Modelling the responses of vegetation to drought with a Stomatal Optimization model based on Xylem hydraulics

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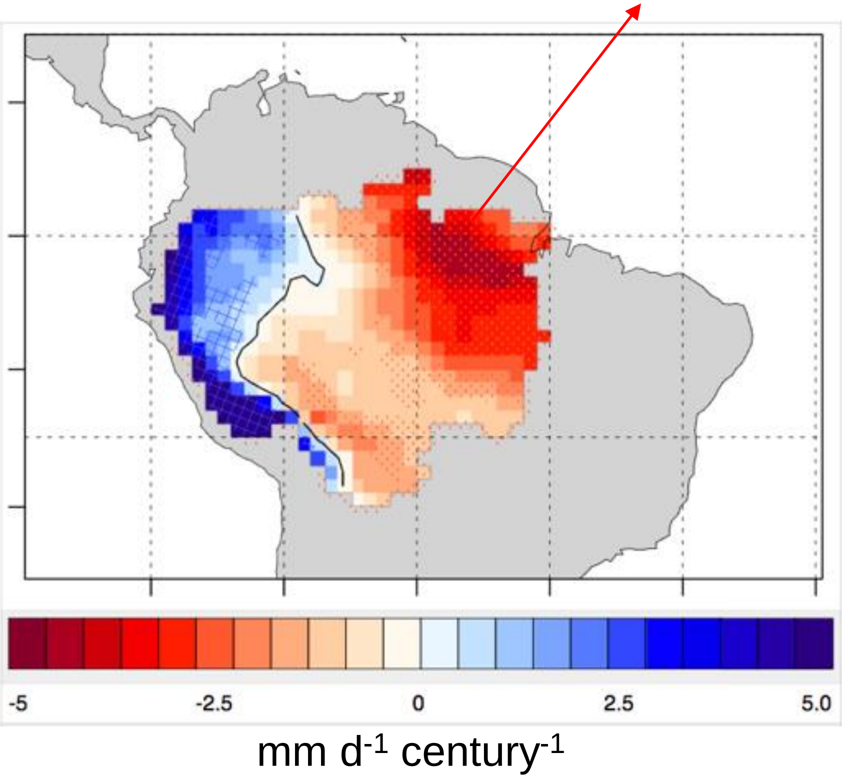
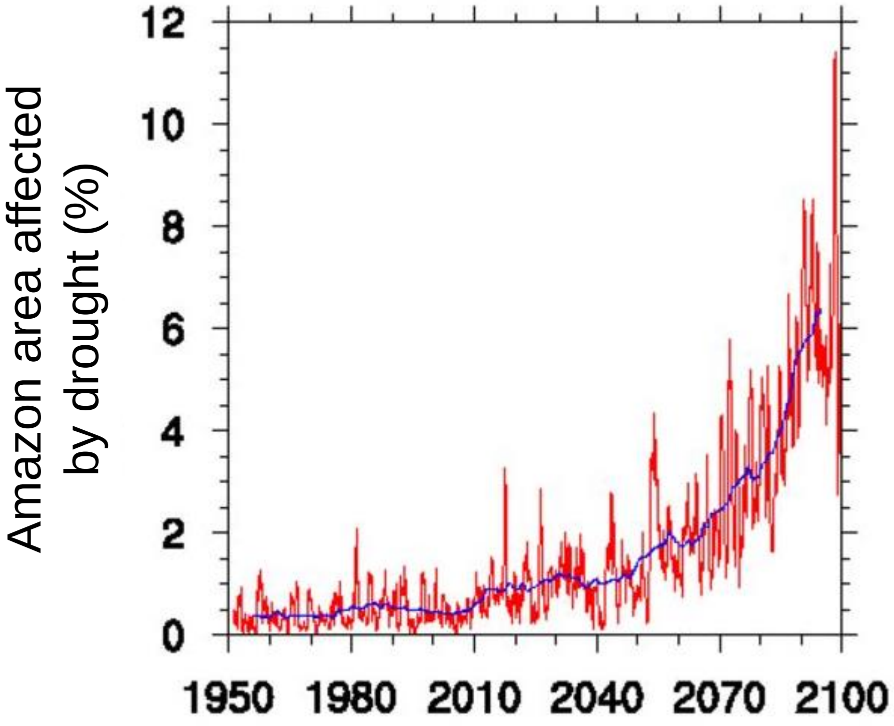
Amazon and other tropical forests might be exposed to a drier climate in the future

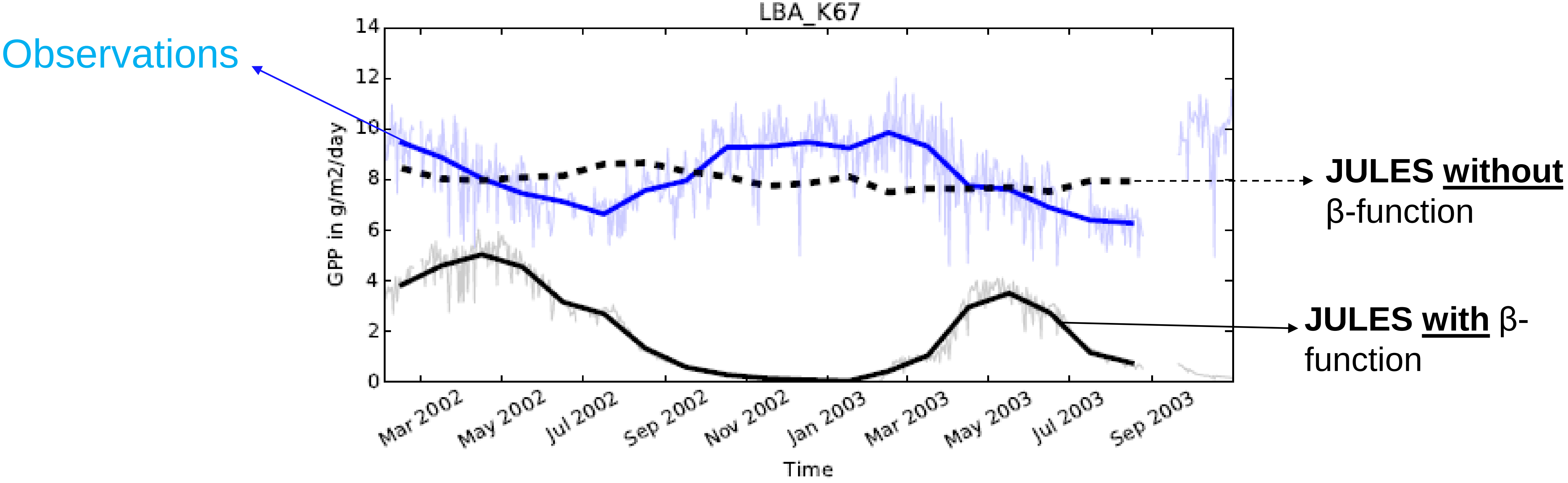
Decreased rainfall





Duffy et al (2015)

The β-function does not represents vegetation responses to drought properly in some sites.

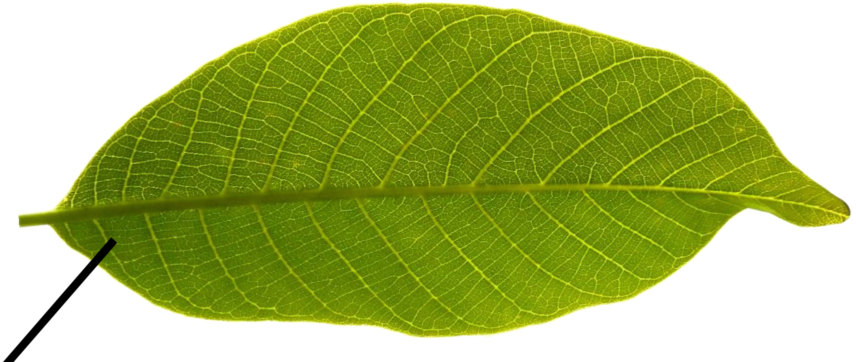


Can we improve how JULES simulates vegetation physiological responses to drought?

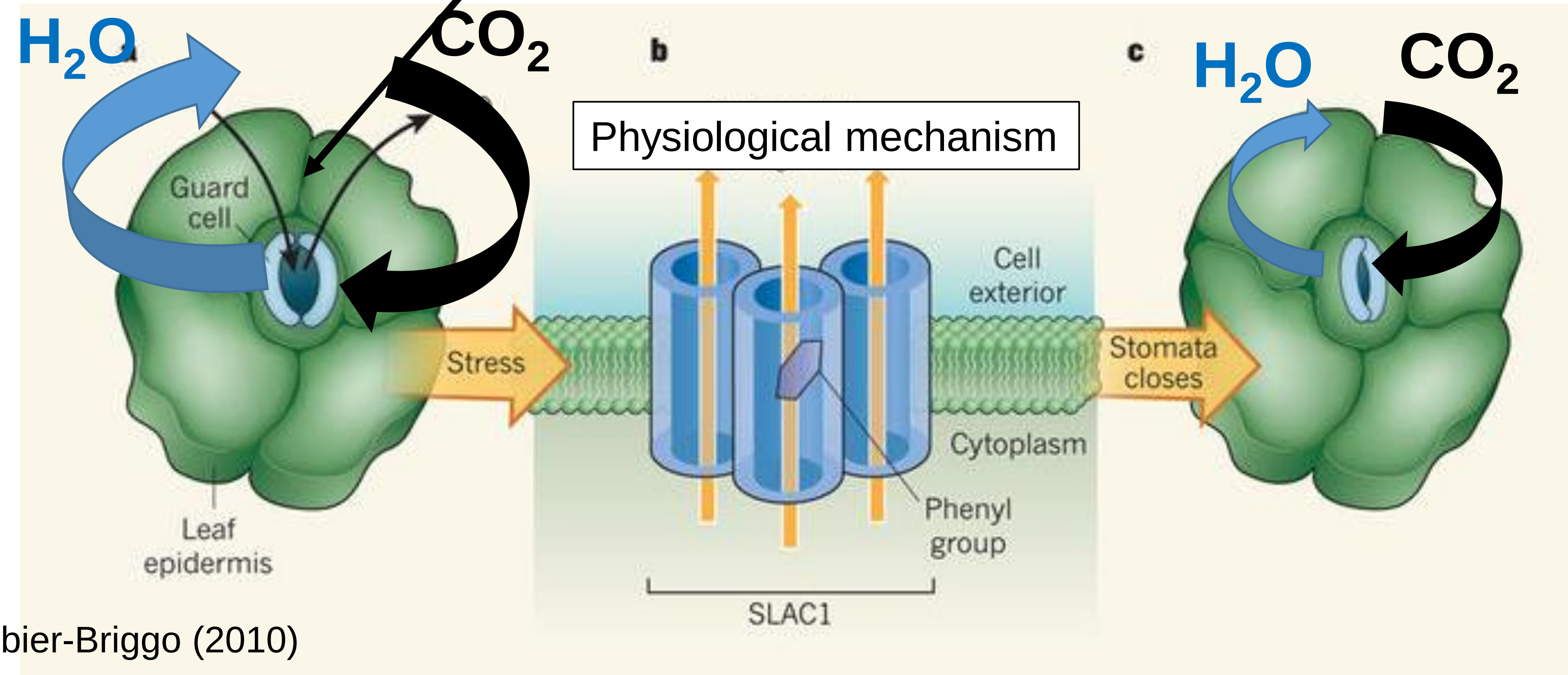
Williams *et al in prep*

How plants respond to drought in reality?

Plants close the **stomata** to avoid dangerous consequences of excessive water loss



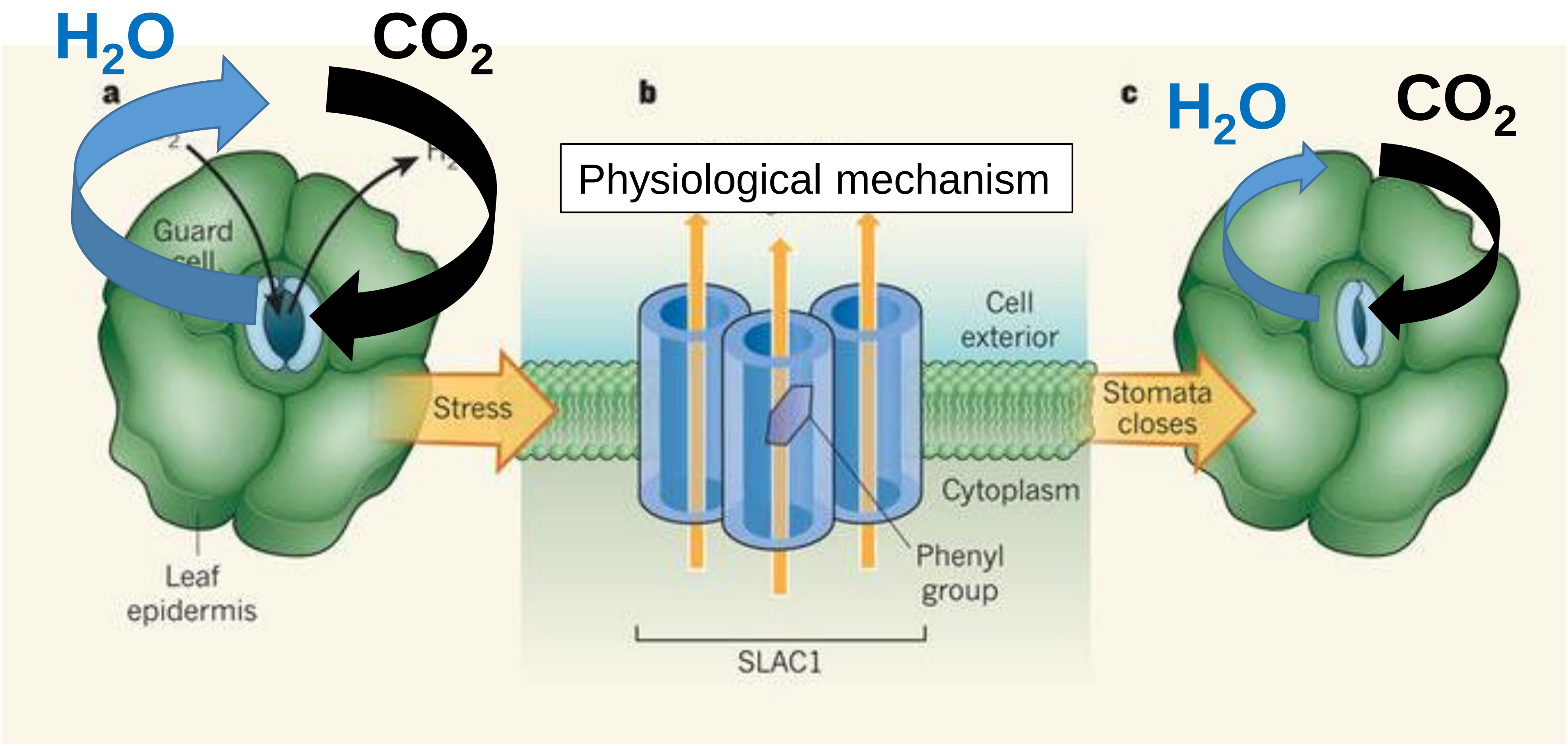
Turgor changes in the **guard cells** that form the stomata caused mostly by hormonal triggers.



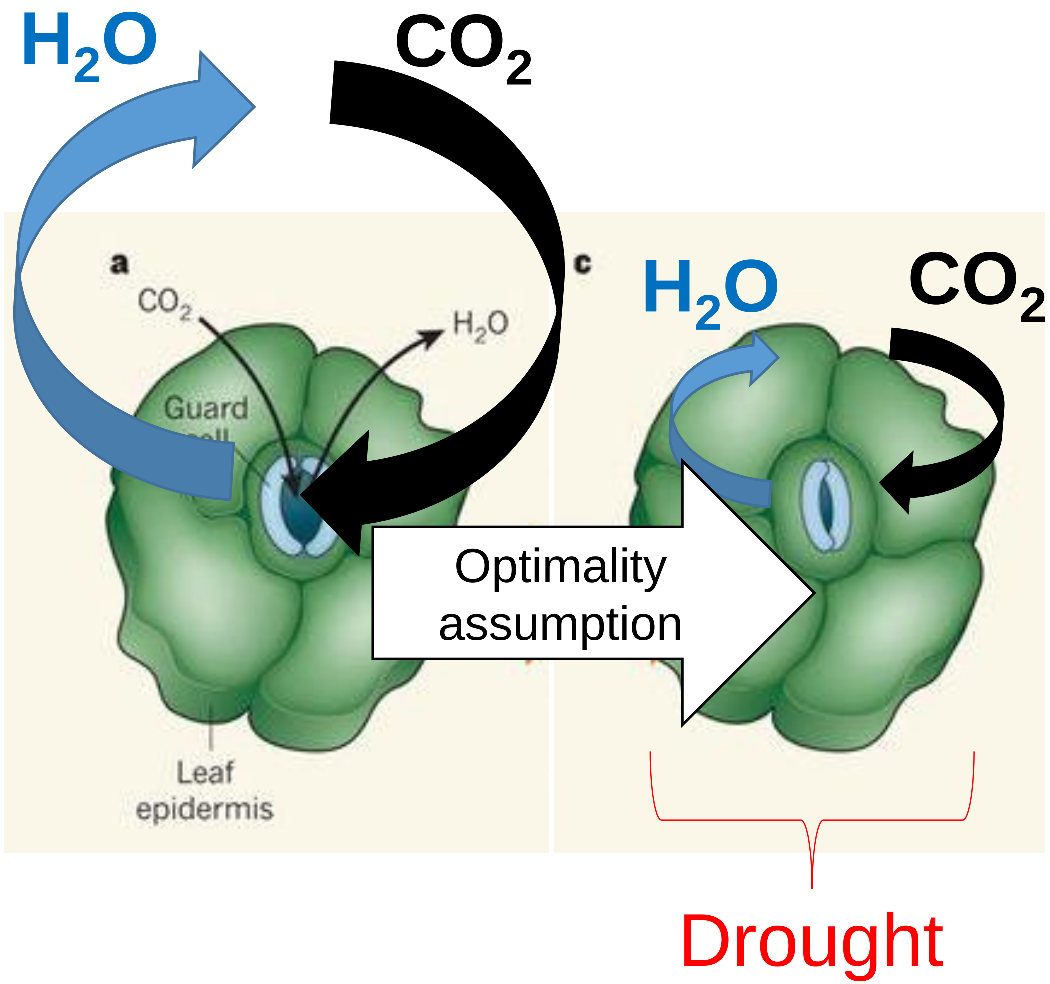
Physiological mechanism

Thomine S & Barbier-Briggo (2010)

Models explicitly representing all the **physiological mechanisms** involved on plant responses to environmental conditions are usually very complex and hard to parametrize in large-scales.

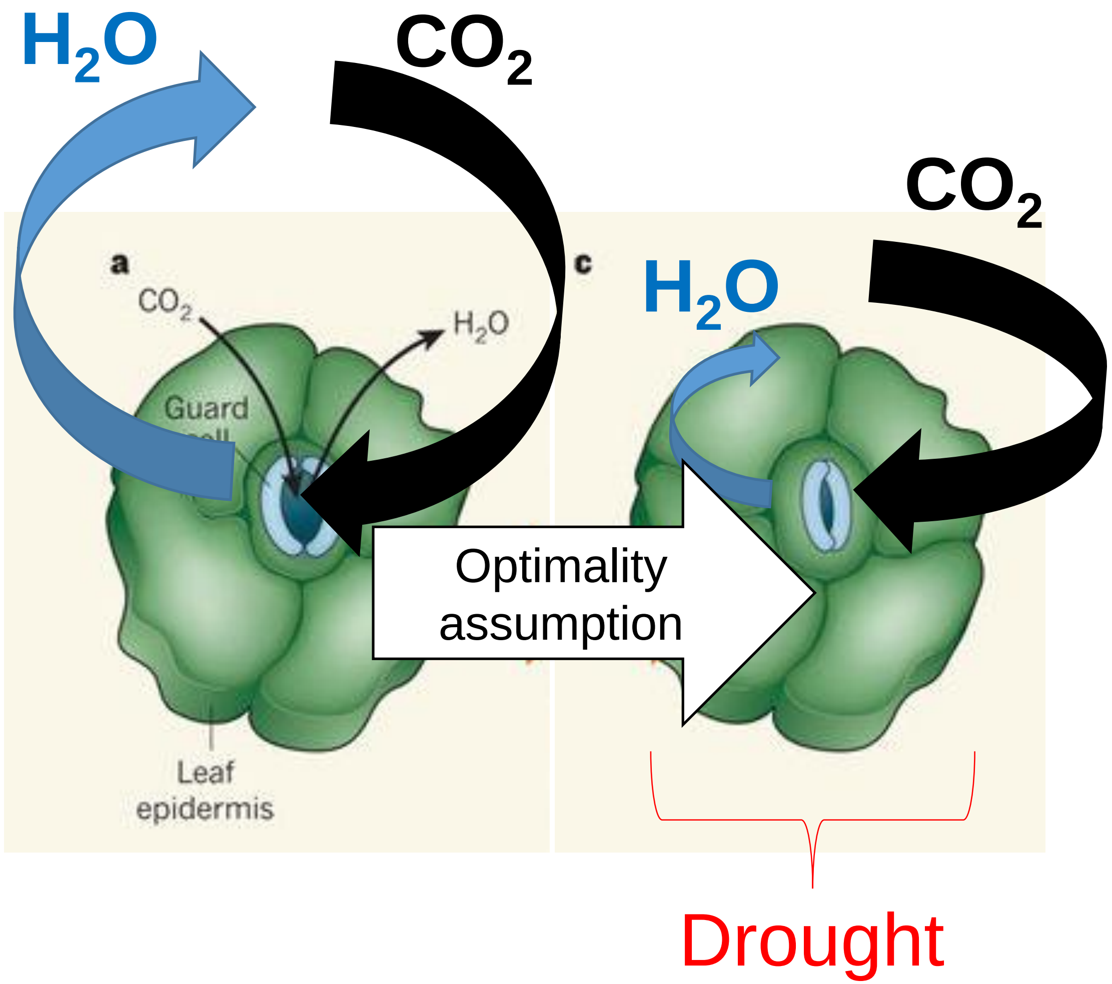


Optimality theory have been successfully used to parsimoniously predict the behaviour of many biological systems.



Substitute the need for detailed physiological parametrization with the assumption that processes and structures **evolved to maximise the fitness** of the organism.

Optimality theory have been successfully used to parsimoniously predict the behaviour of many biological systems.



Cowan & Farquhar (1977) can successfully reproduce plant stomatal responses to atmospheric vapour pressure deficit employing the simple principle that stomata operates to **minimize mass of water lost per mass of carbon gain.**

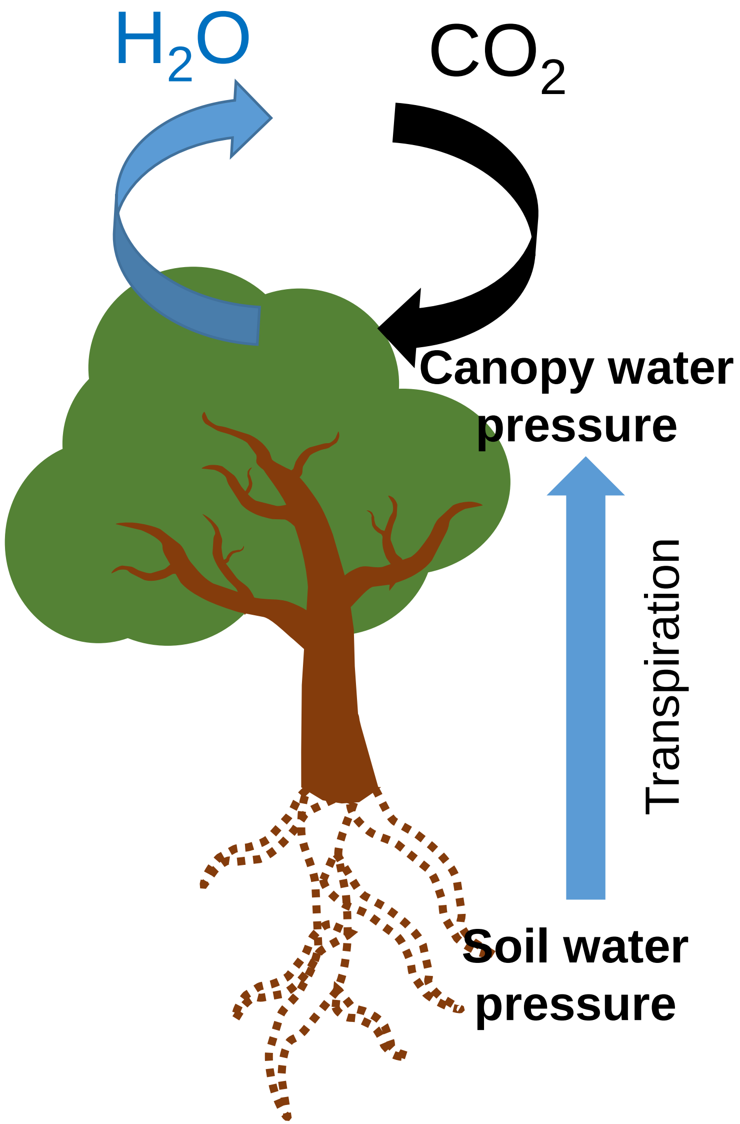
A Stomatal Optimization model based on Xylem hydraulics (SOX)

- The traditional form of the stomatal optimisation theory (Cowan & Farquhar, 1977) does not predicts responses to soil moisture.

- Plant hydraulic theory provides a way to represent the effect of reduced soil moisture on plant stomata behaviour (Sperry & Love, 2015; Wolf et al 2016; Sperry et al 2017): **minimizes loss of hydraulic conductance per mass of carbon gain.**

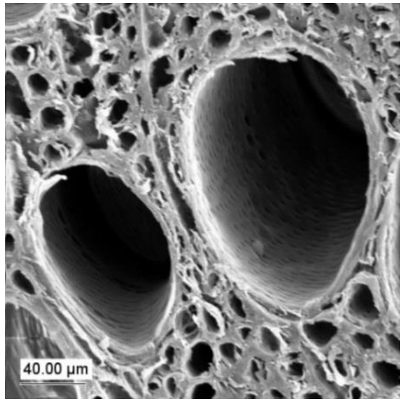
- Uses xylem hydraulic traits available for a large number of species.

Relationship between plant xylem hydraulics and drought

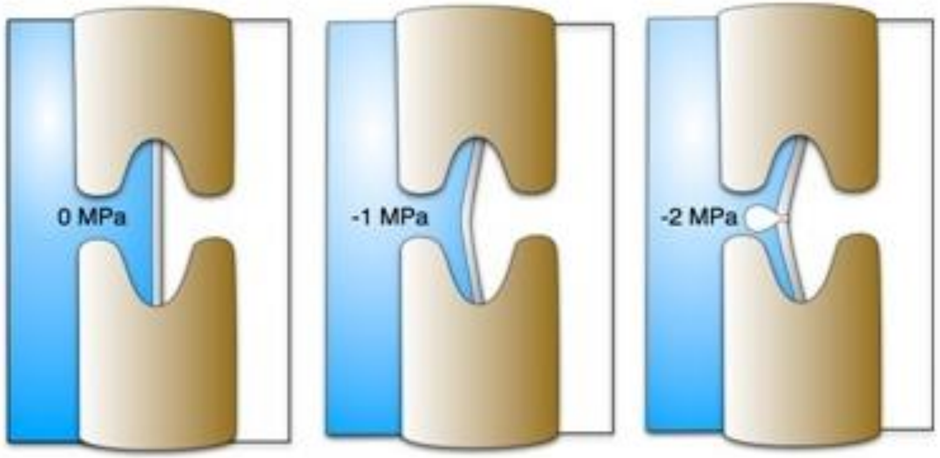


- Carbon assimilation requires stomatal opening and water loss through transpiration
- Transpiration, especially during drought, exposes the water on the xylem to a higher tension (i.e. negative pressure)

Relationship between plant xylem hydraulics and drought



Water transporting vessels
in angiosperms (Xylem)



Air-seeding hypothesis
(Sperry & Tyree, 1988)

- The high water tension in the xylem induces air bubbles to be “sucked” into xylem water stream.
- These air bubbles expands and blocks the vessel in a process known as **embolism**.

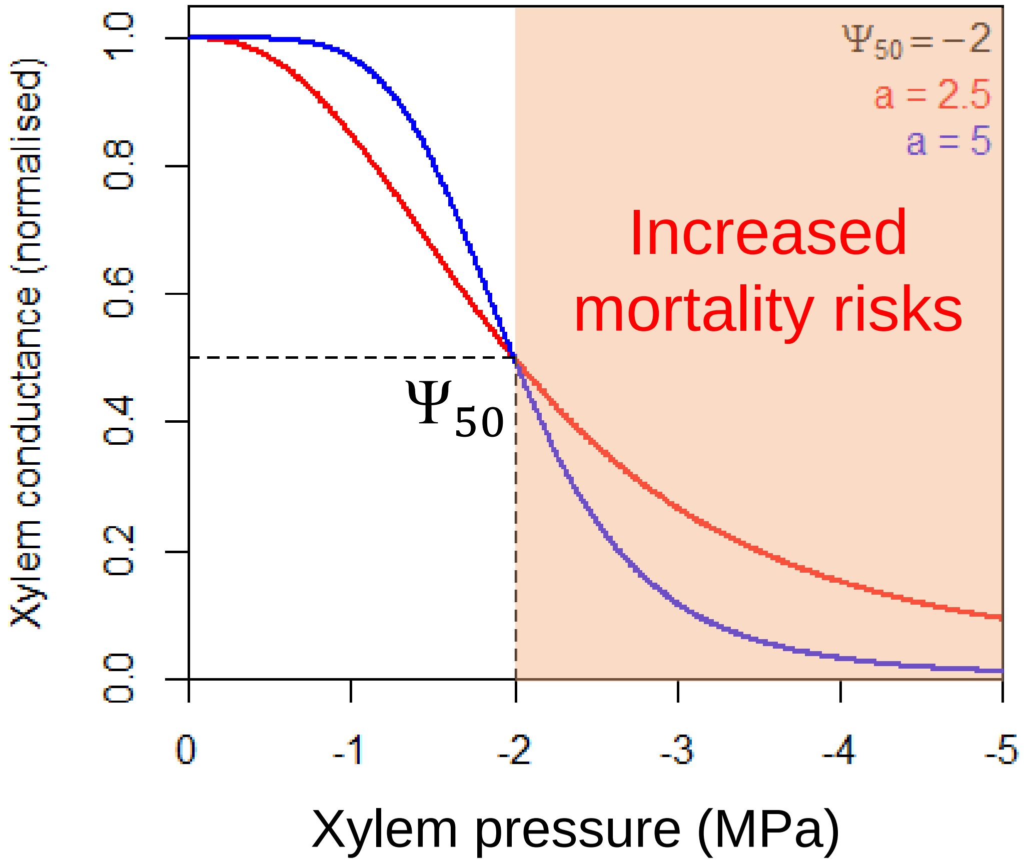
Nature Education (2013) Adapted from Tyree & Zimmermann (2002)

Relationship between plant xylem hydraulics and drought

Shape of the curve

$$k = k_{max}\left[1+\left(\frac{\Psi}{\Psi_{50}}\right)^{a}\right]^{-1}$$

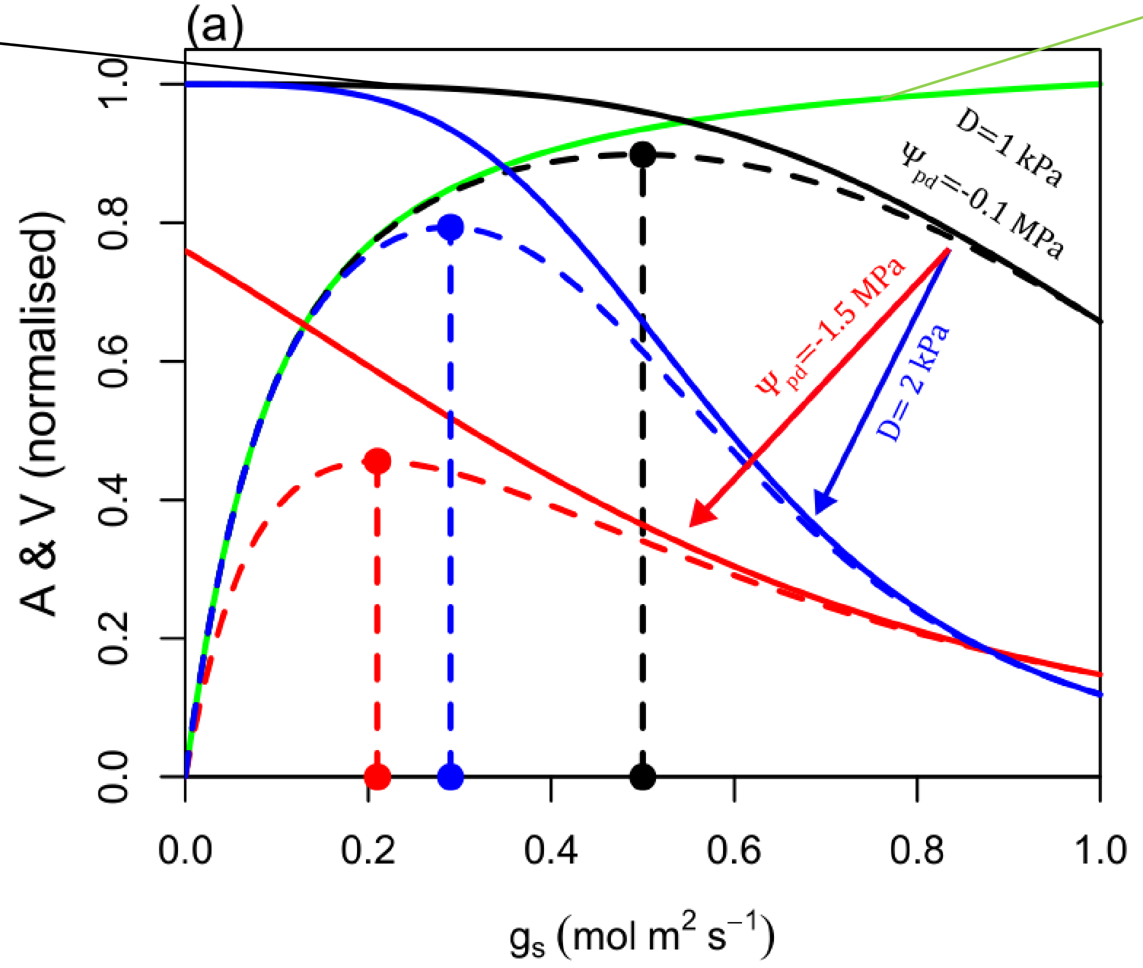
Ψ when k = $k_{max}/2$



A Stomatal Optimization model based on Xylem hydraulics (SOX)

Xylem vulnerability to cavitation (V)

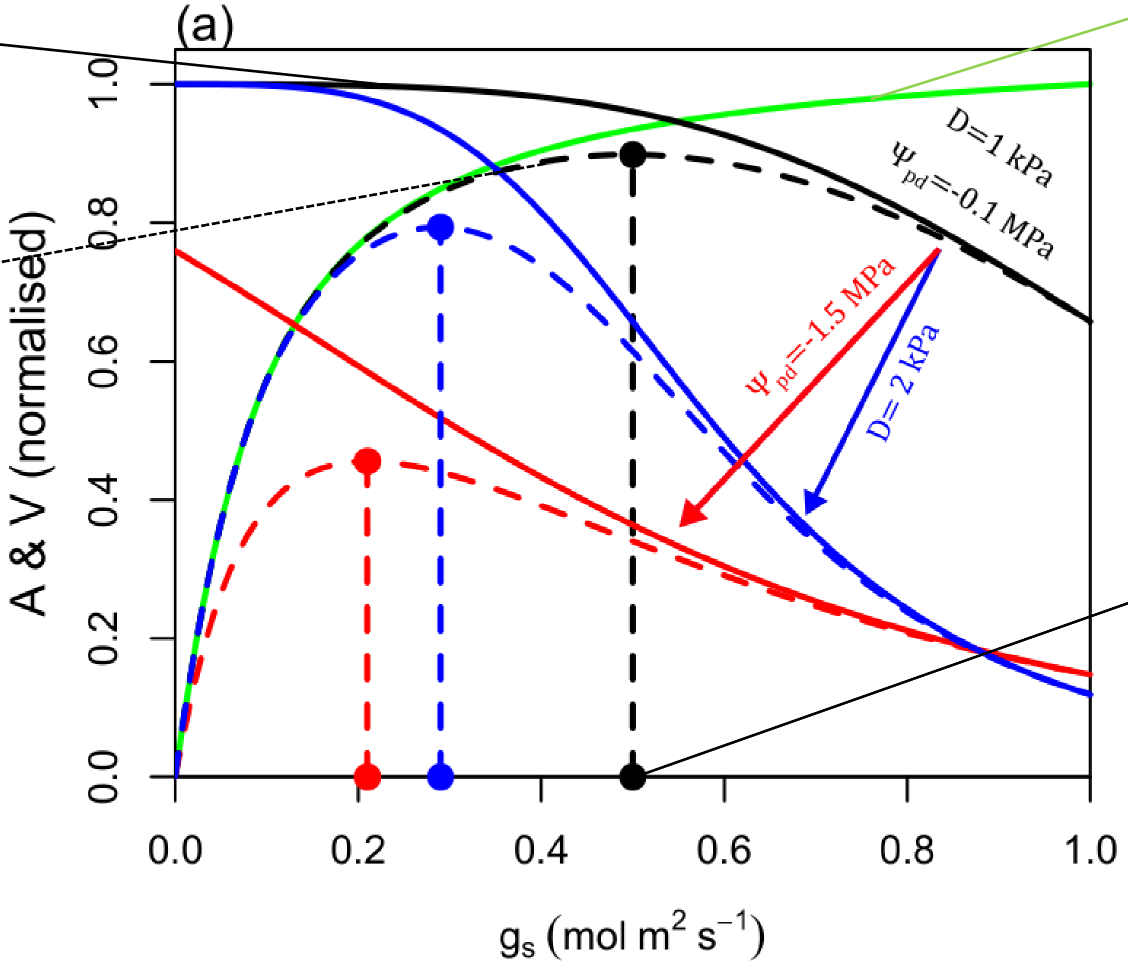
Plant photosynthesis model (A)



A Stomatal Optimization model based on Xylem hydraulics (SOX)

Xylem vulnerability to cavitation (V)

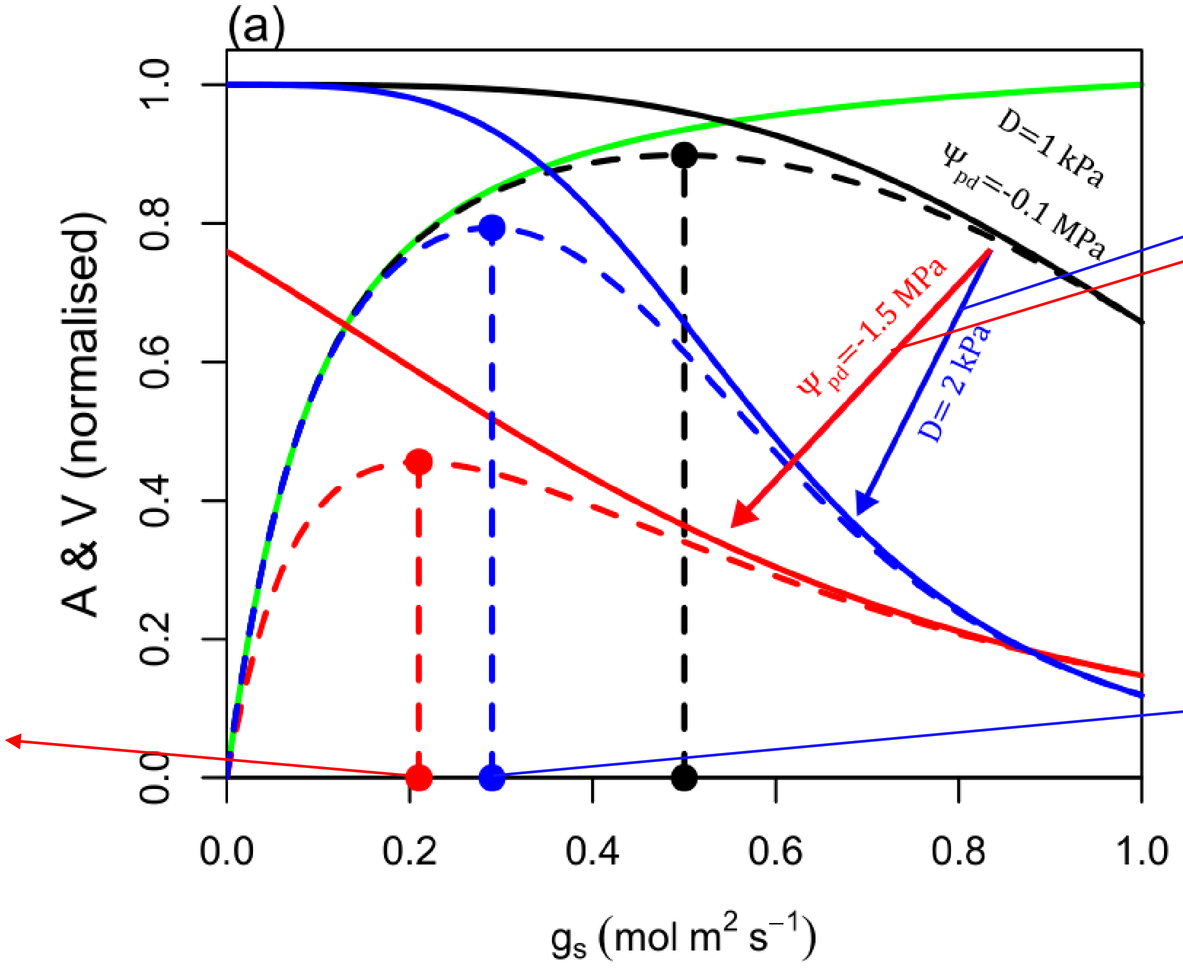
A*V



Plant photosynthesis model (A)

SOX predicts the optimum g_s is the value that maximises the product A and V.

A Stomatal Optimization model based on Xylem hydraulics (SOX)



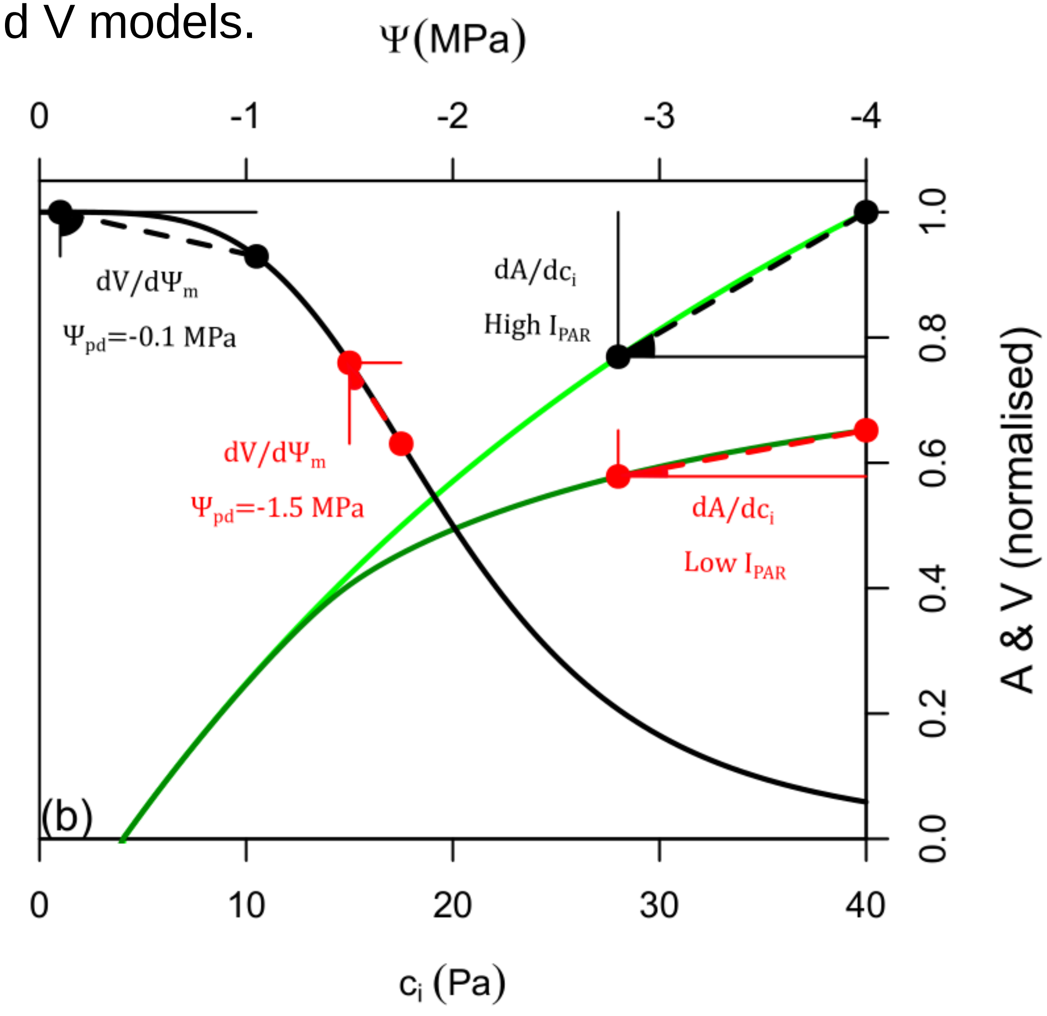
Changes in environmental conditions that affect A or V will shift the optimal g_s.

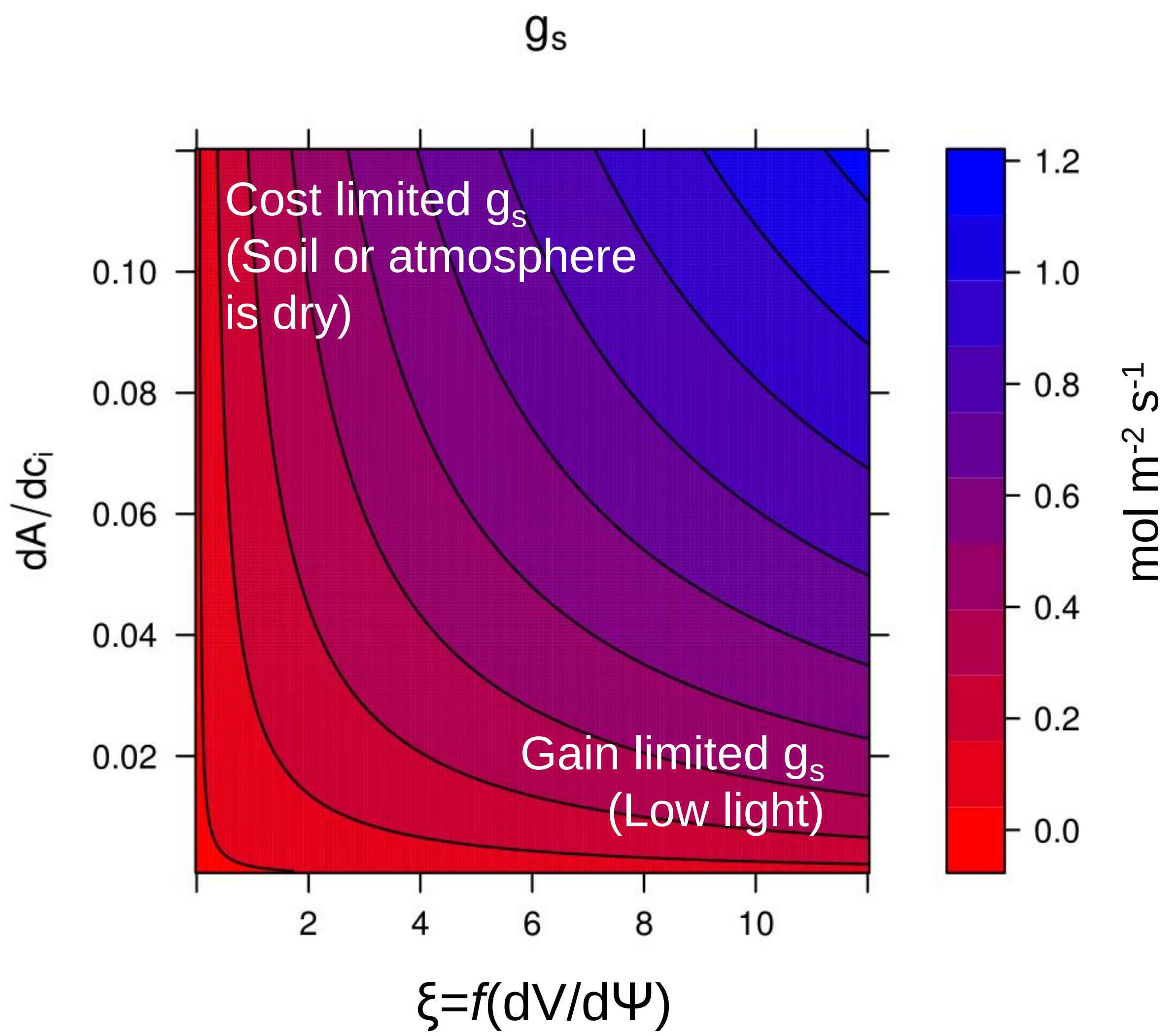
Optimal g_s at high atmospheric demand

Optimal g_s at low soil moisture

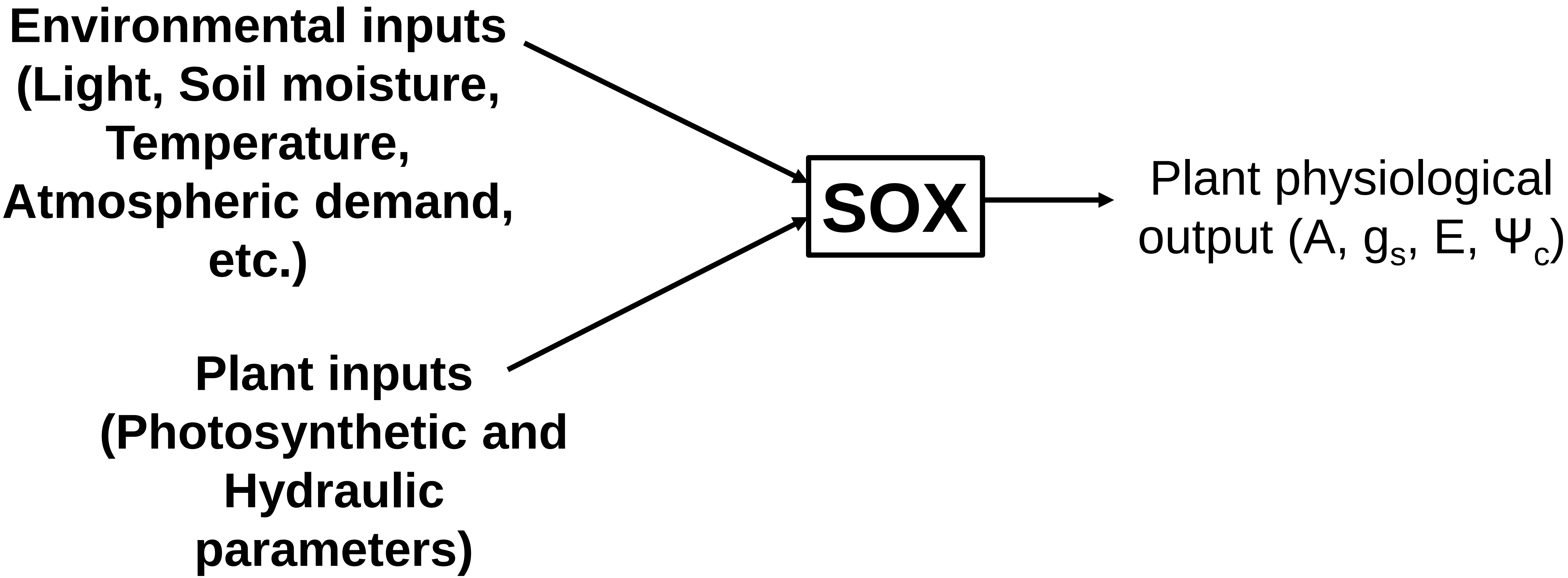
A Stomatal Optimization model based on Xylem hydraulics (SOX)

We can approximate the optimum g_s according with SOX calculating the numerical derivatives of the A and V models.





A Stomatal Optimization model based on Xylem hydraulics (SOX)



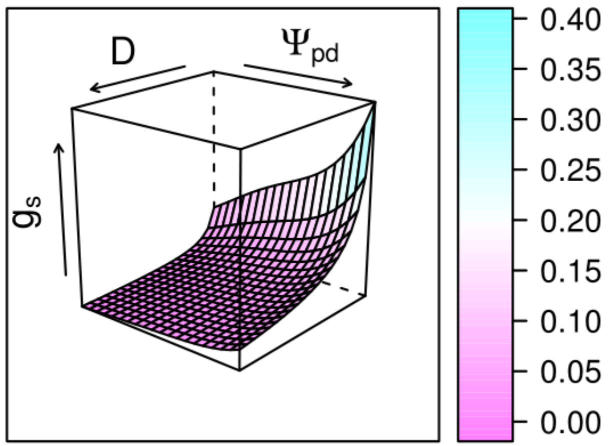
Environmental inputs (Light, Soil moisture, Temperature, Atmospheric demand, etc.)

Plant inputs (Photosynthetic and Hydraulic parameters)

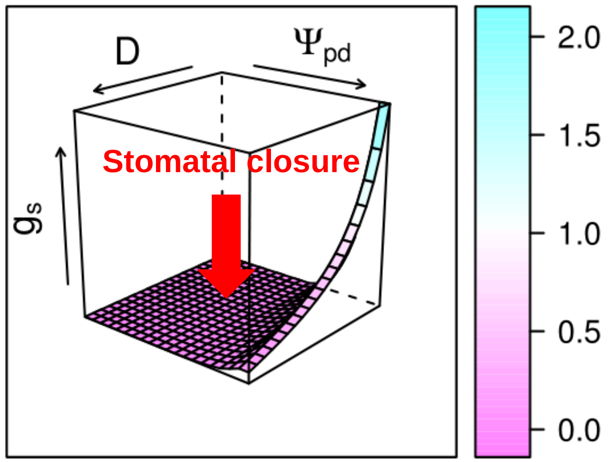
SOX

Plant physiological output (A, g_s, E, Ψ_c)

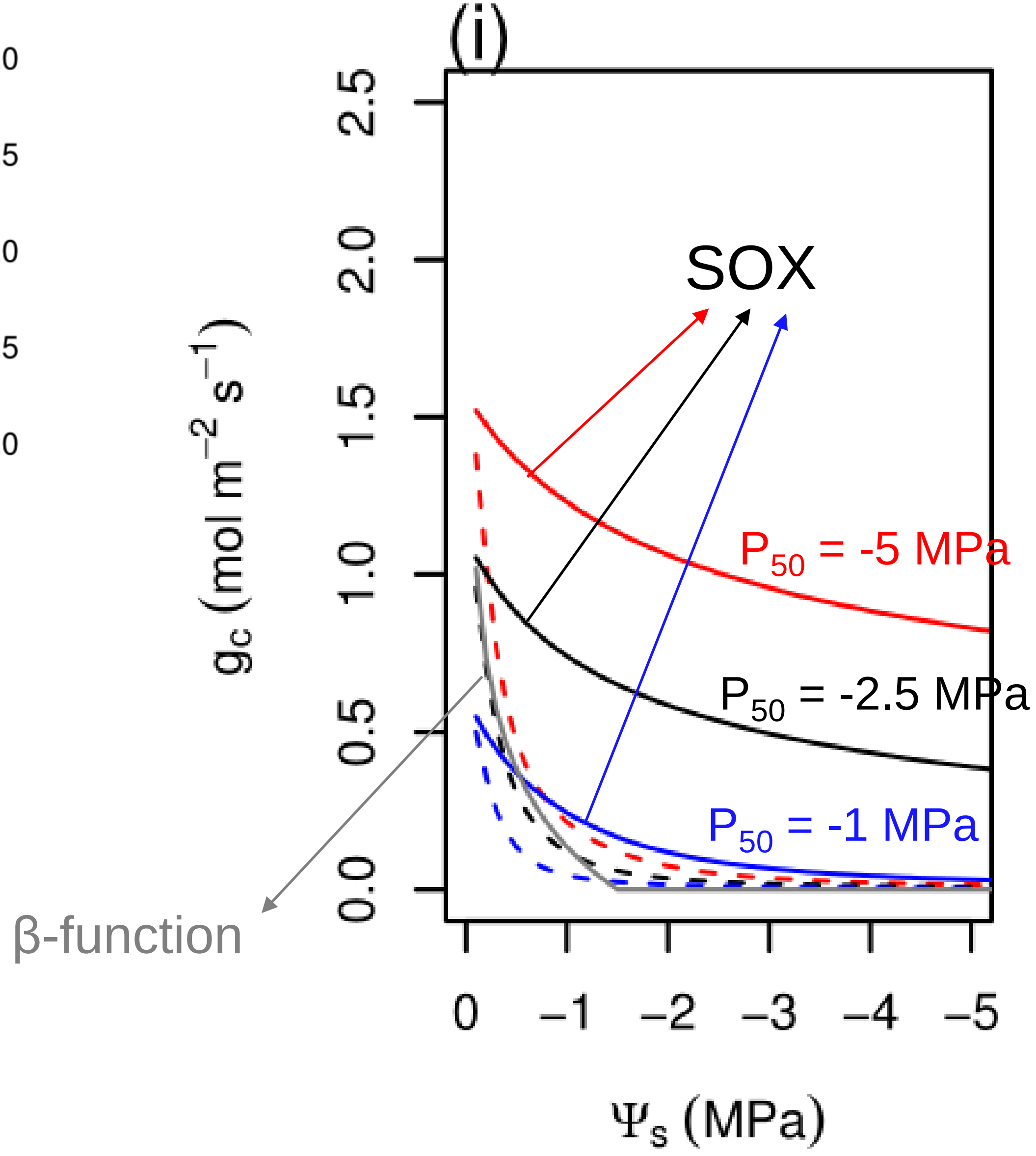
SOX



β-function

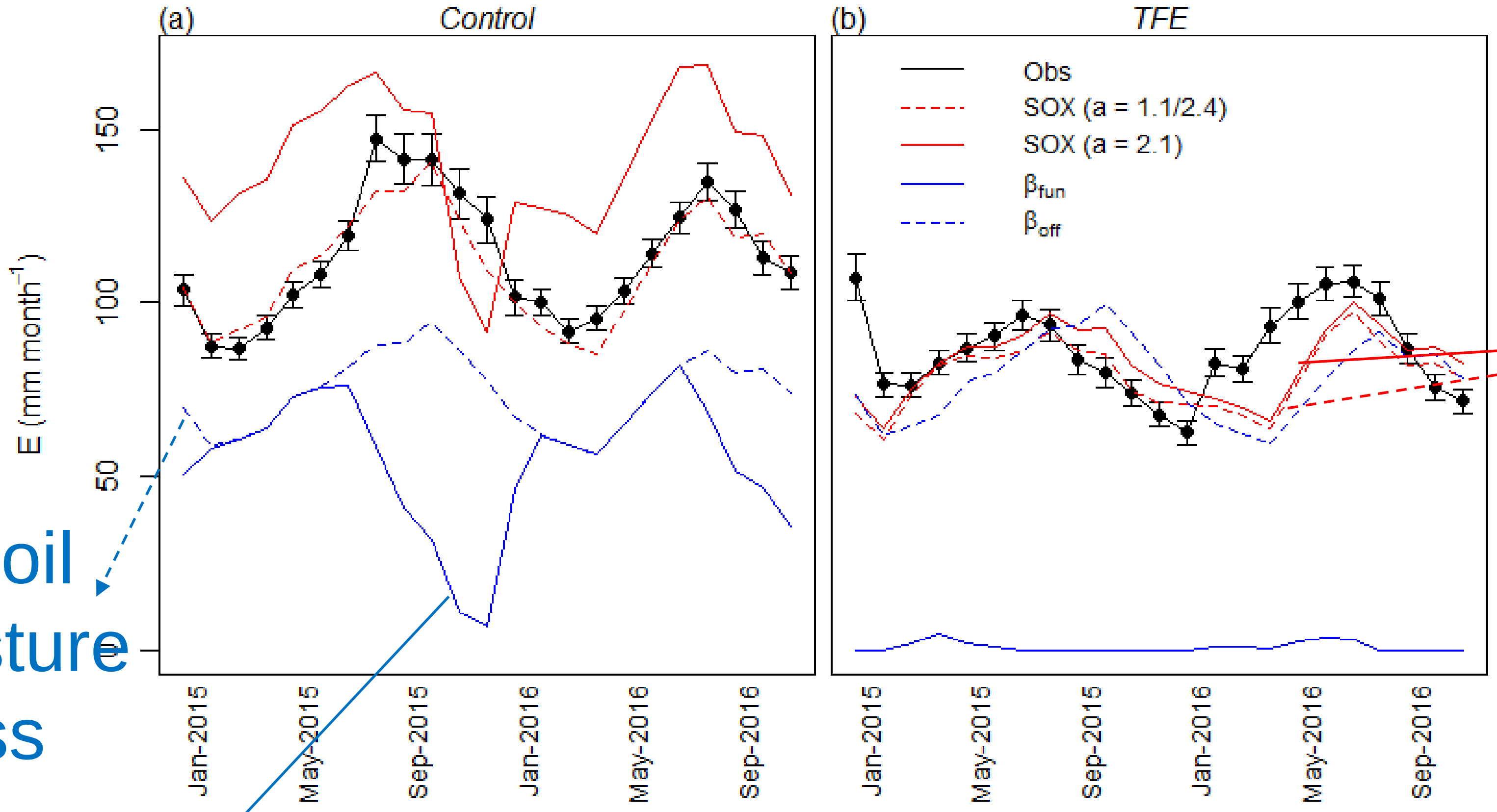


- SOX predicts plants should be much more resistant to drought, both from a dry atmosphere (high D) and from a dry soil (low Ψ_{pd}) than the β-function.



Eller et al *in press*

SOX predictions agree with amazon forest transpiration (*E*) even when the forest has been submitted to long term drought.



No soil moisture stress

β-function

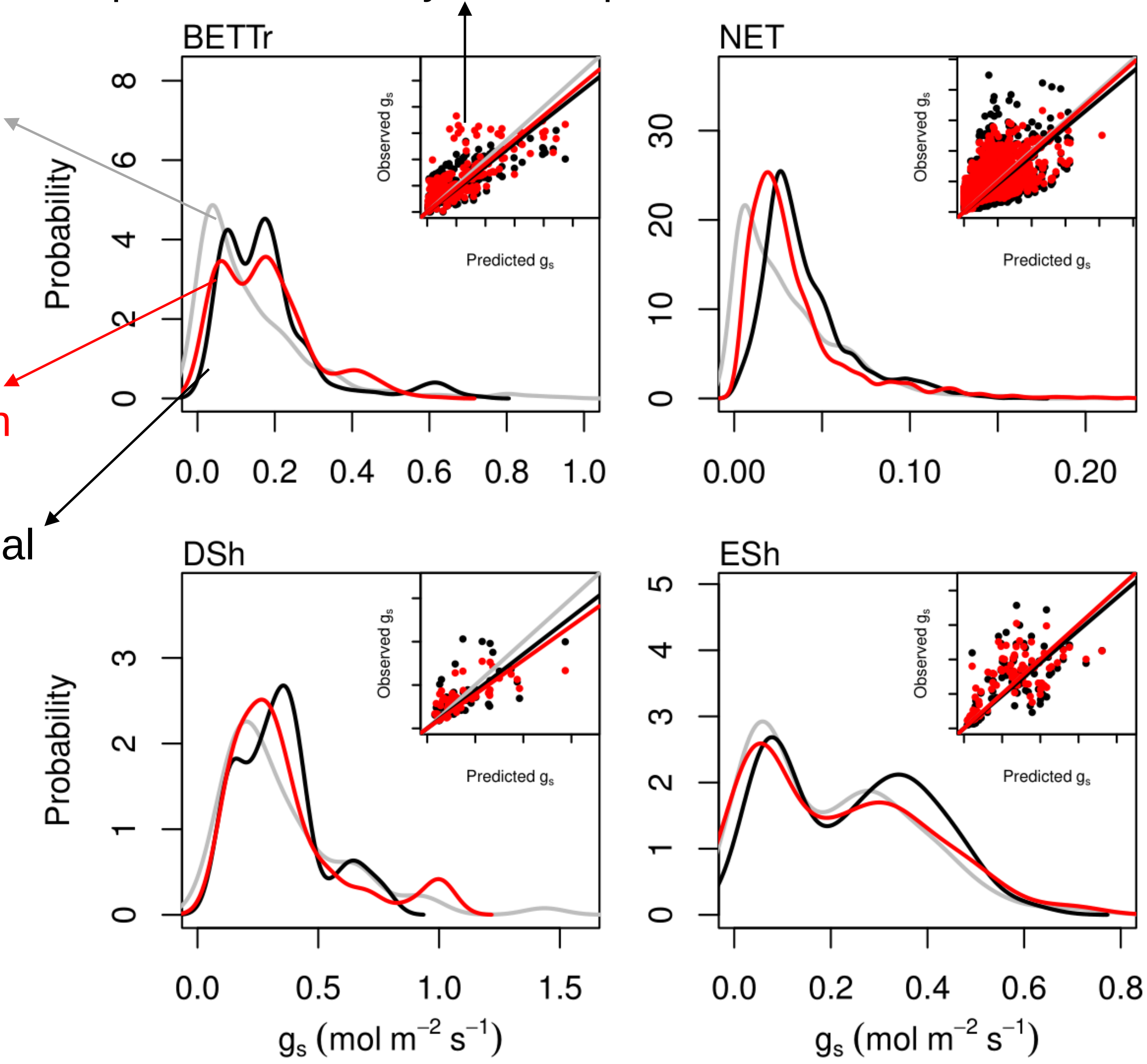
SOX

Throughfall exclusion treatment (TFE) at the Caxiuanã National Forest Drought experiment

Eller et al *in press*

How general is SOX?

- Good agreement with leaf-level observations in a wide range of woody PFTs (30+ species from 14 sites around the world)



Unexplained variability ~ Interspecific variation within PFT

Observed

Analytical approximation of SOX

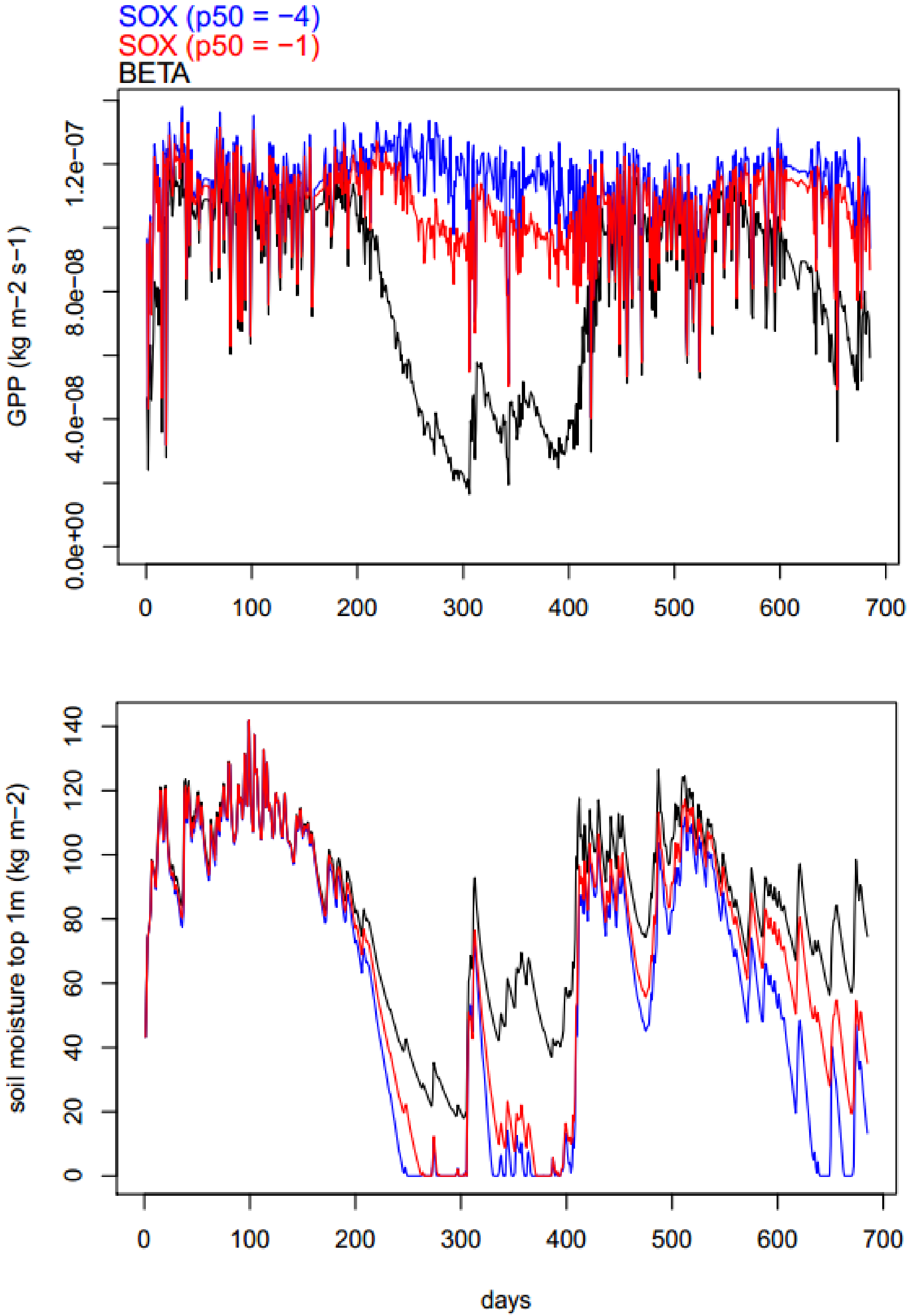
Numerical SOX

BETTr: Broadleaf Evergreen Tree-Tropical; **NET:** Needleleaf Evergreen Tree; **DSh:** Deciduous Shrub; **Esh:** Evergreen Shrub

(Numerical) SOX on JULES

- Even plants highly vulnerable to cavitation (Ψ_{50}=-1 MPa) are more resistant to soil drought than what the beta function predicts – so they allow the vegetation to sustain high GPP during drought.

- This less conservative water use promotes a very fast depletion of soil moisture – adjusts to the function describing the fitness costs of stomatal aperture might be a necessary improvement to the model.



Conclusions

- The Stomatal Optimisation based on Xylem hydraulics (SOX) provides a parsimonious and computationally efficient way to represent vegetation response to drought, using only three xylem hydraulic traits widely available.

- SOX reproduces well instantaneous plant responses of a wide variety of vegetation types.

- Further tests are necessary to evaluate the model capability of predicting long term drought responses on vegetation and its impact on soil moisture dynamics, as well as the need to incorporate additional processes on the cost and gain functions of the model.

Thanks