WUE and water uptake

‘Making the most of every drop’

***Bertrand Muller*[1], *Thierry Simonneau*[1], *Matthieu Bogard*[2], *Jean-Charles Deswartes*[2], *Jaume Flexas*[3], *Jeroni Galmes*[3], *Tracy Lawson*[4], *Andrew Leakey*[5], *Christophe Maurel*[6], *Hilde Nelissen*[7], *Stacia Stetkiewicz*[8]**

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6: CNRS Montpellier
7: VIB Ghent
8: University of Lancaster

WUE in context(s)

WUE and water uptake in the complex landscape of drought resistance

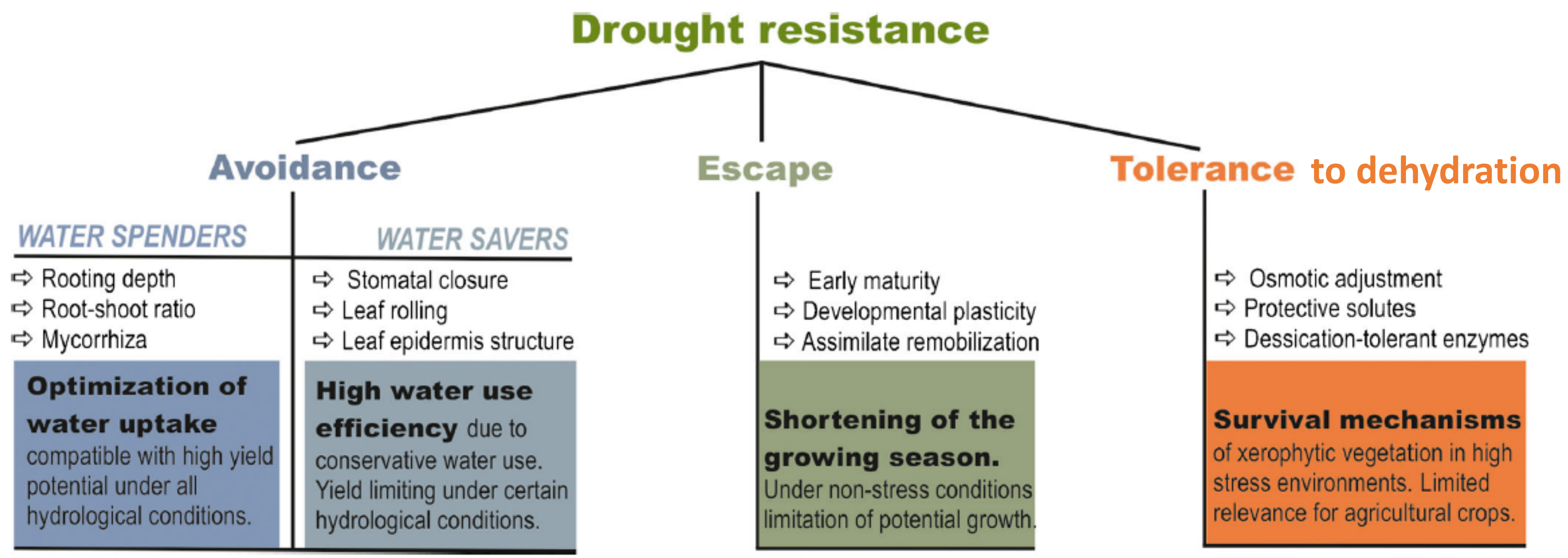


Fig. 6 Drought resistance according to Levitt (1980). Different resistance strategies, examples for corresponding adaptive traits and their potential use/limitation for agricultural crops. Drought avoidance via efficient water uptake is most compatible with high crop yields

Photosynthesis
Root growth
C sequestration

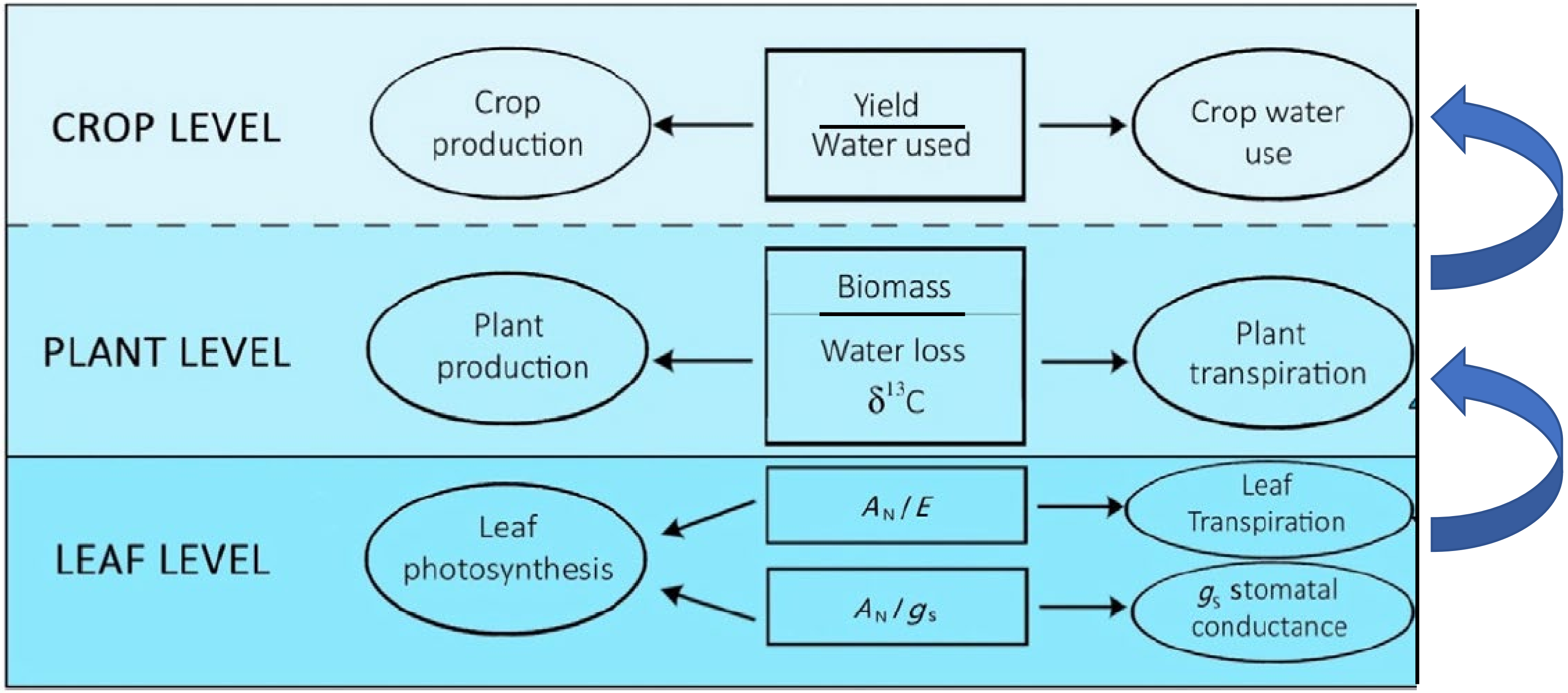
Heat tolerance
Leaf anatomy

Life history,
phenology…

Levitt J (1980) Responses of plants to environmental stresses
Bodner et al 2015 Agron Sust Dev

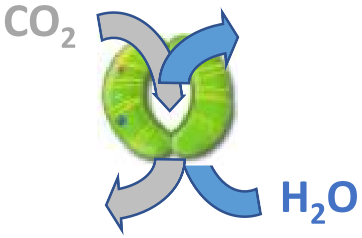
… but which metrix ?

WUE is a straightforward metrix



Medrano et al., 2015 Crop J

Evolution has locked together the regulation of water and carbon fluxes in vascular plants



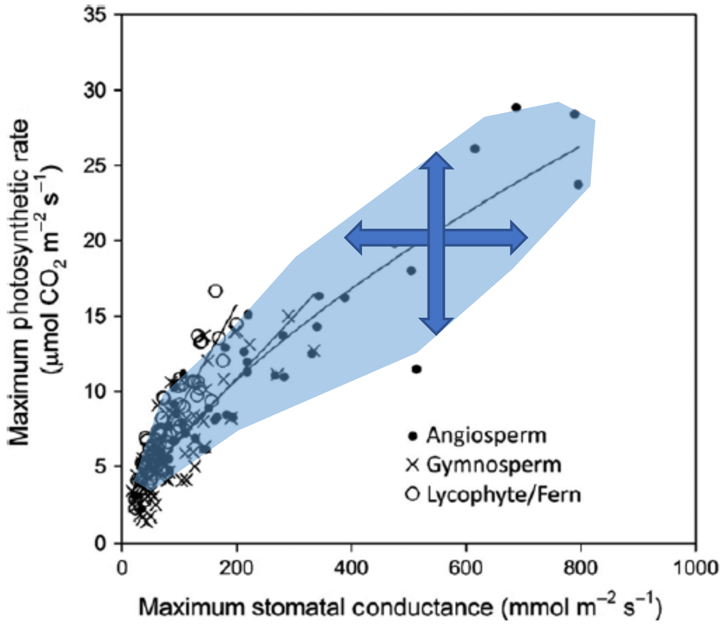
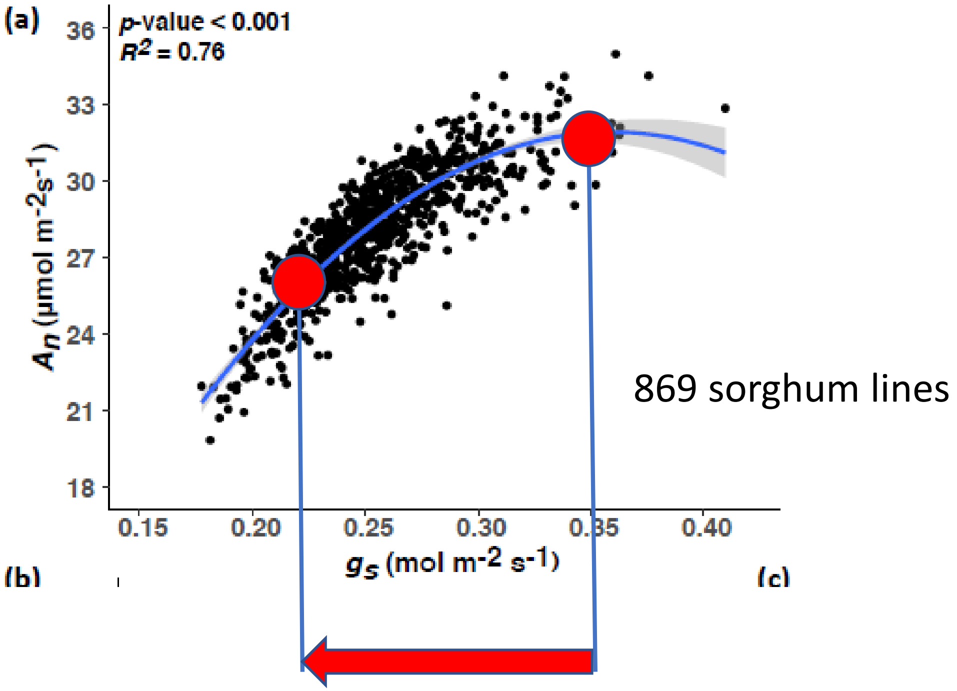


Figure 1. A common connection between stomata and photosynthesis characterizes vascular plants. Maximum instantaneous stomatal conductance and assimilation in leaves from 48 species of angiosperms, 80 species of conifers and 65 species of ferns and lycophytes (data published and unpublished). Similar associations between g_s and A can been seen in each group suggesting that the linkage between diffusive limitation to water loss and CO_2 uptake is common to all major vascular plant lineages.

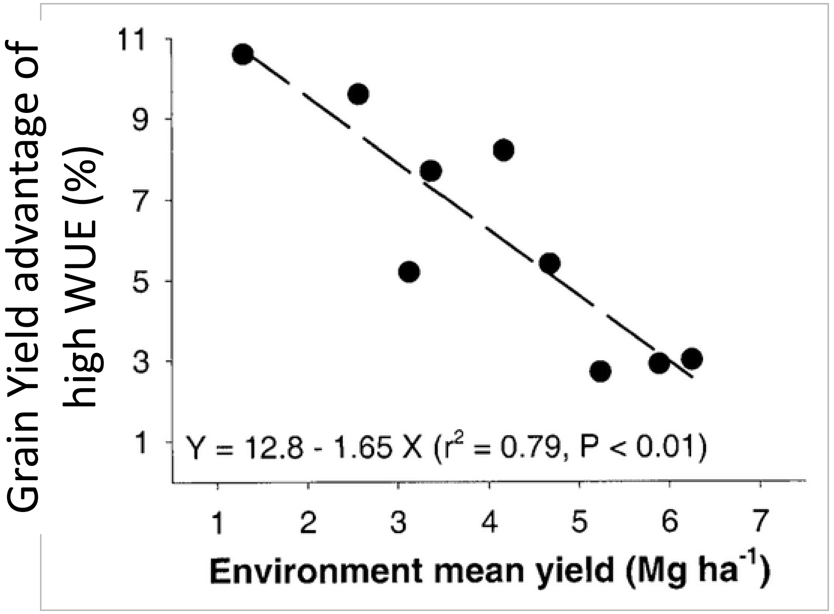
Brodribb et al., 2020 Plant J

High WUE is often associated with conservative behaviour (low T, low A)



20% less A_n
40% less g_s
<u>30% more WUE</u>

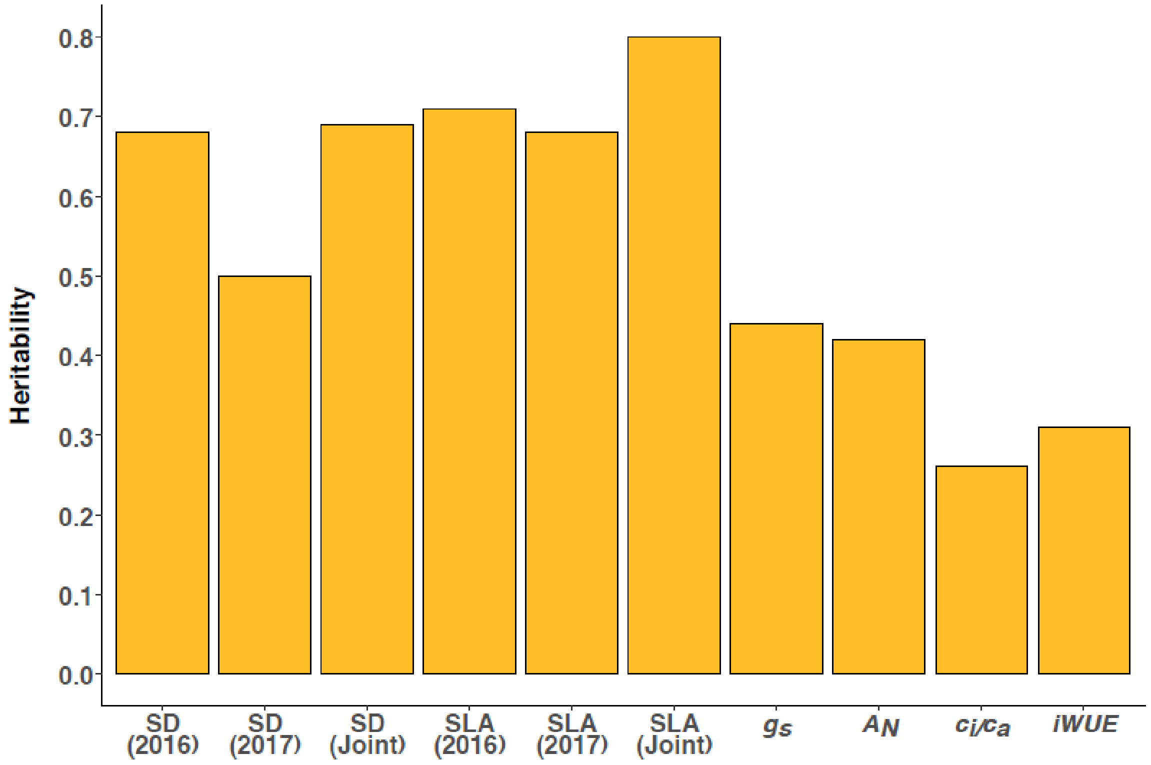
Fergusson et al., 2021 BioRxiv



progeny of crosses between bread wheat under rainfed conditions
Parental lines with low and high values of $\Delta^{13}C$.

Rebetzke et al 2002 Crop Sci

WUE is more a 'phenotype' than a 'phene' (sensu J Lynch)

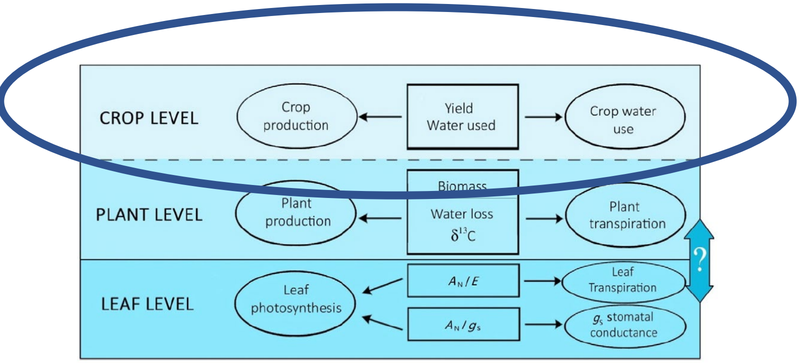


869 sorghum lines

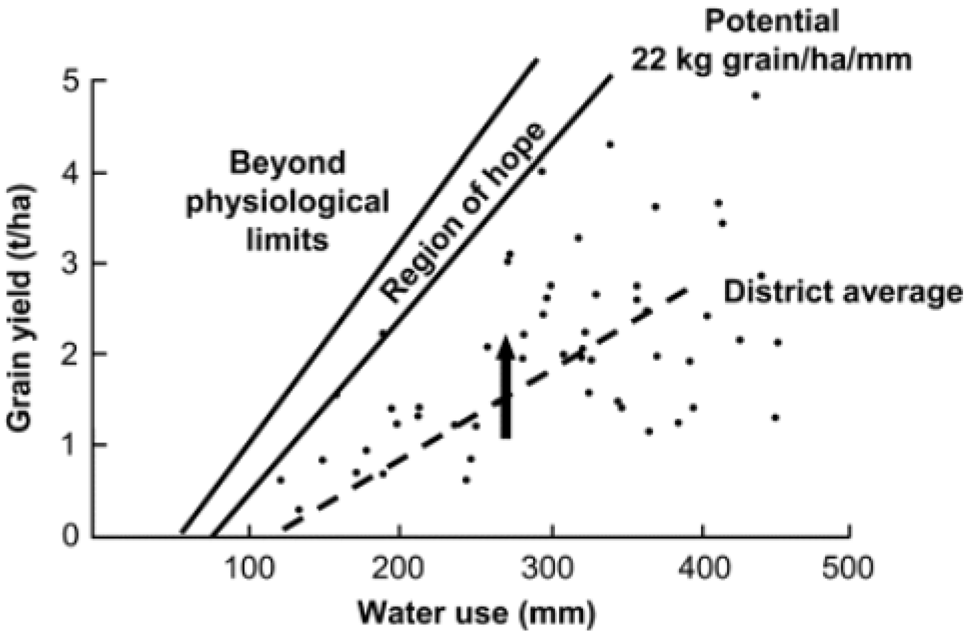
Fergusson et al 2021 BioRxiv

…WUE is more a variable than a parameter

At the crop level, under water limitation, WUE/TE faces a 'physiological' limit



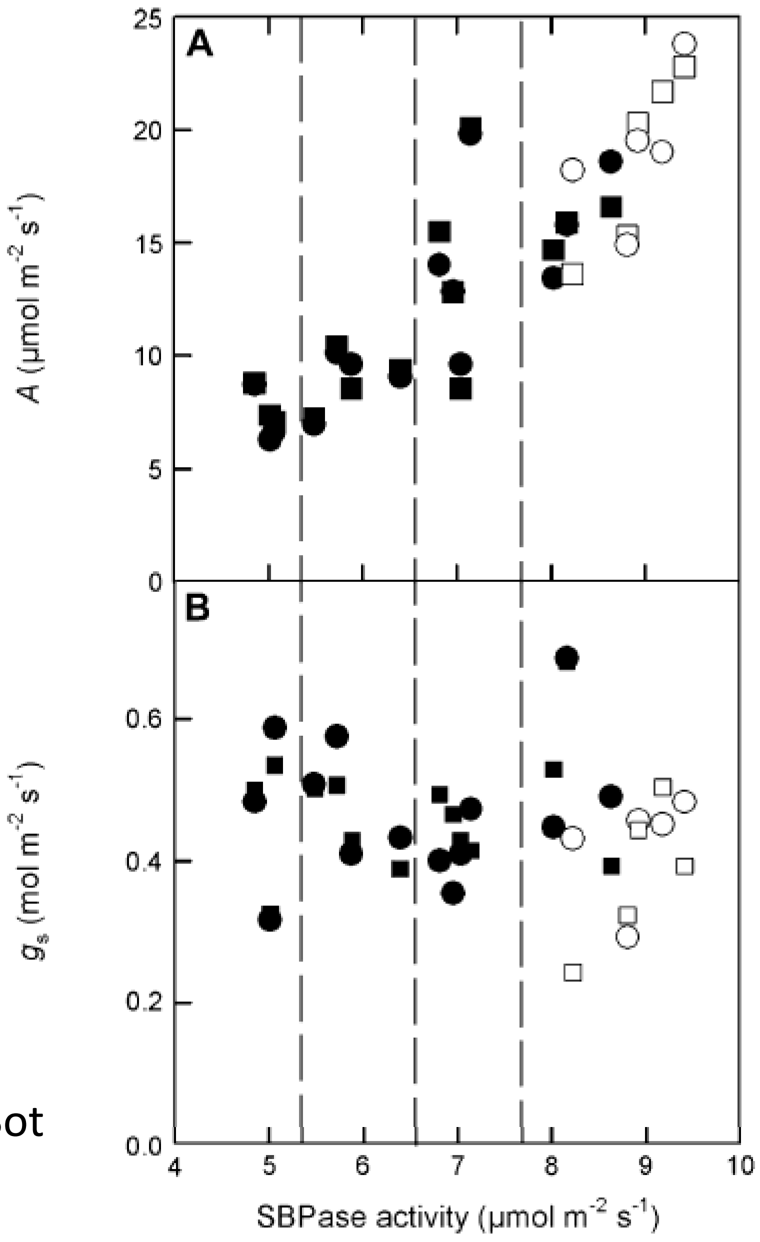
Yield=W (water transpired)
×TE (transpiration efficiency for biomass)
×HI (harvest index)



Passioura 2006 Agricultural Water Management

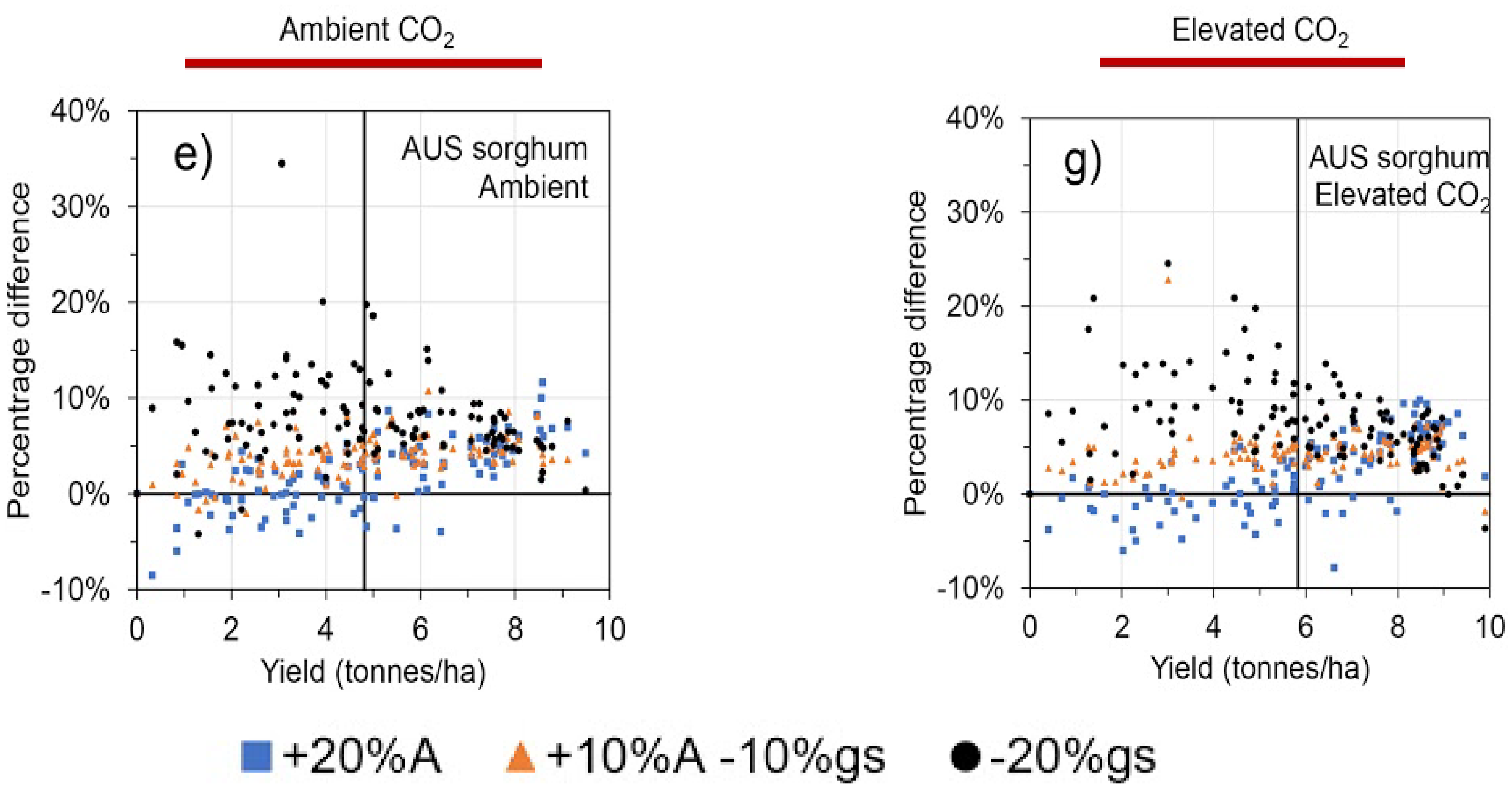
Strategies to improve WUE

A and Gs can be uncoupled



Lawson et al 2008 J Exp Bot

Lowering gs

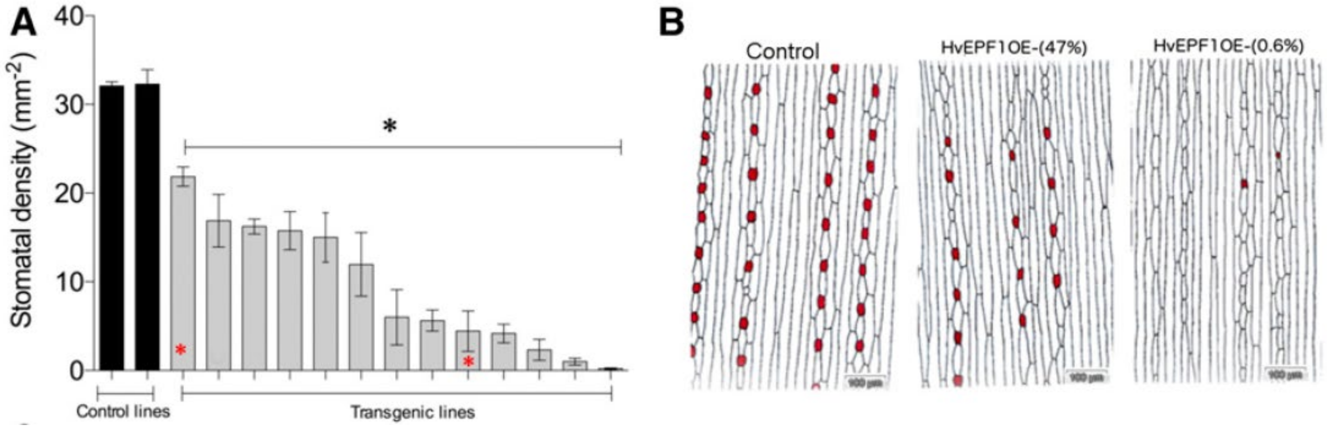


APSIM modeling predicts that:

1) -20% g_s broadly increased yield, with greater benefits in low yielding arid conditions
2) At xeric sites, reducing g_s drives greater yield gain than increasing *A*
3) 550 ppm [CO_2] enhances the benefit of decreasing g_s

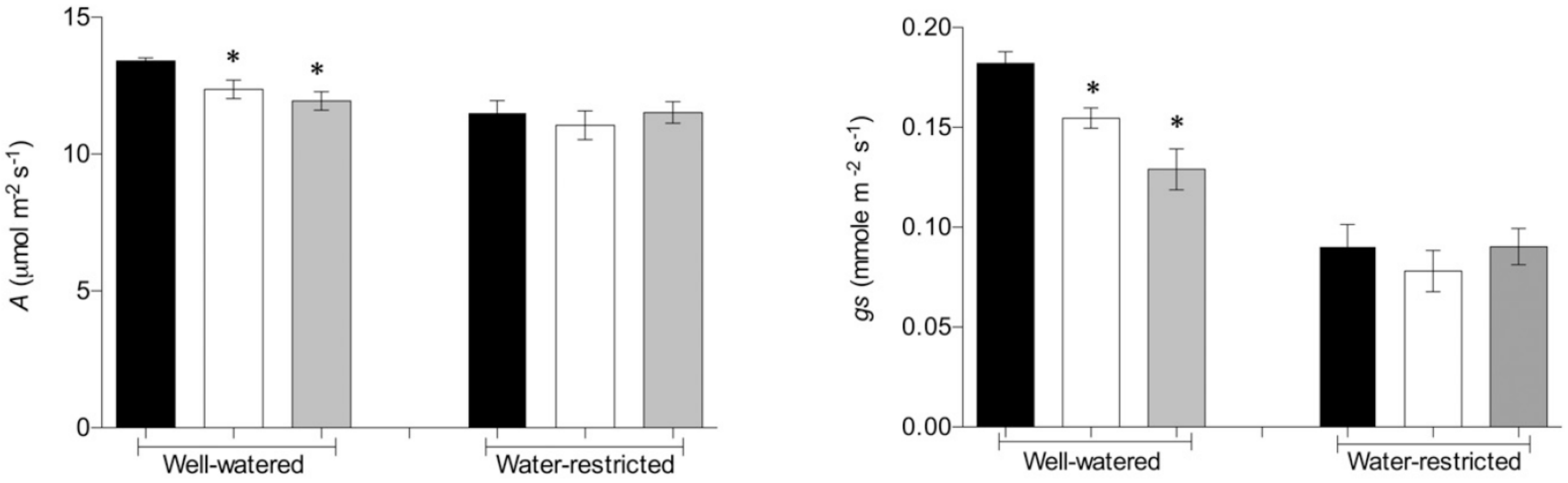
Leakey et al. (2019) Annual Review of Plant Biology

Lowering gs ?



EPF : family of secreted signaling peptides, activate a pathway that regulates SPCH (TF) stability, and the number of cells entering the stomatal lineage

barley



Hughes et al 2017; Plant Physiol

Journal of Experimental Botany, Vol. 70, No. 18 pp. 4737–4747, 2019
doi:10.1093/jxb/erz248 Advance Access Publication June 6, 2019
This paper is available online free of all access charges (see https://academic.oup.com/jxb/pages/openaccess for further details)

RESEARCH PAPER

Reduced stomatal density in bread wheat leads to increased water-use efficiency

Jessica Dunn[1,*], Lee Hunt[1,*], Mana Afsharinafar[1], Moaed Al Meselmani[1], Alice Mitchell[1], Rhian Howells[2], Emma Wallington[2], Andrew J. Fleming[3,†] and Julie E. Gray[1,†]

Reducing Stomatal Density in Barley Improves Drought Tolerance without Impacting on Yield[1[CC-BY]]

Jon Hughes[2], Christopher Hepworth[2], Chris Dutton, Jessica A. Dunn, Lee Hunt, Jennifer Stephens, Robbie Waugh, Duncan D. Cameron, and Julie E. Gray*

Plant Physiology®, June 2017, Vol. 174, pp. 776–787,

New Phytologist

Research

Rice with reduced stomatal density conserves water and has improved drought tolerance under future climate conditions

Robert S. Caine[1], Xiaojia Yin[2], Jennifer Sloan[1], Emily L. Harrison[1], Umar Mohammed[3], Timothy Fulton[1,4], Akshaya K. Biswal[2,5], Jacqueline Dionora[2], Caspar C. Chater[1,6], Robert A. Coe[2,7], Anindya Bandyopadhyay[2], Erik H. Murchie[3], Ranjan Swarup[3], W. Paul Quick[2] and Julie E. Gray[1]

Rice plants overexpressing *OsEPF1* show reduced stomatal density and increased root cortical aerenchyma formation

U. Mohammed[1], R. S. Caine[2], J. A. Atkinson[1], E. L. Harrison[2], D. Wells[1], C. C. Chater[2], J. E. Gray[2], R. Swarup[1] & E. H. Murchie[1]

SCIENTIFIC REPORTS | *(2019) 9:5584* |

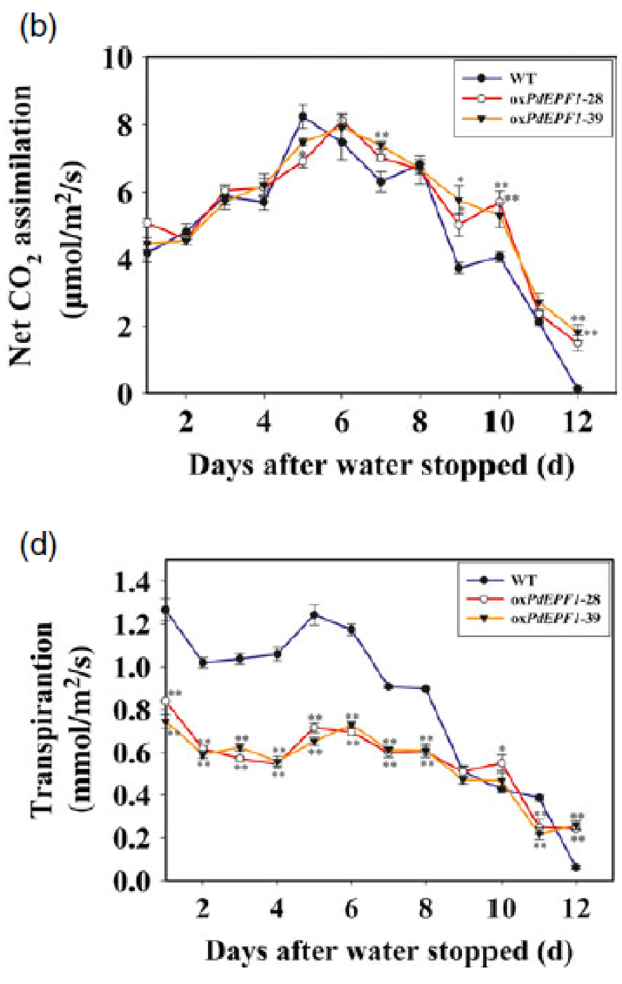
Plant Biotechnology Journal (2016) **14**, pp. 849–860 doi: 10.1111/pbi.12434

PdEPF1 regulates water-use efficiency and drought tolerance by modulating stomatal density in poplar

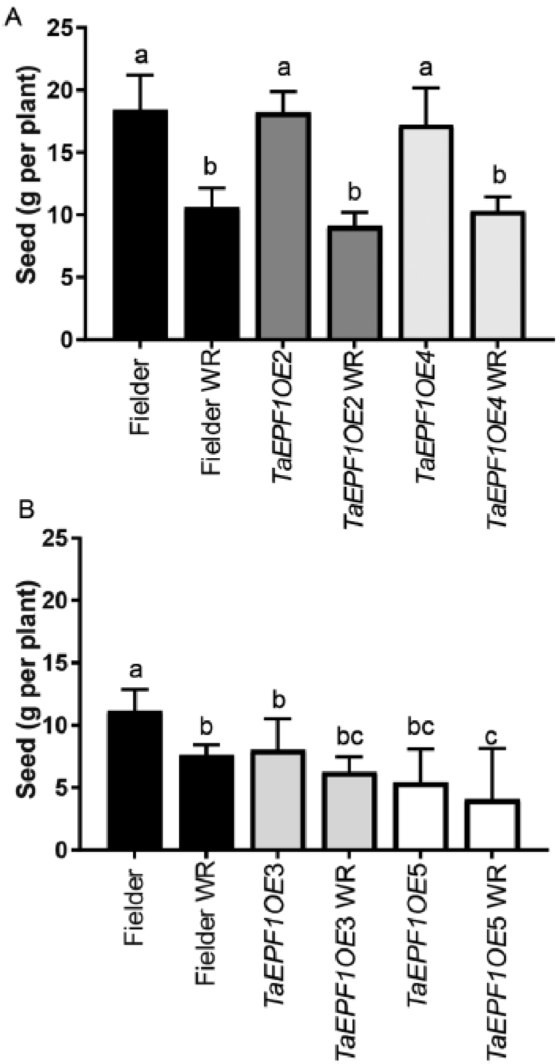
Congpeng Wang[1], Sha Liu[1], Yan Dong[1,2], Ying Zhao[1], Anke Geng[1], Xinli Xia[1,*] and Weilun Yin[1,*]

Potential drawbacks ?

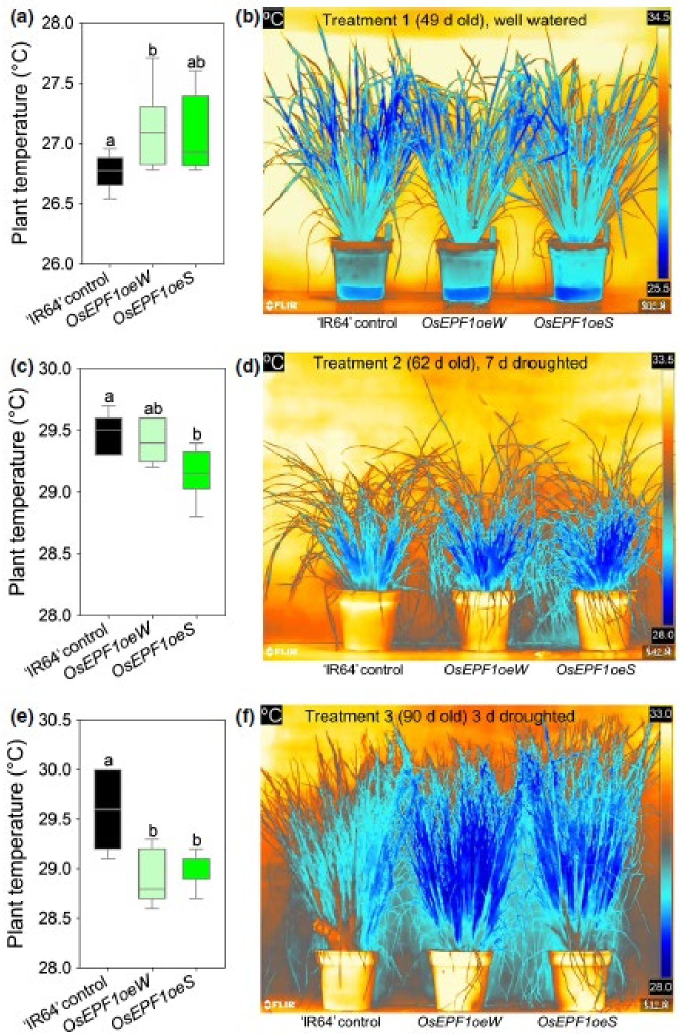
poplar



wheat

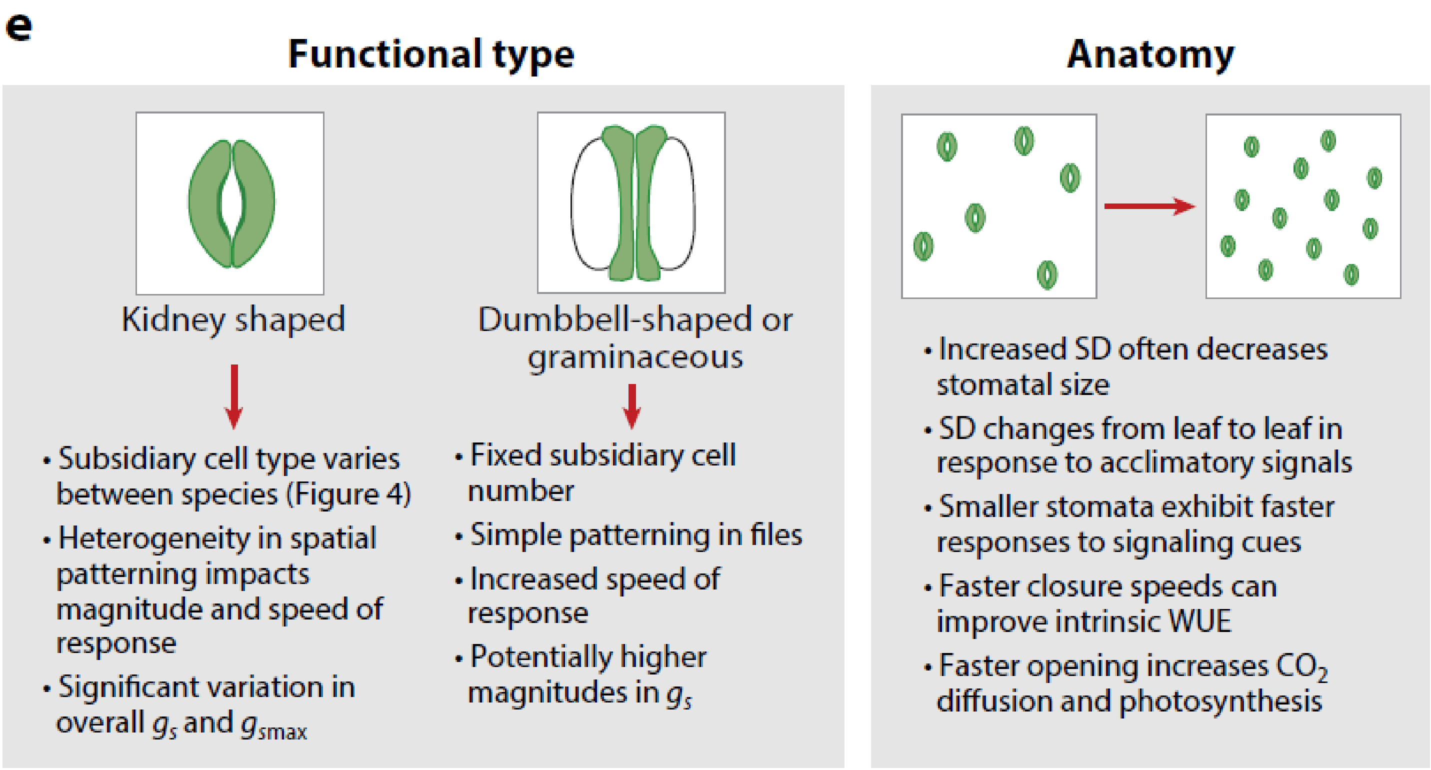


rice



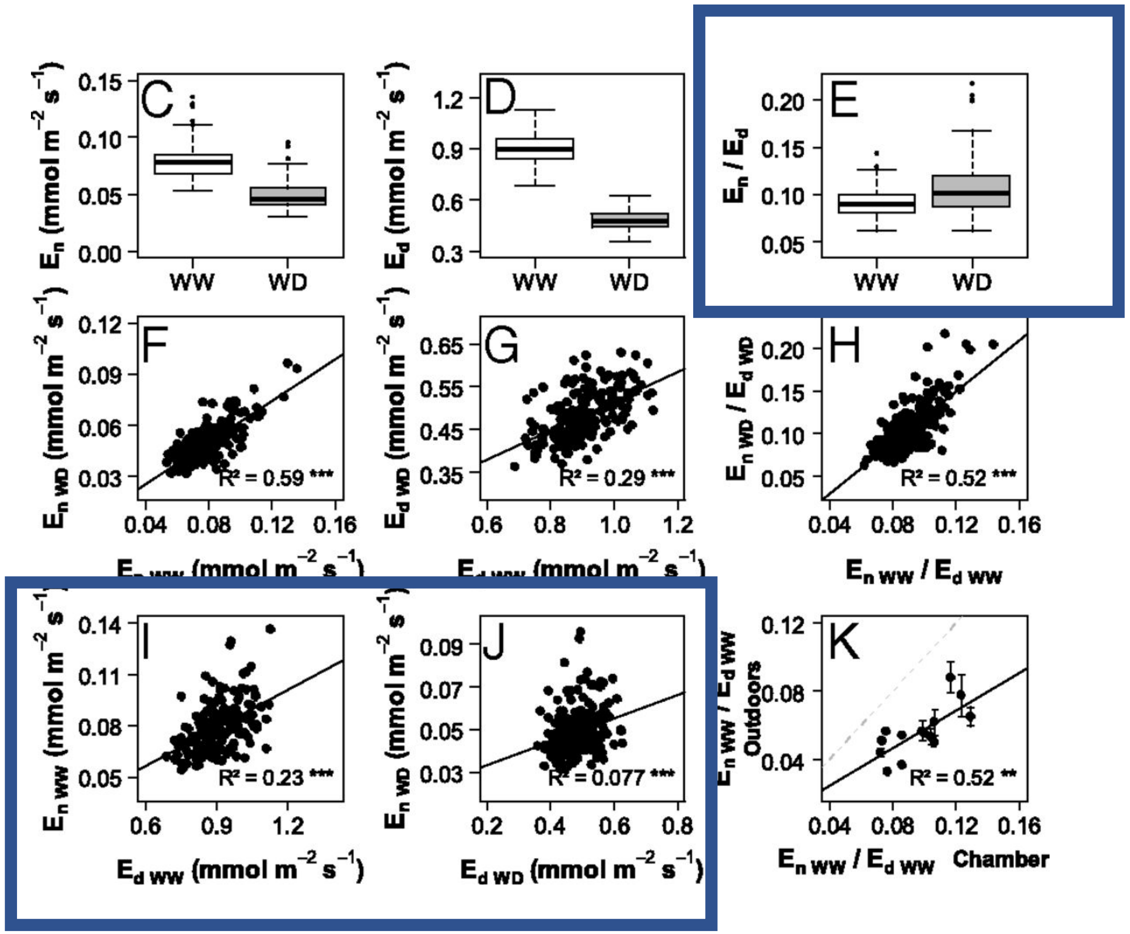
Novel targets

Functional types and size of stomata
Subsidiary cells – Ion channels



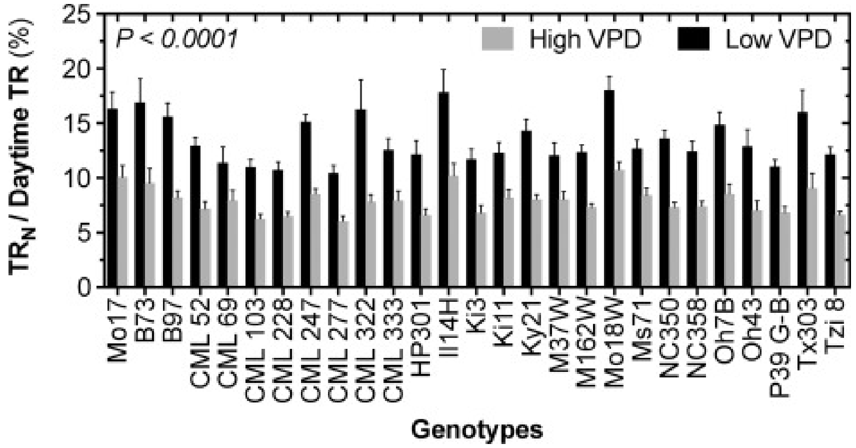
Lawson & Matthews 2020

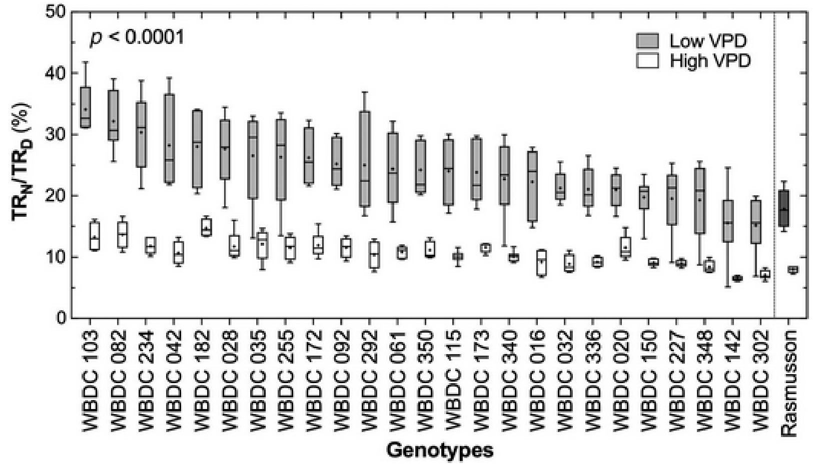
Reducing night transpiration



Aude Coupel-Ledru et al. PNAS 2016

27 maize inbreds



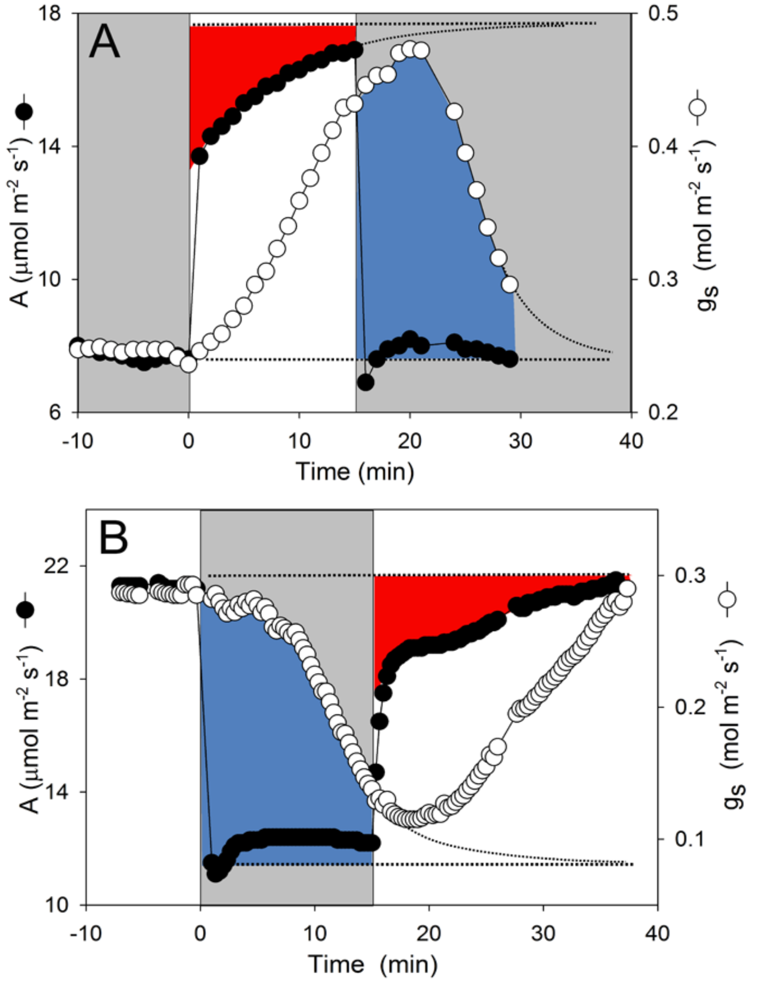


25 local barley genotypes

Tamang, Sadok Environ Exp Bot (2018)

WUE and stomata dynamics

Accelerating stomatal movements in synchrony with mesophyll CO_2 demand and to improve WUE



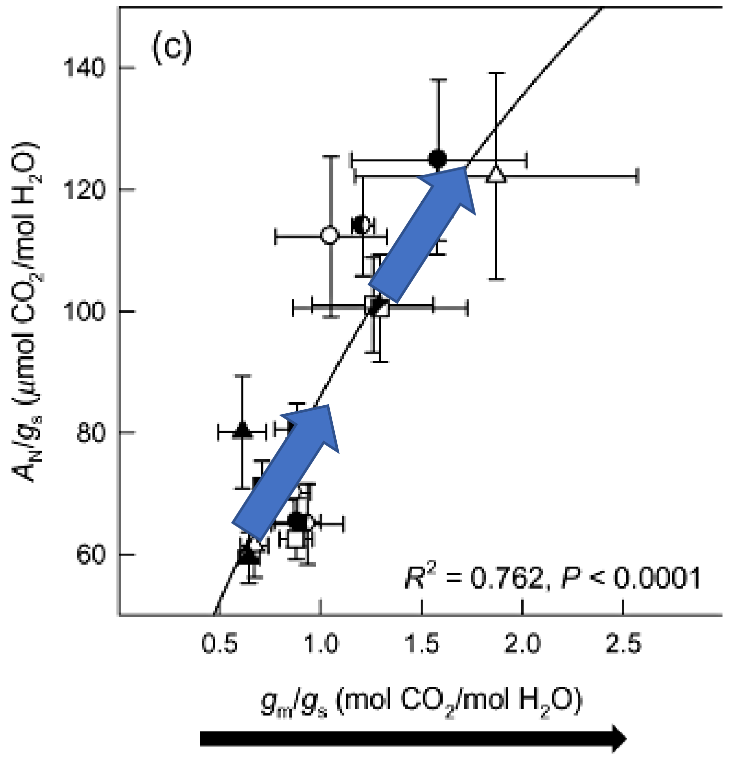
PLANT SCIENCE

Optogenetic manipulation of stomatal kinetics improves carbon assimilation, water use, and growth

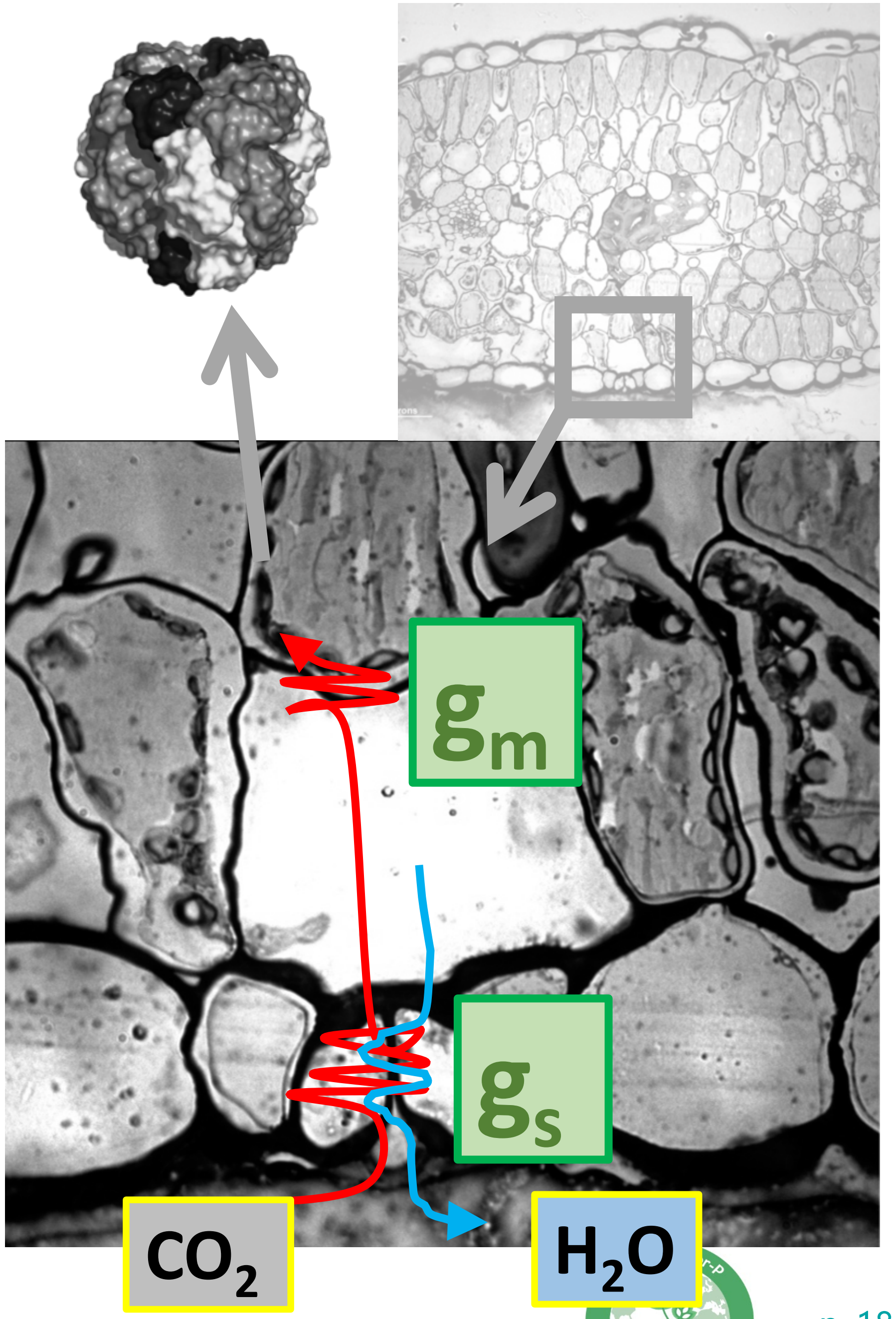
M. Papanatsiou[1,2], J. Petersen[2*], L. Henderson[2], Y. Wang[1,3],
J. M. Christie[2†‡], M. R. Blatt[1,2,3†‡]

Lawson and Blatt 2014

WUE and mesophyll conductance

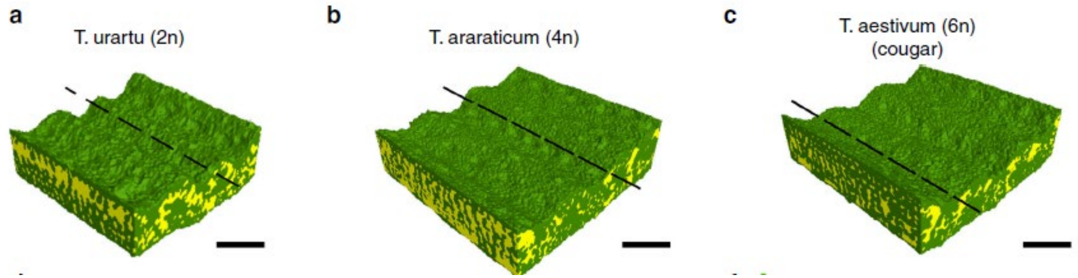


tortuosity in the mesophyll
cell wall thickness,
cell wall composition
chloroplast distribution



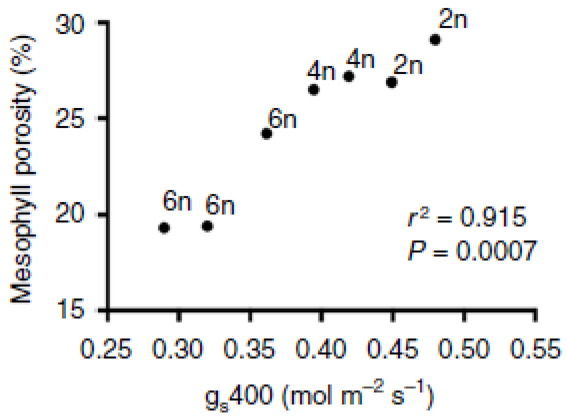
Galmés et al et al. (2011 PCE)

WUE and mesophyll conductance

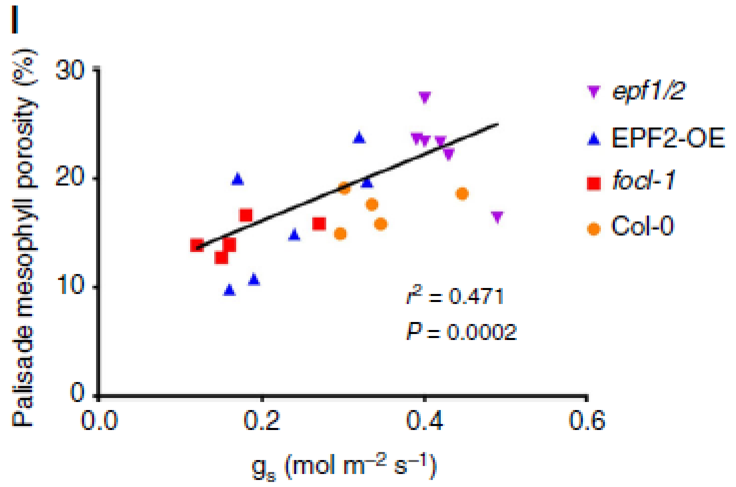


Lundgren et al 2019 Nat Com

MicroCT imaging reveals variation in wheat leaf airspace with ploidy

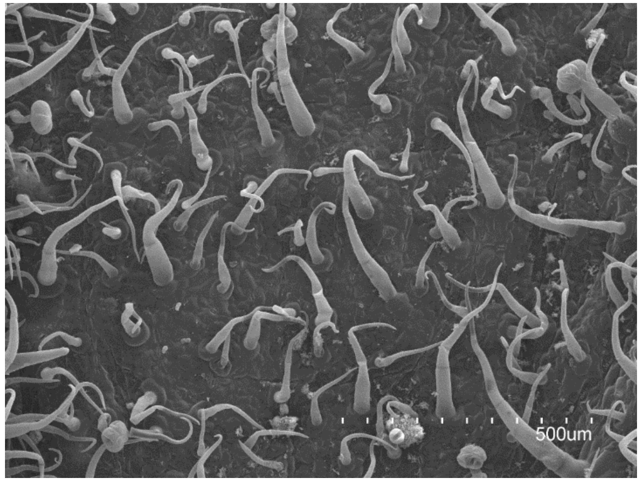


Mesophyll porosity and stomatal conductance shift with ploidy level in wheat.

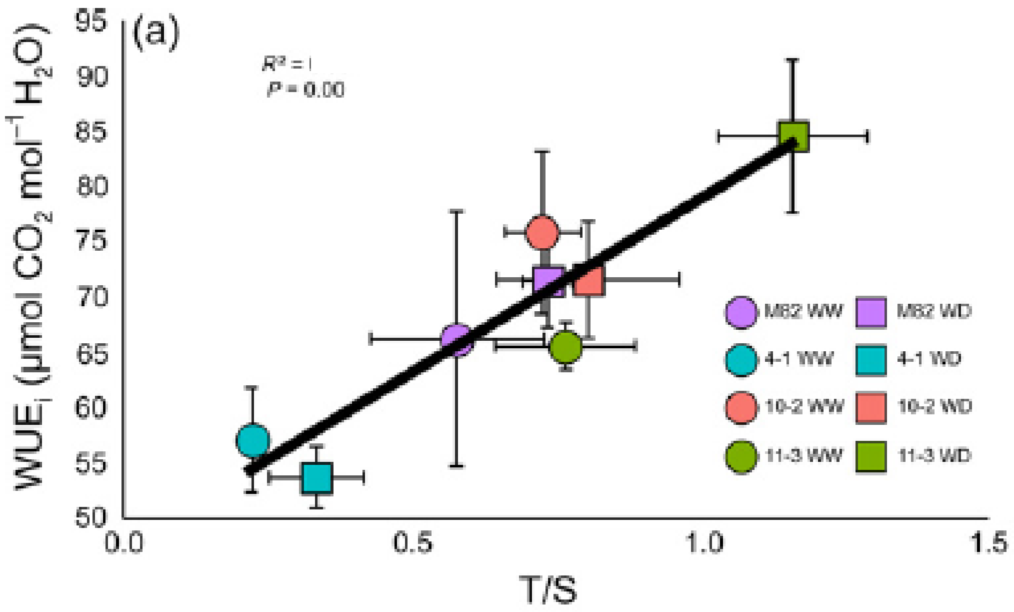


Mesophyll porosity and stomatal conductance in arabidopsis.

WUE and the boundary layer conductance



trichomes density
sunken stomata



Galdón-Armero et al. (2017 Plant J)

WUE and mesophyll conductance

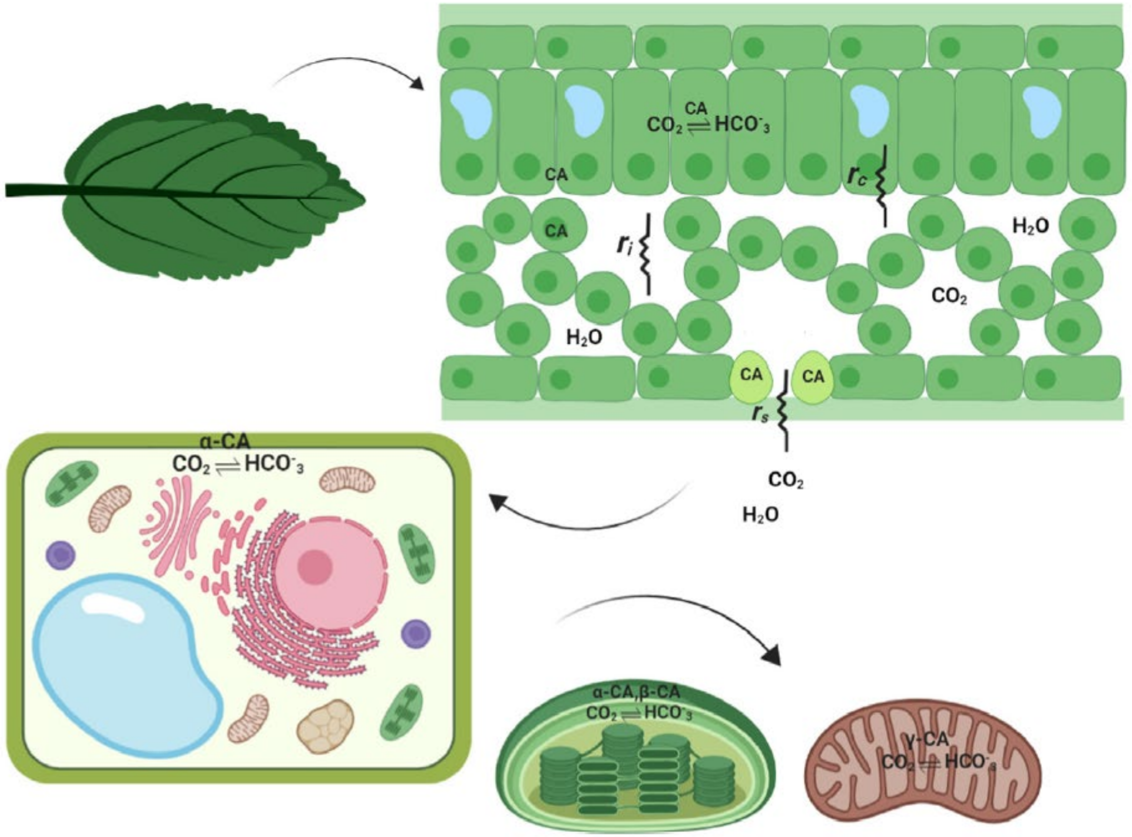
The Plant Journal (2020) **101**, 831–844
doi: 10.1111/tpj.14638

SI ADVANCES IN PHOTOSYNTHESIS

Emerging roles for carbonic anhydrase in mesophyll conductance and photosynthesis

Mina Momayyezi[1,2], Athena D. McKown[1], Shannon C. S. Bell[1] and Robert D. Guy[1,*]
[1]*Department of Forest and Conservation Sciences, Faculty of Forestry, University of British Columbia, Forest Sciences Centre, 2424 Main Mall, Vancouver, BC V6T 1Z4, Canada, and*
[2]*Department of Viticulture and Enology, University of California, Davis, CA 95616, USA*

$$CO_2 + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+.$$



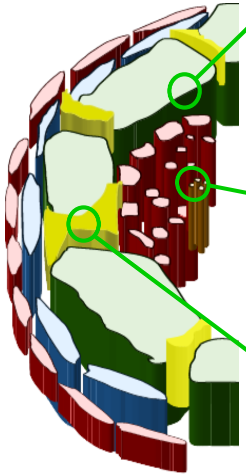
facilitate the reversible interconversion between carbon dioxide (CO_2) and bicarbonate (HCO_3^-)

further studies should focus on the dynamics of the relationship between the activity of CAs and limitations due to CO_2 diffusivity through the mesophyll and supply of CO_2 to photosynthetic reactions.

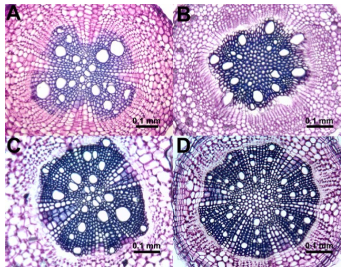
WUE, water uptake and water supply to growing tissues

The well-known players…

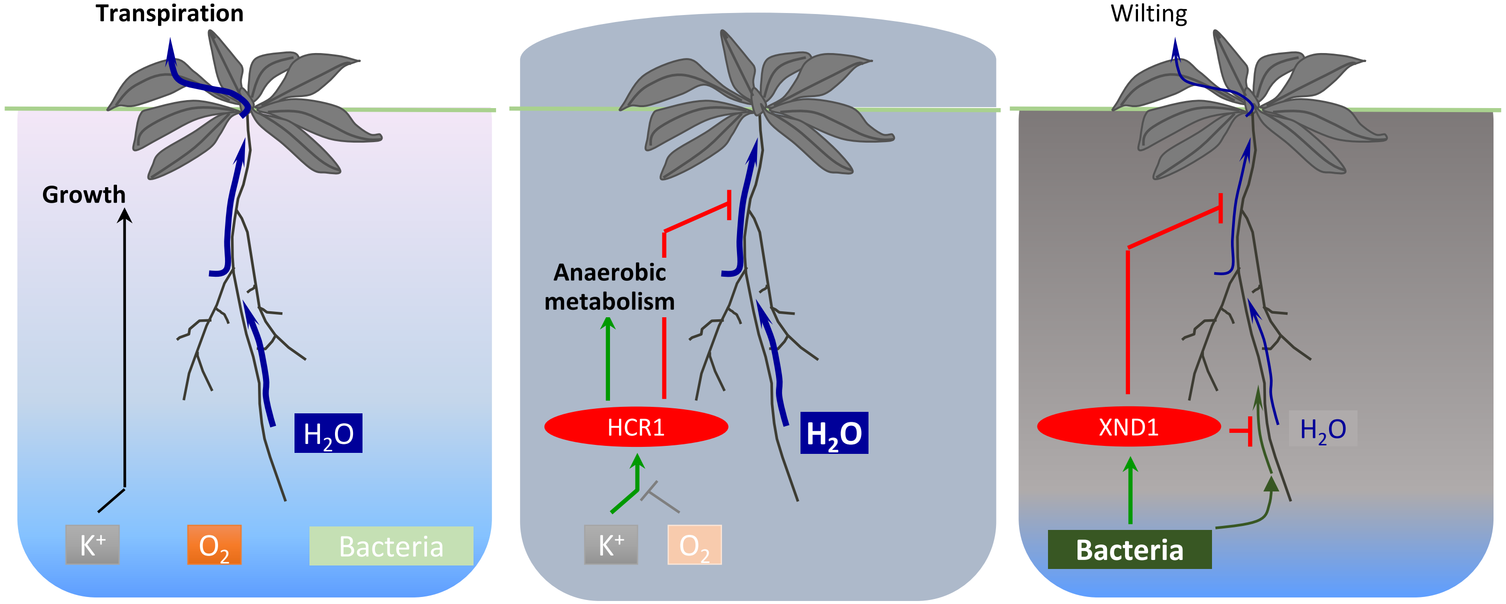
Radial conductivity



Axial conductivity



…and some newcomers in the game (stress combinations)



Aerated, irrigated and fertilized soil
Few pathogens

***HCR1*: Enhanced response to flooding in the presence of nutrients**

***XND1*: Trade-off for plant response to drought and soil vascular pathogens**

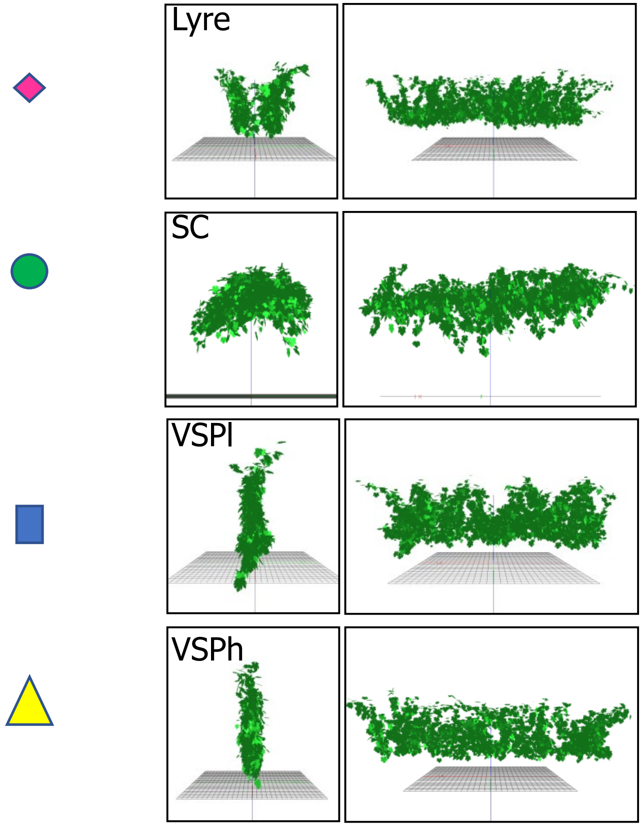
Shahzad *et al.*, Cell, 2016

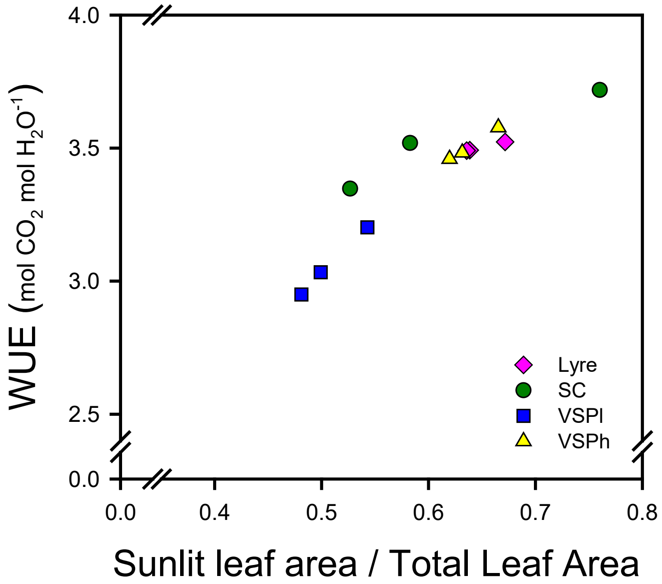
Tang *et al.*, Nature Commun., 2018

WUE and canopy architecture

Shaded leaves in a canopy –

> 5% of plant photosynthesis / 20% of water losses

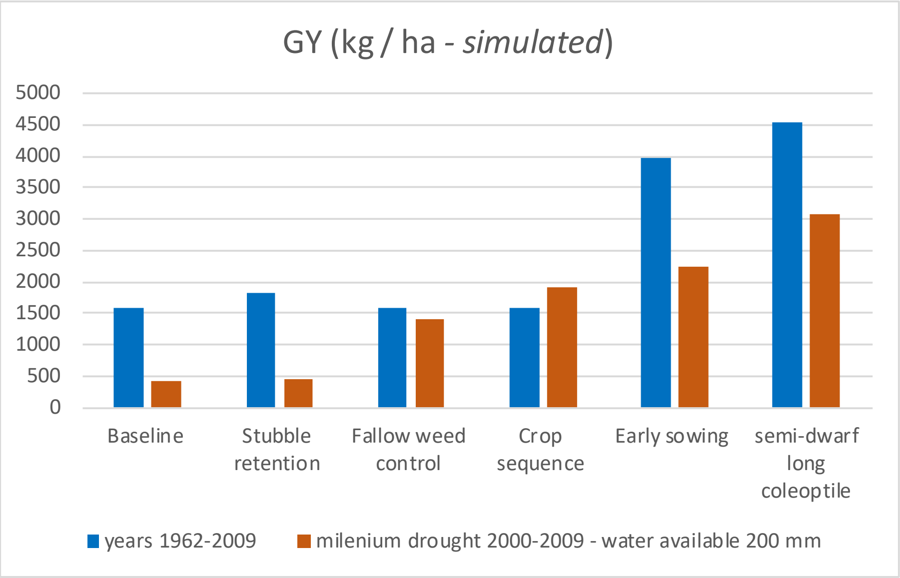


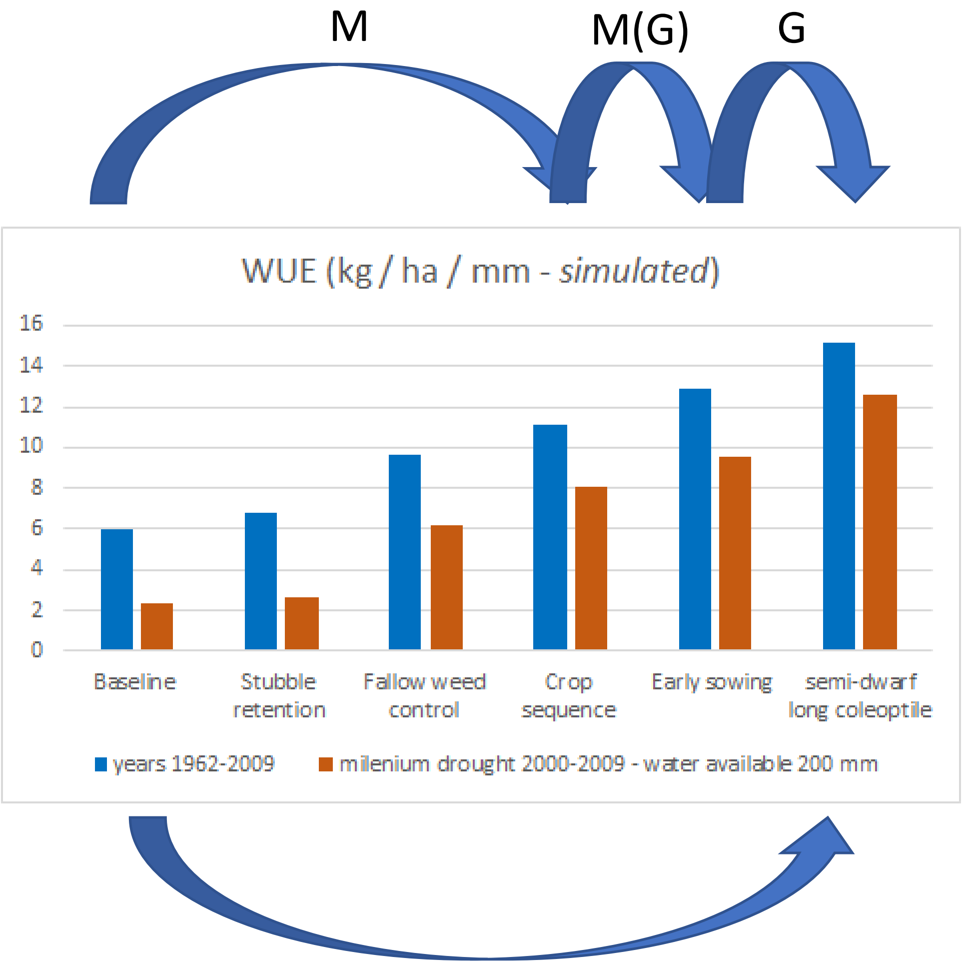


WUE depends on % leaves exposed to the sun

Albasha et al 2020 in Silico Plants; Prieto PhD

Crop management practices have boosted yield and WUE



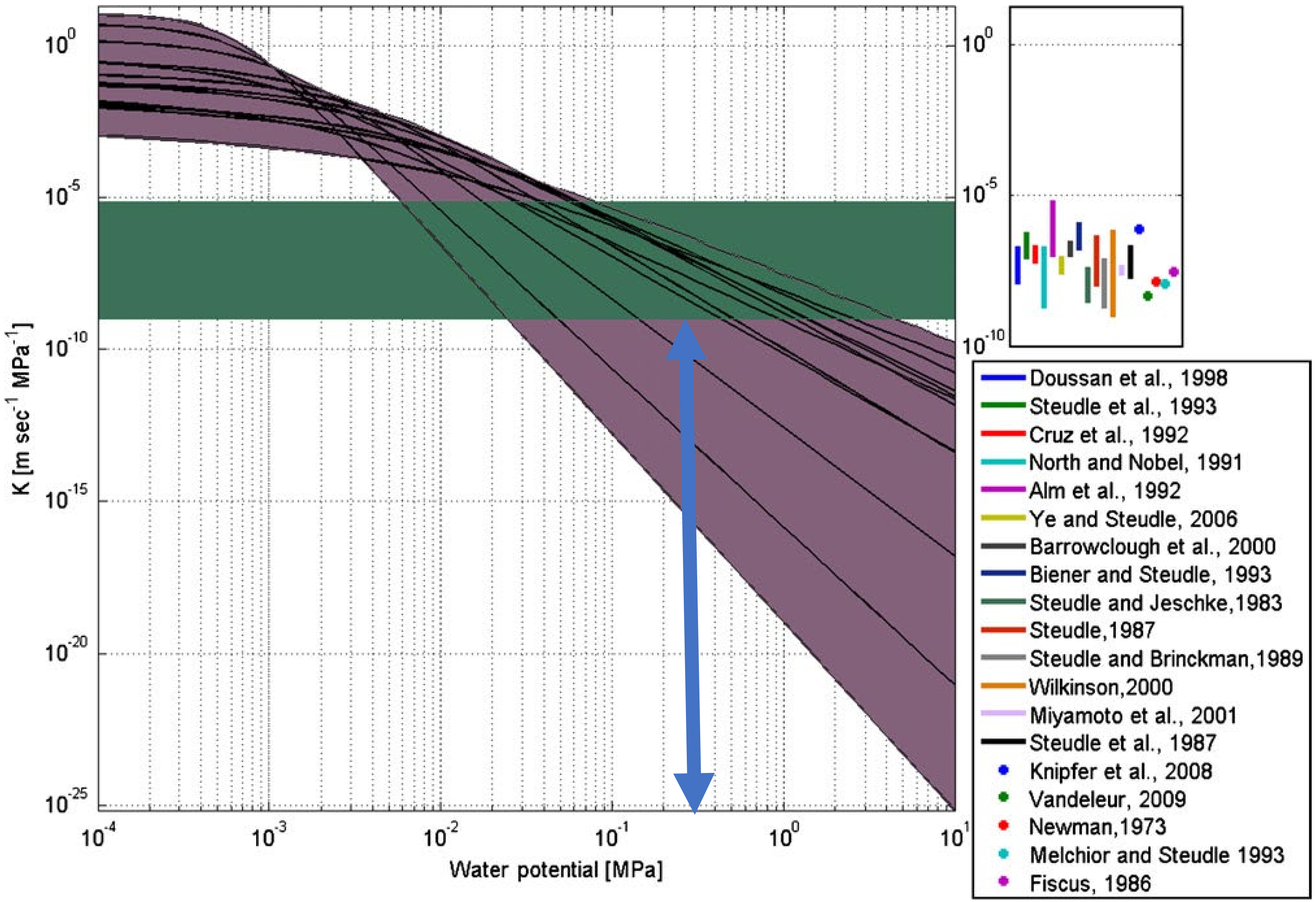


Kirkegaard and Hunt 2010 J Exp Bot

Sadras and Angus 2006 Aust J Agric Res

TE increased by 150% to 400% (severe drought)

An overlooked player in the water flow game : the soil !



Draye et al J Exp Bot. 2010

Carminati & Javaux TIPS 2020

wet dry

Trends in research

Trends (1) : genetics

– GWAS
– exotic germplasm
- transgenics

Trends (2) : modeling

– Cell (guard cell, Blatt et al…)
– Tissue (MECHA, Composite model of water uptake Couvreur et al 2018)
– Soil – root (R-SWMS, Javaux et al 2008, min3P, Gérard et al 2012)
- Whole plant (Hydroshoot – Albasha et al 2020)
- Statistical (trade-offs) -. Karabourniotis et al. 2014
- ….

Trends in research

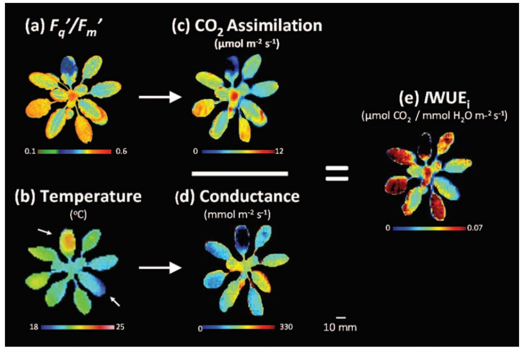
Trends (3) : phenotyping

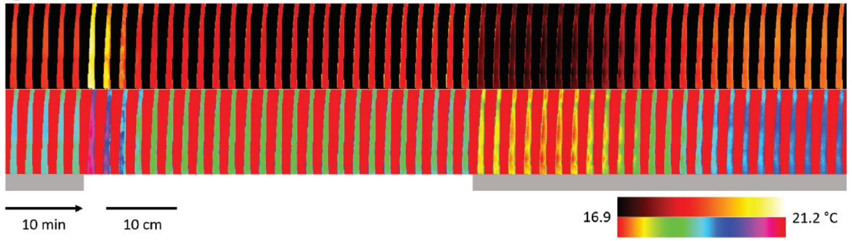
<u>Leaf traits</u>
iWUE and stomate dynamics

<u>Whole plant traits</u>
Biomass production and whole plant stomatal conductance

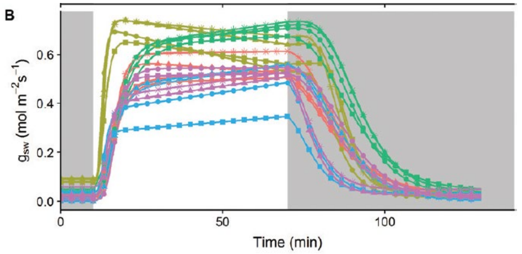
Combined thermal and chlorophyll fluorescence –a screening tool for *iWUE*

McAusland et al., 2013



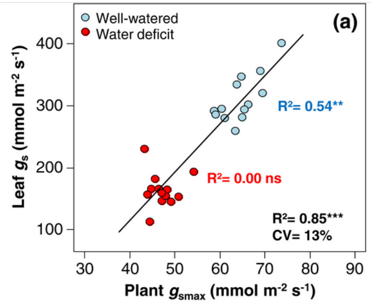


Dynamics thermography



Vialet-Chabrand & Lawson 2019

inversion of the Penman–Monteith equation (g_{smax})



Vadez et al 2015 JXB
Alvarez – Prado et al 2018 PCE

Messages

- WUE / TE is a usefull metrix at various scales
- WUE is a variable poorly heritable and NOT a parameter → work on the underlying processes
- WUE is the outcome of several processes and regulations at various scales -> develop models to account for these processes and scale-up
- There are several molecular actors impacting on WUE
- WUE and WU strongly depend on soil types
- WUE is strongly dependent upon M

To-do list

- A concerted effort for **phenotyping and model parameterization** using experiments in controlled conditions and field trials, all leading to reusable and shared data (eg. through EMPHASIS facilities)
- Develop cheap and quick phenotyping tools for breeders for water uptake, WUE
- A concerted effort towards **model improvement**, eg. to incorporate steady-state / dynamic processes (g_s...) into models
- Develop **systems-view** of water use, considering trade-offs between potentially opposite objectives such as high WUE / yield penalty including optimization, risk analysis (based on probability of drought occurrence), stabilizing farmer's economic yield.
- **Screen large genetic diversity panels** in the field (possibly including genetic resources, mutants, GM) for WUE and allelic diversity
- **Pyramiding interesting traits** to overcome negative impacts of higher WUE
- Manipulating **epidermal/stomatal patterning and dynamics** to optimize gs to current or future CO2 concentrations
- **Co-design of new G with innovative M** (Management practices) for highest benefits in terms of water use
- **Large collaborative public x private partnership** to tackle complex issues demanding concerted effort and large support (field trials, genetic material, model exchanges)
- NBTs would certainly provide more degrees of freedom on the complex, intertwined system.