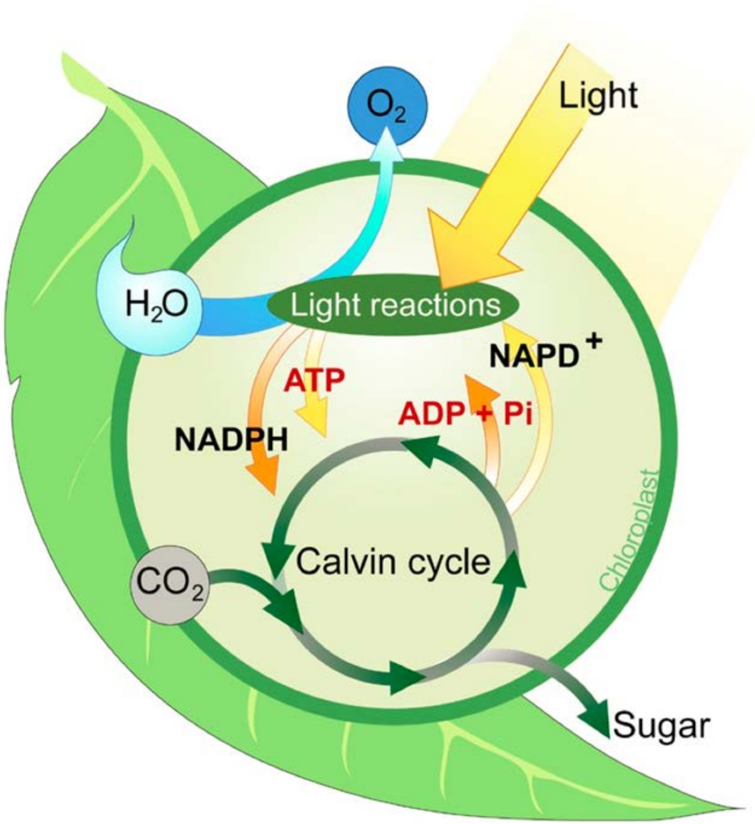
Transgenic Opportunities to Enhance Photosynthetic Efficiency

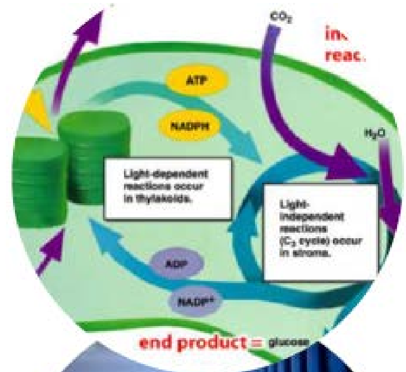
Lisa Ainsworth

USDA ARS Global Change and Photosynthesis Research Unit

USDA-ARS Grape Research Workshop

Why improve photosynthesis?





Photosynthetic process is known in great detail

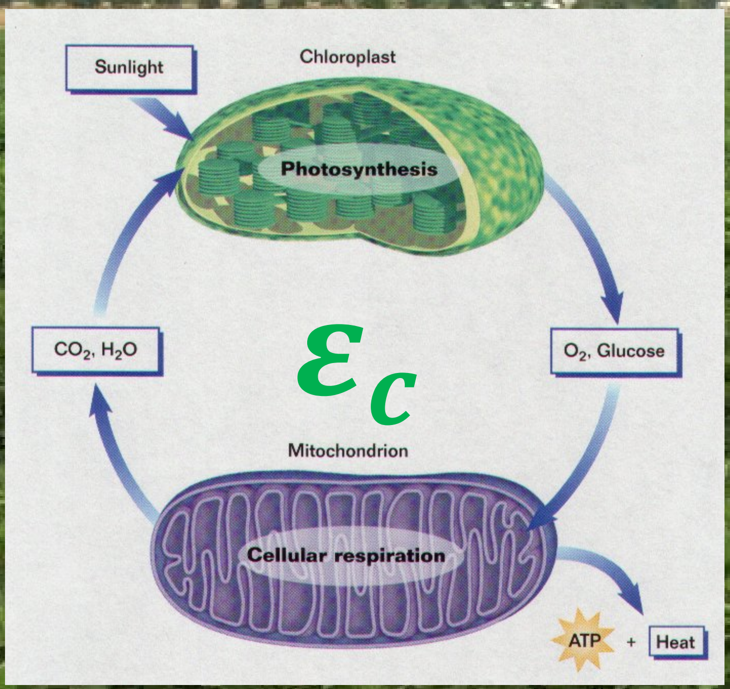
High performance computing for modeling the photosynthetic process

Crop transformation is getting more efficient

Physiological drivers of yield potential

$$Y = 0.487 \cdot S_t \cdot \varepsilon_i \cdot \varepsilon_c \cdot \varepsilon_p$$

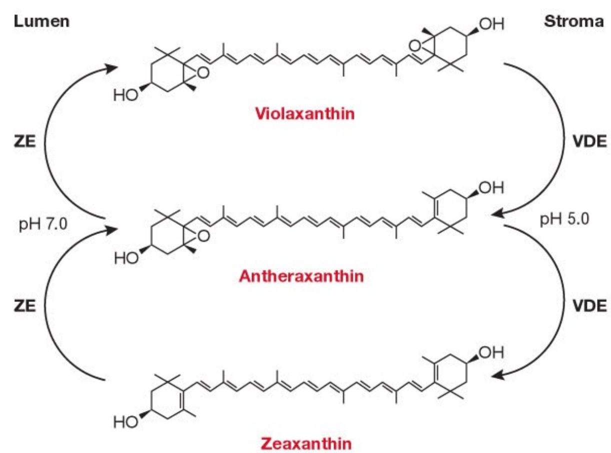
ε_i

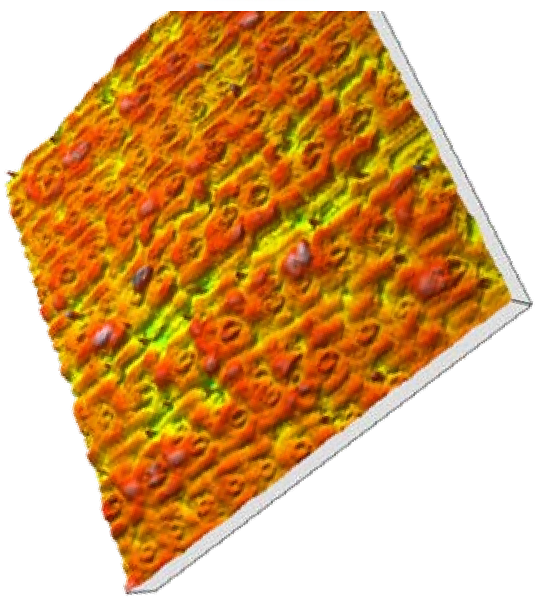


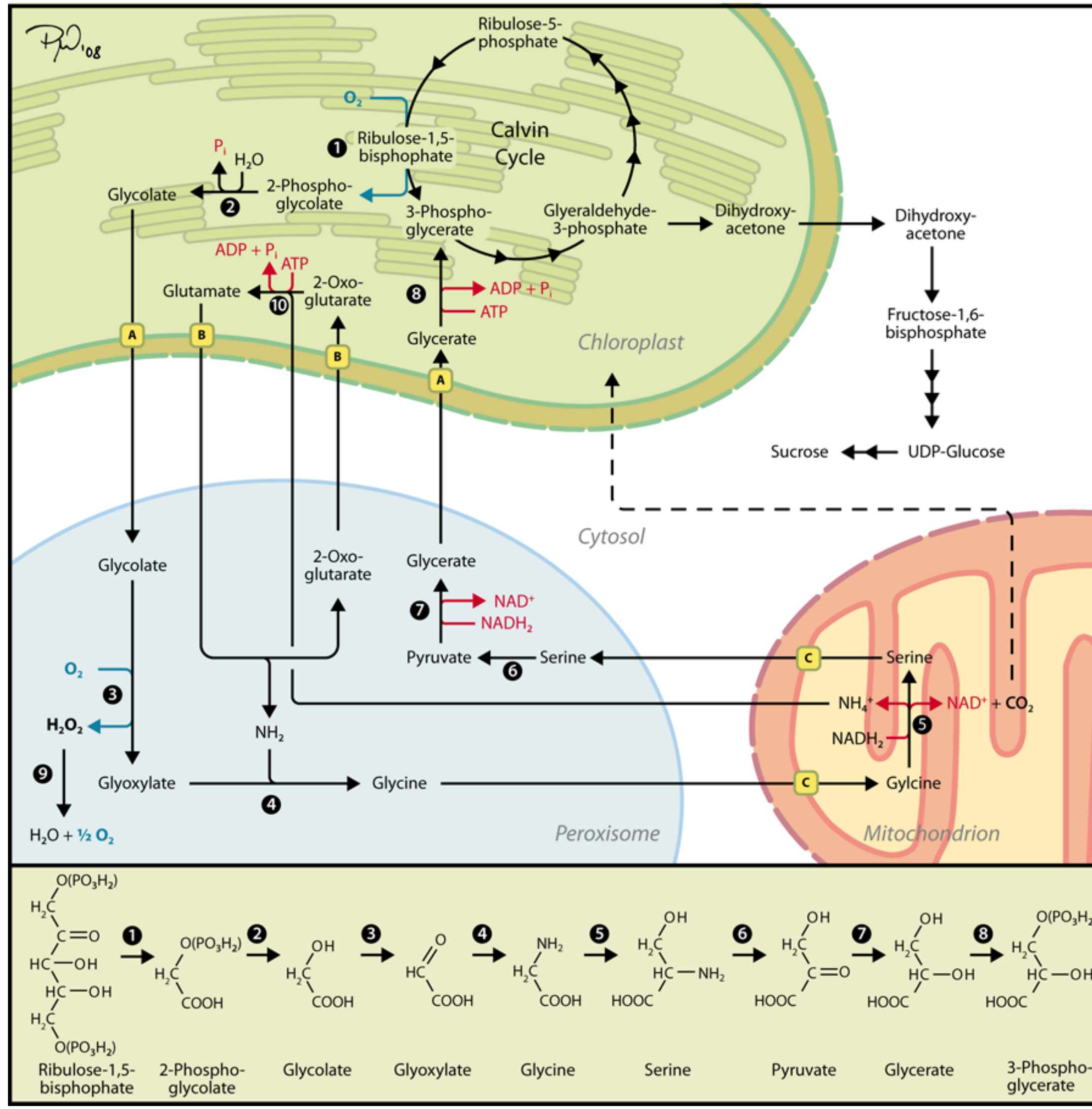
ε_c

ε_p

Inefficiencies in photosynthesis

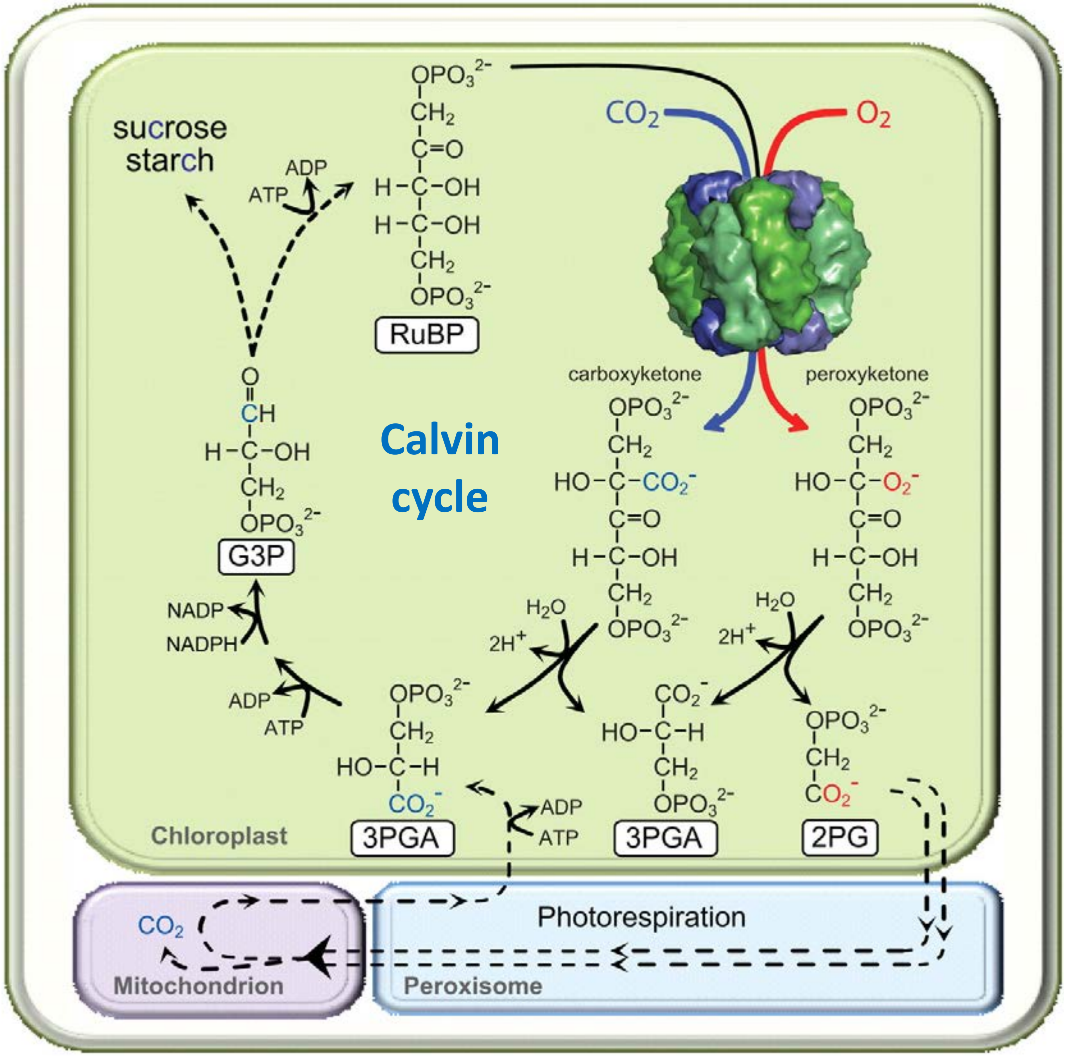






Buchanan, Gruissem, Jones 2000 Biochemistry & Molecular Biology of Plants

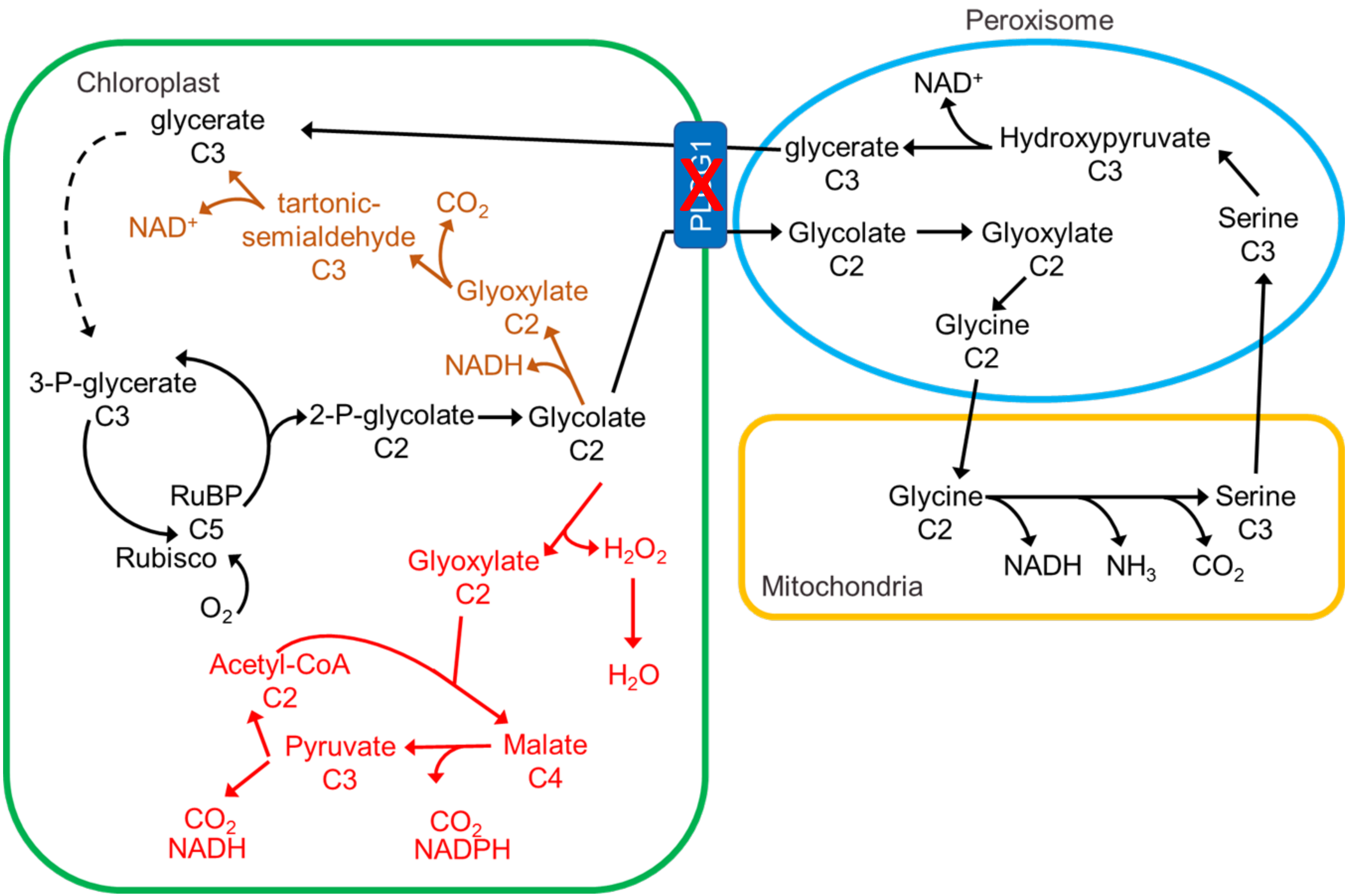
Opportunity 1: Bypass Photorespiration



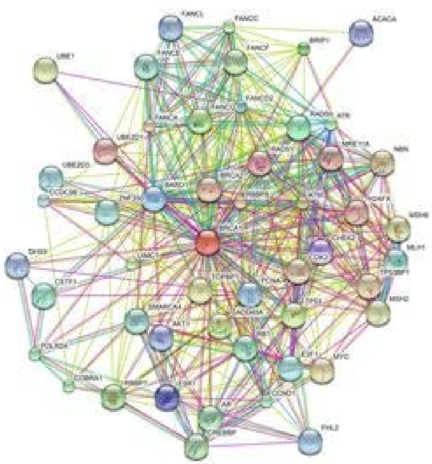
- 25% of Rubisco activity is oxygenation
- Recycling the toxic compound 2-phosphoglycolate (through photorespiration) is energetically expensive
- Estimated that photorespiration decreases soybean and wheat yields by ~148 trillion calories per year

Whitney et al. 2011 Plant Phys 155, 27-35; Walker et al. 2016 Annu Rev Plant Biol. 67, 107-129

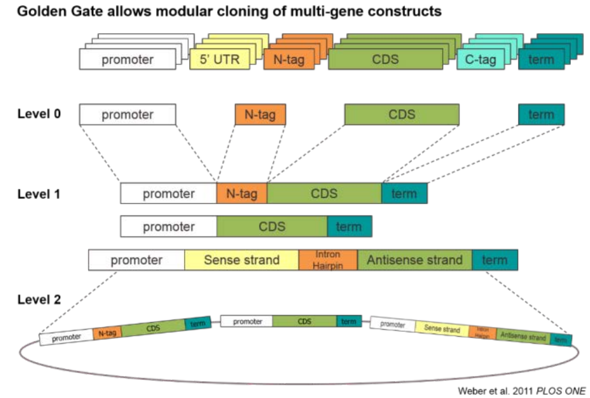
Opportunity 1: Bypass Photorespiration



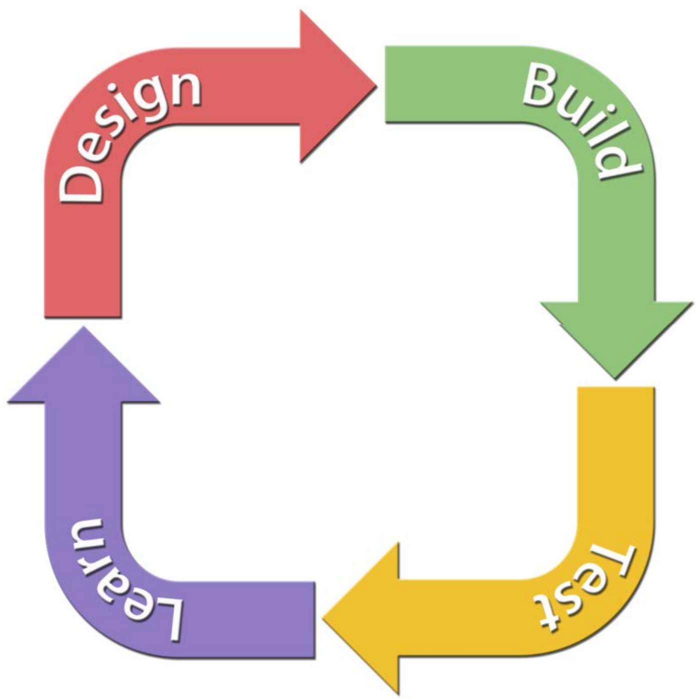
Paul South, Don Ort, et al.



Computation and
Systems biology



Golden Gate Cloning
DNA synthesis



Plant transformation

Paul South, Don Ort, et al.

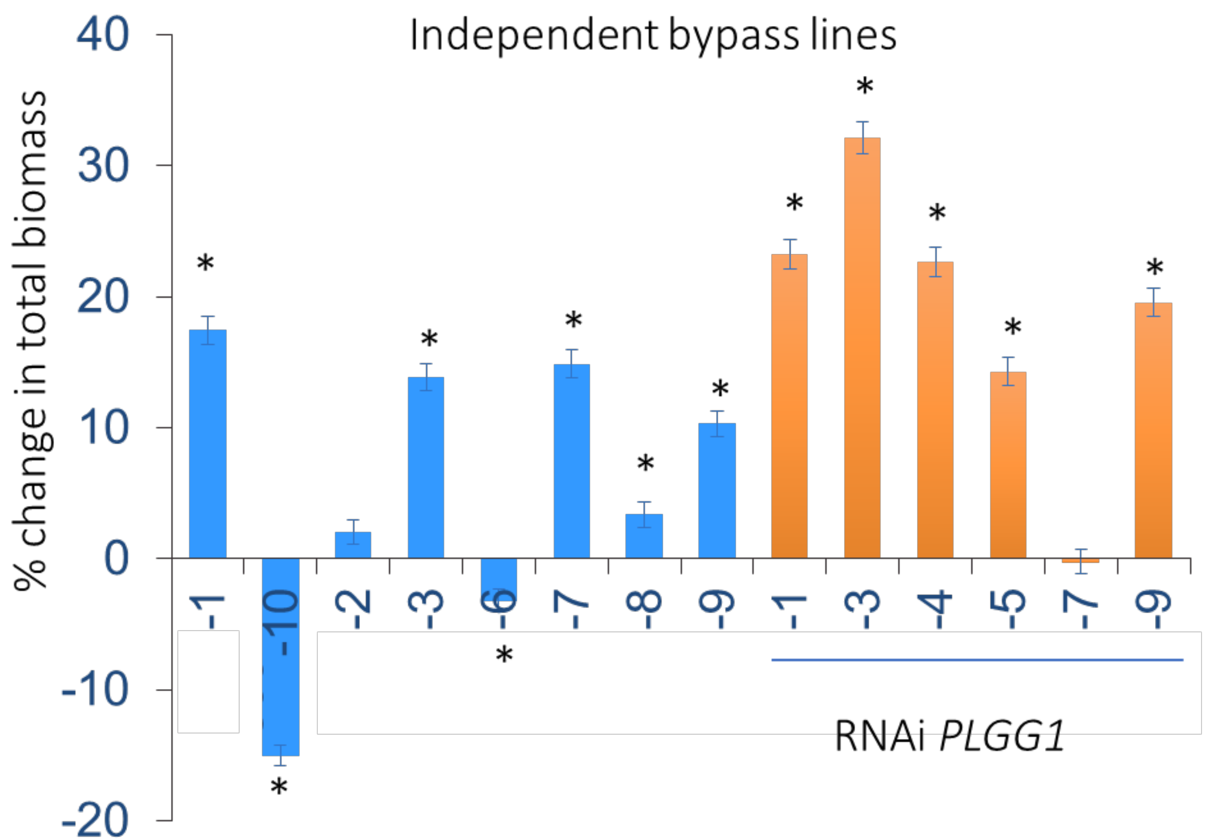
- 24 different photorespiration bypass designs
- With and without RNAi targeting PLGG1
- 140 single insert homozygous T2 lines have been confirmed from ~1500 segregating lines.

Paul South, Don Ort, et al.

Photo taken at 8 weeks

WT

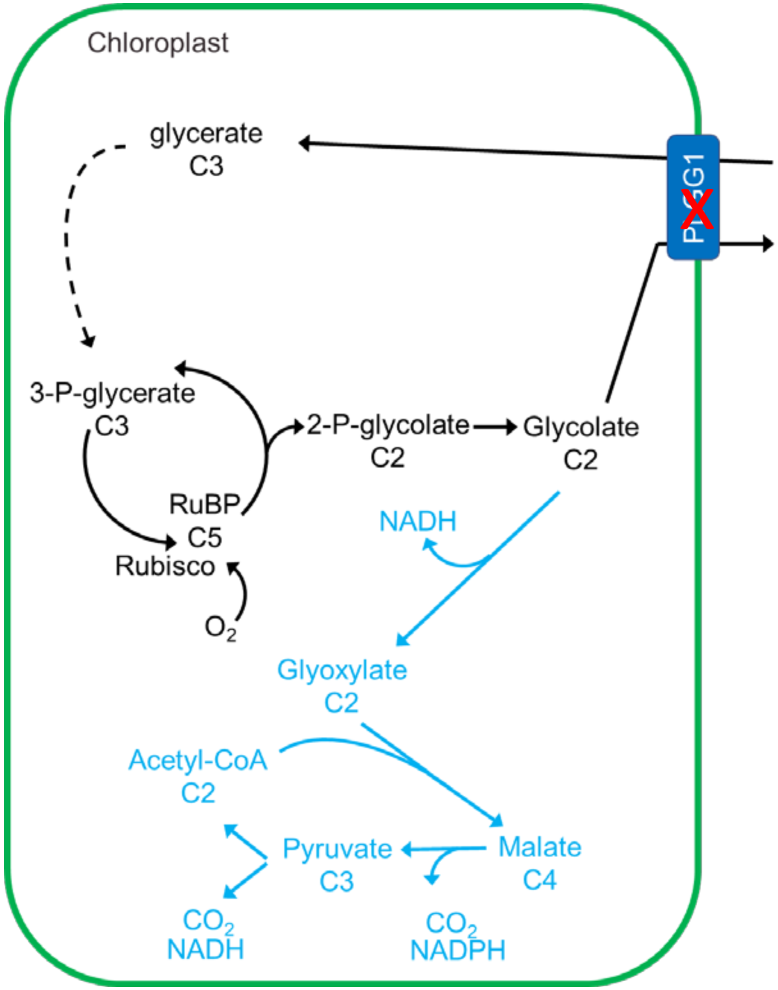
Bypass plus *PLGG1* RNAi

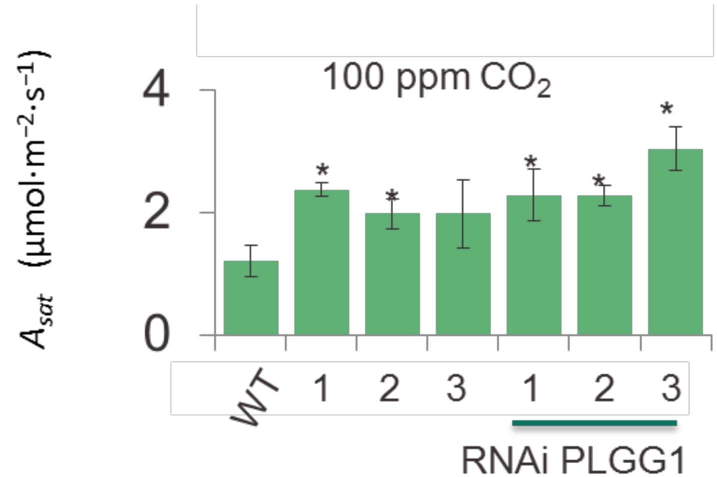


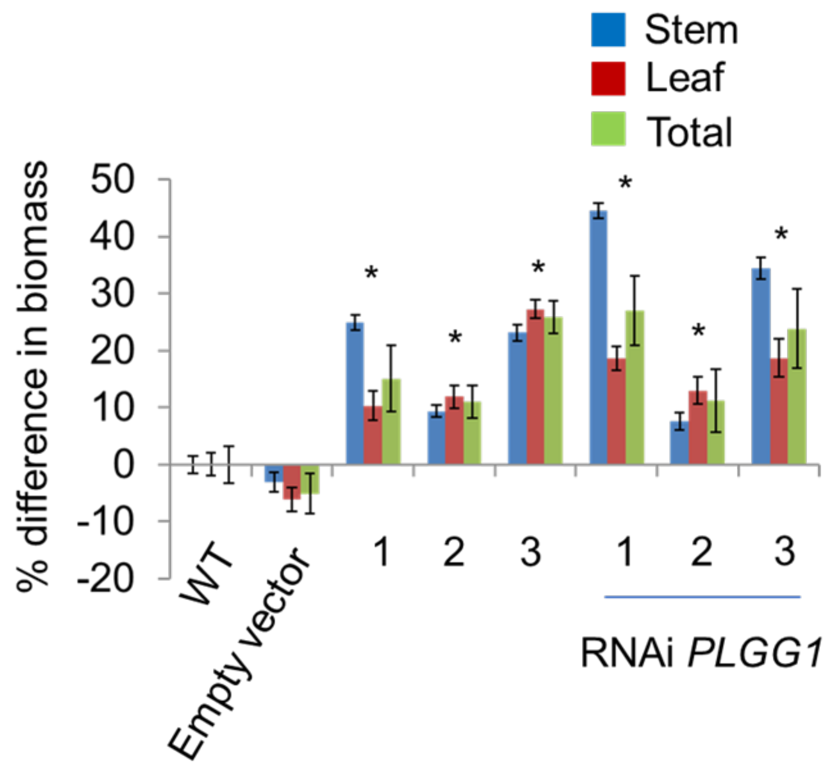
Paul South, Don Ort, et al.

Field Testing Promising Transgenic Lines

Paul South, Don Ort, et al.

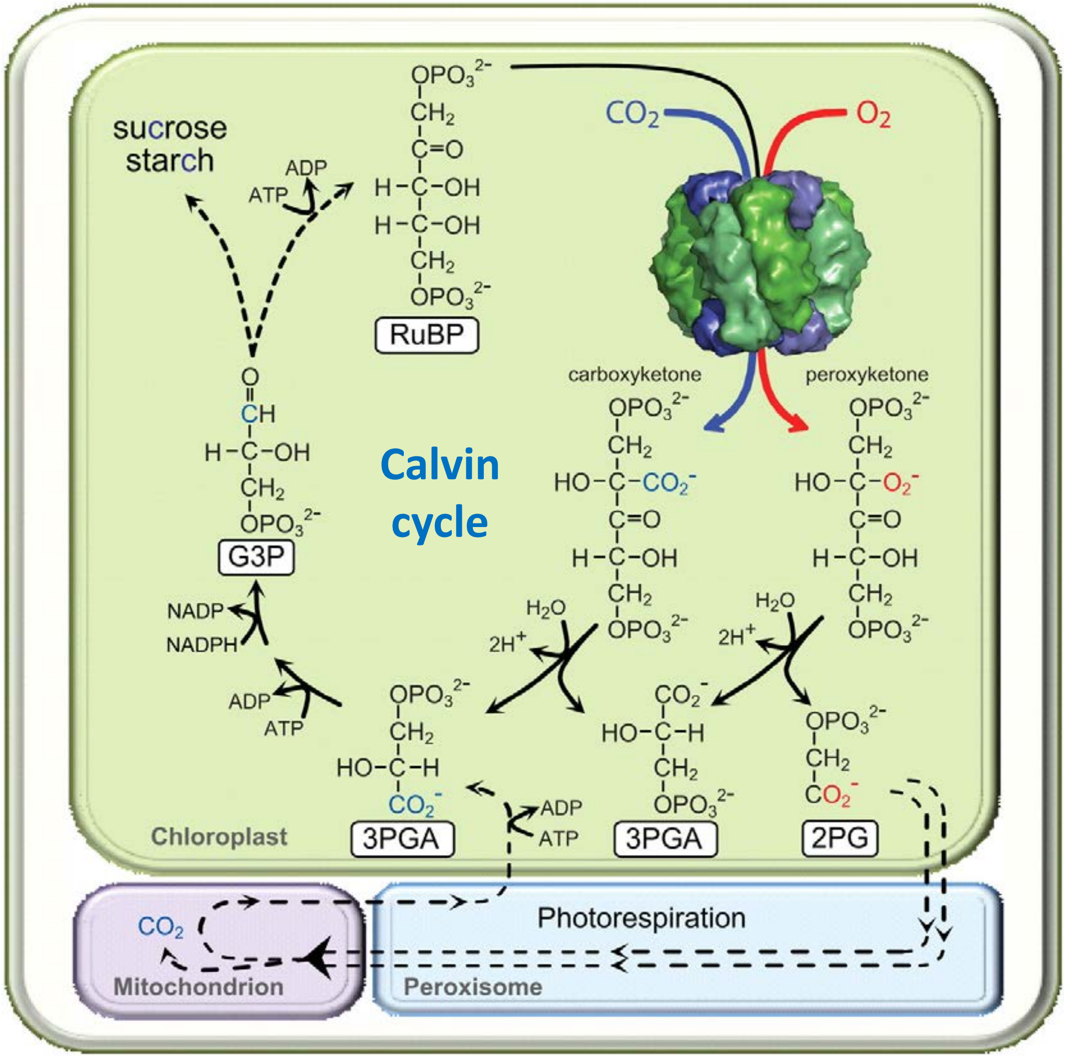






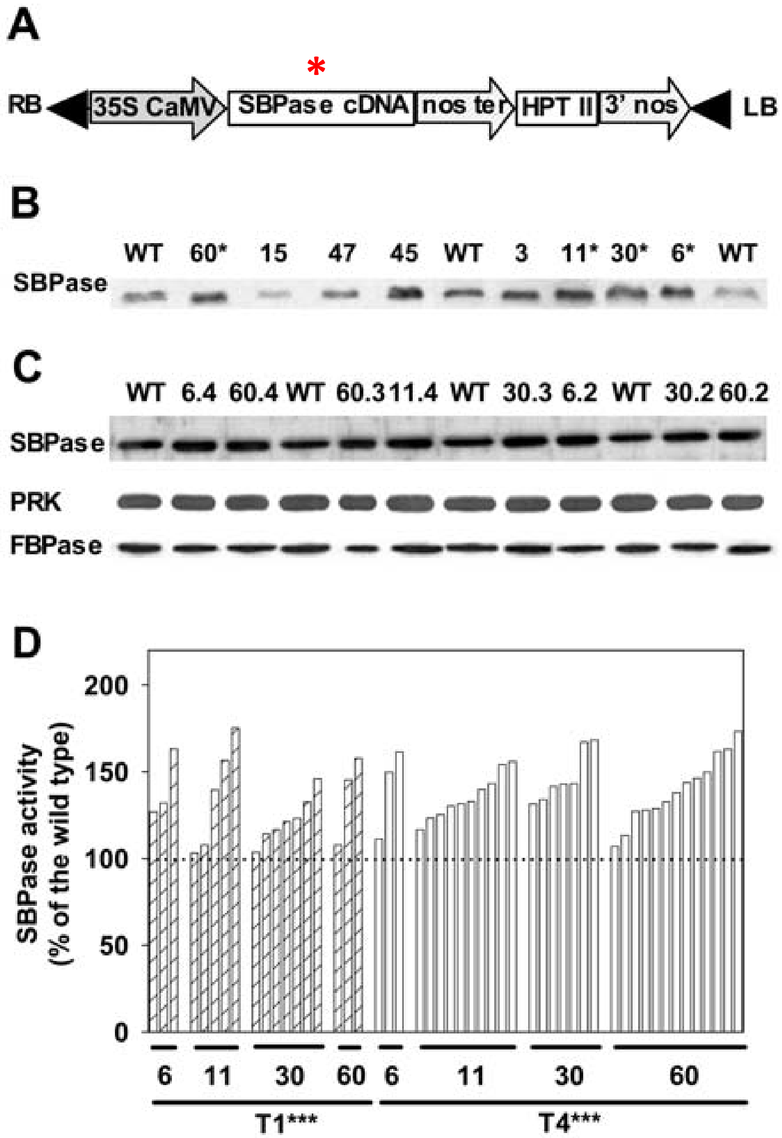
Paul South, Don Ort, et al.

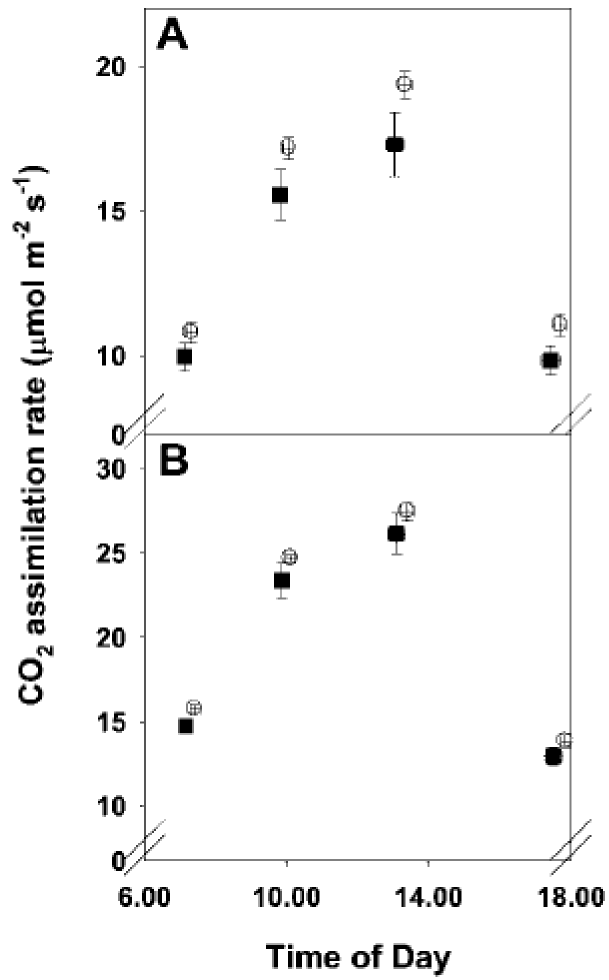
Opportunity 2: Accelerate RuBP Regeneration



- RuBP is the sugar acceptor for CO_2
- Eight enzymes are involved in the regeneration of RuBP for Rubisco
- Metabolic flux measurements and modeling suggest some of those eight enzymes have a role in determining rates of carbon flux into leaves

Opportunity 2: Accelerate RuBP Regeneration





Lefebvre et al. 2005 Plant Phys 138, 451-460

Opportunity 2: Accelerate RuBP Regeneration

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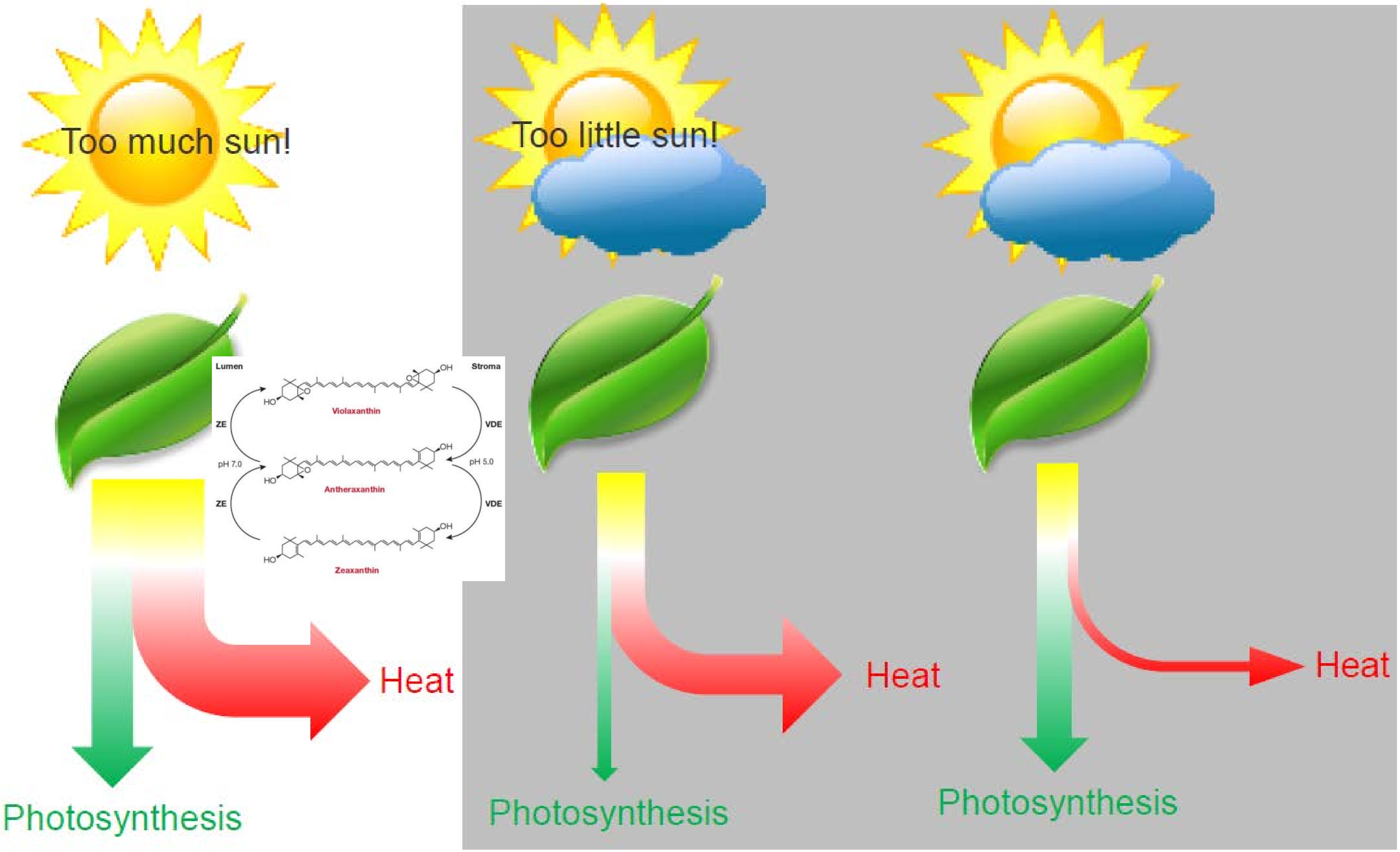
Opportunity 3: Accelerate NPQ Relaxation



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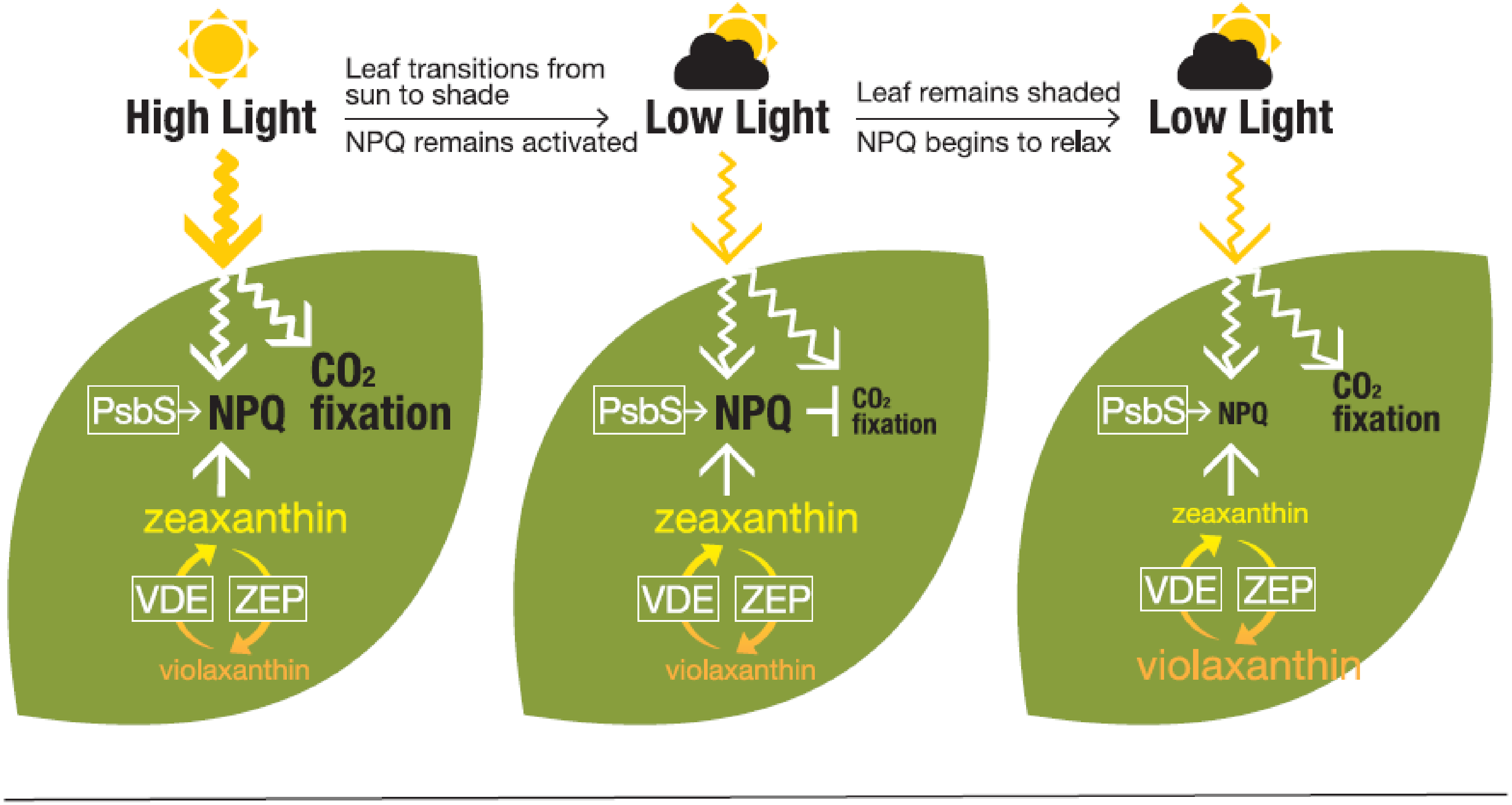


ZEP speeds up NPQ relaxation
VDE balances ZEP activity during NPQ induction
PsbS adjusts NPQ level to maintain WT amplitude

Kromdijk et al. 2016 Science 354, 857-861

Opportunity 3: Accelerate NPQ Relaxation

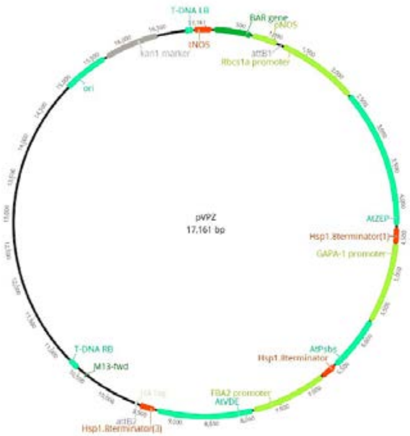
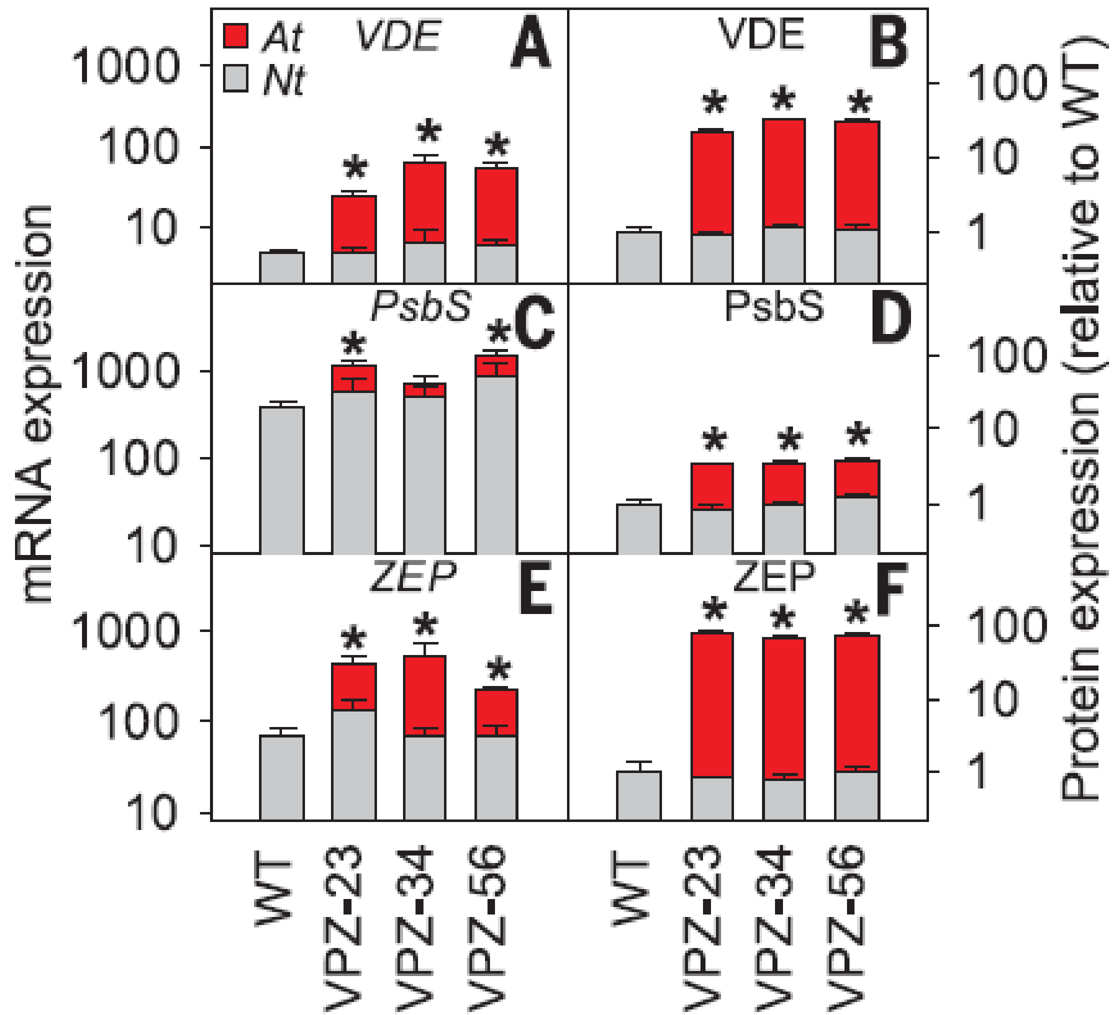


Fig. S1. Plasmid map of VPZ construct used to transform *N. tabacum*.



Kromdijk et al. 2016 Science 354, 857-861

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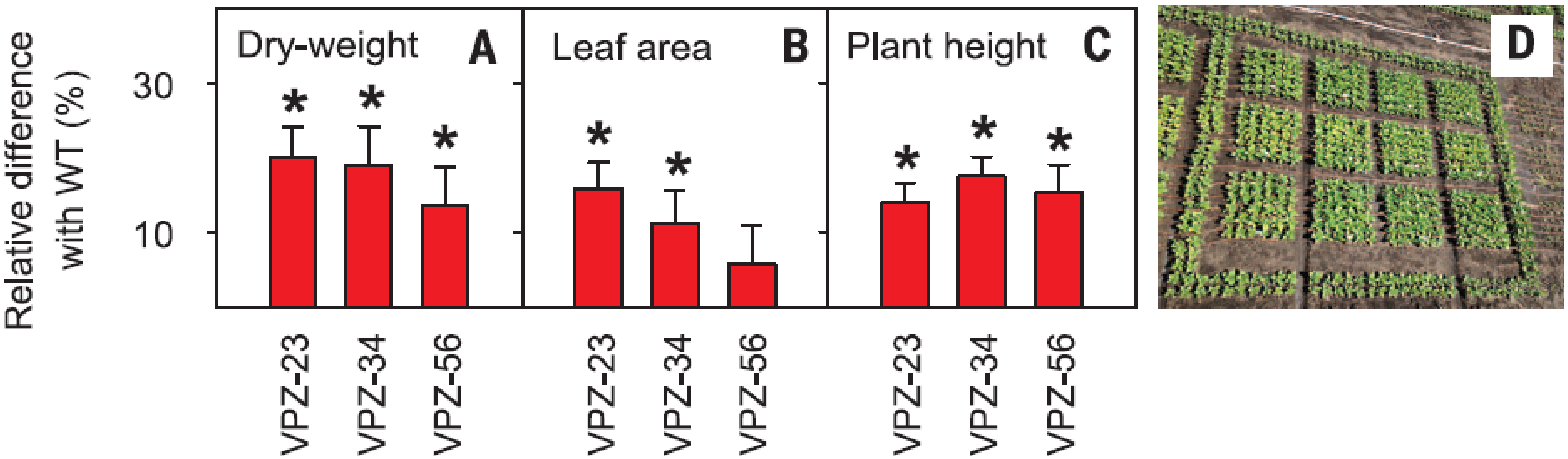
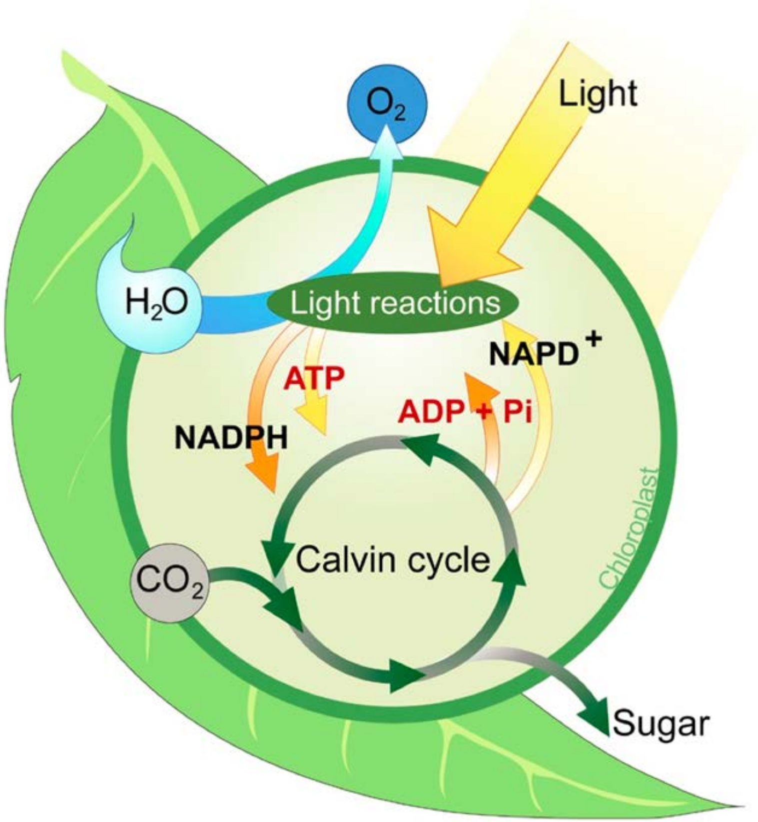


Kromdijk et al. 2016 Science 354, 857-861

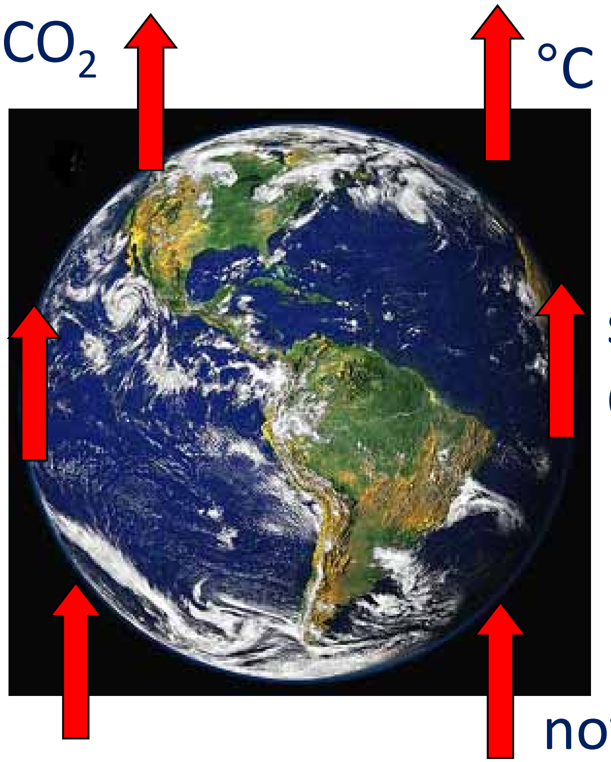
Multiple opportunities to improve crop photosynthesis using transgenic strategies



More efficient light utilization
(NPQ relaxation, altered canopy structure, more cytochrome b6f)

More efficient carbon fixation
(Photorespiratory bypass, increased SPBase, altered Rubisco, activase)

The growing environment is changing



Adapting crops to a future growing environment, with increased [CO_2], higher temperatures, altered water availability and increased pollution is a major challenge for agriculture.

Climatic Change (2011) 109:213–241

Climate Change Ripens Prospects For German Winemakers

https://www.npr.org/sections/thesalt/2017/11/17/564099490/climate-change-ripens-prospects-for-german-winemakers

Climate Change Removes Prospects for Spanish Winemakers

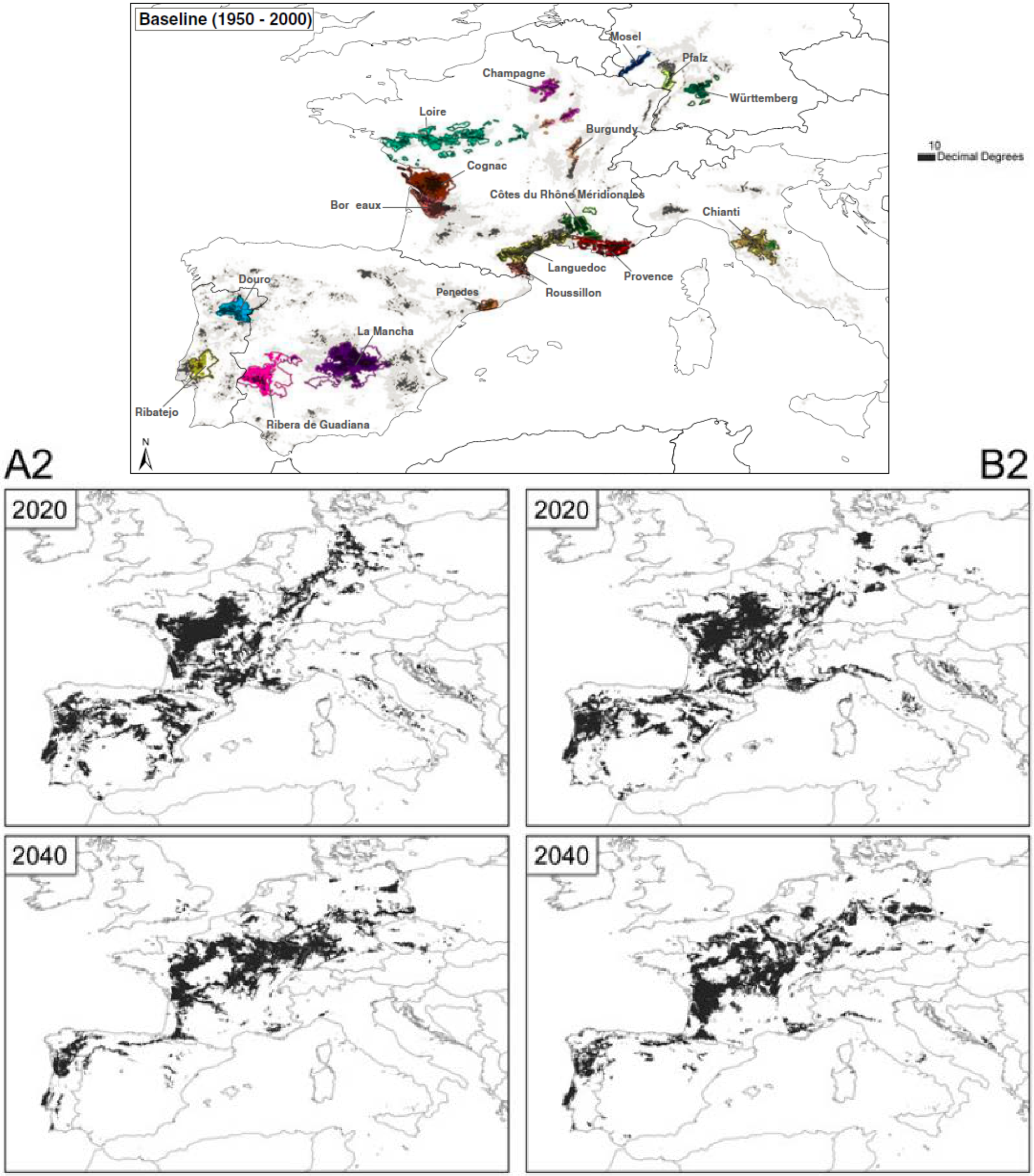


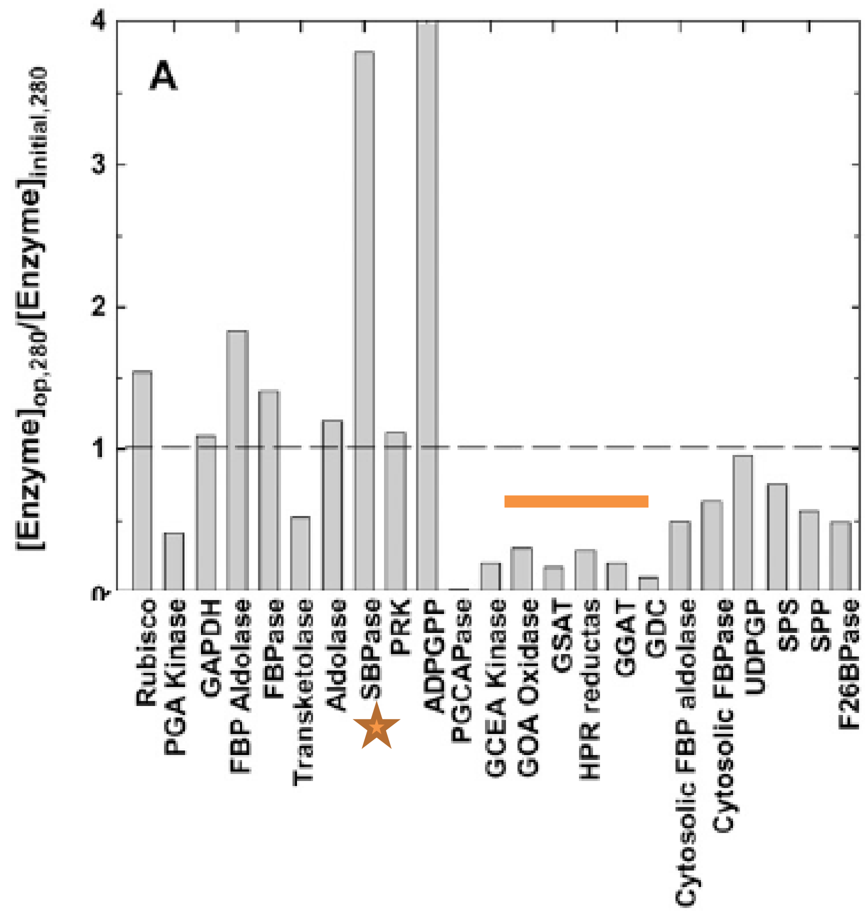
Fig. 2 Predicted grapevine cultivated area for the baseline (1950–2000) and the future time slices 2020 and 2050 in A2 and B2 scenarios

Climatic Change (2013) 119:825–839

Transgenic targets for improving crop responses to future climate conditions

• Current partitioning of nitrogen among the enzymes of C_3 carbon metabolism is not optimized to today's atmospheric [CO_2].

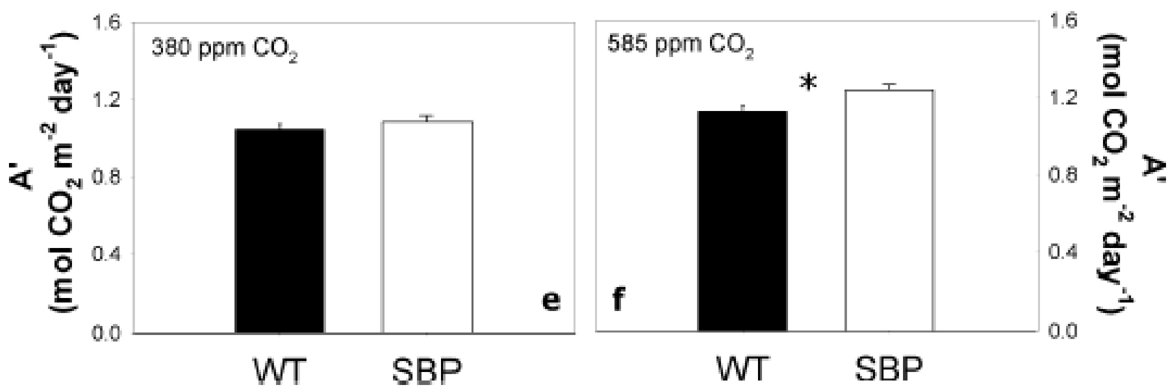
• Investment in photorespiratory enzymes is too high, while investment in SBPase , ADP-Glc pyrophosphorylase is too low.

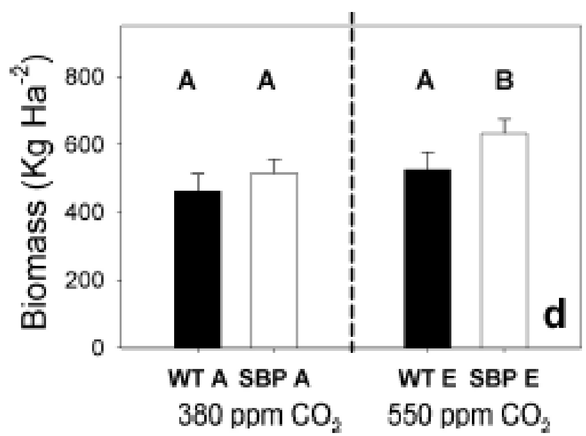


Plant Physiology, October 2007, Vol. 145, pp. 513–526,

Over-expressing the C_3 photosynthesis cycle enzyme Sedoheptulose-1-7 Bisphosphatase improves photosynthetic carbon gain and yield under fully open air CO_2 fumigation (FACE)

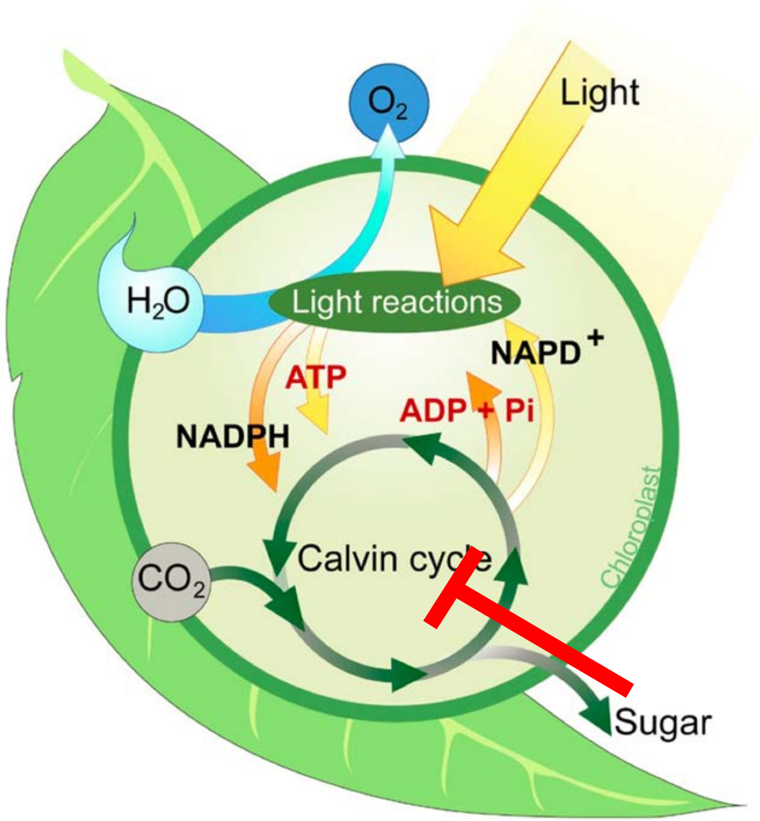
David M Rosenthal[1], Anna M Locke[2], Mahdi Khozaei[3], Christine A Raines[4], Stephen P Long[5] and Donald R Ort[6*]





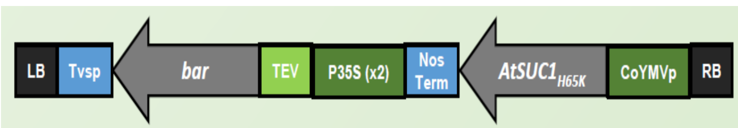
Rosenthal *et al. BMC Plant Biology* 2011, **11**:123

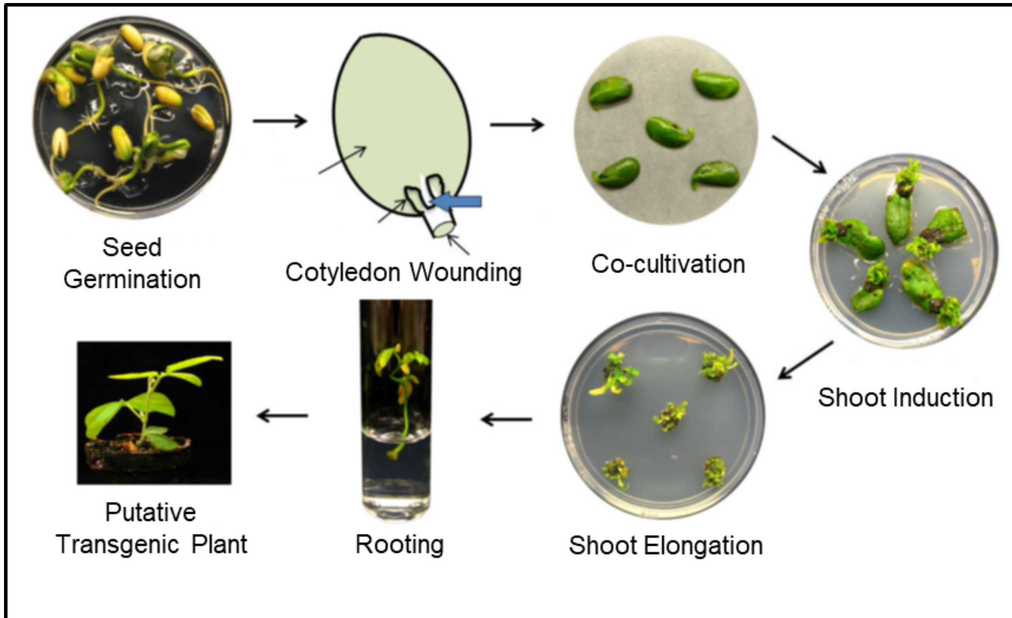
Elevated [CO_2] increases photosynthetic rate in C3 crops



Increased sucrose concentration in leaves can negatively feedback on photosynthesis

Overexpress sucrose transporters





Lee *et al.*, 2013 *A Comprehensive Survey of International Soybean Research*

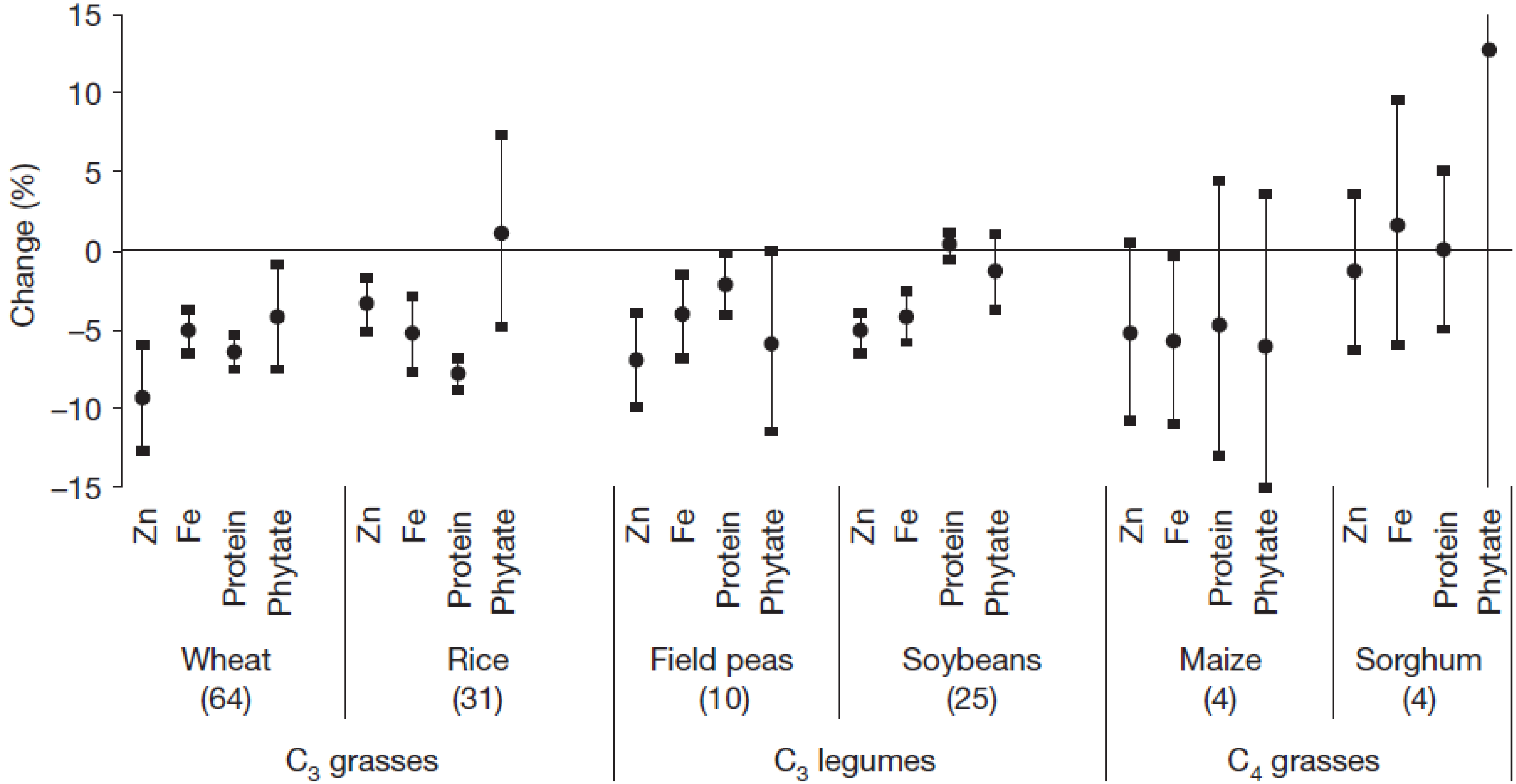
- **Gene of interest *AtSUC1*$_{H65K}$**
- Sucrose/proton symporter from *A. thaliana* with amino acid substitution
- 14-fold higher transport activity than the native protein

- **Promoter from Commelina Yellow Mottle Virus**
- Specific to the companion cells
- Induced by sucrose

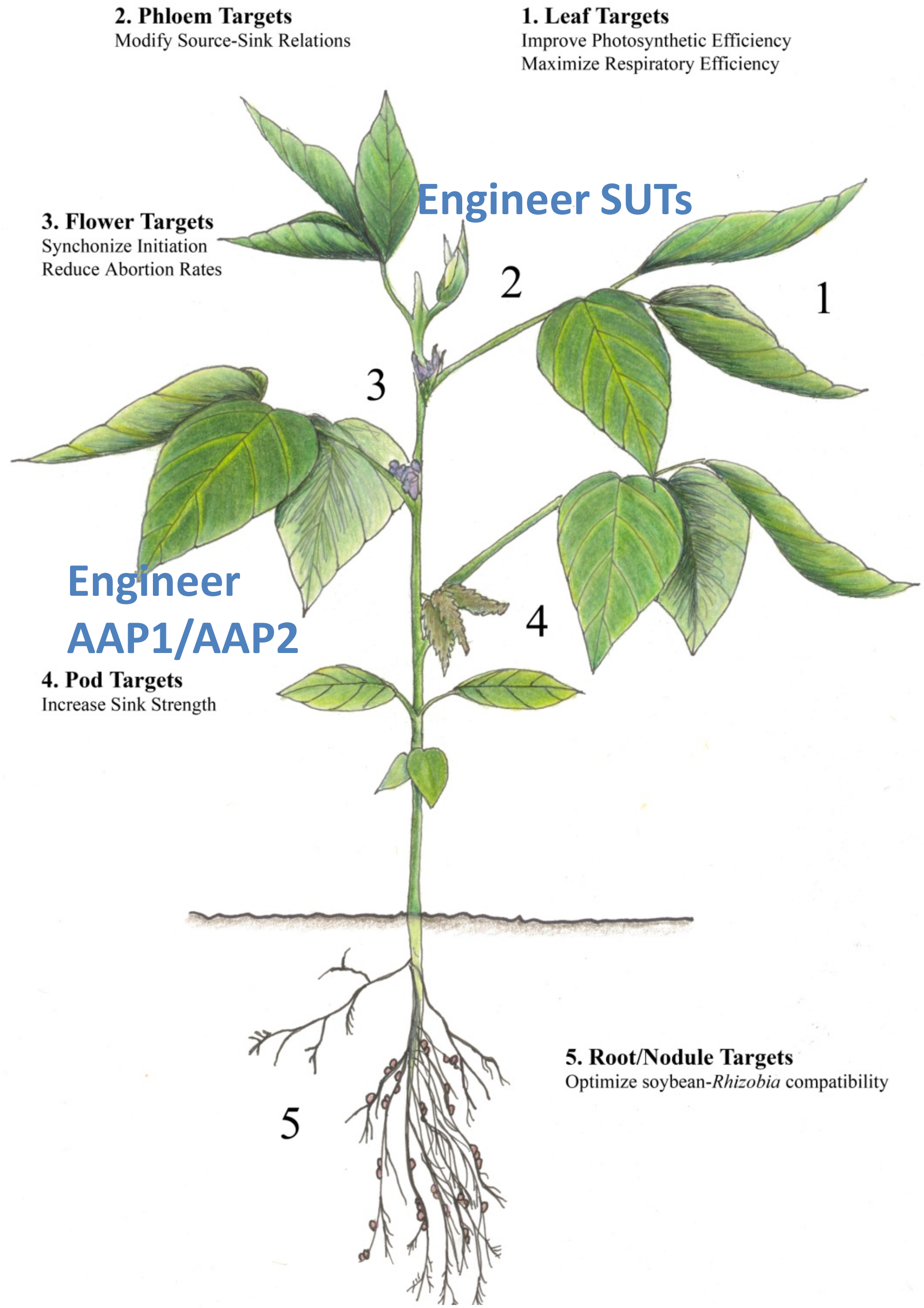
P. Lemonnier, J. Quebedeaux

Increasing CO_2 threatens human nutrition

Samuel S. Myers[1,2], Antonella Zanobetti[1], Itai Kloog[3], Peter Huybers[4], Andrew D. B. Leakey[5], Arnold J. Bloom[6], Eli Carlisle[6], Lee H. Dietterich[7], Glenn Fitzgerald[8], Toshihiro Hasegawa[9], N. Michele Holbrook[10], Randall L. Nelson[11], Michael J. Ottman[12], Victor Raboy[13], Hidemitsu Sakai[9], Karla A. Sartor[14], Joel Schwartz[1], Saman Seneweera[15], Michael Tausz[16] & Yasuhiro Usui[9]



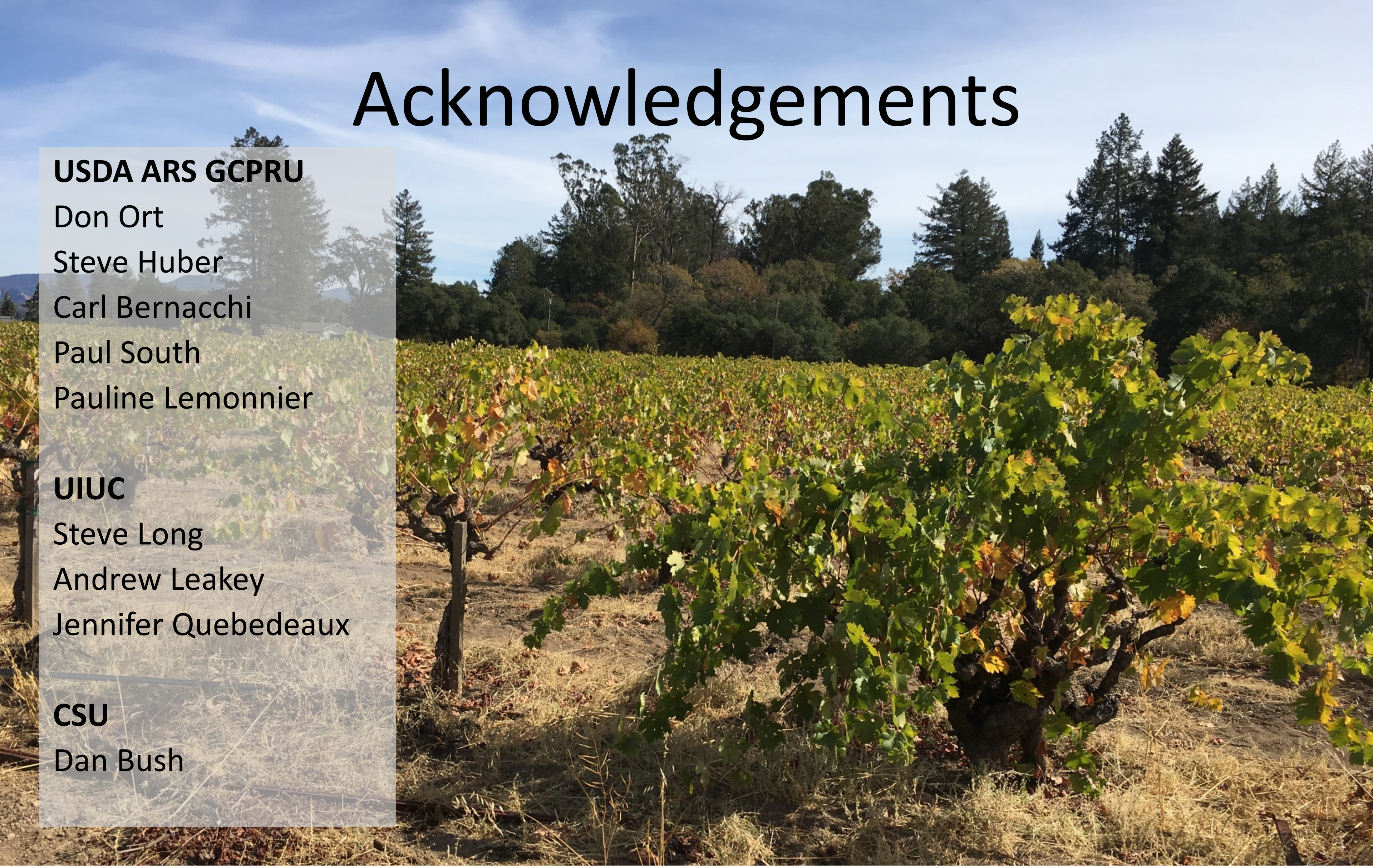
Increasing the capacity for transporting sugars and amino acids to sinks and maximizing sink strength is also important – and will be increasingly as $[CO_2]$ rises.



Plant, Cell and Environment (2012) 35, 38–52

Summary

- Scientific and technological advancements enable rapid tests of potential targets to improve photosynthetic efficiency in crops
- As the climate changes, some growing regions may benefit, while others will suffer.
- New transgenic targets will be needed to adapt photosynthesis to global climate change.



Acknowledgements

USDA ARS GCPRU
Don Ort
Steve Huber
Carl Bernacchi
Paul South
Pauline Lemonnier

UIUC
Steve Long
Andrew Leakey
Jennifer Quebedeaux

CSU
Dan Bush

USDA ARS Agricultural Research Service

Colorado State University

USDA United States Department of Agriculture National Institute of Food and Agriculture

BILL & MELINDA GATES foundation

2015-67013-22836