Characteristics of roughness parameters in boreal, cool-temperate and warm-temperate forests

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Abstract

Zero-plane displacement d and roughness length z_0 were compared among boreal, cool-temperate, and warm-temperate forests. z_0 was large in the forest include coniferous trees, whereas small in the forest consist of broad-leaved trees. The normalized zero-plane displacement d/h (where h is the tree height) increased with stand density, whereas z_0 decreased. On the other hand, d/h showed a negative correlation with plant area index (PAI), which was inconsistent with parameterization of the models. The effect of the vertical structure of the forest might be included in PAI. Seasonal variation in d/h appeared in the forest including deciduous broadleaved trees. The change of d/h corresponded to the change of PAI. However, d/h was underestimated by the models, and the decrease in d/h for cool-temperate forest appeared to be small compared with that predicted using the models.

Keywords: Zero-plane displacement, Roughness length, Stand density, PAI, vertical structure.

1. Introduction

Roughness parameters, such as zero-plane displacement d (m) and roughness length z_0 (m), are necessary factors to estimate transportation of heat, water, and scalar gasses (CO_2, etc.) through aerodynamic resistance in Penman-Monteith equation or atmospheric stability function. These parameters are related to forest structure factors (LAI, stand density, etc.), and their relationships are needed for estimation of plant-physiological factors in wide-scale area of boreal forest by using satellite data. In this study, as a part of CREST project which follows GAME-Siberia study, roughness parameters are compared among boreal forest, cool-temperate forest, and warm-temperate forest, and the characteristics of them are discussed.

2. Material and method

2.1. Study site

We have 5 meteorological towers in 3 research areas. The boreal forest site is located in Spasskaya Pad near Yakutsk, Russia (62° 15' N, 129° 37' N), the cool-temperate forest site is located in Moshiri, Hokkaido, Japan (44° 20' N, 142° 15' N), and the warm-temperate forest site is located in Seto, Aichi, Japan (35° 15' N, 137° 04' N). Figure 1 shows the location of the study sites.

In the boreal forest site, we have two observation sites. The Yakutsk-Larch site (YL) is in the larch forest (deciduous conifers), and the Yakutsk-Pine site (YP) is in the red pine forest (evergreen conifers). We also have two study sites in the cool-temperate forest site. The Moshiri-Birch site (MB) is in the birch forest (deciduous broadleaved trees), and the Moshiri-Mixed site (MM) is in a mixed forest of evergreen conifer and deciduous broadleaved trees. The warm-temperate forest site, the Seto-Mixed site (SM), is in a mixed forest consisting of deciduous and evergreen broad-leaved trees.

The forest structure factors: stand density (trees ha^{-1}), tree height h (m) and plant area index (PAI) of each site are shown in table 1. PAI of the YL and YP site was estimated by fish-eye photos (Toba and Ohta, 2002), whereas a plant canopy analyzer LAI-2000 (Li-COR) was used for the other sites. In the MM site, the forest consists of broadleaved trees (maximum tree height $h_{\max} = 22.9$ m) and coniferous trees ($h_{\max} = 35.5$ m), and the tall coniferous trees appeared to affect the aerodynamic roughness; hence, $h = 25$ m was assumed as the apparent mean tree height of tall coniferous trees.

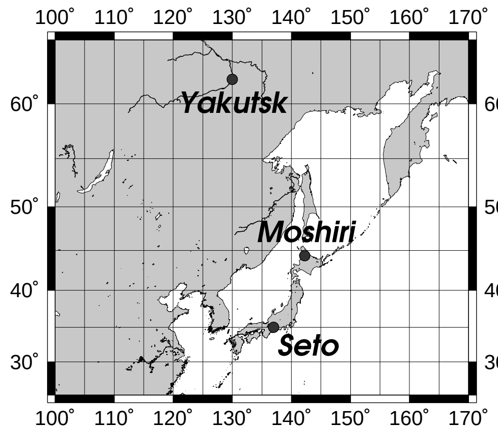

Fig. 1: Location of study sites

2.2. Observation

The data from the Sonic Anemometer-Thermometer (SAT) and the anemometers are used in this study. From the SAT mounted at the height of z_{SAT} (m), the friction velocity u_* (m s^{-1}) and the Monin-Obukhov length L (m) were obtained. The wind speed $U(z)$ (m s^{-1}) was measured by the anemometers at two heights, z_a and z_b (m) ($z_a > z_b$). In the YP site, however, wind profile data was not available, and hence only data from the SAT was used. The height of instruments, z_{SAT}, z_a and z_b of each site are also shown in table 1. The SAT data was sampled in 10 Hz, and was calculated above parameters every 30 minutes with the coordinate correcrion by double rotation method. $U(z)$ was sampled every 10 seconds, and was averaged every 30 minutes.

Table 1: Forest structure factors and observation height at each site

Site	Stand density (trees ha^{-1})	Tree height h (m)	Plant area index (PAI)	z_{SAT} (m)	z_a (m)	z_b (m)
YL	840*	18*	3.71 (Jul. 1997)*	32.0	30	24
YP	2,660**	10*	2.80 (Aug. 2000)*	18.2	—	—
MB	4,000	11.5	2.63 (Jun. 2004)	21.05	20	16
MM	2,585	25***	3.44 (Jul. 2004)	31.56	30	25
SM	1,828	8.1	3.56 (Jun. 2004)	19.5	14	10

*Toba and Ohta (2002), **Hamada *et al.* (2003), ***Apparent mean tree height of tall conifers.

2.3. Calculation of d and z_0

In a condition of neutral stability, mean wind profile is written in logarithmic low with height as follows:

$$U(z) = \frac{u_*}{k} \ln \frac{z-d}{z_0} \tag{1}$$

where k is the von Kármán constant (= 0.4). When the slope of $kU(z)$ to u_* were obtained at two height ($\alpha = kU(z_a)/u_*$ at z_a and $\beta = kU(z_b)/u_*$ at z_b), then d and z_0 could be calculated as follows:

$$d = \frac{z_b(e^\alpha/e^\beta) - z_a}{e^\alpha/e^\beta - 1}, \quad z_0 = \frac{z_a - d}{e^\alpha} \tag{2}$$

The data under the conditions of neutral stability, $|z_{SAT}/L| \leq 0.05$, were selected for the calculation.

On the other hand, for the YP site where only the eddy correlation data was available, the method of Toda and Sugita (2003) were used in calculation of d and z_0. The data was filtered by stability ($-15 \leq z_{SAT}/L \leq 0$), wind speed ($U(z_{SAT}) \geq 1$), sensible heat flux H ($H \geq 100$ W m^{-2}), latent heat flux lE ($0 \leq lE \leq 1000$ W m^{-2}), and steadiness of temperature T (°C) (variation in 30 minutes $|dT_{30\mathrm{min}}| \leq 0.5$ °C 30min^{-1}). Further more, the daytime data (from 10:00 to 14:00) are picked up. In this study, d and z_0 calculated for temperature are adopted.

3. Result and discussion

3.1. Comparison of roughness parameters among different forests

Table 2 shows d and z_0 for each observational site in June 2004, together with normalized values devided by h. In many cases, d and z_0 are parameterized as simple function of h (Brutsaert, 1982), and tipically $d = (2/3)h$ and $z_0 = (1/8)h$ are used (Garratt, 1992). Figure 2 is the scatter diagrams of d (a) and z_0 (b) agenst h in June 2004. The regression coefficient was 0.70 for d and 0.10 for z_0, which is consistent with above parameterization. From fig. 1(a), d strongly depends on h, and hence the normalization with h is necessary in comparison of d among different forests. However, z_0 was not correlated with h. z_0 was large in YL, YP and MM site, that include coniferous trees, whereas small in MB and SM site, that consist of broad-leaved trees. The large z_0 is result in the small aerodynamic resistance r_a (m s^{-1}):

$$r_a = \frac{1}{k^2 U(z)} \left(\ln \frac{z-d}{z_0} \right)^2. \tag{3}$$

It indicates that the scalar is carried by the eddies effectively in the northern forest consists of conifers. These characteristics in z_0, however, did not appear in normalized values of z_0/h (Table 2). It shows that the normalization of z_0 with h is not valid in comparison of the characteristics among different forests. Hence, hereafter, d/h and z_0 are compared among 5 forest sites together with forest structure factors.

Table 2: Comparison of d and z_0 among different forest sites together with normalized values (June 2004).

Site	d (m)	d/h	z_0 (m)	z_0/h
YL	9.42	0.52	2.48	0.14
YP	7.34	0.73	1.45	0.15
MB	9.78	0.85	0.67	0.06
MM	19.25	0.77	1.78	0.07
SM	5.21	0.64	0.92	0.11

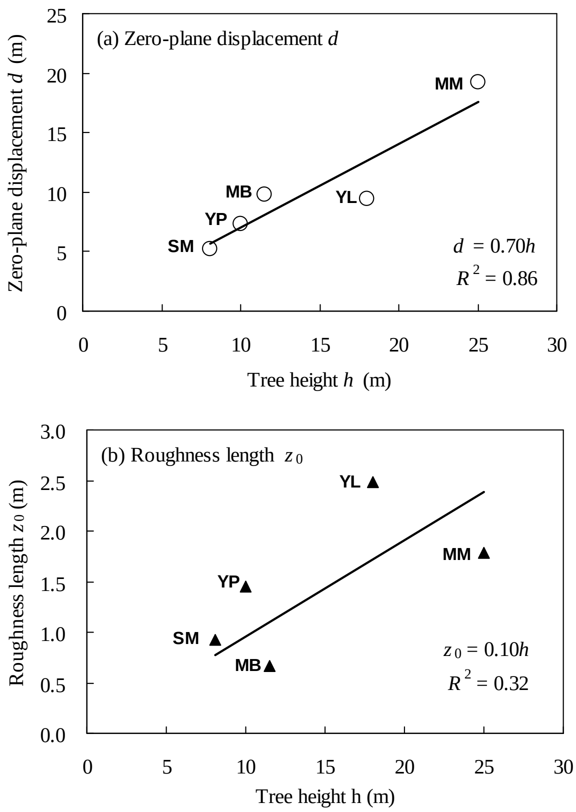

Fig. 2: Scatter diagrams of d (a) and z_0 (b) against h (June 2004).

Figure 3 is the scatter diagram of d/h and z_0 against the stand density. d/h increased with stand density, whereas z_0 decreased. d/h was strongly correlated with h ($R^2 = 0.95$) compared with the correlation between

z_0 and h ($R^2 = 0.56$). This result suggests that the dence forest inhibit the momentum from penetrating into the forest, and make the surface smoother. Hence the stand density is one of the effective forest structure factors to estimate d and z_0. At the YL site in the boreal forest, d/h was the smallest and z_0 was the largest in these sites because of its small stand density.

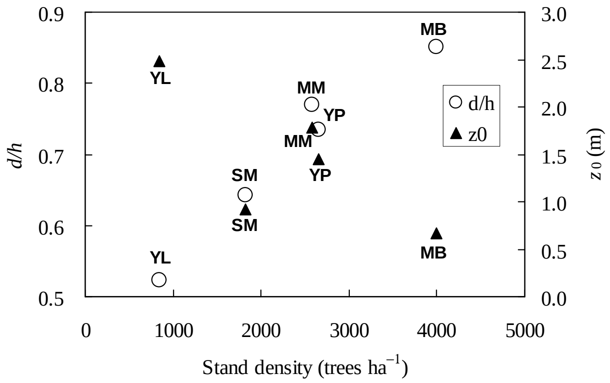

Fig. 3: Scatter diagrams of d/h and z_0 against stand density.

Figure 4 is the scatter diagram of d/h and z_0 against PAI. d/h seems to have negative correlation with PAI, which is inconsistent with the parameterization of some models (*e.g.*, Choudhury and Monteith, 1998), although PAI of the YL and YP site was estimated by different way from that of the other sites. This indicates that d/h and z_0 cannot be estimated only from PAI data.

In the dense forest, the foliage is concentrated on the top of the trees, and hence PAI becomes small. On the other hand, in the sparse forest, the foliage is vertically distributed because solar radiation penetrates deep into the forest, and hence PAI may become large. Here, the plant area per tree A_s (m^2 tree^{-1}) is introduced, which is expected to represent the vertical structure of the forest. Figure 5 is the scatter diagram of d/h and z_0 against A_s. d/h decreased with A_s, although the results for the YL and YP sites were less reliable. This suggests that the vertical structure of the forest has an effect on the aerodynamic roughness, and the parameterization of this structure is important in evaluating d/h and z_0.

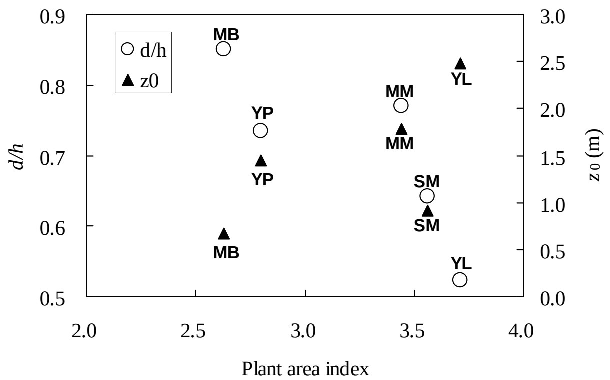

Fig. 4: Scatter diagrams of d/h and z_0 against plant area index.

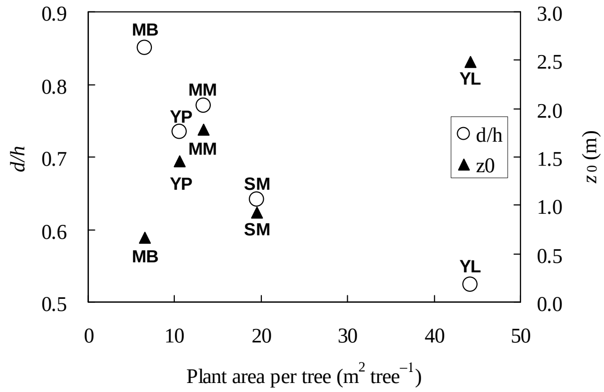

Fig. 5: Scatter diagrams of d/h and z_0 against plant area per tree.

3.2. Seasonal variation in roughness parameters

Figure 6 shows the seasonal variation of d/h in five research sites from July 2003 to August 2004. The MB and MM site had heavy snowfall in winter; hence, the snowdepth h_s (m) was included and d/h was calculated as $(d - h_s)/(h - h_s)$. In the MB, MM and SM site, d/h changed seasonally: small in winter and large in summer. This change corresponded to the seasonal change of PAI shown in fig. 8, which is consistent with the parameterization such as Choudhury and Monteith (1998). Here, the PAI in the MB and MM site shown in fig. 8 was estimated from the downward PAR measured on the tower top and the forest floor, which was fitted to the PAI data measured with LAI-2000. The change in d/h was large in SM site compared with that in MB and MM site. The coefficient of variation CV (%) was 4.5% in MB site, 4.3% in MM site, and 6.4% in SM site. On the other hand, in the YL site, there was no apparent seasonal change of d/h in spite of its foliation in this period. In the YP site, which consits of evergreen conifer, d/h was fluctuated although there was no foliation. As the result, the seasonal variation in d/h appeared in the forest including deciduous broadleaved trees, and it was not clear in coniferous forest.

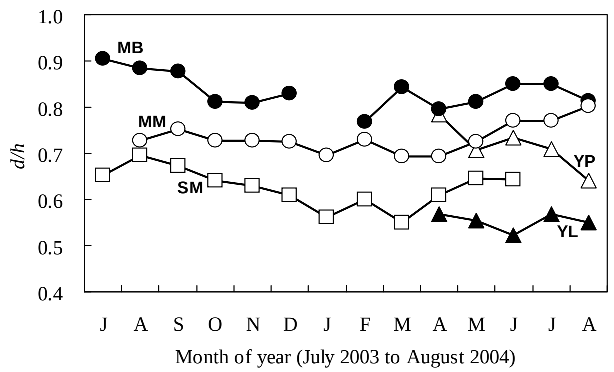

Fig. 6: Seasonal variation of d/h in five research sites.

Figure 7 shows the seasonal variation of z_0. In the MB and MM site, z_0 showed clear seasonal change: large in winter and small in summer. However, this change was not apparent in SM site. CV was 19.6% in MB site, 15.2% in MM site and 10.8% in SM site. This sugests that the evergreen trees in the SM site affected the aerodynamic roughness even though the deciduous trees was defoliated.

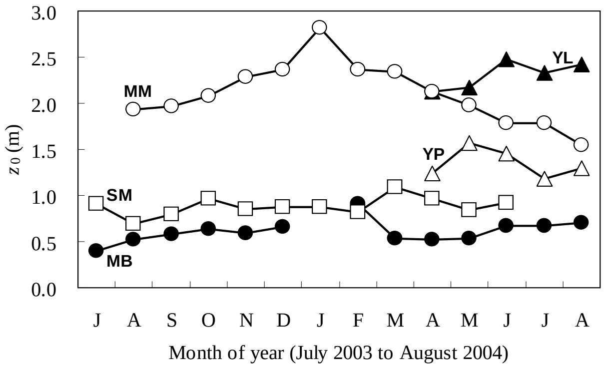

Fig. 7: Seasonal variation of z_0 in five research sites.

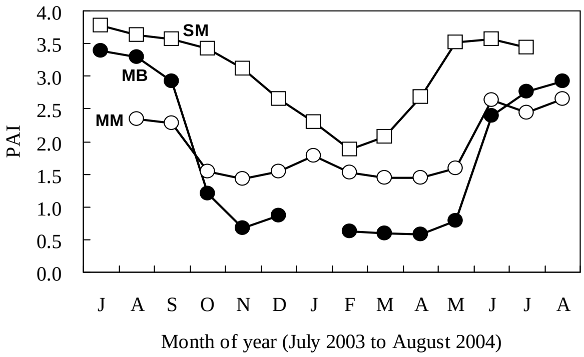

Fig. 8: Seasonal variation of PAI in MB, MM and SM site.

3.3. Comparison of d/h between observation and model prediction

As mentioned above, the change of d/h corresponed to that of PAI, and this relationship was parameterized in some previous study. Here, the observed d/h was compared with that predicted from the models presented by Choudhury and Monteith (1998) and Yamazaki *et al.* (1992).

Choudhury and Monteith (1998) parameterized d/h as follows:

$$\frac{d}{h} = \ln\left(1 - X^{1/6}\right) + 0.03 \ln\left(1 + X^6\right) \tag{4}$$

where $X = 0.2$PAI. This model parameterized d/h only from PAI. On the other hand, Yamazaki *et al.* (1992) wrote d/h as follow equation:

$$\frac{d}{h} = 1 - \left(\frac{h_1}{h} - \frac{2k^2}{c_*}\right) \exp\left[1 - \frac{c_*}{2k^2}\left(1 - \frac{h_1}{h}\right)\right] - \frac{2k^2}{c_*} \tag{5}$$

where h_1 is the height of the bottom of crown (m), $c_* = c_d a h$, c_d is the drag coefficient ($= 0.2$) and a is the plant area density (m^{-1}). This model simply includes the vertical structure of the forest.

Figure 9 shows the seasonal variation of observed d/h in MB site together with predicted values and PAI. The trend in the observed d/h with the change in PAI was consistent with that predicted by the models. However, d/h was underestimated by both models, and the seasonal variation of the observged d/h was small compared with that predicted using the model of Yamazaki *et al.* (1992). As pointed out in section 3.1., d/h cannot be described only by PAI because PAI may indicate vertically-distributed foliage. Furthermore, the birch tree has small dense branches in the crown space; hence, these branches are also expected to affect d/h after defoliation. Accurate evaluation of such forest structure factors is necessary.

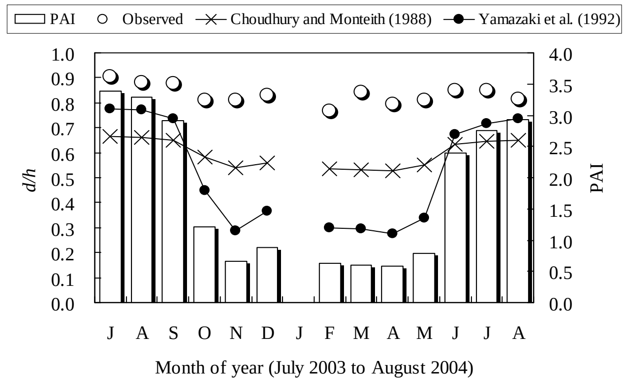

Fig. 9: Comparison of d/h among observed and model-predicted values together with PAI in the MB site.

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