

# When does vapor pressure deficit drive or reduce evapotranspiration?

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## Key Points:

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**Abstract**

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**1 Introduction**

Changes to vapor pressure deficit (VPD) alter the atmospheric demand for water from the land surface. Traditionally, atmospheric scientists and hydrometeorologists generally think that an increase in atmospheric demand induces an increase in evapotranspiration (ET) (citations?). This possible misconception developed in part due to the proliferation of studies examining potential ET (PET) rather than estimates of ET itself (citations?). In contrast, plant physiologists know that stomata have evolved to optimally regulate the exchange of water and carbon, and tend to close in response to increased atmospheric dryness [???]. Therefore, an increase (decrease) in VPD may not correspond to an increase (decrease) in ET because stomatal closure (opening) can cancel the effects of shifts to atmospheric demand.

Quantifying the plant response to a perturbation to atmospheric VPD increases our understanding of land surface response to shifts in atmospheric conditions. If plant response reduces ET in response to atmospheric drying then soil moisture will be conserved. An increase in ET in response to atmospheric drying will reduce soil moisture, but contribute increased moistening to the atmosphere. Clearly, the sign and magnitude of land-surface responses drive the co-evolution of the atmosphere and land-surface at many timescales, from diurnal to interdecadal.

We hypothesize that for most plant types a common response to increase in VPD will actually be a decrease in ET. The exception would be plants such as crops that are evolved (or bred) to prioritize gross primary production (GPP) over water conservation. However, for all other plant types, our hypothesis calls into question the validity of PET-based drought metrics developed by hydrometeorologists and used extensively in operations [e.g. PDSI, P-PET, ??]. These metrics ignore the role of plants as gatekeepers for surface water loss to the atmosphere and have limited physical meaning for drought of vegetated land types. Additionally, plants evolved in arid climates should prioritize water conservation and we would expect a very negative ET response to increase in VPD. Therefore, vegetated locations most likely to experience droughts should show the strongest deviation between reality and a PET-based approximation.

← This section needs to be fleshed out, and I definitely need to add more citations

← more citations needed, including recent PET climate studies like Jack Scheff

In order to quantify plant response to perturbations to atmospheric demand for water, we apply a Penman-Monteith framework to eddy-covariance observations spanning various biomes and climates. Section 2 describes the data used, Section 3 derives the framework, Section 4 presents results, and Section 5 discusses conclusions. The goal of this paper is to use reasonable approximations as a tool to increase intuition for plant response to atmospheric drying. This intuition will aid interpretation of observations and full complexity climate models.

## 2 Data

We use data from FLUXNET2015. Because  $g_1$  coefficients [?] and  $uWUE$  were only both available for five plant functional types (PFTs - see Table 3), only 56 of the 77 sites were used. Figure 1 presents each site and its plant functional type.

## 3 Methods

The Penman-Monteith equation (hereafter PM) estimates ET as a function of atmospheric and land-surface variables:

$$ET = \frac{\Delta R + g_a \rho_a c_p VPD}{\Delta + \gamma(1 + \frac{g_a}{g_s})}, \quad (1)$$

where variable definitions are given in Table 1. ? developed a model for  $g_s$  by combining optimal photosynthesis theory with empirical approaches. The result for leaf-scale stomatal resistance was:

$$g_{l-s} = g_0 + 1.6 \left( 1 + \frac{g_1}{\sqrt{VPD}} \right) \frac{A}{c_s} \quad (2)$$

This can be adapted to an ecosystem-scale stomatal resistance by multiplying by leaf area index (LAI) and converting units to  $m s^{-1}$

$$g_s = LAI \frac{RT}{P} \left( g_0 + 1.6 \left( 1 + \frac{g_1}{\sqrt{VPD}} \right) \frac{A}{c_s} \right) \quad (3)$$

While Equation 3 can be used in PM, it will make analytical work with the function intractable because  $A$  is a function of ET itself. To remove dependence of ET on  $A$  we can use the semi-empirical results of ?. ? showed that:

← map needs to be improved - it's a placeholder for now

$$uWUE = \frac{GPP \cdot \sqrt{VPD}}{ET} \quad (4)$$

is relatively constant across time and space (within plant functional type). If, following ?, we approximate  $g_0$  as 0, we can use  $uWUE$  to remove  $A$  from  $g_s$  in a way that makes PM analytically tractable:

$$g_s = \frac{RT}{P} 1.6 \left( 1 + \frac{g_1}{\sqrt{VPD}} \right) \frac{uWUE ET}{c_s \sqrt{VPD}} \quad (5)$$

Note that  $uWUE$  is fit on the ecosystem scale in ? so GPP in 4 is really  $A \cdot LAI$ . This leads to the cancelation of LAI in addition to  $uWUE$  in Equation 3. Plugging Equation 5 into Equation 1 and rearranging gives:

$$ET = \frac{\Delta R + \frac{g_a P}{T} \left( \frac{c_p VPD}{R_{air}} - \frac{\gamma c_s \sqrt{VPD}}{R * 1.6 uWUE (1 + \frac{g_1}{\sqrt{VPD}})} \right)}{\Delta + \gamma} \quad (6)$$

Given FLUXNET data described in Section 2, every term in Equation 6 is known. However, our sampling of sites and our focus on the growing season may introduce some deviations of  $uWUE$  from those observed in ?. Also, we wish to include some measure of uncertainty in our analysis to guide if our many assumptions and simplifications are reasonable. To account for both mean deviations of  $uWUE$  and uncertainty, we will introduce an uncertainty parameter  $\sigma$  modifying  $uWUE$ :

$$ET = \frac{\Delta R + \frac{g_a P}{T} \left( \frac{c_p VPD}{R_{air}} - \frac{\gamma c_s \sqrt{VPD}}{R * 1.6 \sigma uWUE (1 + \frac{g_1}{\sqrt{VPD}})} \right)}{\Delta + \gamma} \quad (7)$$

Now, from each FLUXNET observation we can calculate single value of  $\sigma$ :

$$\sigma = - \frac{g_a \gamma c_s \sqrt{VPD} L_v P}{(ET (\Delta + \gamma) - \Delta R - g_a \rho_a c_p VPD) 1.6 R T uWUE (1 + \frac{g_1}{\sqrt{VPD}})} \quad (8)$$

The variability of  $\sigma$  across sites and time will provides some measure of uncertainty in our model, assumptions, as well as the fluxnet observations themselves. Mean shifts in  $\sigma$  can be attributed to differences in out sampling from those used to calculat  $uWUE$  in ?. The influence of  $\sigma$  will propagate through any uncertainty to our derivative of Equation 8:

$$\frac{\partial ET}{\partial VPD} = \frac{2 g_a P}{T(\Delta + \gamma)} \left( \frac{c_p}{R_{air}} - \frac{\gamma c_s}{1.6 R^* \sigma uWUE} \left( \frac{2g_1 + \sqrt{VPD}}{2(g_1 + \sqrt{VPD})^2} \right) \right) \quad (9)$$

With Equation 9 we have provided an analytical framework for ecosystem response to atmospheric demand perturbations. There are a few subtleties to taking the derivative in Equation 9:  $\Delta$  ( $\frac{de_s}{dT}$ ) and  $VPD$  are functionally related, so while taking the derivative we evaluate  $\frac{\partial ET}{\partial VPD} = \frac{\partial ET}{\partial e_s} \frac{\partial e_s}{\partial VPD} \Big|_{RH \text{ fixed}} + \frac{\partial ET}{\partial RH} \frac{\partial RH}{\partial VPD} \Big|_{e_s \text{ fixed}}$ .  $RH$  and  $e_s$  are assumed to be approximately orthogonal.

The  $VPD$  dependence in Equation 9 is a little opaque. However, mean  $VPD$  is 1062 Pa, so  $\sqrt{VPD}$  is 32.6 Pa<sup>1/2</sup>, which is much less than  $g_1$  (with the exception of ENF; Table 3). So a series expansion in the limit  $\frac{\sqrt{VPD}}{g_1} \rightarrow 0$  gives an approximation which makes the functional form more clear:

$$\frac{\partial ET}{\partial VPD} \approx \frac{g_a P}{T(\Delta + \gamma)} \left( \frac{c_p}{R_{air}} - \frac{\gamma c_s}{1.6 R^* \sigma uWUE} \left( \frac{1}{g_1} - \frac{3\sqrt{VPD}}{2g_1^2} + \frac{2\sqrt{VPD}^2}{g_1^3} - \frac{5\sqrt{VPD}^3}{2g_1^4} + O\left(\left(\frac{\sqrt{VPD}}{g_1}\right)^4\right) \right) \right) \quad (10)$$

← Should I even include the series expansion?

One final comment on our derivation which will not be discussed further but is relevant for future analysis: if we approximate  $c_s$  at a global mean CO<sub>2</sub> concentration, then the RHS of Equation 6 is fully defined using commonly available weather station data and the constants published in ???. This then begs the question, why use PET for drought metrics in vegetated areas? It appears a much more physically realistic estimate of ET can be had with the same information required to calculate PET.

We restrict our analysis to the daytime (sensible heat > 5 W m<sup>-1</sup> and shortwave radiation > 50 W m<sup>-2</sup>) when there is no precipitation and the plants are growing (GPP > 10% of the 95th percentile). Also, because some sites use half hourly data but some use hourly, we aggregate all data to hourly averages. Only times with good quality control flags are used.

## 4 Results

By construction, the variability in the  $\sigma$  term (Equation ??) contains all model and observational uncertainties. For an observation that perfectly matches our model and assumptions  $\sigma$  will be one. Therefore, if for our assumptions and framework to be reasonable  $\sigma$  should be  $O(1)$ . Figure 2 presents the histogram of calculated  $\sigma$ s with outliers (lowest and

← This GPP thresholding was used by Changjie, do you know if there is a citation for it? Otherwise it seems like something a reviewer would have issue with as it is arbitray

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**Table 1.** Definition of symbols and variables

Variable	Description	Units
$e_s$	saturation vapor pressure	Pa
$T$	temperature	K
$\Delta$	$\frac{\partial e_s}{\partial T}$	Pa K <sup>-1</sup>
$R$	net radiation at land surface minus ground heat flux	W m <sup>-2</sup>
$g_a$	aerodynamic conductance	m s <sup>-1</sup>
$\rho_a$	air density	kg m <sup>-3</sup>
$c_p$	specific heat capacity of air at constant pressure	J K <sup>-1</sup> kg <sup>-1</sup>
$VPD$	vapor pressure deficit	Pa
$\gamma$	psychrometric constant	Pa K <sup>-1</sup>
$g_s$	stomatal conductance	m s <sup>-1</sup>
$g_{l-s}$	leaf-scale stomatal conductance	mol m <sup>-2</sup> s <sup>-1</sup>
$R^*$	universal gas constant	J mol <sup>-1</sup> K <sup>-1</sup>
$LAI$	leaf area index	-
$\sigma$	uncertainty parameter	-
$c_s$	CO <sub>2</sub> concentration	$\mu$ mol CO <sub>2</sub> mol <sup>-1</sup> air

<sup>a</sup>Footnote text here.

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**Table 2.** Plant functional types, their abbreviation, Medlyn coefficient [from ?], and uWfUE [from ?].

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Note that units are converted such that the quantities fit into Equations 1-8 with the variables in Table 1.

Abbreviation	PFT	$g_1$ (Pa <sup>0.5</sup> )	uWUE ( $\mu$ -mol [C] Pa <sup>0.5</sup> J <sup>-1</sup> [ET])
CRO	cropland	183.1	3.80
CSH	closed shrub	148.6	2.18
DBF	deciduous broadleaf forest	140.7	3.12
ENF	evergreen needleleaf forest	74.3	3.30
GRA	grassland (C3)	166.0	2.68

<sup>a</sup>Footnote text here.

highest 5% percent) and nonphysical values ( $\sigma < 0$ .) removed. All remaining  $\sigma$  values are  $O(1)$  which provides confidence in model framework.

An additional concern is that the  $\sigma$  term may in fact be some function of  $VPD$ , in which case the dependence would need to be accounted for when taking the derivative. Figure 3 plots the joint distribution of  $\sigma$  and  $VPD$ , and shows that  $\sigma$  is very weakly a function of  $VPD$ . Given this weak dependence, we argue that Equation 9 is a valid approximation for ET response to  $VPD$ .

Before calculating the sensitivity of ET to  $VPD$ , it is useful to consider the functional form of Equation 9. There are three terms: a scaling term for the full expression we will call Term 1 ( $\frac{g_a P}{T(\Delta+\gamma)}$ ), a relatively constant offset we will call Term 2 ( $\frac{c_p}{R_{air}}$ ), and a variable term we will call Term 3 ( $\frac{\gamma c_s}{1.6 R \bar{u} WUE} \left( \frac{2g_1 + \sqrt{VPD}}{2(g_1 + \sqrt{VPD})^2} \right)$ ). All variables are positive, so the relative magnitude between Term 2 and Term 3 will determine the sign of the derivative, while Term 1 will scale the expression larger or smaller.

Term 2 minus Term 3's role in determining the sign of the sensitivity of ET to  $VPD$  makes it crucial for answering our question "When does  $VPD$  drive or reduce ET?" Exploring these terms more,  $c_s$  and  $\gamma$  variability is relatively less than  $\sigma$  and  $VPD$  variability, so variability within PFT will be solely determined by  $\sigma$  and  $VPD$ . If we fix uncertainty  $\sigma$  at PFT averages, then Term 2 minus Term 3 is just a function of  $VPD$ . We can further determine a  $VPD_{crit}$  where  $\frac{\partial ET}{\partial VPD} = 0$ :

$$VPD_{crit} = \frac{R_{air}}{4c_p} \left( \frac{\gamma c_s}{1.6 R \bar{\sigma} u WUE} + \sqrt{\frac{\gamma c_s}{1.6 R \bar{\sigma} u WUE} \left( \frac{\gamma c_s}{1.6 R \bar{\sigma} u WUE} + 8g_1 \frac{c_p}{R_{air}} \right)} - 4g_1 \frac{c_p}{R_{air}} \right) \quad (11)$$

Values of  $VPD_{crit}$  as a function of PFT are shown in Table 4. For any values of  $VPD$  less than  $VPD_{crit}$ ,  $\frac{\partial ET}{\partial VPD}$  will be negative, and for values of  $VPD$  greater than  $VPD_{crit}$ ,  $\frac{\partial ET}{\partial VPD}$  will be positive.

Figure 4 provides greater description for how (Term 2 - Term 3) varies with  $VPD$ , as a function of PFT. Equation 10 aids interpretation of Figure 4. Larger  $uWUE \cdot \bar{\sigma}$ , and  $g_1$  shift the leading-order constant term ( $\frac{1}{g_1}$ ) towards smaller values, and (Term 2 - Term 3) towards positive values.  $uWUE$  and  $g_1$  are both water-use efficiency type constants. Higher values correspond to plants that are more willing to spend water on primary production and less evolved to conserve water. Figure 4 confirms our physical intuition: CROs are the least wa-

**Table 3.** Values of  $VPD_{crit}$ , where  $\frac{\partial ET}{\partial VPD} = 0$ , evaluated at PFT average values for  $R_{air}$ ,  $\sigma$ ,  $\gamma$ , and  $c_s$ . For reference, these values are also provided. For values of  $VPD$  less than  $VPD_{crit}$ ,  $\frac{\partial ET}{\partial VPD}$  will be negative, and for values of  $VPD$  greater than  $VPD_{crit}$ ,  $\frac{\partial ET}{\partial VPD}$  will be positive.

PFT	$R_{air}$	$c_s$ (ppm)	$\gamma$	$\bar{\sigma}$	$\bar{\sigma} \cdot uWUE$	$VPD_{crit}$ (Pa)
CRO	288.680920	372.567691	65.351523	0.684394	2.602873	<b>133.165438</b>
CSH	289.067152	381.593622	67.613172	0.997224	2.175278	<b>4439.564212</b>
DBF	288.624437	377.449849	63.421812	0.881061	2.746393	<b>888.773243</b>
ENF	288.183849	377.676463	61.559242	1.217892	4.015362	<b>978.084845</b>
GRA	288.425651	377.264645	61.598768	0.850869	2.281074	<b>1141.630778</b>

<sup>a</sup>Footnote text here.

ter conservative so have the smallest constant portion of Term 3, while CSH are the most water conservative and have the largest constant portion of Term 3. For the VPD-dependent terms in Equation 10, differences in  $g_1$  between PFTs exert a greater influence than difference  $uWUE$ , as the power of  $g_1$  increases. Increasing  $uWUE$  and  $g_1$  decreases the VPD-dependence, but  $g_1$  has the bigger effect due to its increasing powers. ENF ( $g_1 = 74.31$ ) has by far the largest VPD dependence of response, while CRO ( $g_1 = 183.1$ ) has the smallest VPD dependence.

Figure 4b shows the location of the minima of ET, as a function of  $\sigma$  and  $VPD$ . For any  $\sigma$  or VPD less (more) than these curves, Term 2 - Term 3 will be negative (positive). It is clear that the portion of VPD observations below/above these curves will be a strong function of  $\sigma$ . However, we can see some general trends. For CSH,  $\frac{\partial ET}{\partial VPD}$  should be negative for the vast majority of observed  $\sigma$  and VPD. The fraction of positive  $\frac{\partial ET}{\partial VPD}$  appears to be more even for ENF, GRA, and DBF, and we might expect a greater frequency of positive  $\frac{\partial ET}{\partial VPD}$  for CRO.

While the above discussion of the sign of  $\frac{\partial ET}{\partial VPD}$  is important to answer our research question, the magnitude of  $\frac{\partial ET}{\partial VPD}$  will also impact statistics of  $\frac{\partial ET}{\partial VPD}$  and the importance of VPD variability for ET variability. So we will more closely examine the scaling Term 1:  $\frac{P}{T} \propto \rho$ , so this should vary little relative to aerodynamic conductance and  $\Delta$ .  $\gamma$  should also be relatively constant, so Term 1 should be primarily a function of aerodynamic conductance and temperature (through the function  $\Delta$ ). This makes sense, as aerodynamic conductance



represents how efficiently response at the surface is communicated to the atmosphere. As it increases, any plant response will be communicated more strongly to the atmosphere (and vice-versa).

$\Delta$ 's presence in the scaling term also matches physical intuition. Evaporative cooling will dampen the ability of the atmosphere to take more moisture, because  $e_s$  decreases with temperature. The decrease in  $e_s$  is proportional to  $\Delta$  ( $\delta e_s = \Delta \delta T$ ). So as  $\Delta$  increases, you will get a larger damping of ET due to evaporative cooling. The functional form of  $\Delta$  will be the same across PFT, but the temperature range may vary slightly. In contrast, aerodynamic conductance will vary strongly with PFT due to the importance of surface roughness. So most of the differences in scaling between PFT should be in the aerodynamic conductance term. One interesting side note is that the coefficient of variability for both aerodynamic conductance and Term 1 is relatively constant across PFT, suggesting that the influence of aerodynamic conductance on the relative (to the PFT mean) variability of Term 1 is approximately similar across PFT.

Figure 5A shows Term 1 normalized by mean aerodynamic conductance (calculated for each plant functional type), and confirms that much of the relative variability of Term 1 is contained in the aerodynamic conductance variability. Generally,  $T$  has less of a role. Additionally, the impact of  $T$  on the relative variability increases with increasing aerodynamic conductance.

While the relative variability of Term 1 is similar across PFT, the absolute value of Term 1 varies strongly across PFT. Figure 5B shows Term 1 evaluated with the mean aerodynamic conductance for each PFT, and at the range of observed temperatures for each PFT. As expected, for the tree PFTs (DBF, ENF) Term 1 is much larger and the temperature dependence is much stronger. Systematic differences in observed temperatures also cause differences in the average magnitude of Term 1. For example, ENF experiences on average colder temperatures and is thus more likely to have a larger scaling term. Additionally, because the variability of aerodynamic conductance increases proportionally to the mean, the spread of Term 1 due to aerodynamic conductance variability will be larger for the tree PFTs, although this is not shown for simplicity. To summarize, the variability of Term 1 within each PFT will look like Figure 5A for each PFT, but the scale of the y-axis will increase or decrease according to mean aerodynamic conductance observed in Figure 5B.

← plot every PFT and show they collapse onto the same curve? - might just be too messy though

#### 4.1 Bulk statistics of $\frac{\partial ET}{\partial VPD}$

Table 3 confirms our expectations for PFT behavior of  $\frac{\partial ET}{\partial VPD}$ . For all PFTs except for CRO, average  $\frac{\partial ET}{\partial VPD}$  is less than zero. However,  $\frac{\partial ET}{\partial VPD}$  evaluated at the average of all variables (e.g.  $\sigma$ ,  $T$ ,  $c_s$ ,  $VPD$ ) is only negative for CSH and GRA. And, DBF in addition to CRO experiences  $\frac{\partial ET}{\partial VPD} < 0$  less than half the time. These observations highlight the effect of the nonlinear function in Figure 4:  $\frac{\partial ET}{\partial VPD}$  has a much steeper slope when the function is negative, and is thus more likely to be large.

The units of  $\frac{\partial ET}{\partial VPD}$  make it difficult to interpret if  $VPD$  is even a meaningful contributor to  $ET$ 's variability. To better understand  $VPD$ 's contribution, we normalize  $\frac{\partial ET}{\partial VPD}$  with  $VPD$ 's standard deviation to define a (linearized) relative change in  $ET$  for variations in  $VPD$ .  $VPD$ 's contribution to  $ET$ 's variability ranges between 30 - 40  $W m^{-2}$  for all PFTs except for CSH, which is about 100  $W m^{-2}$ . Another meaningful comparison is to  $\frac{\partial ET}{\partial R}$ .  $std(R)$ , as net radiation is generally the driver of  $ET$  (cite joe berry here). For all PFTs except for CSH  $VPD$  contributes between 30 - 40 % of  $R$ 's contribution to variability. For CSH the portion is much larger, about 88 %.  $VPD$ 's variability is certainly a primary contributor to  $ET$ 's variability.

So far, idealized plots and statistics have illuminated the form of  $\frac{\partial ET}{\partial VPD}$  and how it varies with PFT. Large mean  $\sigma$  and  $uWUE$  shifts CRO and DBF towards positive  $\frac{\partial ET}{\partial VPD}$ . However, the strongly nonlinear function of  $\frac{\partial ET}{\partial VPD}$  at  $\frac{\partial ET}{\partial VPD} < 0$  pushes  $\frac{\partial ET}{\partial VPD}$  negative for DBF (it does not do this for CRO because of CRO's high  $g_1$ ). ENF's low  $g_1$  value increases the dependence of  $\frac{\partial ET}{\partial VPD}$  on  $VPD$ , and makes the function more strongly nonlinear. This has the side effect of pushing  $\frac{\partial ET}{\partial VPD}$  negative further than other PFTs for a given fraction  $\frac{\partial ET}{\partial VPD} < 0$  and magnitude  $\frac{\partial ET}{\partial VPD}(T, \dots, VPD)$ . GRA shows the opposite behavior; a relatively high  $g_1$  makes the function more linear, decreasing the magnitude of  $-\frac{\partial ET}{\partial VPD}$  for a given [large] fraction  $\frac{\partial ET}{\partial VPD} < 0$  and negative  $\frac{\partial ET}{\partial VPD}(T, \dots, VPD)$  (although aerodynamic conductance and Term 1 also probably have a role in this). Finally, low  $uWUE$  of CSH pushes to toward by far the lowest values  $\frac{\partial ET}{\partial VPD}$  (Figure 4). Variability in  $VPD$  accounts for the largest about of  $ET$  variability for CSH. For the other PFTs,  $VPD$  contributes less to  $ET$  variability, but still represents about 15-20 % of  $R$ 's contributions to  $ET$  variability.

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**Table 4.** Statistics of  $\frac{\partial ET}{\partial VPD}$  as a function of PFT.

PFT	$\overline{\frac{\partial ET}{\partial VPD}}$	$\frac{\partial ET}{\partial VPD}(\overline{env})$	$\frac{\partial ET}{\partial VPD}(\overline{env}) * \text{std}(VPD)$	$\frac{\frac{\partial ET}{\partial VPD}(\overline{env}) * \text{std}(VPD)}{\frac{\partial ET}{\partial R}(\overline{env}) * \text{std}(R)}$	fraction $\frac{\partial ET}{\partial VPD} < 0$ .
CRO	0.000853	0.026241	37.05	0.41	0.473311
CSH	-0.108234	-0.091526	101.72	0.88	0.931660
DBF	-0.012727	0.013794	39.47	0.33	0.461674
ENF	-0.034087	0.000706	33.22	0.30	0.534425
GRA	-0.019637	-0.000921	33.60	0.35	0.631735

<sup>a</sup>Footnote text here.

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**4.2 Testing the theory - does the data match the model?**

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So far we have developed a theory for  $\frac{\partial ET}{\partial VPD}$ 's behavior. In particular, we determined a critical threshold  $VPD_{crit}$  for  $\frac{\partial ET}{\partial VPD}$ . For  $VPD < VPD_{crit}$ ,  $\frac{\partial ET}{\partial VPD} < 0$ , and for  $VPD > VPD_{crit}$ ,  $\frac{\partial ET}{\partial VPD} > 0$ . This  $VPD_{crit}$  is only a function of PFT. However, many assumptions, including constant uWUE, were made in deriving  $VPD_{crit}$ . So, we need to test if our theory and  $VPD_{crit}$  hold up in the face of uncertainty.

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Figure 6 presents calculated  $\frac{\partial ET}{\partial VPD}$  where, unless otherwise noted, all variables in Equation 9 are allowed to vary, including uncertainty. Each column is a different quantity related to  $\frac{\partial ET}{\partial VPD}$ , and each row is a different PFT.

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The full observations generally confirm expectations from Section 4. CRO has the most positive values of  $\frac{\partial ET}{\partial VPD}$ ,  $\frac{\partial ET}{\partial VPD}$  is almost always negative for CSH, and response depends more with the environmental conditions for the other PFTs (especially ENF). Through the columns of Figure 6 we can see the impact of  $\sigma$  and  $g_a$  on the variability of  $\frac{\partial ET}{\partial VPD}$ .  $g_a$ 's scaling (included in columns 1 and 3) alters the magnitude considerably.  $\sigma$  variability (included in columns 1 and 2) adds a lot of additional noise to the signal of  $\frac{\partial ET}{\partial VPD}$ , which is slightly undesirable given  $\sigma$ 's role in representing model and observational uncertainty. However, the general story with the noise appears to match the cleaner signal when  $\sigma$  is held constant and  $VPD_{crit}$  is clearly visible. One exception is possibly with GRA, for which uncertainty represented in  $\sigma$  is high and causes the full complexity plots (Columns 1 and 2) to not match well with  $\sigma$  held fixed (Columns 3 and 4).

For ENF and GRA  $VPD_{crit}$  does not appear to be only a function of  $\sigma$  (most observable in Column 4). It turns out that the site to site variability in  $\gamma$  causes  $VPD_{crit}$  to vary, which is not discussed in the previous section. The impact is observable in both ENF and GRA, but especially for ENF which has a larger  $\frac{\partial^2 ET}{\partial^2 VPD}$  than the other PFTs.

In general the full complexity plots of  $\frac{\partial ET}{\partial VPD}$  match our expectations, even with the large sensitivity to  $\sigma$  measures of uncertainty observed in Figure 4. Our  $\sigma$ -based method of uncertainty propagation blurs the idealized expectations the most for GRA, and also has a considerable effect for CRO. We therefore have the most confidence in our conclusion based on Equation 9 for PFTS CSH, DBF, and ENF, as the full complexity plots with uncertainty included closely match the story when  $\sigma$  is held fixed. \*\*see somewhat preferred alternate figure 7 .

## 5 Conclusions

The idealized representation of ET used here is successful in developing intuition for how ET responds to changes in  $VPD$ . This intuition will aid the community in interpreting observations and output from sophisticated full complexity climate models.

The idealized framework leads to the following general conclusions:

- Aerodynamic resistance plays an important role of scaling  $\frac{\partial ET}{\partial VPD}$ . This is a leading order effect for observing higher magnitude responses in DBF and ENF.
- In general, CSH has the most negative (i.e. ET reduced) response to increases in  $VPD$  (atmospheric drying). So CSH plants will almost always try and conserve water, effectively reducing ET with dry atmospheric perturbation.
- Additionally for CSH,  $VPD$  variability contributes the most to  $ET$  variability.
- CRO has the most positive response (i.e. ET increased) in response to increases in  $VPD$ . This is consistent with CROs that may be evolved or bred to thrive in non-water-limited environments.
- The response is more a function of the environment for DBF, ENF, and GRA. Because as  $VPD$  increases the response is more likely to be positive, if RH is fixed then the response will be more likely to be positive at warmer T, or if T is fixed the response is more likely to be positive with decreasing RH.
- ENF has the strongest dependence on environmental conditions due to its small  $g_l$ .

← I think I like the alternate plot much more as thinking in terms of T and RH is easier, and it makes the story easier to see at relatively low temperatures. However, I used the other plot because Fig 5 does not discuss things in terms of temperature, as this would make things more complicated (adding another dimension). I could just include both versions of figure 6 though (using figure 6a as a bridge to figure 6b)

← also need to flesh this section out

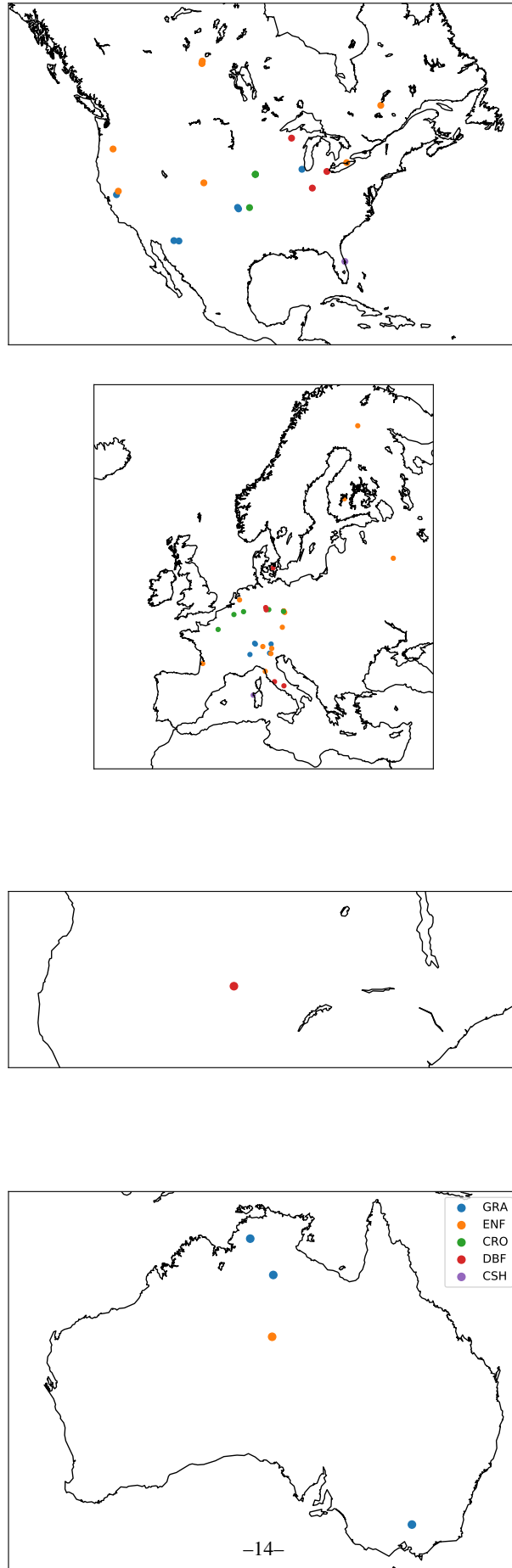
- Model and observational uncertainty is highest for GRA and CRO, so conclusions about those PFTs should be tempered.
- However, inclusion of uncertainty doesn't alter conclusions about DBF, ENF, and CSH.

The intuition developed using this framework can be used to understand how the land surface will respond and contribute to changes in the environment. Additionally, Equation 6 gives provides an estimate of ET that requires no additional information beyond that required to calculate PET. Given that for all PFTs, with the exception of CRO, we found a high frequency and magnitude of negative  $\frac{\partial ET}{\partial VPD}$ , PET is a physically unrealistic representation of ET for vegetated surfaces and PET-based drought metrics are not useful. We advocate for drought metrics using Equation 6 instead of PET.

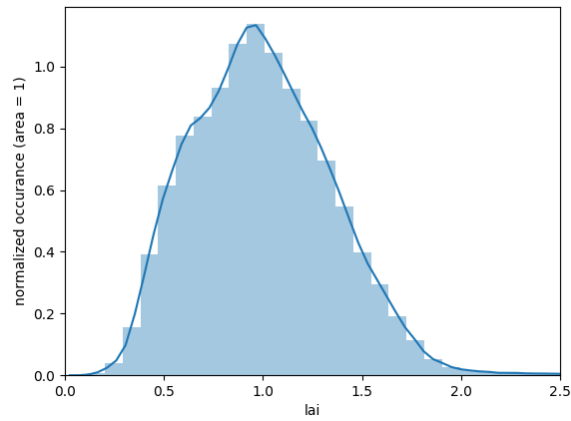
### Acknowledgments

This work used eddy covariance data acquired and shared by the FLUXNET community, including these networks: AmeriFlux, AfriFlux, AsiaFlux, CarboAfrica, CarboEuropeIP, CarboItaly, CarboMont, ChinaFlux, Fluxnet-Canada, GreenGrass, ICOS, KoFlux, LBA, NECC, OzFlux-TERN, TCOS-Siberia, and USCCC. The ERA-Interim reanalysis data are provided by ECMWF and processed by LSCE. The FLUXNET eddy covariance data processing and harmonization was carried out by the European Fluxes Database Cluster, AmeriFlux Management Project, and Fluxdata project of FLUXNET, with the support of CDIAC and ICOS Ecosystem Thematic Center, and the OzFlux, ChinaFlux and AsiaFlux offices.

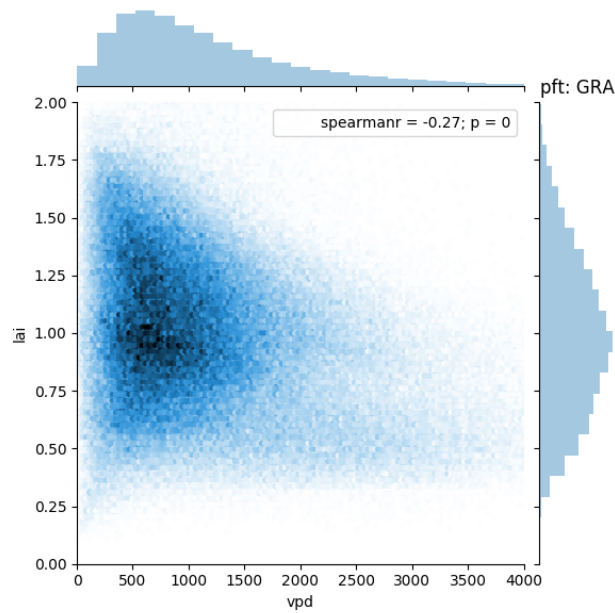
### References



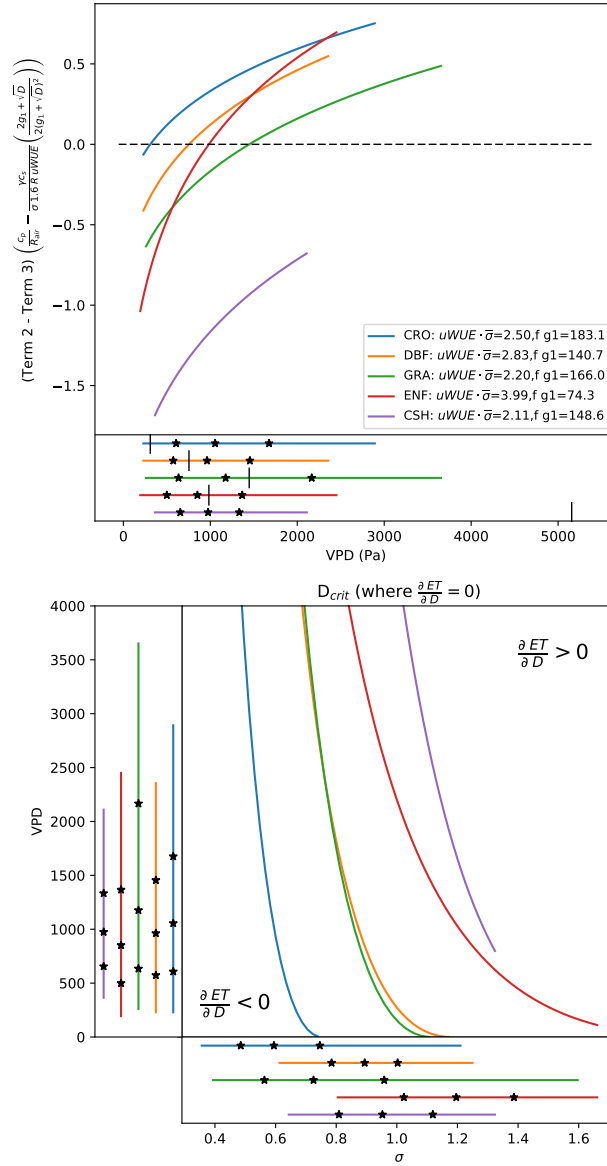
**Figure 1.** Plant functional type and location of sites used in analysis. \*\*\*This is just a placeholder for now and needs to be improved i.e. with lat lon, better placement of continents, etc.)\*\*\*



**Figure 2.** Histogram of  $\sigma$  values calculated for each site and time according to Equation ???. The lowest and highest 5% are removed as outliers, as well as any values below 0. The curve is normalized such that its area is 1.



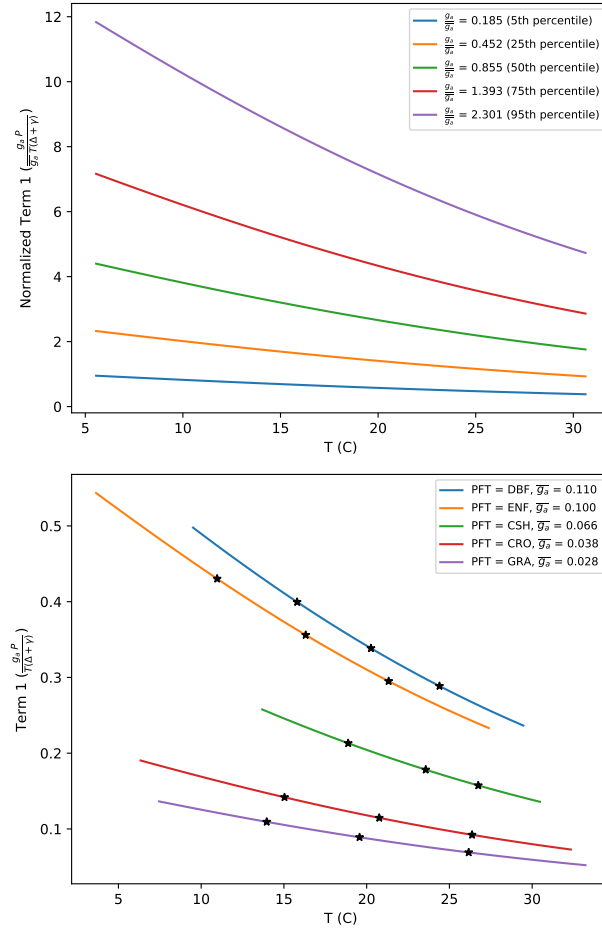
**Figure 3.** The joint distribution of  $VPD$  and  $\sigma$ .  $\sigma$  has only a weak dependence on  $VPD$ . \*\*\*This plot could probably benefit from a box plot of site specific correlations, because some sites do have stronger dependence than others. Note also Figs 3 and 2 can probably be combined because this figure shows  $\sigma$ 's histogram.\*\*\*



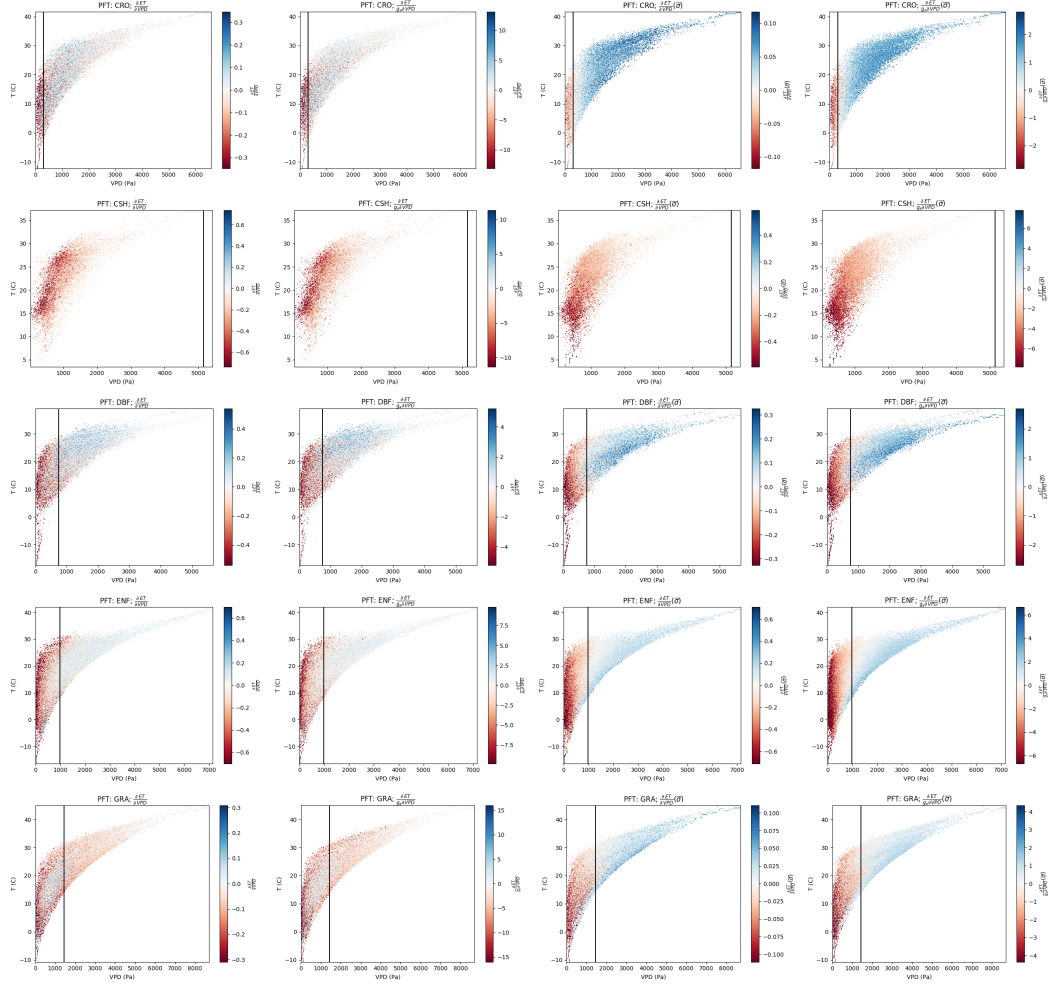
**Figure 4.** Sources of variability for Term 2 - Term 3. Top: Term 2 - Term 3 as a function of VPD, with  $\sigma$  held fixed at PFT averages. The observed range of VPD for each PFT is also shown below the x-axis. Line extent corresponds to 5th and 95th percentiles, while stars denote the location of the 25th, 50th, and 75th percentiles.

Bottom: The location of the minima of ET, as a function of VPD and  $\sigma$ . Lines and stars denote the distribution of VPD and  $\sigma$  next to each axis, following the same percentiles as above.

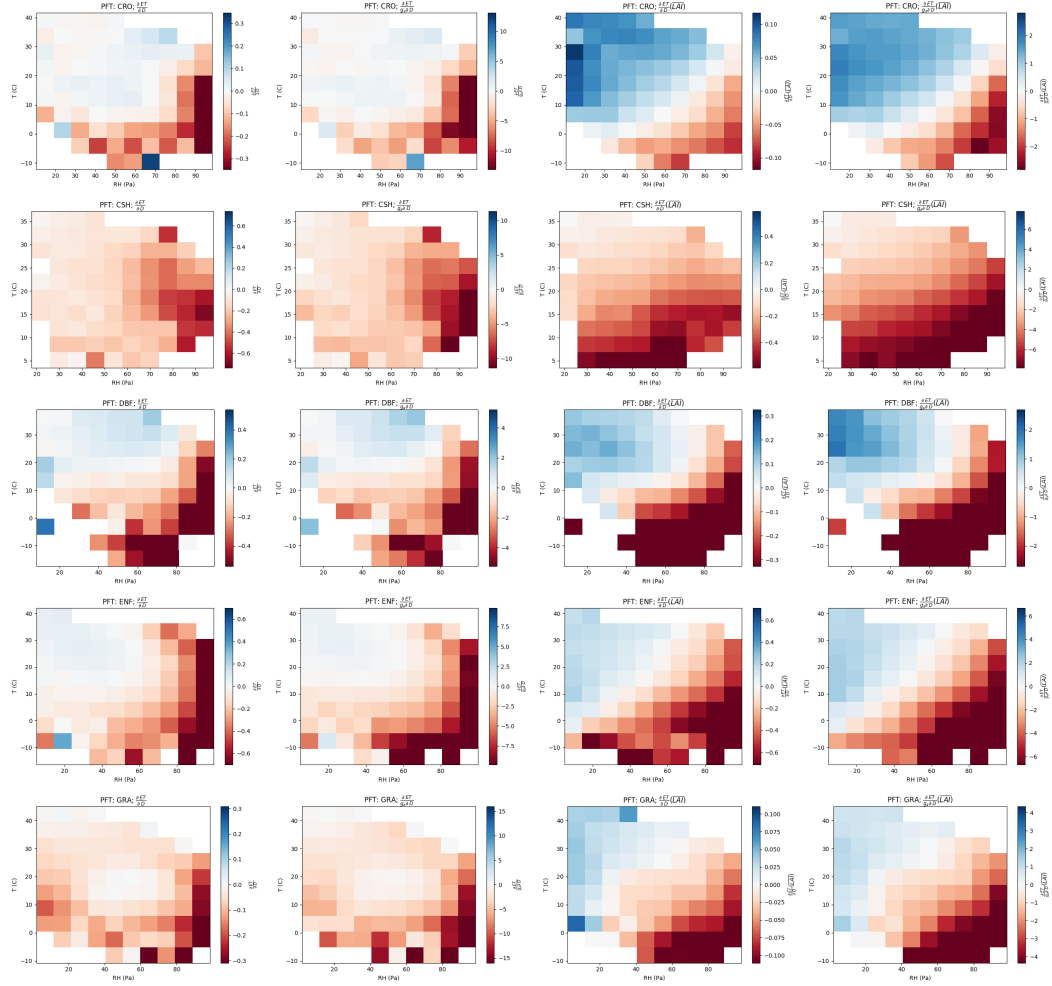




**Figure 5.** Primary sources of variability for Term 1. A) Variability within each PFT: Term 1 normalized by mean  $g_a$  for each PFT. B) Variability between each PFT: Term 1 evaluated at mean  $g_a$  for each PFT. Temperature range is 5-95th percentile for each PFT. Additionally, stars denote the location of the 25th, 50th, and 75th percentiles.



273 **Figure 6.** Scatter plots of  $\frac{\partial ET}{\partial VPD}$ . Each row is a different PFT, and each column is a different quantity  
 274 related to  $\frac{\partial ET}{\partial VPD}$ , as labeled: Column 1 -  $\frac{\partial ET}{\partial VPD}$ ; Column 2 -  $\frac{\partial ET}{\partial VPD}$  normalized by  $g_a$ ; Column 3 -  $\frac{\partial ET}{\partial VPD}$   
 275 with  $\sigma$  held fixed at PFT average; and Column 4 -  $\frac{\partial ET}{\partial VPD}$  normalized by  $g_a$  and with  $\sigma$  held fixed. For ref-  
 276 erence, lines corresponding to RH = 20% and RH = 90 % are drawn. Please note differences in the colorbar  
 277 scale. \*\*\*see alternate (or additional) plot below.\*\*\*



285 **Figure 7.** \*\*\*\*alternate Fig 06\*\*\*\* Scatter plots of  $\frac{\partial ET}{\partial VPD}$ . Each row is a different PFT, and each column  
 286 is a different quantity related to  $\frac{\partial ET}{\partial VPD}$ , as labeled. If I end up using this, I could also draw on the curve of  
 287  $VPD_{crit}$  with  $\frac{LAI}{LAI_{ref}}$ .