.10
	Lower 2	21	*C. japonica*	3.4	4.7	37	0.80
		22	*F. crenata*	3.9	5.7	37	0.80
		23	*C. japonica*	10.1	13.9	37	0.95
		24	*F. crenata*	7.8	9.6	38	0.95

*: measured at 13th March, 2016 (on the day AMeDAS presented the daily maximum snow depth of 44 cm).

formula:

$$E = \frac{aL^3}{48I \cdot 10^3} \quad (2)$$

where a is the inclination of the load/displacement magnitude line (N mm^{-1}), L is the distance between fulcrums (mm), and I is a cross-sectional secondary moment (mm^4).

After the bending test, specimens were sliced into rounds around the middle point to obtain disks of several centimeters thickness, and these specimens were used to measure moisture content (%; by the full-drying method) and wood density (kg m^{-3}).

Based on the obtained Young's modulus, the strain under the proportional limit was estimated. The correlation between the strain ε and the stress (N mm^{-2}) was obtained using the following formula:

$$\varepsilon = \frac{\sigma}{E \cdot 10^3} \quad (3)$$

The strain measurements had both positive and negative values, whereas the stress value was expressed by its absolute value.

3. Results

3.1 Seasonal patterns of trunk bending and strain

At the Tadami site, large trees with a DBH>30 cm showed almost no strain at any of the study points (Nos. 4, 6, 10, and 11; Fig. 5b, d, & e, Table 1). However, three patterns of changes in strain were observed in mid-sized to small trees. The first pattern included the observation of considerable strain immediately after the start of snowfall and the maintenance of a particular strain value during the snow-cover period. Afterward, the trees were rapidly relieved from strain at the end of the snow-cover

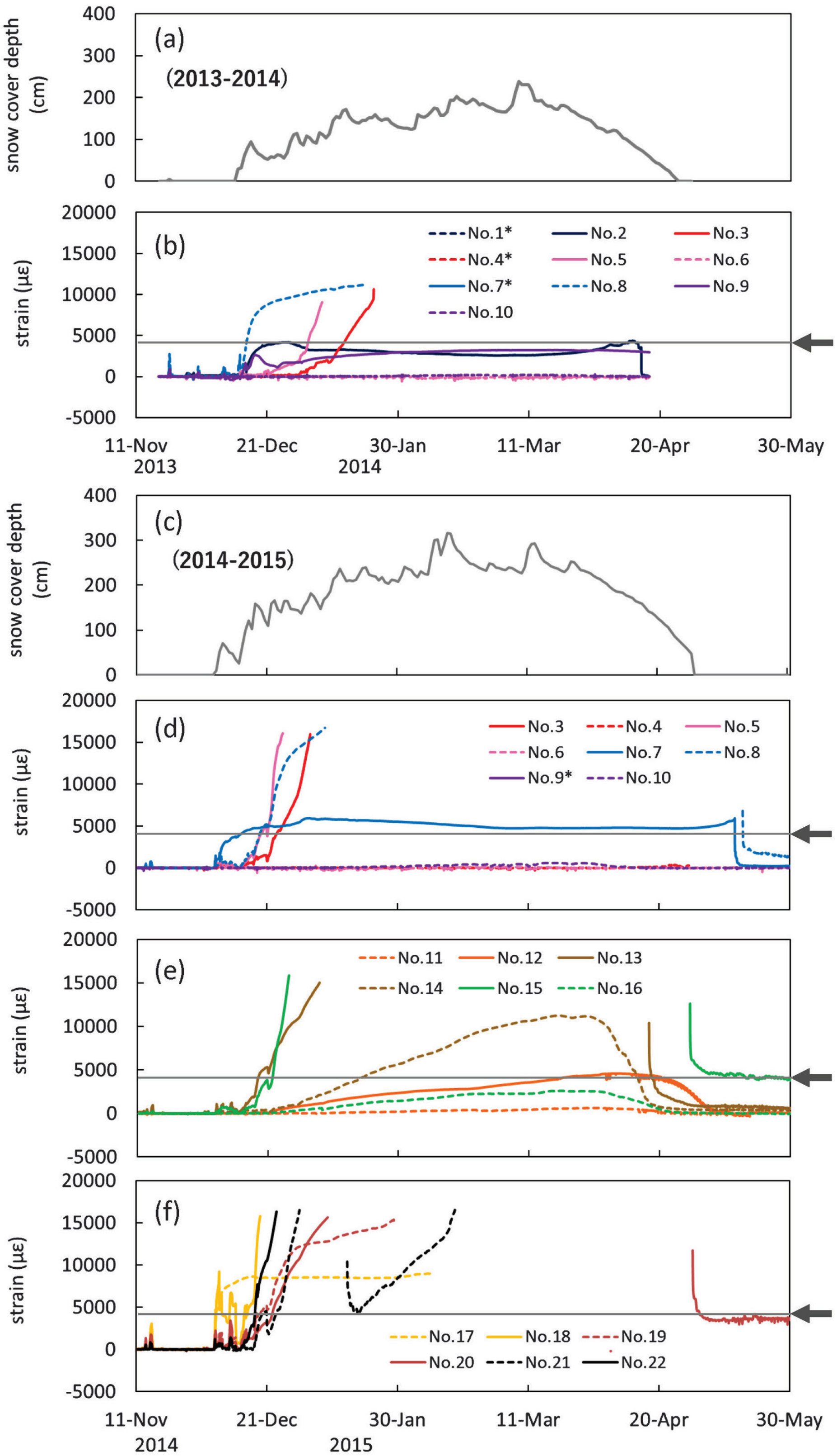

Fig. 5. Strain-measurement results at the Tadami site. (a) Changes in the maximum depth of accumulated snow observed by AMeDAS (2013–2014). (b) Changes in the strain in trees on the SW slope (2013–2014). (c) Changes in the maximum depth of accumulated snow observed by AMeDAS (2014–2015). (d) Changes in the strain in trees on the SW slope (2014–2015), (e) the upper NE slope (2014–2015), and (f) the lower NE slope (2014–2015). The numbers on each panel indicate the individual tree numbers. Asterisks (*) indicate that data were lacking or stopped early in the season. Arrows show the mean strain value when the proportional limit stress (Table 3) was reached.

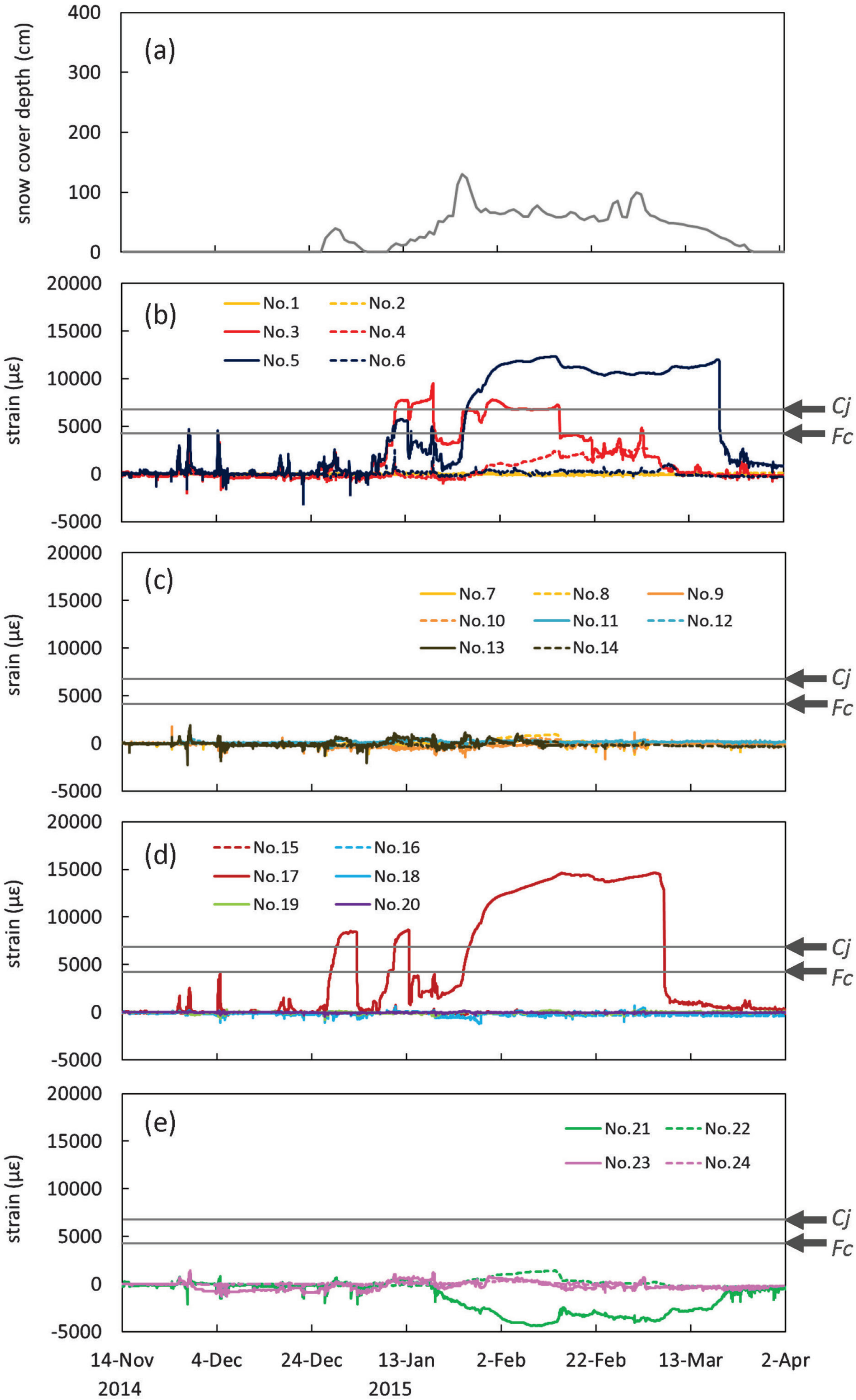

Fig. 6. Strain measurement results at the Kaneyama site. (a) Changes in the maximum depth of accumulated snow observed by AMEDAS. (b) Results of trees on the SW slope (c); upper SW slope 2 (d); lower SW slope 2 lower 1; and (e) SW slope 2 lower 2. The numbers in each panel indicate individual tree numbers. The arrows on each panel show the mean strain values when the proportional limit stress (Table 3) was reached for Japanese beech trees (*Fagus crenata*, *Fc*) and Japanese cedars (*Cryptomeria japonica*, *Cj*), respectively.

period. In the second pattern, there was a rapid increase in strain after the start of snowfall, and the strain value soon exceeded the measurement limit. In the third pattern, the strain increased gradually toward the late snow-cover period, reached its peak, and then decreased. The first pattern was observed in a very slender individual (No. 2 on the upper SW slope) and in individuals with a DBH＜7 cm (No. 7 in 2014–2015 and No. 9 in 2013–2014; Fig. 5b & d, Table 1) among individuals with substantially curved trunks. The second pattern was observed in erect individuals (Nos. 3, 5, and 13; Fig. 5b, d, & e, Table 1) on the relatively steep slope and deformed individuals (Nos. 8 and 15; Fig. 5b, d, & e, Table 1) with a relatively large DBH (～9 cm). The third pattern was observed in individuals with a DBH of 10–30 cm on the upper NE slope (Nos. 12, 14, and 16; Fig. 5e, Table 1), and the maximum strain decreased with larger DBH values. In addition to these patterns, on the lower NE slope, where avalanches frequently occurred, strain values changed considerably (Nos. 17–22; Fig. 5f). Data for some individuals are missing in the middle of the study period because the gauges and lead lines were destroyed.

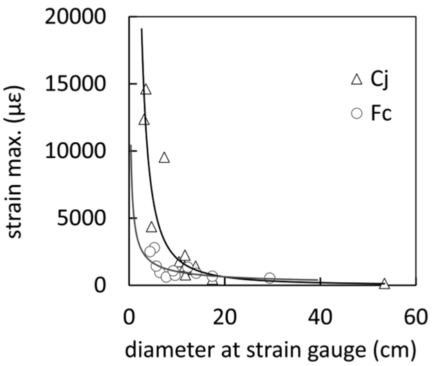

Fig. 7. Comparison of maximum strain values in beech and cedar trees by DBH based on values measured at the Kaneyama site. Absolute strain values are used. Cj, *C. japonica*; Fc, *F. crenata*.

At the Kaneyama site, large strains ＞1 % were observed in slender trees with a DBH ≤ 6 cm, all of which were cedars (No. 3, 5, and 17, but for No. 21; Fig. 6b &d, Table 2). In 2015, at the Kaneyama site, the snowfall season started on 27 December, after which the strain values of the slender cedars changed substantially. The strain values observed in beech trees with a DBH ≤ 6 cm were far smaller than those observed in cedars (trees 4, 6, 8, 10, and 22; Fig. 6b, c, & e; Table 2). The measurement data of all individuals demonstrated that maximum strain values were higher in cedars than in beech trees with the same DBH. However, a significant difference was observed for individuals with a DBH ≤ 10 cm (Fig. 7).

3.2 *Bending stress in the field*

The bending tests showed that estimated mean strain values using Eq. (3) under the PLS were 4,150 με for beech trees and 6,730 με for cedars (Table 3). However, no proportional relationship was established between stress and the deformation volume when the PLS was exceeded. Therefore, the strain value under maximum stress could not be determined using Eq. (3). Accordingly, based on our preliminary measurements, the strain values under maximum stress were estimated to be 30,000–50,000 με.

The stress on trunks of substantially curved beech trees at the Tadami site showed a tendency to be higher with increasing DBH. Individuals 2 and 9 had approximately the same amount of stress, or less, than the mean PLS values (Fig. 5b). However, the stress on tree 7 in 2014–2015 was continuously maintained at a level exceeding the PLS (Fig. 5d), and the stress on trees 8 and 15 far exceeded the PLS (Fig. 5b, d, & e). Furthermore, all individuals on the lower NE slope were possibly exposed to stresses considerably higher than the PLS

Table 3. Result of bending test.

species	*Fagus crenata*				*Crypromeria japonica*			
	avg.	±s.d	max.	min.	avg.	±s.d	max.	min.
Wood density (kg m^{-3})	596.8	±33.7			517.5	±31.6		
Moisture content* (%)	71.4	±6.9	80.2	61.8	72.9	±15.9	100.8	54.2
Young's modulus E (kN mm^{-2} / GPa)	6.45	±2.17	10.67	4.06	2.18	±0.53	2.88	1.49
Proportional limit stress (N mm^{-2}/ MPa)	27.0	±7.1	39.9	20.9	14.8	±1.1	16.5	13.4
Maximum stress (N mm^{-2}/ MPa)	57.9	±13.7	82.1	45.2	29.8	±5.3	38.7	23.6

*: Moisture content (%)＝(mass of water in specimen)/(mass of oven-dried specimen)＊100

(Fig. 5f). However, the stresses on erect individual trees were lower for trees with a larger DBH. Small trees (Nos. 3 and 5 on the SW slope, and No. 13 on the NE upper slope; Fig. 5b, d & e) appeared to experience stress higher than the PLS, and the peak stress recorded exceeded the mean PLS and was in No. 14, which had a DBH of 10 cm and was located on the NE upper slope (Fig. 5e). The stress in individual trees with larger DBH values was likely lower than the PLS (Nos. 11, 12, and 16, Fig. 5e).

At the Kaneyama site, it was estimated that cedar individuals with a DBH of 3–6 cm (Nos. 3, 5, and 17, excluding 21; Fig. 6b, d & e) had stress values exceeding the PLS. The stress values of all the beech trees were below the PLS values. It was estimated that individuals with a DBH ≤ 7 cm (trees 4, 6, 8, 10, 14, and 22; Fig. 6b, c, & e) experienced higher stress.

4. Discussion

4.1 *Strain patterns and loading of tree trunks*

The states of tree trunks during snow cover can be predicted based on changes in strain values. Pattern one in the abovementioned results occurred when a tree trunk suddenly lodged on the ground surface at the start of snowfall because of the weight of snow. We considered the strain value, which rapidly returned to almost zero at the end of the snow-cover period, to reflect the state while the trunk was bending towards the ground surface; the strain was suddenly released when the snow melted. The strain in No. 9 did not return to zero at the end of the measurement period because it remained buried under the snow. Pattern two included trees did not fully lodge while the strain values were being observed. In these trees, a significant increase in strain values was observed shortly after snowfall started, and as snow cover developed on the slope the trees experienced greater strain. Pattern three was associated with erect tree trunks in the snow, for which data were acquired throughout the season. Similar to pattern-two trees, in which strain increased as snow accumulated on the slope, peak strain occurred around the time when the depth of accumulated snow started to decrease. This implies that the load on trees continued to increase until the start of snow melting because of snow creep, consolidation, glide, and other factors. The late restoration of tree 12 from strain was due to differences in the depth of accumulated snow among study points.

For trees Nos. 3–10 (excluding Nos. 7 and 9) at the Tadami site, we monitored strain during two snow seasons (2013–2014 and 2014–2015). The two winters had different snowfall patterns and snow cover depths: cover was higher during the second season throughout the season, and the maximum depth was greater. A comparison of the results for the small erect trees (Nos. 3 and 5) shows that trunk strain was dependent on snowfall patterns and snow cover depth (Fig. 5a–d). Tree No. 8, which had a mostly deformed trunk, experienced more substantial trunk strain in the second season than in the first season (Fig. 5b & d). This implies that even in the case of a tree with a substantially curved trunk, the trunk does not always bend consistently, or it needs to experience substantial strain to bend fully.

At the Kaneyama site, where the levels of accumulated snow were lower, almost all individuals with a DBH >6 cm maintained an erect position. The observed strain values were often negative, indicating bending toward the mountainside, and the pulsed values likely reflect wind vibrations. The negative strain values during the experimental period seen in No. 21 (Fig. 6e) were possibly due to a faulty wire connection, with the mountain-side and valley-side strain gauges switched.

4.2 *Growth in a heavy snow environment: the case of beech trees at the Tadami site*

Figure 8 shows the growth patterns of beech trees at the Tadami site in a heavy snow region. First, young trees easily became lodged on the ground surface, thereby escaping the load on them. However, as the trees' diameter increased, they grew more erect, making it difficult to lodge, because the wood of live trees has a limited deformation volume of ~3% (Minamino, unpublished data). Therefore, as trunk diameter increased, a more substantially curved trunk was required to lodge on the ground surface. Even in an environment in which there were erect trees nearby, the trunks of erect saplings with a DBH<10 cm (trees 3, 5, and 13) were exposed to stress that exceeded the maximum stress level. If such trees are able to continue growing and thickening, they will become capable of enduring the pressures exerted by snow, as indicated by the results from the upper NE slope. However, if they are continually exposed to excessive snow pressure, they are forced to lodge on the ground surface for long periods. The results for the trees on the lower SW slope show that trees lodged on the ground surface are able to escape further snow pressure. However, they are inevitably exposed to high stress as their DBH approaches or exceeds 10 cm (c.f. trees 8 and 15). Therefore, even in the case of individuals with substantially curved trunks, lodging on the ground surface becomes more difficult as the trunk thickens, and they therefore become exposed to greater stress. At points where the snow layer moves rapidly, as seen on the slopes prone to avalanches, both slender and deformed individuals received substantial irregular stresses. Previous studies have shown that the trunks of trees growing on slopes that lack tall trees due to snow had a DBH<10 cm in almost all cases (Tanimoto, 1993; Onodera *et al*., 1995). Our results support these prior studies in terms of the mechanics involved.

Our findings can be used to determine the conditions under which beech trees can grow in an erect position. The maximum strains on the saplings in our study with DBH ≤ 10 cm can be explained by the slope inclination

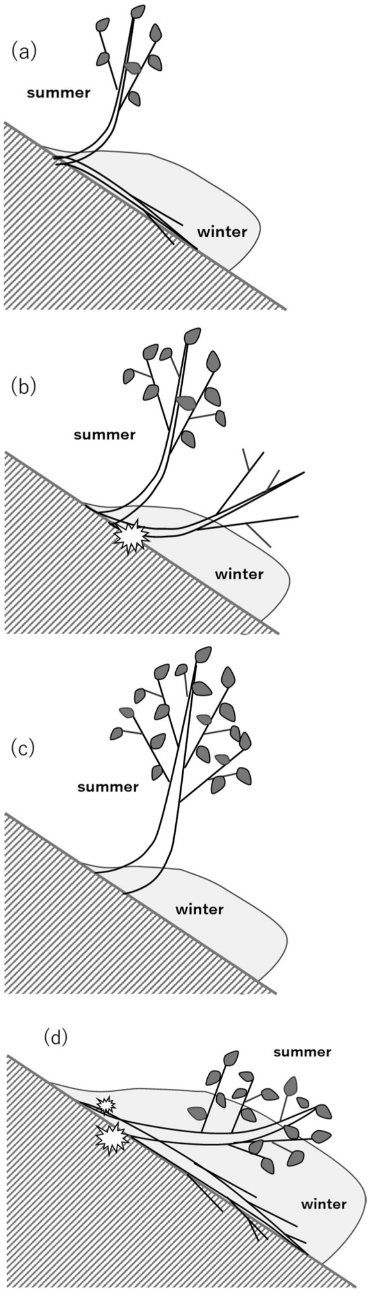

Fig. 8. Growth progress of the aboveground part of beech trees in snowy regions. (a) The trees lodge relatively easily on the ground surface during the snow-cover period once they have grown from seed to reach a DBH of several centimeters. (b) As growth thickness increases, trees resist the pressure of the snow and remain erect, which makes it difficult for them to lodge. Large stress is experienced by individuals with DBH ~10 cm. (c) Trees continue to increase in thickness and become capable of withstanding the snow pressure. (d) By contrast, if trees are exposed to excessive snow pressure over a long time, they continue to lodge on the ground surface, but large stresses are exerted on deformed tree trunks once they reach a DBH of 10 cm. Thickening induces a further increase in stress, causing the tree to be deformed.

angle and the maximum depth of the accumulated snow, as listed in Table 1. The following regression equation was obtained by multiple regression analyses (coefficient

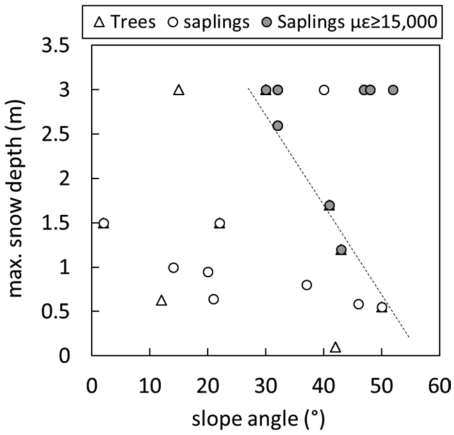

Fig. 9. Plots of beech tree individuals observed at both the Tadami and Kaneyama sites against the slope inclination angle and the maximum depth of accumulated snow. "Sapling" represents an individual with a DBH ≤10 cm. The broken line in the figure represents the boundary line dividing the two areas where tree individuals with a maximum strain <15,000 με were located.

of determination, $r^2=0.66$):

$$(\text{maximum strain})=154.1\times(\text{slope angle})+4527.3\times(\text{max. snow cover depth})-504.2 \tag{4}$$

Both the depth of the accumulated snow and the slope inclination angle have positive effects on the maximum strain (p value was <0.05, for coefficient of each explanatory variable), and large strains exceeding 15,000 με were observed in saplings when their combination exceeded a certain level, for example, when both the slope inclination angle and depth of accumulated snow exceeded 30° and 3 m, and 45° and 1.5 m, respectively (Fig. 9). The snow pressure of 50–170 kPa estimated using the maximum moment values for erect beech trees with a DBH of 15–30 cm (Nos. 11, 12, 14 & 16) indicates that beech trees struggled to grow in an erect position in more severe environments. Aiura (1996) showed that the amounts of snow glide and pressure were ~1 m and 100–300 kPa, respectively, during one winter season at a site with an accumulated snow depth >3 m and a slope inclination angle of ~35°, which is similar to the conditions on the upper NE slope at the Tadami site. Our estimated values are comparable to those of Aiura (1996). However, Homma (1997) estimated the snow pressure at a heavy-snowfall mountain site using Haefeli's snow-pressure estimation equation and demonstrated that erect beech trees might grow at snow-pressure levels of ~10–15 t per the area of (snow depth)×(1 m width). These values are equivalent to 30–50 kPa, assuming that the snow cover depth is 3 m. This value is quite small compared to the results of our study and that of Aiura (1996). However, it may be difficult to estimate snow pressure at a given point under local conditions. According to measurements by Yamaya and Tsukahara (1996), the snow pressure on a valley (concave) slope was about twice that on the ridge (convex) slope, even in places under the same local conditions. In the future, we aim to collect snow-pressure measurement data that will help us to quantitatively clarify the potential vegetation distribution regions for various species of trees, in addition to beech trees.

4.3 *Differences between cedars and beech trees*

We observed considerable differences in the physical properties of the live wood materials between the cedar and beech trees studied. Peltola *et al*. (1997) concluded in their snow-damage risk-prediction model that crown areas, where snow may deepen, are larger for evergreen needle-leaved trees than for deciduous broad-leaved trees, thus ensuring that the former are more susceptible to snow damage. However, our results showed no considerable differences in the bending moment exerted on the point of strain gauges between beech trees and cedars, both of which had the same DBH, although only small numbers of trees were measured. Thus, the primary differences between the beech and cedar trees measured in this study are the Young's modulus values and the degree of deformation of trunks. The Young's modulus and bending-strength values of cedars were approximately one-third and one-half those of beech trees, respectively (Table 3).

Our Young's modulus and bending strength values were lower than those previously reported. For air-dried wood, Young's modulus and bending strength are 10–13 GPa and 83–107 MPa for beech trees, and 7–10 GPa and 59–82 MPa for cedars, respectively (Department of Wood Materials, the Japanese Government Forestry Experiment Station, 1975). Generally, the physical properties of greenwood are usually weaker than those of air-dried wood. According to the Wood Handbook (Forest Products Laboratory, 2010), the Young's modulus and the modulus of rupture of green wood are ~80 % and ~60 % of the values of air-dried wood, respectively. According to Ido *et al*. (2012), the Young's modulus and the bending strength of round cedar timber under green and air-dried conditions were 7.75 and 7.93 GPa, and 56.0 and 59.8 MPa, respectively. Compared to these previous data, the values measured in our study were small. This could be caused by the conditions of our specimens differed from those commonly used for Young's modulus measurements: the two cedar individuals were decayed and blackened at their centers. Moreover, the Young's modulus of cedar trees differs among different cultivars. According to Yamashita *et al*. (2000), who measured 18 cedar cultivar, a dynamic Young's modulus was observed within the range of 3.63 to 9.71 GPa. The cedars at our study site probably have unusually small Young's modulus values.

Our results show that the trunks of cedars bent more easily than those of beech trees. Therefore, Japanese cedars have a disadvantage compared to beech trees in snowy regions in terms of their ability to grow into tall trees. Observation shows that cedar trees grow in more stable habitats, such as along ridges, than do beech trees. However, it is also thought that cedars take advantage of the elasticity of their trunks to overcome snow cover while young. To elucidate their growth strategy, we need to examine the differences in the growth rates of trunk diameters between cedars and beech trees, because wood strength is proportional to the cube of the diameter.

4.4 *Issues with strain gauge measurements*

This study shows that strain gauges can be used to determine the magnitude and time-course changes in stress in trees in the field during the snow-cover period. Installation of gauges at given locations in mountains and forests is not easy, and the risks include damage to the devices and snow breaking the wires of the strain gauges. Nevertheless, strain gauges are simple devices that can be used to monitor trees in the field for extended periods and serve as a very useful tool for mechanical studies of trees in their natural environment. However, there were limitations to this study, which should be addressed in future studies. First, the strain-gauge recordings of certain individuals did not return to zero, even after the snow had melted, and the reason for this was unclear. A possible reason is that plastic deformation caused resistance values to change as a result of a strong force being repeatedly exerted on the gauges. Another issue was that the method used to measure the deformation of trunks made it difficult to determine the cause of stress in some instances. For instance, pulsed changes in strain were notable in individuals at the Kaneyama site and in tree No. 4 at the Tadami site throughout the measurement period; the changes were small and were not notable in trees with a large DBH, as was clear when converted into stress. These sudden changes may not have been caused by snow. Considerable numbers of pulses seemed to occur on windy days, when a maximum instantaneous wind speed ≥ 10 m s^{-1} was observed at the local AMeDAS meteorological station, and thus may reflect the temporal influence of wind. However, paradoxically, strain gauges measure the total stress under environmental conditions. For example, loads from snow and wind may become problematic in trees with larger diameters, which maintain their erect shape even during the snow-cover period. Therefore, sufficient measurements should be taken using strain gauges to fully explain the processes underlying the occurrence of meteorological damage to erect trees in forests.

5. Conclusion

Deformation of the trunks of beech and cedar trees was measured using strain gauges during a snow-cover period in a field environment. The measurements revealed the magnitude of mechanical stress in trunks and the different patterns of stress during the snow-cover period: The patterns depended on the environment, tree size, and tree species. Our results are expected to elucidate growth processes and forest formation in snowy regions.

Acknowledgments

We would like to express our deepest gratitude to Dr. H. Ido and the Forestry and Forest Products Research Institute for operating the measuring instruments and collating the data measured in the bending tests, and to J-Power for providing the power source for the measurements at the Tadami-cho site. This study was subsidized by a Tadami-cho Grant-in-Aid for Scientific Research and The International Garden and Greenery Exposition Memorial Association.

References

Aiura, H., Kato, A. and Hasegawa, M. (1996): Occurrence of shallow landslides following uprooting of stumps after clear-cutting beech on heavy-snow mountain slopes (in Japanese with English summary). *J. Jpn. For. Soci.*, **78**, 150–156, doi:10.11519/jjfs1953.78.2_150.

Bebi, P., Kulakowski, D. and Rixen, C. (2009): Snow avalanche disturbances in forest ecosystems — State of research and implications for management, *For. Ecol. Manage.*, **257**, 1883–1892, doi:10.1016/j.foreco.2009.01.050.

Blackburn, G.R.A. (1997): The growth and mechanical response of trees to wind loading. Ph.D. Thesis, Manchester University, Manchester, UK.

Cannell, M.G.R. and Morgan, J. (1989): Branch breakage under snow and ice loads. *Tree Physiol.*, **5** (3), 307–317, doi:10.1093/treephys/5.3.307.

Charles, D., Leaphart, R. Hungerford, R.D. and Johnson, H.E. (1972): Stem deformities in young trees caused by snowpack and its movement. *USDA Forest Service Res. Note,* INT-158.

Cremer, K.W., Carter, P.R. and Minko, G. (1983): Snow damage in Australian pine plantations. *Aust. For.*, **46** (1), 53–66, doi:10.1080/00049158.1983.10674378.

Curtis, J.D. (1936): Snow Damage in Plantations. *J. Forestry*, **34** (6), 613–619, doi:10.1093/jof/34.6.613.

Department of Wood materials, the Japanese Government Forestry Experiment Station (1975): 300 species of world useful wood: A property and use (in Japanese). Wood Technological Association of Japan, Tokyo, Japan.

Díaz-Yáñez, O., Mola-Yudego, B., González-Olabarria, J. R. and Pukkala, T. (2017): How does forest composition and structure affect the stability against wind and snow? *For. Ecol. Manage.*, **401**, 215–222, doi:10.1016/j.foreco.2017.06.054.

Ennos, A.R. (1995): Development of buttresses in rain forest trees: the influence of mechanical stress. In *Wind and Trees.* Eds M.P., Coutts and J., Grace. Cambridge University Press, UK, pp 293–301.

Flesch, T.K. and Wilson, J.D. (1999): Wind and remnant tree sway in forest cutblock. Ⅱ. Relating measured tree sway to wind statics. *Agric For. Meteorol.*, **93**, 243–258, doi:10.1016/S0168-1923 (98) 00113-0.

Forest Products Laboratory (2010): Wood handbook—Wood as an engineering material. *General Technical Report* FPL-GTR-190, U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, Madison, 5–4–5–8.

Haefeli, R. (1939): Schneemechanik mit Hinweisen auf die Erdbaumechanik (in German). Ph.D. Thesis, ETHZ, Zürich, Switzerland.

Hanewinkel, M., Hummel, S. and Albrecht, A. (2011): Assessing natural hazards in forestry for risk management: a review. *Eur. J. For. Res.*, **130** (3), 329–351, doi:10.1007/s10342-010-0392-1.

Hlásny, T., Křístek, Š., Holuša, J., Trombik, J. and Urbaňcová, N. (2011): Snow disturbances in secondary Norway spruce forests in Central Europe: regression modeling and its implications for forest management. *For. Ecol. Manage.*, **262** (12), 2151–2161, doi:10.1016/j.foreco.2011.08.005.

Höller, P., Fromma, R. and Leitinger, G. (2009): Snow forces on forest plants due to creep and glide. *For. Ecol. Manage.*, **257** (2), 546–552, doi:10.1016/j.foreco.2008.09.035.

Homma, K. (1997): Effects of snow pressure on growth form and life history of tree species in Japanese beech forest. *J. Veget. Sci.*, **8**, 781–788, doi:10.2307/3237022.

Ido, H., Nagao, H., Kato, H. and Miura, S. (2012): Strength properties and effect of moisture content on the bending and compressive strength parallel to the grain of sugi (*Cryptomeria japonica*) round timber. *J. Wood Sci.*, **59** (1), 67–72, doi:10.1007/s10086-012-1297-z.

Kajimoto, T., Seki, T., Ikeda, S., Daimaru, H., Okamoto, T. and Onodera, H. (2002): Effects of snowfall fluctuation on tree growth and establishment of subalpine *Abies mariesii* near upper forest-limit of Mt. Yumori, northern Japan. *Arct. Antarct. Alp. Res.*, **34** (2), 191–200, doi:10.1080/15230430.2002.12003484.

Margreth, S. (2007): Defense structures in avalanche starting zones. *Technical guideline as an aid to enforcement.* Environment in Practice no. 0704. Federal Office for the Environment, Bern; WSL Swiss Federal Institute for Snow and Avalanche Research SLF, Davos, 134 pp.

Martín-Alcón, S., González-Olabarria, J.R. and Coll, L. (2010): Wind and snow damage in the Pyrenees pine forests: effect of stand attributes and location. *Silva Fennica*, **44** (3), 399–410, doi:10.14214/sf.138.

Milne, R. (1991): Dynamics of swaying *Picea sitchensis*. *Tree Physiol.*, **9** (3), 383–399, doi:10.1093/treephys/9.3.383.

Minamino, R. and Tateno, M. (2014): Variation in susceptibility to wind along the trunk of an isolated Larix kaempferi (Pinaceae) tree. *Am. J. Bot.*, **101** (7), 1085–1091, doi:10.3732/ajb.1400135.

Moore, J.R., Gardiner, B.A., Blackburn, G.R.A., Brickman, A. and Maguire, D.A. (2005): An inexpensive instrument to measure the dynamic response of standing trees to wind loading. *Agric. For. Meteor.*, **132**, 78–83, doi:10.1016/j.agrformet.2005.07.007.

Onodera, H., Tanabe, H., Kajimoto, T. and Daimaru, H. (1995): Snow dynamics and ecological characteristics of tree on snowy mountain slope (in Japanese with English summary). *Jpn. J. For. Environ.*, **37**, 59–66.

Päätalo, M.L., Peltola, H. and Kellomäki, S. (1999): Modelling the risk of snow damage to forests under short-term snow loading. *For. Ecol. Manage.*, **116** (1–3), 51–70, doi:10.1016/S0378-1127 (98) 00446-0.

Peltola, H., Nykänen, M. L. and Kellomäki, S. (1997): Model computations on the critical combination of snow loading and windspeed for snow damage of scots pine, Norway spruce and Birch sp. at stand edge. *For. Ecol. Manage.*, **95** (3), 229–241, doi:10.1016/s0378-1127(97)00037-6.

Suzuki, S., Sakamoto, T. and Noguchi, H. (2016): Wind damage risk estimation for strip cutting under current and future wind conditions based on moment observations in a coastal forest in Japan. *J. For. Res.*, **21** (5), 223–234, doi:10.1007/s10310-016-0539-0.

Shidei, T. (1954): Studies on the damage on forest tree by snow pressures (in Japanese with English summary). *Bulletin of Forestry and Forest Products Research Institute*, **73**, 1–89.

Takahashi, K., Kataoka, K. and Sato, S. (1968): Pressure of Snow Cover acting on Trees (1) (in Japanese with English summary). *Bulletin of Forestry and Forest Products Research Institute*, **210**, 155–174.

Tani, K. (2015): Development of 'Web contour maker' and the algorithm using the elevation tile (in Japanese). *Saitama Univ. Department of Geography occasional paper*, **35**, 78–83.

Tanimoto, T. (1993): Sprouting of beech (*Fagus crenata* Blume) in the regeneration of the beech forests and its environmental condition (in Japanese with English summary). *J. Jpn. Soci. For. Environ.*, **35** (1), 42–29.

Valinger, E. and Fridman, J. (1997): Modelling probability of snow and wind damage in Scots pine stands using tree characteristics. *For. Ecol. Manage.*, **97** (3), 215–222, doi:10.1016/S0378-1127 (97) 00062-5.

Viglietti, D., Maggioni, M., Bruno, E., Zanini, E. and Freppaz, M. (2013): Snow gliding and loading under two different forest stands: a case study in the north-western Italian Alps. *J. For. Res.*, **24** (4), 633–642, doi:10.1007/s11676-013-0401-6.

Wallentin, C. and Nilsson, U. (2014): Storm and snow damage in a Norway spruce thinning experiment in southern Sweden. *Forestry*, **87**, 229–238, doi:10.1093/forestry/cpt046.

White, R. G., White, M. F. and Mayhead, G. J. (1976): Measurement of the Motion of Trees in Two Dimensions, Tech. Report 86. Institute of Sound and Vibration Research, University of Southampton, 22 pp.

Yamanoi, K. (2006): Snow Cover Stability and Avalanche Protection on Coppice Forest Slopes (in Japanese with English summary). Ph.D. Thesis, Niigata University, Niigata, Japan.

Yamashita, K., Hirakawa, Y., Fujisawa, Y. and Nakada, R. (2000): Effects of microfibril angle and density on variation of modulus of elasticity of Sugi (*Cryptomeria japonica*) logs among eighteen cultivars (in Japanese with English summary). *J. Jpn. Wood Res. Soci.*, **46** (6), 510–522.

Yamaya, M. and Tsukahara, H. (1996): Differences of snow pressure on partial sloping forms (in Japanese with English summary). *J. Jpn. Soci. Snow Ice 'Seppyo'*, **58** (6), 463–468, doi:10.5331/seppyo.58.463.

Zhu, J., Li, X., Liu, Z., Cao, W., Gonda, Y. and Matsuzaki, T. (2006): Factors affecting the snow and wind induced damage of a montane secondary forest in northeastern China. *Silva Fennica*, **40** (1), 37–51, doi:10.14214/sf.351.