What is the best way to represent surface conductance for a range of vegetated sites?

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Abstract:

Surface conductance G_s is a significant parameter for indicating the evaporative and photosynthetic properties of a vegetated surface. When comparing G_s values between different observation sites, some studies have used G_{smax} and others have used $\hat{G}_{smax}$ (where G_{smax} is the maximum G_s value measured during the measurement period, and $\hat{G}_{smax}$ is the maximum G_s value obtained with a vapour pressure deficit (VPD) of ≥ 1.0 kPa during the measurement period).

In this study, we demonstrate a clear justification for using $\hat{G}_{smax}$ instead of G_{smax} when comparing G_s values between different sites. We examined whether both $\hat{G}_{smax}$ and G_{smax} lead to the same conclusions in classifying vegetated sites. Komatsu (2003b) [*Hydrological Processes* 17: 2503–2512] reported a clear relationship between canopy height h and $\hat{G}_{smax}$ for coniferous forests with a projected leaf area index (LAI) of ≥ 3.0 . We examined not only the relationship between h and $\hat{G}_{smax}$ but also the relationship between h and G_{smax} for coniferous forests with a projected LAI of ≥ 3.0 .

Both $\hat{G}_{smax}$ and G_{smax} decreased with increasing h . However, the relationship between h and G_{smax} was less well defined than the relationship between h and $\hat{G}_{smax}$ because of biased G_{smax} data. Consequently, we conclude that $\hat{G}_{smax}$ is a more appropriate index than G_{smax} to represent G_s for sites with different vegetation. Copyright © 2007 John Wiley & Sons, Ltd.

KEY WORDS surface conductance; maximum surface conductance; vegetation; vapour pressure deficit

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INTRODUCTION

Surface conductance G_s is an important parameter used to indicate the evaporative and photosynthetic properties of a vegetated surface. G_s is calculated from the evapo-transpiration rate using the inverse form of the Penman–Monteith equation (Dolman *et al.*, 1991; Kelliher *et al.*, 1997, 1998; Kumagai *et al.*, 2004; Komatsu *et al.*, 2005); it indicates the significance of physiological control of evaporation by plants (Kelliher *et al.*, 1995; Raupach, 1995; Baldocchi and Meyers, 1998; Lai *et al.*, 2000). Since the stomata control photosynthesis as well as evapo-transpiration (Leuning, 1990, 1995; Jones, 1992; Campbell and Norman, 1998; Komatsu *et al.*, 2007), G_s also indicates the significance of physiological photosynthesis control (e.g. Schulze *et al.*, 1994, 1995).

We can use G_s to quantify differences in the significance of physiological control between observation sites (Shuttleworth, 1989; Kelliher *et al.*, 1993, 1995; Schulze *et al.*, 1994, 1995; Dolman *et al.*, 1998; Kostner, 2001; Komatsu, 2003a,b, 2005; Komatsu and Hotta, 2005). In this way, we can quantify differences in the evaporative and photosynthetic properties not only of observation sites but also of different vegetation categories.

Such comparisons are improved by using an index based on G_s , but with reduced dependence on varying meteorological conditions (Tan and Black, 1976; Stewart, 1988; Komatsu, 2004; Kumagai *et al.*, 2004). To compare G_s values from different observation sites, we thus need to determine a reference G_s value that is not affected by meteorological differences between sites.

Many studies have represented G_s by G_{smax} , where G_{smax} is the maximum G_s value obtained during the measurement period (Kelliher *et al.*, 1993, 1995; Schulze *et al.*, 1994, 1995; Dolman *et al.*, 1998; Kostner, 2001). As G_s decreases with increasing vapour pressure deficit (VPD) (e.g. Herbst, 1995; Law *et al.*, 2001; Humphreys *et al.*, 2003; Blanken and Black, 2004), G_{smax} is usually measured in low VPD conditions.

In contrast to these studies that use G_{smax} , Komatsu (2003a,b, 2005) represented G_s by $\hat{G}_{smax}$, where $\hat{G}_{smax}$ is the maximum G_s value obtained with VPD ≥ 1.0 kPa during the measurement period. As G_s decreases with increasing VPD (Herbst, 1995; Law *et al.*, 2001; Humphreys *et al.*, 2003; Blanken and Black, 2004), $\hat{G}_{smax}$ is usually found when VPD is just above 1.0 kPa. Thus, use of $\hat{G}_{smax}$ avoids selecting G_s in low VPD conditions (VPD < 1.0 kPa) as the reference value for the site, but this use of $\hat{G}_{smax}$ is not yet commonly accepted. A similar concept has been employed in several studies (Komatsu, 2003a,b, 2005) for modelling surface or canopy conductance. Granier *et al.* (1996a,b,

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2000); Oren *et al.* (1999); Komatsu (2004); Ewers *et al.* (2005) and Komatsu *et al.* (2006) gave reference values at $VPD = 1.0$ kPa when modelling surface or canopy conductance. However, many well known studies have used reference values at $VPD = 0.0$ kPa when modelling surface or canopy conductance (e.g. Lindroth, 1985; Gash *et al.*, 1989; Granier and Loustau, 1994; Ogink-Hendriks, 1995).

It would be useful to determine whether there is any advantage in using either $\hat{G}_{smax}$ or G_{smax} to compare G_s values between observation sites. Komatsu (2003a,b, 2005) speculated that using $\hat{G}_{smax}$ is better because G_s data obtained in low VPD conditions can cause several problems, which are outlined in the next section. However, to our knowledge, no clear justification has been offered for preferring $\hat{G}_{smax}$ to G_{smax} .

We examined whether $\hat{G}_{smax}$ and G_{smax} lead to the same results when comparing G_s values between different observation sites. We show that the use of $\hat{G}_{smax}$ leads to clearer results than G_{smax} , and we conclude that $\hat{G}_{smax}$ is a more appropriate index than G_{smax} when comparing G_s values between different observation sites.

THEORY

This section describes the theoretical background for the use of $\hat{G}_{smax}$ instead of G_{smax} . Komatsu (2003a,b, 2005) speculated that $\hat{G}_{smax}$ is better in the following three respects.

First, G_{smax} is highly dependent on the length of the measurement period (Kelliher *et al.*, 1995; Dolman *et al.*, 1998), while $\hat{G}_{smax}$ is not. G_{smax} tends to be measured during high irradiance and low VPD conditions, which occur comparatively rarely. Therefore, G_{smax} obtained from short-term measurements tends to be underestimated. On the other hand, $\hat{G}_{smax}$ tends to occur along with high irradiance and VPD just above 1.0 kPa (Figure 1), a more common set of conditions. Therefore, $\hat{G}_{smax}$ obtained from short-term measurements does not tend to be underestimated as often as G_{smax} .

Second, G_{smax} tends to be determined as a high G_s value because of wet-canopy evaporation after rain or heavy dew, while $\hat{G}_{smax}$ does not. The G_s of a wet canopy is generally higher than that of a dry canopy and tends to occur in low VPD conditions. Therefore, it is likely that a high G_s value caused by wet-canopy evaporation will be selected as G_{smax} . This problem can usually be avoided by using $\hat{G}_{smax}$ instead of G_{smax} ; (however, the problem may be avoided by careful data filtering when using G_{smax}).

Third, G_{smax} tends to be strongly affected by error in VPD measurement, while $\hat{G}_{smax}$ does not. As G_{smax} is usually obtained in low VPD conditions (Figure 1), a small absolute error in VPD measurement causes a large error in calculating G_s , as is the case when calculating stomatal conductance from sap-flux measurements (Ewers and Oren, 2000).

If there were no differences in the lengths of measurement periods, in the methods for eliminating G_s data of

Figure 1. Schematic drawing of the relationship between VPD and surface conductance G_s . $\hat{G}_{smax}$ and G_{smax} are illustrated, where $\hat{G}_{smax}$ is the maximum surface conductance satisfying $VPD \geq 1.0$ kPa during the measurement period, and G_{smax} is the maximum surface conductance during the measurement period

a wet canopy, and in the accuracy in VPD measurements between observation sites, G_{smax} would correlate well with $\hat{G}_{smax}$, and both $\hat{G}_{smax}$ and G_{smax} would produce nearly the same results when comparing G_s values from different observation sites. In practice, however, there are differences in the lengths of measurement periods, in the methods for eliminating G_s data of a wet canopy, and in the accuracy in VPD measurements between observation sites, and thus, there can be a bias in G_{smax} estimates that does not apply to $\hat{G}_{smax}$. When using G_{smax} , such biased G_{smax} samples can tend to confuse results more than when using $\hat{G}_{smax}$.

MATERIALS AND METHODS

We examined whether $\hat{G}_{smax}$ and G_{smax} lead to the same results in the following way. We examined the relation between canopy height h and $\hat{G}_{smax}$ and between h and G_{smax} for coniferous forests with a projected leaf area index (LAI) of ≥ 3.0 . These relationships were then compared to each other. Komatsu (2003b) has shown that there is a clear relationship between h and $\hat{G}_{smax}$ for coniferous forests. $\hat{G}_{smax}$ decreases with increasing h ; this relation is especially strong when the projected LAI is ≥ 3.0 ($R^2 = 0.69$). Our focus here was on whether G_{smax} also decreased with increasing h , and whether the relationship between h and G_{smax} was as well defined as the relationship between h and $\hat{G}_{smax}$.

For these comparisons, we used G_s data derived from micrometeorological measurements. Additionally, we used canopy conductance data from sap flux measurements, assuming that canopy conductance $G_c = G_s$. G_c differs from G_s in that G_c does not include the effect of soil surface evaporation (including understory evaporation) (Kelliher *et al.*, 1995; Raupach, 1995). However,

G_c is approximately equal to G_s when the projected LAI is $\geq ca$ 3 because of the insignificant contribution of soil surface evaporation to total evaporation (Kelliher *et al.*, 1995). Thus, our assumption ($G_c = G_s$) is reasonable. Although G_c can also be obtained by scaling up from leaf gas exchange measurements (Whitehead *et al.*, 1984; Milne *et al.*, 1985; Loustau *et al.*, 1996), we did not use such data. They are not very representative of forest gas exchange characteristics, as there is large variation in the gas exchange rate between leaves in a forest (Leverenz *et al.*, 1982).

As detailed above, we used G_s data based on different measurement methods. The effects of these differences in measurement methods on the analysis results have been discussed by Komatsu (2003b).

RESULTS AND DISCUSSION

Figure 2(a) shows the relation between canopy height h and $\hat{G}_{smax}$ for coniferous forests with projected LAI ≥ 3.0 , which is the same as Figure 2(b) of Komatsu (2003b). Figure 2(b) of our paper shows the relation between h and G_{smax} for coniferous forests with projected LAI ≥ 3.0 . $\hat{G}_{smax}$ and G_{smax} data used in Figure 2(a) and (b) are shown in Table I. Note that we have included two samples (Arain *et al.*, 2003; Restrepo and Arain, 2005) that had not been included in the Komatsu (2003b) analysis. As a result, the R^2 value in Figure 2(a) ($R^2 = 0.61$) differed slightly from that in Figure 2(b) of Komatsu (2003b) ($R^2 = 0.69$).

Both $\hat{G}_{smax}$ and G_{smax} decreased with increasing h . However, the relation between h and $\hat{G}_{smax}$ was less well defined than the relationship between h and G_{smax} . The R^2 for Figure 2(b) ($R^2 = 0.49$) was lower than that for Figure 2(a) ($R^2 = 0.61$).

The less well defined relationship in Figure 2(b) was caused by the two data samples indicated by arrows. These two samples were from Tanaka *et al.* (1996) and Restrepo and Arain (2005), respectively. We believe that the G_{smax} values for Tanaka *et al.* (1996) and Restrepo and Arain (2005) are biased, for the following reasons. First, the R^2 values for Figure 2(a) and (b) are similar to each other if these two data samples are excluded. When they are excluded, the R^2 values for Figure 2(a) and (b) are 0.68 and 0.67, respectively. Second, G_{smax} values for Tanaka *et al.* (1996) and Restrepo and Arain (2005) are much higher than those expected from their $\hat{G}_{smax}$ values. Figure 3 shows the relationship between $\hat{G}_{smax}$ and G_{smax} . Data from Tanaka *et al.* (1996) and Restrepo and Arain (2005) are indicated by arrows. There is a clear linear relationship between $\hat{G}_{smax}$ and G_{smax} ($R^2 = 0.70$), which explains qualitatively the same results between Figure 2(a) and (b). However, the data of Tanaka *et al.* (1996) and Restrepo and Arain (2005) deviate noticeably from the regression line (Figure 3). The two data samples show much higher G_{smax} values than those expected from the regression line between $\hat{G}_{smax}$ and G_{smax} .

The scatter in the G_{smax} value for Tanaka *et al.* (1996) and Restrepo and Arain (2005) may be explained by

Figure 2. (a) The relationship between canopy height h and $\hat{G}_{smax}$ for coniferous forests with projected LAI ≥ 3.0 , where $\hat{G}_{smax}$ is the maximum surface conductance satisfying VPD ≥ 1.0 kPa during the measurement period. The function determined by least-square regression is written as $\hat{G}_{smax} = 23.7 \exp(-0.0624h)$. Data from Tanaka *et al.* (1996) and Restrepo and Arain (2005) are indicated by arrows. (b) The relationship between canopy height h and G_{smax} for coniferous forests with projected LAI ≥ 3.0 , where G_{smax} is the maximum surface conductance during the measurement period. The function determined by least-square regression is written as $G_{smax} = 47.7 \exp(-0.0731h)$. Data from Tanaka *et al.* (1996) and Restrepo and Arain (2005) are indicated by arrows

wet-canopy evaporation and/or VPD measurement error factors. As described in the Theory section, there are three possible factors that explain scatter in G_{smax} : short measurement period, wet-canopy evaporation, and VPD measurement error factors. The short measurement period factor cannot explain the scatter. It can only cause underestimation of G_{smax} values. However, Figure 3 suggests that the G_{smax} is overestimated rather than underestimated. Apart from the short measurement period factor, both wet-canopy evaporation and VPD measurement error factors can cause overestimation of G_{smax} values.

CONCLUSIONS

We examined whether $\hat{G}_{smax}$ and G_{smax} both lead to the same conclusions when used for comparing G_s

Table I. $\hat{G}_{smax}$ and G_{smax} values for coniferous forests with projected LAI of ≥ 3.0 summarized from earlier papers

Species	Latitude, Longitude	Canopy height (m)	Projected leaf area index	Measure- ment methods ^a	$\hat{G}_{smax}$ (mm s ⁻¹)	G_{smax} (mm s ⁻¹)	Reference
<i>Abies bornmuelleiana</i>	?	11	8.9	SF	18 ^b	—	Granier <i>et al.</i> (2000)
<i>Chamaecyparis obtusa</i>	34°58'N, 136°00'E	14	3.0	EC	8	34	Tanaka <i>et al.</i> (1996)
<i>Larix gmelinii</i>	62°15'N, 129°37'E	18	3.7	EC	8	20	Ohta <i>et al.</i> (2001)
<i>Picea abies</i>	56°34'N, 13°13'E	14	9	SF	9	25	Cienciala <i>et al.</i> (1994)
<i>Picea abies</i>	50°09'N, 11°52'E	15	6.5	SF	11	13	Alsheimer <i>et al.</i> (1998)
<i>Picea abies</i>	50°09'N, 11°52'E	16	5.3	SF	6	7	Alsheimer <i>et al.</i> (1998)
<i>Picea abies</i>	50°09'N, 11°52'E	18	7.1	SF	7	8	Alsheimer <i>et al.</i> (1998)
<i>Picea abies</i>	50°09'N, 11°52'E	24	7.9	SF	6	8	Alsheimer <i>et al.</i> (1998)
<i>Picea abies</i>	50°09'N, 11°52'E	25	6.5	SF	4	5	Alsheimer <i>et al.</i> (1998)
<i>Picea abies</i>	50°09'N, 11°52'E	26	7.6	SF	8	10	Alsheimer <i>et al.</i> (1998)
<i>Picea abies</i>	?	11	9.5	SF	17 ^b	—	Granier <i>et al.</i> (2000)
<i>Picea abies</i>	?	13	6.1	SF	14 ^b	—	Granier <i>et al.</i> (2000)
<i>Picea sitchensis</i>	55°20'N, 3°53'W	7	5 ^d	ECEB	14	25	Milne (1979)
<i>Pinus banksiana</i>	53°59'N, 105°07'W	11	4.5	EC	9	15	Arain <i>et al.</i> (2003)
<i>Pinus pinaster</i>	44°42'N, 0°46'W	12	6	SF	16	30	Granier and Loustau (1994)
<i>Pinus radiata</i>	42°52'S, 172°45'E	9	6.5 ~ 7.5	EC	12	19	Arneeth <i>et al.</i> (1998)
<i>Pinus strobus</i>	42°43'N, 80°23'W	22	3.2 ~ 4.0	EC	10	28	Restrepo and Arain (2005)
<i>Pinus sylvestris/Picea abies</i>	60°05'N, 17°29'E	28	3 ~ 4	SF	3	4	Cienciala <i>et al.</i> (1997)
<i>Pinus sylvestris/Picea abies</i>	60°05'N, 17°29'E	23	4 ~ 5	SF	4	8	Cienciala <i>et al.</i> (1997)
<i>Pseudotsuga menziesii</i>	?	10	7.5 ~ 8.0	BREB	9	25	Tan and Black (1976)
<i>Pseudotsuga menziesii</i>	52°15'N, 5°41'W	18	11	EC	6	10	Bosveld and Bouten (2001)

^a BREB: Bowen ration energy balance method; EC: eddy correlation method; ECEB: eddy correlation energy balance method; SF: sap flux method.

^b Derived from the regression model of Granier *et al.* (2000), which expresses G_s as a function of meteorological factors. We assumed that $\hat{G}_{smax}$ equals the maximum G_s at VPD = 1.0 kPa. Even when these data samples are excluded, our conclusions are not altered.

^c G_{smax} could not be derived from the regression model of Granier *et al.* (2000), because G_s was assumed to approach infinity as VPD approaches 0 kPa.

^d Estimated by dividing the total surface area index by 2.4, which is an intermediate value for conifers (Landsberg and Gower, 1997).

Figure 3. The relationship between $\hat{G}_{smax}$ and G_{smax} , where $\hat{G}_{smax}$ is the maximum surface conductance satisfying VPD ≥ 1.0 kPa during the measurement period, and G_{smax} is the maximum surface conductance during the measurement period. Data from Tanaka *et al.* (1996) and Restrepo and Arain (2005) are indicated by arrows. The function determined by least-square regression is written as $G_{smax} = 1.79 \cdot \hat{G}_{smax}$. For this regression, data from Tanaka *et al.* (1996) and Restrepo and Arain (2005) were excluded

h and $\hat{G}_{smax}$, and between h and G_{smax} for coniferous forests with projected LAI of ≥ 3.0 . Both $\hat{G}_{smax}$ and G_{smax} decreased with increasing h . However, the relation between h and G_{smax} was less well defined than the relationship between h and $\hat{G}_{smax}$, because of biased G_{smax} data samples. Thus, we have shown a clear justification for using $\hat{G}_{smax}$ instead of G_{smax} . Consequently, we conclude that $\hat{G}_{smax}$ is a more appropriate index than G_{smax} to represent G_s for different vegetated sites.

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