Parameterisation of aerodynamic roughness over boreal, cool- and warm-temperate forests

Taro Nakai [a,b,*], Akihiro Sumida [b], Ken'ichi Daikoku [c], Kazuho Matsumoto [c], Michiel K. van der Molen [d], Yuji Kodama [b], Alexander V. Kononov [e], Trofim C. Maximov [e], Albertus J. Dolman [d], Hironori Yabuki [f], Toshihiko Hara [b], Takeshi Ohta [c,a]

[a] *CREST, Japan Science and Technology Agency, Kawaguchi, Saitama 332-0012, Japan*

[b] *Institute of Low Temperature Science, Hokkaido University, N19 W8, Kita-Ku, Sapporo 060-0819, Japan*

[c] *Graduate School of Bioagricultural Sciences, Nagoya University, Nagoya 464-8601, Japan*

[d] *Department of Hydrology and Geo-Environmental Sciences, Faculty of Earth and Life Sciences, Vrije Universiteit, de Boelelaan 1085, 1081 HV, Amsterdam, The Netherlands*

[e] *Institute for Biological Problems of Cryolithozone, Siberian Division of Russian Academy of Sciences , 41 Lenin ave., Yakutsk 678891, Russia*

[f] *Institute of Observational Research Center for Global Change, Yokosuka 237-0061, Japan*

Preprint submitted to Agricultural and Forest Meteorology *11 March 2008*

Abstract

Roughness length and zero-plane displacement over boreal, cool- and warm-temperate forests were observed and parameterised using forest structure data. Previous models for roughness length and zero-plane displacement using leaf area index and frontal area index did not describe intersite differences, and the model for zero-plane displacement did not express seasonal variations with the change of leaf area that was smaller in dense forest than in sparse forest. The observed results show that intersite differences of normalised zero-plane displacement were related to stand density, and seasonal variations were related to leaf area index at each forest, with the degree depending on stand density. From these observations, a new concept is proposed for normalised zero-plane displacement: the basal part is primarily determined by the density of stems and branches (stand density), while the seasonal variation depends on the density of leaves (leaf area index), which is limited to the residual of the basal part. Based on this concept, a new model was developed and verified to express both intersite differences and seasonal variations in observed roughness length and zero-plane displacement.

Key words: roughness length, zero-plane displacement, stand density, leaf area index

* Corresponding author. Tel.: +81-11-706-7437; fax: +81-11-706-7142.
Email address: taro@pop.lowtem.hokudai.ac.jp (Taro Nakai).

1 Introduction

Zero-plane displacement d (m) and roughness length z_0 (m) are essential for micrometeorological studies over tall vegetation canopies. d is regarded as the level of action of the drag on the roughness elements (Thom, 1971), and is required for many variables, such as the stability parameter $\zeta = (z - d)/L$ (where z [m] is the measurement height above the actual ground surface, and L [m] is the Obukhov length), since most theories of the atmospheric boundary layer are built for the scale height $z - d$ (e.g. Garratt, 1994). On the other hand, z_0 is the length scale that characterises the loss of wind momentum attributable to the roughness elements (Minvielle et al., 2003). d and z_0 are calculated from the vertical profile of wind speed measured at several heights. However, it is recognised that determination of d and z_0 is practically difficult since they can vary with uncertainty in the measurements (e.g. Schaudt, 1998). When d and z_0 are used for length scale, as mentioned above, representative values of these terms are required.

d and z_0 are also important factors in global climate models. The land surface models for general circulation models require d and z_0 to be representative for the scale of each grid cell of the models (e.g. Verhoef et al., 1997; Schaudt and Dickinson, 2000). Since the site-specific data of d and z_0 represent small local scales, d and z_0 for such models are expected to be parameterised as a function of forest structure factors that can be obtained from satellite data.

From the above circumstances, many efforts have been made to develop parameterisations for d and z_0 with canopy structures (Yang and Friedl, 2003). The simple relations of d and z_0 to canopy height h (m), such as $d/h = 0.64$

(Cowan, 1968) and $z_0/h = 0.13$ (Tanner and Pelton, 1960), are frequently used. However, d/h and z_0/h are not constants and vary with the density of roughness elements (see Garratt, 1994). To represent the density of the canopy, two parameters have been used. Choudhury and Monteith (1988) used leaf area index (LAI) to parameterise d/h and z_0/h based on the second-order closure model results of Shaw and Pereira (1982). Raupach (1994) provided the method to derive d/h and z_0/h using frontal area index (FAI), which is the total frontal area (width $\times$ height of elements) per unit ground area. Recently, FAI and the model of Raupach (1994) were adopted to estimate d/h and z_0/h from satellite data (e.g. Jasinski and Crago, 1999; Schaudt and Dickinson, 2000). However, few studies have checked the applicability of these models to d/h and z_0/h obtained from field experiments over forests (e.g. Yang and Friedl, 2003).

The objectives of this study were to assess the validity of previous models of d/h and z_0/h against observed data from five different forests in boreal, cool-temperate and warm-temperate areas, and to provide alternative parameterisation to describe the observed d/h and z_0/h using forest structure factors.

2 Previous models for d/h and z_0/h

Choudhury and Monteith (1988) proposed the following parameterisations of d/h and z_0/h with LAI, A (m^2 m^{-2}), by fitting them to curves derived from the second-order closure model given by Shaw and Pereira (1982).

$$\frac{d}{h} = 1.1 \ln \left[1.0 + (c_{\mathrm{d}} A)^{1/4} \right] \tag{1}$$

$$\frac{z_0}{h} = \frac{z_0'}{h} + 0.3\sqrt{c_\mathrm{d}A} \qquad (c_\mathrm{d}A \leq 0.2) \tag{2}$$

$$\frac{z_0}{h} = 0.3\left(1.0 - \frac{d}{h}\right) \qquad (c_\mathrm{d}A > 0.2) \tag{3}$$

where $c_\mathrm{d}(= 0.2)$ is the mean drag coefficient for individual leaves and z_0' is the roughness length of the soil surface. Following Schaudt and Dickinson (2000), the value of $z_0'/h = 0.000860$ was used as the asymptotic value for bare soil.

However, Raupach (1994) related d/h and z_0/h to FAI, λ (m^2 m^{-2}), and derived the following expressions.

$$\frac{d}{h} = 1.0 - \frac{1.0 - \exp(-\sqrt{a_1\lambda})}{\sqrt{a_1\lambda}} \tag{4}$$

$$\frac{z_0}{h} = a_2 \exp\left(-b_2\lambda^{c_2}\right)\lambda^{d_2} + \frac{z_0'}{h} \qquad (\lambda \leq 0.152) \tag{5}$$

$$\frac{z_0}{h} = \frac{a_3}{\lambda^{d_3}}\left[1.0 - \exp\left(-b_3\lambda^{c_3}\right)\right] + f_2 \qquad (\lambda > 0.152) \tag{6}$$

where $a_1 = 15.0$, $a_2 = 5.86$, $b_2 = 10.9$, $c_2 = 1.12$, $d_2 = 1.33$, $a_3 = 0.0537$, $b_3 = 10.9$, $c_3 = 0.874$, $d_3 = 0.510$ and $f_2 = 0.00368$ (Schaudt and Dickinson, 2000).

After Raupach (1994), Schaudt and Dickinson (2000) considered effects of both LAI and FAI on d/h and z_0/h. Their method is based on Raupach (1994), and included the effect of LAI using the dependence of d/h and z_0/h on LAI from Lindroth (1993). They proposed the functions f_d for d as

$$f_\mathrm{d} = 1.0 - 0.3991\exp(-0.1779A), \tag{7}$$

and f_z for z_0/h as

$$f_\mathrm{z} = 0.3299A^{1.5} + 2.1713 \qquad (A < 0.8775), \tag{8}$$

$$f_{\mathrm{z}} = 1.6771 \exp(-0.1717A) + 1.0 \qquad (A \geq 0.8775), \tag{9}$$

and parameterised d/h and z_0/h by multiplying Eq. (4) by f_{d} and Eq. (5) or Eq. (6) by f_{z}.

Hereafter, the models of Choudhury and Monteith (1988), Raupach (1994) and Schaudt and Dickinson (2000) are referred to as CM88, R94 and SD00, respectively.

3 Observations

Meteorological observations and forest surveys were conducted in five forest sites: a larch (deciduous conifer) forest (YL) and a pine (evergreen conifer) forest (YP) in Spasskaya Pad, near Yakutsk, Russia (boreal forests); a birch (deciduous broadleaf) forest (MB) and a mixed forest of evergreen conifer and deciduous broadleaf (MM) in Moshiri, Japan (cool-temperate forests); and a mixed forest of evergreen and deciduous broadleaf species (SM) in Seto, Japan (warm-temperate forest). Figure 1 shows the locations of these regions. Locations and altitudes (m) of the sites are listed in Table 1.

Figure 1

Table 1

To calculate d and z_0, we observed two wind speeds U_1, U_2 (m s^{-1}) at heights z_1 and z_2 (m) with cup anemometers, and friction velocity u_* (m s^{-1}) at z_{e} (m) with an ultrasonic anemometer. These observation heights are also listed in Table 1. The cup anemometers used at these sites were AC-750 (Makino,

Japan) at sites YL and YP, and 010C (MetOne, USA) at sites MB, MM and SM; the ultrasonic anemometers were R3-50 Solent ultrasonic anemometers (Gill Instruments, UK) at sites YL, YP, MB and MM, and DAT-540 (Kaijo, Japan) at site SM. U_1 and U_2 were sampled at 10-s intervals and averaged over 30 min, and u_* was calculated every 30 min from wind speed data sampled at a rate of 10 Hz. For R3-50, angle-of-attack-dependent errors were corrected in calculating u_* (Nakai et al., 2006). d and z_0 under neutral conditions were then calculated as follows (e.g. Rooney, 2001):

$$d = \frac{z_2 \exp(kU_1/u_*)/\exp(kU_2/u_*) - z_1}{\exp(kU_1/u_*)/\exp(kU_2/u_*) - 1} \tag{10}$$

$$z_0 = \frac{z_1 - d}{\exp(kU_1/u_*)}, \tag{11}$$

where $k = 0.4$ (dimensionless) is the von Kármán constant. In calculating daily and monthly d and z_0, daily- and monthly-averaged U_1, U_2 and u_* were calculated using data under neutral conditions ($|z_\mathrm{e}/L| < 0.05$, where L [m] is the Obukhov length) and within a limited range of wind directions (see Table 1) to avoid the shadow effect of the tower. Data from 2006 were used for sites YL and YP, from 2004, 2005, and 2006 for sites MB and MM, and from 2004 and 2006 for site SM.

Forest surveys were conducted in 2003 (YL, YP, MB), 2004 (YL, YP, MM), 2005 (SM) and 2006 (YP) to obtain stand density ρ_s (trees ha^{-1}), tree height h_t (m), height to the lowest live branch h_b (m), and stem diameter at breast height (1.3 m in height) D (m). The number of sampled trees taller than 1.3 m for each forest was 202 (YL), 643 (YP), 471 (MB), 1029 (MM) and 475 (SM). LAI of these sites was measured using a plant canopy analyser (LAI-2000, LI-COR, Inc., USA) and is thus considered 'effective LAI' (Chen et al., 1991);

i.e., the ratio of the total one-sided area of vegetation elements over the unit ground area (Nackaerts et al., 2000). FAI λ was calculated using the method of Schaudt and Dickinson (2000). The frontal area of each tree sample A_f was calculated for broadleaf trees as

$$A_\mathrm{f} = h_\mathrm{b} \times D + \frac{\pi}{4} \times r \times (h_\mathrm{t} - h_\mathrm{b})^2 \tag{12}$$

and for coniferous trees as

$$A_\mathrm{f} = h_\mathrm{b} \times D + \frac{1}{2} \times r \times (h_\mathrm{t} - h_\mathrm{b})^2 \tag{13}$$

where r is the crown aspect (height-to-width) ratio given in Table 1 of Schaudt and Dickinson (2000). A_f was calculated for all samples, and λ was then calculated as total A_f divided by plot area. Stand density ρ_s, LAI A and FAI λ are listed in Table 1.

In comparing d and z_0 between different forest sites, canopy height h is a key parameter to normalise d and z_0 as d/h and z_0/h, respectively. This h should be determined by the same objective means without arbitrariness. Mean tree height was the most commonly used parameter. However, for site MM, although the maximum tree height was 33.6 m, the mean tree height was 5.3 m because of the presence of a large number of shorter trees. Thus, a mean tree height does not always represent the canopy structure of a forest.

The representative height of a forest canopy would be better expressed by taking into account the basal areas (cross-sectional area of the trunk at 1.3 m in height) of trees, since taller trees composing the crown surface or the upper canopy would have large basal areas. If several such taller trees occur within a similar height class, the basal areas of trees belonging to this height

class would be largest. Therefore, we could reasonably consider the height of the distribution peak of the basal areas of trees belonging to each tree height class as the representative canopy height of a forest. To evaluate this canopy height analytically, we adopted the following procedure.

(1) Sort tree height of samples in increasing order.
(2) Plot cumulative basal area against the tree height of samples.
(3) Fit this plot by the Gompertz function (e.g. Gompertz, 1825; Franses, 1994; Jukić et al, 2004).
(4) Differentiate the fit function of (3) and find the peak of this derivative.

Figure 2 shows the plots of the observed cumulative basal area against tree height, the fitting curve (Gompertz function) to the observed data, and the derivative of this fit function for each forest site. The canopy height h was determined as the height at which the peak of this derivative appeared. Table 1 lists the value of h of each forest. Note that although the maximum tree height of site MM was taller than the measurement height, this highest tree was located downslope and distant from the tower (Nakai et al., 2006). Similarly, the meteorological tower of site SM was located on a mountain ridge, and relatively tall trees were located downslope. In both sites, the tree heights near the tower were almost the same as the canopy heights obtained here.

Figure 2

4 Results and discussion

4.1 Validity of previous models

The validity of previous models was checked against observed d/h and z_0/h in the five forest sites. For these analyses, the summertime (JJA) averaged data of daily d/h and z_0/h were used.

Plots in Fig. 3 are scatter diagrams of d/h and z_0/h against LAI, A (Fig. 3a) and FAI, λ (Fig. 3b) together with the model outputs of CM88 (Fig. 3a) and R94 (Fig. 3b), respectively. Observed d/h and z_0/h deviated from both CM88 and R94 outputs, especially in site YL, indicating that both models were insufficient to describe actual roughness parameters of forests.

Figure 3

The LAI-based model, CM88, is based on the numerical simulation results of Shaw and Pereira (1982). The model of Shaw and Pereira (1982) dealt with agricultural crops, such as a corn canopy, and thus CM88 would be appropriate for herbaceous plants. However, no attempt was made to represent forest-like stands with a relatively open trunk space in the model of Shaw and Pereira (1982). In the case of agricultural crops, LAI may represent the canopy density, and thus d/h may monotonically increase with LAI. However, for forest stands, stems and branches may affect d/h. For example, Dolman (1986) reported that d/h of non-foliated oak forest was 0.57 (stand density 3000 trees ha^{-1}). This effect cannot be described by models with only LAI data. In addition, natural self-pruning of branches occurs in forests and may be influenced by stand density (e.g. Mäkinen, 1999). Actually, the relationship between stand density

and LAI in our sites was not clear, and in the case of sites MB, MM and SM, LAI decreased with stand density (Fig. 4). Furthermore, LAI of the forest may reflect effects of stand density and seasonal variation that would be hard to distinguish. Therefore, LAI may not be a good parameter to represent the density of a forest.

However, FAI may also present problems. FAI in this study was calculated using the stand inventory data and crown aspect ratio given by Schaudt and Dickinson (2000). However, this is only an approximate estimate, and the exact (or actual) FAI would be hard to estimate since the shapes of trees are complex. Raupach (1994) indicated that FAI can be estimated as half of LAI, $\lambda = 0.5A$. In this case, the same problem as encountered with CM88 is again raised. So far, arbitrariness or uncertainty in determining FAI cannot be eliminated. In addition, a further question is raised: since FAI is the total frontal area (width $\times$ height of elements) per unit ground area, does the same FAI indicate a high stand density in a short canopy or a low density in a tall canopy (see Fig. 5)? If so, d/h would be large in a short canopy and small in a tall canopy even if both canopies had the same FAI. Hence, FAI also may not represent the density of the forest. The relationship between stand density and FAI in our sites was similarly scattered (Fig. 4).

Figure 4

Figure 5

Figure 6 shows calculated results of d/h and z_0/h with R94 and SM00 against observed values. Considering the effect of LAI, d/h with SD00 became smaller than R94, whereas z_0/h with SD00 was larger than R94. As a result, SM00 provided better estimates in all sites than R94, although the z_0/h results in

YP were less accurate than the R94 results. Nevertheless, the outputs of SM00 still seemed to deviate from the observed d/h and z_0/h.

Figure 6

4.2 Parameterisation using observed data

Since previous models did not properly represent our observed results for d/h and z_0/h, alternative parameterisation is required. From a previous observational study, d/h and z_0/h varied in two ways: intersite differences and seasonal variations (Nakai et al., 2005). In analysing the relationships between roughness parameters and forest structure factors, JJA averaged d/h and z_0/h were used for intersite differences, and monthly data of d/h and z_0/h were used for seasonal variations.

Intersite differences of d/h and z_0/h were well described by stand density ρ_s, although the results of site YP deviated somewhat (Fig. 7a). This result indicates that ρ_s well represented the density of the forest.

However, monthly-averaged d/h in sites MB, MM and SM increased with LAI A, indicating that seasonal variations in d/h can be parameterised by A (Fig. 7b). When these variations were fitted by linear regressions, the slopes of the regression lines decreased with ρ_s, whereas the intercepts increased with ρ_s (Fig. 7c), indicating that seasonal variation in d/h with LAI was large in sparse forests and small in dense forests. This phenomenon might be construed as follows. In the case of dense forest, many branches remain in the crown space after defoliation, and these act as the resistance for momentum transfer into the forest, and hence the decrease in d due to defoliation is small. On the

other hand, in a sparse forest, the momentum can be easily transferred into the forest after defoliation, and hence the seasonal variation in d becomes large. To parameterise these phenomena, it is necessary to consider the effect of stems/branches and leaves separately. Therefore, we introduce a new concept below.

- The basal part of d/h is primarily determined by the density of stems and branches (stand density).
- The seasonal variation depends on the density of leaves (LAI), and the degree of this variation is dependent on stand density.
- Final d/h is the sum of these variable components.

This concept is similar to that of Schaudt and Dickinson (2000), but different in that they assumed the effect of plant spacing and shapes (R94 model: Eqs. (4), (5), (6)) correspond to either fully-vegetated plants or solid objects, and considered the effect of LAI by multiplying f_{d} and f_{z} by Eqs. (4) and (5) or (6), respectively. As a result, SD00 provides that seasonal variation in d/h with LAI is large in a dense canopy and small in a sparse canopy, which is inconsistent with our observations.

In the case of z_0/h, this was sufficiently parameterised using the linear relationship between d/h and z_0/h from Fig. 7(d), which is almost the same as Eq. (3) which was originally proposed by Thom (1971). It should be noted that this relation is valid for relatively dense canopies where z_0/h decreases with the density of the canopy, since z_0/h would have a peak at a moderate canopy density and increases with canopy density in sparse canopies, as described by the CM88 and R94 models or the often reported (e.g. Seginer, 1974; Shaw and Pereira, 1982). In our study sites, where the stand density was no less than

808 trees ha^{-1}, this phenomenon for lower density was not observed, and thus it could not be parameterised from our observed results.

Figure 7

4.3 New models

Based on the concept introduced in section 4.2 and the observed results, new models for d/h and z_0/h over forests were developed. The basal part of d/h is parameterised with ρ_s as follows.

$$\frac{d}{h} = 1.0 - \frac{1.0 - \exp(-\alpha\rho_\mathrm{s})}{\alpha\rho_\mathrm{s}} = 1.0 - f_\mathrm{D}, \tag{14}$$

where α is a constant, and f_D represents the residual of basal d/h. The behaviour of Eq. (14) is shown in Fig. 8(a).

Seasonal variations in d/h were represented by regression lines in section 4.2, but the relationship between d/h and A would also be a curve close to unity for infinite A. Thus the similar curve function to Eq. (14) was applied for the function of A as follows, neglecting the effect of ρ_s.

$$\frac{d}{h} = 1.0 - \frac{1.0 - \exp(-\beta A)}{\beta A} = 1.0 - f_\mathrm{A}, \tag{15}$$

where β is a constant and f_A represents the residual of the effect of leaves on d/h. From section 4.2, the slope of the linear regression between A and d/h decreased with ρ_s, whereas intercepts increased with ρ_s (Fig. 7c). This observation can be interpreted as the effect of seasonal variation being limited to the residual of the basal part of d/h, f_D. Therefore, the actual effect of leaves on d/h in a forest can be represented by $f_\mathrm{D}\,(1.0 - f_\mathrm{A})$, which provides

the behaviour as shown in Fig. 8(b), depending on ρ_{s}.

Finally, the total effect of stems/branches and leaves on d/h is given by the sum of Eq. (14) and $f_{\mathrm{D}}\,(1.0 - f_{\mathrm{A}})$ and written as follows.

$$\begin{aligned}\frac{d}{h} &= (1.0 - f_{\mathrm{D}}) + f_{\mathrm{D}}\,(1.0 - f_{\mathrm{A}}) = 1.0 - f_{\mathrm{D}} f_{\mathrm{A}} \\ &= 1.0 - \frac{1.0 - \exp(-\alpha\rho_{\mathrm{s}})}{\alpha\rho_{\mathrm{s}}}\frac{1.0 - \exp(-\beta A)}{\beta A}\end{aligned} \tag{16}$$

The behaviour of this total effect (Eq. (16)) is shown in Fig. 8(c). The values of the coefficients α and β were determined by fitting Eq. (16) to monthly-averaged d/h of five forest sites as $\alpha = 0.000724$ and $\beta = 0.273$, respectively.

z_0/h was parameterised by linear regression between d/h and z_0/h (Fig. 7d) as follows.

$$\frac{z_0}{h} = 0.264\left(1.0 - \frac{d}{h}\right) \tag{17}$$

Figure 8

Figure 9 shows the comparison of observed and calculated results of d/h (Fig. 9a) and z_0/h (Fig. 9b) for JJA averaged values. The new models in this study provided almost valid results against observed d/h and z_0/h. Compared to the results of previous models, CM88, R94 and SD00, validity of the new models in this study was improved in accuracy and applicability to all sites, although the accuracy of d/h in site YP was somewhat worse. Since d/h in site YP varied largely and the standard deviation was larger (0.24) than for other sites (0.11 in YL, 0.07 in MB, 0.05 in MM and 0.09 in SM) for JJA, the result of the new model might represent the observation for site YP adequately. On the other hand, the estimation errors of the previous one-parameter models, CM88 and

R94, were significant in site YL (section 4.1, Fig. 3). Therefore, the concept of a two-parameter model proposed in this study is adequate to describe d/h and z_0/h of forests, including the boreal forests, YL and YP.

Figure 9

Figure 10 shows the seasonal variation in d/h and z_0/h of monthly and daily values and calculated results from the new models. In calculating model outputs, seasonal variations in LAI of the five forest sites were approximated by the Gompertz curve (e.g. Sánchez-Guerrero et al., 2005). LAI in site YP was constant ($A = 1.0$) since it is an evergreen conifer forest and no significant seasonal variation was observed. Although observed values were somewhat scattered, seasonal variations in observed d/h and z_0/h of different types of forests in different climatic zones were almost represented by the same, simple two-parameter models. Since LAI can be obtained from satellite data (e.g. Pisek and Chen, 2007) and some efforts have recently been made to estimate stand density using satellite data (e.g. Sivanpillai et al., 2006), the new two-parameter model proposed in this study would provide an alternative method for land surface models and climate models to represent d/h and z_0/h, considering both intersite differences and seasonal variations.

Figure 10

5 Conclusion

In this study, we proposed a new model to represent d/h and z_0/h observed in five different forests located in three climatic zones. Previous models using LAI and FAI were not valid for our observed results. Observed d/h and z_0/h had

two variable components: intersite differences and seasonal variations. Intersite differences in d/h were related to stand density, and seasonal variations in d/h were related to LAI at each forest with the degree depending on stand density. To explain these observations, a new concept was proposed for d/h.

(1) The basal part is primarily determined by the density of stems and branches (stand density).
(2) The seasonal variation depends on the density of leaves (LAI).
(3) The degree of seasonal variation with LAI is dependent on stand density.

From the concepts (2) and (3), the seasonal variation part in d/h was regarded as limited to the residual of the basal part. In the case of z_0/h, the linear relationship between d/h and z_0/h (Thom, 1971) was adopted by fitting it to our observed results, though it should be valid for relatively dense canopies. The parameterisation of z_0/h for sparse canopy conditions cannot be provided in this study, since the studied forests were not appropriate for such a condition.

Based on this concept, a new two-parameter model was developed using stand density and LAI. With this model, both intersite differences and seasonal variations in observed roughness length and zero-plane displacement were relatively well represented. Since both LAI and stand density are recorded in most micrometeorological observation sites, and both parameters have recently become available from satellite data, the new two-parameter model proposed in this study provides an alternative method to estimate d/h and z_0/h in actual experiment sites and in land surface models.

Acknowledgements

We thank Drs. Takashi Kuwada and Kyoko Kato for providing stand inventory data for Yakutsk (YL, YP) and Moshiri (MB, MM), and Dr. Motomu Toda of Hokkaido University, Japan, for providing LAI data for site MB. We acknowledge the staff of the Institute for Biological Problems of the Cryolithozone, Siberian Division of the Russian Academy of Sciences, Russia, and Uryu Experimental Forest, Hokkaido University, Japan. Finally, we thank the reviewers for valuable comments. This study was conducted as part of the CREST/WECNoF project (P.I.: Prof. Takeshi Ohta, Nagoya University, Japan) sponsored by the Core Research for Evolutional Science and Technology (CREST), Japan Science and Technology Agency (JST).

References

Chen, J.M., Black, T.A., Adams, R.S., 1991. Evaluation of hemispherical photography for determining plant area index and geometry of a forest stand. Agric. For. Meteorol. 56, 129–143.

Choudhury, B.J., Monteith, J.L., 1988. A four-layer model for the heat budget of homogeneous land surfaces. Q. J. R. Meteorol. Soc. 114, 373–398.

Cowan, I.R., 1968. Mass, heat and momentum exchange between stands of plants and their atmospheric environment. Q. J. R. Meteorol. Soc. 94, 523–544.

Dolman, A.J., 1988. Estimates of roughness length and zero plane displacement for a foliated and non-foliated oak canopy. Agric. For. Meteorol. 36, 241–248.

Franses, P.H., 1994. Fitting a Gompertz curve. J. Oper. Res. Soc. 45, 109–113.

Garratt, J.R., 1994. The atmospheric boundary layer. Cambridge University Press, 316 pp.

Gompertz, B., 1825. On the nature of the function expressive of the law of human mortality, and on a new mode of determining the value of life contingencies. Phil. Trans. Roy. Soc. 115, 513–585.

Jasinski, M.F., Crago, R.D., 1999. Estimation of vegetation aerodynamic roughness of natural regions using frontal area density determined from satellite imagery. Agric. For. Meteorol. 94, 65–77.

Jukić, D., Kralik, G., Scitovski, R., 2004. Least-squares fitting Gompertz curve. J. Comput. Appl. Math. 169, 359–375.

Lindroth, A., 1993. Aerodynamic and canopy resistance of short-rotation forest in relation to leaf area index and climate. Boundary-Layer Meteorol. 66, 265–279.

Mäkinen, H., 1999. Growth, suppression, death, and self-pruning of branches of Scots pine in southern and central Finland. Can. J. For. Res., 29, 585–594

Minvielle, F., Marticorena, B., Gillette, D.A., Lawson, R.E., Thompson, R., Bergametti, G., 2003. Relationship between the aerodynamic roughness length and the roughness density in cases of low roughness density. Environ. Fluid Mech. 3, 249–267.

Nackaerts, K., Coppin, P., Muys, B., Hermy, M., 2000. Sampling methodology for LAI measurements with LAI-2000 in small forest stands. Agric. For. Meteorol. 101, 247–250.

Nakai, T., Kuwada, T., Kodama, Y., Ohta, T., Maximov, T.C., 2005. Comparison of aerodynamic characteristics among boreal, cool-temperate and warm-temperate forests. J. Agric. Meteorol. 60(5), 689–692.

Nakai, T., van der Molen, M.K., Gash, J.H.C., Kodama, Y., 2006. Correction of sonic anemometer angle of attack errors. Agric. For. Meteorol. 136, 19–30.

Pisek, J., Chen, J.M., 2007. Comparison and validation of MODIS and VEGETATION global LAI products over four BigFoot sites in North America.

Remote Sens. Environ. 109, 81–94.

Raupach, M.R., 1994. Simplified expressions for vegetation roughness length and zero-plane displacement as functions of canopy height and area index. Boundary-Layer Meteorol. 71, 211–216.

Rooney, G.G., 2001. Comparison of upwind land use and roughness length measured in the urban boundary layer. Boundary-Layer Meteorol. 100, 469–486.

Sánchez-Guerrero, M.C., Lorenzo, P., Medrano, E., Castilla, N., Soriano, T., Baille, A., 2005. Effect of variable CO_2 enrichment on greenhouse production in mild winter climates, Agric. For. Meteorol. 132, 244–252.

Schaudt, K.J., 1998. A new method for estimating roughness parameters and evaluating the quality of observations. J. Appl. Meteorol. 37, 470–476.

Schaudt, K.J., Dickinson, R.E., 2000. An approach to deriving roughness length and zero-plane displacement height from satellite data, prototyped with BOREAS data. Agric. For. Meteorol. 104, 143–155.

Seginer, I., 1974. Aerodynamic roughness of vegetated surfaces. Boundary-Layer Meteorol. 5, 383–393.

Shaw, R.H., Pereira, A.R., 1982. Aerodynamic roughness of a plant canopy: a numerical experiment. Agric. Meteorol. 26, 51–65.

Sivanpillai, R., Smith, C.T., Srinivasan, R., Messina, M.G., Ben Wu, X., 2006. Estimation of managed loblolly pine stand age and density with Landsat ETM+ data. For. Ecol. Manage. 223, 247–254.

Tanner, C.B., Pelton, W.L., 1960. Potential evapotranspiration estimates by the approximate energy balance of Penman. J. Geophys. Res. 65, 3391–3413.

Thom, A.S., 1971. Momentum absorption by vegetation. Q. J. R. Meteorol. Soc. 97, 414–428.

Verhoef, A., McNaughton, K.G., Jacobs, A.F.G., 1997. A parameterization of

momentum roughness length and displacement height for a wide range of canopy densities. Hydrol. Earth Sys. Sci., 1, 81–91.

Yang, R., Friedl, M.A., 2003. Determination of roughness lengths for heat and momentum over boreal forests. Boundary-Layer Meteorol. 107, 581–603.

Captions of figures

Fig. 1. Locations of Yakutsk, Moshiri and Seto, where our observations were conducted.

Fig. 2. Plots of the observed cumulative basal area against tree height, fitting curve (Gompertz function) to the observed data and the derivative of this fit function for each forest site.

Fig. 3. Scatter diagrams of observed d/h and z_0/h against leaf area index A (a) and frontal area index λ (b) together with the model outputs of CM88 (a) and R94 (b), respectively. Summertime (JJA) data were used for observations.

Fig. 4. Scatter diagram of leaf area index A and frontal area index λ against stand density ρ_{s}.

Fig. 5. Schematic diagram of a fundamental question of frontal area index (FAI), i.e., since FAI is the total frontal area (width $\times$ height of elements) per unit ground area, does the same FAI indicate a high stand density in a short canopy or a low density in a tall canopy? If so, d/h would be large in a short canopy and small in a tall canopy even if both canopies had the same FAI.

Fig. 6. Scatter diagrams of calculated results of d/h (a) and z_0/h (b) with the models R94 and SD00 against observations (JJA).

Fig. 7. Scatter diagrams of observed results in this study: (a) d/h and z_0/h (JJA) against stand density ρ_{s}, (b) d/h (monthly) against leaf area index A, (c) slope and intercept of the regression line in Fig. 6(b) against stand density ρ_{s}, (d) z_0/h against d/h (monthly).

Fig. 8. Behaviour of the new model for d/h developed in this study. (a) Effect of stems and branches on d/h, (b) effect of leaves on seasonal variation part

of d/h, $f_{\mathrm{D}}(1 - f_{\mathrm{A}})$, (c) total effect of stems/branches and leaves on d/h.

Fig. 9. Scatter diagrams of calculated results of d/h (a) and z_0/h (b) with the new model developed in this study and previous models against observations (JJA).

Fig. 10. Seasonal variations in d/h and z_0/h in five forest sites. Open circles and triangles indicate the monthly data of d/h and z_0/h, and closed circles and triangles indicate daily data of d/h and z_0/h, respectively. Solid and dashed lines are the model output of d/h and z_0/h, respectively, calculated with the new two-parameter model proposed in this study.

Certificate of English revision

The English in this document has been checked by at least two professional editors, both native speakers of English. For a certificate, see:

http://www.textcheck.com/cgi-bin/certificate.cgi?id=Dw9Yh7

Table 1

Table 1: Location, measurement conditions and stand characteristics of the five observation sites.

Site	YL	YP	MB	MM	SM
Latitude	62° 15′ 18″ N	62° 14′ 29″ N	44° 23′ 03″ N	44° 19′ 19″N	35° 15′ 29″ N
Longitude	129° 37′ 08″ E	129° 39′ 02″ E	142° 19′ 07″ E	142° 15′ 41″E	137° 04′ 54″ E
Altitude (m ASL)	220	220	585	340	205
Height of ultrasonic anemometer z_e (m)	32.0	18.2	21.1	31.6	19.5
Height of cup anemometer z_1 (m)	32.0	18.2	21.1	31.6	14.0
Height of cup anemometer z_2 (m)	27.0	13.8	16.0	28.0	10.0
Wind direction (clockwise from north)	−30° to 30°	30° to 90°	255° to 270°	255° to 285°	290° to 320°
Stand density ρ_s (trees ha^{-1}	808	2572	3925	2573	1900
Leaf area index A (m^2 m^{-2})	0.8 – 1.3	1.0	0.6 – 3.2	1.2 – 3.4	1.7 – 4.2
JJA averaged A (m^2 m^{-2})	1.2	1.0	2.5	3.0	3.5
Frontal area index λ (m^2 m^{-2})	0.86	0.47	6.24	3.26	3.63
Canopy height h (m)	20.5	10.4	11.9	25.0	8.9

Figure 01

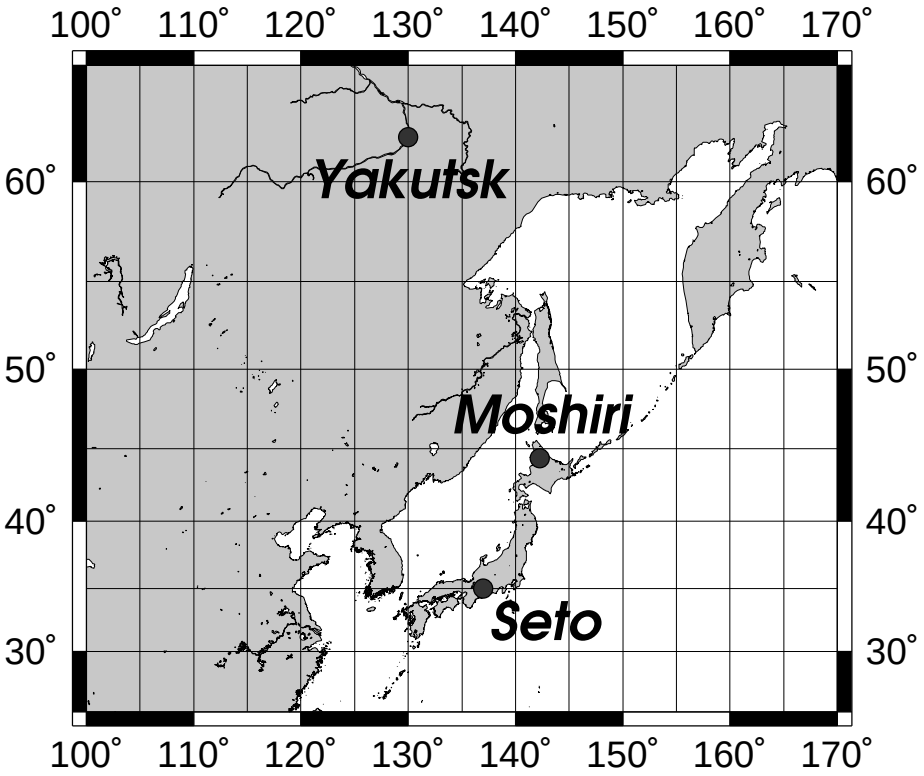

100° 110° 120° 130° 140° 150° 160° 170°
60°
50°
40°
30°
Yakutsk
Moshiri
Seto

Figure 02

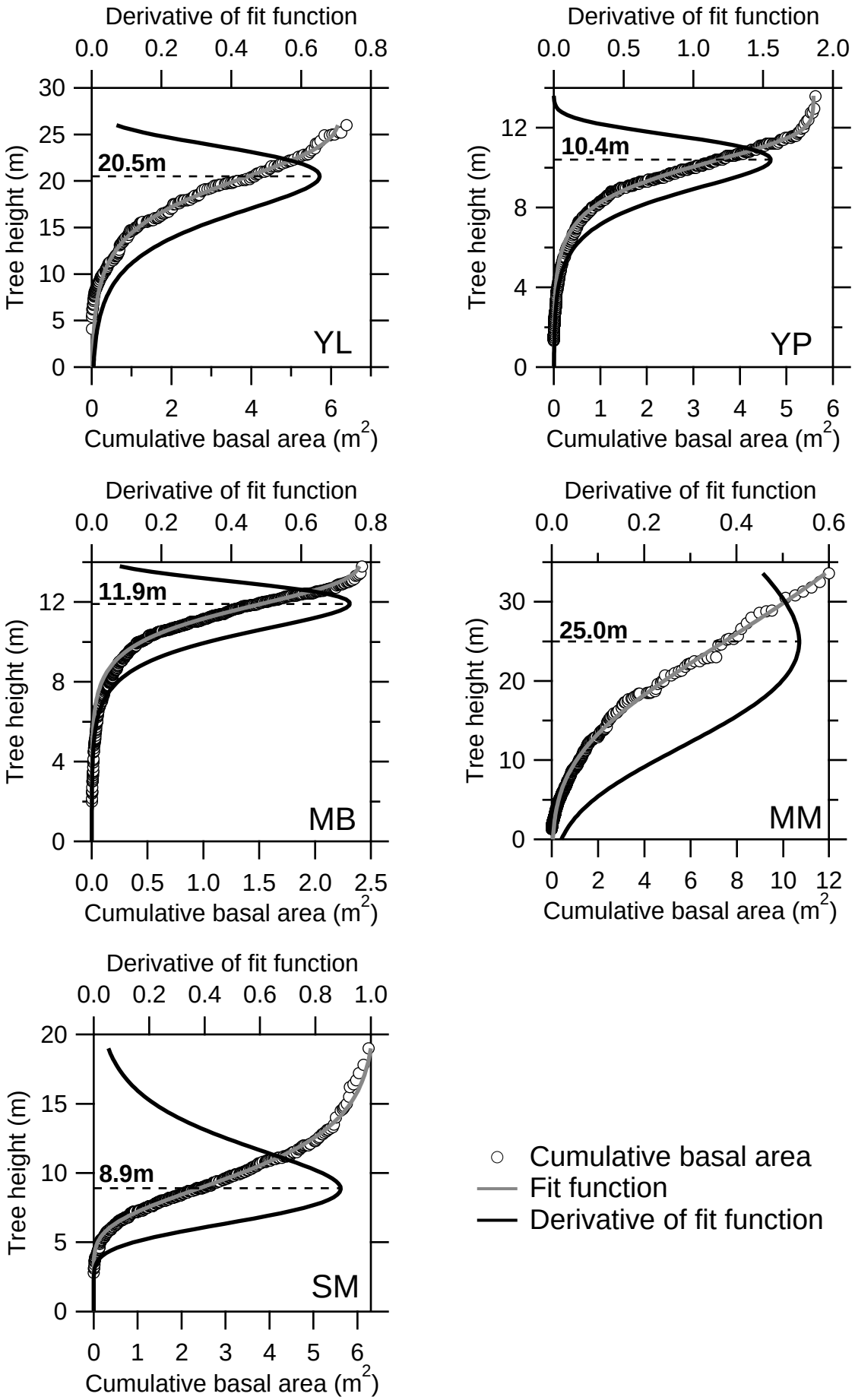

Derivative of fit function
Tree height (m)
Cumulative basal area (m2)
20.5m
YL
10.4m
YP
11.9m
MB
25.0m
MM
8.9m
SM
Cumulative basal area
Fit function
Derivative of fit function

Figure 03

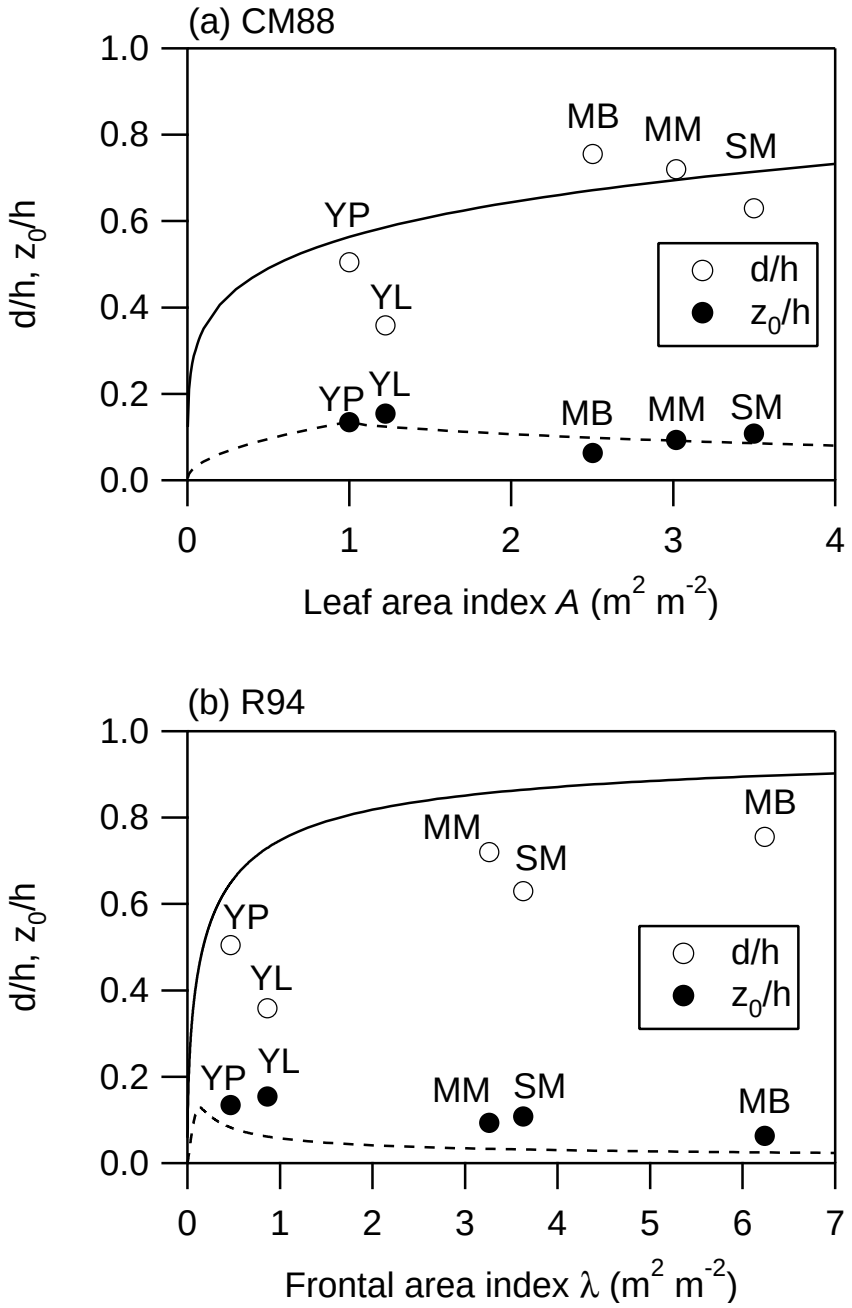

(a) CM88
1.0
0.8
0.6
0.4
0.2
0.0
d/h, z0/h
MB
MM
SM
YP
YL
YP
YL
MB
MM
SM
d/h
z0/h
0
1
2
3
4
Leaf area index A (m2 m-2)
(b) R94
1.0
0.8
0.6
0.4
0.2
0.0
d/h, z0/h
MB
MM
SM
YP
YL
YP
YL
MM
SM
MB
d/h
z0/h
0
1
2
3
4
5
6
7
Frontal area index λ (m2 m-2)

Figure 04

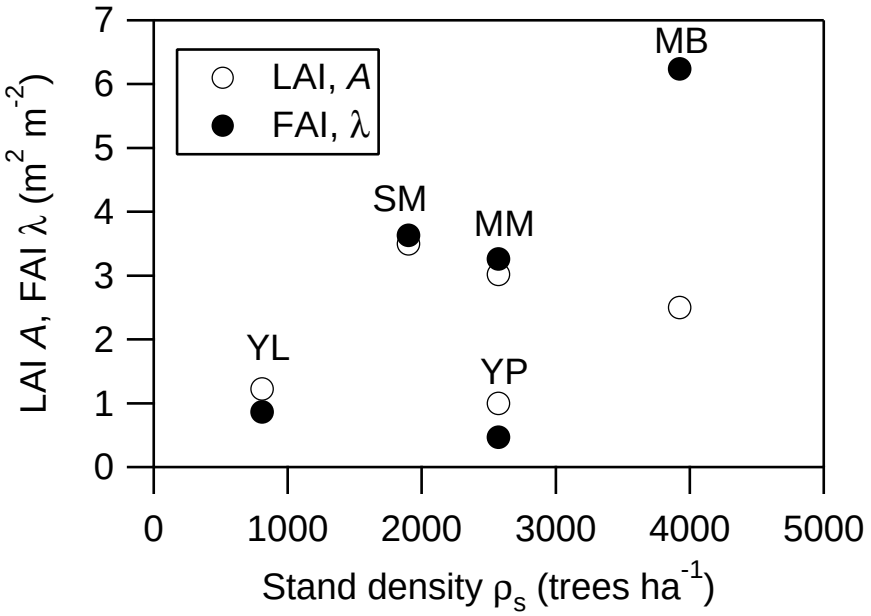

LAI, A
FAI, λ
MB
SM
MM
YL
YP
LAI A, FAI λ (m2 m-2)
Stand density ρs (trees ha-1)
0
1
2
3
4
5
6
7
0
1000
2000
3000
4000
5000

Figure 05

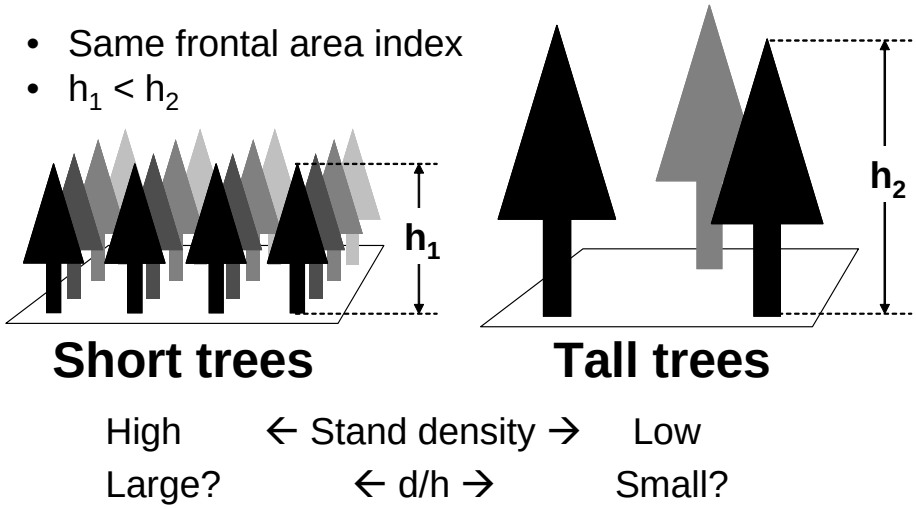

• Same frontal area index
• $h_1 < h_2$
h_1
h_2
Short trees
Tall trees
High ← Stand density → Low
Large? ← d/h → Small?

Figure 06

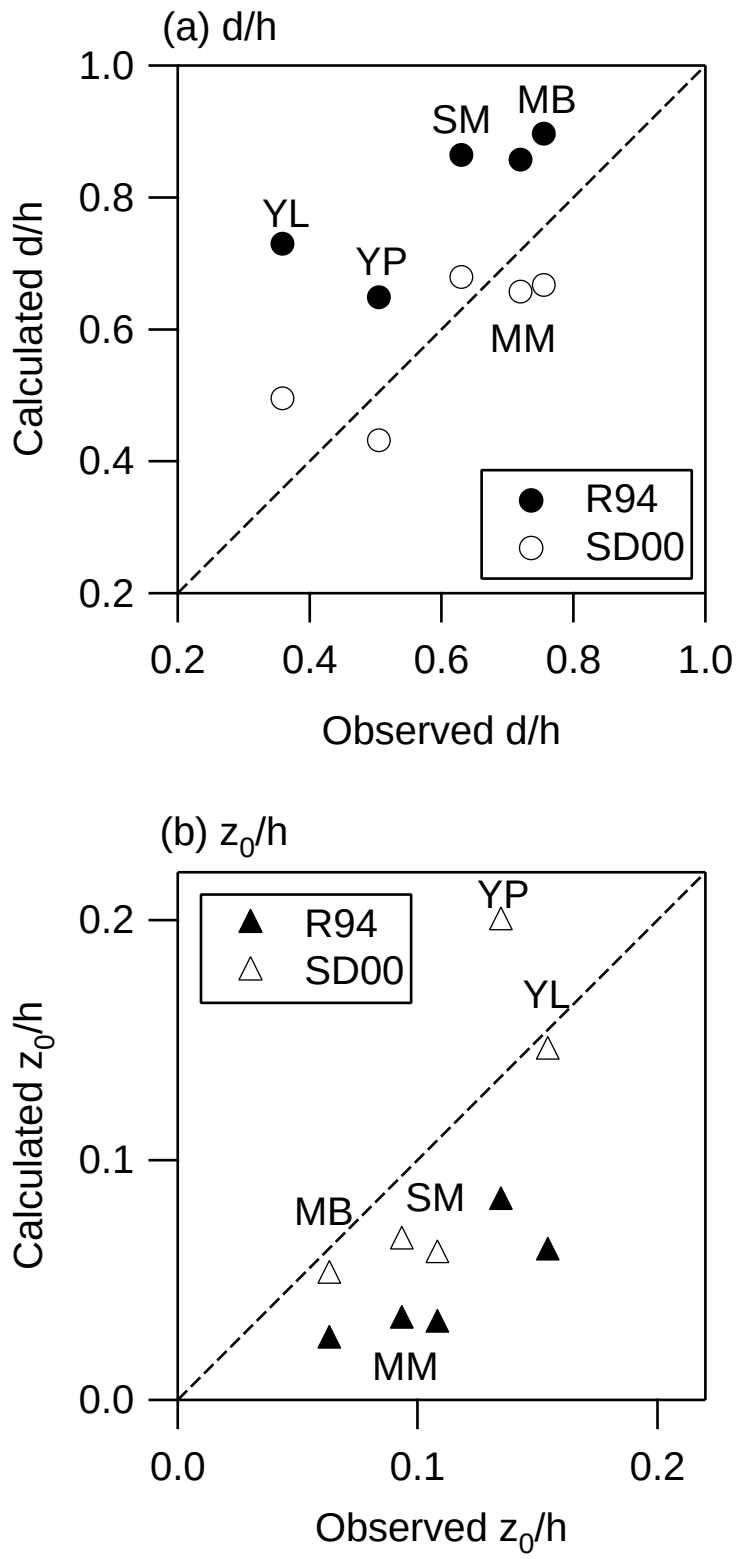

(a) d/h
1.0
0.8
0.6
0.4
0.2
Calculated d/h
0.2
0.4
0.6
0.8
1.0
Observed d/h
SM
MB
YL
YP
MM
R94
SD00
(b) z0/h
0.2
0.1
0.0
Calculated z0/h
0.0
0.1
0.2
Observed z0/h
R94
SD00
YP
YL
MB
SM
MM

Figure 07

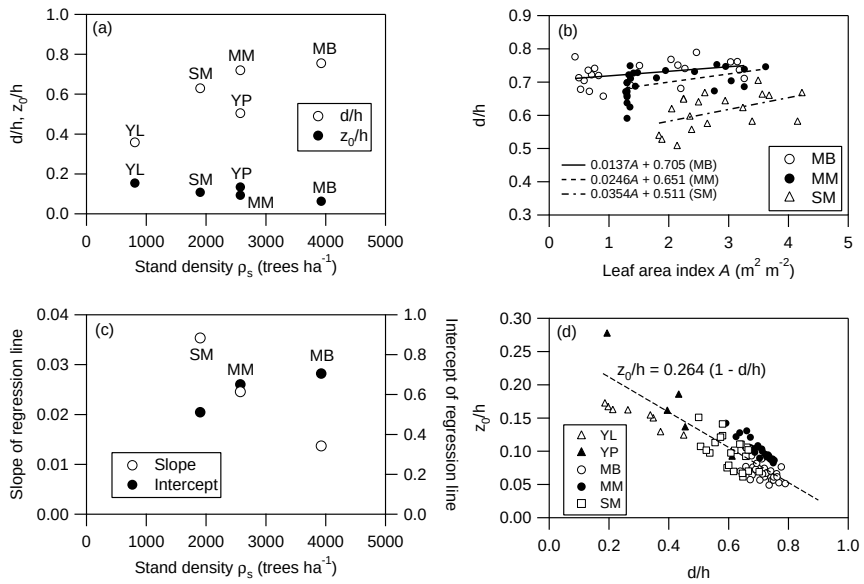

(a)
d/h, z0/h
Stand density ρs (trees ha-1)
MM
MB
SM
YP
YL
YL
SM
YP
MM
MB
d/h
z0/h
(b)
d/h
Leaf area index A (m2 m-2)
0.0137A + 0.705 (MB)
0.0246A + 0.651 (MM)
0.0354A + 0.511 (SM)
MB
MM
SM
(c)
Slope of regression line
Intercept of regression line
Stand density ρs (trees ha-1)
SM
MM
MB
Slope
Intercept
(d)
z0/h
d/h
z0/h = 0.264 (1 - d/h)
YL
YP
MB
MM
SM

Figure 08

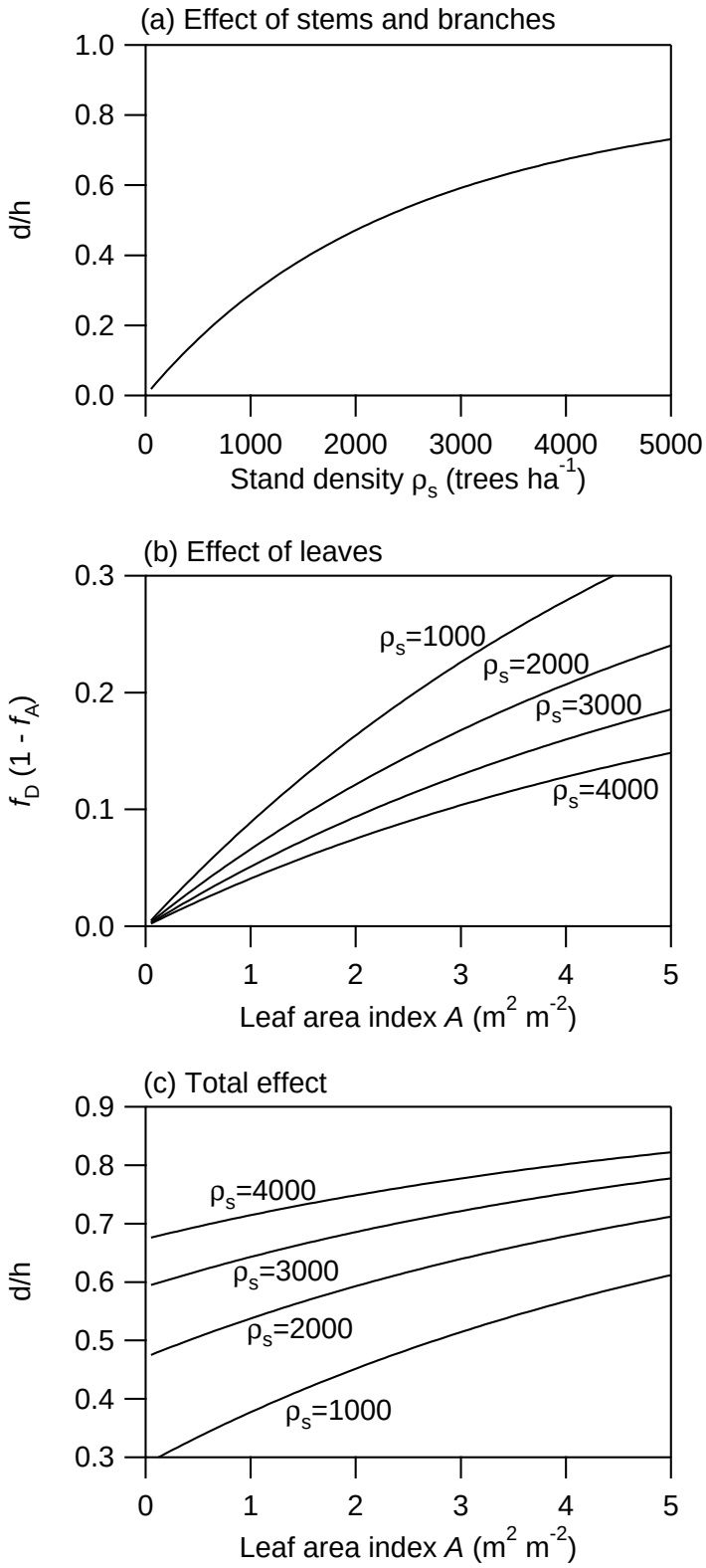

(a) Effect of stems and branches
d/h
1.0
0.8
0.6
0.4
0.2
0.0
0
1000
2000
3000
4000
5000
Stand density ρs (trees ha-1)
(b) Effect of leaves
fD (1 - fA)
0.3
0.2
0.1
0.0
ρs=1000
ρs=2000
ρs=3000
ρs=4000
0
1
2
3
4
5
Leaf area index A (m2 m-2)
(c) Total effect
d/h
0.9
0.8
0.7
0.6
0.5
0.4
0.3
ρs=4000
ρs=3000
ρs=2000
ρs=1000
0
1
2
3
4
5
Leaf area index A (m2 m-2)

Figure 09

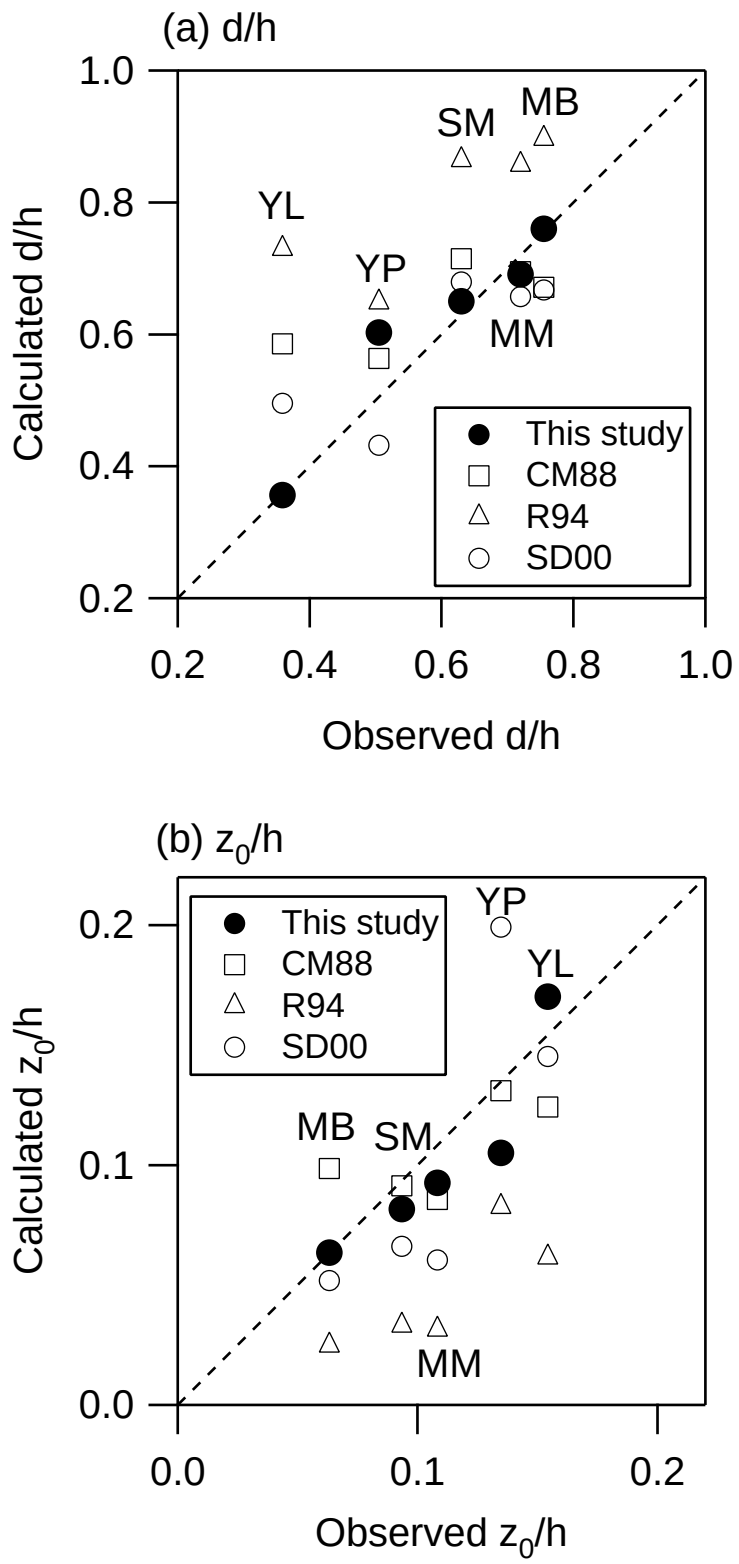
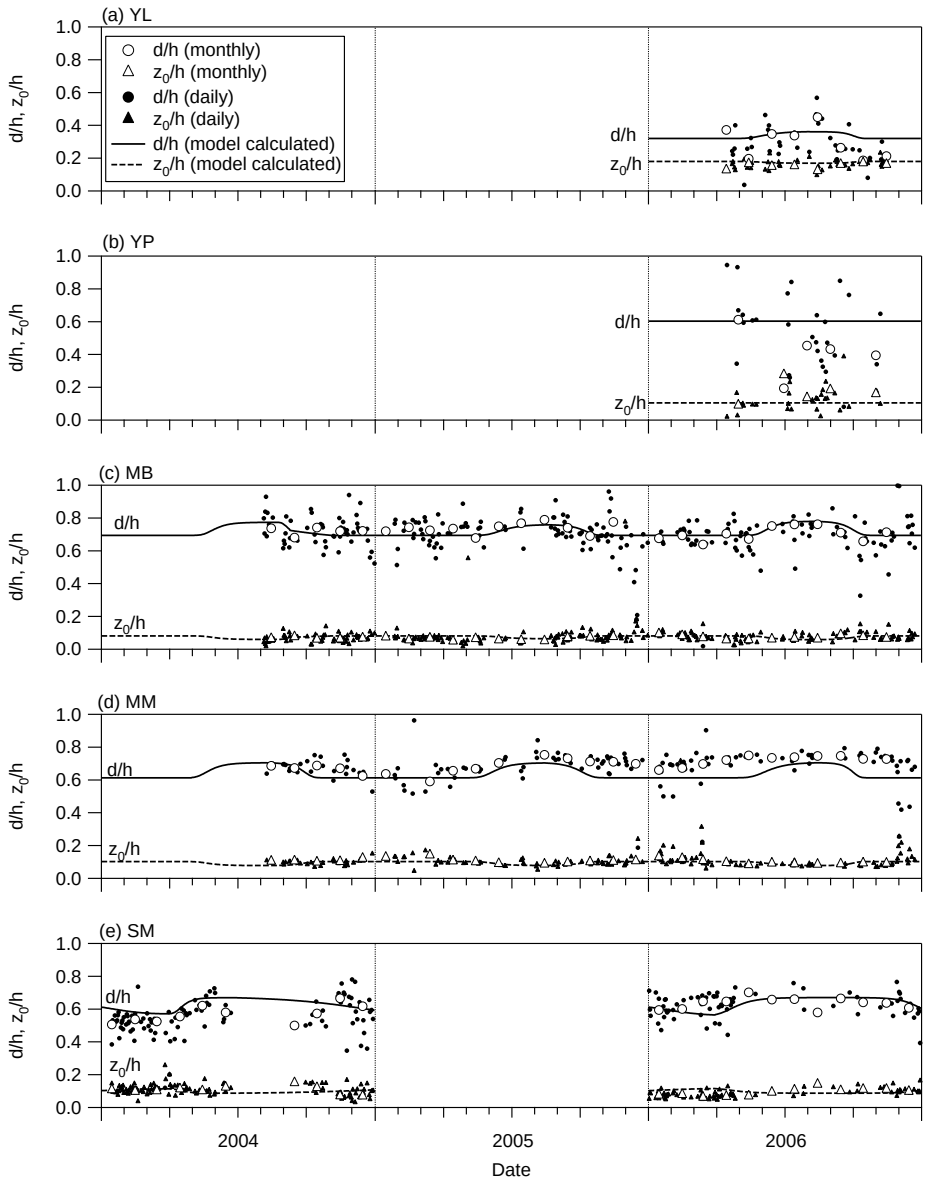

(a) d/h
1.0
0.8
0.6
0.4
0.2
Calculated d/h
0.2
0.4
0.6
0.8
1.0
Observed d/h
MB
SM
YL
YP
MM
This study
CM88
R94
SD00
(b) z0/h
0.2
0.1
0.0
Calculated z0/h
0.0
0.1
0.2
Observed z0/h
YP
YL
MB
SM
MM
This study
CM88
R94
SD00

Figure 10


(a) YL
(b) YP
(c) MB
(d) MM
(e) SM
d/h (monthly)
z0/h (monthly)
d/h (daily)
z0/h (daily)
d/h (model calculated)
z0/h (model calculated)
d/h
z0/h
d/h, z0/h
1.0
0.8
0.6
0.4
0.2
0.0
2004
2005
2006
Date