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Evaluation of drag coefficients of poplar-tree crowns by a field test method

by
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Key words
Drag coefficient, Poplar tree crown, Windthrow resistance, Field test method

Abstract

To estimate the wind force that causes windthrow damage to a tree, the drag coefficients of actual-sized trees were evaluated by a field test method. In this method, the wind velocity and stem deflection were monitored simultaneously. The wind force acting on a tree crown was calculated from the stem deflection; the stem stiffness was evaluated by conducting tree-bending tests. The results of tests conducted on three poplar trees showed that the drag coefficients decreased with an increase in the wind velocity. Although the variation in the drag coefficients was large at low wind velocity because of the vibrating behavior of the stem subjected to variable wind force, the variation at wind velocities above 10 m/s was small. The average drag coefficient at a wind velocity of 30 m/s was estimated by the curve fitting of a power function to the wind velocity-drag coefficient relationship, and it was found to be 0.102, which was smaller than that of actual-sized conifers studied in previous wind tunnel experiments. The drag coefficients of these crown areas in the defoliation season were smaller than those measured in the leaved season.

Introduction

Windthrow damages to trees in plantation forests and along roadsides in urban districts have caused enormous economic loss and danger involving human lives[1]. In order to predict wind damage to trees, such as stem breaking or uprooting, it is essential to quantitatively estimate the wind force acting on a tree crown. Drag coefficient of a tree crown (C_D) defined in Eq. 1, which is necessary to estimate wind force (P_w), have been evaluated from wind tunnel studies [2-7].

$$P_W = \frac{1}{2} C_D \rho A U^2 \tag{1}$$

Where ρ, the air density (1.20 kg/m^3); A, the horizontally projected crown area; U, the wind velocity.

Most of the specimens used for the wind tunnel studies were dwarf potted trees or small models because of the restriction of the wind tunnel size. However, with regard to the wind-force response, it is noteworthy that the similarity rule is not applicable to the relationship between dwarf trees and actual trees. In fact, the drag coefficients of small trees at a wind velocity of 10 m/s were found to be 0.95–1.35 [4], 0.75–0.95 [5], and 1.00 [6], and these values were considerably greater than those of actual-sized trees[3], i.e., 0.29–0.88. These actual-sized specimens were coniferous species for plantations. The drag coefficients of actual-sized broadleaf species have not yet been obtained. These C_D values are necessary for the wind break assessment for park trees or roadside trees.

The aim of this study is to develop a test method to evaluate C_D of actual-sized trees in the field which is more convenient method compared with wind tunnel experiments. In this paper, the drag coefficients of actual-sized poplar trees were evaluated by the proposed field test method that involved monitoring the wind velocity and stem deflection simultaneously.

Materials and methods

Sample trees

Three trees were sampled from the east-west row of black poplars (*Populus nigra* var. *italica*) planted in 2000 in the Hokkaido University Campus. The south side of the row of trees was an open space without any buildings, and the prevailing wind direction was south. The dimensions of two of the sample trees (tree nos.1 and 2) were measured in October 2007 and those of tree no.3 were measured in October 2008 (Table 1).

Field tests

The wind velocity and stem deflection of the sample trees were monitored simultaneously (Fig. 1). The north-south and east-west components of the wind velocity (U) were monitored using an ultrasonic anemometer (Young Company, Model 85000) by placing it near each sample tree. The height of the anemometer was adjusted with respect to the height of the wind pressure center (H_W) (Eq. 2), which corresponds to the center of gravity of the crown; a crown was considered to be an ellipse whose major and minor axes are the length and breadth of the crown, respectively.

$$H_W = H_C + \frac{1}{2} L_C \qquad (2)$$

where H_C is the height of the crown base and L_C is the length of the crown.

Stem deflections were measured using a self-made middle-ordinate gauge[8], both ends of which were screwed into a stem at a height of 115–165 cm. A deflection sensor (Kyowa Dengyo, DTH-A-5) was set at the center of the gauge span (s = 500 mm). The wind velocity and stem deflections (δ) were measured along both the north-south and the east-west orientations and recorded in a data logger at 10-Hz intervals. The measurements were performed on windy days in both leaved and defoliation seasons; the measurement results are listed in Table 2. The measured data were divided into 1-h intervals, and data for 389 h, which included those measured at wind velocities above 5 m/s, were analyzed.

In order to measure the stiffness of the tree stems, bending tests of the sample trees were conducted once on calm days in each measurement period. A bending moment below the elastic limit was applied by pulling the stem from the north and east directions using a hand winch. The applied force was measured using a load cell connected between the sling, which was tied to the stem, and the hand winch, and it was recorded in the data logger. From the elastic relationship between the moment applied at the middle-ordinate gauge (M_L) and the stem deflection (δ), the stem stiffness (K) was determined for both the north-south and the east-west orientations.

$$K = \frac{M_L}{\delta} \tag{3}$$

After the bending tests, the natural periods of the sample trees were determined from the free-swaying movements of the stems.

Calculation of C_D

The wind force acting on a crown (P_w) was calculated from Eq. 4.

$$P_W = \frac{K\delta}{(H_W - H_D)} \tag{4}$$

where H_D is the height of the deflection sensor (Fig. 1).

Then, C_D was calculated every second from the ratio of P_W to U^2 using Eq. 1. C_D of the north-south component was analyzed because the east-west component was rather small and it might have been disturbed by the adjacent trees.

Results and discussion

Shapes of tree crowns

The actual areas and heights of the centers of gravity of the sample tree crowns were obtained by binarizing their photographs (Fig. 2). The actual areas of the crowns were found to be smaller than those obtained by assuming an ellipsoidal shape by 19–27% and greater than those obtained by assuming a triangular shape, as is the case with conifers[3], by 15–27%. The heights of the centers of gravity were estimated to be 47–48% of L_C from the crown base. In this study, the projected frontal area of the crowns was assumed to be an ellipsoid. This assumption was also used for calculating C_D of defoliated crowns.

The effect of the wind force acting on the stem below a crown was neglected because of the small area of the stem as compared to that of the crown, slow wind velocity near the ground level, and short distance between the wind-pressure center of a stem and the height of the middle-ordinate gauge (H_D).

Relationship between wind velocity and C_D

The stem deflections showed positive relationship with wind velocity as shown in Fig. 3. The average C_D calculated from this relationship decreased with an increase in the wind velocity (Fig. 4). This decrease in C_D can be explained by the decrease in the projected area of the crowns because of the swaying movement of leaves and branches, as observed in a wind tunnel study[3]. The variation in C_D was found to be large at a low wind velocity. This could be explained by the vibrating behavior of a stem subjected to a variable wind force; fine fluctuations were observed in stem deflection (Fig. 3). The variation in C_D was small at wind velocities above 10 m/s. In order to reduce the effect of vibrations at low wind velocities such as 5 m/s, C_Ds were calculated by generating moving averages from 1 to 10 s; this range includes the natural periods of the sample trees (2.8 to 3.7 s) (Fig. 5). However, no significant change was found in standard deviations as well as the average C_D.

The average C_D was calculated at wind velocity intervals of 0.5 m/s using all data for each measurement period (Fig. 6). C_D decreased with the wind velocity, as discussed before. The average C_D of the leaved crowns at a wind velocity of 10 m/s was 0.250.

Comparison between C_D values of poplars and conifers

Because wind velocity above 30 m/s is assumed as a maximum possible velocity and is considered in building design in urban areas, critical wind velocity could also be assumed as 30 m/s concerning wind resistance of roadside trees[6]. In order to estimate C_D at the wind velocity of 30 m/s, C_D as a function of U was curve-fitted with power function (Fig. 6). The curves for seven conifers studied previously in a wind tunnel experiment[3] are shown in Fig. 6. The average C_D of poplar crowns was found to be smaller than that of western hemlock, which had the smallest value among those for conifers. The results suggested that the wind permeability of poplar crowns is larger than conifer crowns due to the difference in flexibility of a leaf. The average extrapolated value of C_D at 30 m/s was 0.102; This value can be used for estimating wind velocity that induce wind damage to poplar trees.

Effect of leaves on C_D

C_D in the defoliation season was smaller than that in the leaved season, because the same crown areas were used for the calculation. The average C_D of defoliated crowns at 10 m/s was 0.133 (Fig. 7). The change in the crown area with the wind velocity variation would be small in the defoliation season because the swaying movement of the defoliated branches would be small. In fact, the decrease in C_D with an increase in the wind velocity was small for tree nos.1 and 2, as shown in Fig. 7. The ratio of C_D of defoliated crowns to that of leaved crowns increased with the wind velocity. The ratio at a wind velocity of 10 m/s was in the range of 0.553 to 0.770.

Conclusions

1. Drag coefficients of poplar crowns were successfully evaluated by a field test method in which the wind velocity and stem deflection were monitored simultaneously.
2. The drag coefficient decreased with an increase in the wind velocity.
3. The drag coefficient of poplar crowns was smaller than that of conifers studied in previous wind tunnel experiments.
4. The drag coefficient of defoliated crowns was smaller than that of leaved crowns.

Acknowledgements

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Figure legends

Fig. 1 Field test method for monitoring wind velocity and stem deflections

Fig. 2 Photographs and binarized images of crowns of sample trees (Left: no.1, center: no.2, right: no.3)

Fig. 3 An example of the time-series fluctuations for wind velocity (U) and stem deflections (δ)

Fig. 4 Relationship between drag coefficient (C_D) and wind velocity (U)

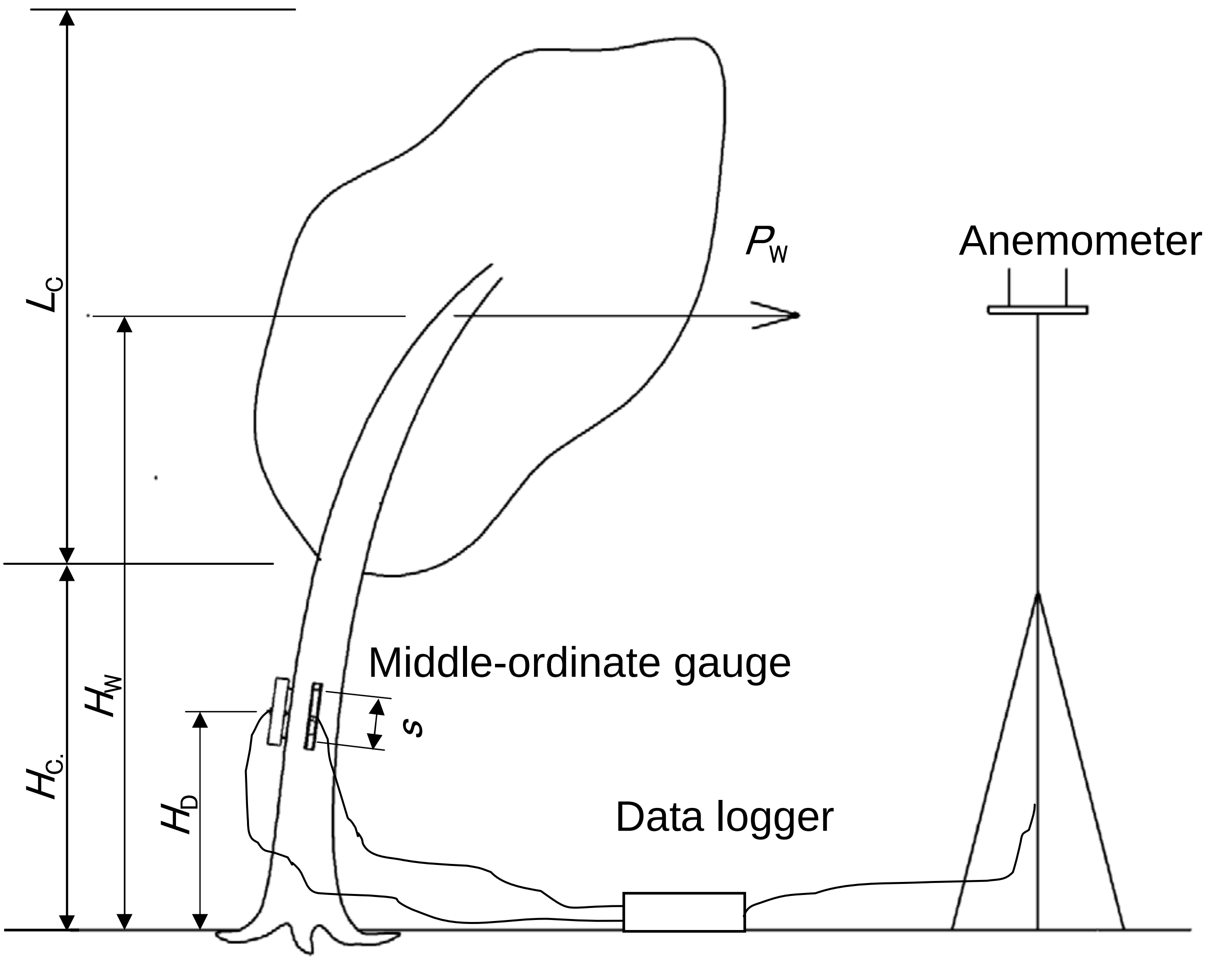
Fig. 5 Average and standard deviations in C_D calculated by generating moving averages from 1 to 10 s

Fig. 6 Comparison between C_D values of poplars and conifers obtained from a wind tunnel study

[a] Reported by Mayhead[3]

[b] No.1: $Y = 1.77\,X^{-0.911}$, no.2: $Y = 1.14\,X^{-0.824}$, no.3: $Y = 1.79\,X^{-0.714}$

Fig. 7 Relationship between wind velocity (U) and drag coefficient (C_D) for defoliated crowns and C_D ratio (defoliated/leaved)



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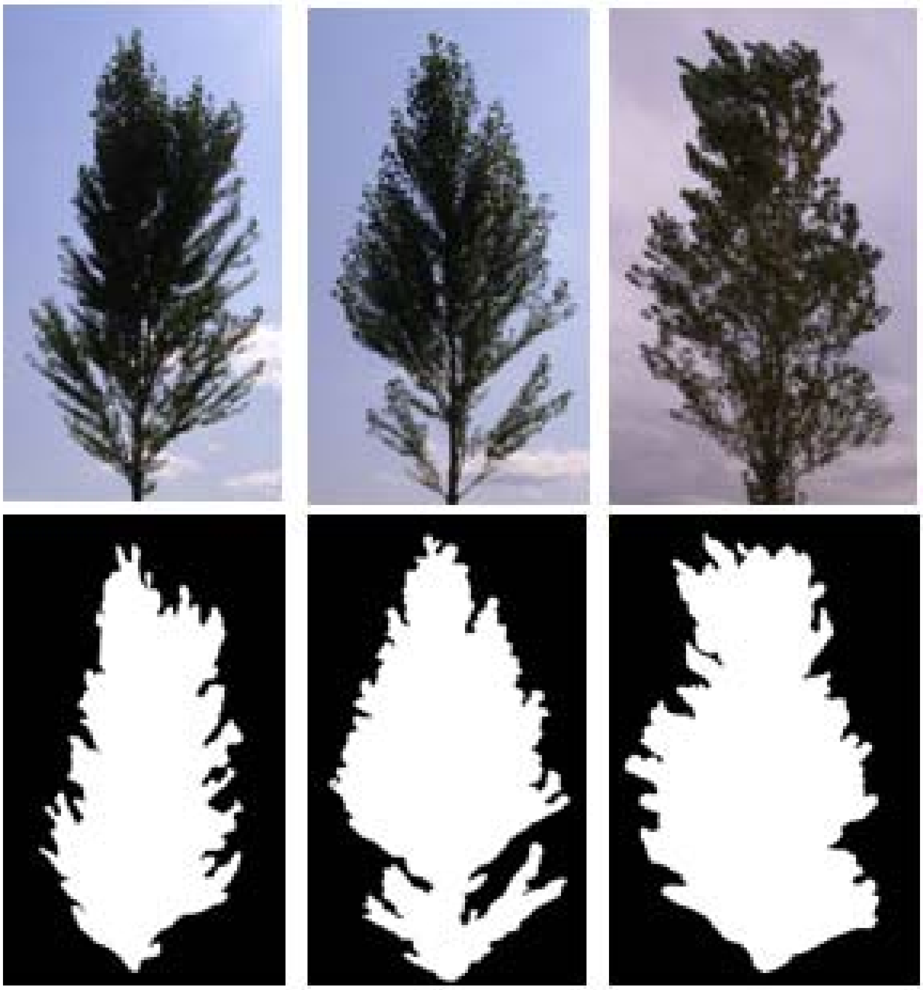


Fig. 2 Photographs and binarized images of crowns of sample trees (Left: no.1, center: no.2, right: no.3)

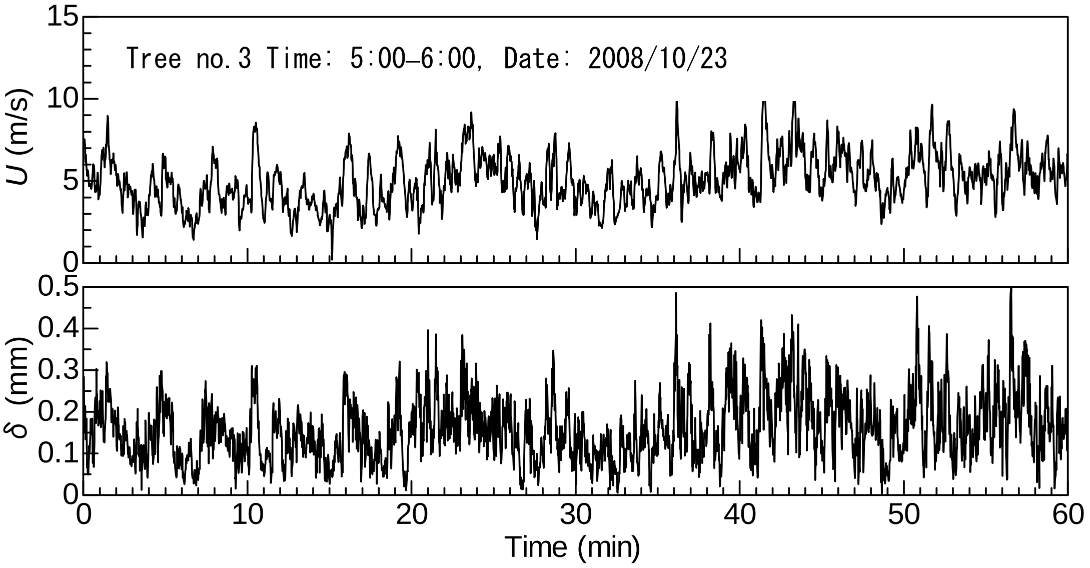
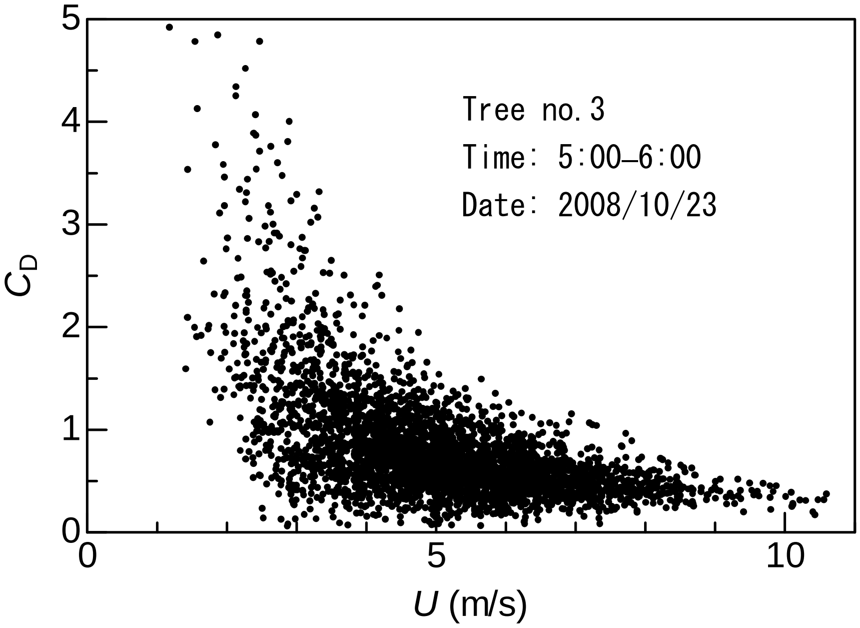


Fig. 3 An example of the time-series fluctuations for wind velocity (*U*) and stem deflections (*δ*)



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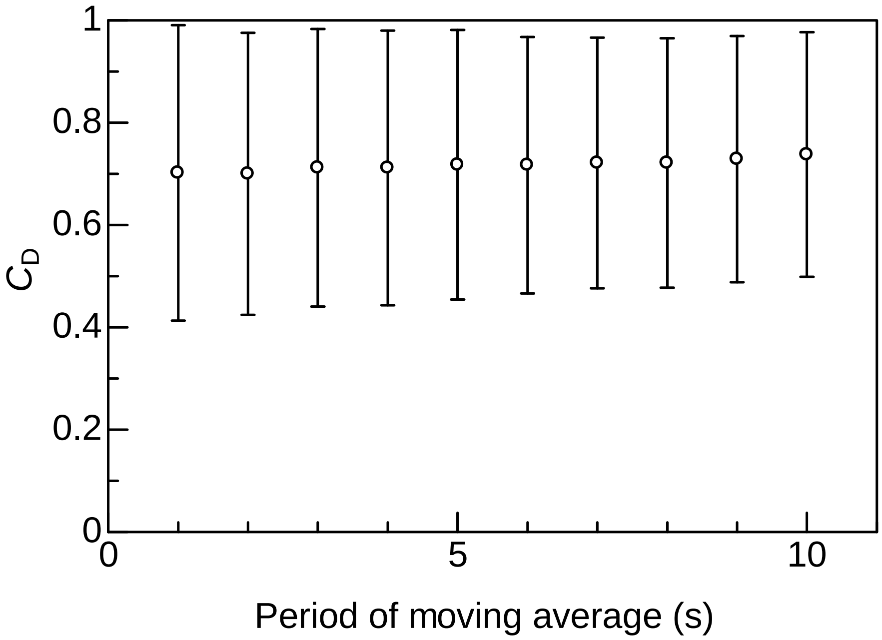

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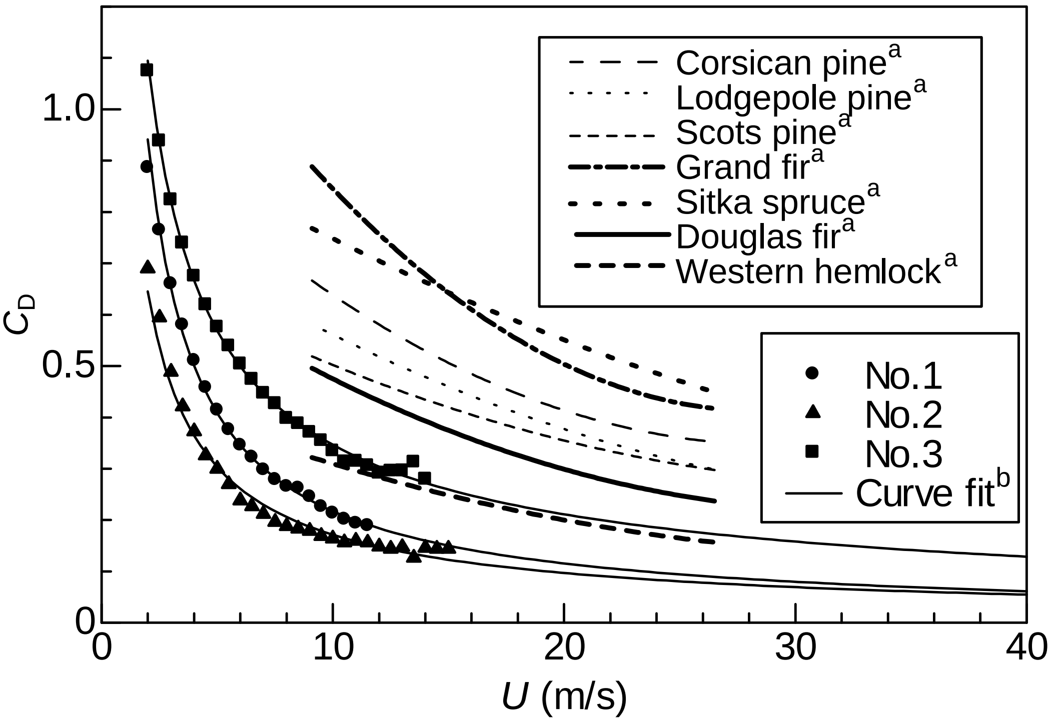

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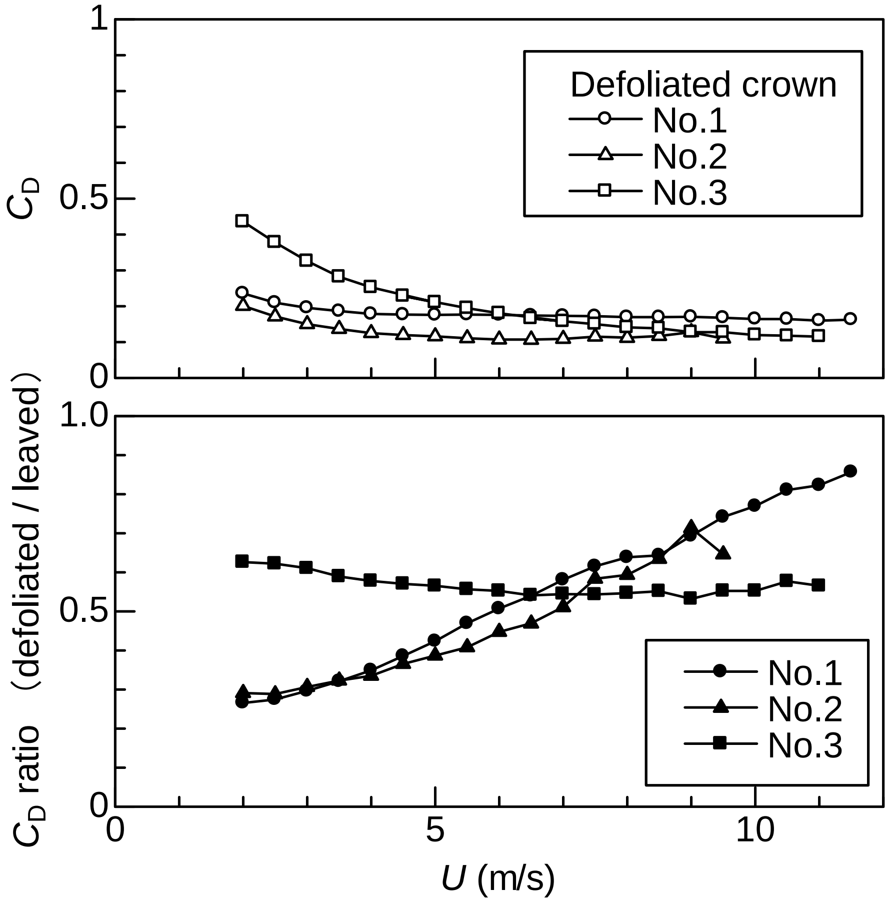

Fig. 7 Relationship between wind velocity (U) and drag coefficient (C_D) for defoliated crowns and C_D ratio (defoliated/leaved)

Table 1. Dimensions of sample trees

No.	H (m)	D_B (cm)	L_C (m)	B_C (m)	A (m^2)	H_W (m)
1	13.1	24.2	9.3	4.4	32.5	8.4
2	12.3	19.3	7.8	3.6	22.0	8.4
3	12.9	24.1	8.9	4.1	29.0	8.5

H, Tree height; D_B, Breast-height diameter; L_C, Crown length;
B_C, Crown breadth (east-west direction);
A, Horizontal projected area of crown assuming an ellipsoidal crown (east-west direction);
H_W, Height of wind pressure center

Table 2. Measurement periods for wind velocity and stem deflections

Tree no.	Leaf condition	Measurement period	Measurement time (h）	Analysis time[a] （h）
1	Leaved	Oct. 2007	232	82
	Defoliated	Apr. 2008	120	59
2	Leaved	Oct. 2007	235	58
	Defoliated	Apr. 2008	117	31
3	Leaved	Oct. 2008	402	115
	Defoliated	Apr. 2008	48	44

[a] Data for wind velocities above 5 m/s were included.