Will drought kill the carbon sink?

CMI 2017

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Over half of emitted CO$_2$ is kept from the atmosphere by natural sinks in forests and the ocean.

Fate of anthropogenic CO$_2$ emissions (2006-2015):
- 34.1 GtCO$_2$/yr (91%)
- 11.6 GtCO$_2$/yr (31%)
- 3.5 GtCO$_2$/yr (9%)

2005 Amazon drought 5.9 GtCO2
2010 Amazon drought 4.0 GtCO2
¾ due to tree mortality, ¼ due to reduced tree growth
Colors = 2010 drought index
We have no capacity to predict drought kill.

Tree death from drought is mysterious. Trees typically grow their stems rapidly while their canopies thin and then die years later. Worldwide phenomenon (Anderegg et al. Science 31: 2015).

Scientific controversy: Is this hydraulic damage or carbon starvation?

In contrast, the primary regulation of plant water loss was considered largely settled.
How is **stomatal conductance** regulated?
Collaborators and Former PU postdocs

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Assistant Professor
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Adam Wolf
CEO of Arable
With a Pulsepod
**Water potential (ψ)** - energy required to convert water from its current state to the reference state of liquid water at room temperature and pressure, which is defined as water potential equal to zero.

Water potentials in nature are typically negative. Plants who are sucking really hard on dry soil have very negative water potentials in their pipes (xylem).

Generally, I will use the words “water tension” which is minus water potential. Big tension means low potential or high suction.
An Empirical Model of Stomatal Conductance


Stomatal Conductance (mol H$_2$O m$^{-2}$ s$^{-1}$) is proportional to photosynthesis.

Stomatal Conductance (mol H$_2$O m$^{-2}$ s$^{-1}$) is inversely proportional to CO$_2$.

Stomatal Conductance (mol H$_2$O m$^{-2}$ s$^{-1}$) is inversely with dryness of air.

Ball and Berry


Luening

Evaporative water loss from plants in modern Earth System Models is constrained by a simple empirical model of stomatal conductance (usually Lueening).

The empirical models have enormous empirical support from many species and biomes under current environmental conditions.

But what guards against the wrong out-of-sample behavior in future climates?
The Water Use Efficiency Hypothesis or WUEH. From CF77, a 40 year-old paper:

With fixed available water, carbon gain will be highest if stomates are regulated to keep marginal water use efficiency constant (at least for days to weeks):

\[
\begin{align*}
\text{Increase in the rate of carbon gain caused by a small increase stomatal aperture.} & \quad = \quad \text{Corresponding increase in the rate of water loss.} \\
\end{align*}
\]

\[
\times \quad \text{Constant water price } \lambda.
\]
Approximate analytical solution:

\[ \Delta C_{\text{gain}} / \Delta E = \lambda \]

Implies:

Formula for the optimal stomatal conductance which is statistically indistinguishable from the empirical models.
Five cracks in the firmament.

1. No generally accepted way to predict $\lambda$, even over short time scales, or how it changes over weeks to seasons.
Crack 2: A Second Type of Shut-off Valve

Rate of flow through the stem equals the sum (integral) of the conductances of all the little segments of stem from root to leaf. Because of embolism:
Crack 3: The model is missing something fundamental during drought. It does not predict observed stomatal closure at low leaf water potential.

To predict drought response, Earth System Models add a **TUNED** Beta-Factor: usually a Weibull function of soil water potential:

\[
\beta(\psi_L) = \frac{1}{1 + e^{-(\psi_L - \psi_0)/\Delta \psi}}
\]

Stomatal Conductance = Formula from empirical model or optimum from WUEH \( \times \beta(\psi_L) \)
GPP (total photosynthetic carbon gain) reduction caused by the Beta-factor in 9 CMIP5 models.

A. Trugman and W. Anderegg (MS)

Inter-model variation is double global GPP!

This shows the dangers of model tuning. How will these models predict the out-of-sample droughts of the future?
Crack 4. Fundamentally, the WUEH optimization only makes sense if plants can save water below ground for later use.

But, super-abundant evidence sows that plants steal each other’s water:

Root radius 3X crown radius.


Adam Wolf: Half the heavy water added to a NJ oak’s crown area is transpired by neighbors.
Crack 5. Missing Carbon Costs of Low Xylem Potential

Cost of refilling embolized vessels. Reduced current photosynthesis due to partial leaf desiccation. Reduced future photosynthesis when xylem damage cannot be completely repaired.

Source: ZMEscience.com
Wolf, Anderegg and Pacala (PNAS 2016)

Added:
• Competition with below-ground water is a commons.
• Xylem embolism (the other shut-off valve)
• Hydraulic costs.

Nash equilibrium stomatal algorithm maximizes carbon gain at every instant:

$$\Delta C_{\text{gain}} / \Delta g_s = 0 \quad \text{not} \quad \Delta C_{\text{gain}} / \Delta E = \lambda$$

Carbon Maximization Hypothesis (CMH) \quad \text{WUEH}
Wolf et al. (2016) PNAS

The competitive (NASH) equilibrium predicts the empirical stomatal algorithm as well as the classical hypothesis, but also predicts observed stomatal closure at high leaf water tension. This constrains a critical unknown in Earth System Models.
Anderegg et al. (2017) assembled data from 34 species to directly test two hypotheses against one another (WUEH Vs. CMH). Three possible outcomes:

- **Water Use Efficiency Hypothesis**: Plants plan ahead and control their appetites.
- **Carbon Maximization Hypothesis**: Plants live in the moment and have no self control.
- **Not enough data.**
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![Graph showing the relationship between mean annual precipitation and temperature for different plant groups.](image)
1. Improve representation of topical rainforests in Earth System Models.


**LM3-PPA**

**Key patterns:**
- Carbon production
- Carbon Storage
- Evapotranspiration
- Growth/Death
- Leaf Area
- Size distribution

**Temporal scales:**
- Interannual
- Seasonal
- Diurnal cycles
Conclusions

Limiting climate change to 2 degrees means net-zero emissions after mid-century: carbon sinks dictate the size of the fossil economy.

The longevity of the terrestrial carbon sink depends on its response to drought. Amazonian droughts in 2005 and 2010 decreased the global sink by ~ 10 GtCO$_2$.

Existing carbon cycle models cannot predict the response of leaves, plants, forests or the carbon cycle to drought.

A new theory is supported by all available data and predicts the responses of leaves and plants to drought. We have the trees, now on to the forest and global carbon cycle.