

When does vapor pressure deficit drive or reduce evapotranspiration?

Adam Massmann, Pierre Gentine and Changjie Lin

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Does VPD drive or reduce ET? - atmospheric demand perspective

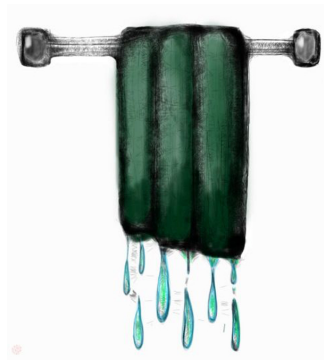
Increase in VPD (**increase in atmospheric demand**) drives an **increase in ET**.

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

Does VPD drive or reduce ET? - atmospheric demand perspective

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

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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**.

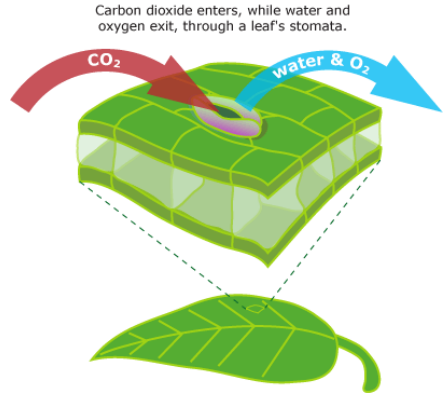


Figure 1: from evolution.berkeley.edu

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 simplify the problem (increase transparency) while still capturing the leading order behavior the system.
 - ▶ Simplifying the system aids intrinsic understanding, but at a physical realism.
- ▶ Because we run the risk of over-simplification, we will use FLUXNET2015 data to test how well our theory matches the data.
 - ▶ We will test in the growing season of 5 plant types: Deciduous broadleaf forest, evergreen needleleaf forest, shrub, grass, and crops.

Simple theory - start with Penman-Monteith

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

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

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):

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

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

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

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

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

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

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

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

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

Consequences of theory - “sign” term

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

- ▶ c_p and R^* are constants

Consequences of theory - “sign” term

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

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

Consequences of theory - “sign” term

$$\frac{\partial ET}{\partial VPD} = \text{scaling} \cdot \left(\frac{c_p}{R_{air}} - \frac{\gamma c_s}{1.6 R^* \text{ uWUE}} \left(\frac{2\text{ g1} + \sqrt{VPD}}{2(\text{ g1} + \sqrt{VPD})^2} \right) \right)$$

- ▶ c_p and R^* are constants
- ▶ R_{air} , γ , and c_s are approximately constant (relative to \sqrt{VPD})
- ▶ **uWUE** and **g1** are constants within plant type.

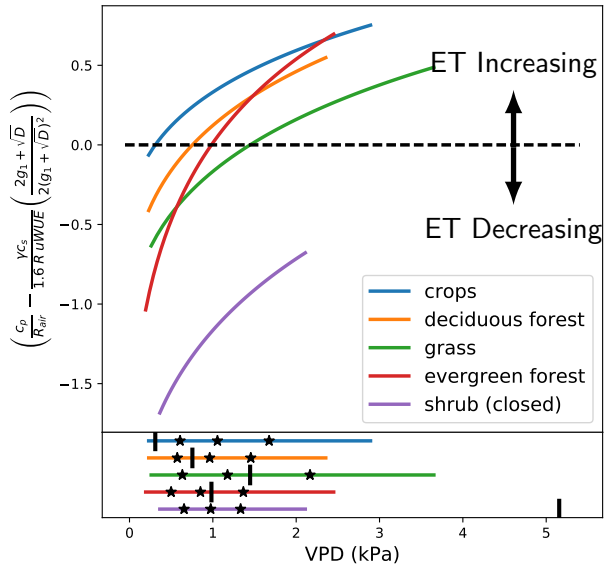
Consequences of theory - “sign” term

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

- ▶ c_p and R^* are constants
- ▶ R_{air} , γ , and c_s are approximately constant (relative to \sqrt{VPD})
- ▶ $uWUE$ and g_1 are constants within plant type

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!**

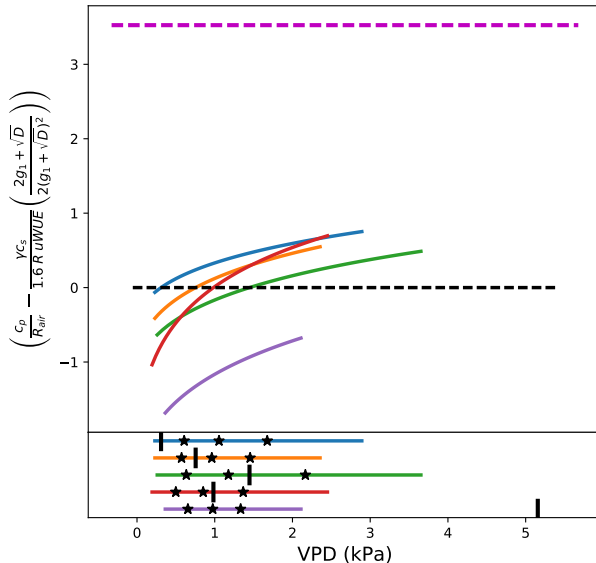
“Sign” term as a function of VPD and PFT



“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 σ to Penman Monteith:

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

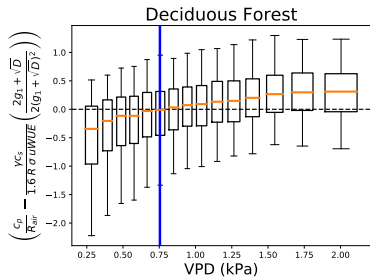
At each observation from FLUXNET (56 sites) calculate a unique σ :

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

Then propagate uncertainty forward by including σ in the derivative:

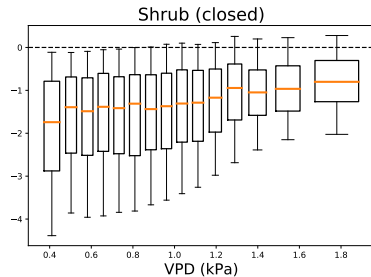
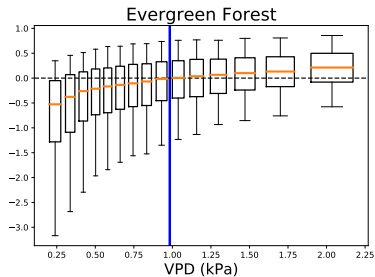
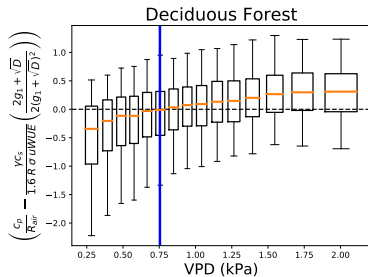
$$\frac{\partial ET}{\partial VPD} = \text{scaling} \cdot \left(\frac{c_p}{R_{air}} - \frac{\gamma c_s}{1.6 R * \sigma uWUE} \left(\frac{2g_1 + \sqrt{VPD}}{2(g_1 + \sqrt{VPD})^2} \right) \right)$$

Test theory with FLUXNET data - the good



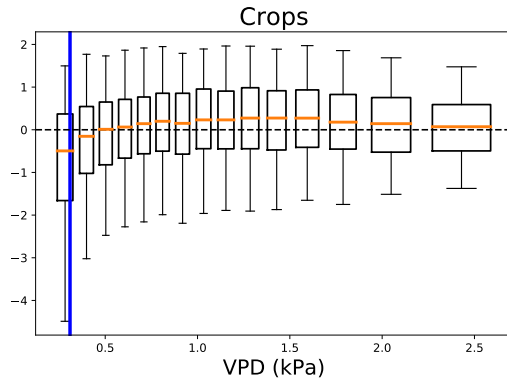
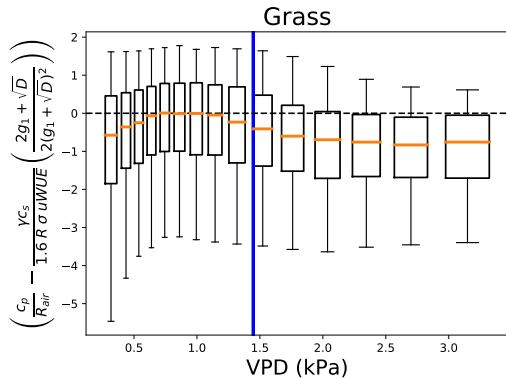
Blue line is theory's critical VPD.

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 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 complement for PET in drought indices over vegetated surfaces.

Acknowledgments - Thank you NSF and FLUXNET!!!

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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

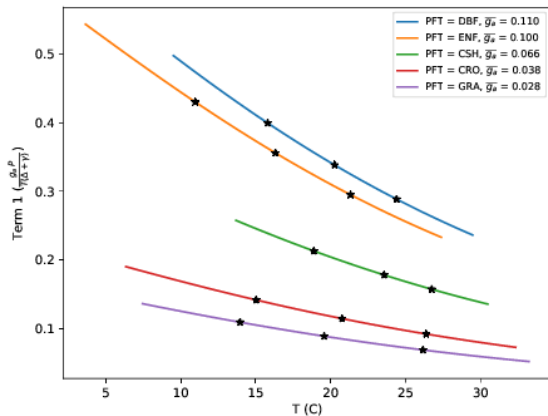
Statistics with uncertainty

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

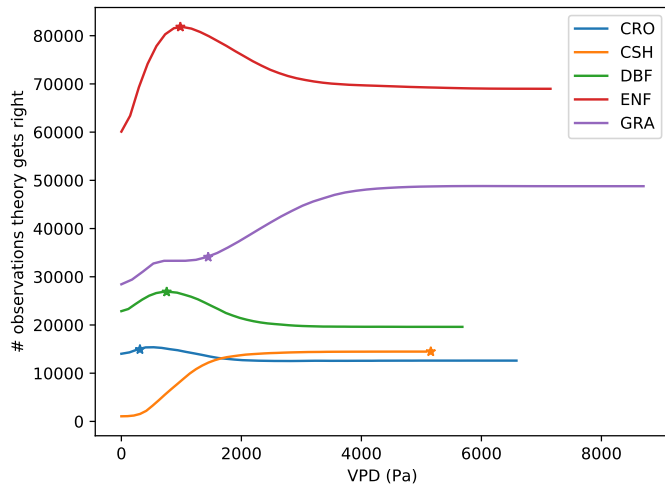
PFT	$\overline{\frac{\partial ET}{\partial VPD}}$	$\frac{\partial ET}{\partial VPD}(\overline{env})$	$\frac{\partial ET}{\partial VPD}(\overline{env}) * \text{std}(VPD)$	$\frac{\frac{\partial ET}{\partial VPD}(\overline{env}) * \text{std}(VPD)}{\frac{\partial ET}{\partial R}(\overline{env}) * \text{std}(R)}$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

Scaling Term

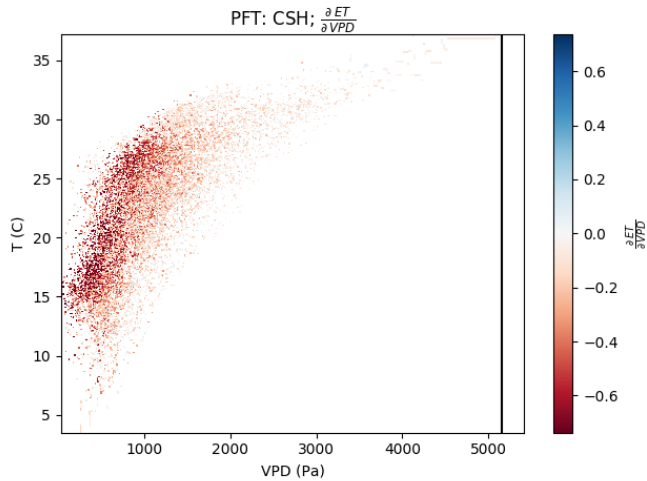
$$\frac{\partial ET}{\partial D} = \frac{\mathbf{g_a P}}{\mathbf{T(\Delta + \gamma)}} \left(\frac{c_p}{R_{air}} - \frac{LAI_{ref}}{LAI} \frac{\gamma c_s}{1.6 R^*} \frac{1}{uWUE} \left(\frac{2g_1 + \sqrt{D}}{2(g_1 + \sqrt{D})^2} \right) \right)$$



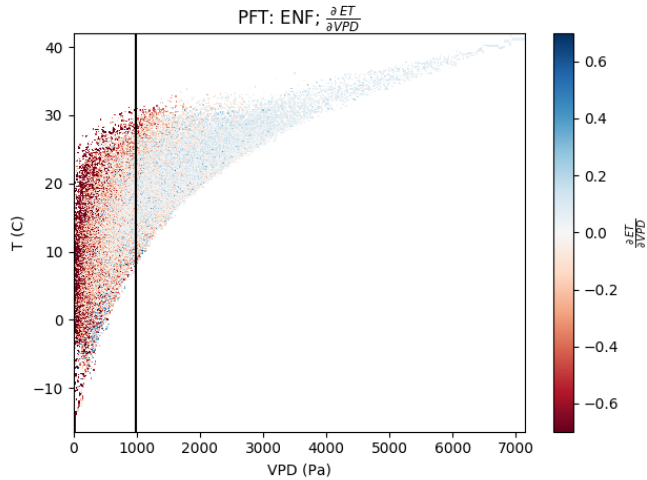
Extra slide - is theory VPD_{crit} optimum?



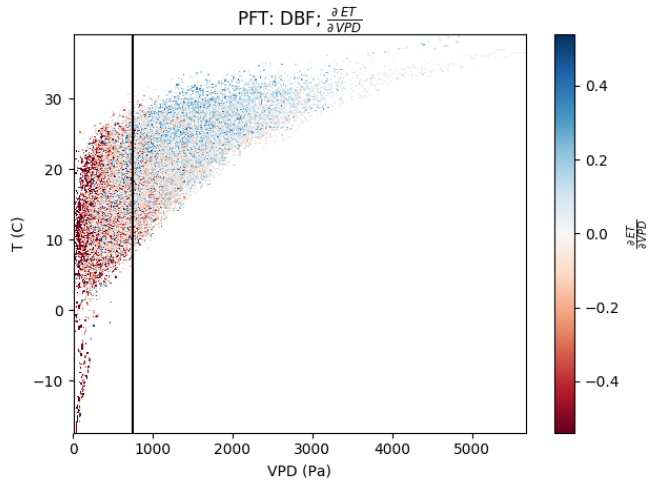
Test theory with FLUXNET data - CSH



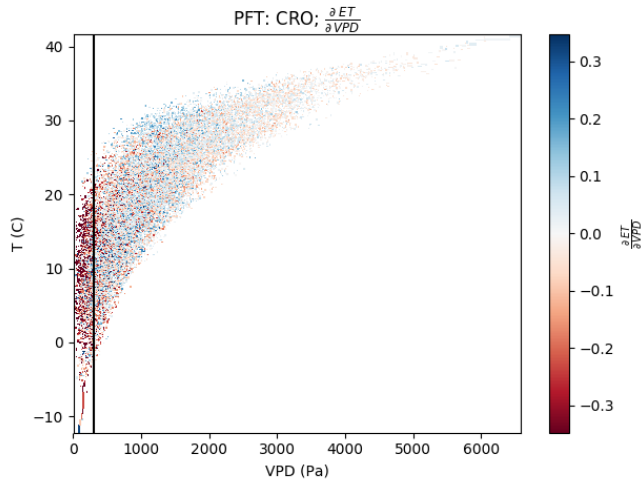
Test theory with FLUXNET data - ENF



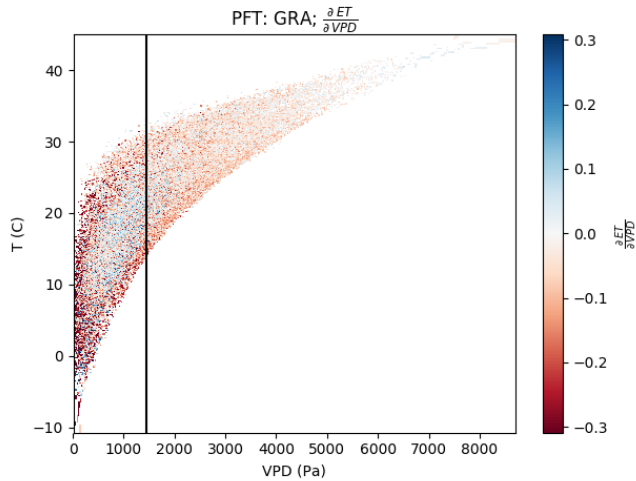
Test theory with FLUXNET data - DBF



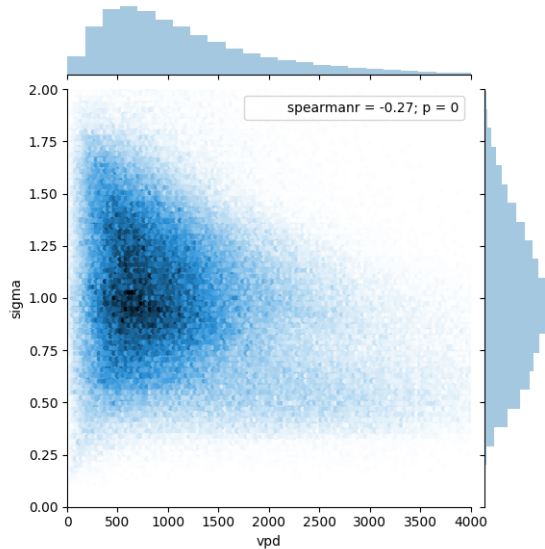
Test theory with FLUXNET data - CRO



Test theory with FLUXNET data - GRA



Is uncertainty a function of VPD?



How to take VPD derivative?

