When does vapor pressure deficit drive or reduce evapotranspiration?

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Does VPD drive or reduce ET? - atmospheric demand perspective

Increase in VPD (**increase in atmospheric demand**) drives an **increase in ET**.

$$VPD = (1 - RH) \cdot e_s(T)$$

Does VPD drive or reduce ET? - atmospheric demand perspective

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Does VPD drive or reduce ET? - plant response perspective

However, plants evolved to use stomata to conserve and regulate water use. So **stomata closure** in response to increases in VPD may **decrease ET**.

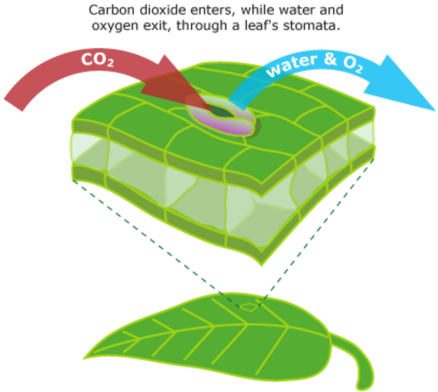

Figure 1: from evolution.berkeley.edu

The question is, which effect dominates with an increase in VPD: plant response (decrease in ET) or atmospheric demand (increase in ET)?

- Prior expectation:
  - Should be a function of plant type: plants that are evolved to conserve water will tend to reduce ET with increases in VPD.
  - But the environment still matters: if the atmosphere dries enough, plant water conservation strategies will reach their limit and atmospheric demand will drive increases in ET with increases in VPD.

Develop a theory to quantify VPD effects

- The goal is to simply the problem (increase transparency) while still capturing the leading order behavior the system.
  - While simplifying the system aids intrinsic understanding, simplifying assumptions sacrifice physical realism.
- Because we run the risk of over-simplification, we will use FLUXNET2015 data to test how well our theory matches the data.

Simple theory - start with Penman-Monteith

We can use Penman-Monteith (PM) to estimate ET:

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

Problem: g_s (stomatal conductance) is a function of photosynthesis, which is a function of ET itself. So ET in Penman-Monteith is really an implicit function of itself and we cannot take derivatives!

Use physically reasonable assumptions remove implicit dependence

Apply a constant uWUE assumption (conserved within plant type; see Zhou et al. 2016):

$$uWUE = \frac{GPP \cdot \sqrt{VPD}}{ET},$$

To derive a new form of Penman-Monteith without implicit ET dependence:

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

Now just take $\frac{\partial \; ET}{\partial \; VPD}$

With our new form of Penman-Monteith we can now take derivatives, giving:

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

In the interest of time, we will just focus in the "sign" term:

$$\text{sign} \left[\frac{\partial \; ET}{\partial \; VPD} \right] = \text{sign} \left[\left(\frac{c_p}{R_{air}} - \frac{\gamma c_s}{1.6 \; R * \quad \text{uWUE}} \left(\frac{2 g_1 + \sqrt{VPD}}{2(g_1 + \sqrt{VPD})^2} \right) \right) \right]$$

Consequences of theory - "sign" term

$$\frac{\partial\, ET}{\partial\, VPD} = \text{scaling} \cdot \left(\frac{\boldsymbol{c_p}}{R_{air}} - \frac{\gamma c_s}{1.6\ \boldsymbol{R*}\ \text{uWUE}} \left(\frac{2g_1 + \sqrt{VPD}}{2(g_1 + \sqrt{VPD})^2} \right) \right)$$

- $\boldsymbol{c_p}$ and $\boldsymbol{R*}$ are constants

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$$\frac{\partial\, ET}{\partial\, VPD} = \text{scaling} \cdot \left(\frac{c_p}{\boldsymbol{R_{air}}} - \frac{\gamma \boldsymbol{c_s}}{1.6\ R*\ \ \text{uWUE}} \left(\frac{2g_1 + \sqrt{VPD}}{2(g_1 + \sqrt{VPD})^2} \right) \right)$$

- c_p and $R*$ are constants
- $\boldsymbol{R_{air}}$, γ, and $\boldsymbol{c_s}$ are approximately constant (relative to $\sqrt{VPD}$)

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$$\frac{\partial\, ET}{\partial\, VPD} = \text{scaling} \cdot \left(\frac{c_p}{R_{air}} - \frac{\gamma c_s}{1.6\ R * \quad \mathbf{uWUE}} \left(\frac{2\boldsymbol{g_1} + \sqrt{VPD}}{2(\boldsymbol{g_1} + \sqrt{VPD})^2} \right) \right)$$

- c_p and $R*$ are constants
- R_{air}, γ, and c_s are approximately constant (relative to $\sqrt{VPD}$)
- **uWUE** and $\boldsymbol{g1}$ are constants within plant type (e.g. grass, crops, deciduous broadleaf forest, evergreen needleleaf forest, shrub)

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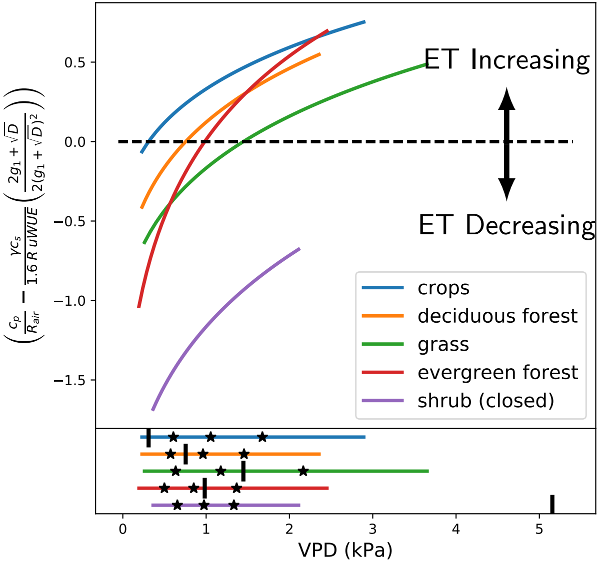
So **within each plant type**, whether the atmospheric demand (ET increasing with VPD) or plant response (ET decreasing with VPD) dominates is approximately **just a function of VPD**!

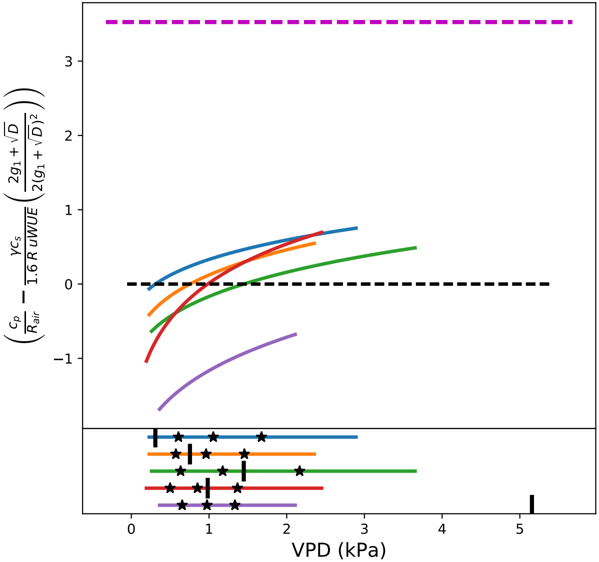
“Sign” term as a function of VPD and PFT



"Sign" term as a function of VPD and plant type

Dashed line gives response for potential evapotranspiration (PET).

Plants are crucial for land response!



The theory seems nice, but we need to test with data!

Introduce a free uncertainty parameter $\boldsymbol{\sigma}$ to Penman Monteith:

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

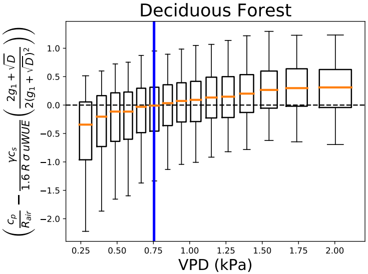
At each observation from FLUXNET (56 sites) calculate a unique $\boldsymbol{\sigma}$:

$$\boldsymbol{\sigma}(t, \text{site}) = f(ET_{obs})$$

Then propagate uncertainty forward by including $\boldsymbol{\sigma}$ in the derivative:

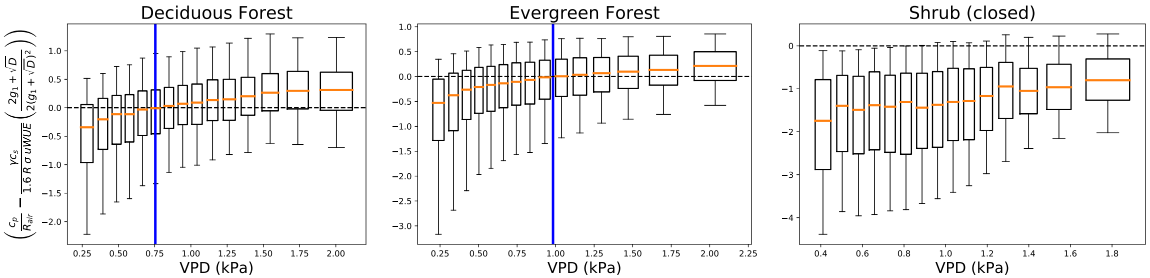
$$\frac{\partial\ ET}{\partial\ VPD} = \text{scaling} \cdot \left(\frac{c_p}{R_{air}} - \frac{\gamma c_s}{1.6\ R * \ \boldsymbol{\sigma}\ \text{ uWUE}}\left(\frac{2g_1 + \sqrt{VPD}}{2(g_1 + \sqrt{VPD})^2}\right)\right)$$

Test theory with FLUXNET data - the good



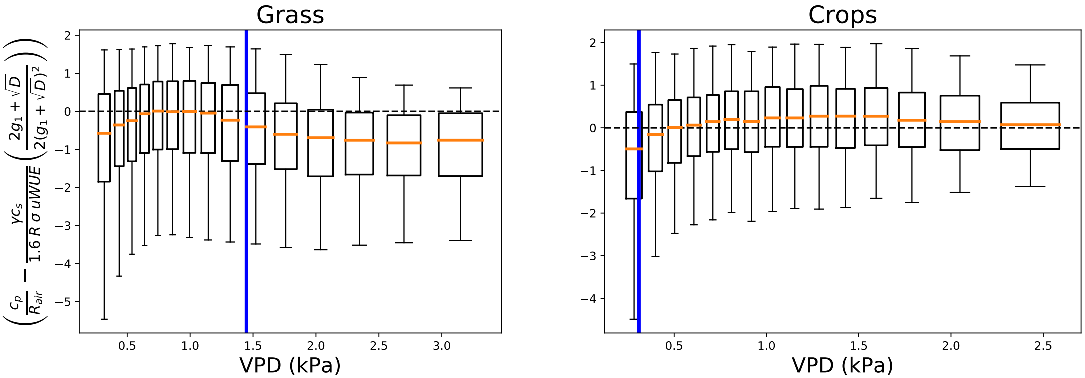
Blue line is theory's critical VPD.

Test theory with FLUXNET data - the good



Blue line is theory's critical VPD.

Test theory with FLUXNET data - the bad



Blue line is theory's critical VPD.

Summary - When does VPD drive or reduce ET?

- Theory predicts that each plant type has a **critical VPD below which ET will decrease** (plant response dominates), and **above which ET will increase** (atmospheric demand dominates).
- For forest sites, environmental VPD approximately straddles the critical VPD.
- For shrubs environmental VPD never exceeds the critical VPD.
- Theory tested poorly with FLUXNET data for for crops and grass.
- All plant types exhibited a response far below that of PET.
- The new uWUE-version of Penman-Monteith we derived could be used as a replacement for PET in drought indices over vegetated surfaces.

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Extra slide - statistics

Table 1: More quantitative test of theory.

PFT	Fraction of Obs. Theory is Correct	Mean ($\frac{\partial\, ET}{\partial\, VPD} < 0$)	Mean ($\frac{\partial\, ET}{\partial\, VPD} > 0$)
CRO	0.566517	-0.209152	0.005856
CSH	0.931660	-0.264746	NaN
DBF	0.633363	-0.135679	0.042910
ENF	0.633138	-0.150665	0.029281
GRA	0.442306	-0.042158	-0.042480

Quantitative VPD_{crit}

Table 2: Values of VPD_{crit}, where $\frac{\partial\ ET}{\partial\ VPD} = 0$, evaluated at PFT average values for R_{air}, σ, γ, 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)	γ	uWUE	VPD_{crit} **(Pa)**
CRO	288.680920	372.567691	65.351523	2.602873	**133.165438**
CSH	289.067152	381.593622	67.613172	2.175278	**4439.564212**
DBF	288.624437	377.449849	63.421812	2.746393	**888.773243**
ENF	288.183849	377.676463	61.559242	4.015362	**978.084845**
GRA	288.425651	377.264645	61.598768	2.281074	**1141.630778**

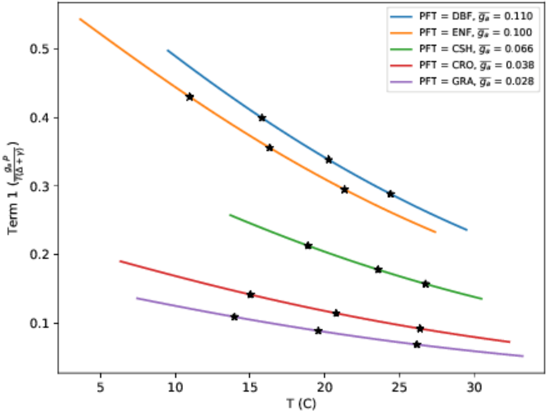
Statistics with uncertainty

Table 3: Statistics of $\frac{\partial\ ET}{\partial\ VPD}$ as a function of PFT.

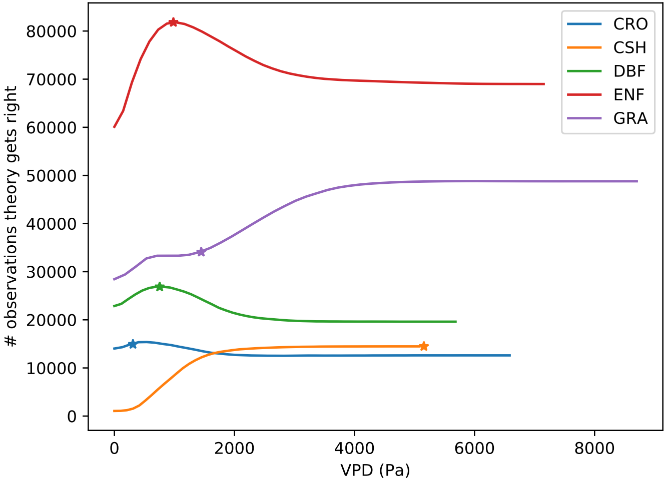
PFT	$\overline{\frac{\partial\ ET}{\partial\ VPD}}$	$\frac{\partial\ ET}{\partial\ VPD}(\overline{env})$	$\frac{\partial\ ET}{\partial\ VPD}(\overline{env}) * \mathrm{std}(VPD)$	$\frac{\frac{\partial\ ET}{\partial\ VPD}(\overline{env}) * \mathrm{std}(VPD)}{\frac{\partial\ ET}{\partial\ R}(\overline{env}) * \mathrm{std}(R)}$	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

Scaling Term

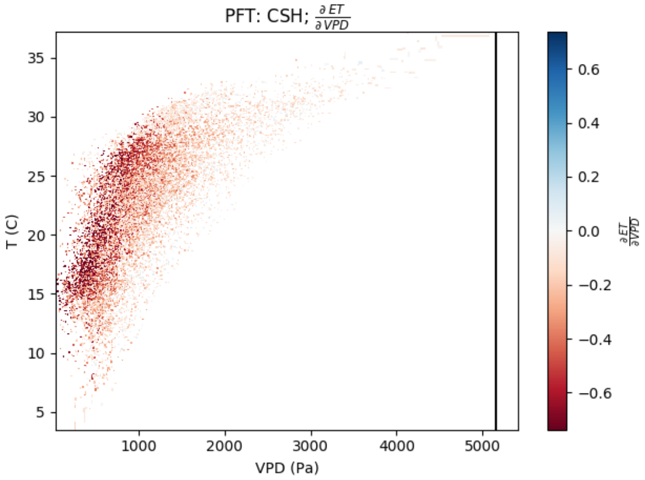
$$\frac{\partial\ ET}{\partial\ D} = \frac{\mathbf{g_a\ P}}{\mathbf{T}(\mathbf{\Delta} + \gamma)} \left(\frac{c_p}{R_{air}} - \frac{\mathrm{LAI}_{ref}}{\mathrm{LAI}} \frac{\gamma c_s}{1.6\ R * \quad \mathrm{uWUE}} \left(\frac{2g_1 + \sqrt{D}}{2(g_1 + \sqrt{D})^2} \right) \right)$$



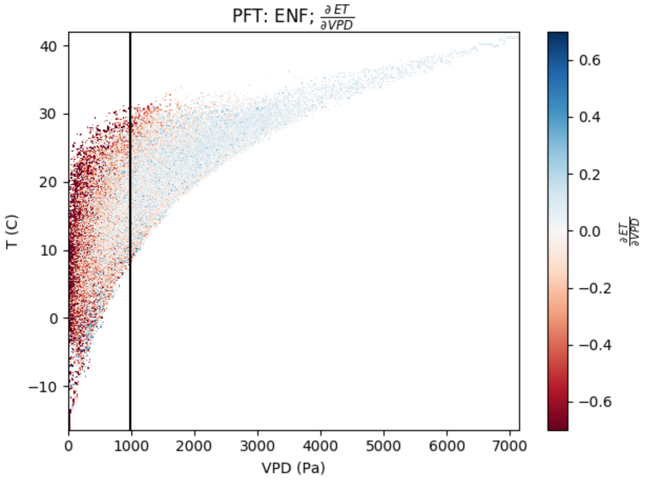
Extra slide - is theory VPD$_{crit}$ optimum?



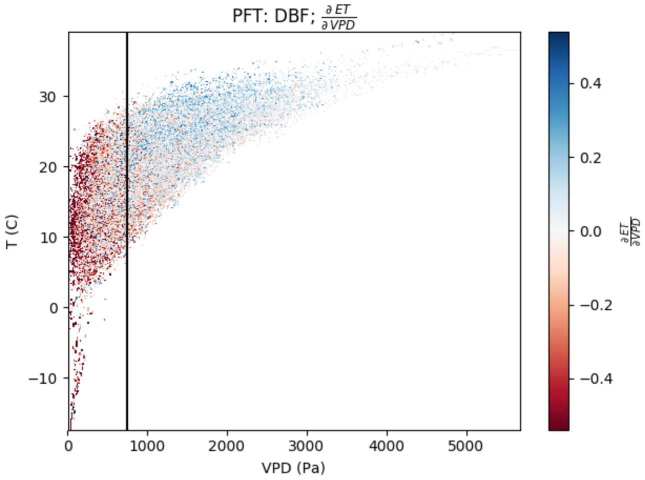
Test theory with FLUXNET data - CSH



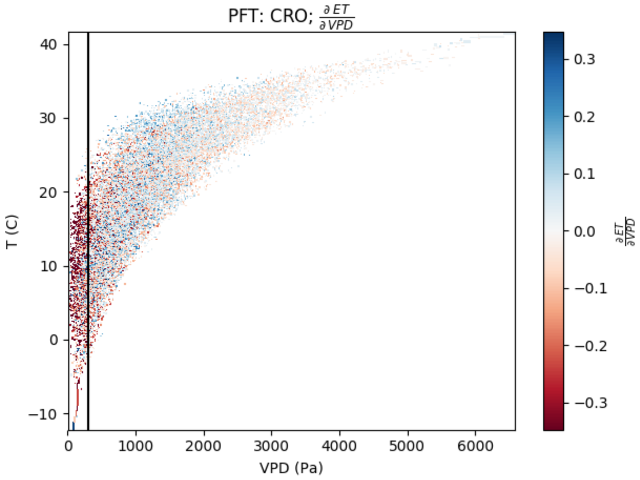
Test theory with FLUXNET data - ENF



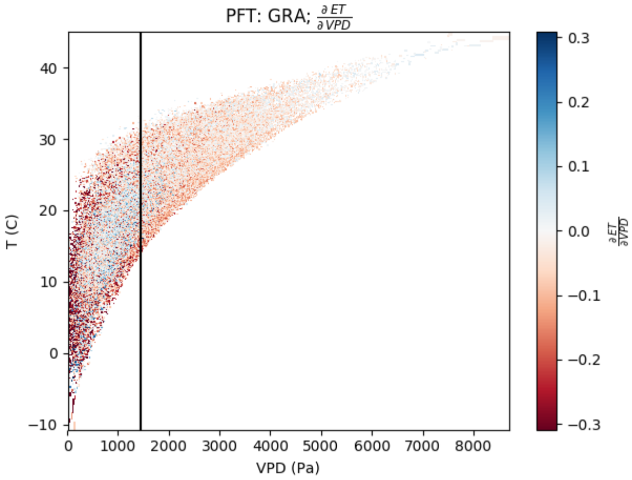
Test theory with FLUXNET data - DBF



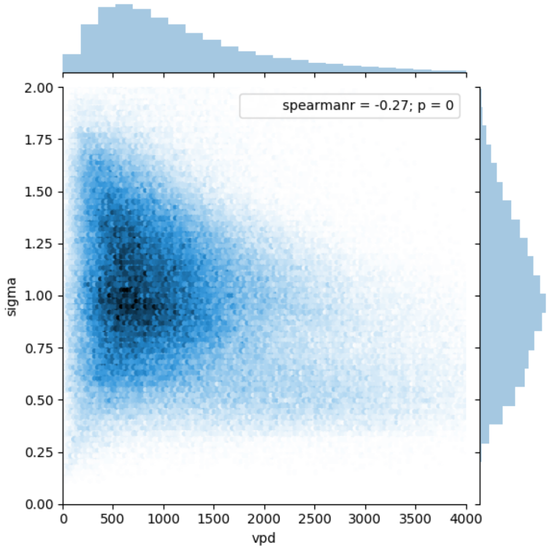
Test theory with FLUXNET data - CRO



Test theory with FLUXNET data - GRA



Is uncertainty a function of VPD?



How to take VPD derivative?