CARBON GAIN AND RISK IN MODELING LEAF GAS EXCHANGE

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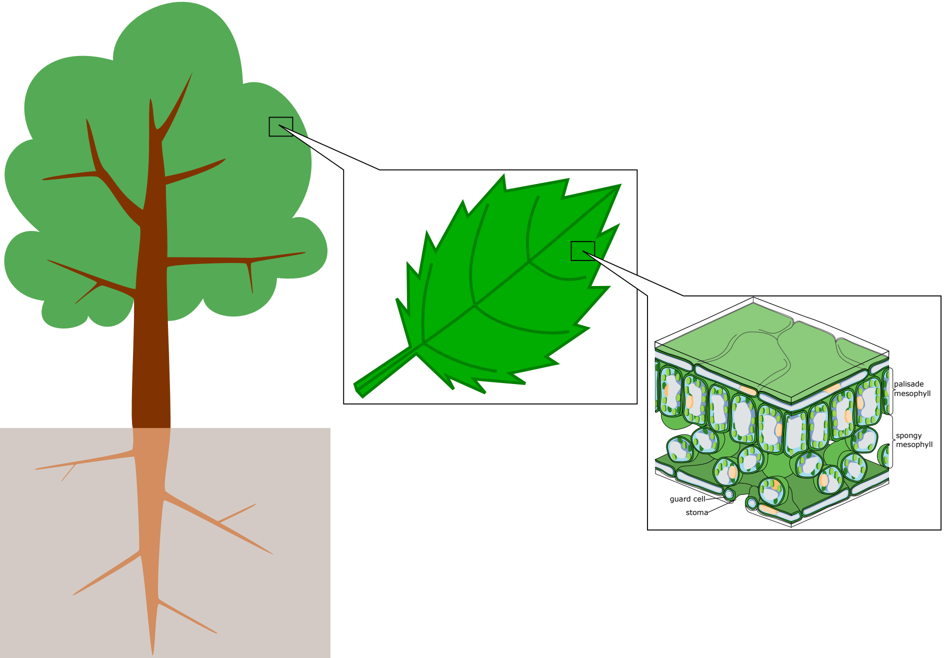
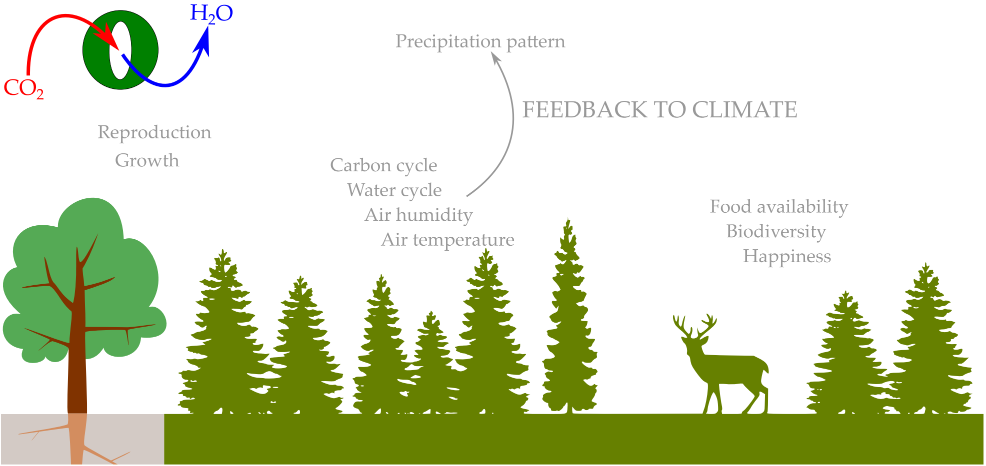

palisade mesophyll
spongy mesophyll
guard cell
stoma

Significance of leaf gas exchange



Uncertainty in land surface system

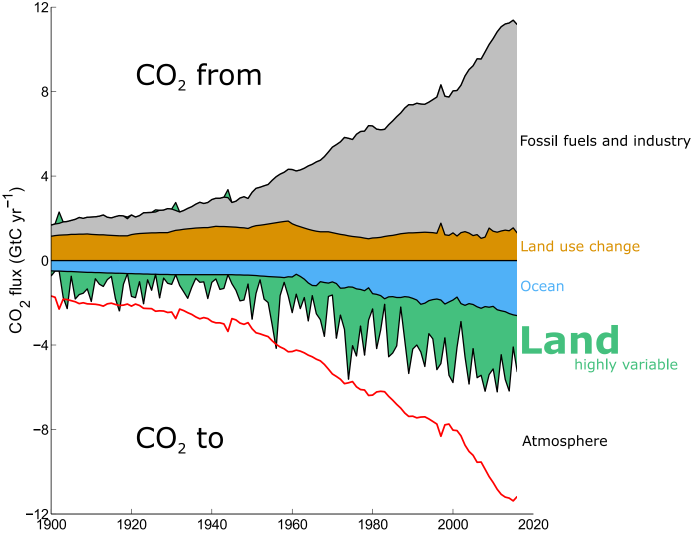
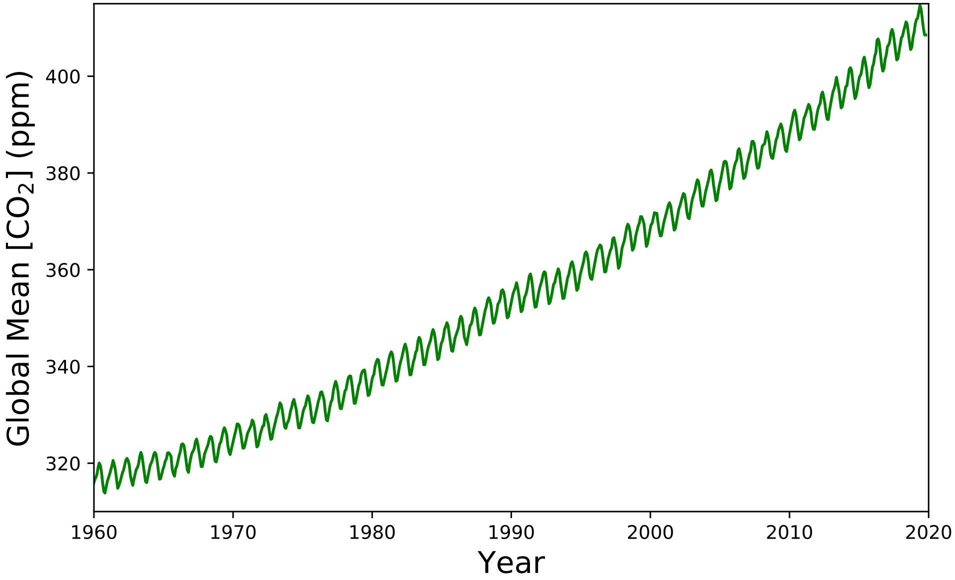
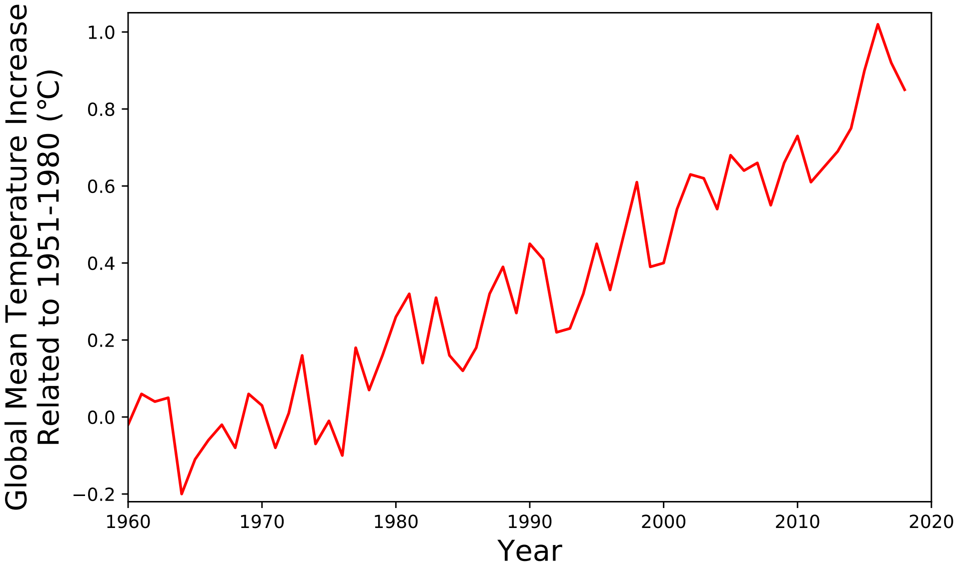


Figure adapted from Le Quéré et al. (2018)

Increasing CO_2 concentration



Increasing temperature



Soil moisture change

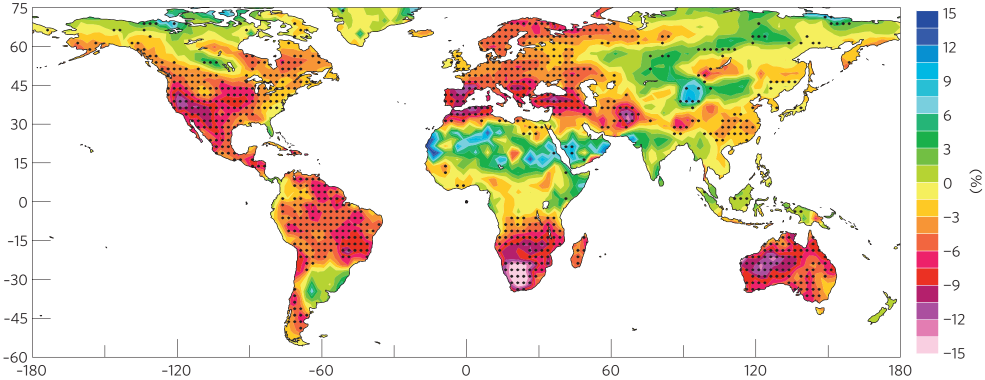


Figure from Dai (2013)

Role of land in the future

CO_2 Sink?

CO_2 Source?

Leaf gas exchange through stomata

PLANT PHYSIOLOGY

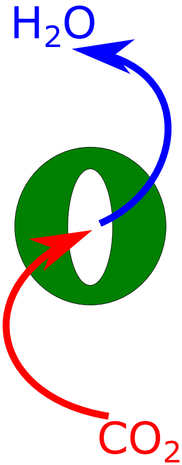
Abscisic acid

Leaf turgor pressure

Hydraulic conductance

Photosynthetic capacity

Mesophyll conductance



ENVIRONMENT

Atmospheric CO_2

Vapor pressure deficit

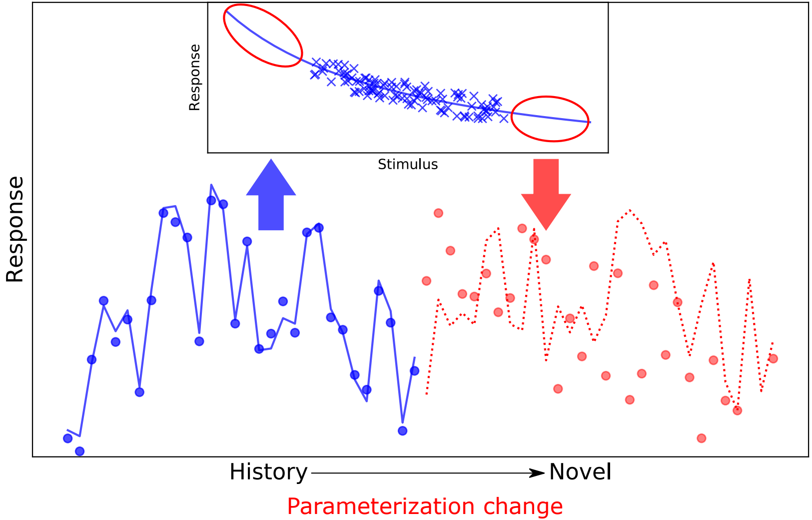
Air temperature

Solar radiation

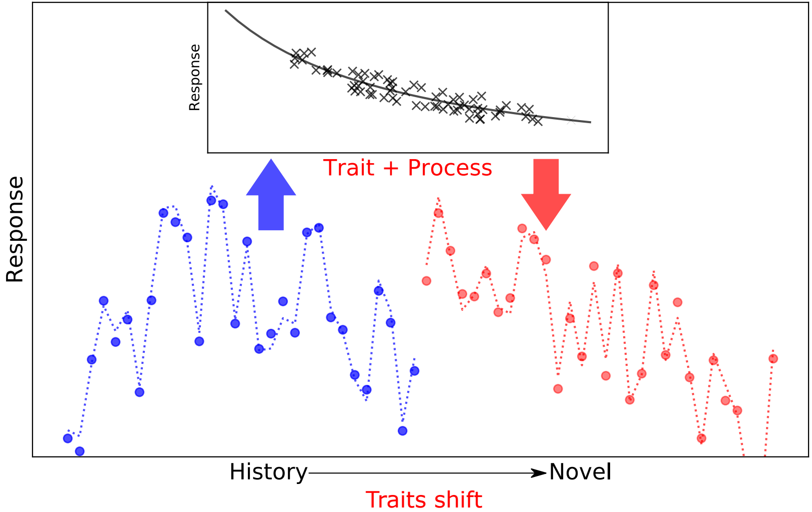
Wind speed

Soil moisture

The easiest way—statistical regression approach



A better way—physiological trait-based approach

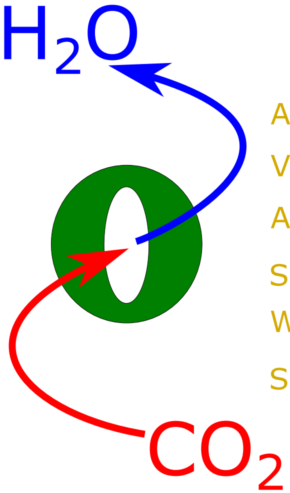


A better way—challenges

- How to model stomatal behavior from traits?
- How to model the shift of traits?

What we know

PLANT PHYSIOLOGY



Abscisic acid

Leaf turgor pressure

Hydraulic conductance

Photosynthetic capacity

Mesophyll conductance

ENVIRONMENT

Atmospheric CO_2

Vapor pressure deficit

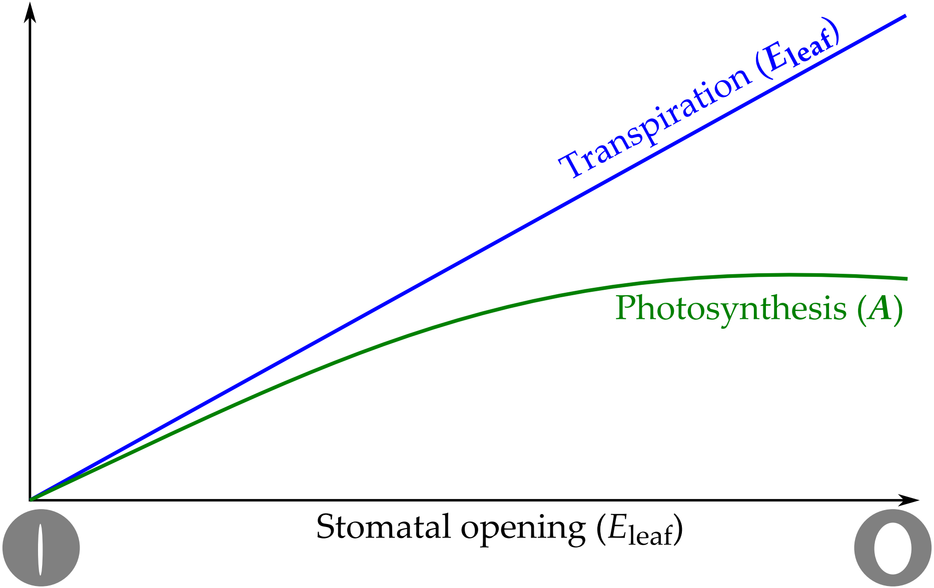
Air temperature

Solar radiation

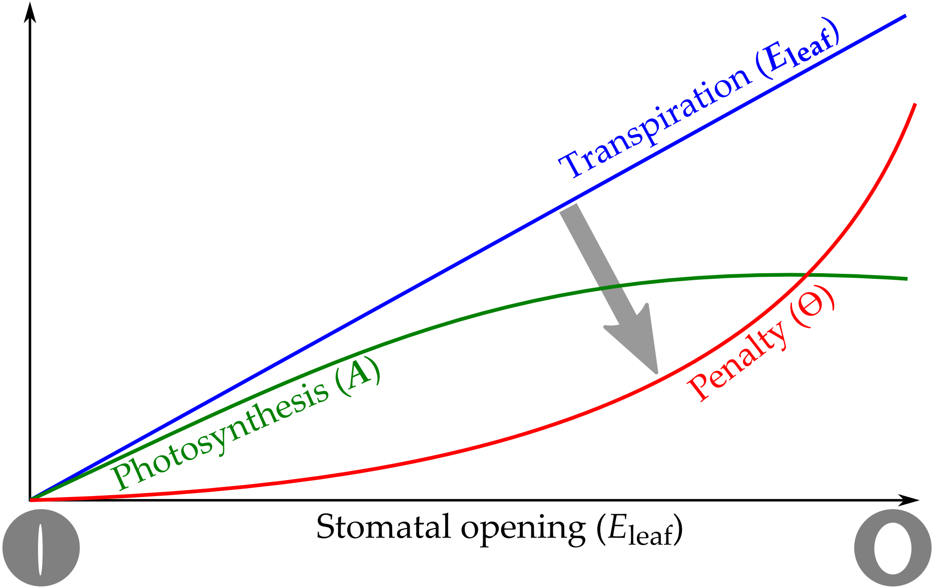
Wind speed

Soil moisture

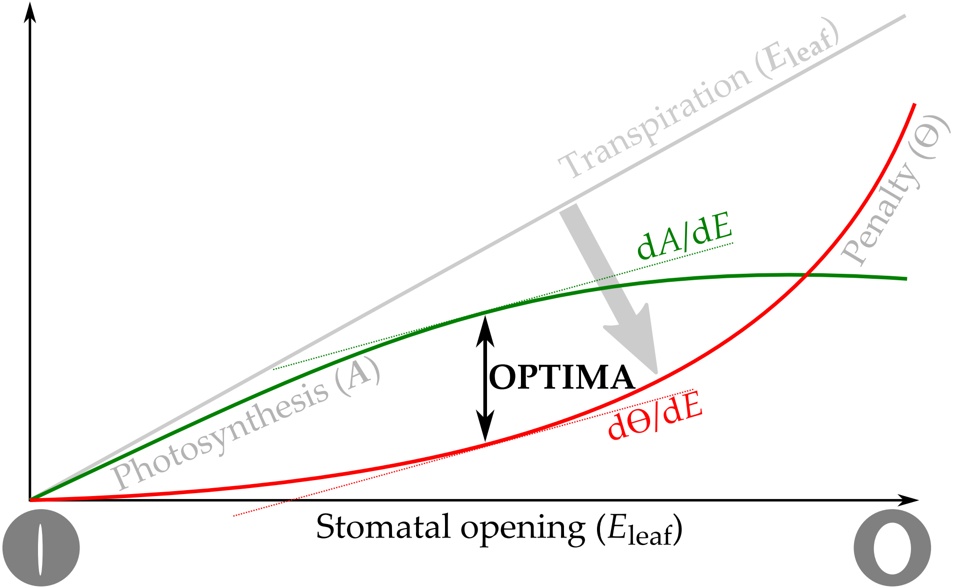
Quantify transpiration and photosynthesis



Translation to water penalty



Optimal stomatal opening



Stomatal optimization

$$\max(A(E_{\mathrm{leaf}}) - \Theta(E_{\mathrm{leaf}}))$$

The optimal solution is:

$$\frac{\mathrm{d}A}{\mathrm{d}E} = \frac{\mathrm{d}\Theta}{\mathrm{d}E}$$

Wolf et al. (2016)

1. Quantify $A(E_{\text{leaf}})$
2. Quantify $\Theta(E_{\text{leaf}})$
3. Test different optimization models
4. Way forward—long-term prediction

Symbols

A Photosynthesis;

Θ Penalty;

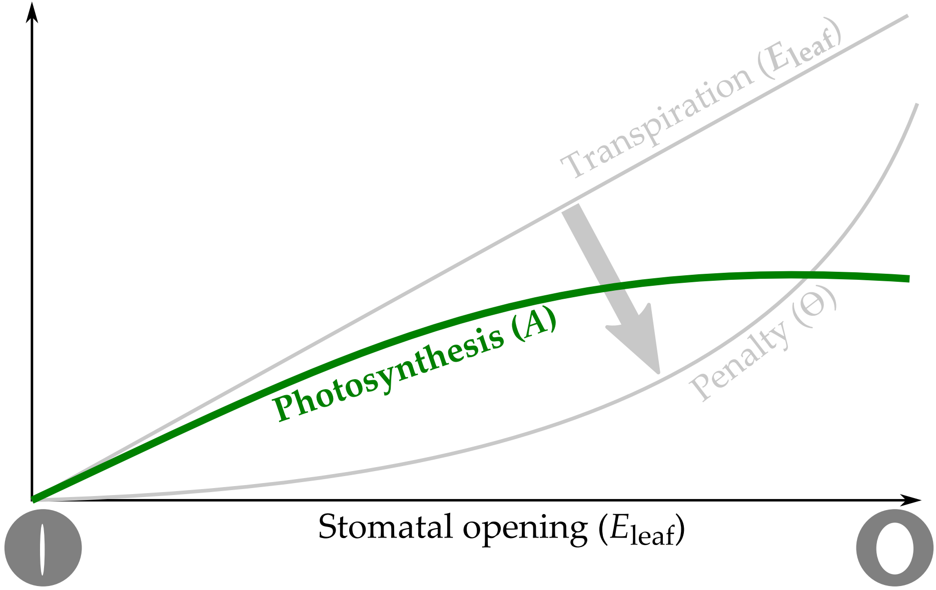
E, E_{leaf} Transpiration;

$\mathrm{d}A/\mathrm{d}E$ Marginal carbon gain;

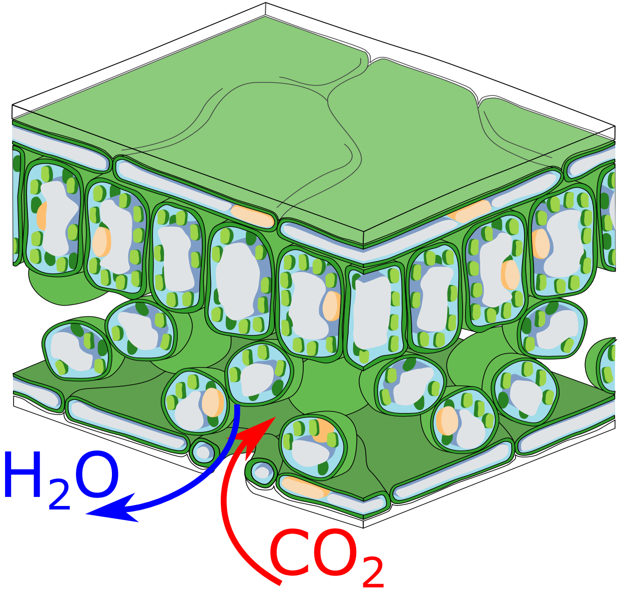
$\mathrm{d}\Theta/\mathrm{d}E$ Marginal water penalty.

Part I
Quantify Carbon Gain

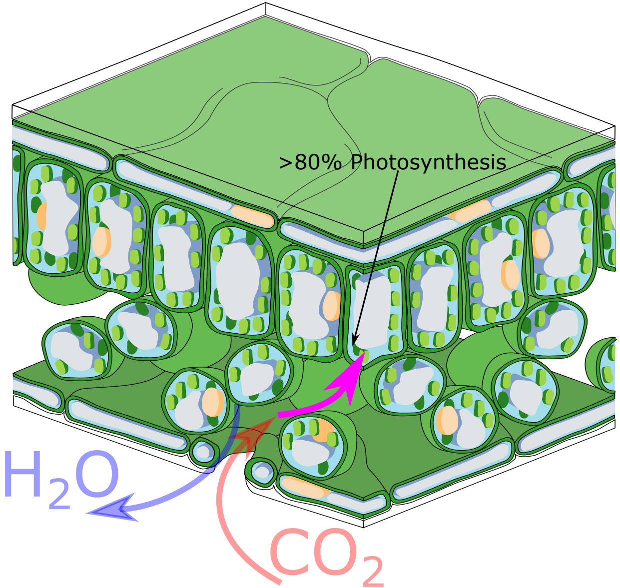
Quantify carbon gain—photosynthesis (A)



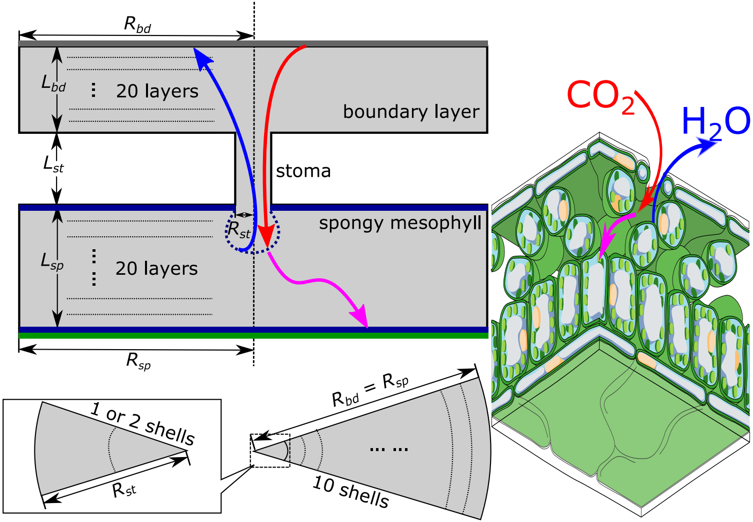
Classic photosynthesis model



The "missing" components

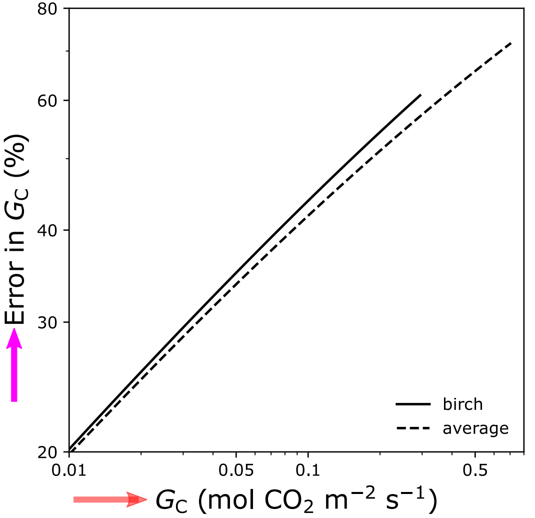


Mysophyll limitation



Wang et al., (in review)

Mesophyll limitation as an "error"



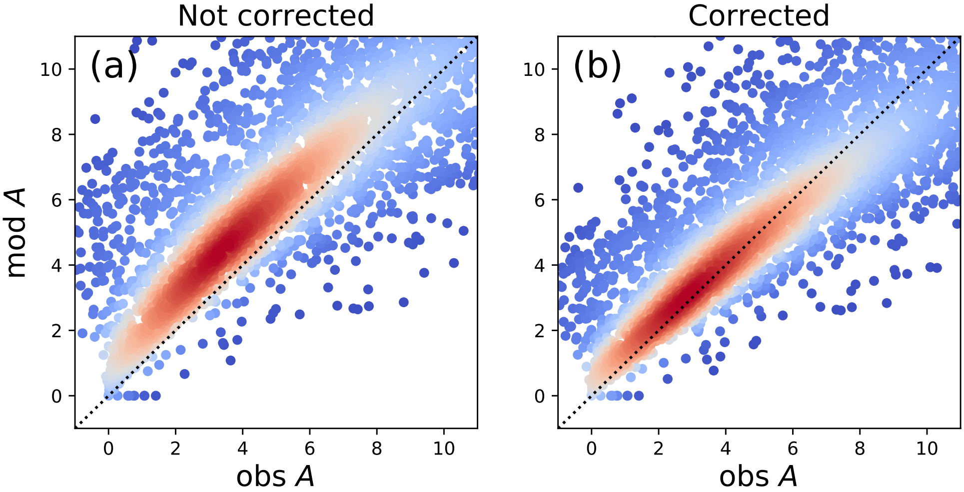
Improved photosynthesis model

classic model

$$G_C' = \frac{G_C}{1 + a \cdot G_C^b}$$

corrected model

Improvement of modeled A

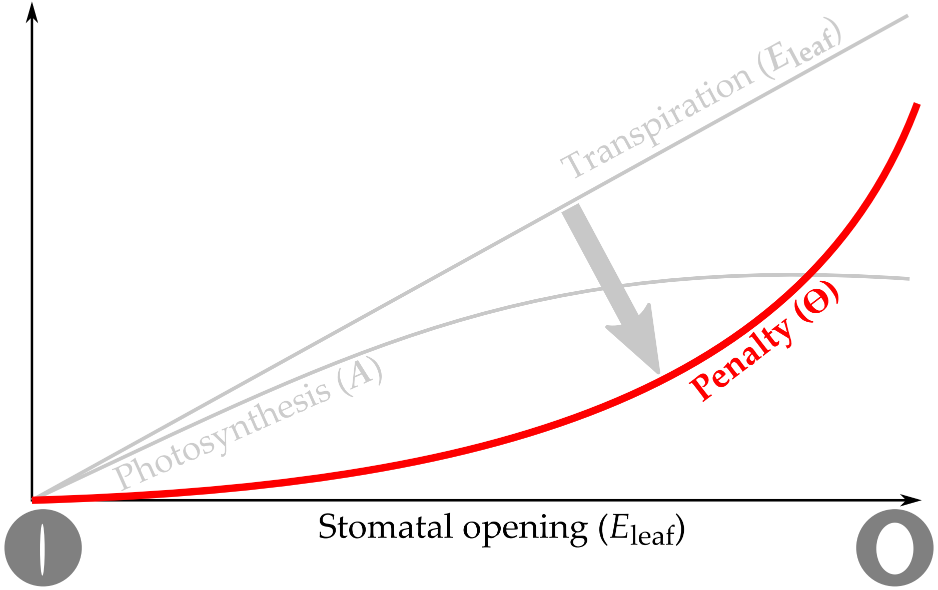


✓ Quantify $A(E_{\mathrm{leaf}})$

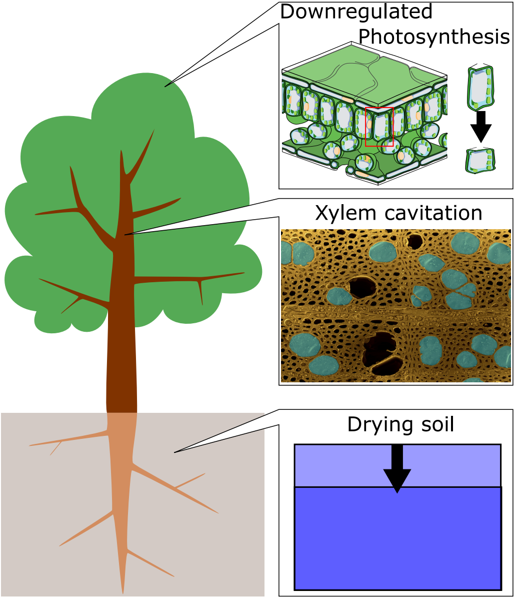
2. Quantify $\Theta(E_{\mathrm{leaf}})$
3. Test different optimization models
4. Way forward—long-term prediction

Part II
Quantify Water Penalty

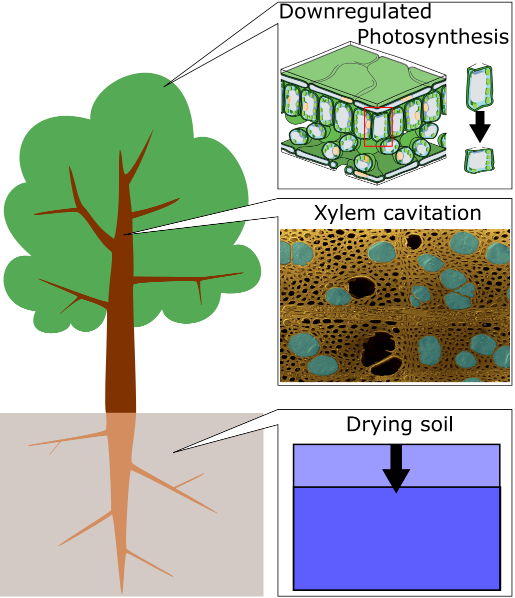
Quantify water penalty (Θ)



Causes of water penalty (Θ)



Models based on different Θ



Holtta *et al.* (2017)
Dewar *et al.* (2018)
Huang *et al.* (2018)
... ...

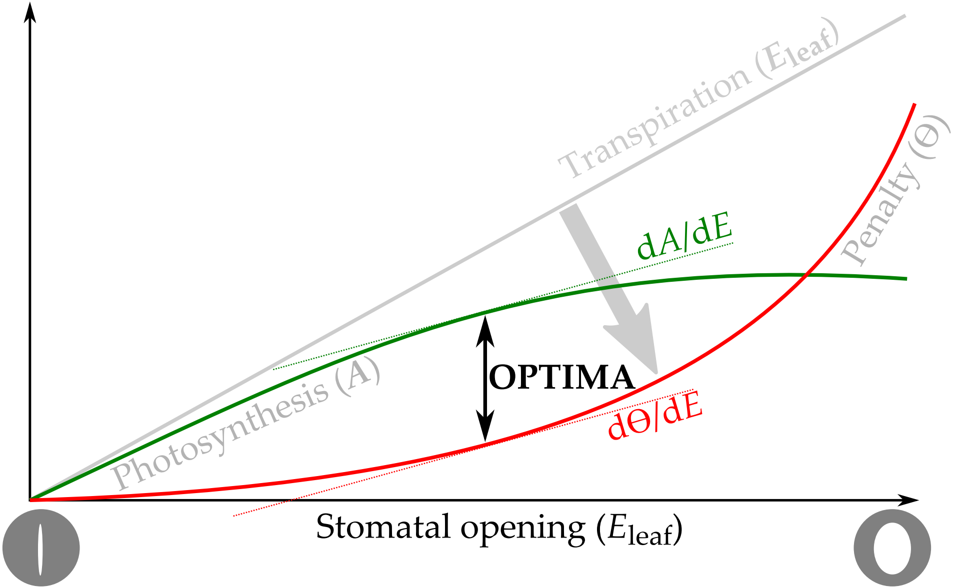
Wolf *et al.* (2016)
Sperry *et al.* (2017)
Anderegg *et al.* (2018)
Eller *et al.* (2019)
... ...

Cowan & Farquhar (1977)
... ...
Manzoni *et al.* (2013)
Prentice *et al.* (2014)
Lu *et al.* (2016)
... ...

Model reviewed

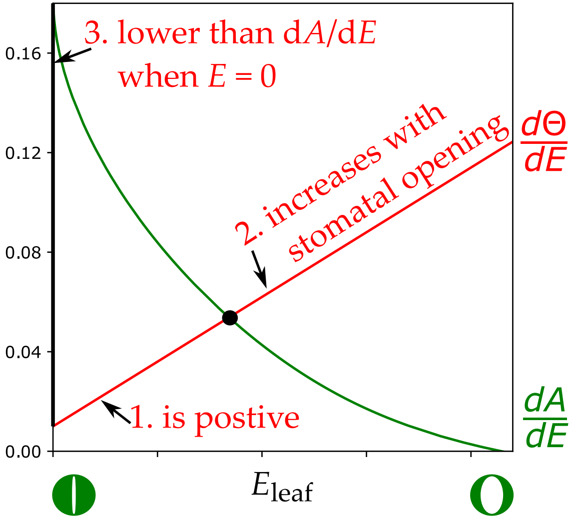
Model	Reference	Water Penalty (Θ or Θ')	Marginal Penalty ($\mathrm{d}\Theta/\mathrm{d}E$ or $\mathrm{d}\Theta'/\mathrm{d}E$)	Criteria I–III	Response Criteria IV–VII DCPK	Fitting parameters
Cowan-Farquhar	(Cowan and Farquhar, 1977)	$\Theta = \frac{E_{\mathrm{leaf}}}{\lambda}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{1}{\lambda}$	YNN	NNNN	λ
Manzoni	(Manzoni et al., 2013)	$\Theta = \frac{E_{\mathrm{leaf}}}{\Lambda}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{1}{\Lambda}$	YNN	NNNN	Λ
Prentice	(Prentice et al., 2014)	$\Theta = A \cdot \left(1 - \frac{1}{c_{\mathrm{E}} E_{\mathrm{leaf}} + c_{\mathrm{V}} V_{\mathrm{cmax}}}\right)$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{A}{E_{\mathrm{leaf}} + \frac{c_{\mathrm{V}}}{c_{\mathrm{E}}} V_{\mathrm{cmax}}}$	YNY	YYNN	c_{E}, c_{V}
Lu	(Lu et al., 2016)	$\Theta = \frac{E_{\mathrm{leaf}}}{\lambda}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{1}{\lambda}$	YNN	NNNN	λ
Wolf-Anderegg	(Wolf et al., 2016) (Anderegg et al., 2018)	$\Theta = aP^2 + bP + c$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{2aP + b}{K}$	YYN	NNYY	a, b, K_{rhiz}
Sperry	(Sperry et al., 2017)	$\Theta = A_{\mathrm{max}} \cdot \left(1 - \frac{K}{K_{\mathrm{max}}}\right)$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = -\frac{\mathrm{d}K}{\mathrm{d}E} \cdot \frac{A_{\mathrm{max}}}{K_{\mathrm{max}}}$	YYY	YYYY	K_{rhiz}
Eller	(Eller et al., 2018)	$\Theta = A \cdot \left(1 - \frac{K}{K_{\mathrm{max,0}}}\right)$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = -\frac{\mathrm{d}K}{\mathrm{d}E} \cdot \frac{A}{K}$	YYY	YYYN	K_{rhiz}
New Model		$\Theta = A \cdot \frac{E_{\mathrm{leaf}}}{E_{\mathrm{crit}}}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{A}{E_{\mathrm{crit}} - E_{\mathrm{leaf}}}$	YYY	YYYY	K_{rhiz}
Hölttä	(Hölttä et al., 2017)	$\Theta' = A_{\mathrm{ww}} \cdot \frac{\mathrm{SC}}{\mathrm{SC}_{\mathrm{max}}}$	$\frac{\mathrm{d}\Theta'}{\mathrm{d}E} = \frac{A}{\mathrm{SC}_{\mathrm{max}} - \mathrm{SC}} \cdot \frac{\mathrm{dSC}}{\mathrm{d}E}$	YYY	YYYY	$\mathrm{SC}_{\mathrm{max}}$, K_{rhiz}, anatomy
Dewar CAP	(Dewar et al., 2018)	$\Theta' = A_{\mathrm{ww}} \cdot \frac{P}{P_{\mathrm{crit}}}$	$\frac{\mathrm{d}\Theta'}{\mathrm{d}E} = \frac{A}{K \cdot (P_{\mathrm{crit}} - P)}$	YYY	YYYY	K_{rhiz}

Mathematical tips

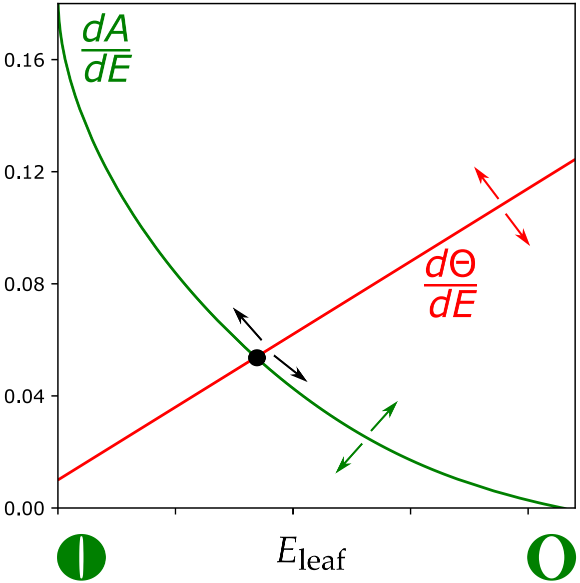


Criteria for a unique solution

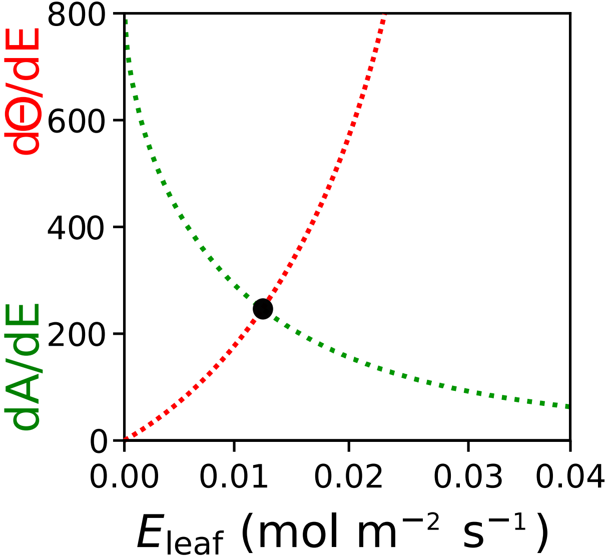
$$\frac{dA}{dE} = \frac{d\Theta}{dE}$$



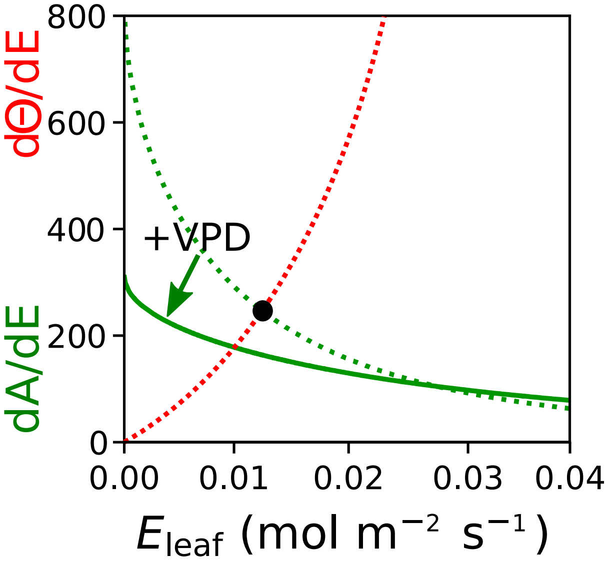
Criteria for responses to the environment



4. decreases with higher VPD (drier air)



4. decreases with higher VPD (drier air)



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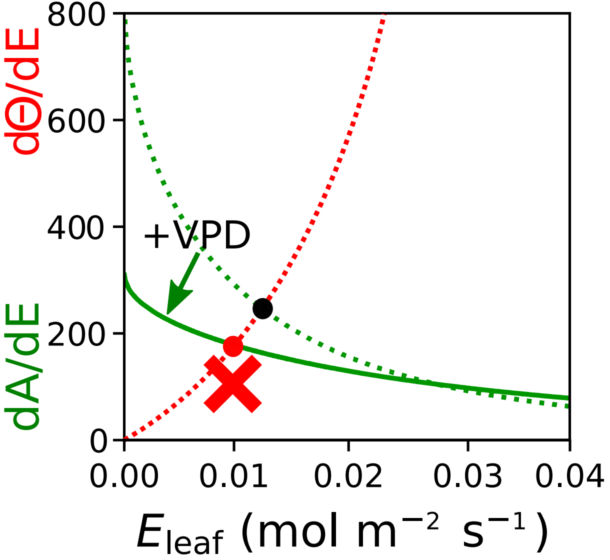

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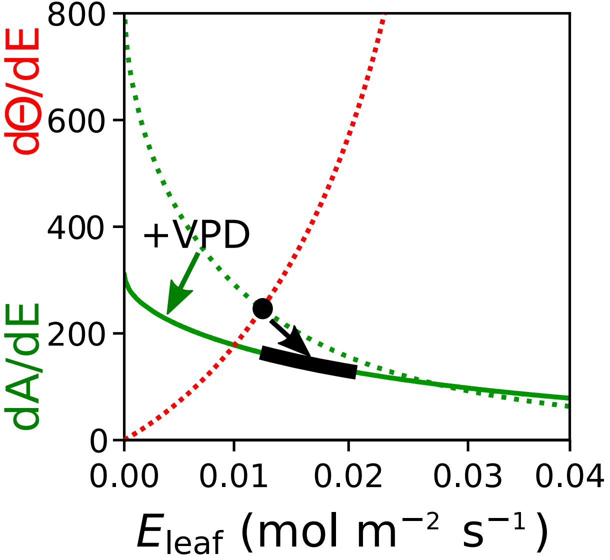

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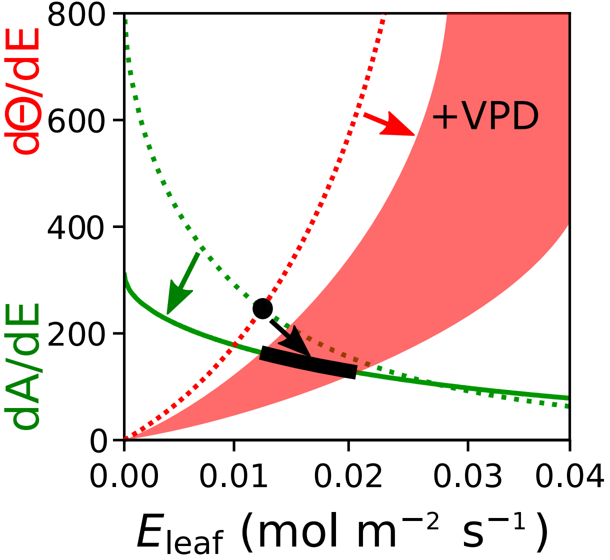
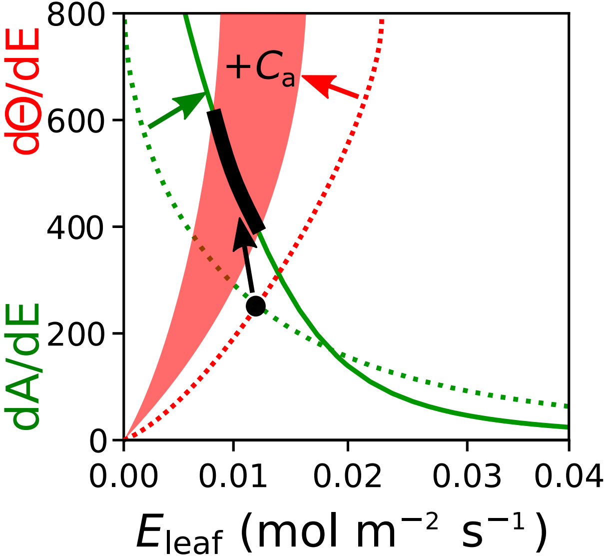
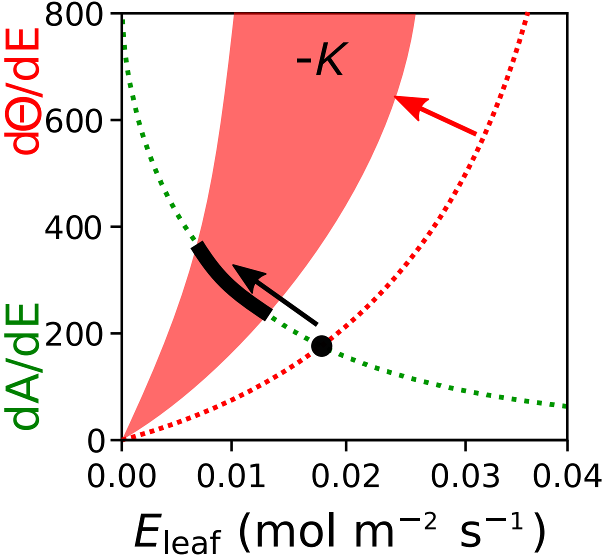


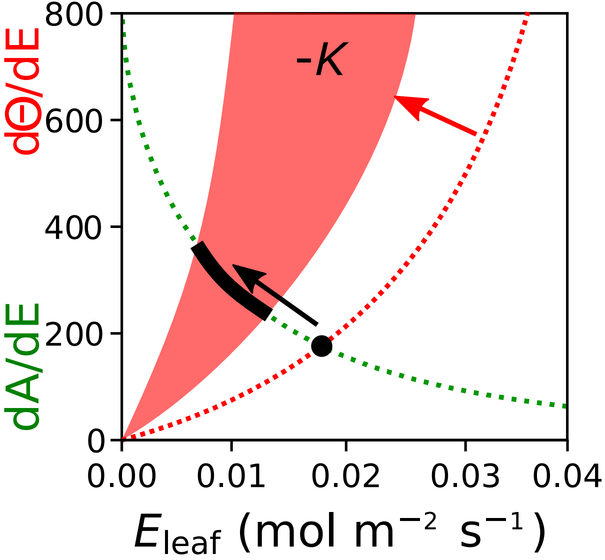
5. increases with higher CO_2



6. increases with drier soil



7. increases with lower hydraulic conductance



Criteria for $\mathrm{d}\Theta/\mathrm{d}E$

Criteria for a unique solution

1. $\mathrm{d}\Theta/\mathrm{d}E > 0$
2. $\mathrm{d}\Theta/\mathrm{d}E \Uparrow$ when $E_{\mathrm{leaf}} \Uparrow$
3. $\mathrm{d}\Theta/\mathrm{d}E < \mathrm{d}A/\mathrm{d}E$ when $E_{\mathrm{leaf}} = 0$

Criteria for stomatal responses

4. $\mathrm{d}\Theta/\mathrm{d}E \Downarrow$ when air gets drier
5. $\mathrm{d}\Theta/\mathrm{d}E \Uparrow$ when $[CO_2] \Uparrow$
6. $\mathrm{d}\Theta/\mathrm{d}E \Uparrow$ when soil gets drier
7. $\mathrm{d}\Theta/\mathrm{d}E \Uparrow$ when hydraulic conductance $\Downarrow$

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Eller	(Eller et al., 2018)	$\Theta = A \cdot \left(1 - \frac{K}{K_{\mathrm{max,0}}}\right)$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = -\frac{\mathrm{d}K}{\mathrm{d}E} \cdot \frac{A}{K}$	YYY	YYYN	K_{rhiz}
New Model		$\Theta = A \cdot \frac{E_{\mathrm{leaf}}}{E_{\mathrm{crit}}}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{A}{E_{\mathrm{crit}} - E_{\mathrm{leaf}}}$	YYY	YYYY	K_{rhiz}
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Lu	(Lu et al., 2016)	$\Theta = \frac{E_{\text{leaf}}}{\lambda}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{1}{\lambda}$	YNN	NNNN	λ
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Sperry	(Sperry et al., 2017)	$\Theta = A_{\text{max}} \cdot \left(1 - \frac{K}{K_{\text{max}}}\right)$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = -\frac{\mathrm{d}K}{\mathrm{d}E} \cdot \frac{A_{\text{max}}}{K_{\text{max}}}$	YYY	YYYY	K_{rhiz}
Eller	(Eller et al., 2018)	$\Theta = A \cdot \left(1 - \frac{K}{K_{\text{max},0}}\right)$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = -\frac{\mathrm{d}K}{\mathrm{d}E} \cdot \frac{A}{K}$	YYY	YYYN	K_{rhiz}
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Hölttä	(Hölttä et al., 2017)	$\Theta' = A_{\text{ww}} \cdot \frac{\text{SC}}{\text{SC}_{\text{max}}}$	$\frac{\mathrm{d}\Theta'}{\mathrm{d}E} = \frac{A}{\text{SC}_{\text{max}} - \text{SC}} \cdot \frac{\mathrm{dSC}}{\mathrm{d}E}$	YYY	YYYY	$\text{SC}_{\text{max}}, K_{\text{rhiz}}$, anatomy
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Example 1: The Cowan-Farquhar model

Criterion

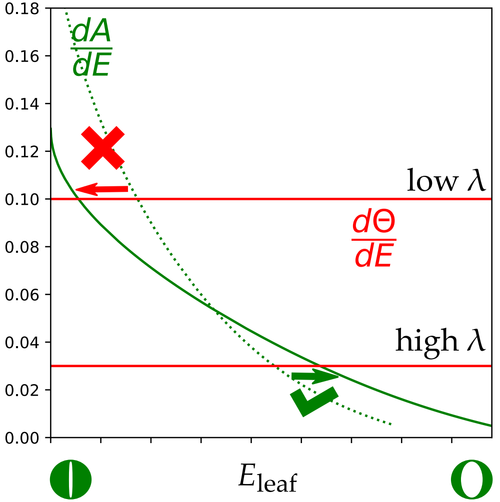
$$\max\left(A - \frac{E_{\text{leaf}}}{\lambda}\right)$$

Marginal penalty

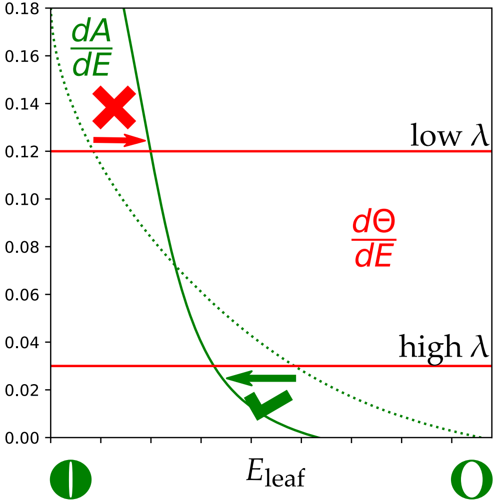
$$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{1}{\lambda}$$

Cowan and Farquhar (1977)

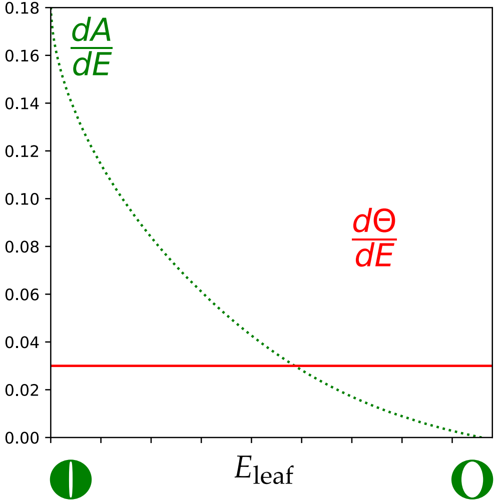
Response to VPD



Response to CO_2



Response to drought (history)



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Prentice	(Prentice et al., 2014)	$\Theta = A \cdot \left(1 - \frac{1}{c_E E_{leaf} + c_V V_{cmax}}\right)$	$\frac{d\Theta}{dE} = \frac{A}{E_{leaf} + \frac{c_V}{c_E} V_{cmax}}$	YNY	YYNN	c_E, c_V
Lu	(Lu et al., 2016)	$\Theta = \frac{E_{leaf}}{\lambda}$	$\frac{d\Theta}{dE} = \frac{1}{\lambda}$	YNN	NNNN	λ
Wolf-Anderegg	(Wolf et al., 2016) (Anderegg et al., 2018)	$\Theta = aP^2 + bP + c$	$\frac{d\Theta}{dE} = \frac{2aP + b}{K}$	YYN	NNYY	a, b, K_{rhiz}
Sperry	(Sperry et al., 2017)	$\Theta = A_{max} \cdot \left(1 - \frac{K}{K_{max}}\right)$	$\frac{d\Theta}{dE} = -\frac{dK}{dE} \cdot \frac{A_{max}}{K_{max}}$	YYY	YYYY	K_{rhiz}
Eller	(Eller et al., 2018)	$\Theta = A \cdot \left(1 - \frac{K}{K_{max,0}}\right)$	$\frac{d\Theta}{dE} = -\frac{dK}{dE} \cdot \frac{A}{K}$	YYY	YYYN	K_{rhiz}
New Model		$\Theta = A \cdot \frac{E_{leaf}}{E_{crit}}$	$\frac{d\Theta}{dE} = \frac{A}{E_{crit} - E_{leaf}}$	YYY	YYYY	K_{rhiz}
Hölttä	(Hölttä et al., 2017)	$\Theta' = A_{ww} \cdot \frac{SC}{SC_{max}}$	$\frac{d\Theta'}{dE} = \frac{A}{SC_{max} - SC} \cdot \frac{dSC}{dE}$	YYY	YYYY	SC_{max}, K_{rhiz}, anatomy
Dewar CAP	(Dewar et al., 2018)	$\Theta' = A_{ww} \cdot \frac{P}{P_{crit}}$	$\frac{d\Theta'}{dE} = \frac{A}{K \cdot (P_{crit} - P)}$	YYY	YYYY	K_{rhiz}

Example 2: The Sperry model

Optimization criterion

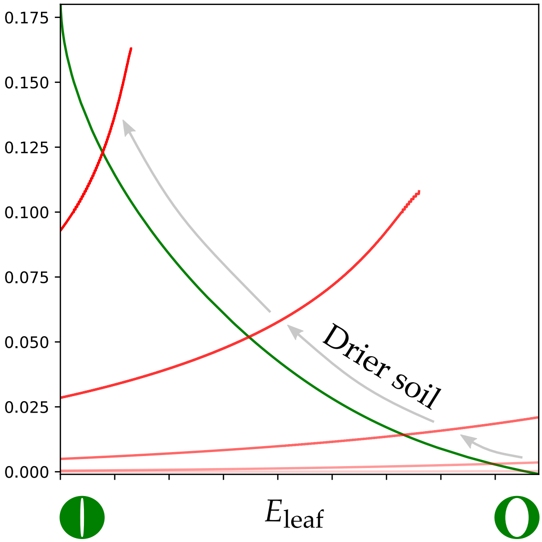
$$\max\left(\frac{A}{A_{\mathrm{max}}} - \left(1 - \frac{K}{K_{\mathrm{max}}}\right)\right), K = \frac{\mathrm{d}E}{\mathrm{d}P}$$

Marginal penalty

$$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = -\frac{\mathrm{d}K}{\mathrm{d}E} \cdot \frac{A_{\mathrm{max}}}{K_{\mathrm{max}}}$$

Sperry et al. (2017)

Response to drought



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Eller	(Eller et al., 2018)	$\Theta = A \cdot \left(1 - \frac{K}{K_{\mathrm{max},0}}\right)$	$\frac{d\Theta}{dE} = -\frac{dK}{dE} \cdot \frac{A}{K}$	YYY	YYYN	K_{rhiz}
New Model		$\Theta = A \cdot \frac{E_{\mathrm{leaf}}}{E_{\mathrm{crit}}}$	$\frac{d\Theta}{dE} = \frac{A}{E_{\mathrm{crit}} - E_{\mathrm{leaf}}}$	YYY	YYYY	K_{rhiz}
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Example 3: A new model

Criterion

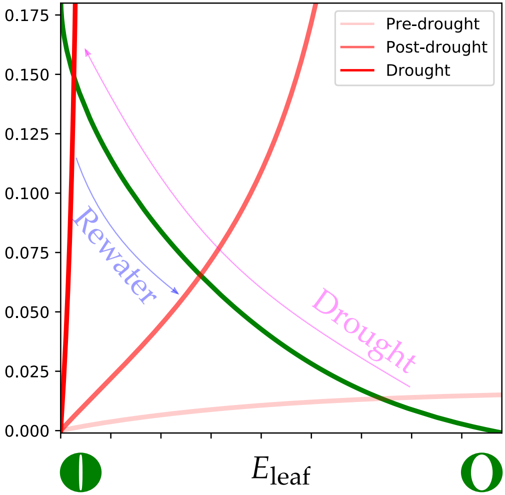
$$\max\left(A\cdot\left(1-\frac{E_{\mathrm{leaf}}}{E_{\mathrm{crit}}}\right)\right)$$

Marginal penalty

$$\frac{\mathrm{d}\Theta}{\mathrm{d}E}=\frac{A}{E_{\mathrm{crit}}-E_{\mathrm{leaf}}}$$

Wang et al. (in review)

Response to drought



✓ Quantify $A(E_{\text{leaf}})$

✓ Quantify $\Theta(E_{\text{leaf}})$

3. Test different optimization models
4. Way forward—long-term prediction

Part III
Testing The Models

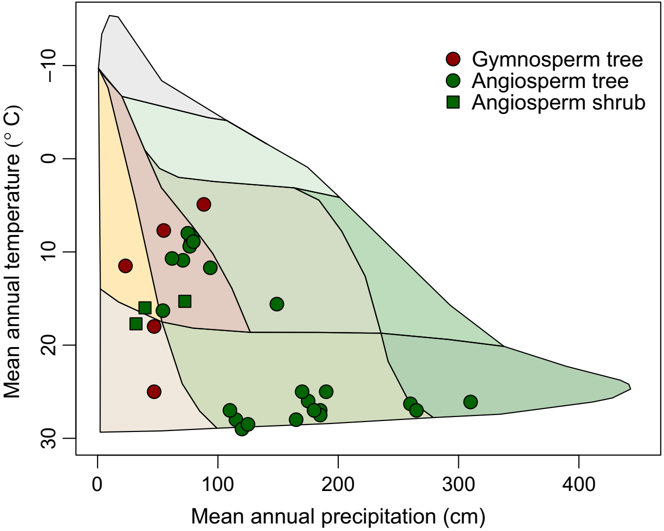
Birch dataset

Wang et al. (2019)

Aspen dataset

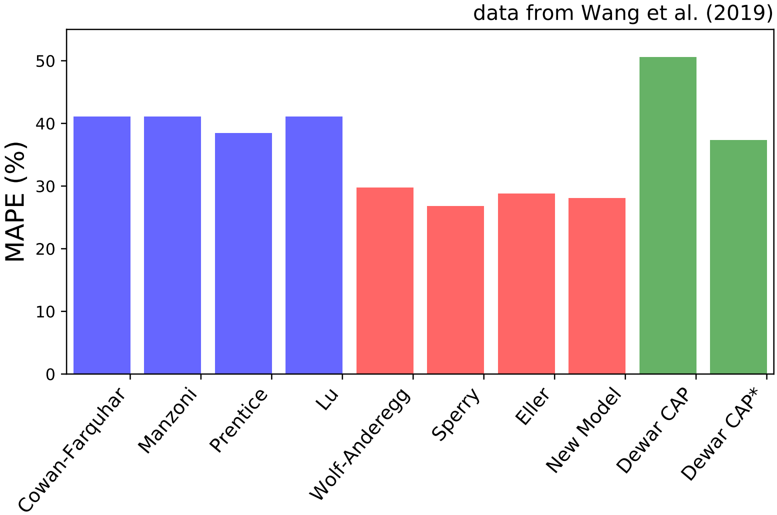
Venturas et al. (2018)

Anderegg dataset



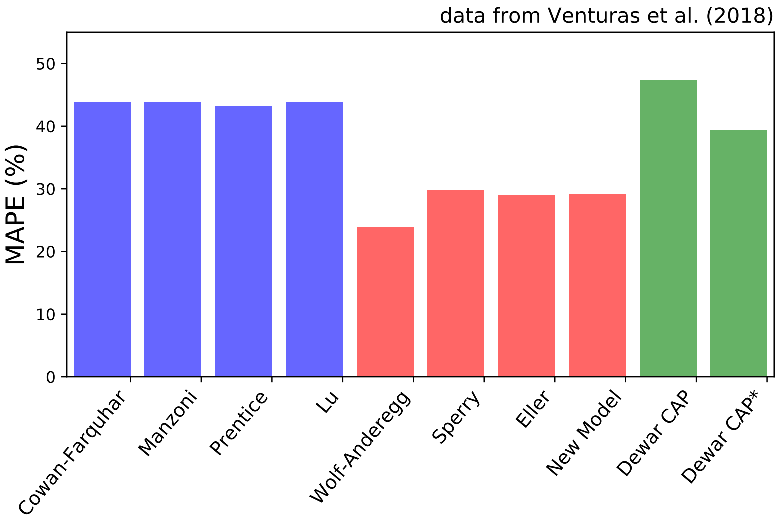
Anderegg et al. (2018)

Birch dataset

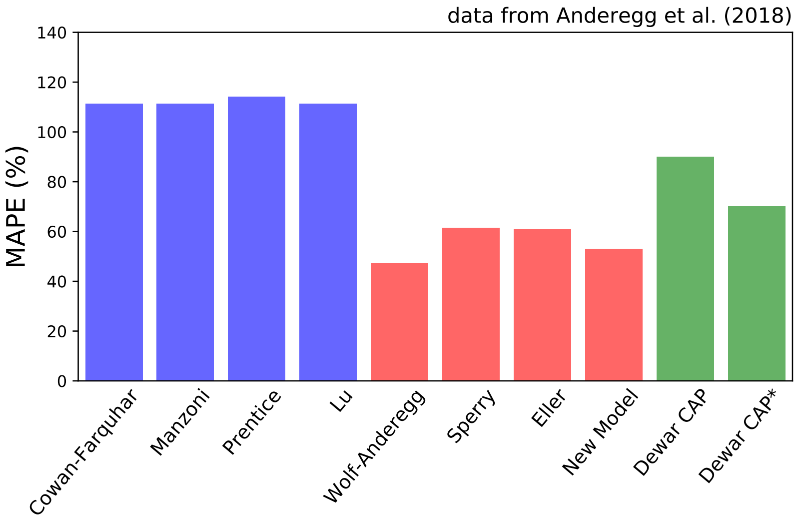


MAPE: mean absolute percentage error for A, P, and E

Aspen dataset



Anderegg dataset



Model	Reference	Water Penalty (Θ or Θ')	Marginal Penalty ($\mathrm{d}\Theta/\mathrm{d}E$ or $\mathrm{d}\Theta'/\mathrm{d}E$)	Criteria I–III	Response Criteria IV–VII DCPK	Fitting parameters
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Prentice	(Prentice et al., 2014)	$\Theta = A \cdot \left(1 - \frac{1}{c_{\mathrm{E}} E_{\mathrm{leaf}} + c_{\mathrm{V}} V_{\mathrm{cmax}}}\right)$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{A}{E_{\mathrm{leaf}} + \frac{c_{\mathrm{V}}}{c_{\mathrm{E}}} V_{\mathrm{cmax}}}$	YNY	YYNN	$c_{\mathrm{E}}, c_{\mathrm{V}}$
Lu	(Lu et al., 2016)	$\Theta = \frac{E_{\mathrm{leaf}}}{\lambda}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{1}{\lambda}$	YNN	NNNN	λ
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New Model		$\Theta = A \cdot \frac{E_{\mathrm{leaf}}}{E_{\mathrm{crit}}}$	$\frac{\mathrm{d}\Theta}{\mathrm{d}E} = \frac{A}{E_{\mathrm{crit}} - E_{\mathrm{leaf}}}$	YYY	YYYY	K_{rhiz}
Hölttä	(Hölttä et al., 2017)	$\Theta' = A_{\mathrm{ww}} \cdot \frac{\mathrm{SC}}{\mathrm{SC}_{\mathrm{max}}}$	$\frac{\mathrm{d}\Theta'}{\mathrm{d}E} = \frac{A}{\mathrm{SC}_{\mathrm{max}} - \mathrm{SC}} \cdot \frac{\mathrm{dSC}}{\mathrm{d}E}$	YYY	YYYY	$\mathrm{SC}_{\mathrm{max}}, K_{\mathrm{rhiz}}$, anatomy
Dewar CAP	(Dewar et al., 2018)	$\Theta' = A_{\mathrm{ww}} \cdot \frac{P}{P_{\mathrm{crit}}}$	$\frac{\mathrm{d}\Theta'}{\mathrm{d}E} = \frac{A}{K \cdot (P_{\mathrm{crit}} - P)}$	YYY	YYYY	K_{rhiz}

Take-home message

MATH is important.

Take-home messages

- Penalty is well represented by plant hydraulics
- Penalty is likely weighted by photosynthesis
- Trait-based models are very promising

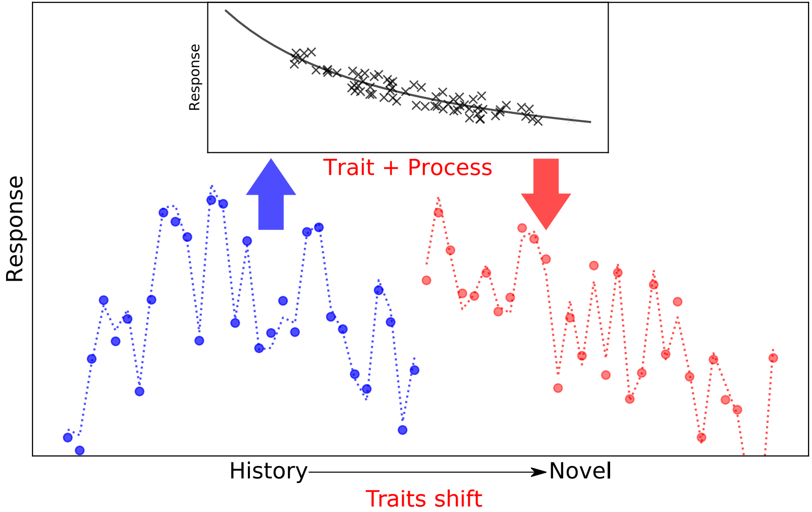
✓ Quantify $A(E_{\text{leaf}})$

✓ Quantify $\Theta(E_{\text{leaf}})$

✓ Test different optimization models

4. Way forward—long-term prediction

How about trait change?

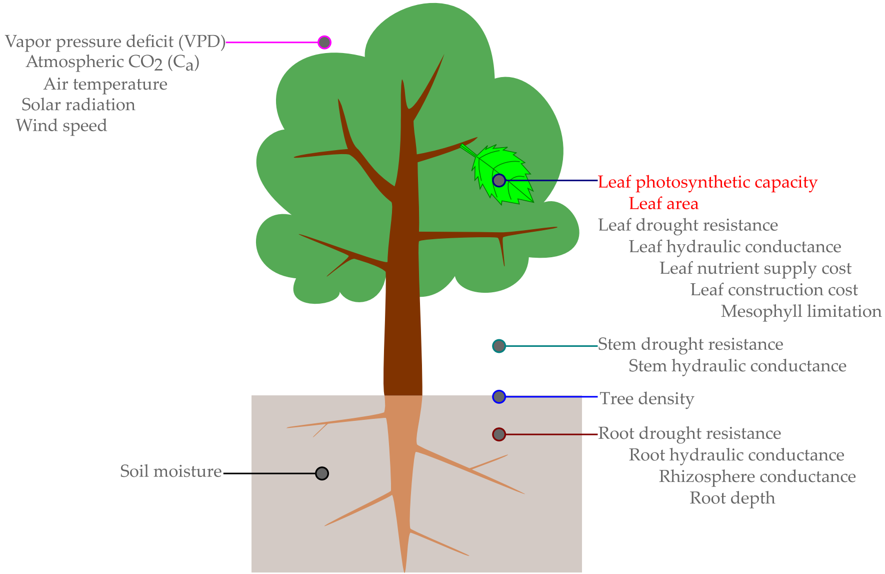


Part IV
Modeling Trait Shifts

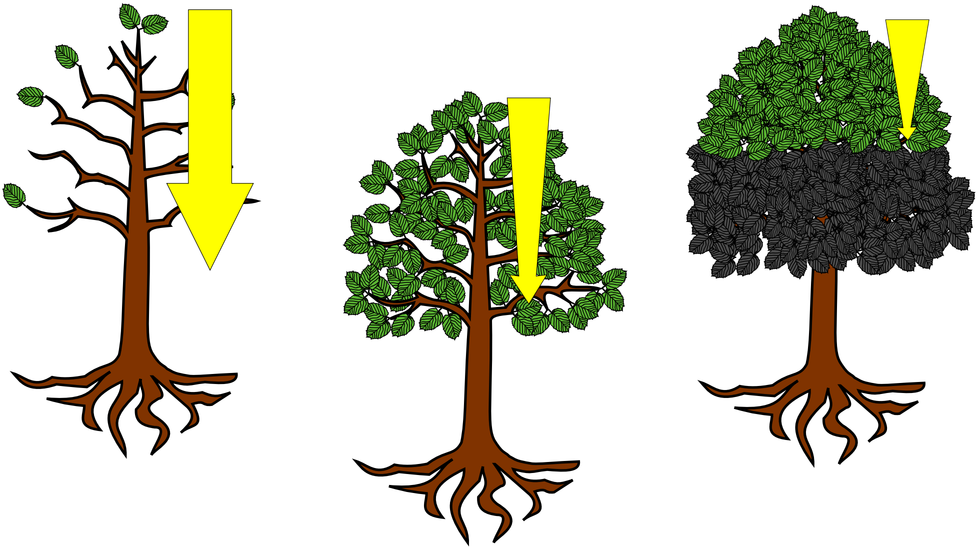
Disadvantages of trait-based model

- The model needs a lot of trait inputs;
- The traits are not constant spatially or temporally.

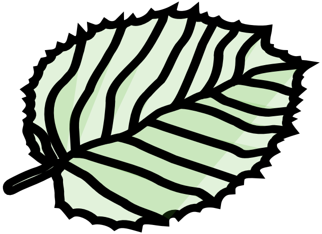
Environmental and physiological variables

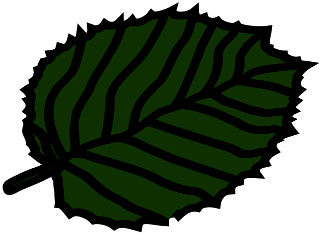


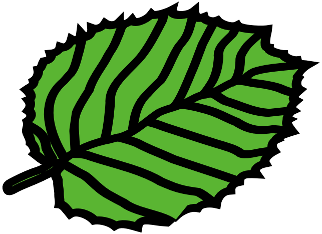
Optimal leaf area



Optimal leaf photosynthesis







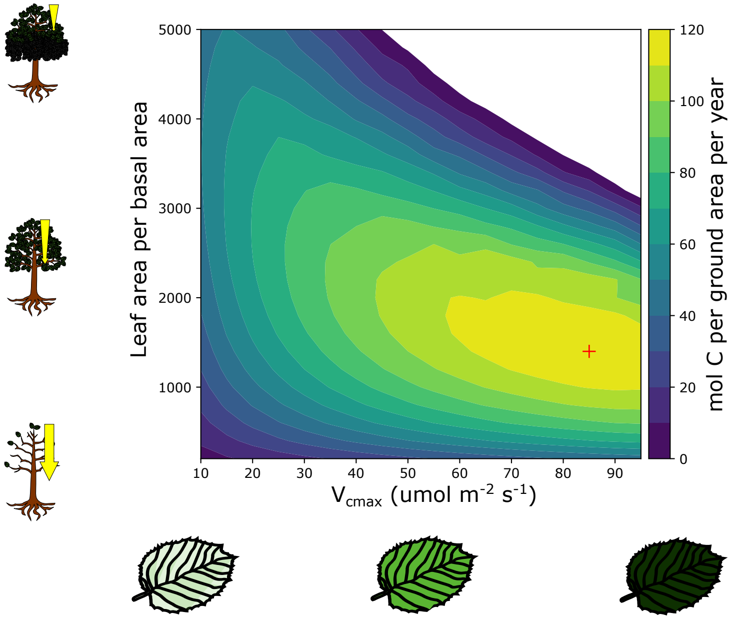
Optimal leaf investment

Optimization criterion

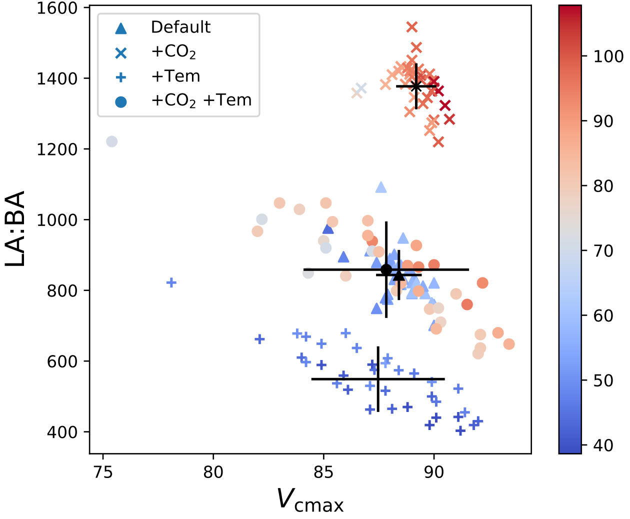
$$\max\left(\int A_{\mathrm{day}} - \int R_{\mathrm{night}} - \mathrm{LCBM} - \mathrm{NS}\right)$$

A_{day}	Net photosynthetic rate in the day
R_{night}	Respiratory rate in the night
LCBM	Leaf construction costs in carbon biomass
NS	Leaf construction costs in nutrient supply

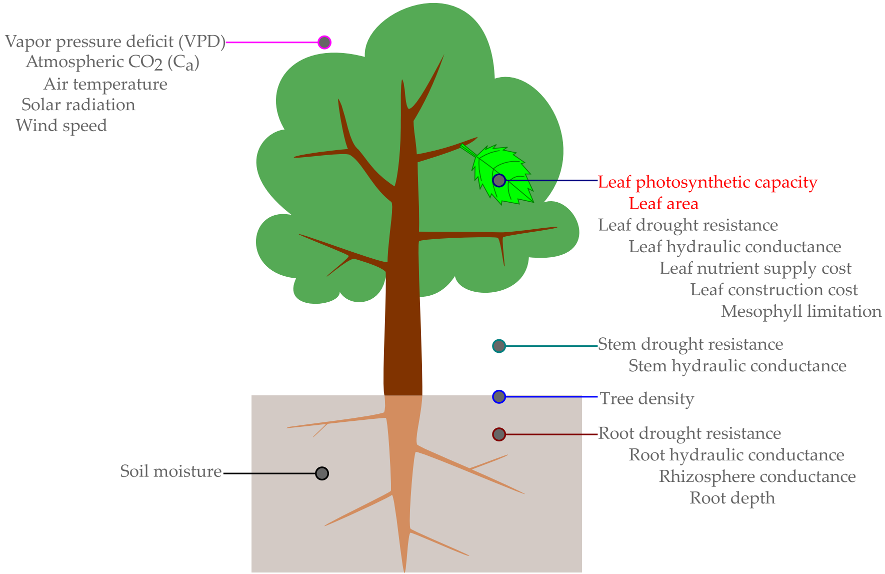
Wang et al., (in prep)


Leaf area per basal area
5000
4000
3000
2000
1000
10
20
30
40
50
60
70
80
90
Vcmax (umol m-2 s-1)
mol C per ground area per year
120
100
80
60
40
20
0

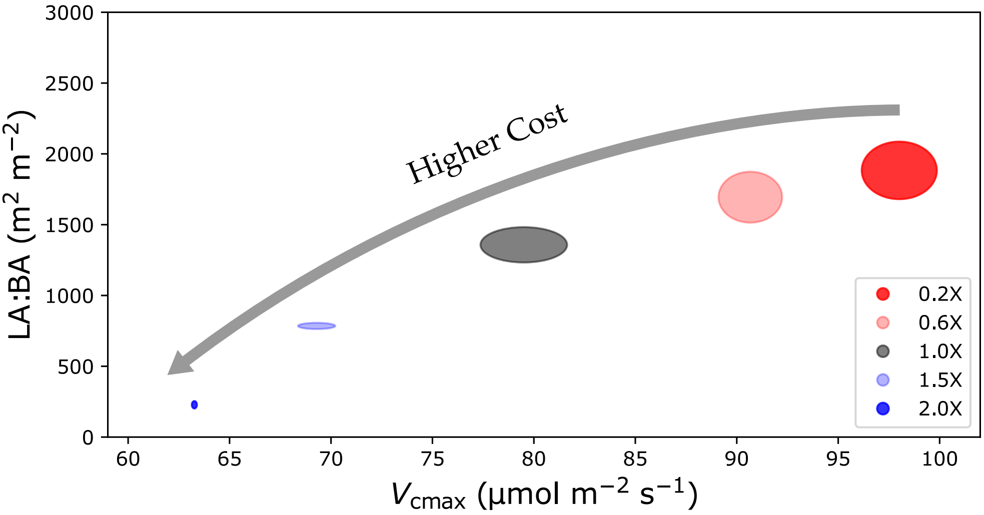
Optimal leaf investment vs. climate



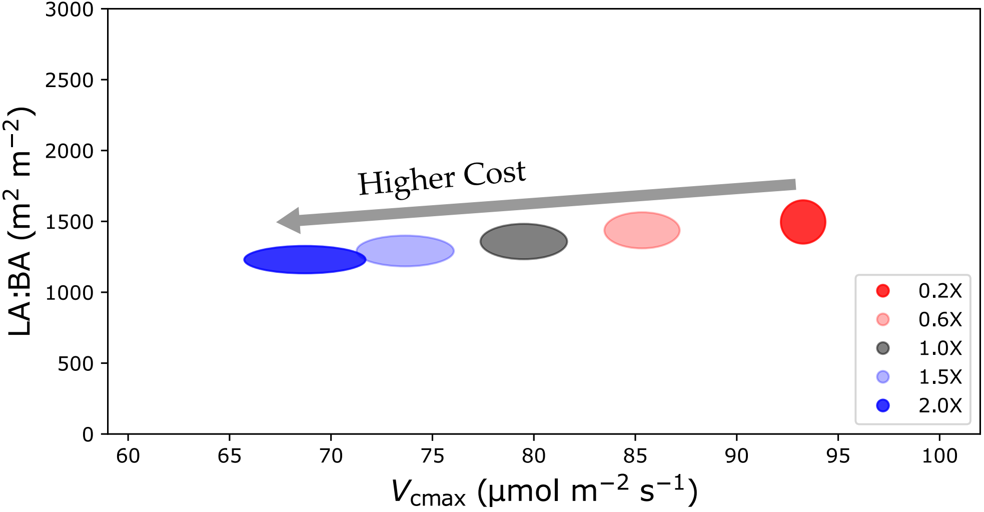
Other traits?



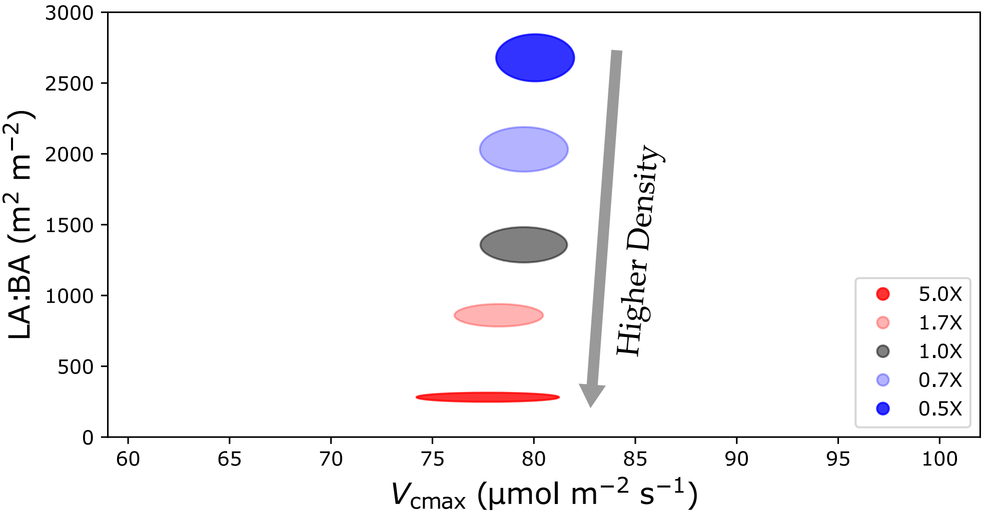
Optimal leaf investment vs. carbon cost (LCBM)



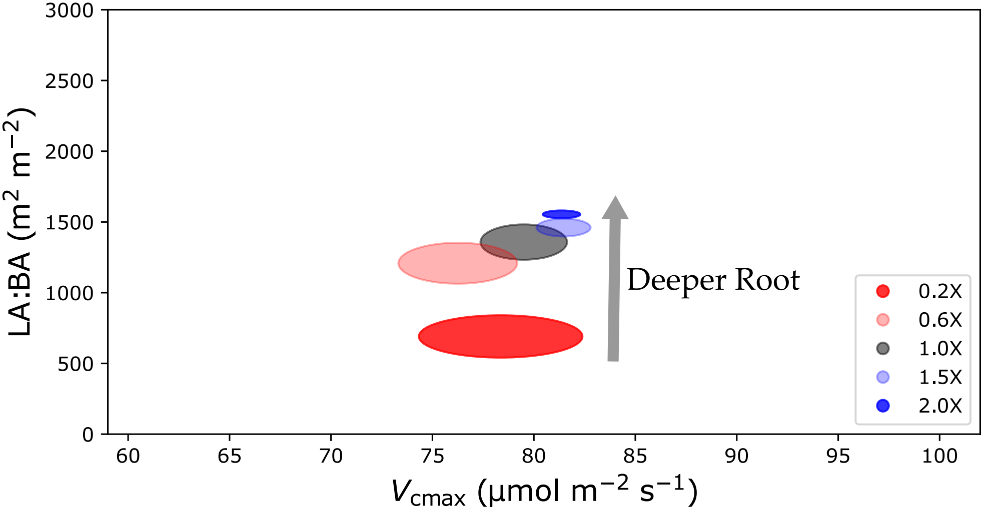
Optimal leaf investment vs. nutrient cost (NS)



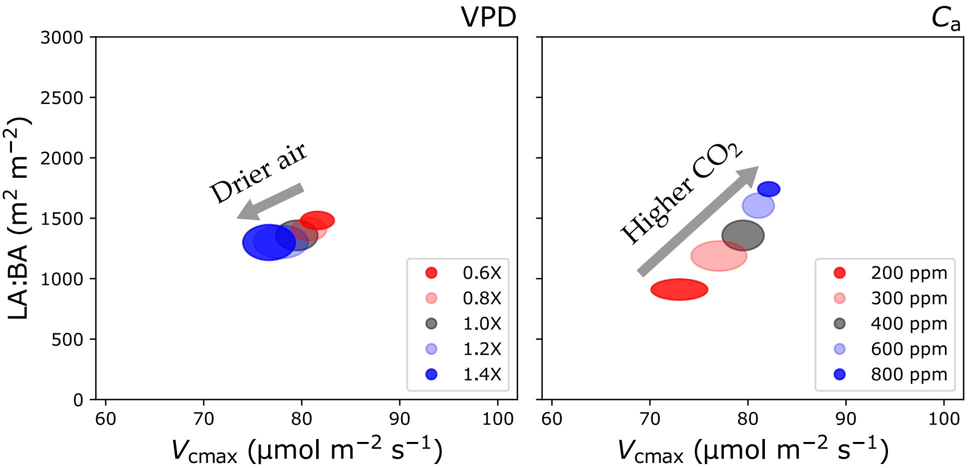
Optimal leaf investment vs. stand density



Optimal leaf investment vs. root depth



Optimal leaf investment vs. VPD and CO_2



Major drivers for leaf investment

Plant traits

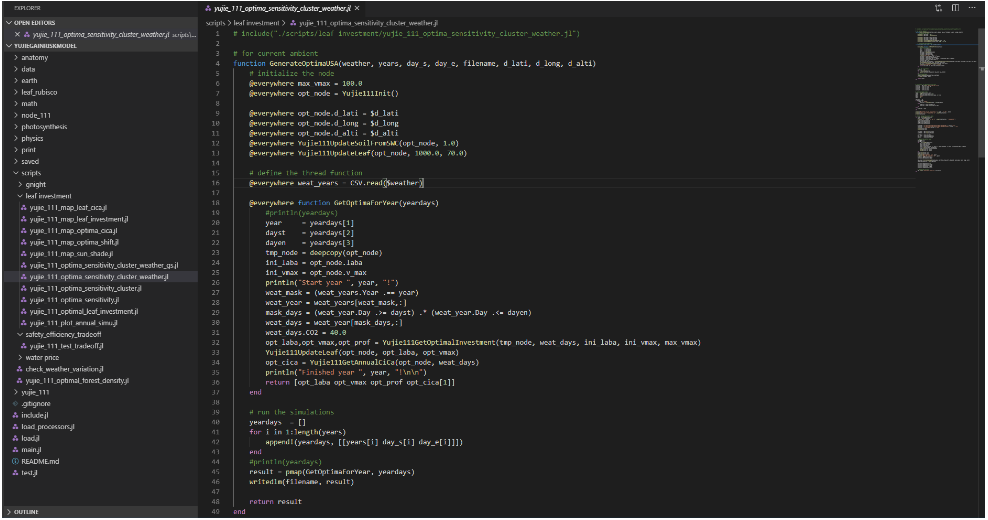
- Leaf construction costs (carbon and nutrients)
- Root depth

Environmental conditions

- Stand density
- VPD
- Atmospheric CO_2

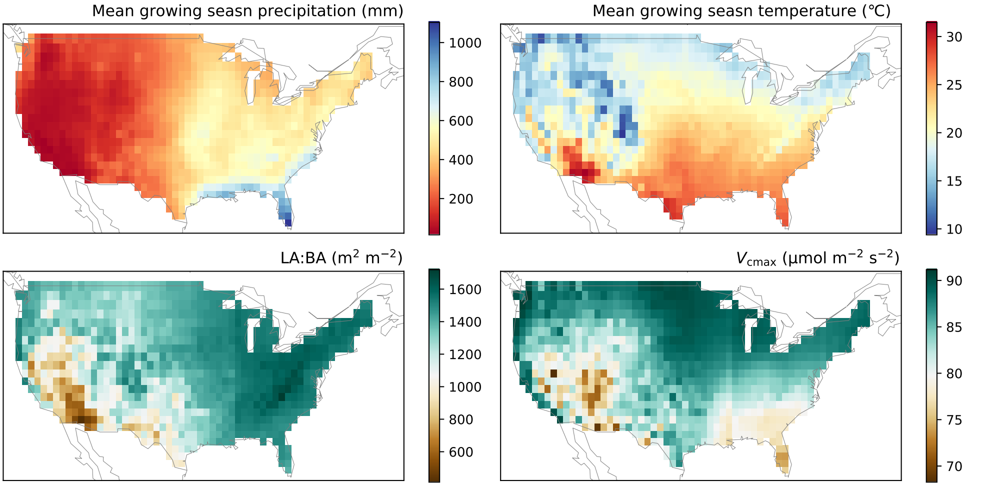
Plant trees!

Plant trees!

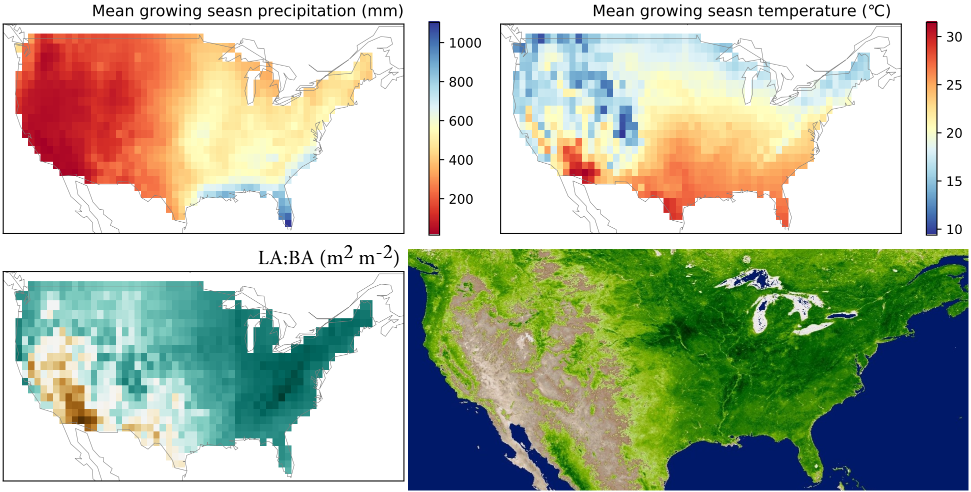


```
# include("./scripts/leaf investment/yujie_111_optima_sensitivity_cluster_weather.jl")

# for current ambient
function GenerateOptimaUSA(weather, years, day_s, day_e, filename, d_lati, d_long, d_alti)
    # initialize the node
    @everywhere max_vmax = 100.0
    @everywhere opt_node = Yujie111Init()

    @everywhere opt_node.d_lati = $d_lati
    @everywhere opt_node.d_long = $d_long
    @everywhere opt_node.d_alti = $d_alti
    @everywhere Yujie111UpdateSoilFromSWC(opt_node, 1.0)
    @everywhere Yujie111UpdateLeaf(opt_node, 1000.0, 70.0)

    # define the thread function
    @everywhere weat_years = CSV.read($weather)

    @everywhere function GetOptimaForYear(yeardays)
        #println(yeardays)
        year     = yeardays[1]
        dayst    = yeardays[2]
        dayen    = yeardays[3]
        tmp_node = deepcopy(opt_node)
        ini_laba = opt_node.laba
        ini_vmax = opt_node.v_max
        println("Start year ", year, "!")
        weat_mask = (weat_years.Year .== year)
        weat_year = weat_years[weat_mask,:]
        mask_days = (weat_year.Day .>= dayst) .* (weat_year.Day .<= dayen)
        weat_days = weat_year[mask_days,:]
        weat_days.CO2 = 40.0
        opt_laba,opt_vmax,opt_prof = Yujie111GetOptimalInvestment(tmp_node, weat_days, ini_laba, ini_vmax, max_vmax)
        Yujie111UpdateLeaf(opt_node, opt_laba, opt_vmax)
        opt_cica = Yujie111GetAnnualCiCa(opt_node, weat_days)
        println("Finished year ", year, "!\n\n")
        return [opt_laba opt_vmax opt_prof opt_cica[1]]
    end

    # run the simulations
    yeardays  = []
    for i in 1:length(years)
        append!(yeardays, [[years[i] day_s[i] day_e[i]]])
    end
    #println(yeardays)
    result = pmap(GetOptimaForYear, yeardays)
    writedlm(filename, result)

    return result
end
```

Sensitivity to climate



Sensitivity to climate



- ✓ Quantify $A(E_{\text{leaf}})$
- ✓ Quantify $\Theta(E_{\text{leaf}})$
- ✓ Test different optimization models
- ✓ Way forward—long-term prediction

Conclusions

Conclusions

- Incorporating gas-phase mesophyll conductance improves photosynthesis modeling
- Water penalty is linked to plant hydraulic integrity
- Water penalty is weighted by photosynthesis opportunity
- Leaf investment is very sensitive to leaf construction costs and root depth
- Future research on how traits coordinate and acclimate to the environment is required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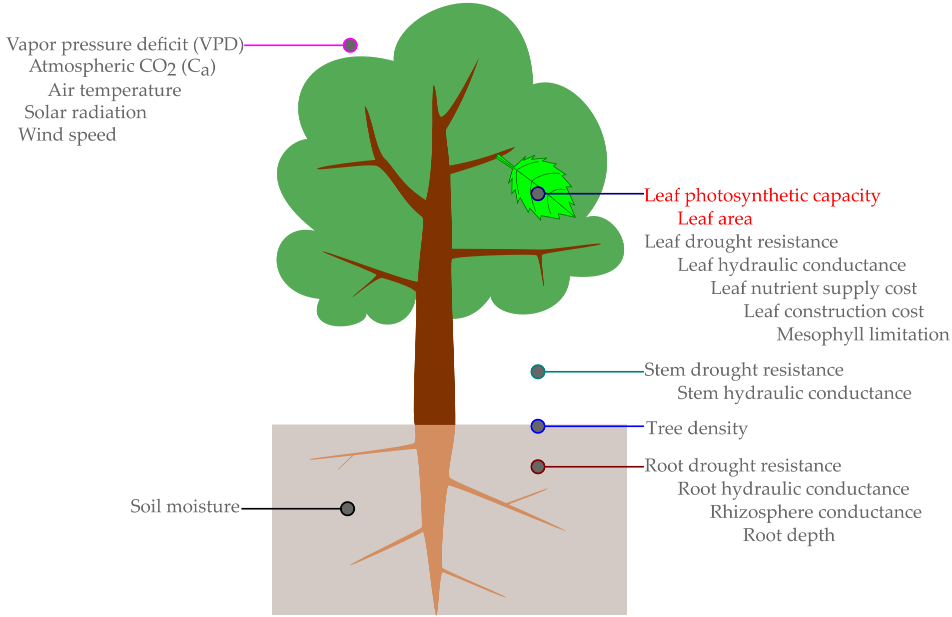
Vapor pressure deficit (VPD)
Atmospheric CO_2 (C_a)
Air temperature
Solar radiation
Wind speed
Leaf photosynthetic capacity
Leaf area
Leaf drought resistance
Leaf hydraulic conductance
Leaf nutrient supply cost
Leaf construction cost
Mesophyll limitation
Stem drought resistance
Stem hydraulic conductance
Tree density
Root drought resistance
Root hydraulic conductance
Rhizosphere conductance
Root depth
Soil moisture

Acknowledgments

Supervisory committee

- John Sperry
- Bill Anderegg
- Fred Adler
- David Bowling
- Jim Ehleringer
- Tom Kursar

Sperry lab

- I am the last one...

Anderegg lab

- Martin Venturas
- Anna Trugman
- Xiaonan Tai

School of Biological Sciences

- Shannon Nielsen
- April Mills
- Christopher Morrow