When does VPD drive or reduce ET?

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G-Lab Meeting

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When does VPD drive or reduce ET?

- **Hydrometeorologists** would say that an increase in VPD (increase in **atmospheric demand**) would drive an **increase in ET**.
- However, **plant physiologists** know that plants have evolved to use stomata to conserve and regulate water use. So **stomata closure** in response to increases in VPD may **decrease ET**.

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

- It should be a function of plant type and the environment:
  - Plants that are evolved to conserve water will tend to reduce ET with increases in VPD.
  - However the environment can overwhelm plant response: at some threshold (i.e. very high VPD) the atmospheric demand should dominate and plants will not be able to conserve water, no matter how much they have evolved to do so.

We will try an analytical approach to this question:

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

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

But in (MEDLYN et al. 2011):

$$g_s = g_0 + 1.6 \left(1 + \frac{g_1}{\sqrt{D}}\right) \frac{A}{c_s}$$

A is a function of ET. So ET in PM is really an implicit function of itself.

Remove dependence of ET on A

Zhou et al. 2016 shows that uWUE:

$$uWUE = \frac{GPP \cdot \sqrt{D}}{ET}$$

is conserved across space and time (within PFT).

So we can use uWUE to remove dependence of g_s on A:

$$g_s = \frac{R\ T}{P} 1.6 \left(1 + \frac{g_1}{\sqrt{D_s}}\right) \frac{uWUE\ ET}{c_s\ \sqrt{D}}$$

Derive new form of PM

If we plug in our new expression for g_s we can solve for ET to get a new form of PM:

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

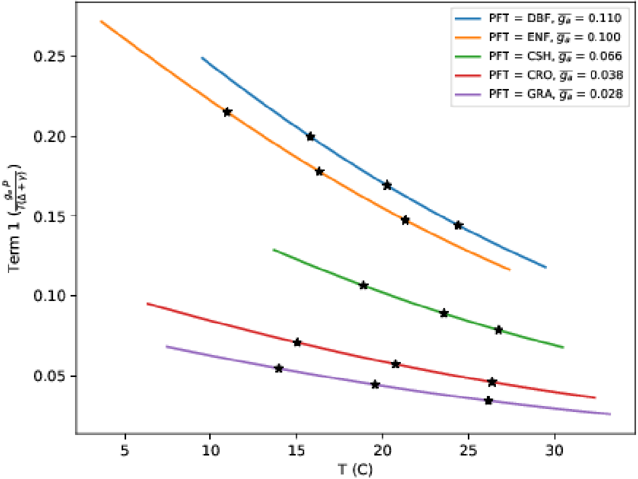
Now, we can take derivatives, and:

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

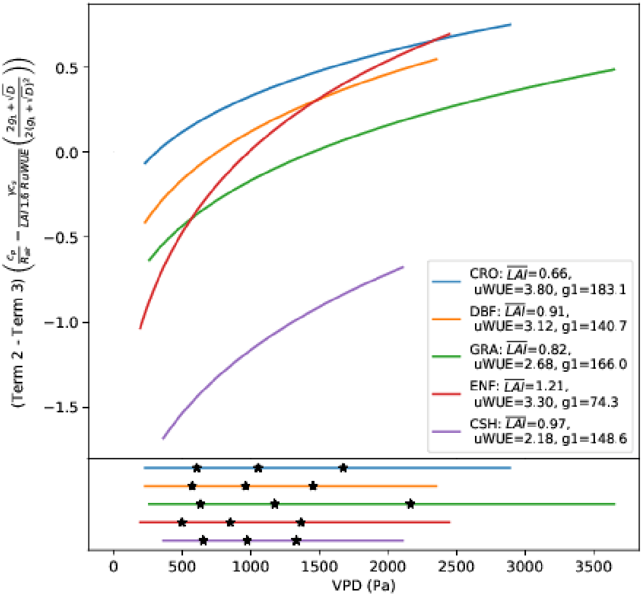
[1] note that all terms are known, except for $\frac{\text{LAI}_{ref}}{\text{LAI}}$

Scaling Term

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



“Sign” Term

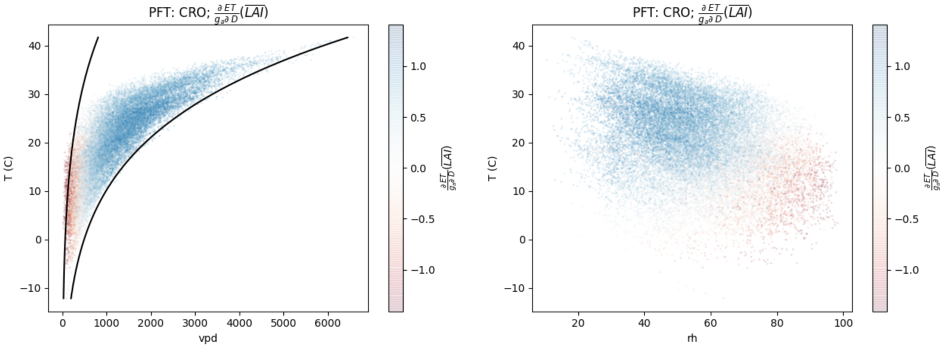


0.5
0.0
−0.5
−1.0
−1.5
(Term 2 - Term 3)
CRO: $\overline{LAI}$=0.66, uWUE=3.80, g1=183.1
DBF: $\overline{LAI}$=0.91, uWUE=3.12, g1=140.7
GRA: $\overline{LAI}$=0.82, uWUE=2.68, g1=166.0
ENF: $\overline{LAI}$=1.21, uWUE=3.30, g1=74.3
CSH: $\overline{LAI}$=0.97, uWUE=2.18, g1=148.6
0
500
1000
1500
2000
2500
3000
3500
VPD (Pa)

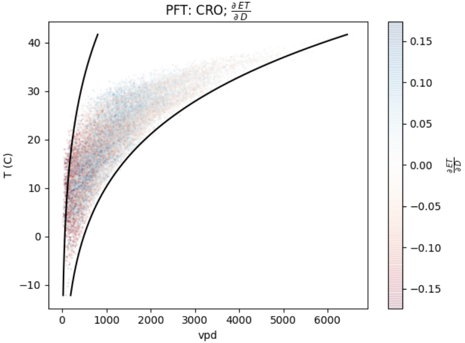
Summary of theory

- We use Zhou et al. 2016's uWUE to derive a new analytically tractable form of PM.
- This new analysis suggests that the "tipping" point for which atmospheric demand overwhelms plant response will be almost exclusively a function of VPD.
  - For each PFT there will be a VPD_{crit} above which atmospheric demand will dominate and ET will increase with VPD.
- Plant types evolved to conserve water (CSH) have a higher VPD_{crit} than plants evolved (or bred) to use water and prioritize GPP (CRO). Trees and grasslands are somewhere between these two extremes.
- Aerodynamic conductance scales the response, so plants with large surface roughness will be more likely to have a larger response as there is less resistance between the surface and the atmosphere.

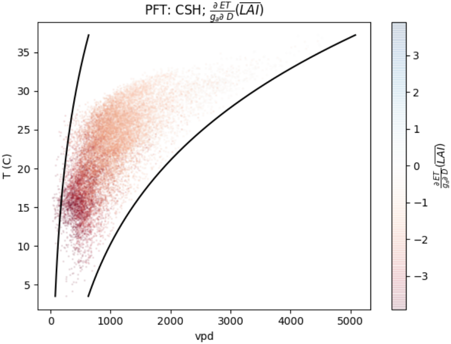
Idealized results - CRO

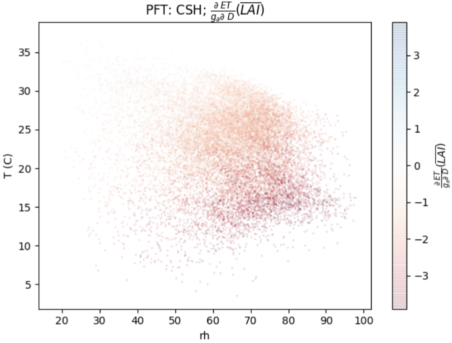


Results with uncertainty - CRO

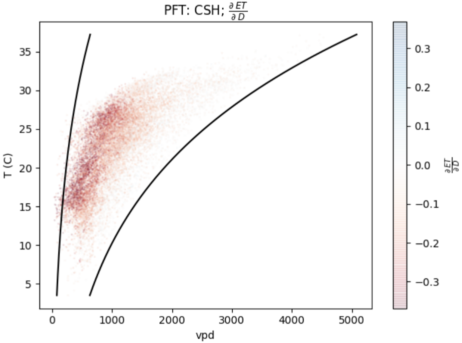


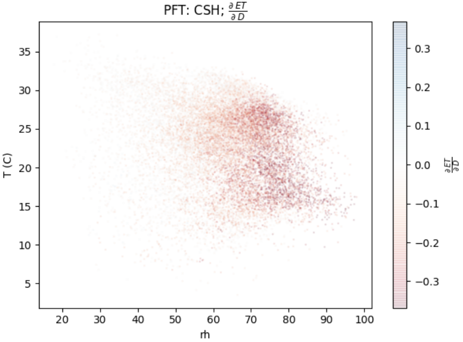
Idealized results - CSH



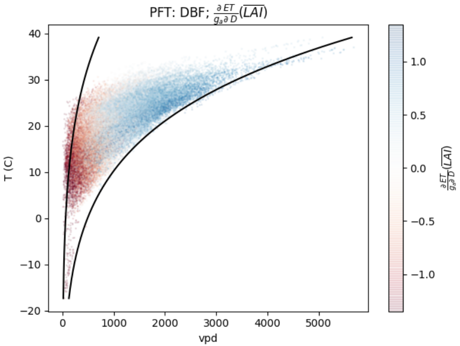


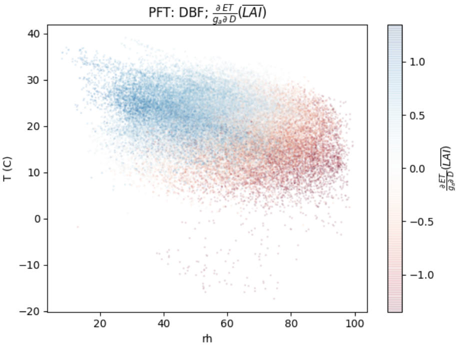
Results with uncertainty - CSH



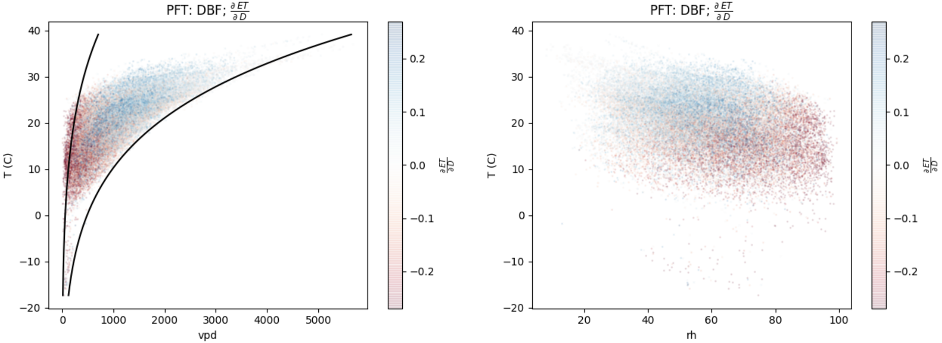


Idealized results - DBF

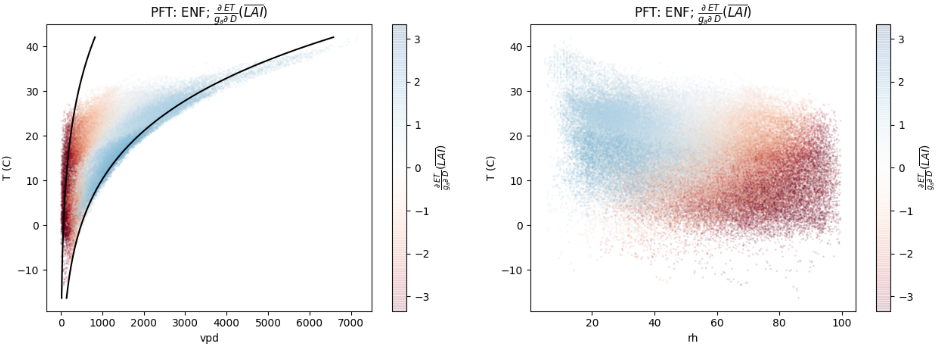




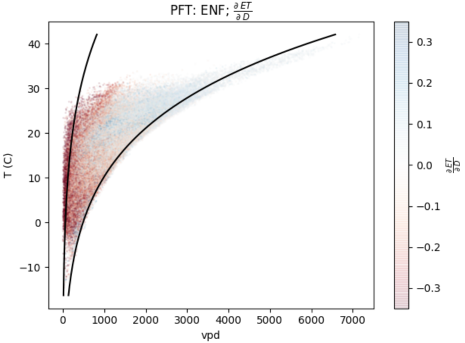
Results with uncertainty - DBF

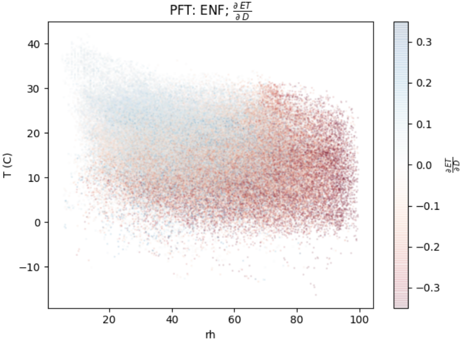


Idealized results - ENF

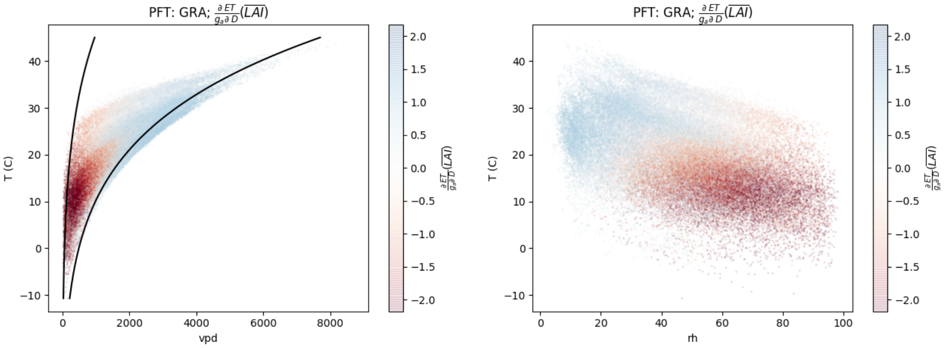


Results with uncertainty - ENF

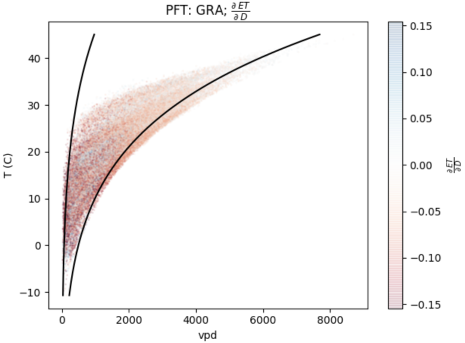


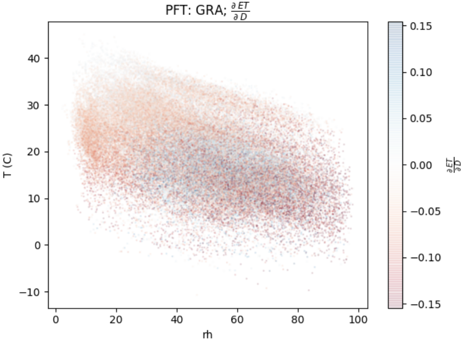


Idealized results - GRA



Results with uncertainty - GRA





Summary statistics

Table 1: Statistics of $\frac{\partial\, ET}{\partial\, D}$ as a function of PFT.

PFT	$\overline{\frac{\partial\, ET}{\partial\, VPD}}$	fraction $\frac{\partial\, ET}{\partial\, VPD} < 0.$
CRO	0.000853	0.473311
CSH	-0.108234	0.931660
DBF	-0.012727	0.461674
ENF	-0.034087	0.534425
GRA	-0.019637	0.631735

Summary

- Theory finds that the "tipping" point for which atmospheric demand overwhelms plant response will be almost exclusively a function of VPD. Plant types evolved to conserve water (CSH) have a higher VPD_{crit} (and more negative ET response) than plants evolved (or bred) to use water and prioritize GPP (CRO).
- On average, ecosystem response to VPD follows roughly what we might expect: CRO (prioritize GPP) has positive ET response to VPD, while all others have a negative response. Ordering by increasing magnitude of negative response gives: DBF, GRA, ENF, CSH; which roughly correspond to expectations for increasing water conservation as a function of PFT.
- Uncertainty is high, especially for CRO and GRA. However, inclusion of uncertainty does not change the story for ENF or CSH.

References

MEDLYN, BELINDA E. et al. (2011). “Reconciling the optimal and empirical approaches to modelling stomatal conductance”. In: *Global Change Biology* 17.6, pp. 2134–2144. DOI: 10.1111/j.1365-2486.2010.02375.x. URL: https://doi.org/10.1111%2Fj.1365-2486.2010.02375.x.

Zhou, Sha et al. (2016). “Partitioning evapotranspiration based on the concept of underlying water use efficiency”. In: *Water Resources Research* 52.2, pp. 1160–1175. DOI: 10.1002/2015wr017766. URL: https://doi.org/10.1002%2F2015wr017766.