Calculating Canopy Stomatal Conductance from Eddy Covariance Measurements, in Light of the Energy Budget Closure Problem

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Abstract. Canopy stomatal conductance (g_{sV}) is commonly estimated from eddy covariance (EC) measurements of latent heat flux (LE) by inverting the Penman-Monteith (PM) equation. That method implicitly represents the sensible heat flux (H) as the residual of all other terms in the site energy budget — even though H is measured at least as accurately as LE at every EC site while the rest of the energy budget almost never is. We argue that g_{sV} should instead be calculated from EC measurements of both H and LE, using the flux-gradient formulation that defines conductance and underlies the PM equation. The flux-gradient formulation dispenses with unnecessary assumptions, is conceptually simpler, and provides more accurate values of g_{sV} for all plausible scenarios in which the measured energy budget fails to close, as is common at EC sites. The PM equation, on the other hand, contributes biases and erroneous spatial and temporal patterns to g_{sV}, skewing its relationships with drivers such as light and vapor pressure deficit. To minimize the impact of the energy budget closure problem on the PM equation, it was previously proposed that the eddy fluxes should be corrected to close the long-term energy budget while preserving the Bowen ratio ($B = H/LE$). We show that such a flux correction does not fully remedy the PM equation but should produce accurate values of g_{sV} when combined with the flux-gradient formulation.

1 Introduction

Leaf stomata are the main coupling between the terrestrial carbon and water cycles, simultaneously controlling the passage of carbon dioxide and transpired water. The many stomata in a plant canopy experience a wide range of micro-environmental conditions and therefore exhibit a wide range of behaviors at any given moment in time; yet it has proven useful in many contexts to approximate the canopy as a single ‘big leaf’ with a single stoma (Baldocchi et al., 1991; Wohlfahrt et al., 2009; Wehr et al., 2017). The aggregate canopy stomatal conductance to water vapor (g_{sV}) is then defined as the total canopy transpiration divided by the transpiration-weighted average water vapor gradient across the many real stomata.

The standard method to estimate g_{sV} is from eddy covariance (EC) measurements of the latent heat flux (LE) via the Penman-Monteith (PM) equation (Monteith, 1965; Grace et al., 1995) — but the EC method and the PM equation make a strange pairing. The latter was designed to estimate transpiration without knowing the sensible heat flux (H), which was difficult to measure at the time. The Penman-Monteith derivation therefore replaced H with the residual of all other terms in the energy budget. The EC method, however, always measures H along with LE. When applied at EC sites, the PM equation simply ignores those H measurements and in their place requires measurements of net radiation (R_n), heat flux to the deep soil (G), and heat storage (S) in the shallow soil, canopy air, and biomass. In wetland ecosystems, heat flux by groundwater discharge (W) can also be important (Reed et al., 2018). While net radiation measurements are ubiquitous at EC sites, ground heat flux measurements are less common (Stoy et al., 2013; Purdy et al., 2016) and heat storage and discharge measurements are rare (Lindroth et al., 2012; Reed et al., 2018). As such it is common practice to simply omit S and W and sometimes G from the PM equation.

In general, neither S nor G is negligible. Insufficient measurement of S in particular has been shown (Lindroth et al., 2010; Leuning et al., 2012) to be a major contributor to the infamous energy budget closure problem at EC sites, which is that the measured turbulent heat flux $H + LE$ is about 20% less than the measured available energy $R_n - G$ on average across the FLUXNET EC site network (Wilson et al., 2002; Foken, 2008; Franssen et al., 2010; Leuning et al., 2012; Stoy et al., 2013). The other major contributor is systematic underestimation of $H + LE$ by the EC method (Foken, 2008; Stoy et al., 2013), which also induces error in the PM equation, via LE. Leuning et al (2012) assessed the relative contributions of S and $H + LE$ to the closure problem using the fact that S largely averages out over 24 hours while R_n, H, and LE do not; thus S contributes to the hourly but not the daily energy budget (Lindroth et al., 2010; Leuning et al., 2012). Analyzing over 400 site-years of data, they found that the median slope of $H + LE$ versus R_n - G was only 0.75 when plotting hourly averages but went up to 0.9 when plotting daily averages. This result suggests that on average across FLUXNET, 60% of the energy budget gap is attributable to S and 40% to $H + LE$. Depending on the depth at which G is measured (which is not standard), G might also average down considerably over 24 hours and thereby share some of the 60% attributed to S. Conversely, the part of G that does not average out over 24 hours might share some of the 40% attributed to $H + LE$, as might R_n and W. But S and $H + LE$ are the most likely sources of large systematic error.

On account of the energy budget closure problem, it was proposed a decade ago that the PM equation should use values of H and LE that have been adjusted (explicitly or implicitly) to close the energy budget while preserving the Bowen ratio $B = H/LE$ (Wohlfahrt et al., 2009). Preservation of the Bowen ratio is advisable because the most likely causes of pervasive underestimation by EC (such as anemometer tilt, advective loss, and large-scale air motions) afflict H and LE proportionally or nearly so. On the other hand, attributing the entire budget gap to $H + LE$ is inadvisable given the above evidence for the importance of S.

Rather than trying to kluge an accurate method for using the PM equation at EC sites, we propose that the underlying flux-gradient (FG) equations for sensible heat and water vapor should be applied directly to the calculation of g_{sV} (as in Baldocchi et al., 1991; Wehr and Saleska, 2015). As we will show, the FG equations take advantage of the H measurements provided by EC, do not require measurements of R_n, G, S, or W, and are universally more accurate than the PM equation by a substantial margin.

We present the FG and PM equations in Section 2, describe our methods for comparing them in Section 3, and report our findings in Section 4.

2 Theory

By definition, conductance is the proportionality coefficient between a flux and its driving gradient. In the case of g_{sV}, the flux is transpiration and the gradient is the vapor pressure differential across the stomata. It is therefore relatively straightforward to calculate g_{sV} from the flux-gradient (FG) equations for transpiration and sensible heat (Baldocchi et al., 1991), rearranged as follows (Wehr and Saleska, 2015):

$$r_{sV} = \frac{e_s(T_L) - e_a}{RT_a E} - r_{bV} \tag{1}$$

$$T_L = \frac{H r_{bH}}{\rho_a c_p} + T_a \tag{2}$$

where r_{sV} (s m^{-1}) is the stomatal resistance to water vapor, r_{bV} is the leaf boundary layer resistance to water vapor (s m^{-1}), r_{bH} is the leaf boundary layer resistance to heat (s m^{-1}), E is the flux of transpired water vapor (mol m^{-2} s^{-1}), H is the sensible heat flux (W m^{-2}), T_a is the canopy air temperature (K), T_L is the effective canopy-integrated leaf temperature (K), ρ_a is the density of the (wet) canopy air (kg m^{-3}), c_p is the specific heat capacity of the (wet) canopy air (J kg^{-1} K^{-1}), e_a is the vapor pressure in the canopy air (Pa), $e_s(T_L)$ is the saturation vapor pressure inside the leaf as a function of T_L (Pa), and R is the molar gas constant (8.314472 J mol^{-1} K^{-1}). The equation for the saturation vapor pressure (Pa) as a function of temperature (K) is (World Meteorological Organization, 2008):

$$e_s(T) = 611.2 e^{\left(\frac{17.62(T-273.15)}{243.12+(T-273.15)}\right)} \tag{3}$$

An empirical model such as the one given in the Appendix can be used to calculate r_{bH} as a function of wind speed and other variables. Using that model in a temperate deciduous forest, r_{bH} was found to vary only between 8 and 12 s m^{-1} (Wehr and Saleska, 2015), and so we simply take it to be constant at 10 s m^{-1} here. The corresponding resistance to water vapor transport can be calculated from r_{bH} via (Hicks et al., 1987):

$$r_{bV} = \frac{1}{f} r_{bH} \left(\frac{Sc}{Pr}\right)^{\frac{2}{3}} \quad (4)$$

where Sc is the Schmidt number for water vapor (0.67), Pr is the Prandtl number for air (0.71), and f is the fraction of the leaf surface area that contains stomata ($f = 0.5$ for hypostomatous leaves, which have stomata on only one side, and $f = 1$ for amphistomatous leaves, which have stomata on both sides).

The stomatal conductance to water vapor (mol m^{-2} s^{-1}) is obtained from r_{sV} by (Grace et al., 1995):

$$g_{sV} = \left(\frac{P}{RT_L}\right)\frac{1}{r_{sV}} \quad (5)$$

where P is the atmospheric pressure.

The Penman-Monteith (PM) equation for a leaf (Monteith, 1965), when inverted to solve for the stomatal resistance (Grace et al., 1995), can be expressed as:

$$r_{sV} = \frac{s(R_n - G - S - D - LE_{\mathrm{tr}} - LE_{\mathrm{ev}})r_{bH} + \rho_a c_p (e_s(T_a) - e_a)}{\gamma LE_{\mathrm{tr}}} - r_{bV} \quad (6)$$

where LE_{tr} is the latent heat flux associated with transpiration (W m^{-2}), LE_{ev} is the latent heat flux associated with evaporation that does not pass through the stomata (W m^{-2}), $e_s(T_a)$ is the saturation vapor pressure of the air as a function of T_a (Pa), s is the slope of the e_s curve at T_a (Pa K^{-1}), and γ is the psychrometric constant at T_a (Pa K^{-1}). R_n, G, S, and W also have units of W m^{-2}. Latent heat flux is water vapor flux (E) times the latent heat of vaporization of water (about 44.1×10^3 J mol^{-1}).

The inverted PM equation is usually expressed in a slightly simpler form by neglecting the distinctions (a) between transpiration and evaporation, and (b) between the leaf boundary layer resistances to heat and water vapor. We retain those distinctions here in order to highlight two important points:

1. Absent a means to accurately partition the measured eddy flux of water vapor into transpiration and non-stomatal evaporation (e.g. from soil or wet leaves), the FG and PM equations are applicable only when evaporation is negligible, which is a difficult situation to verify but does occur at particular times in particular ecosystems (see, e.g., Wehr et al., 2017).

2. Setting $r_{bV} = r_{bH}$ instead of using Eq. (4) is a good approximation for amphistomatous leaves (stomata on both sides) but a poor approximation for the more common hypostomatous leaves (stomata on only one side) (Schymanski and Or, 2017). Indeed, we find that if r_{bV} is set equal to r_{bH} for hypostomatous leaves, the PM equation underestimates g_{sV} by about 10% (depending on the relative resistances of the stomata and boundary layer) even when the site energy budget is closed.

Note that the PM equation can be derived from the FG equations by invoking energy balance to eliminate H from Eq. (2) and by making the psychrometric approximation:

$$s \approx \frac{e_s(T)-e_s(T_L)}{T-T_L} \Rightarrow e_s(T_L) \approx e_s(T) - s(T - T_L) \quad (7)$$

Those are the only two differences between the FG and PM formulations. Both rely on water flux measurements to estimate transpiration and both approximate the canopy as a ‘big leaf’.

Also note that in the above equations, T_a, e_a, ρ_a, and c_p refer to the canopy air; that is, the air just outside the leaf boundary layer. In practice, these variables may be measured above the canopy and converted to canopy air values via the turbulent eddy or aerodynamic transport resistance, which may be calculated by various methods that do not agree particularly well with one another (e.g. see Baldocchi et al., 1991; Grace et al., 1995; Wehr and Saleska, 2015). Fortunately, that resistance is often much smaller than the stomatal and leaf boundary layer resistances during the day and can sometimes be neglected in the calculation of g_{sV}.

3 Methods

We assessed the percent error in g_{sV} calculated via the PM and FG formulations by simulating energy flux observations and using them to estimate g_{sV}. The simulations were of three snapshots in time roughly typical of midday in three different ecosystems: a temperate deciduous forest in July (the Harvard Forest in Massachusetts, USA; Wehr et al., 2017), a tropical rainforest in May (the Reserva Jaru in Rondônia, Brazil; Grace et al., 1995), and a tropical savannah in September (Virginia Park in Queensland, Australia; Leuning et al., 2005). The purpose of including three different ecosystems was to test the FG and PM formulations across a broad range of environmental and biological input variables (especially Bowen ratios), not to provide a lookup table of quantitative g_{sV} corrections for other sites. The particular sites and time periods within each ecosystem were chosen merely for convenience, as the requisite variables were readily obtainable from the literature or from our past work.

The simulations began by specifying the true value of g_{sV}. For that, the (approximate) values in Table 1 were obtained from measurements reported in the papers cited above or from our own work at the Harvard Forest, except that the precise values of H and LE were calculated to satisfy B and energy balance. With all the true fluxes and conditions now specified, we used the FG equations (Eqs. (1-5)) to calculate the true value of g_{sV}. Note that because the true energy fluxes necessarily close the energy budget, the FG and PM equations become mathematically equivalent aside from the psychrometric approximation (Eq. (7)), which causes a small (< 5%) positive error in PM-derived g_{sV}. That error is the reason why PM-derived g_{sV} does not quite converge on the true value even when the entire energy budget gap is due to the EC fluxes and those fluxes are corrected for 24-hour budget closure (solid red line at the righthand edge of Fig. 1). Thus one could calculate the true g_{sV} from the PM equation (Eq. (6)) instead and thereby incur only a minor error that would not qualitatively affect the results to follow.

Next, we simulated erroneous energy flux observations suffering from a 20% gap in the energy budget, and used those "observations" to estimate g_{sV} via the FG and PM equations, with and without flux correction (see next paragraph). When simulating the observations, we variously apportioned the measurement error between the available energy $R_n - G - S - W$ and the turbulent flux $H + LE$ while preserving the Bowen ratio. As mentioned in the introduction, the most likely causes of pervasive underestimation by EC afflict H and LE proportionally and therefore do not alter B. In fact, we know of no plausible, pervasive mechanism that would cause the proportional measurement error in H to exceed that in LE (it being more difficult to measure fast water vapor fluctuations than fast temperature fluctuations), nor any evidence of a pervasive mechanism that would cause the converse. Of course, various instrument or data processing problems (e.g. sensor miscalibration) could induce positive or negative errors in H or LE during particular periods at particular sites. Note that Gerken et al 2018 was mistaken in suggesting that anemometer error could cause the proportional measurement error in H to systematically exceed that in LE: the papers cited in support of that suggestion (Kochendorfer et al., 2012; Frank et al., 2013) both concluded that anemometer error would affect all EC fluxes equally.

The two turbulent flux correction schemes that we simulated both effectively adjust the eddy fluxes to close the energy budget while preserving the Bowen ratio, as suggested by Wohlfahrt et al. (2009). The first scheme closes the hourly or half-hourly budget, thereby attributing all blame for the closure gap to the EC method. In our simulations of a single point in time, this scheme was represented simply by increasing H and LE proportionally such that $H + LE$ became equal to the observed (possibly erroneous) value of $R_n - G - S - W$. The second scheme closes the long-term (e.g. 24-hour) energy budget, thereby sharing the blame appropriately between (a) the EC method, which contributes bias to both hourly and daily averages, and (b) heat storage, which contributes bias to hourly but not daily averages. In our simulations, this scheme was represented by increasing H and LE proportionally such that $H + LE$ became equal to the true value of $R_n - G - S - W$. Note that the hourly-closure scheme corresponds to Method 3 and the daily-closure scheme to Method 4 in Wohlfahrt et al. (2009).

In order to show how the various approaches differ from one another over the diurnal cycle, we also calculated time series of g_{sV} from real hourly measurements at Howland Forest as recorded in the AmeriFlux EC site database (Site US-Ho1; Hollinger, 1996), again using the FG and PM formulations with and without flux correction. Howland Forest is a mostly coniferous forest in Maine, USA (45°12'N, 68°44'W), which we chose for its intermediate Bowen ratio, for variety, and otherwise for convenience. For the hourly-closure scheme, we computed the slope of $H + LE$ versus $R_n - G$ from a plot of all hourly averages in the summer of 2014 and then divided both H and LE by that slope. Similarly, for the daily-closure scheme, we computed the slope of $H + LE$ versus $R_n - G$ from a plot of all 24-hour averages in the summer of 2014 and then divided both H and LE by that slope. The slopes could be computed across a shorter or longer time period, rather than seasonally, but dividing H and LE by individual hourly values of $(H + LE)/(R_n - G)$ — as is done implicitly in Eq. (2) of Wohlfahrt et al. (2009) — increases the noise in g_{sV} substantially and is not recommended.

4 Results and Discussion

Figure 1 shows the results of our error simulations, which demonstrate that the flux-gradient formulation (black) is substantially more accurate than the Penman-Monteith equation (red) in all three ecosystems regardless of the cause of the energy budget gap and regardless of the flux correction scheme used. The reason is that whether the gap is due to negative measurement bias in S or in $H + LE$, the PM equation overestimates H (as the residual of the other fluxes) and therefore also the water vapor gradient, which exacerbates underestimation of the conductance. Fig. 1 also shows that the daily-closure correction (solid lines) always leads to more accurate values of g_{sV} than does the hourly-closure correction (dotted lines) or the uncorrected measurements (dashed lines). In fact, if the assumptions in these simulations are correct — i.e., if S does indeed average out over 24 hours, if the errors in R_n, G, and W are indeed much smaller than the errors in S and in $H + LE$, and if the measured Bowen ratio is indeed accurate — then pairing the daily-closure correction with the FG formulation yields the true value of g_{sV} regardless of whether S or $H + LE$ is responsible for the hourly budget gap. The daily-closure PM equation, on the other hand, still suffers from errors in S at the hourly timescale, which is the timescale at which canopy stomatal conductance is invariably calculated.

As comparison of its three panels reveals, the qualitative patterns in Fig. 1 do not depend on the values of the environmental and biological variables in Table 1, but the severity of the error in g_{sV} does. The error in g_{sV} is also proportional to the relative energy budget gap, i.e. $(H + LE)/(R_n - G)$, and will therefore be larger (smaller) than shown here at sites with gaps larger (smaller) than 20%. Because the error in g_{sV} varies with environmental and biological site characteristics, it will lead to erroneous spatial patterns in g_{sV} and to erroneous relationships with potential drivers.

Although not likely to be pervasive and of consistent sign, measurement error in the Bowen ratio could conceivably impact g_{sV} during particular periods at particular sites. To investigate that potential impact, we reran the simulations with a range of measurement errors in B. The results are included in Figure 2, which shows that the resultant proportional error in g_{sV} is roughly the negative of the proportional error in B, and that for each flux correction scheme, the FG formulation tends to remain more accurate than the PM equation even when B is inaccurate.

Figure 3 compares the diurnal patterns of g_{sV} calculated from real measurements at Howland Forest (Hollinger, 1996), again using the FG and PM formulations with and without flux correction. As usual at EC sites, heat storage was not measured and was therefore omitted from the PM equation. If the assumptions of our error simulations (stated above) are correct, then the true values of g_{sV} in Fig. 3 are those obtained from the FG formulation with the EC fluxes corrected for daily closure (solid black lines). That flux correction was relatively small at this site in the summer of 2014: the slope of hourly $H + LE$ versus hourly $R_n - G$ was only 0.63, while the slope using daily data was 0.92, suggesting that 78% of the hourly energy budget gap was due to the omission of S and only 22% was due to EC. Besides the expected negative bias in the PM approach, Fig. 3 shows that the PM and FG formulations claim noticeably different diurnal patterns for g_{sV}. In particular, the PM equation gives substantially lower values than the FG formulation through the morning and early afternoon but then converges on the FG formulation in the late afternoon. The diurnal curve obtained from the PM equation is therefore too flat, leading to an understated picture of the response of g_{sV} to the vapor pressure deficit (which peaks in the afternoon), and/or to an exaggerated picture of the saturation of g_{sV} at high light. This time-varying discrepancy between the FG and PM approaches can be explained by the fact that S (and therefore negative bias in the PM equation) generally peaks in the late morning and approaches zero in the late afternoon (Grace et al., 1995; Lindroth et al., 2010), as reflected in the energy budget gap shown in the bottom panel of Fig. 3 (grey shading).

On the basis of these results, we suggest that when calculating canopy stomatal conductance from eddy covariance data: (1) the sensible and latent heat fluxes should be corrected by a single common factor such that the monthly or seasonal slope of daily average $H + LE$ versus daily average $R_n - G$ becomes equal to 1, and (2) the flux-gradient formulation presented here should be used instead of the Penman-Monteith equation. That combination gives the more accurate result regardless of environmental and biological site characteristics.

It is also worth bearing in mind that even when calculated accurately, the canopy stomatal conductance g_{sV} is not simply the sum of the individual leaf-level conductances and does not vary with time or environment in quite the same way as they do (Baldocchi et al., 1991). Rather, g_{sV} is total canopy transpiration divided by the transpiration-weighted average water vapor gradient across the stomata. As such, it varies not only with the individual leaf-level conductances but also with changes in the relative contributions of different leaves to canopy transpiration as a whole—due, for example, to changes in the distribution of light within the canopy.

5 Conclusion

We have shown that for the purpose of determining canopy stomatal conductance at eddy covariance sites, the Penman-Monteith equation is an unnecessary and inaccurate approximation to the flux-gradient equations for sensible heat and water vapor. Incomplete measurement of the energy budget at EC sites causes substantial bias and misleading spatial and temporal patterns in canopy stomatal conductance derived via the PM equation, even after attempted flux corrections. The errors in stomatal conductance vary between 0 and 35% depending on the time of day and the site characteristics, resulting in erroneous relationships between stomatal conductance and driving variables such as light and vapor pressure deficit. Models trained on those relationships can be expected to misrepresent canopy carbon-water dynamics and to make incorrect predictions.

The reason that the PM equation is sensitive to inaccuracies and omissions in the site energy budget is because the PM equation estimates sensible heat flux as the residual of all other fluxes under assumed energy balance, eschewing the direct measurements of sensible heat flux that are made at every eddy flux site. To obtain more accurate values of canopy stomatal conductance at all sites, we propose using the flux-gradient equations presented here along with measured sensible and latent heat fluxes that have been corrected to close the long-term energy budget while preserving the Bowen ratio. That correction should properly account for underestimation by the EC method regardless of whether the energy budget includes accurate measurements of ecosystem heat storage.

Appendix: An empirical formula for the leaf boundary layer resistance to heat transfer

The canopy flux-weighted leaf boundary layer resistance to heat transfer from all sides of a leaf or needle (s m^{-1}) can be estimated approximately as (McNaughton and Hurk 1995, Wehr et al 2015):

$$r_{bH} = \frac{150}{\mathrm{LAI}}\sqrt{\frac{L}{u_h}}\int_0^1 e^{\alpha(1-\zeta)/2}\phi(\zeta)d\zeta \qquad \text{(A1)}$$

where LAI is the single-sided leaf area index, L is the characteristic leaf (or needle cluster) dimension (e.g. 0.1 m), u_h is the mean wind speed (m s^{-1}) at the canopy top height h (m), ζ is height normalized by h, $\phi(\zeta)$ is the vertical profile of the heat source (which can be approximated by the vertical profile of light absorption) normalized such that $\int_0^1 \phi(\zeta)d\zeta = 1$, and α is the extinction coefficient for the assumed exponential wind profile:

$$\frac{u(\zeta)}{u_h} = e^{\alpha(\zeta-1)} \qquad \text{(A2)}$$

where $\alpha = 4.39 - 3.97e^{-0.258\mathrm{LAI}}$. The wind speed at the top of the canopy can be obtained from Eq. (A2) with ζ set to correspond to the wind measurement height atop the flux tower.

Code availability

The R code used for the simulations and the Igor Pro code used for the Howland Forest data analysis are freely available in the Dryad data archive under the digital object identifier doi:10.5061/dryad.h44j0zpgp (Wehr and Saleska, 2020).

Author contribution

RW conceived and designed the study, wrote the software code, performed the simulations, and prepared the manuscript with contributions from SRS.

Competing interests

The authors declare that they have no conflict of interest.

Acknowledgements

This work was supported by the National Science Foundation (award #1754803). Funding for AmeriFlux data resources was provided by the U.S. Department of Energy's Office of Science. The Howland Forest data was produced under the supervision of Dr. David Hollinger.

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Variable	Temperate Forest (representing July at the Harvard Forest, U.S.A., 42°32'N, 72°10'W)	Tropical Forest (representing May at Reserva Jaru, Brazil, 10°5'S, 61°57'W)	Tropical Savannah (representing September at Virginia Park, Australia, 35°39'S, 148°9'E)
Bowen Ratio, B	0.6	0.35	8
Sensible Heat Flux, H (W m^{-2})	236	140	418
Latent Heat Flux, LE (W m^{-2})	394	400	52
Net Radiation, R_n (W m^{-2})	700	600	600
Heat Storage, $S + G$ (W m^{-2})	70	60	130
Air Temperature, T_a (K)	298	296	303
Atmospheric Vapor, e_a (Pa)	1700	1800	1800

For all sites, $W = 0$ W m^{-2}, $r_{bH} = 10$ s m^{-1}, $r_e = 0$ s m^{-1}, $P = 101325$ Pa, $f = 0.5$.

Table 1. Values of environmental and biological variables used in the error simulations (representing midday).

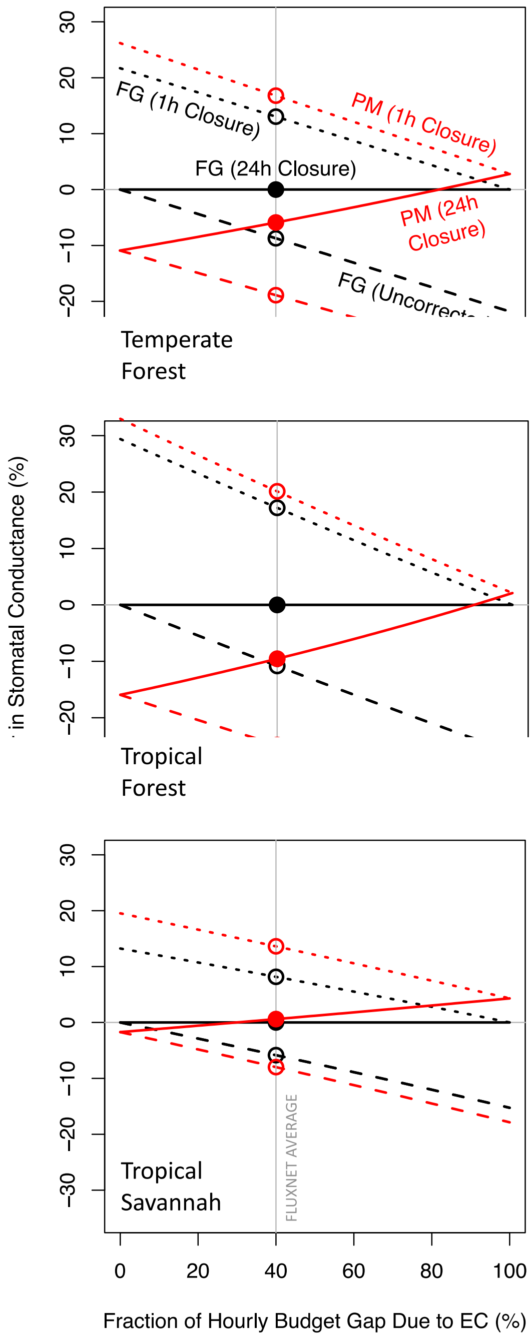


Figure 1. Percent error in canopy stomatal conductance versus the fraction of the average hourly energy budget gap that is caused by error in the eddy fluxes rather than by error in the available energy, for three different ecosystem types and for the flux-gradient (FG, black) and Penman-Monteith (PM, red) equations without flux correction (dashed lines), with daily-closure flux correction (solid lines), and with hourly-closure flux correction (dotted lines). The average estimated contribution of eddy covariance error to the budget gap across FLUXNET is indicated by the grey vertical line (Leuning et al., 2012). Circles highlight where the various lines cross the FLUXNET average.

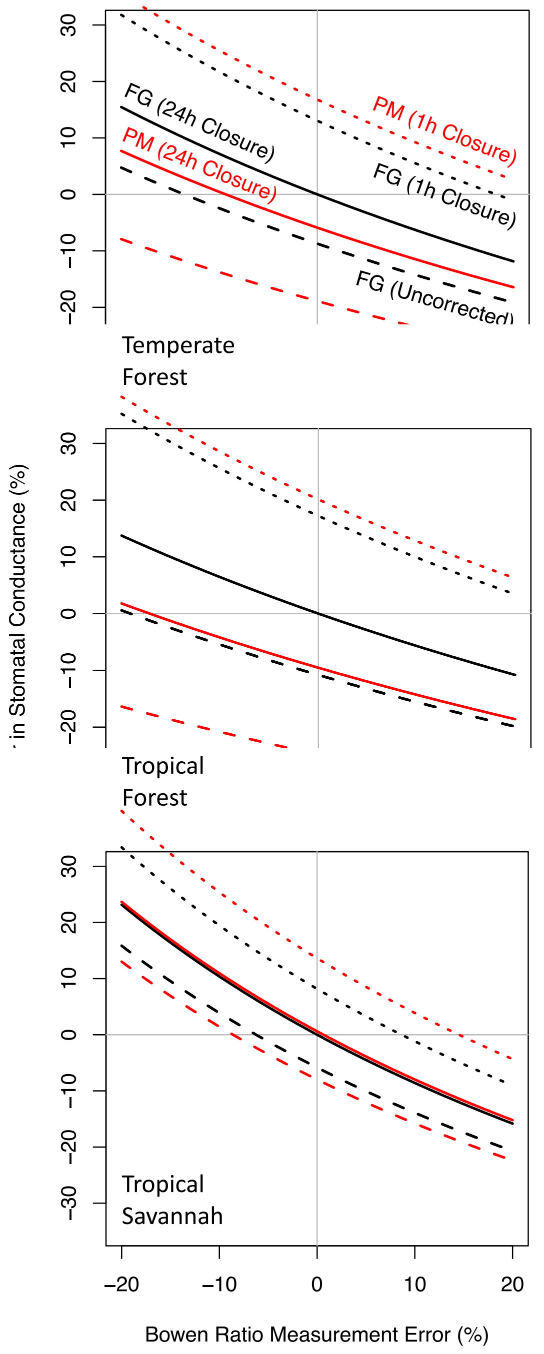
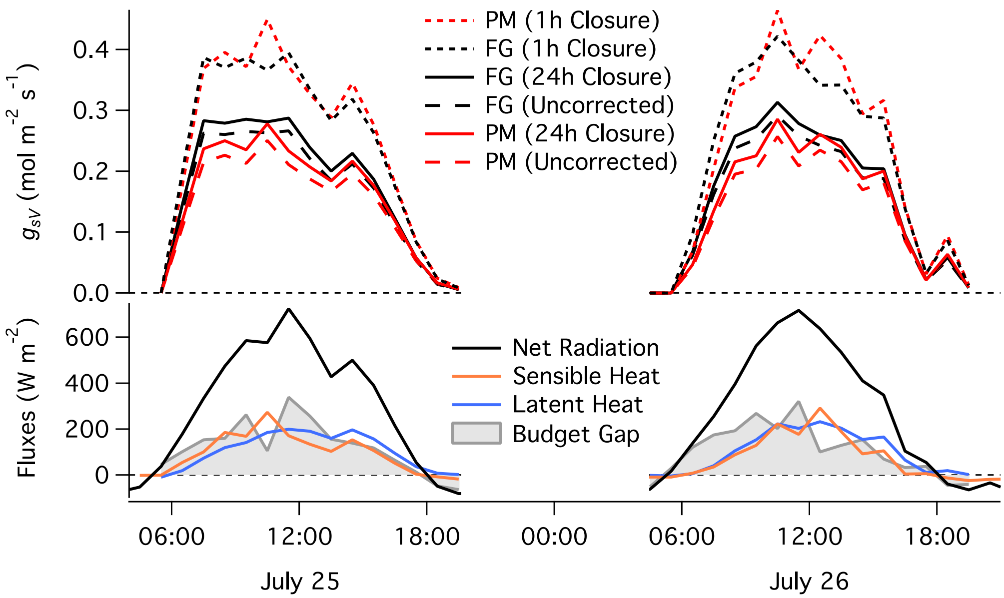


Figure 2. Percent error in canopy stomatal conductance versus percent error in the measured Bowen ratio, assuming that 40% of
390 **the energy budget gap is caused by the eddy fluxes, for the same ecosystem types and approaches as in Fig 1. Measurement bias in the Bowen ratio is not likely to be systematic across multiple sites, but could occur at particular sites due to instrument or data processing errors (see main text).**



395 **Figure 3. Top panel: hourly canopy stomatal conductance to water vapor calculated at Howland Forest (Hollinger, 1996) over two days in 2014 by the same approaches as in Fig. 1. Bottom panel: measured energy fluxes and budget gap.**