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Source: Arctic, Antarctic, and Alpine Research, 37(1) : 34-40

Published By: Institute of Arctic and Alpine Research (INSTAAR), University of Colorado

URL: https://doi.org/10.1657/1523-0430(2005)037[0034:MDOAMT]2.0.CO;2

Arctic, Antarctic, and Alpine Research, Vol. 37, No. 1, 2005, pp. 34–40

Mechanical Damage on *Abies mariesii* Trees Buried below the Snowpack

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Abstract

On a gentle leeward slope in a snowy forest limit in northern Honshu Island, Japan, mechanical damage by snow settlement and creep on *Abies mariesii* trees buried below the snowpack was examined to detect signs of the snow-damage effect on future survival and crown development. Damage types were recorded based on direct observation of crowns in 1996, a year of high snow accumulation exceeding 4.5 m, and 1997, a year of moderate snow accumulation. Of 153 trees examined, 63% were damaged in 1996 and 15% were damaged in 1997. The most destructive damage type was breakage of stems $\geq$5 cm in diameter, which occurred on eight trees in 1996 and three in 1997, resulting in foliage loss and death of some trees. The prevalent damage type was branch tearing at branch-stem junctions primarily within a height range of 4–6 m, which occurred on 171 branches in 1996 and 5 in 1997. Under snowy and windy conditions, stem breakage and branch tearing, caused by forces active within restricted layers of the snowpack, may reduce the future survival and crown development of *A. mariesii* buried below the snowpack in years of heavy snowfall.

Introduction

Tree crowns below the snowpack are sometimes mechanically damaged (Ishizuka, 1981; Minnich, 1984; Morin and Payette, 1986; Boivin and Bégin, 1997; Kajimoto et al., 2002). In general, the snowpack protects these crowns from cold air, wind-blown snow or ice particles, and desiccation in cold regions such as subarctic forest tundra or treeline (Hadley and Smith, 1986; Payette and Filion, 1985; Lavoie and Payette, 1992; Scott et al., 1993; Payette et al., 1996; Boivin and Bégin, 1997), but snowpack-induced damage also occurs in these regions (Morin and Payette, 1986; Boivin and Bégin, 1997).

In cold regions, snowpack-induced damage on tree crowns is rather restricted to local regions under the current climatic regimes (Ishizuka, 1981; Minnich, 1984; Takaoka, 1999; Yamanaka et al., 1973), in comparison with frost desiccation damage in winter (Tranquillini, 1979; Wardle, 1981; Hadley and Smith, 1983, 1986) and needle removal by windblown snow and ice particles above the snowpack (Scott et al., 1993). However, the increase of snowfall through climatic change can affect tree growth. For instance, narrow tree rings during years of heavy snow are shown for *Picea mariana* trees in a subarctic forest-tundra site where over-accumulation of windblown snow and accompanying increase of snow depth affected dense stands developed after climatic warming (Boivin and Bégin, 1997). Under the ongoing global climate change, snowpack-induced mechanical damage may increase in some regions where snow accumulation increases.

Effects of snowpack-induced mechanical damage on the survival and crown development of damaged trees are different depending on the damage types or portions. For instance, in *Abies* and *Picea* with conical-shaped crowns, stem breakage near the crown base is almost always fatal due to loss of large numbers of branches. On the other hand, stem breakage in the upper portions of the crown does not affect the survival but decreases height growth. Thus, it may be helpful to examine damage types and portions in order to predict future survival and crown development of the damaged trees.

Abies mariesii is one of the tree species that forms forest limits in snowy regions in north to central Honshu Island in Japan (Kaji, 1982; Sugita, 1992). At forest limits in these regions, upper portions of crowns are exposed to prevailing western winds. This exposure occurs not only on west-facing slopes or ridges but also on east-facing slopes, where snowdrift is formed by western winds. Since *A. mariesii* trees are sometimes buried below the snowpack by snowdrift (Ishizuka, 1981), *A. mariesii* crowns on the east-facing slopes in the snowy regions may be affected by both snow-induced mechanical damage and wind-induced damage, e.g., frost desiccation.

This study examines mechanical damage on *A. mariesii* trees buried below the snowpack to a depth >4.5 m during the winter of 1996 as a result of heavy snowfall, near the forest limit where the canopy consists of only *A. mariesii* (Kajimoto et al., 2002). Based on the types and positions of snowpack-induced damage, we discuss the process of snow damage and the effect of damage on further survival and crown development.

Materials and Methods

STUDY SITE

This study was conducted on an east-facing slope (39°46′N, 140°50′E) on Mount Yumori (1472 m a.s.l.) in the Ohu mountains, northern Honshu Island, Japan (Fig. 1). The bedrock of the study site is characterized by Quaternary andesite originating from the Yumori volcano, whose crater is not well defined (Suto and Ishii, 1987). Mean annual air temperature at the study site (1360 m a.s.l.) is 2.8°C, the mean air temperature for the coldest month (February) is −10.2°C, and that of the warmest month (August) is 17.0°C (October 1998 to September 2001), measured with a thermo-recorder (TR-52, T&D Co., Ltd.) set at 7 m in height above the maximum snow level in winter on a dead *A. mariesii* stem. Mean summer precipitation from July to September is 1160 mm at Komagatake station (1003 m a.s.l.), 4 km south of our study site (Iwate Meteorological Observatory, 1982–1998).

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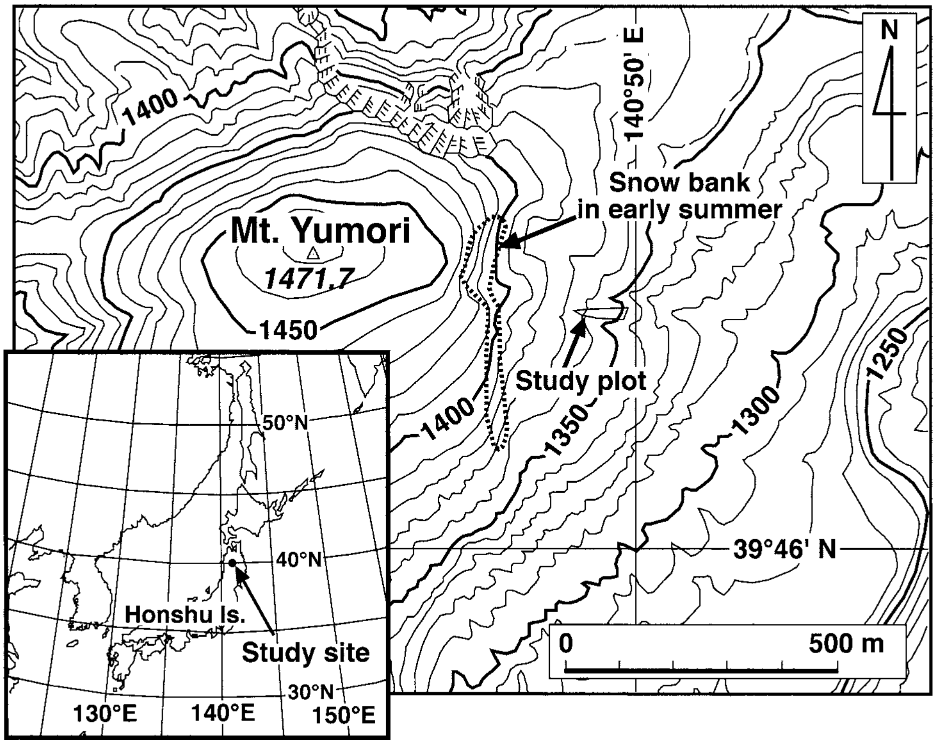

FIGURE 1. Location map of the study site. The boundary of the snow bank in early summer fluctuates annually and seasonally due to winter snowfall and summer temperature.

Vegetation around the study site consists of subalpine forests, snow-patch communities, dwarf scrubs, and dwarf bamboo scrubs. Subalpine forests are distributed at elevations of 1100–1370 m on gentle slopes dominated by *A. mariesii* together with some broad-leaved shrubs, such as *Acer tchonoskii*, *A. ukurunduense*, *Sorbus commixta*, and *Ilex sugerokii* var. *brevipedunculata*. Snow-patch communities, consisting of grasses (*Calamagrostis fauriei*, *Carex blepharicarpa*) and an herb (*Fauria crista-galli*) with a dwarf shrub (*Phyllodoce aleutica*), are formed on the upper part of the east-facing steep concave slope at 1370–1440 m in altitude, where snow banks generally remain until June or August (Fig. 1). Dwarf scrubs, consisting of dwarf conifers (*Pinus pumila*, *Juniperus communis* var. *nipponica*) and broad-leaved woody species (e.g., *Vaccinium ovalifolium*, *V. smallii*, *Rhododendron brachycarpum*, *Ledum palustre*) (Kajimoto et al., 1998), are distributed on the exposed gentle ridge and the summit of Mount Yumori, above 1420 m. Dwarf bamboo (*Sasa kurilensis*) scrubs are widespread on both gentle and steep slopes where the snow-patch community or dwarf scrub is absent. The bamboo grows densely on the ground surface without the cover of *A. mariesii* and/or broad-leaved shrubs.

In September 1994, a study plot of ca. 0.24 ha was established in a forest limit formed by scattered patches of *A. mariesii* canopy trees (Fig. 2), on the east-facing gentle slope from 1350 to 1370 m (Fig. 1). On the slope, snow accumulates not only by snowfall but also due to the prevailing west wind. Accumulated snow in the forest limit reaches nearly 3 m in mid-March in usual years and remains until late May to

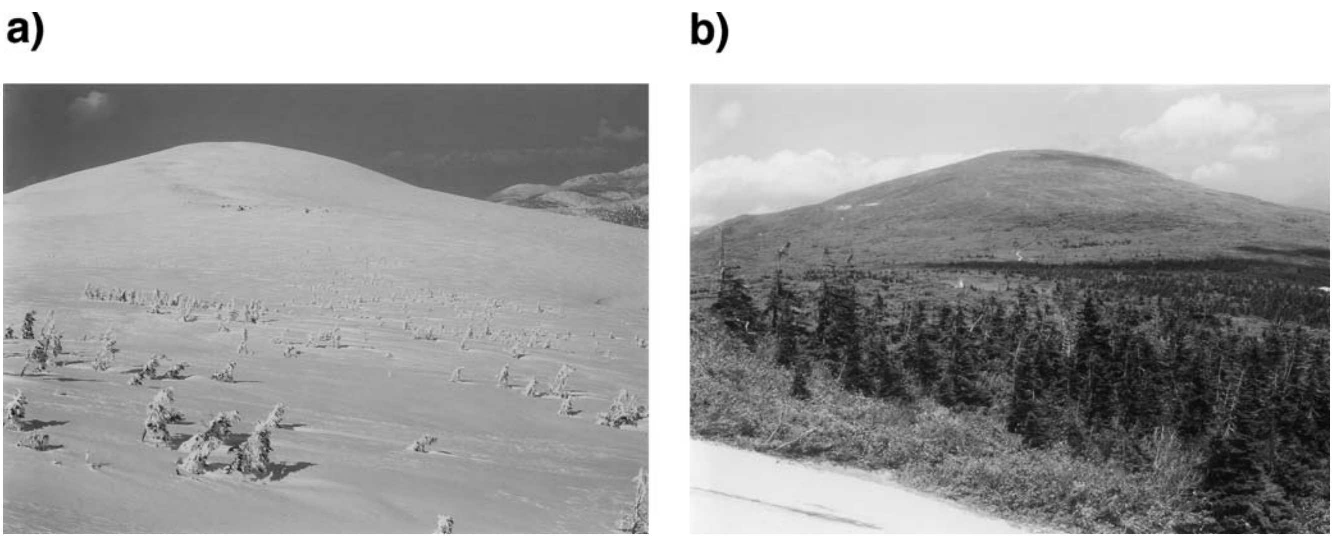

FIGURE 2. Forest limit of Abies mariesii *trees at the study site. These photographs were taken from south to north. (a)* A. mariesii *trees directionally inclined or bent east which were partly buried in snowpack over 4.5 m in depth on 22 April 1996. (b)* A. mariesii *trees standing erect with sparse branches on western side of the crowns after snowmelt on 2 July 1996.*

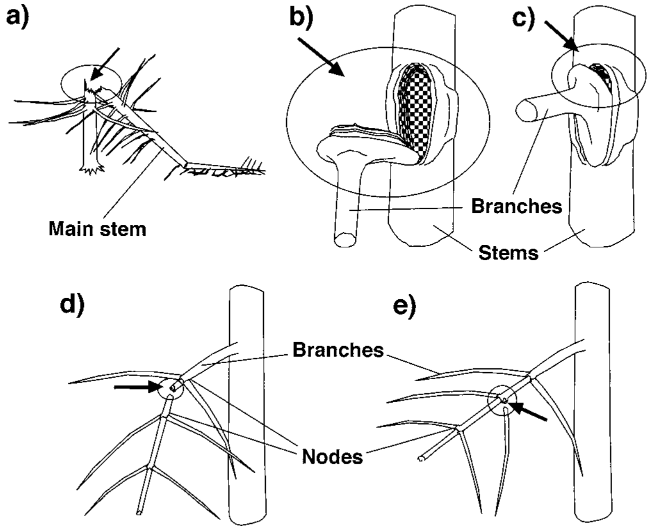

FIGURE 3. Major snow-damage types that occurred in 1996 and 1997. Arrows and circles show the damaged parts. (a) Stem breakage. (b) Branch tearing at branch-stem junction (TJ). (c) Crack at branch-stem junction (CJ). (d) Branch breakage at internode (BI). (e) Branch breakage at node (BN).

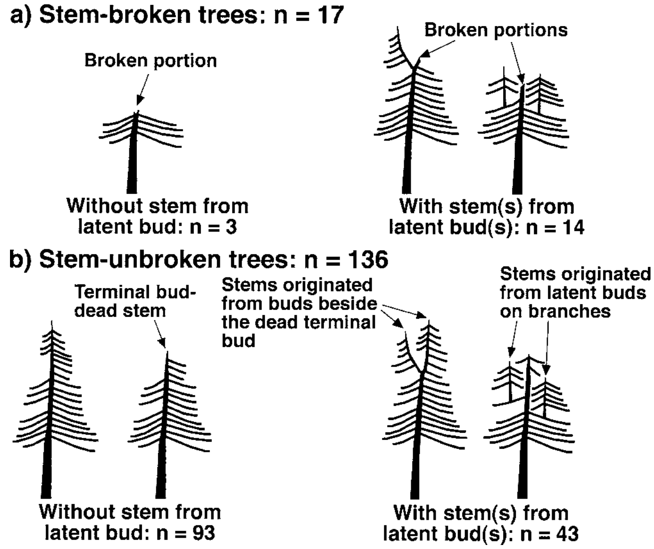

FIGURE 4. Trees with broken stems before snow damage in 1996 and trees without these stems. The existence of stems originating from latent buds before 1996 is also shown. (a) Trees with broken stems. (b) Trees without broken stems.

late June. In 1996, however, mean snow depth in the study site was 4.7 m on April 30. Snow depth in 1997 was 2.9 m on March 13, which was almost the usual-year level (Seki et al., 2000; Kajimoto et al., 2002).

STEM TYPES AND SNOW-DAMAGE TYPES

In the summer of 1996, stem breakage (Fig. 3a) from the previous winter was checked for 153 trees, of which heights and diameters at breast height, 1.3 m high, were already measured at the study plot. After that, stem breakage before 1996 was examined. For both trees with broken stems before 1996 and trees without these stems, the existence of stems originating from latent buds before 1996 was checked (Fig. 4). These latent-bud-originating stems were also checked for fallen stems of stem-broken trees in 1996. In the summer of 1997, newly occurring stem breakage was recorded.

Damage was surveyed and recorded from the crown top to the ground by accessing the crowns after snowmelt. Free tree climbing was adopted for access to the sample trees taller than 4.5 m, while access with a ladder was adopted for trees shorter than 4.5 m in order to preserve crowns from destruction by the survey. After marking this damage, the above-ground height of each occurrence was recorded. Directions faced by snow damage were also recorded.

The survey of damage was conducted for trees without broken stems ≥5 cm in diameter at the break. On the other hand, damage was not surveyed for the trees with broken stem(s) of such size because most of these broken stems had fallen to the ground, suggesting that some of the damage on the fallen stem(s) was caused by the falling.

Damage was classified into several breakage types according to the morphology. With respect to the damage at branch-stem junctions, branch tearing that leads to branch loss was distinguished from cracking that leaves the damaged branches (Fig. 3b, c). For the breakage on branches, breakage on internodes was distinguished from that on nodes (Fig. 3d, e).

INCLINATION OF STEMS PARTLY BURIED IN SNOWPACK

To estimate the prevalent directions of stem inclination below the snowpack at the study site, the directions of stem inclination were examined for the stems partly buried below snowpack in mid-March of 2002 when the snow depth was about 3 m.

Results

NUMBER AND SIZE OF SNOW-DAMAGED TREES

Of the 153 trees initially examined, 96 trees (63%) were damaged in 1996. After 2 trees died in the summer of 1996, 23 (15%) of the remaining trees were damaged in 1997, when snow depth was lower than 1996 (Seki et al., 2000; Kajimoto et al., 2002).

In 1996, trees in all height classes were snow damaged. Nearly half of the trees in the 3–4 m class were damaged, and nearly 80% or more were damaged in the classes ≥4 m (Fig. 5a). In 1997, the percent of damaged trees in individual height classes was almost 30%, being lower than that in the same classes of 1996, except in the 1.3–2 m class (Fig. 5b).

STEM BREAKAGE

During the study period, the most destructive snow damage was stem breakage. For trees with broken stem(s) ≥5 cm in diameter at the breaks (DB), 8 trees were stem-broken in 1996 and 3 trees in 1997 (Table 1, Fig. 5). Stem breakage on 1 tree (no. 342) had occurred on the main stem cracked in 1996 (TS, personal observation). Break height (BH) ranged from 1.0 to 4.3 m (Table 1), being lower than the maximum snowpack depth. The breaks were located in mid- to lower portions of the crowns for most of these stem-broken trees. With respect to crown development, most of these stem-broken trees had developed stems from latent buds (Table 1). For trees with broken stem(s) <5 cm in DB, 7 trees were stem broken in 1996 and 1 tree in 1997 (Table 2, Fig. 5).

Stem breakage in 1996 and 1997 occurred in most height classes (Fig. 5). In particular, ≥20% of the trees in the 5–6 m class were stem broken in 1996. On the other hand, there were no stem-broken trees in the 2–3 m class during this 2-year period.

Before the snow damage in 1996, 17 of the 153 trees (11%) were broken on their stems (Fig. 4). Of the 17 stem-broken trees, 14 trees (82%) had stems originating from latent buds. On the other hand, of

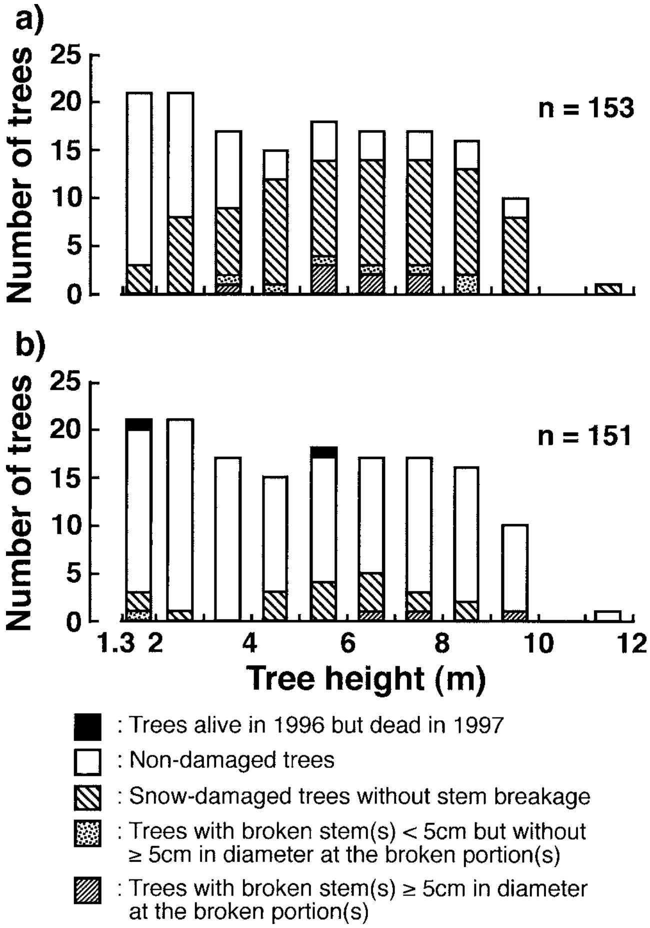

FIGURE 5. Numbers of snow-damaged and undamaged trees in tree-height classes. Of snow-damaged trees, stem-broken trees are shown as different patterns from those for trees without broken stems.

the other 136 trees without broken stems, 43 trees (32%) had latent-bud-originating stems, indicating that stem-broken trees had a higher probability of stem development by latent buds than trees without broken stems (Fisher's exact probability: $p = 0.000071$).

TABLE 1

Trees with broken stems $\geq$5 cm in diameter at the break by snow damage in 1996 and 1997. Breakage height (BH) is the lowest height of the break. Crown-base height (CBH) was measured for living trees in 1998. DBH is the stem diameter measured at 1.3-m height.

Year of break	Tree no.	DBH (cm)	H (m)	BH (m)	CBH (m)	Past stem breakage	Stem(s) from latent bud(s)
1996	219	22.1	3.6	1.0	[a]	−	−
	260	19.8	6.0	3.0	1.4	−	+
	268	27.0	5.7	4.3	1.8	−	+
	270	24.4	5.2	2.8[b]	1.2	+	+
	278	26.7	7.1	4.0	1.2	−	−
	287	29.5	5.1	2.6	[a]	−	+
	293	27.5	6.9	2.9	1.3	−	+
	341	29.8	7.4	4.3[b]	1.9	+	+
1997	329	17.3	6.2	1.3	[a]	−	+
	341	29.8	4.3	3.7[b]	1.9	+	+
	342	32.4	9.1	2.1	[a]	−	+

[a] Dead trees in 1998.

[b] Breakage on stems originating from latent buds.

TABLE 2

Numbers of trees and major types of snow damage in 1996 and 1997.

Damage type	1996 Number of trees	1996 Number of parts	1997 Number of trees	1997 Number of parts
Branch tearing at branch-stem junction (TJ)	61 (70%)	171 (64%)	5 (29%)	5 (28%)
Crack at branch-stem junction (CJ)	21 (24%)	24 (9%)	2 (12%)	2 (11%)
Branch breakage at internode (BI)	19 (22%)	28 (11%)	2 (12%)	2 (11%)
Branch breakage at node (BN)	16 (18%)	16 (6%)	3 (18%)	3 (17%)
Stem breakage <5 cm in diameter at the break (SBtip)	7 (8%)	7 (3%)	1 (6%)	1 (6%)
Others	13 (15%)	20 (8%)	5 (29%)	5 (31%)
Total damage	87 (100%)	266 (100%)	17 (100%)	18 (100%)

Note: Trees with broken stems $\geq$5 cm in diameter at the break were excluded. Numbers in parentheses indicate the percentage to total damaged trees or parts. Because several trees have more than one type of damage, the sum of percentages for damaged trees exceeds 100%.

PREVALENT DAMAGE TYPE AND DAMAGED POSITIONS

For trees without broken stems $\geq$5 cm in DB, total numbers of damaged trees were 87 in 1996 and 17 in 1997 (Table 2). In 1996, of the 87 trees, 61 trees (70%) had branch tearing at branch-stem junction (TJ), followed by a crack at the junction (CJ) (24%), branch breakage at an internode (BI) (22%), branch breakage at a node (BN) (18%), and stem breakage at a portion <5 cm in DB (SBtip) (8%) (Table 2, Fig. 3). Damaged trees in 1997 were fewer than those in 1996 for all the damage types (Table 2).

With respect to damage, total numbers were 266 in 1996 and 18 in 1997 (Table 2). In 1996, of the 266, the prevalent damage type was TJ with 171 (64%) (Table 2, Fig. 3). Instances of damage in 1997 were also fewer than those in 1996 for all damage types (Table 2). For these damage types, the average number of instances of damage per tree exceeded 2 only for TJ in 1996, whereas the number did not reach 2 for the other types in 1996 and for all types in 1997 (Table 2).

Of the 61 trees with TJ in 1996, the number of torn branches was generally low, with 1 torn branch on 30 trees (45%) and 2 torn branches on 11 trees (18%). On the other hand, 8 branches or more were torn on 5 trees (8%); in particular, there were 20 branches torn on 1 tree (Fig. 6).

The torn-branch heights for trees with TJ in 1996 were concentrated from 4 to 6 m for $\geq$4 m tree-height classes, with 40 of 55 branches (73%) in the 4–6 m tree-height class, 68% in the 6–8 m class, and 83% in the 8–10 m class (Fig. 7a). On the other hand, the torn-branch heights in 1997 were scattered among various heights (Fig. 7b).

The directions of torn branches for trees with TJ in 1996 were biased toward western directions, with 77 of the 171 branches (45%) north to west and 50 (29%) south to west (Fig. 8a). The torn-branch directions were significantly different from an even distribution ($\chi^2 = 53.70$, $p < 0.00001$). The directions of torn branches in 1997 were not significantly biased toward any direction, but 4 of the 5 torn branches had western directions (Fig. 8b).

INCLINATION OF STEMS PARTLY BURIED IN THE SNOWPACK

In late April of 1996, when the snowpack depth was over 4.5 m (Seki et al., 2000; Kajimoto et al., 2002), stems above the snowpack

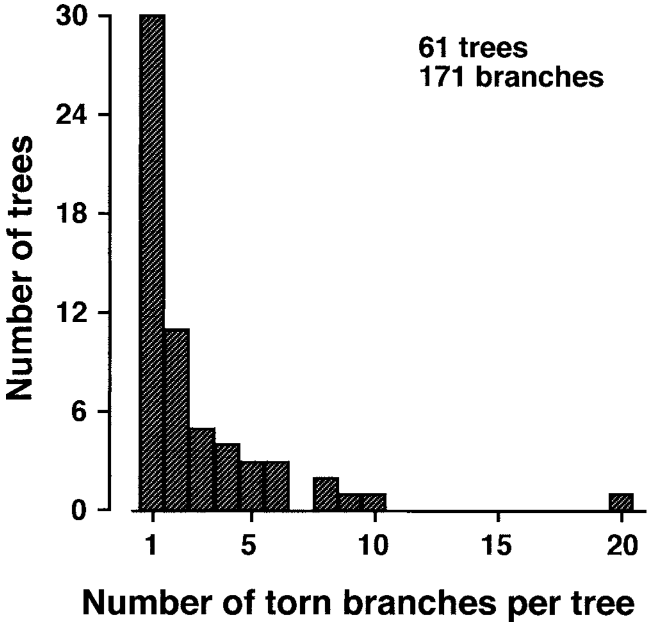

FIGURE 6. Distribution of the number of branches torn in 1996 per tree.

were inclined or bent in eastern directions (Fig. 2a). At the measurement in mid-March of 2002, when the stems were partly buried in the snowpack, the directions of stem inclination were clearly concentrated east to south (Fig. 9), with 54 of 64 stems (84%).

Discussion

PREVALENT SNOW-DAMAGE TYPES AND POSITIONS

Prevalent damage types and positions on the snow-buried trees are affected by (1) the mechanical characteristics of trees, (2) the tree form below the snowpack, and (3) the vertical distribution of forces below the snowpack.

For mechanical characteristics of trees, branch-stem junctions may experience notch and shear stresses rather than branches or stems themselves because these junctions are connecting portions of different-oriented axes, between branches and stems. For notch stresses, since downward forces on branches by snow settlement divert from branch- to stem axes, the junctions connecting these axes may experience notch stresses with deformation of these junctions by stem bending below the snowpack over 4.5-m depth, in contrast to normal-shaped junctions that can avoid notch-stress concentration by optimized structure (Mattheck, 1995). In comparison with notch stresses through the force diversion from branches, shear stresses can occur directly on these junctions, where the main stem and primary branches are nearly right-angled. For several conifer species developing these right-angled junctions, branch tearing occurs on snow-buried trees on the gentle slopes and flat planes, e.g., *Larix kaempferi* (Ishikawa et al., 1970), *Picea glauca* (Morin and Payette, 1986), and *P. mariana* (Morin and Payette, 1986; Boivin and Bégin, 1997), suggesting that shear stresses by snow settlement and snow creep tend to occur on right-angled junctions connecting the erect-standing stems and the horizontally developed primary branches. For branch tearing of *A. mariesii* in this study (Fig. 3b), the degrees of notch- and shear stresses on branch-stem junctions were uncertain, but such stresses may have occurred on the same trees.

With respect to the component of tree form below the snowpack, the directions of stem inclination may have affected the torn-branch base directions, with a bias toward western directions (Fig. 8a). Based on eastern-oriented stem inclination for partly snow-buried stems in spring (Figs. 2a and 9) and the right-angled branch-stem junctions, many western-facing branches of completely snow-buried stems may have been ascendant from the inclined stems. For the right-angled junctions, since the ascendant branches experience a larger moment of rotation by downward forces than the pendant ones, shear stresses on the junctions at the bases of the ascendant branches are stronger than those of the pendant ones. Thus, stem inclination below the snowpack might have caused the bias of torn branches toward western directions within individual damaged trees.

The stem inclination of *A. mariesii* trees below the snowpack may have been caused by biased snow accumulation on branches among directions and snow movement below the snowpack. Accumulated snow on the eastern-facing branches is heavier than that on the western-

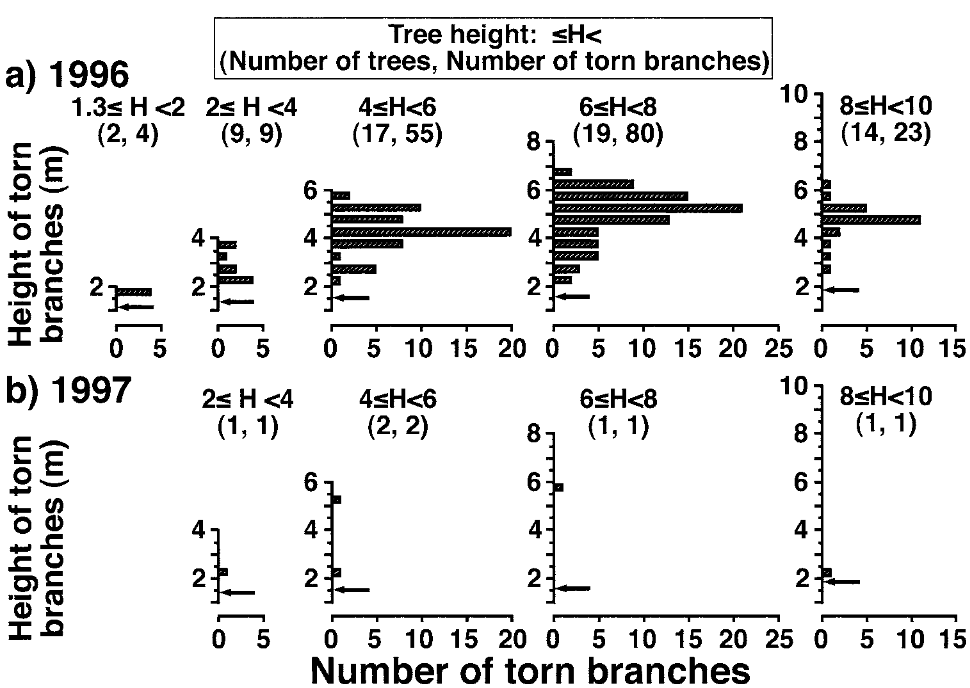

FIGURE 7. Distribution of the number of torn-branch heights in each tree-height class. Arrow indicates the mean height of the crown base in each height class. (a) Branches torn in 1996. (b) Branches torn in 1997.

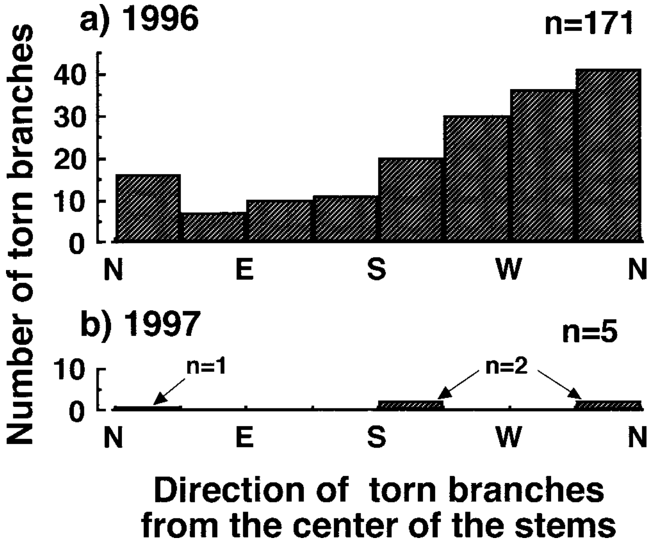

FIGURE 8. Distribution of directions faced by torn-branch bases. (a) Branches torn in 1996. (b) Branches torn in 1997.

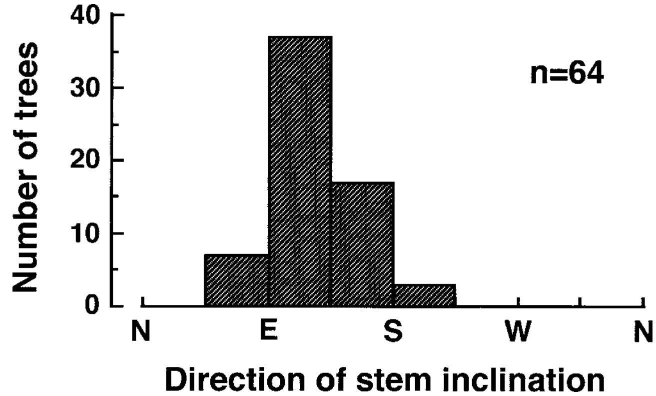

FIGURE 9. Distribution of inclined directions of stems partly buried in snowpack in mid-March of 2002.

facing ones, because the former branches retain dense needles more than the latter ones, which have less ability to capture snow (Fig. 2). This might result in stem inclination toward eastern directions. For snow movement, snowdrift due to the prevailing western wind can deposit much snow in front of the western-faced surface of stems, and movement of the snowpack, such as snow creep, can occur along a gentle slope (10° inclination) from west to east. Snowdrift combined with snow creep might contribute to the eastern-oriented stem inclination of *A. mariesii*.

For the vertical distribution of forces below the snowpack, snow settlement and snow creep may have been effective within a restricted height range because of the concentration of torn-branch bases 4–6 m high (Fig. 7a). On the other hand, some damage, in particular higher than 6 m, may not have been affected by snow movement due to location above the maximum snow level, according to snowpack depth in spring (Seki et al., 2000; Kajimoto et al., 2002). Strong wind with snow above the snow level can be a possible cause of branch tearing at this height. Despite such uncertainty of the height range of snow activity, heavy snow accumulation in extremely snowy winters can cause damage on the mid- to upper portions of tree crowns at the snowy forest limit.

EFFECT OF SNOW DAMAGE ON SURVIVAL AND CROWN DEVELOPMENT

Snowpack-induced damage on *A. mariesii* trees leads to death if large numbers of branches are lost to the damage. Branch loss decreases not only the foliage but also latent buds that can develop stems and/or branches. Therefore, branch loss caused by snowpack-induced damage affects the future survival and crown development of the damaged trees. Branch tearing at branch-stem junctions and stem breakage are the types of damage that caused branch loss during the 1996 and 1997 winters.

For more than half of the branch-torn trees, the effect of branch loss may be low because the average number of torn branches per tree was only 1 or 2 (Fig. 6). However, only 1 tree with 20 torn branches died from this branch tearing after 5 years (TS, personal observation), suggesting that branch tearing is harmful to the survival within several years if large numbers of branches are torn.

Besides branch loss, branch tearing from the stems causes xylem wounding in the stems. Xylem wounding destroys tracheids, resulting into the reduction of water transportation above the destroyed parts, in particular, in the windy environment at forest limits. To determine this possibility, the effect of xylem wounding caused by branch tearing should be estimated on the basis of anatomical and physiological methods.

In contrast to branch tearing, stem breakage can lead to the death of individual trees within a few years if the breakage occurs near the crown base, due to the loss of large numbers of branches. Stem breakage in 1996 and the breakage in 1997 on 1996's cracks on stems are examples of such branch loss. For the snow-damaged trees, the 4 of 10 with breakage on stems $\geq$5 cm in diameter were dead within 2 years after the breakage (Table 1), indicating that breakage on thick stems was harmful to survival.

This short-period death after stem breakage may affect growth-form composition at the snowy forest limit. For instance, the number of newly stem-broken trees in 1996 and 1997 winters ($n = 15$; TS, personal observation) are not simply added to that of the living trees with stem(s) broken before 1996 ($n = 17$, Fig. 4). If several stem-broken trees die during the short period after the breakage, the number of living trees with broken stem(s) will not increase easily. Several disturbances at this site, suggested by dendrochronological analyses (Kajimoto et al., 2002), might also enhance the short-period death for the stem-broken trees.

This study suggested that the future survival of snow damaged *A. mariesii* trees is affected by the extent of branch loss. However, as shown in previous studies (Hadley and Smith, 1983; Scott et al., 1993; Payette et al., 1996), the forest limit is also a windy environment that sometimes reduces the activity of branches, stems, and latent buds on these branches and stems. Thus, crown development after mechanical damage (i.e., traumatic reiteration; Bégin and Filion, 1999) may be affected by both snow and wind. The combined effects of snow and wind should be investigated in future studies to understand the dynamics of tree crowns in snowy environments.

Conclusions

At the forest limits in snowy regions, all or part of the crowns of short trees are sometimes buried below the snowpack. For the snow-buried trees, snow movement in years of heavy snowfall causes stem breakage and branch tearing within a height range, resulting in branch loss and xylem wounding. The mechanism of these types of damage will be one of the keys to the prediction of future survival and crown development. For the mechanism, the effects of snow-accumulation patterns on snow movement are still unclear. Understanding of these effects may be useful to predict the dynamics of forest limits in snowy regions with ongoing global change.

Acknowledgments

We thank Y. Bégin, Y. Ichihara, and Y. Masuya for valuable comments about the manuscript. We also thank H. Onodera, T. Otani, and T. Saitoh for help with the field survey. We thank the Aomori District forest office of the Forest Agency for helpful suggestions for the field survey. This study was financially supported by the Japan Environment Agency as a research project: Effects of Global Warming on Local Vegetation and the Conservation in Asian-Pacific Regions (B-52).

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Ms submitted December 2003