Frost Damage on Basal Stems in Young Trees*

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Abstract

To clarify the mechanism of frost damage on basal stems in young trees, some experiments were made using various trees. The basal stem near the ground surface is exposed to a remarkable fluctuation in temperature, especially to a sharp drop in temperature due to radiation at night. Also, the frost resistance of the basal part on a stem was invariably lower than that of the upper part, the difference between the two amounting to about 7 to 10°C. From these facts, it is apparent that basal stem is very sensitive to frost damage. It was also demonstrated that osmotic concentration increases with the increasing height on a stem from the main root to the upper stem. Further, it was confirmed that exposure to temperatures higher than about 13°C rather than a remarkable daily temperature fluctuation itself is responsible for the decrease in frost resistance in winter.

I. Introduction

In Japan, not only in the northern cold climates, but also in the southern mild climates, frost damage of slender stems near the ground surface is often observed in *Acacia mollisima*, cryptomeria, Japanese cypress, tea, orange, chestnut, rose, mulberry tree, apple, Marie's fir, etc. The frost damage of this type exercises a great negative influence upon the development of individual plants and plantations. The prevention of this frost damage is closely connected with the practical aims in silviculture and horticulture. For this reason, this type of frost damage has been studied by many investigators in various countries, especially by Day *et al.*[1-3] and Eiche[4]. However, they have chiefly dealt with either environmental factors causing the damage or its morphological problems, but have not considered this damage as a phenomenon

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associated with the hardening process and frost resistance in plants.

Thus, in an attempt to clarify the mechanism of frost damage on basal stems in young trees, some physiological experiments were made using various young trees.

II. Materials and Methods

Materials

The species used in this experiment were cryptomeria (*Cryptomeria japonica* D. Don), Japanese cypress (*Chamaecyparis Obtusa* Endl.), apple tree (*Malus pumila* Mill *et* Kudo, var. *Delicious*), chestnut (*Castanea crenata* Sieb. *et* Zucc. var. *Akanaka* and *Ibuki*), Marie's fir (*Abies sachalinensis* Mast.), mulberry tree (*Morus bombycis* Koidz.). In all experiments, only young trees (1.0 to 1.5 cm in diameter near the ground surface, 50 to 100 cm in height) were used. In cryptomeria, mulberry tree, apple and Marie's fir, materials wintering in Sapporo* were used. Materials such as chestnut, Japanese cypress, cryptomeria were sent from Mito* (Ibaragi Prefecture) to Sapporo in December.

Methods

Stems wetted with water were placed in a polyethylene bag, and were then cooled in a cold room at −5°C. After one hour, they were inoculated with frost and were then gradually transferred at hourly intervals to cold chambers set at various temperatures from −5 to −30°C graded at 5 or 2.5°C intervals. After these twigs were cooled to the desired temperatures, they were kept there for various hours, and then thawed at 0°C. In some experiments, a part of a stem (about 5 cm in length) was locally frozen at various temperatures with a thermoelectric apparatus.[5] This apparatus is composed of two components. A part of a basal stem was fixed between each component and was then cooled slowly to the desired temperatures. This apparatus can be cooled down to −30°C with an accuracy ±0.3°C.

The temperature inside a stem was measured with a 0.2 mm copper-constantan thermocouple and recorded. The environmental temperature was measured in a shelter.

The extent of damage was determined within a few days after thawing. Browning of various tissues was taken as a sign of damage. The degree of frost damage was classified into 5 grades on the basis of extent of browning. The degree of frost resistance was represented by the lowest temperature at

* Average temperatures in January in Sapporo and in Mito were about −8° and 0°C respectively.

Fig. 1. Frost damage on basal stems in young trees

1 : Partial sloughing on a basal stem in Satsuma orange
2 : Partial sloughing on a basal stem in chestnut
3 : Circular sloughing on a basal stem in cryptomeria
4 : Partial sloughing on a basal stem in cryptomeria
5 : Circular browning in the cortex of a basal stem in larch
6 : Circular browning in the cortex of a basal stem in Marie's fir

B, damaged portion ; G, ground surface

which a stem or a stem piece could withstand freezing without injury.

To investigate the effect of daily temperature fluctuations on the frost resistance of stems in winter, various temperature fluctuations were given to a part of the stem (5 cm in length) for 12 days with the thermoelectric apparatus which was placed in a hardening chamber with an illumination of about 1000 lux.

III. Results

Damaged area on stems in young trees

In mild climates, *Acacia mollisima*, orange, tea, chestnut, cryptomeria, Japanese cypress, etc. are often damaged severely during a period from late autumn to early spring. In severe cold climates, this type of damage occurs even in late frost in May and June. The damaged area on a stem differs considerably with the intensity of frost, the grass dominations and configurations. In a cold and snowy area, the level of the damage is connected with the changes in the depth of the snow cover. However, in mild climates and

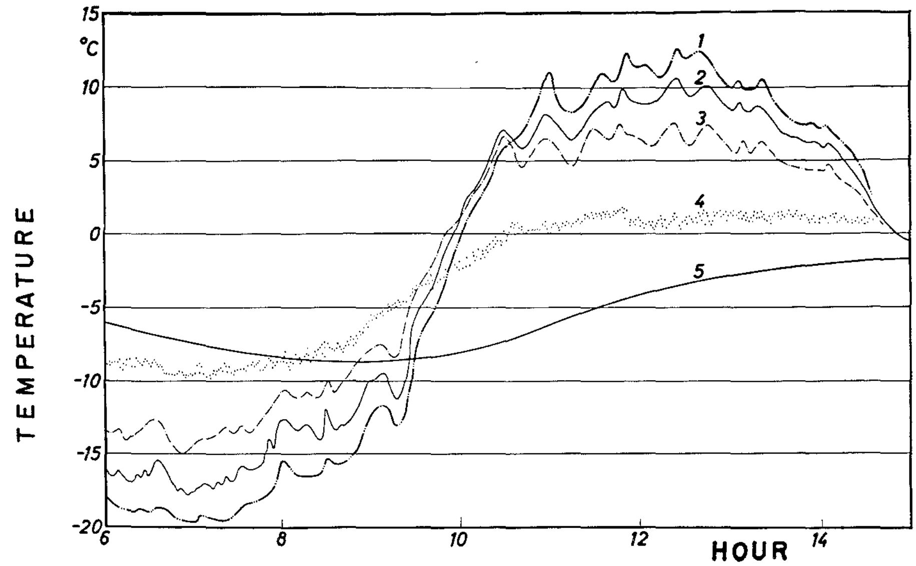

Fig. 2. Bark temperature on south side in a slender stem at various heights above the snow surface

Material: Mulberry tree (1 cm in diameter near the ground surface)
Curves: Bark temperature 10 cm (1), 18 cm (2), and 33 cm (3) above the snow surface, environmental temperature (4), and the temperature 10 cm below the snow surface (5)

in spring frost in cold climates, the damaged area is usually situated near the ground surface (Fig. 1).

Bark temperature in a slender stem at various heights above the snow surface

To investigate the daily fluctuations in bark temperatures in a slender stem with a diameter of about 1 cm, thermojunctions were inserted into the bark on the south side 10 cm below the snow surface and 10, 18 and 33 cm above the snow surface respectively. On this day, there was about 30 cm of snow cover.

As shown in Fig. 2, the rise in bark temperature varied considerably at different heights above the snow surface. On a clear fine day, the bark temperature fell with the increase in height above the snow suface, while at night, it rose considerably with the increase in height. On a clear fine night, the area near the snow surface was cooled remarkably by radiation. The same determination was made in the bark on the south and north sides. The difference in the bark temperature on the north and south sides at the same height amounted to about 7° (Fig. 3). The same daily fluctuations as seen in Fig. 2 in bark temperature were also obtained as shown in Fig. 3. From these results, it is obvious that in the case of a slender stem, the bark on the south side 5 to 10 cm above the snow surface is subjected to the

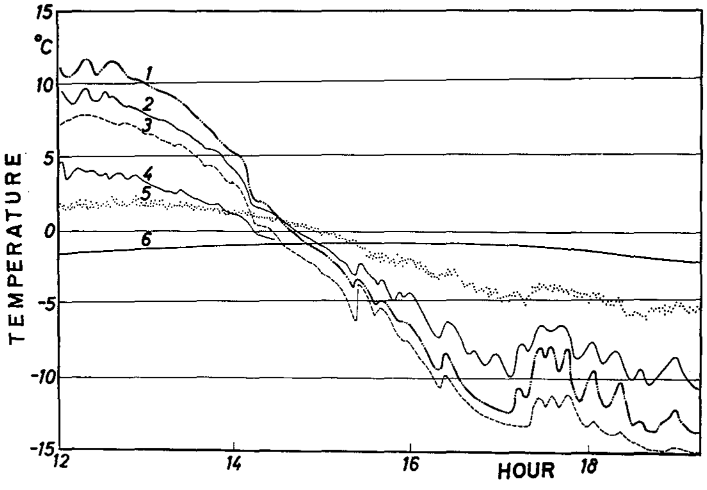

Fig. 3. Bark temperature in a slender stem at various heights above the snow surface

Material: Mulberry tree (1 cm in diameter)

Curves: Bark temperatures south-15 cm (1), south-30 cm (2), south-5 cm (3), and north-15 cm (4) above the snow surface, environmental temperature (5) and the temperature 10 cm below the snow surface (6) most remarkable fluctuations in temperature. The same results were obtained in a slender stem at various heights above the ground without snow.

Difference in frost resistance among different parts on a stem

To investigate the frost resistance at different parts on a slender stem, stems of 4 year cryptomerias (60 cm in height) growing in Sapporo were frozen at different temperatures in the middle of November. As shown in Table 1, the frost resistance in the basal part (3 to 4-year-old part) on a stem near the ground surface was much lower than that of the higher part (1 to 2-year-old part). Further, stems of 4 year cryptomerias (60 cm in height) were frozen at various temperatures in late December. From the results obtained in Table 2, it is apparent that frost resistance in a stem increases with the increase in

Table 1. Frost resistance in different parts on a stem (Middle November, 1966)

Tissue tested	Freezing conditions			
	−10°C for 2 hrs		−13°C for 13 hrs	
	Upper part*	Basal part*	Upper part	Basal part
Cortex	1**	4	2	4
Cambium and surface layer of xylem	2	4	2	4

Material: Cryptomeria wintering in Sapporo
* Upper and basal parts mean 20 to 25 cm and 5 to 10 cm above the ground surface respectively
** Degree of frost damage is represented by numerals
The increase in numerals indicates the increase in damage: 0, normal; 1, slight; 2, medial; 3, serious; 4, dead

Table 2. Frost resistance in different parts on a stem (Early December, 1966)

Tissue tested	Freezing conditions						
	−15°C for 6 hours				−20°C for 6 hours		
	Upper* part	Middle* part	Basal* part	Main root	Upper part	Middle part	Basal part
Cortex	0**	1	2	3	0	1	3
Cambium and surface layer of xylem	0	1	2	3	0	2	3

Material: Cryptomerias wintering in Sapporo
* Basal part: 0 to 5 cm above the ground; Middle part: 15 to 20 cm above the ground; Upper part: Part higher than 20 cm above the ground
** Numerals represent the degree of damage as indicated in Table 1

height above the ground surface. The frost resistance in the main root under the ground is much lower than that in the basal stem above the ground surface.

Seasonal variations of frost resistance in different parts on stems

Seasonal variations of frost resistance in the upper and basal stems of 3 to 4 year cryptomerias wintering in Sapporo and Mito were investigated. As shown in Fig. 4, in any season, frost resistance in the upper part of a stem

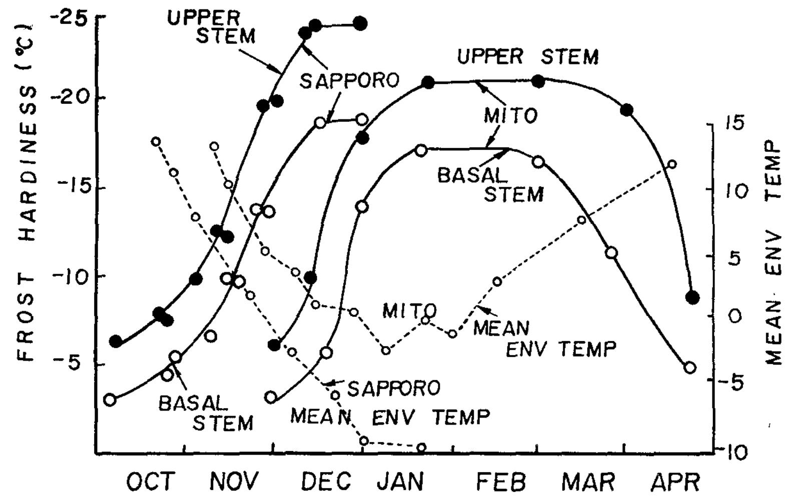

Fig. 4. Seasonal variations of frost resistance in different parts on stems
Material: 3 to 4 year cryptomerias growing in Sapporo and Mito
Degree of frost resistance was represented by the minimum temperature at which stems can withstand freezing without any damage

was much greater than that in the basal part in both places. It was also found that the basal part on a stem became frost hardy about 10 or 14 days later than the upper part in autumn and also lost its frost resistance earlier than the latter in spring, and that the frost resistance of the former was invariably lower than that of the latter. The difference between the two amounted to 5 to 7°C.

In the middle of April in Mito, at which time the mean environmental temperature rose to about 13°C, even basal stems of cryptomerias still could withstand freezing at -5 to -7°C.

As shown in Table 3, in April, the frost resistance of bark on the south side in a stem was far less than that of the bark on the north side, especially at the basal stem.

Table 3. Frost resistance on the north and south sides on a stem in spring (April 17, 1967)

Part on a stem	Basal part	Middle part	Upper part
South side	4*	2	0
North side	2	0	0

Material: 3 year cryptomeria sent from Mito
* Degree of frost damage as indicated in Table 1

Difference in frost resistance among tissues

When a stem of chestnut sent from Mito was frozen at -15°C in early December, the basal part (0 to 8 cm above the ground surface) of a stem was locally damaged (Fig. 5). Microscopic examination of sections, taken from the basal stem, revealed that the cambium and the adjacent cortical cells were most frost sensitive (Fig. 6–1, 2). The same fact was observed in other species such as cryptomeria, Japanese pine and Japanese cypress.

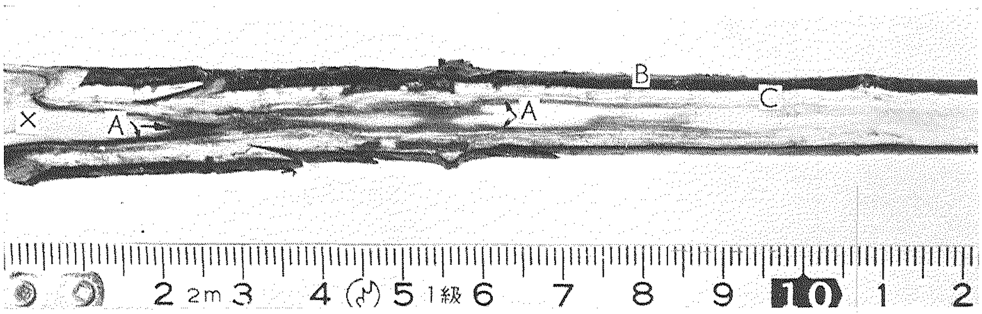

Fig. 5. Frost damage on a basal stem of a chestnut tree
This stem was frozen at -15°C in early December. A, cambium; B, outer bark; C, cortex; X, xylem

In Marie's fir, a native tree in Hokkaido, the basal stem was also most susceptible. However, the cambial cells were most frost resistant, unlike the other species used. As shown in Fig. 6–3, Marie's fir was frozen at -5° for 3 hours in early April and the cortical cells (B), especially in the middle part of cortex, and xylem ray cells (X) were damaged, although the cambium (C) still remained normal. Also, as shown in Fig. 6–4, in a Marie's fir damaged by late frost in spring. Although most of cortical cells (A) were killed, cambial initials still remained alive and continued to differentiate new cortex (B) and xylem (D). However, the xylem mother cells and differentiating tracheids were killed, leaving a permanent band, namely a frost ring (R). The same

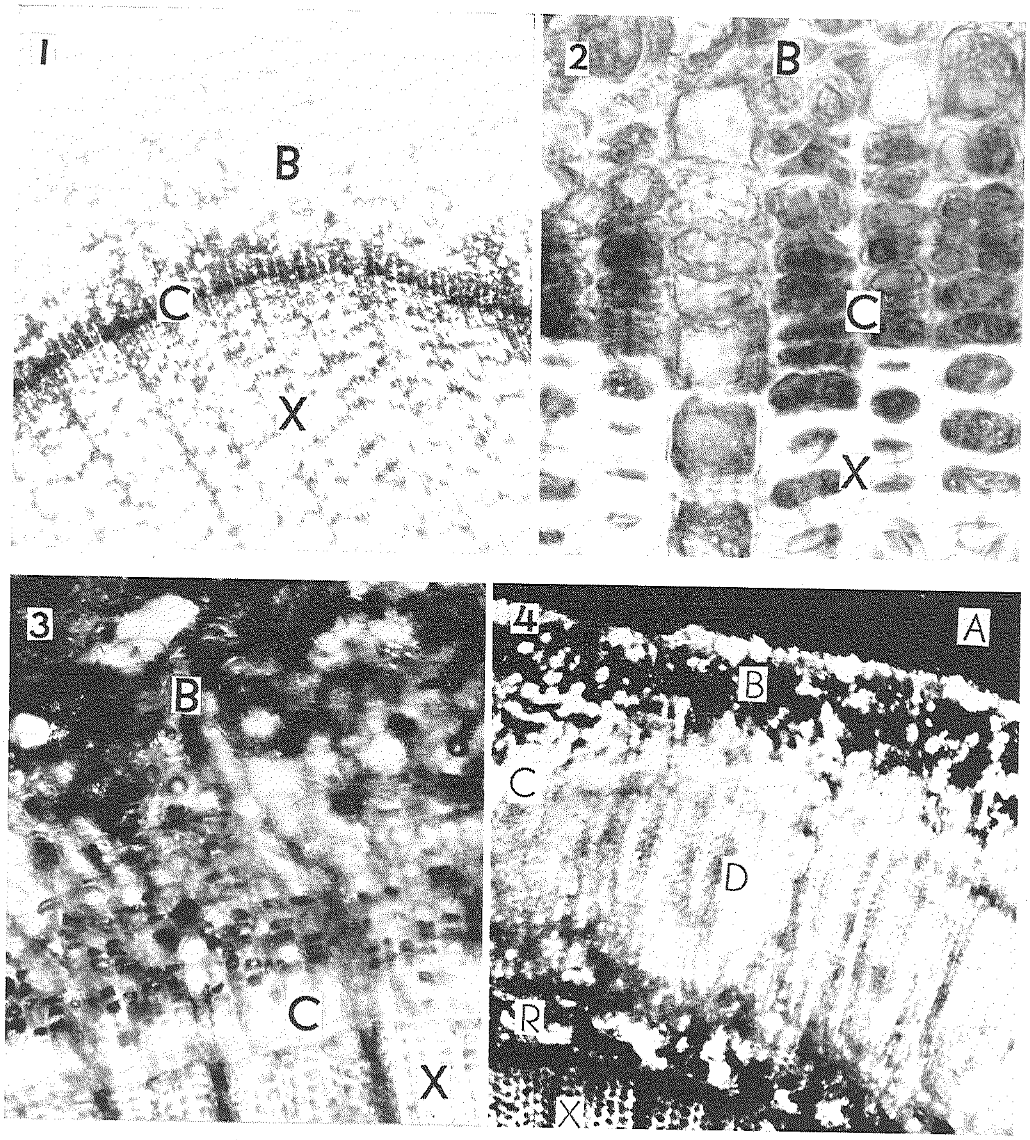

Fig. 6. Difference in frost resistance among tissues

1. Cross section of the stem of chestnut tree presented in Fig. 5. Cambium cells and the adjacent cortical cells are selectively damaged. B, cortical parenchyma cells; C, cambium; X, xylem. ×100
2. Details of 1. C, cambium; X, xylem ray cells. ×800
3. Tissue section from a stem of Marie's fir frozen at −6°C in early April B, cortical parenchyma cells; C, cambium; X, xylem. ×600
4. Tissue section from a stem of Marie's fir damaged by spring frost in late May The stem was examimed in September. A, cortical parenchyma cells killed by spring frost in late May; B, newly formed cortical parenchyma cells; C, cambium; D, newly formed xylem; R, frost ring caused by a spring frost in late May; X, xylem formed in the previous year. ×600

fact was observed in other seasons. These facts indicate that the cambium of Marie's fir is most frost resistant among the stem tissues, unlike the other species native to mild climates.

Effect of temperature fluctuation upon a decrease in frost resistance

To clarify further the effect of daily temperature fluctuations on the frost resistance of stems in early winter, the middle part of a stem (5 cm in length) of a potted cryptomeria was locally subjected to different fluctuations in temperature for 12 days with a thermoelectric apparatus. In this experiment, cryptomerias were subjected to a light of about 1000 lux. This experiment was made during December.

The results obtained are summarized in Table 4. The fluctuation of temperatures, amounting to a total of 8 hours at 10°C, 2 hours at 0°C and 14 hours at −5 or −10°C per day for 12 days and continuous exposure at 10°C for 10 days produced no decrease in frost resistance in all cases. Also, the exposure to daily fluctuation of temperature between 13°C and −5 or −10°C for 12 days and continuous exposure at 13°C for 12 days resulted in

Table 4. Effect of daily temperature fluctuations upon frost resistance (December, 1966)

Temperature treatments (°C)	Frost resistance					
	Before treatment		After treatment			
	Freezing temperature for 3 hrs (°C)		Freezing temperature for 3 hrs (°C)			
	−23	−20	−23	−20	−17	−15
0∼−5	3*	0	3	0		
5∼−5	3	0	3	0		
10∼−5	3	0	4	0		
13∼−5	3	0	4	1		
20∼−5	3	0	4	3		
20∼−10	4	0	4	3		
0	4	0	4	0		
10	4	0	4	0		
13	3	0	4	2	1	
20	3	0		4	4	3

Material: Potted 4 year cryptomeria

* Numerals represent the degree of damage as indicated in Table 1

Middle parts of stems were locally subjected to various temperature fluctuations for 12 days in December. During the day time (for 8 hours), twigs were kept at high temperatures and at night were kept frozen by a thermoelectric apparatus only a slight decrease in frost resistance. However, exposure to daily fluctuations of temperatures between 20°C and −10 or −5°C and continuous exposure to 20°C for 12 days caused a considerable decrease in frost resistance in all cases. From these facts, it seems that exposure to temperatures higher than 13°C or thereabouts rather than a remarkable daily temperature fluctuation itself is responsible for the decrease in frost resistance in winter.

Frost resistance and water content of cryptomerias wintering in snow

Frost resistance and water content of cryptomerias buried in snow for 1 month and a half from the middle of December, were studied in late January in comparison with those wintering in a vinyl covered house in which the temperature fluctuated from 5 to −10°C. As shown in Table 5, frost resistance of cryptomerias wintering in deep snow was far less than those in the vinyl covered house, and the water content of various tissues in the former were much greater than those in the latter.

Table 5. Frost resistance and water content of a cryptomeria wintering in snow (Late January, 1967)

Wintering conditions	Water content (% per wet weight)				Frost resistance (°C)		
	Leaf	Stem (Middle part)	Stem (Basal part)	Root	−20	−15	−10
In snow*	174	170	162	158	4**	3	1
In vinyl covered house***	144	108	110	121	0	0	0

* Cryptomerias were buried in deep snow (1 m in depth) for 1 month and half

** Degree of damage as indicated in Table 1

*** Cryptomerias wintering in vinyl covered house (temperature fluctuation: 5 to −10°C)

Table 6. Relation between osmotic concentration and frost resistance in cortical cells at various heights on a stem (April 12, 1967)

Part on a stem	Upper part (1-year-old part)	Middle part (2-year-old part)	Basal part (3-year-old part)	Main root
Osmotic concentration (M)	0.86	0.61	0.54	0.49
Degree of damage*	0	3	4	5

Material: 4 year Marie's fir (33 cm in height)

* A stem was frozen at −15°C for 16 hours. Degree of damage was represented by numerals as indicated in Table 1

Heights above or below the ground surface of tested parts are as follows: Upper part (20–30 cm), middle part (7–20 cm), basal part (0–7 cm) and main root (0–7 cm) respectively

Osmotic concentrations of cortical cells at various heights on a stem

To investigate whether osmotic concentrations of cortical cells increase with the increase in height on a stem, the osmotic concentrations of bark taken from different heights above or below the ground surface on a stem were determined. From the results obtained in Table 6, it is apparent that osmotic concentration increases with the increasing height on a stem from the main root to the upper part, and that there is a parallel correlation between frost resistance and osmotic concentration.

IV. Discussion

The basal part of a stem near the ground surface is exposed to a remarkable fluctuation in temperature, especially to a sharp drop in temperature due to radiation at night. Also, the frost resistance of the basal part on a stem was invariably lower than that of the upper part, and the former became frost hardy about 10 days later in late autumn, and about 10 days earlier in spring than that of the latter in cryptomerias. The difference between the two amounted to about 7 to 10°C. From these facts, it is apparent that the basal part on a stem is most susceptible to frost damage.

This type of frost damage on the basal stem in young trees usually occurs in frost basins, flat lands, plateaus situated on slopes and southern and south-western slopes of mountain areas.

Horiuchi investigating the time at which cryptomerias growing in Mito suffer frost damage, found that the frost damage on their basal stems occurred every year in a period from late November to early December for the past 3 years. Regarding the time of the damage sustained, the same facts were recently found in Kyushu, a far south-western island in Japan, by Ogata, Takagi and Kaminaka in cryptomeria. In these areas, the basal stems of cryptomerias become first frost resistant in a period from late November to early December unlike the upper part of the stems. Thus, when a severe frost occurs, only the basal stems suffer damage. Therefore, this period is an important threshold to wintering for cryptomerias. The cryptomerias which pass successfully through the barrier, can increase their frost resistance remarkably as the season advances, and in midwinter, even the basal stems of cryptomerias become resistant to freezing at -15 to -20°C. Therefore, in mild climates, cryptomerias rarely suffer frost damage in midwinter. Moreover, if there is no severe frost in late autumn and in early winter, all cryptomerias can pass successfully through the barrier including even less hardy individuals. Therefore, in late spring, at which time the frost resistance becomes small, less hardy individuals may be damaged when subjected to a severe frost.

Cryptomerias growing on the northern slopes cease their growth earlier than those on the southern slopes. Hence, cryptomerias growing on the southern and south-western slopes become frost hardy considerably later than those on the northern slopes in late autumn. In spring, in contrast, the former becomes less hardy earlier than the latter. For this reason, cryptomerias on the southern and south-western slopes are more sensitive to frost damage than those on the northern slopes.

In deep snow areas, frost damage on the basal stem may be caused after snow melting as well as before the formation of the snow cover. Cryptomerias buried in deep snow for one month at least become remarkably less hardy. Therefore, in deep snow areas, this kind of damage may also occur after snow melting. However, to clarify the time at which these trees suffer frost damage, it is necessay to know the temperatures at various parts of trees wintering in various conditions and their seasonal changes in frost resistance from autumn to spring. In mild climates or in late frost in spring in Hokkaido, in the majority of cases, the damage occurs on the stem at 5 to 20 cm above the ground surface, in mild temperature conditions, only on the southern side on a basal stem. Horiuchi confirmed that the damage sustaining zone on stems differs considerably in the height above the ground surface ranging from 5 to 50 cm from year to year even on the same plantation, according to the degree of low temperature exposed.

In this paper, it was also confirmed that the basal stem was less hardy than the upper stem, and that osmotic concentrations, namely the sugar content[6] in the former was far less than that in the latter. It is not clear, however, whether the cause can be attributed to the temperature conditions to which the basal stems are subjected, or to physiological problems accompanying the aging of a stem. To clarify this problem, further studies are required.

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