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1. Title of the paper:

Difference in uprooting resistance among coniferous species planted in soils of volcanic origin

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Abstract

Uprooting resistance against wind force for coniferous plantations in soils of volcanic origin was studied.   The difference in uprooting resistance among *Abies sachalinensis*, *Picea jezoensis,* and *Larix kaempferi* was discussed.   Sample site was set in Chitose plantations in Hokkaido Japan, where typhoon 0418 caused fatal uprooting damage in 2004. An uproot resistance index—ratio of the geometrical moment of area for uprooted root-plate to the moment susceptibility to wind force—was defined to quantify relative uprooting resistance against wind force; it was calculated from the dimensional measurements for the tree forms and root plates of 100 uprooted sample trees after the typhoon attack.   As a result, the uprooting resistance for *Picea jezoensis*, which was less damaged among the sample species, was estimated to be greater than those for the other two species.

Key words

Introduction

Coniferous plantations have a tendency to be fatally damaged by stormy winds. The types of failure can be classified into two categories: uprooting of a root system and windbreak that is bending or shear failure of a stem.

Basically, uprooting as well as windbreak is caused by wind force applied on a tree crown. Therefore, wind force susceptibility of tree crown must be quantified to evaluate critical wind force applied on a tree. The drag coefficients (C_D) for tree crowns have been obtained from wind tunnel studies (Hirata 1953; Fraser 1964; Yamamoto 1979; Johnson et al. 1982; Murakami et al. 1984) in order to estimate wind force susceptibility for various species. Although most of the studies used miniature tree models as specimens, Fraser (1964) performed full-scale experiments for some coniferous species.

Koizumi (1987) estimated the failure types for coniferous trees grown in plantations based on the dimensions of the tree forms and the uprooting strength obtained from pull-down tests. To evaluate uprooting resistance, pull-down tests had been performed at the sites with various soil conditions and the proportional relationships between stem diameters and the uprooting strengths were reported (Tamate et al. 1965; Kamata 1956; Koizumi 1987). However, inter-species difference in the uprooting strength based on the dimensions of root plate that contribute uprooting resistance, has not been reported.

The aim of this study is to propose an index to uprooting resistance using the tree form that control the moment applied on root system and the dimension of root plate that affects the uprooting strength, and to discuss the inter-species difference in the uprooting resistance.

Materials and methods

Sample site

Sample stands were set in the Chitose plantations of the national forest, where a large-scale

Fig. 1
Table 1
uprooting damage occurred due to typhoon 0418 (Fig. 1; Table 1).

Typhoon 0418 that attacked Hokkaido in September, 2004 was characterized by strong winds; and an average wind velocity of 22 m/s was recorded in Chitose near the sample site. The

damaged area reached 50,000 ha for the national forest and prefectural forest (Tsushima et al. 2004). Especially, extensive uprooting damages for coniferous plantations occurred around the sample site, where the soil was composed of a thick volcanic pumice layer that originated in the Mt. Tarumae explosion from 9000 years ago. Large-scale uprooting disasters had been observed at plantations around Mt. Tarumae where the volcanic soil restricts the downward root extension and forms a thin root plate with weak cohesion of the soil (Mishima et al. 1955; Mishima et al. 1958; Kawase and Ota 1983).

The sample stands were on an almost flat plateau consisted of thick layer of volcanic pumice (augite-hypersthene andesite pumice) and ash, whose maximum particle size was about 5 cm, covered with few-centimeter-thick humus layer (Soya and Sato 1980).

Fig. 2

The investigated species were todomatsu (*Abies sachalinensis*), ezomatsu (*Picea jezoensis*), and karamatsu (*Larix kaempferi*) (Fig. 2). The dominant direction of uprooting was toward the east which agreed with the direction of wind blow. Almost all the todomatsu (Plots 1–3) were uprooted with few exceptions of windbreak of stems. On the other hand, in the case of the ezomatsu (Plots 4 and 5) and karamatsu (Plot 6), some of the trees survived without uprooting.

Measurements

A total of 10 or 20 uprooted trees, excluding those growing along forest edges, were sampled at random for each stand. The diameter at breast height (D_B), crown height (H_C), crown length (L_C), crown breadth (B_C), root-plate breadth (B_R), and root-plate height (H_R) were measured for the sample

Fig. 3

trees, as defined in Fig. 3. The depths of the root plates were not measured for individual trees because the difference in depth among the uprooted trees was small. The approximate root-plate depth was 0.6 m.

Evaluation of uproot resistance index

The uprooting resistance is in inverse proportion to the wind force susceptibility of a tree and in direct proportion to the uprooting strength of a root system. By assuming the trees to be cantilever beams fixed at the ground level, the moment at the tree base (M_R) induced by a wind force acting on

the crown is expressed by Eq. 1.

$$M_R = \frac{1}{2} C_D \rho v^2 A H_W \qquad (1)$$

Here, C_D is the drag coefficient of the tree crown; ρ, the air density (1.20 kg/m^3); v, the wind

velocity; A, the projected crown area; and H_w, the height of the wind pressure center.

The moment factor (MF), which is an index to wind force susceptibility, was defined in

this study as a function of the tree form and C_D (Eq. 2). If the wind velocity is constant, the amount

of the moment applied on a root system will be proportional to the MF. The shape of a crown is

assumed to be a circular cone so that the height of the wind pressure center is one-third of the crown

length above the crown height.

$$MF = C_D A H_W = \frac{C_D D_C L_C}{2} \left(H_C + \frac{L_C}{3} \right) \qquad (2)$$

Mayhead (1973) analyzed the wind tunnel study for full-scale trees conducted by Fraser

(1964) and indicated a considerable reduction in C_D with an increase in the wind velocity because

the projected frontal area of the tree crown decreased with the swaying of the branches at a high

wind velocity. He concluded that C_D converges to a nearly constant value at the wind velocity

range likely to cause windthrow and reported C_D at 30 m/s in wind velocity as 0.41 for tree species

having dense crowns (grand fir and Sitka spruce), which are subjected to a large wind pressure per

projected area, 0.31 for pines (Corsican pine, lodgepole pine, and Scots pine), 0.22 for Douglas fir,

and 0.14 for western hemlock.

In the present study, C_D used in Eq. 2 was assumed to be 0.41 for the ezomatsu (*Picea*

spp.) and todomatsu (*Abies* spp.) which have dense crowns, and was assumed to be 0.31 for the

karamatsu (*Larix* spp.) which has thin crown as pines.

The uprooting strength is expected to be positively proportional to the dimension of the

root plate. The uprooting mechanism had been explained as an over-turn failure of a thin root plate

initiated by the tensile failure of the horizontal root at windward side of a root plate in the case of

shallow-rooted trees, and a shear slip at the boundary surface between a root bowl and soil in the

case of deep-rooted trees (Thomas 2000).

In the case of over-turn failure of shallow-rooted trees as considered in this study, the amount of tensile stresses acting on the windward side of the root plate caused by M_R will be proportional to the distance from the rotation center of the root plate. Assuming that the rotation center lies at the ground level along the stem line, the uprooting moment will be proportional to the geometrical moment of area for windward side of an ellipse-shaped root plate (G_R) under the condition that the initial tensile failure of a horizontal root occurs at the windward edge of a root plate (see Fig. 4).

$$G_R = \int_0^{H_R} y\, \mathrm{d}A$$

$$= \int_0^{\frac{\pi}{2}} H_R \sin\theta \cdot B_R \cos\theta \cdot H_R \cos\theta \cdot \mathrm{d}\theta$$

$$= \frac{H_R{}^2 B_R}{3} \tag{3}$$

Finally, the uproot resistance index (URI) was defined as the ratio of G_R to MF and calculated for the sample trees.

$$\mathrm{URI} = \frac{G_R}{\mathrm{MF}} \tag{4}$$

Results and discussion

Uproot resistance index

The dimensional measurements of the sample trees are summarized in Table 2. MF and G_R calculated from the measurements increased with D_B as shown in Fig. 5. By comparing the regression equations (power functions) concerning MF, similar trends were observed for the three species. Meanwhile, G_R of ezomatsu was greater than that of todomatsu and karamatsu.

The average URI was the greatest for ezomatsu. A part of the reason for this trend may be

attributed to the large diameters of ezomatsu samples. However, the positive effect of D_B on URI was not clear for each species, because D_B affected both MF and G_R. The statistical t test revealed a highly significant difference (significance level: 0.4%) in the URI between ezomatsu and other two species. The average value of URI for ezomatsu was 29.9×10^{-3} which was 65% and 93% larger than that for karamatsu, and todomatsu, respectively.

The result suggested that the ezomatsu has a greater uprooting resistance than karamatsu and todomatsu plantations in volcanic-origin soils. Although todomatsu is known as comparatively deep rooted species, the downward extension of the taproot of todomatsu might be restricted due to the pumice layer. Consequently, the failure type of uprooting was to be over-turn type and todomatsu stands, which had the smallest URI among tested three species, were destroyed completely as shown in Fig. 2.

Effects of stand age

The plantations are thinned according to a prearranged scheme, and the stem density, which might affect MF or G_R, decreases with stand age. Although the stem density might give the effects on the behavior of wind flow inside a stand or on the mechanism of scramble-type windthrow damage, these effects were not considered here.

Fig. 6
Fig. 7

The effects of stand age were discussed for todomatsu that had 3 age classes (27, 40, and 50 years). MF increased from 27 years old to 50 years old and G_R also increased with the stand age from 27 years old to 40 years old and maintained an approximately constant value up to an age of 50 years (Fig. 6). Since both MF and G_R were positively correlated with stand age, URI was found to be stable with the change in stand-age.

Meanwhile, the average ratios for the section modulus of the stem at the breast height (Z_B), which is an index indicating the amount of moment causing bending failure of a stem, increased more rapidly than G_R as the stand age increased (Fig. 7). The result suggests that a liability of the failure modes of wind damage for todomatsu will change from the bending failure of a stem (windbreak or bent stem) to an uprooting of a root system. Further experimental studies are required to make conclusive discussion concerning the effect of stand age on the failure mode because the

sample size of this study was too small compared to the large variation in the results.

Conclusions

The uprooting resistance for the coniferous species planted in soils of volcanic origin was evaluated using the uproot resistance index (URI). The URI was defined as ratio of the geometrical moment of area for windward side of a root plate (G_R) to the amount of moment applied on the root plate. The URI was evaluated for ezomatsu, todomatsu and karamatsu in the fatally damaged plantations.

The G_R and URI for ezomatsu were found to be greater than that for todomatsu and karamatsu. The result suggested that ezomatsu has greater uprooting resistance than the other two species in soils of volcanic origin. Todomatsu stands, which were found to have the smallest URI, had been completely destroyed at the sample site.

Further experimental studies for pull-down tests will be necessary in order to verify the effect of the URI on the uprooting resistance.
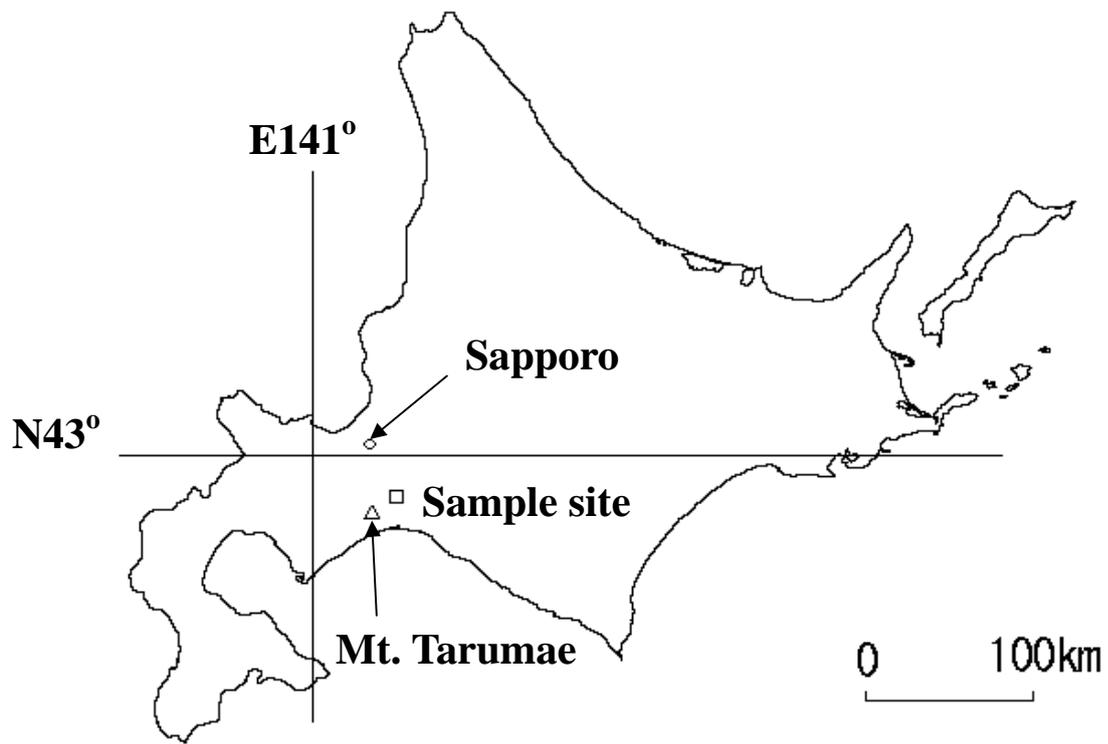
Fig. 1. Location of the sample site (Chitose).

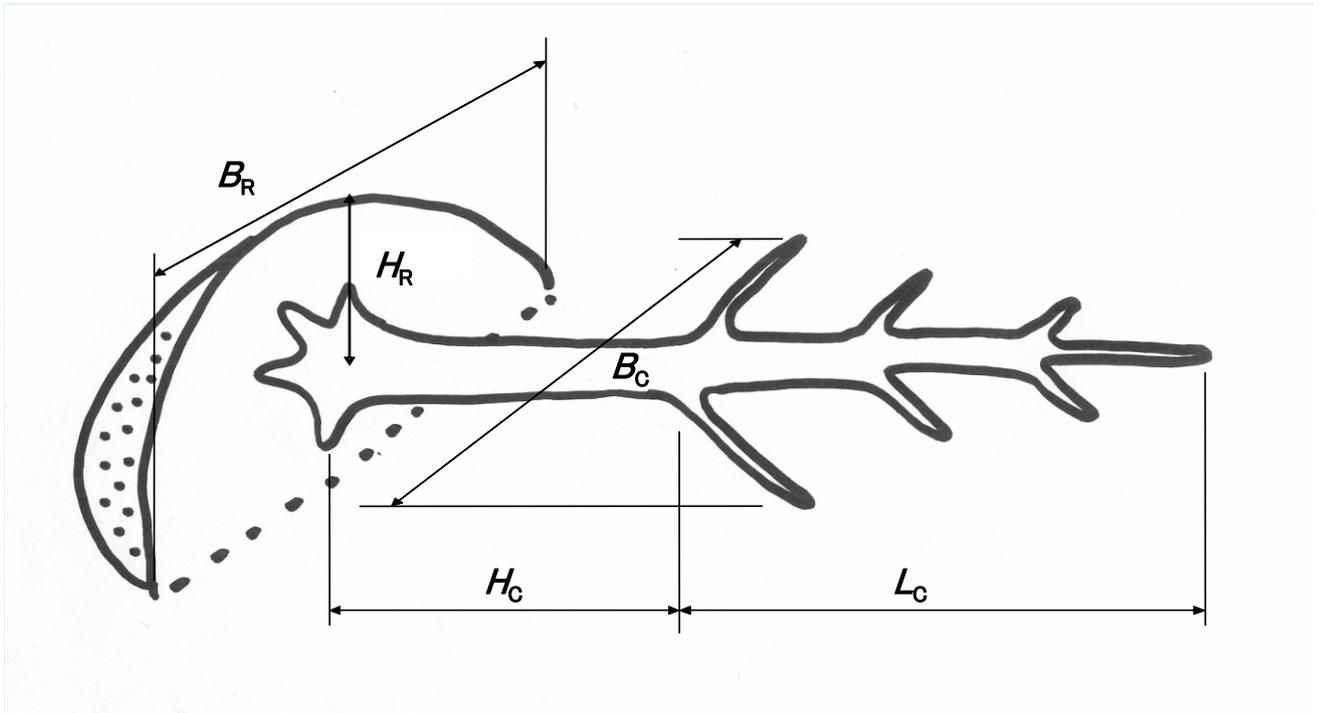Fig. 2. Condition of the damaged sample stands.　Plot numbers are listed in Table 1.

Fig. 3.   Dimensional measurements of the uprooted sample trees.

$dA = B_R \cos\theta \, dy$

$(B_R/2 \cos\theta, \; H_R \sin\theta)$
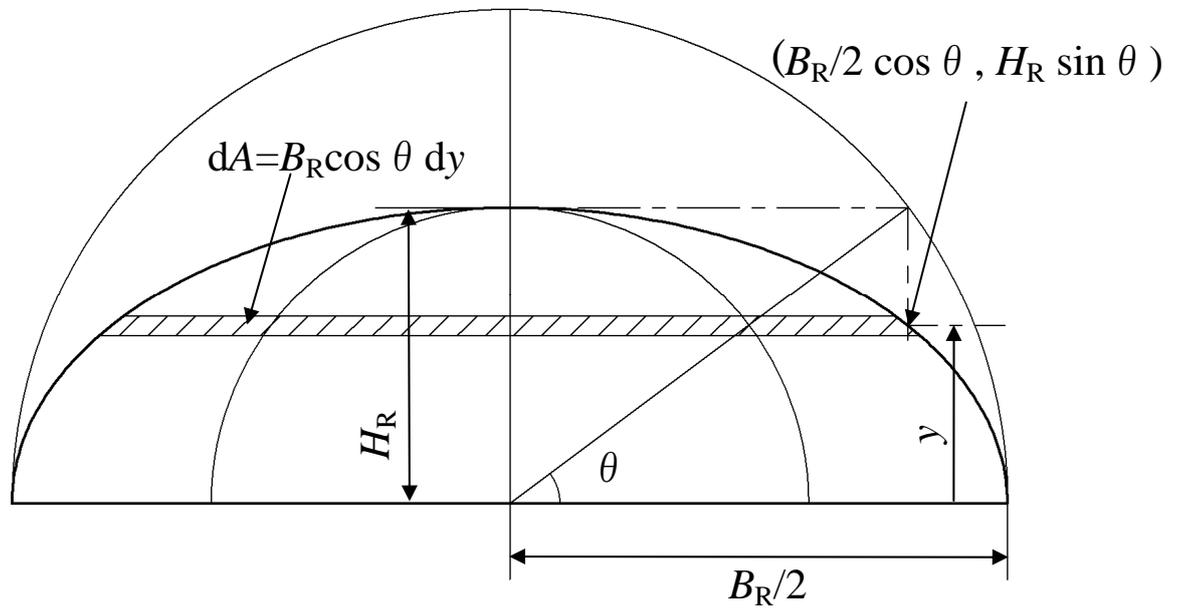
H_R

θ

y

$B_R/2$

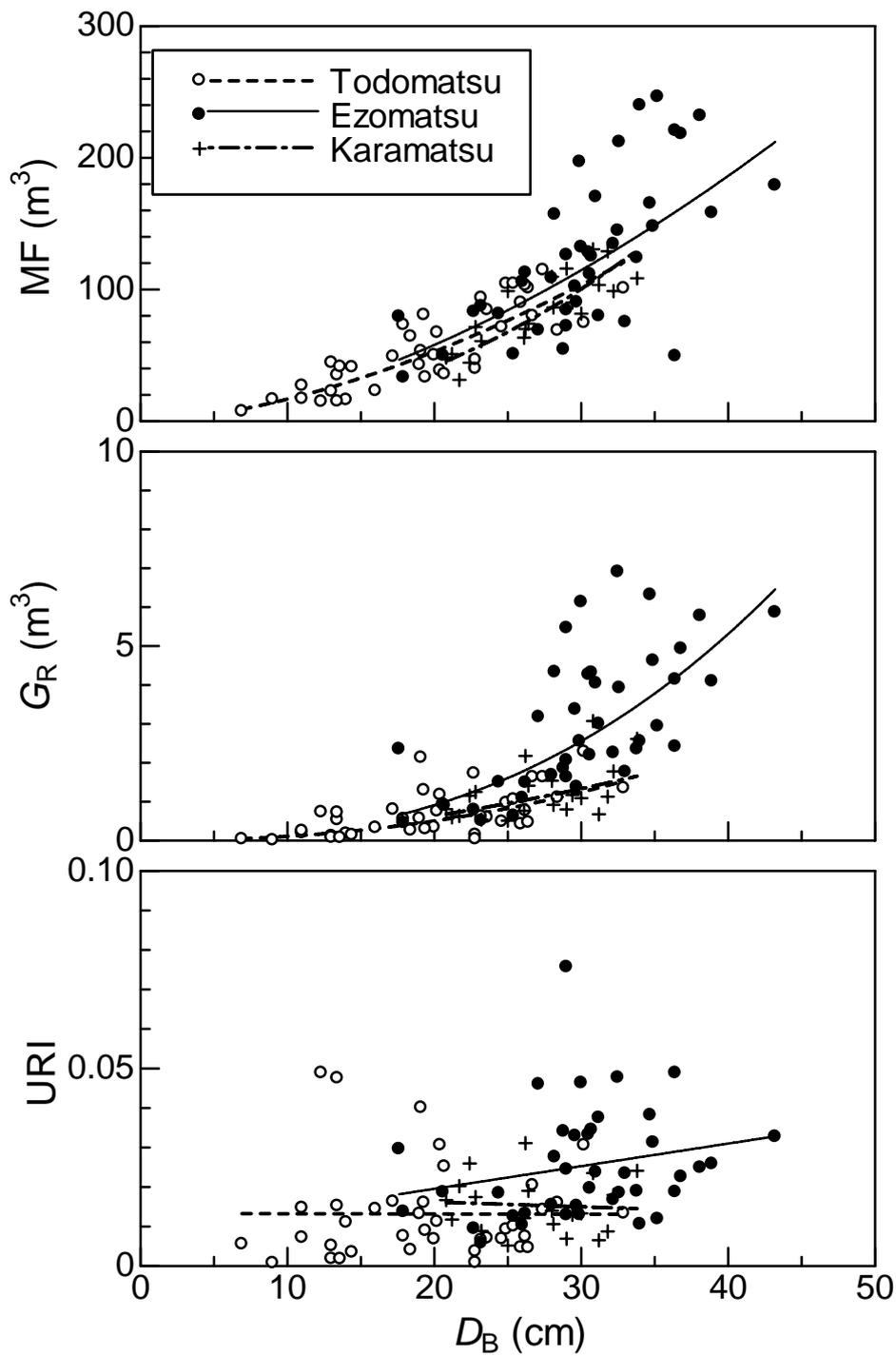Fig. 4 Geometry of uprooted root-plate (windward side) assumed as a half ellipse

Fig. 5.   Moment factor (MF), geometrical moment of area for root plate (G_R), and uproot resistance index (URI) as a function of the breast height diameter (D_B).   Regression curves are power functions for MF and G_R and a linear function for URI.
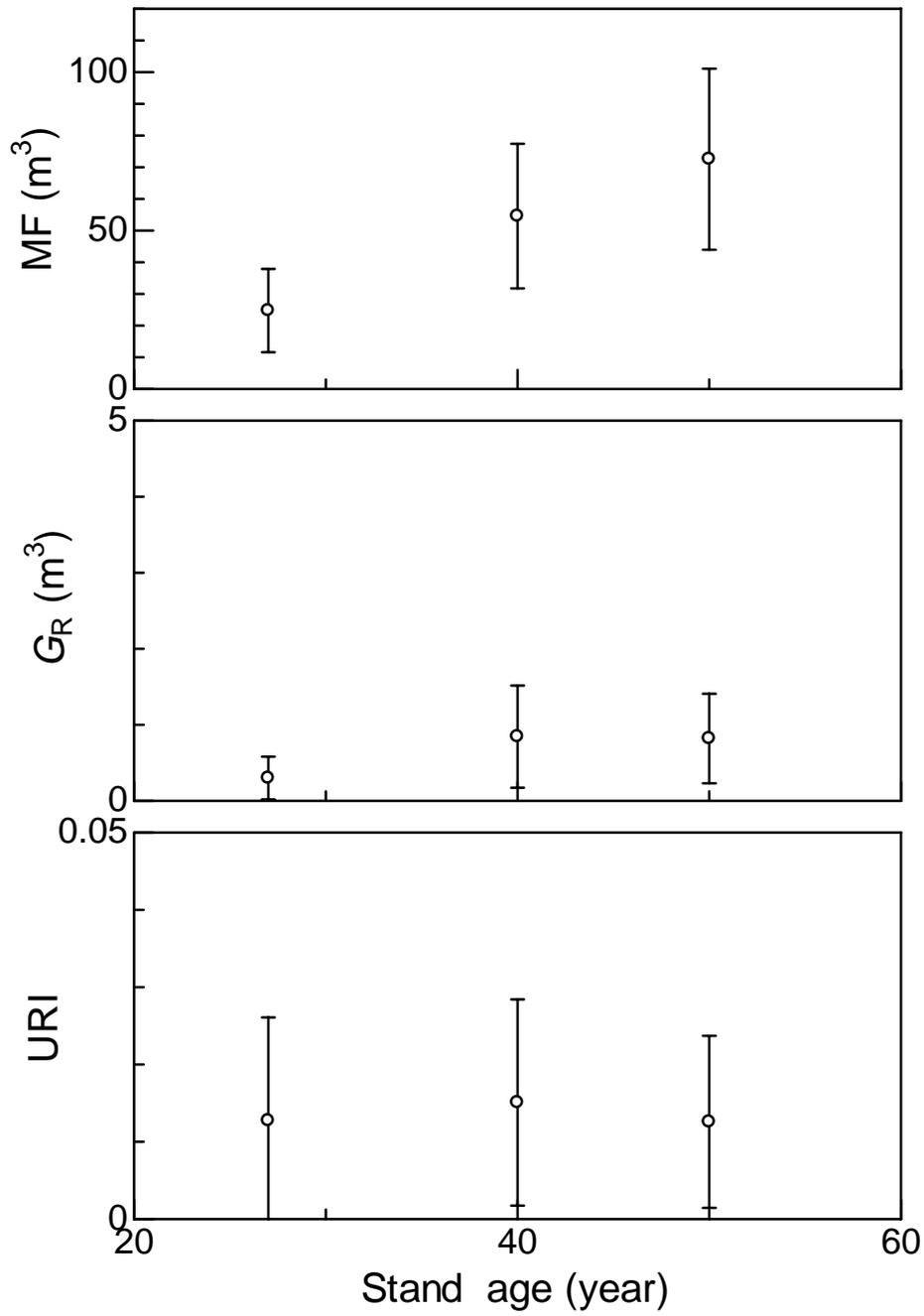
Fig. 6. Stand averages for MF, G_R, and URI as a function of stand age in the case of todomatsu. Error bars denote standard deviations.
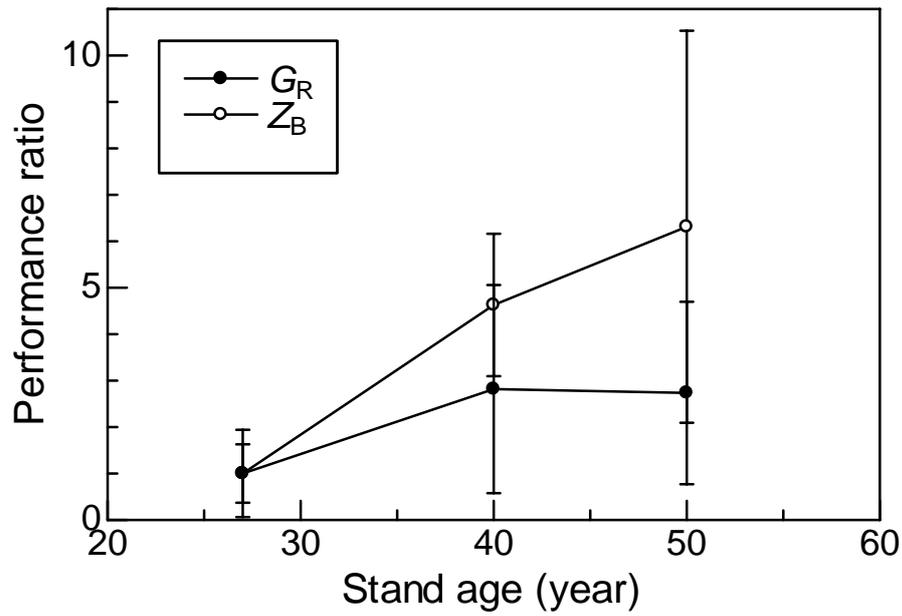
Fig. 7. Relationship between the stand age and the ratios of G_R and the section modulus of a stem at the breast

height (Z_B) to their initial values (values at the stand age of 27 years) in the case of todomatsu.

$Z_B = \pi D_B^3 / 32$,

Error bars denote standard deviations.

Table 1. Sample stands

Plot No.	Species[a]	Stand age	Elevation (m)	Area (ha)	Density (tree/ha)	Number of specimens	Thinning ratio (%)[b]
1	AS	27	180	1.3	2000	10	
2	AS	40	180	16.8	1145	10	
3	AS	50	140	13.0	842	20	25(2000)
4	PJ	69	90	28.7	713	20	30(1998)
5	PJ	74	210	35.8	730	20	20(1999)
6	LK	43	90	22.3	497	20	25(2000)

[a] AS: *Abies sachalinensis*, PJ: *Picea jezoensis*, LK: *Larix kaempferi*

[b] The last thinning ratio performed in the year in parentheses

Table 2. Dimensions of sample trees

Plot No.	DB (cm)		H (m)		HC (m)		BC (m)		BR (m)		HR (m)	
	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.	Mean	S.D.
1	12.3	2.94	11.5	3.35	4.6	0.83	2.9	0.58	1.47	0.48	0.68	0.30
2	21.3	2.30	17.3	2.67	9.8	2.12	2.9	0.75	1.99	0.39	1.04	0.39
3	22.5	5.89	18.3	2.30	10.6	1.79	3.4	0.92	2.18	0.69	0.97	0.32
4	28.4	6.64	16.5	2.81	8.3	1.90	5.5	1.16	3.62	0.95	1.39	0.46
5	32.0	3.25	20.7	2.27	11.6	1.84	5.3	0.92	3.93	0.57	1.57	0.27
6	27.0	4.03	17.9	1.66	9.5	1.34	5.2	1.40	2.66	0.66	1.14	0.20

DB: Breast height diameter, H: Tree height, HC: Crown height, BC: Crown breadth, BR: Root-plate breadth, HR: Root-plate height

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