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

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1 Abstract

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

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

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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 $d/h = 0.64$

1 (Cowan, 1968) and $z_0/h = 0.13$ (Tanner and Pelton, 1960), are frequently
 2 used. However, d/h and z_0/h are not constants and vary with the density of
 3 roughness elements (see Garratt, 1994). To represent the density of the canopy,
 4 two parameters have been used. Choudhury and Monteith (1988) used leaf
 5 area index (LAI) to parameterise d/h and z_0/h based on the second-order clo-
 6 sure model results of Shaw and Pereira (1982). Raupach (1994) provided the
 7 method to derive d/h and z_0/h using frontal area index (FAI), which is the
 8 total frontal area (width $\times$ height of elements) per unit ground area. Recently,
 9 FAI and the model of Raupach (1994) were adopted to estimate d/h and z_0/h
 10 from satellite data (e.g. Jasinski and Crago, 1999; Schaudt and Dickinson,
 11 2000). However, few studies have checked the applicability of these models
 12 to d/h and z_0/h obtained from field experiments over forests (e.g. Yang and
 13 Friedl, 2003).

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

18 **2 Previous models for d/h and z_0/h**

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

$$22 \quad \frac{d}{h} = 1.1 \ln \left[1.0 + (c_d A)^{1/4} \right] \quad (1)$$

$$\frac{z_0}{h} = \frac{z'_0}{h} + 0.3\sqrt{c_d A} \quad (c_d A \leq 0.2) \quad (2)$$

$$\frac{z_0}{h} = 0.3 \left(1.0 - \frac{d}{h} \right) \quad (c_d A > 0.2) \quad (3)$$

where $c_d (= 0.2)$ 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 ($\text{m}^2 \text{ m}^{-2}$), and derived the following expressions.

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

$$\frac{z_0}{h} = a_2 \exp(-b_2 \lambda^{c_2}) \lambda^{d_2} + \frac{z'_0}{h} \quad (\lambda \leq 0.152) \quad (5)$$

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

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

$$f_d = 1.0 - 0.3991 \exp(-0.1779A), \quad (7)$$

and f_z for z_0/h as

$$f_z = 0.3299A^{1.5} + 2.1713 \quad (A < 0.8775), \quad (8)$$

$$f_z = 1.6771 \exp(-0.1717A) + 1.0 \quad (A \geq 0.8775), \quad (9)$$

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):

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

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

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 ($|z_e/L| < 0.05$, 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);

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

$$5 \quad A_f = h_b \times D + \frac{\pi}{4} \times r \times (h_t - h_b)^2 \quad (12)$$

6 and for coniferous trees as

$$7 \quad A_f = h_b \times D + \frac{1}{2} \times r \times (h_t - h_b)^2 \quad (13)$$

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

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

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

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

- 5 (1) Sort tree height of samples in increasing order.
- 6 (2) Plot cumulative basal area against the tree height of samples.
- 7 (3) Fit this plot by the Gompertz function (e.g. Gompertz, 1825; Franses,
8 1994; Jukić et al, 2004).
- 9 (4) Differentiate the fit function of (3) and find the peak of this derivative.

10 Figure 2 shows the plots of the observed cumulative basal area against tree
11 height, the fitting curve (Gompertz function) to the observed data, and the
12 derivative of this fit function for each forest site. The canopy height h was
13 determined as the height at which the peak of this derivative appeared. Table
14 1 lists the value of h of each forest. Note that although the maximum tree
15 height of site MM was taller than the measurement height, this highest tree was
16 located downslope and distant from the tower (Nakai et al., 2006). Similarly,
17 the meteorological tower of site SM was located on a mountain ridge, and
18 relatively tall trees were located downslope. In both sites, the tree heights
19 near the tower were almost the same as the canopy heights obtained here.

20 Figure 2

1 4 Results and discussion

2 4.1 *Validity of previous models*

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

6 Plots in Fig. 3 are scatter diagrams of d/h and z_0/h against LAI, A (Fig.
7 3a) and FAI, λ (Fig. 3b) together with the model outputs of CM88 (Fig. 3a)
8 and R94 (Fig. 3b), respectively. Observed d/h and z_0/h deviated from both
9 CM88 and R94 outputs, especially in site YL, indicating that both models
10 were insufficient to describe actual roughness parameters of forests.

11 Figure 3

12 The LAI-based model, CM88, is based on the numerical simulation results of
13 Shaw and Pereira (1982). The model of Shaw and Pereira (1982) dealt with
14 agricultural crops, such as a corn canopy, and thus CM88 would be appropriate
15 for herbaceous plants. However, no attempt was made to represent forest-like
16 stands with a relatively open trunk space in the model of Shaw and Pereira
17 (1982). In the case of agricultural crops, LAI may represent the canopy density,
18 and thus d/h may monotonically increase with LAI. However, for forest stands,
19 stems and branches may affect d/h . For example, Dolman (1986) reported that
20 d/h of non-foliated oak forest was 0.57 (stand density 3000 trees ha^{-1}). This
21 effect cannot be described by models with only LAI data. In addition, natural
22 self-pruning of branches occurs in forests and may be influenced by stand
23 density (e.g. Mäkinen, 1999). Actually, the relationship between stand density

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

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

20 Figure 4

21 Figure 5

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

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

3 Figure 6

4 4.2 *Parameterisation using observed data*

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

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

15 However, monthly-averaged d/h in sites MB, MM and SM increased with LAI
16 A , indicating that seasonal variations in d/h can be parameterised by A (Fig.
17 7b). When these variations were fitted by linear regressions, the slopes of
18 the regression lines decreased with ρ_s , whereas the intercepts increased with
19 ρ_s (Fig. 7c), indicating that seasonal variation in d/h with LAI was large in
20 sparse forests and small in dense forests. This phenomenon might be construed
21 as follows. In the case of dense forest, many branches remain in the crown
22 space after defoliation, and these act as the resistance for momentum transfer
23 into the forest, and hence the decrease in d due to defoliation is small. On the

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

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

11 This concept is similar to that of Schaudt and Dickinson (2000), but different
 12 in that they assumed the effect of plant spacing and shapes (R94 model: Eqs.
 13 (4), (5), (6)) correspond to either fully-vegetated plants or solid objects, and
 14 considered the effect of LAI by multiplying f_d and f_z by Eqs. (4) and (5) or
 15 (6), respectively. As a result, SD00 provides that seasonal variation in d/h
 16 with LAI is large in a dense canopy and small in a sparse canopy, which is
 17 inconsistent with our observations.

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

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

3 Figure 7

4 4.3 New models

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

$$8 \quad \frac{d}{h} = 1.0 - \frac{1.0 - \exp(-\alpha\rho_s)}{\alpha\rho_s} = 1.0 - f_D, \quad (14)$$

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

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

$$15 \quad \frac{d}{h} = 1.0 - \frac{1.0 - \exp(-\beta A)}{\beta A} = 1.0 - f_A, \quad (15)$$

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

1 the behaviour as shown in Fig. 8(b), depending on ρ_s .

2 Finally, the total effect of stems/branches and leaves on d/h is given by the
 3 sum of Eq. (14) and $f_D(1.0 - f_A)$ and written as follows.

$$\begin{aligned} \frac{d}{h} &= (1.0 - f_D) + f_D(1.0 - f_A) = 1.0 - f_D f_A \\ &= 1.0 - \frac{1.0 - \exp(-\alpha \rho_s)}{\alpha \rho_s} \frac{1.0 - \exp(-\beta A)}{\beta A} \end{aligned} \quad (16)$$

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

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

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

10 Figure 8

11 Figure 9 shows the comparison of observed and calculated results of d/h (Fig.
 12 9a) and z_0/h (Fig. 9b) for JJA averaged values. The new models in this study
 13 provided almost valid results against observed d/h and z_0/h . Compared to the
 14 results of previous models, CM88, R94 and SD00, validity of the new models in
 15 this study was improved in accuracy and applicability to all sites, although the
 16 accuracy of d/h in site YP was somewhat worse. Since d/h in site YP varied
 17 largely and the standard deviation was larger (0.24) than for other sites (0.11
 18 in YL, 0.07 in MB, 0.05 in MM and 0.09 in SM) for JJA, the result of the new
 19 model might represent the observation for site YP adequately. On the other
 20 hand, the estimation errors of the previous one-parameter models, CM88 and

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

4 Figure 9

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

19 Figure 10

20 5 Conclusion

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

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

5 (1) The basal part is primarily determined by the density of stems and
6 branches (stand density).

7 (2) The seasonal variation depends on the density of leaves (LAI).

8 (3) The degree of seasonal variation with LAI is dependent on stand density.

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

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

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1 Captions of figures

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

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

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

11 **Fig. 4.** Scatter diagram of leaf area index A and frontal area index λ against
12 stand density ρ_s .

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

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

21 **Fig. 7.** Scatter diagrams of observed results in this study: (a) d/h and z_0/h
22 (JJA) against stand density ρ_s , (b) d/h (monthly) against leaf area index
23 A , (c) slope and intercept of the regression line in Fig. 6(b) against stand
24 density ρ_s , (d) z_0/h against d/h (monthly).

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

1 of d/h , $f_D(1 - f_A)$, (c) total effect of stems/branches and leaves on d/h .

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

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

10 **Certificate of English revision**

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

13 <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

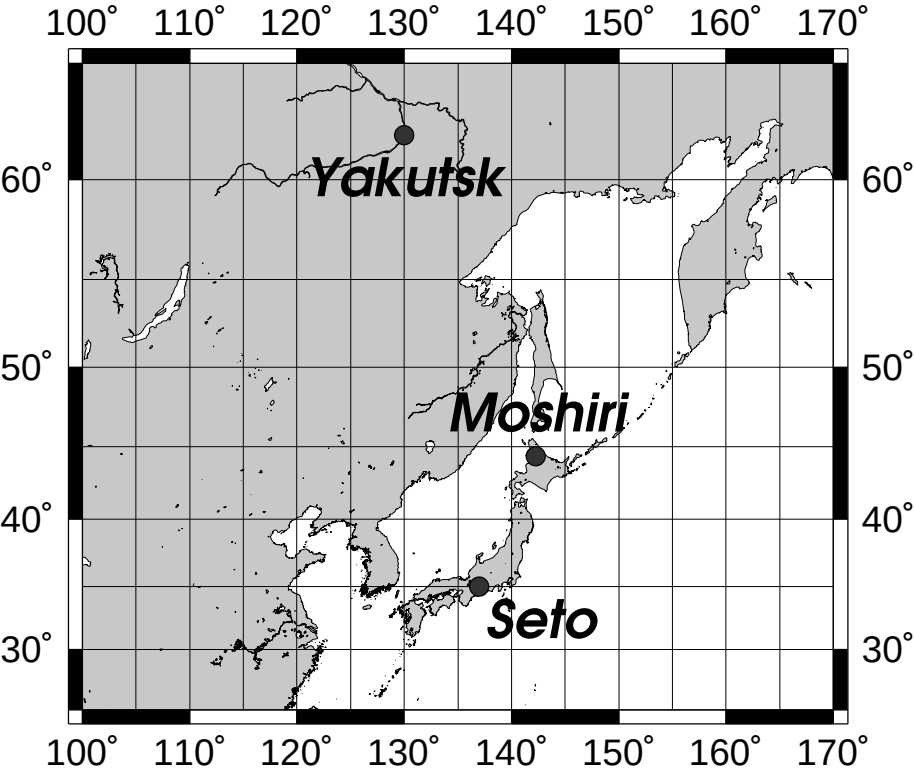


Figure 02

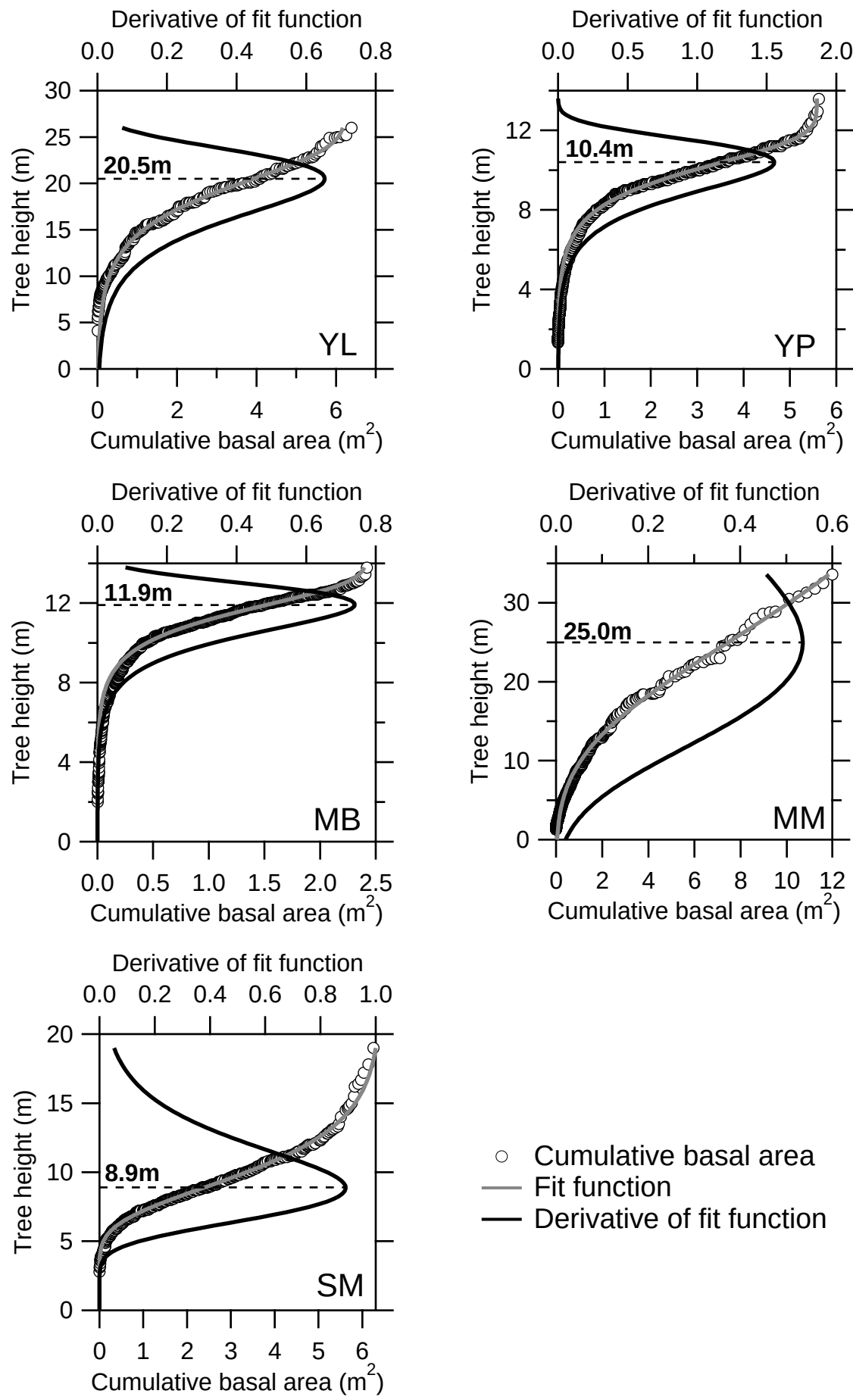


Figure 03

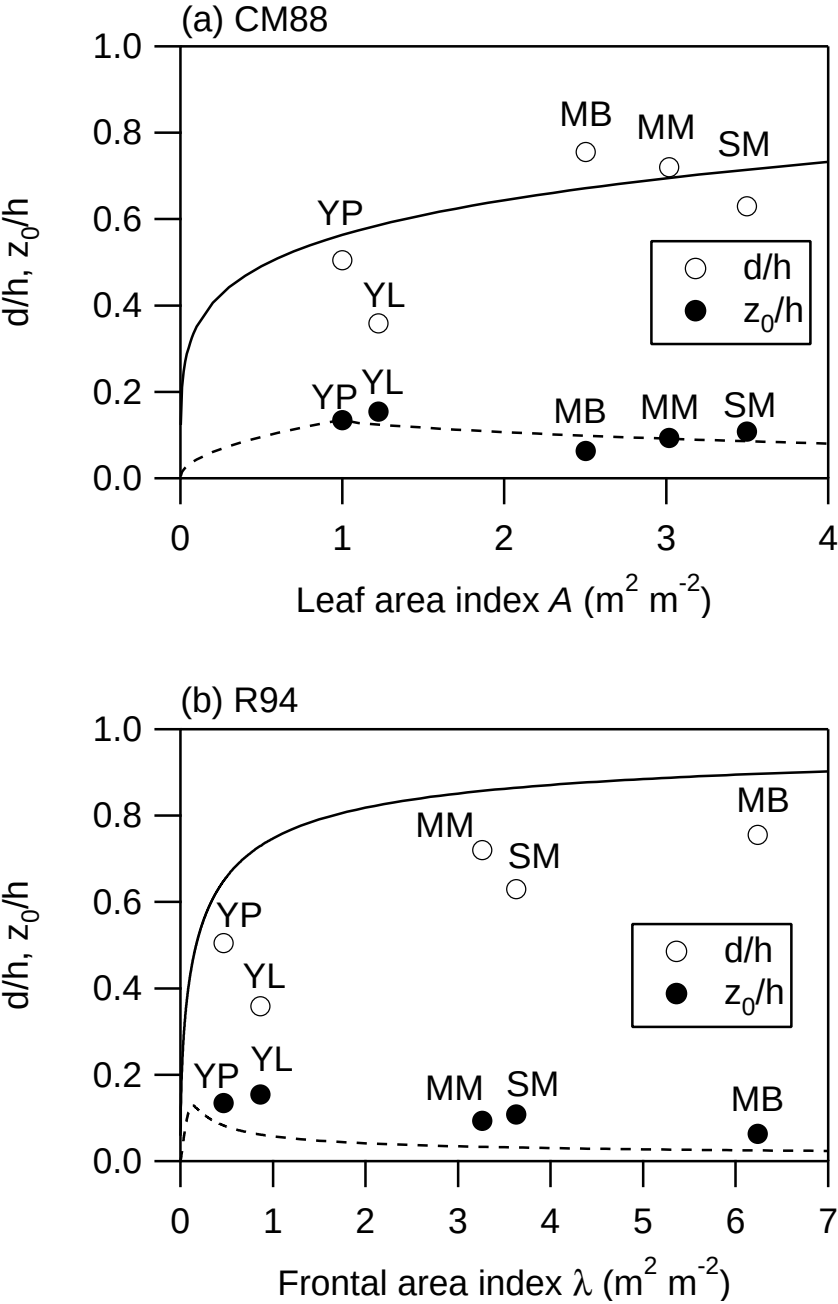


Figure 04

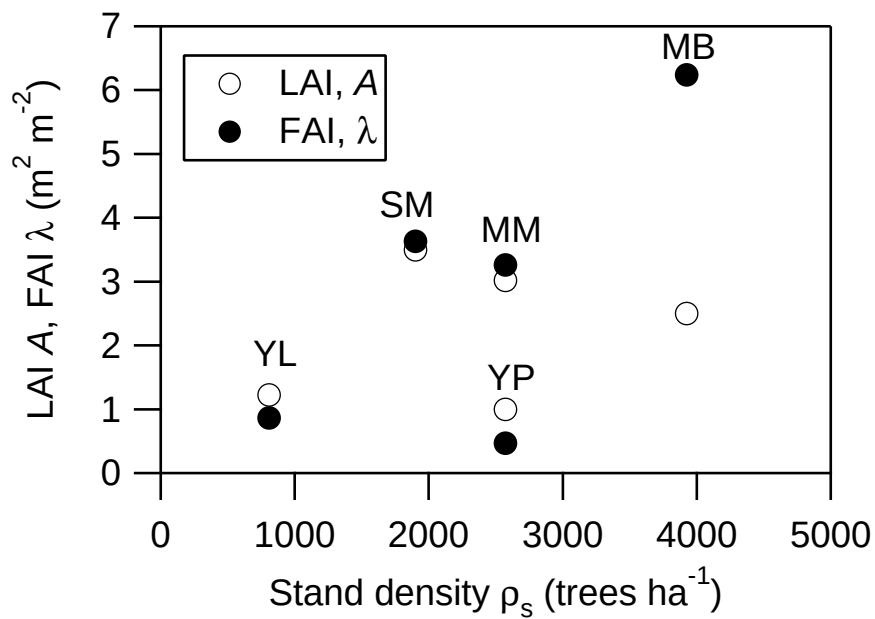


Figure 05

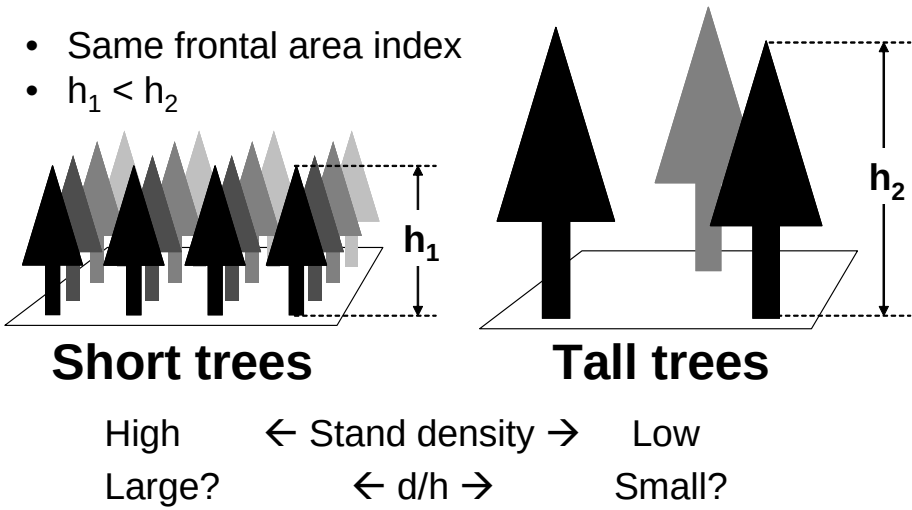


Figure 06

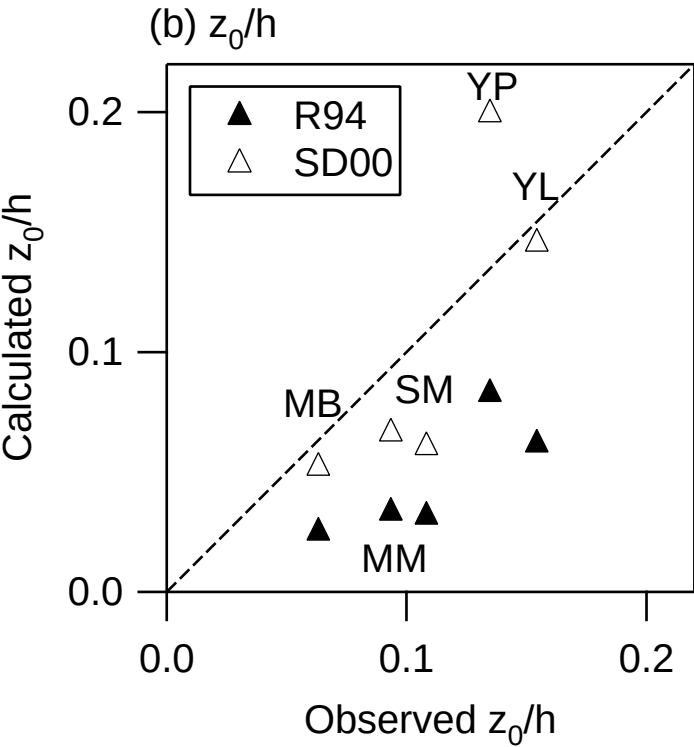
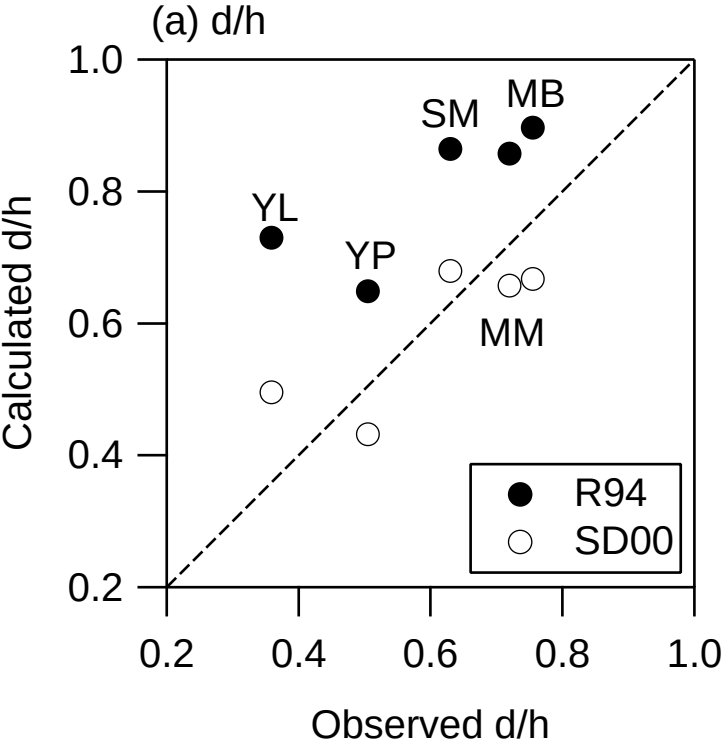


Figure 07

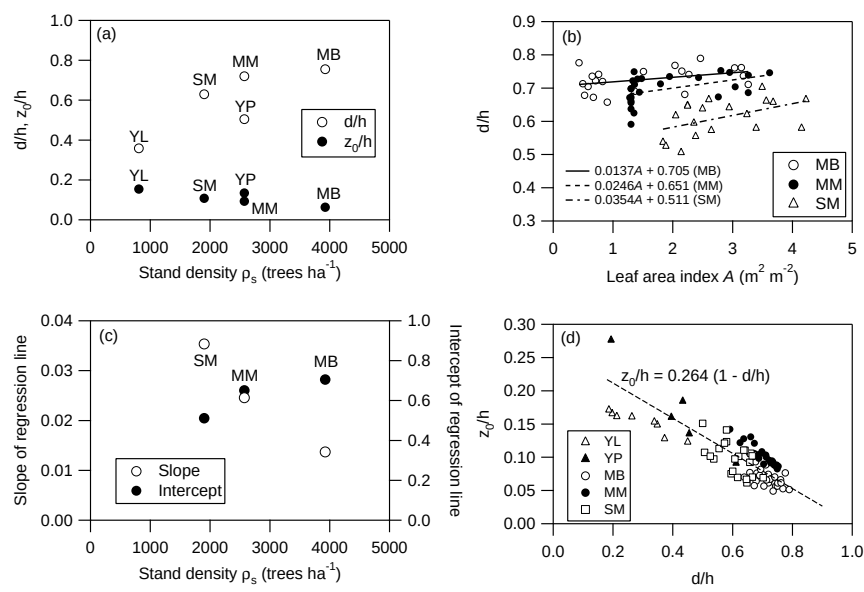


Figure 08

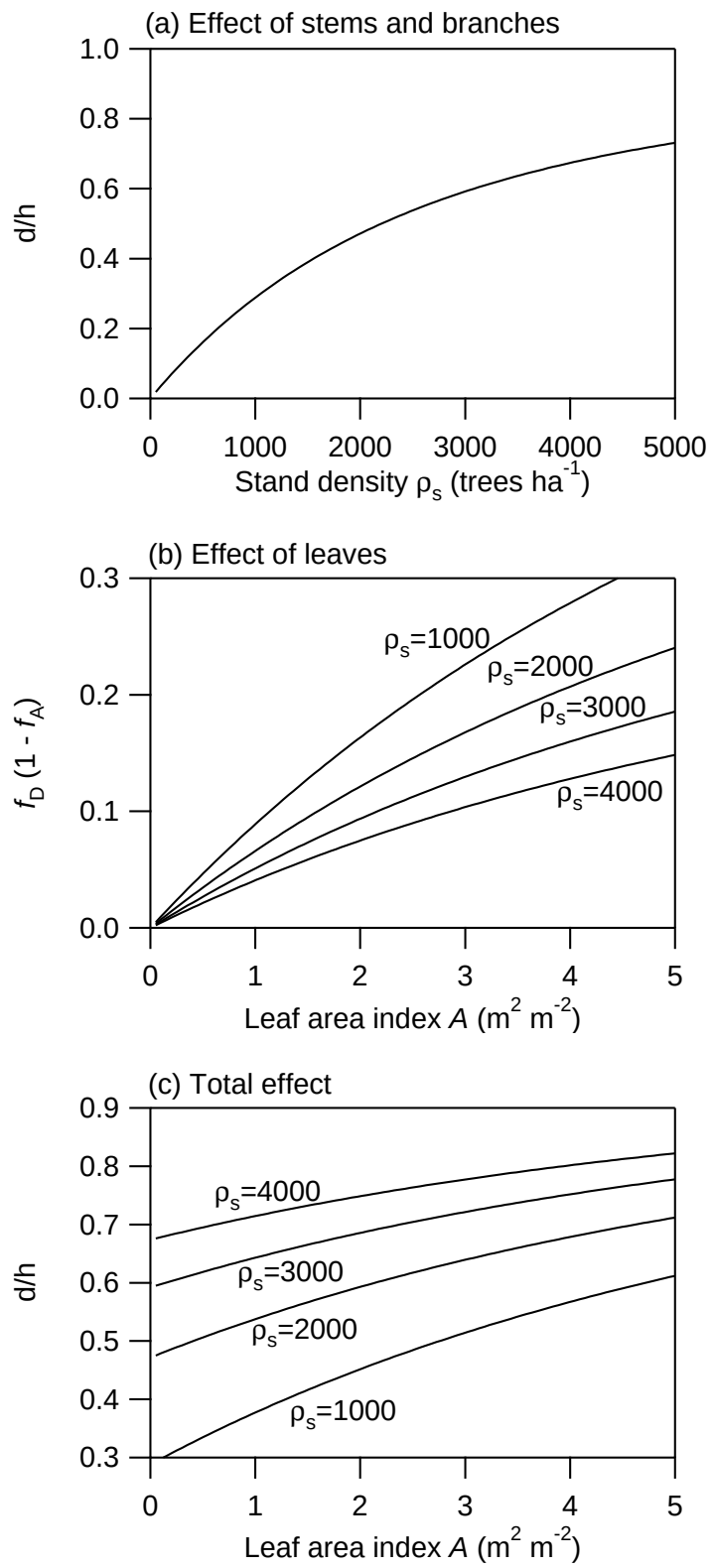


Figure 09

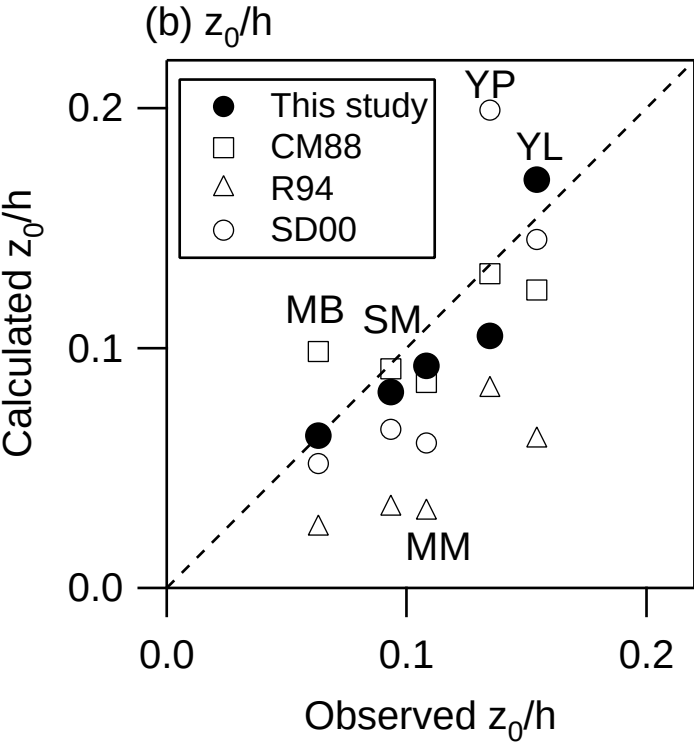
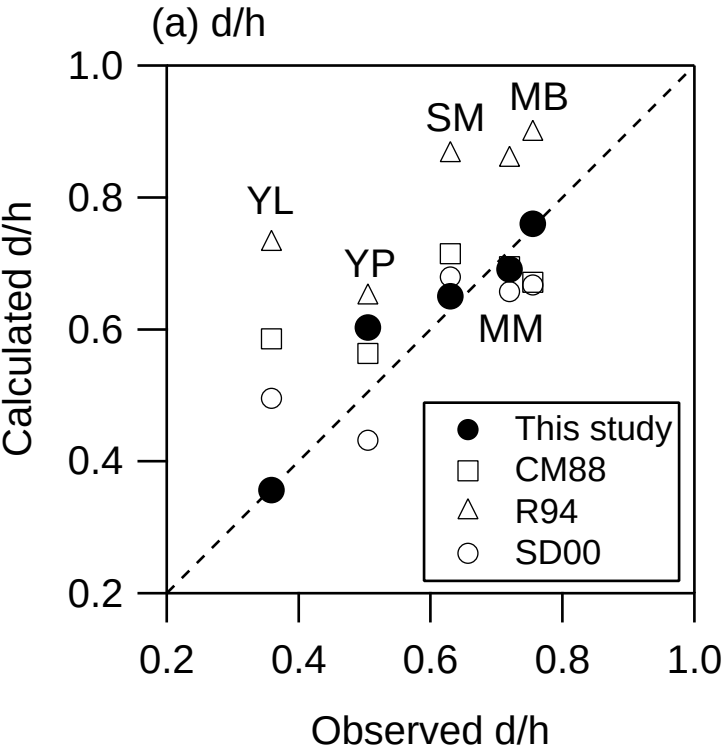


Figure 10

