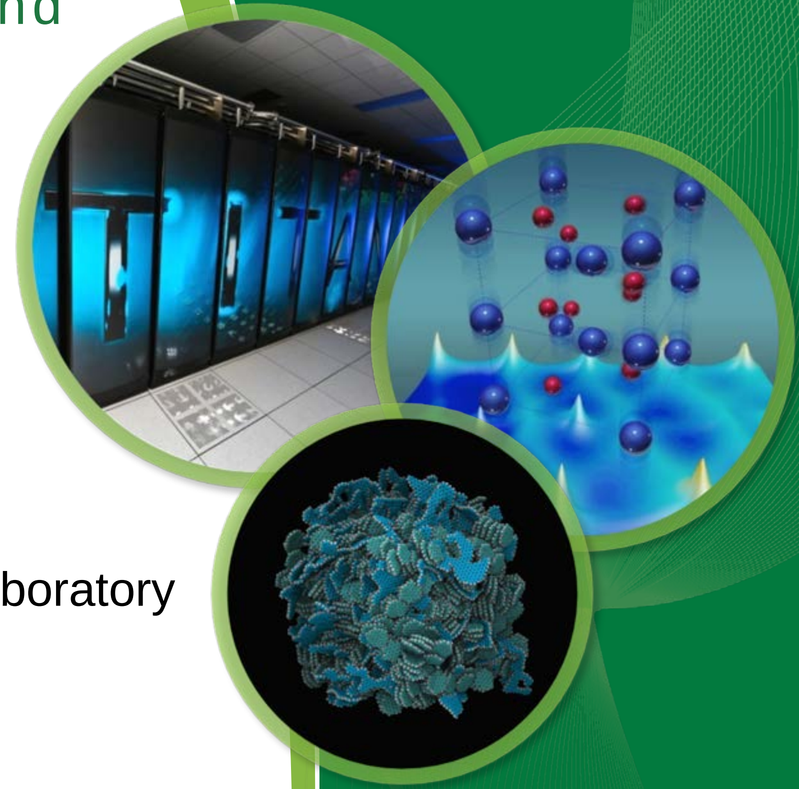
Genetic Improvement of Crop Water-Use Efficiency and Yield for Sustainable Production of Food and Biofuels on Degraded and Non-Arable Lands



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December 8, 2017

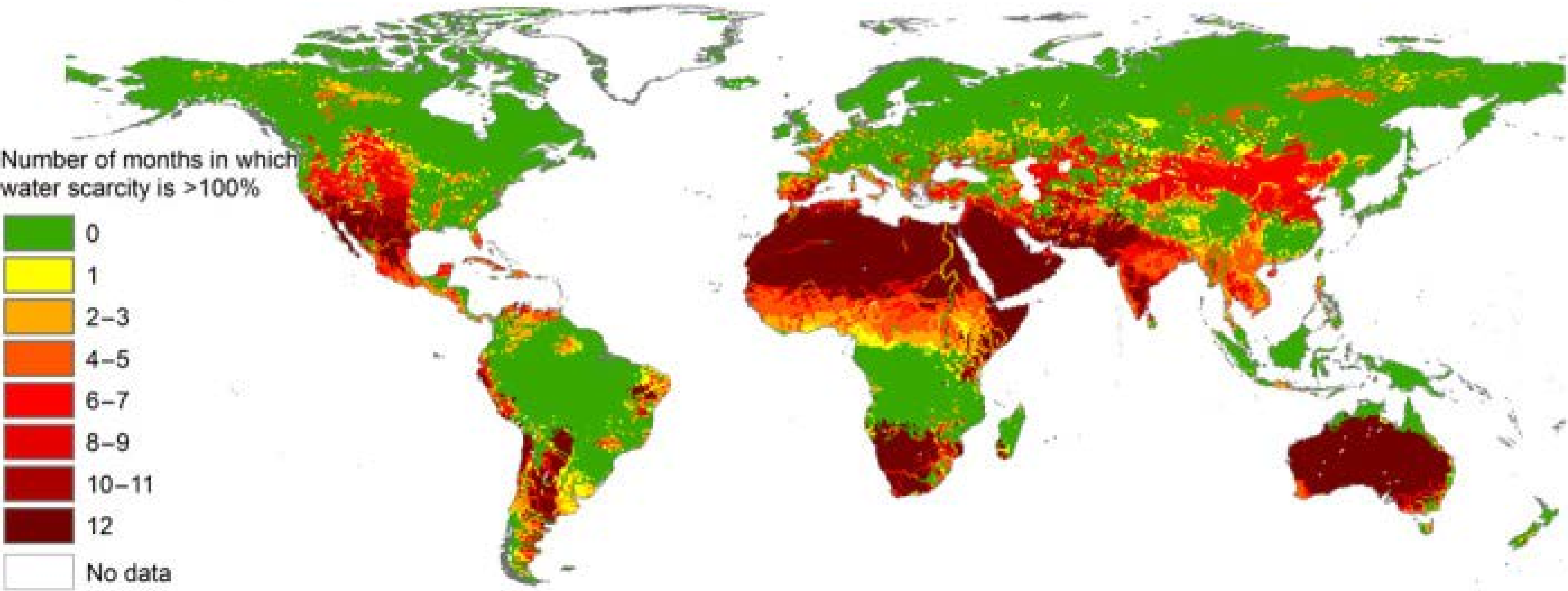
Challenge and Solution

Challenge:
Competition for land and water between bioenergy and food production

Solution:
Genetic modification of existing crops or development of new crops for sustainable food and bioenergy production on marginal and non-arable land.

Global blue water scarcity

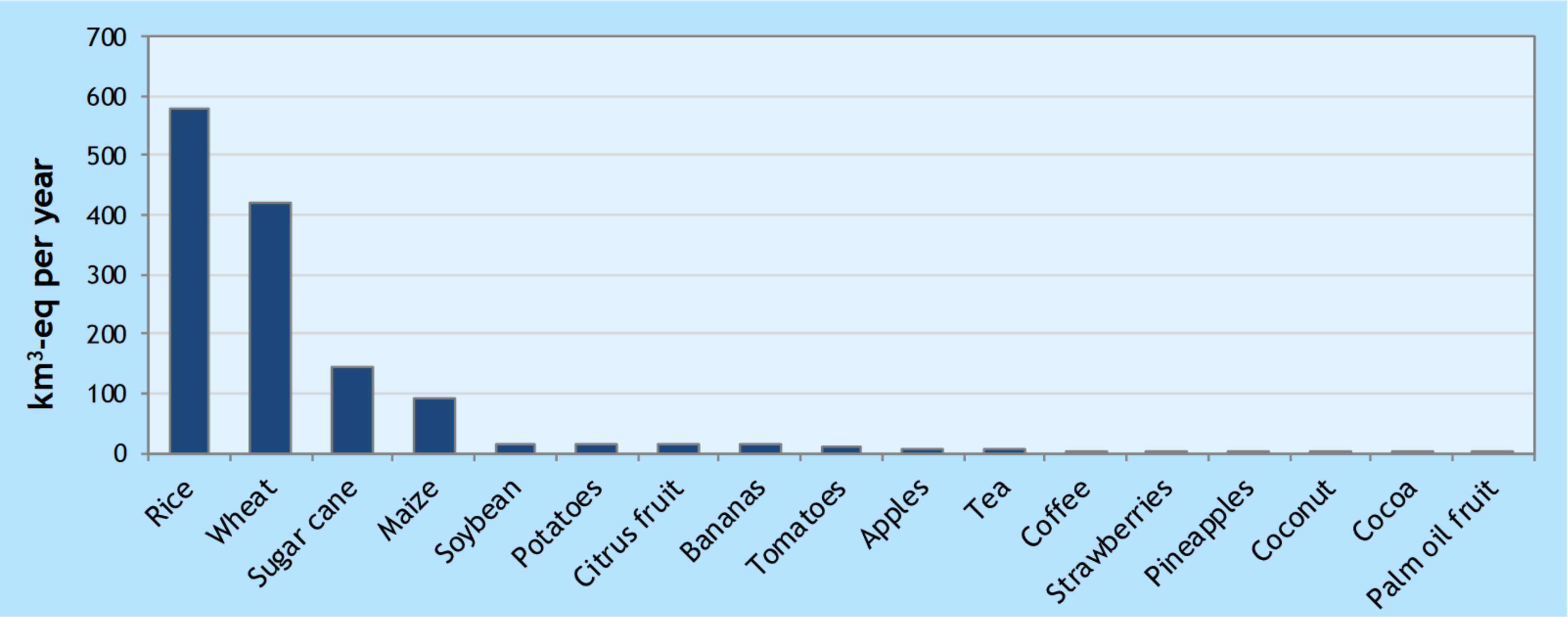
- Severe water scarcity: consumption exceeds availability
- Two-thirds of the global population (4.0 billion people) live with severe water scarcity at least 1 month of the year.
- Nearly half of those people live in India and China.
- Half a billion people face severe water scarcity all year round.



Mekonnen *et al*. 2016. Science Advances

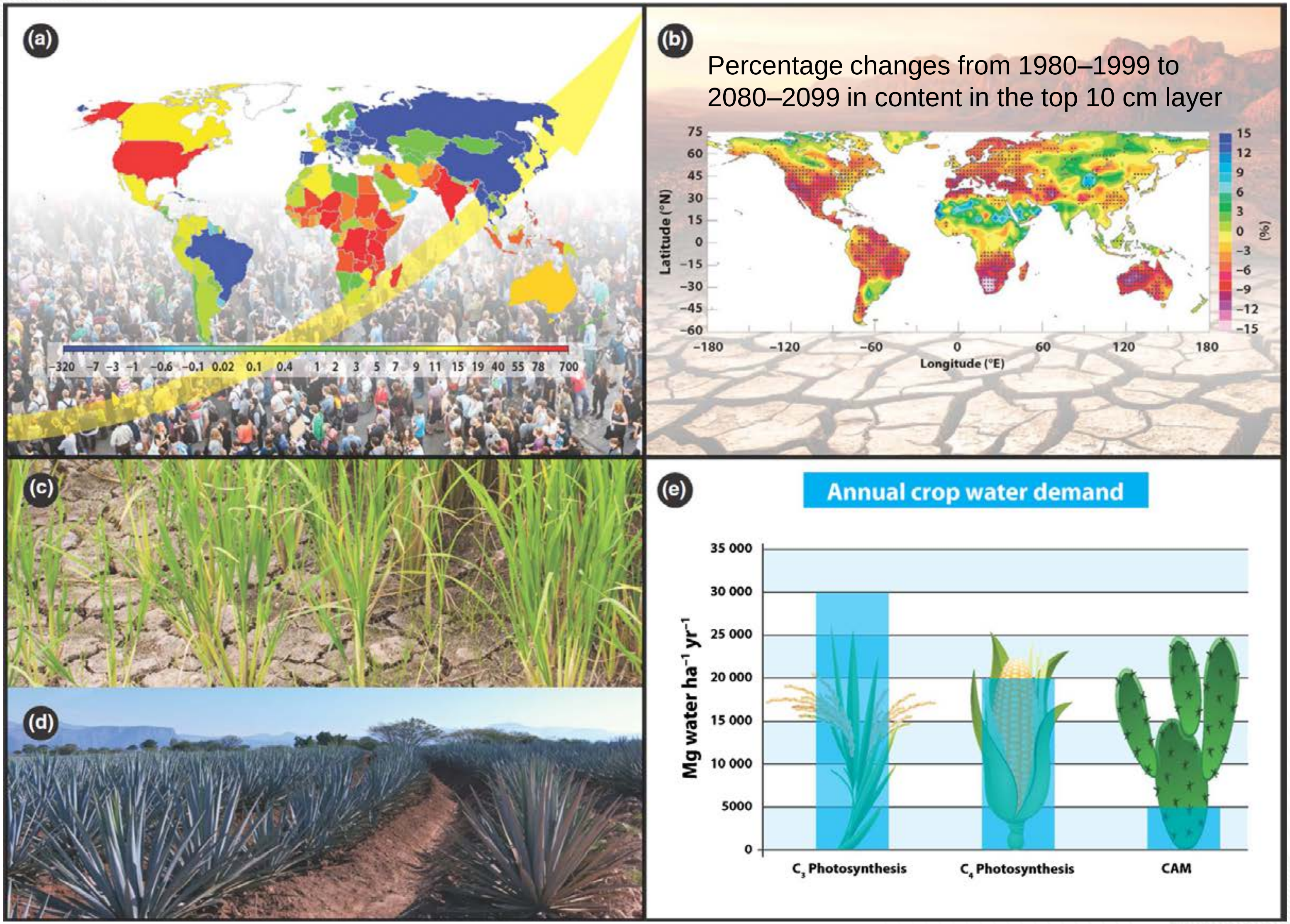
Agriculture accounts for 70 percent of global water usage

- Globally, rice and wheat are the biggest drivers of water scarcity among food commodities.
- It is urgent to create water-use efficient and drought-resistant strains of key crops.



https://www.oxfamamerica.org

CAM photosynthesis is a natural solution to the water scarcity challenge

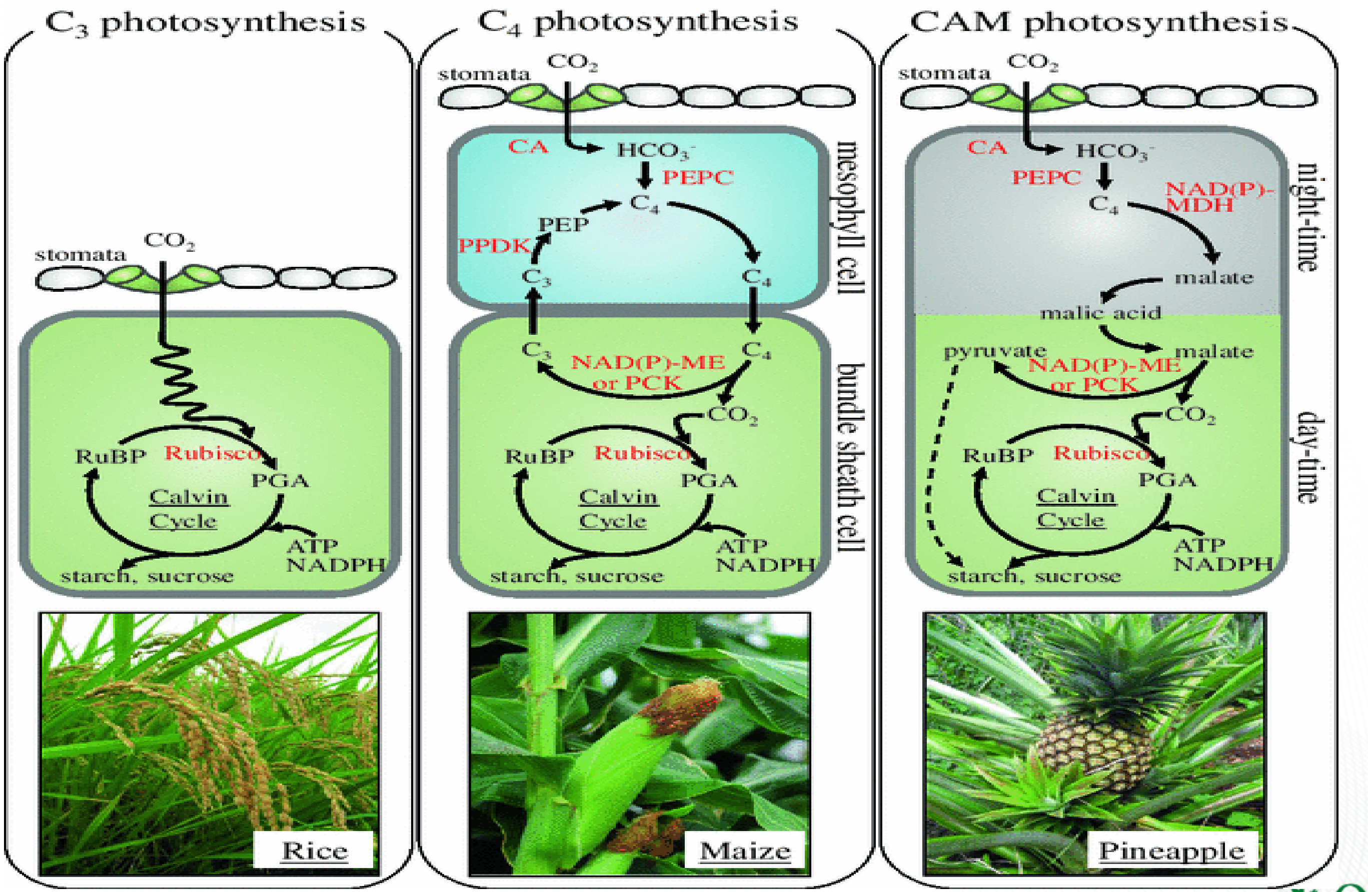


Percentage changes from 1980–1999 to 2080–2099 in content in the top 10 cm layer

Yang *et al*. 2015. New Phytologist

Water-use efficient photosynthesis

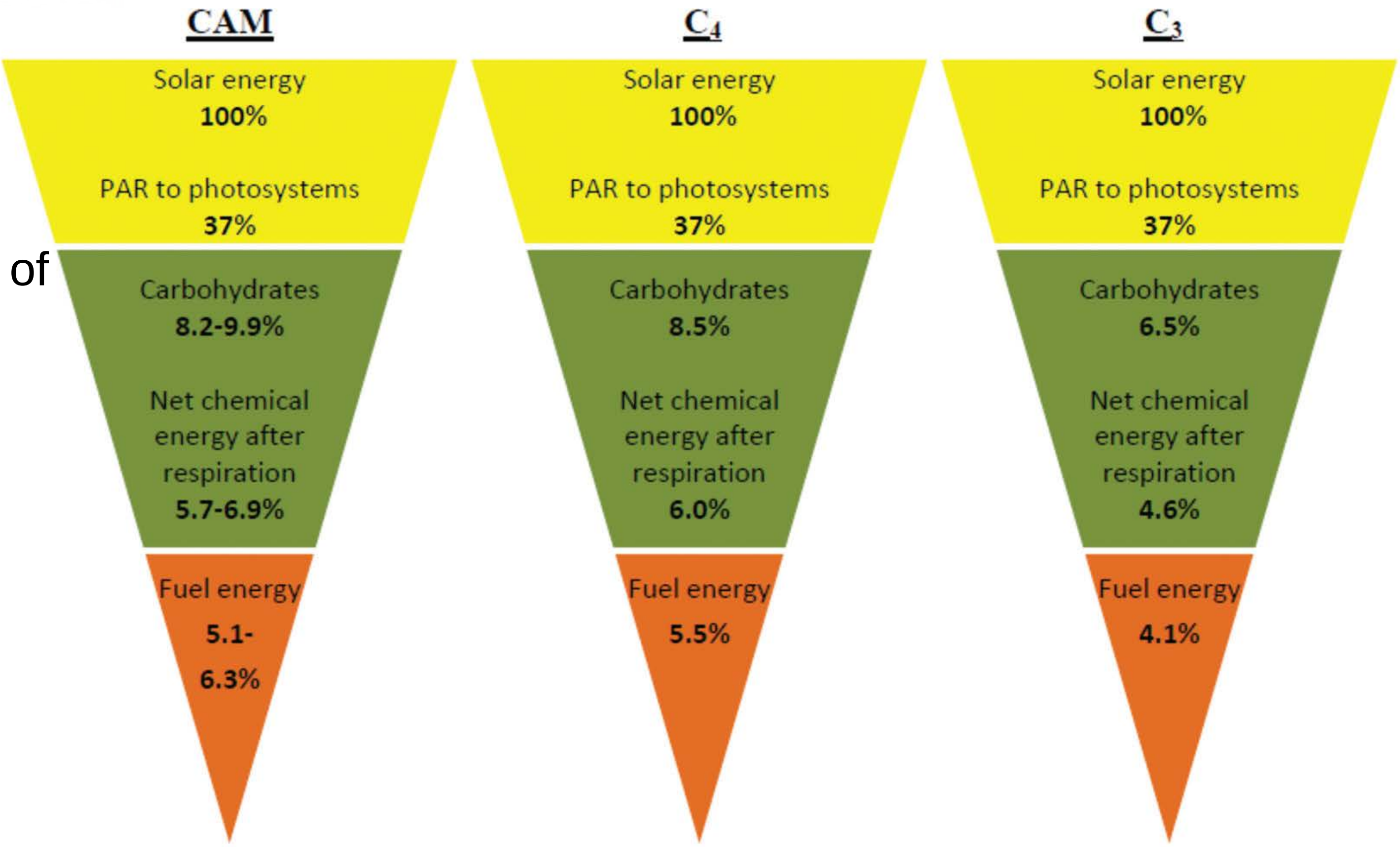
Crassulacean acid metabolism (CAM) features CO2 uptake through open stomata (specialized pores in the leaves of plants) at night when temperature is lower and stomatal closure during the daytime when temperature is higher to reduce water loss caused by evaporation, CAM photosynthesis plants have much higher water-use efficiency than C3 or C4 photosynthesis plants.



Yamori *et* al. 2014. Photosyn Res

Theoretical and incremental energy conversion efficiency

Incremental efficiency of the conversion of sunlight to liquid fuel (ethanol) based on theoretical maximums



CAM

Solar energy
100%

PAR to photosystems
37%

Carbohydrates
8.2-9.9%

Net chemical energy after respiration
5.7-6.9%

Fuel energy
5.1-6.3%

C_4

Solar energy
100%

PAR to photosystems
37%

Carbohydrates
8.5%

Net chemical energy after respiration
6.0%

Fuel energy
5.5%

C_3

Solar energy
100%

PAR to photosystems
37%

Carbohydrates
6.5%

Net chemical energy after respiration
4.6%

Fuel energy
4.1%

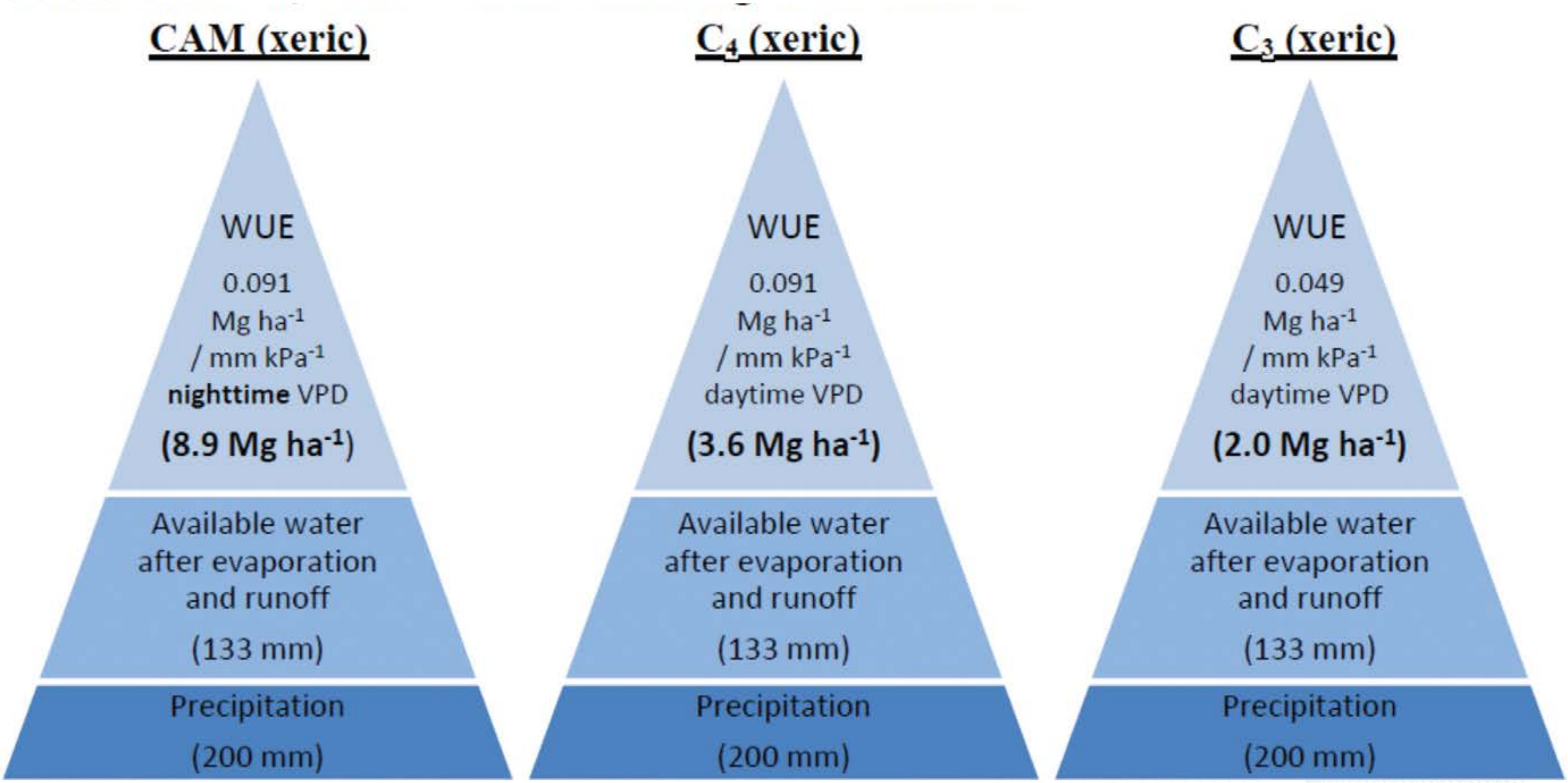
Actual fuel energy potentials as a percentage of annually available solar energy

0.17% - 0.50% *Agave* spp.	0.19% *Zea mays* 0.24% - 0.64% *Miscanthus x giganteus*	0.077% - 0.17% *Populus* spp.

Davis *et al*. 2014. Journal of Experimental Botany

Comparison CAM, C_3 and C_4 crop yield

In arid conditions, yields of CAM plants can exceed those of C_3 and C_4 crops due to the greater water-use efficiency

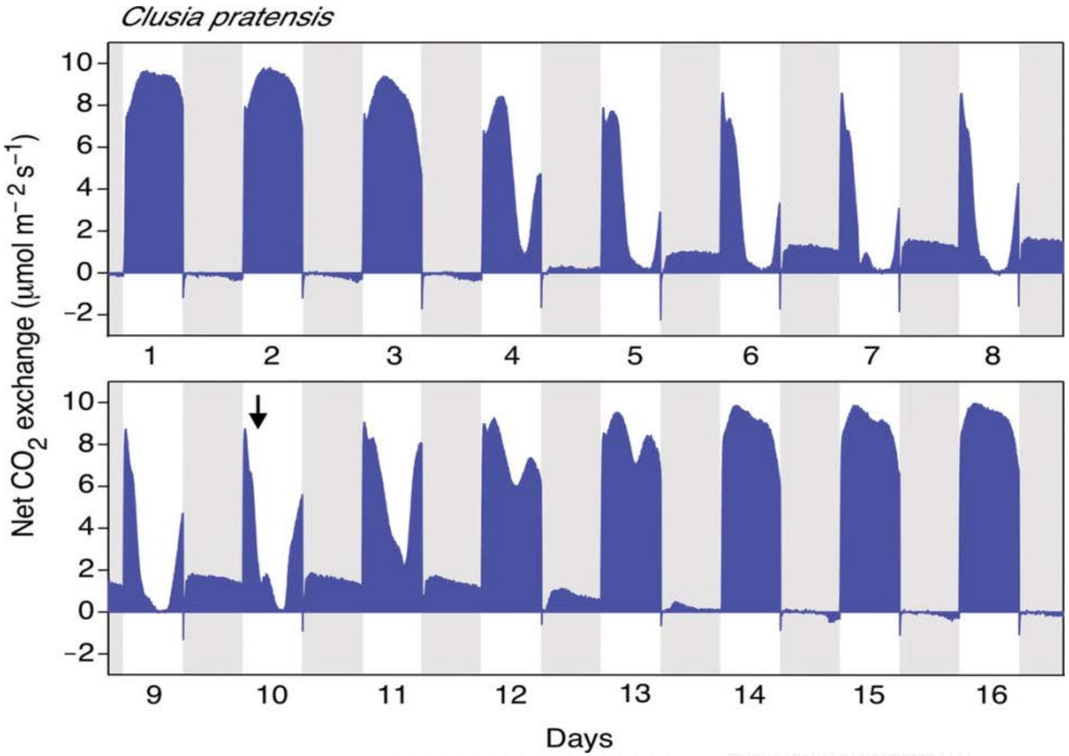


Davis *et al*. 2014. Journal of Experimental Botany

Can C_3 photosynthesis be converted into CAM photosynthesis?

The answer from the nature:
Yes!

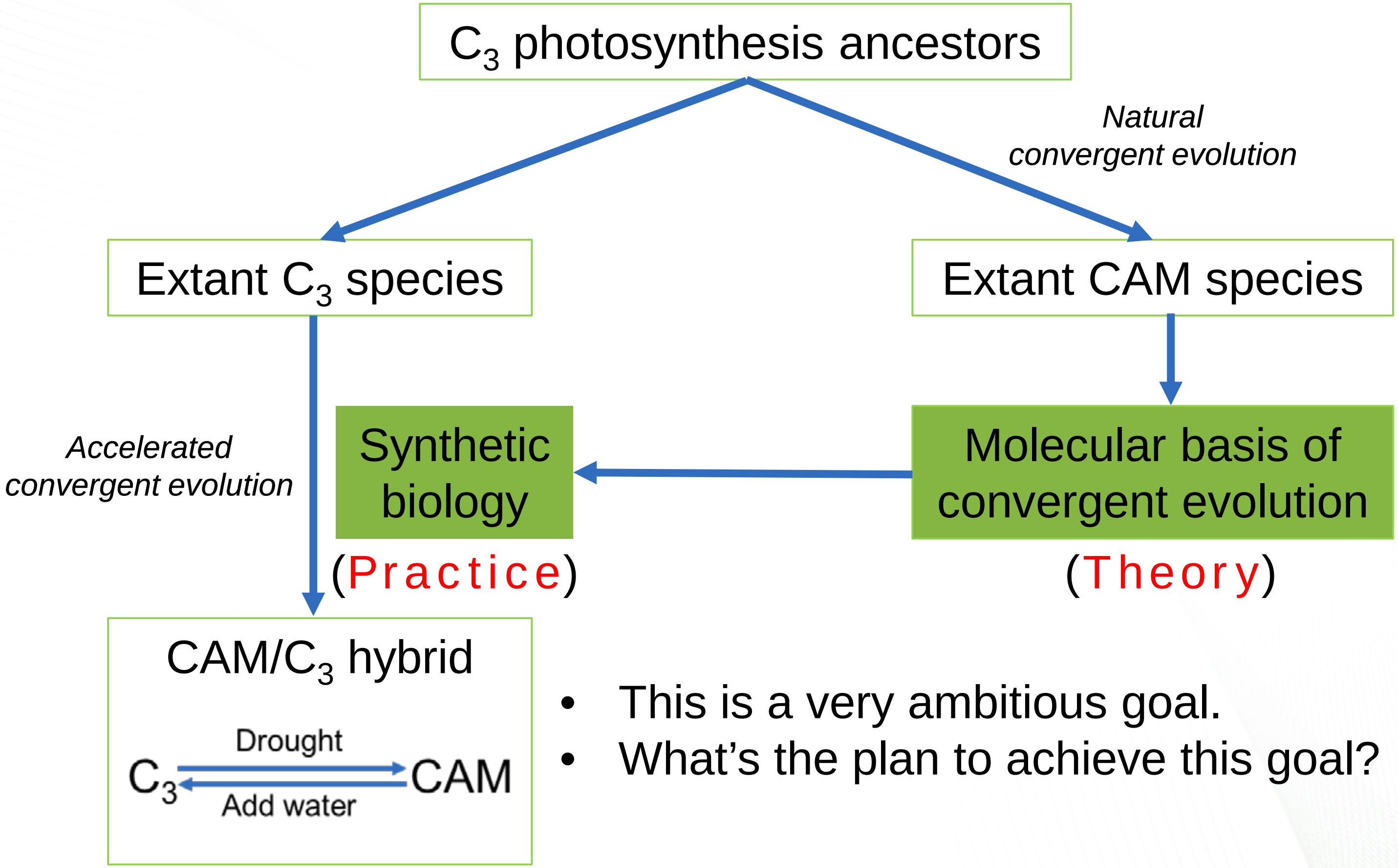
$$C_3 \xrightleftharpoons[\text{Add water}]{\text{Drought}} \text{CAM}$$



Winter and Holtum 2014. J. Exp. Bot.

How to covert C_3 photosyn into CAM?

Answer: Accelerated convergent evolution



C_3 photosynthesis ancestors

Natural convergent evolution

Extant C_3 species

Extant CAM species

Accelerated convergent evolution

Synthetic biology

(Practice)

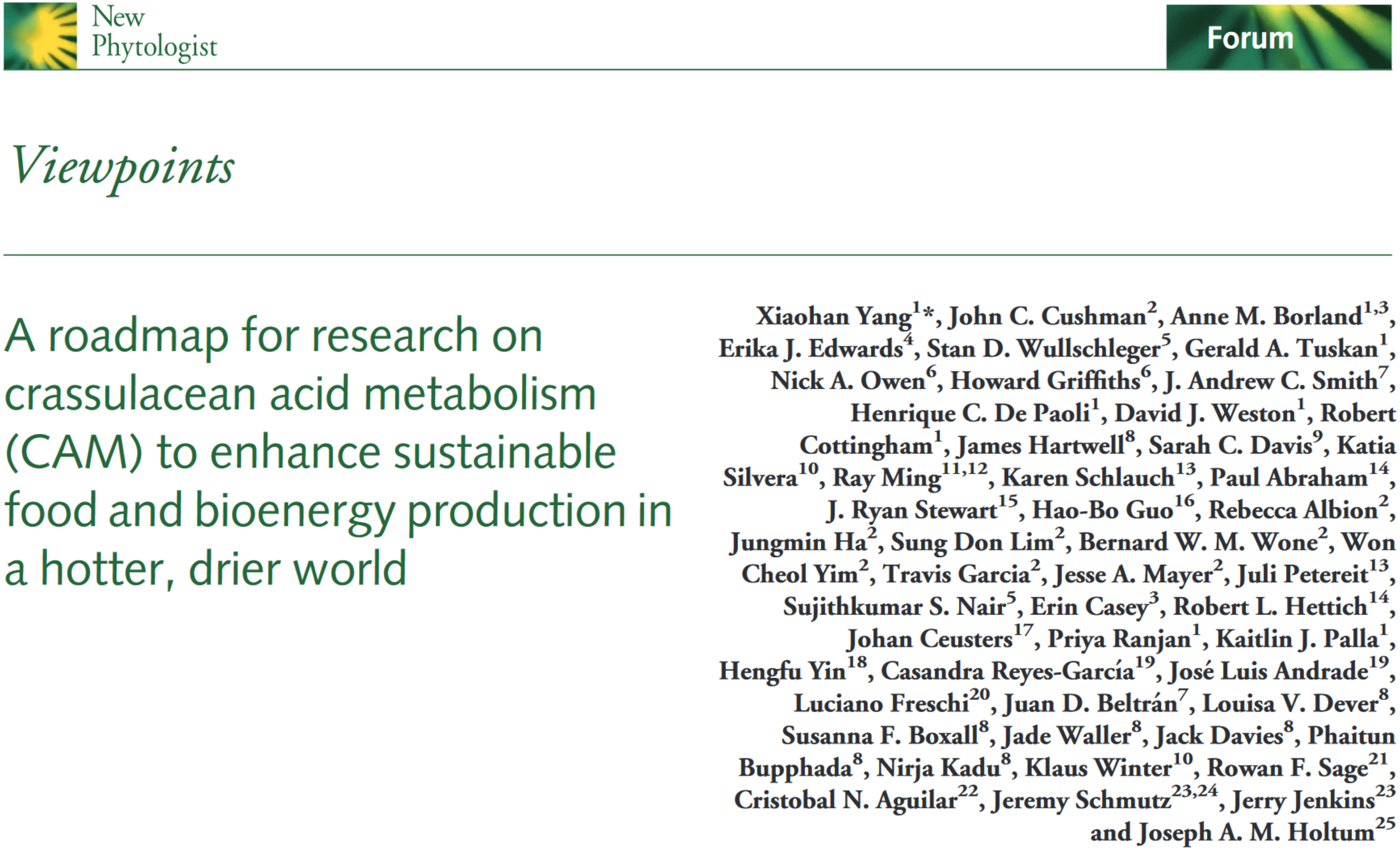
Molecular basis of convergent evolution

(Theory)

CAM/C_3 hybrid

$C_3 \underset{\text{Add water}}{\overset{\text{Drought}}{\rightleftarrows}} CAM$

- This is a very ambitious goal.
- What’s the plan to achieve this goal?



New Phytologist

Forum

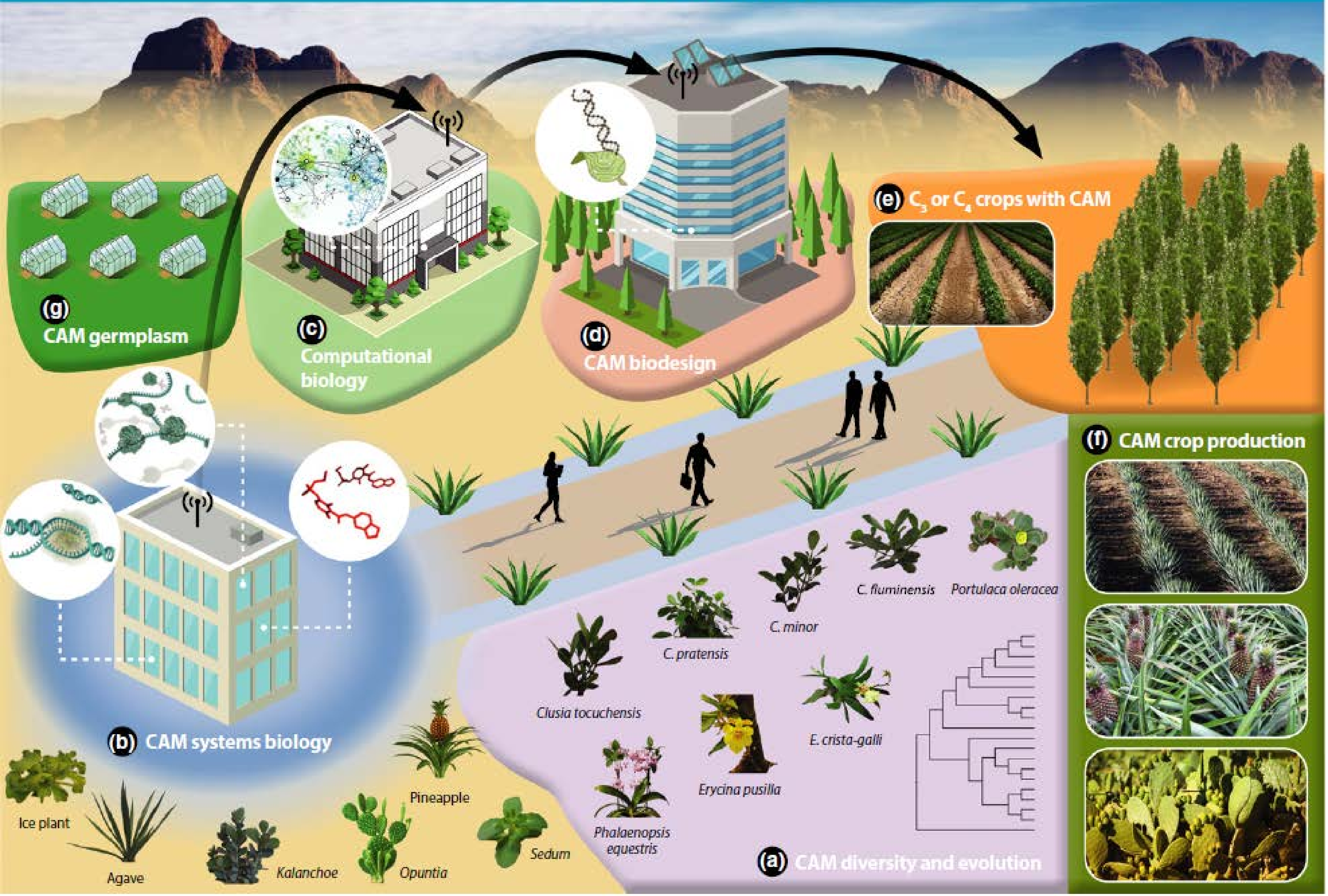
Viewpoints

A roadmap for research on crassulacean acid metabolism (CAM) to enhance sustainable food and bioenergy production in a hotter, drier world

Xiaohan Yang[1]*, John C. Cushman[2], Anne M. Borland[1,3], Erika J. Edwards[4], Stan D. Wullschleger[5], Gerald A. Tuskan[1], Nick A. Owen[6], Howard Griffiths[6], J. Andrew C. Smith[7], Henrique C. De Paoli[1], David J. Weston[1], Robert Cottingham[1], James Hartwell[8], Sarah C. Davis[9], Katia Silvera[10], Ray Ming[11,12], Karen Schlauch[13], Paul Abraham[14], J. Ryan Stewart[15], Hao-Bo Guo[16], Rebecca Albion[2], Jungmin Ha[2], Sung Don Lim[2], Bernard W. M. Wone[2], Won Cheol Yim[2], Travis Garcia[2], Jesse A. Mayer[2], Juli Petereit[13], Sujithkumar S. Nair[5], Erin Casey[3], Robert L. Hettich[14], Johan Ceusters[17], Priya Ranjan[1], Kaitlin J. Palla[1], Hengfu Yin[18], Casandra Reyes-García[19], José Luis Andrade[19], Luciano Freschi[20], Juan D. Beltrán[7], Louisa V. Dever[8], Susanna F. Boxall[8], Jade Waller[8], Jack Davies[8], Phaitun Bupphada[8], Nirja Kadu[8], Klaus Winter[10], Rowan F. Sage[21], Cristobal N. Aguilar[22], Jeremy Schmutz[23,24], Jerry Jenkins[23] and Joseph A. M. Holtum[25]

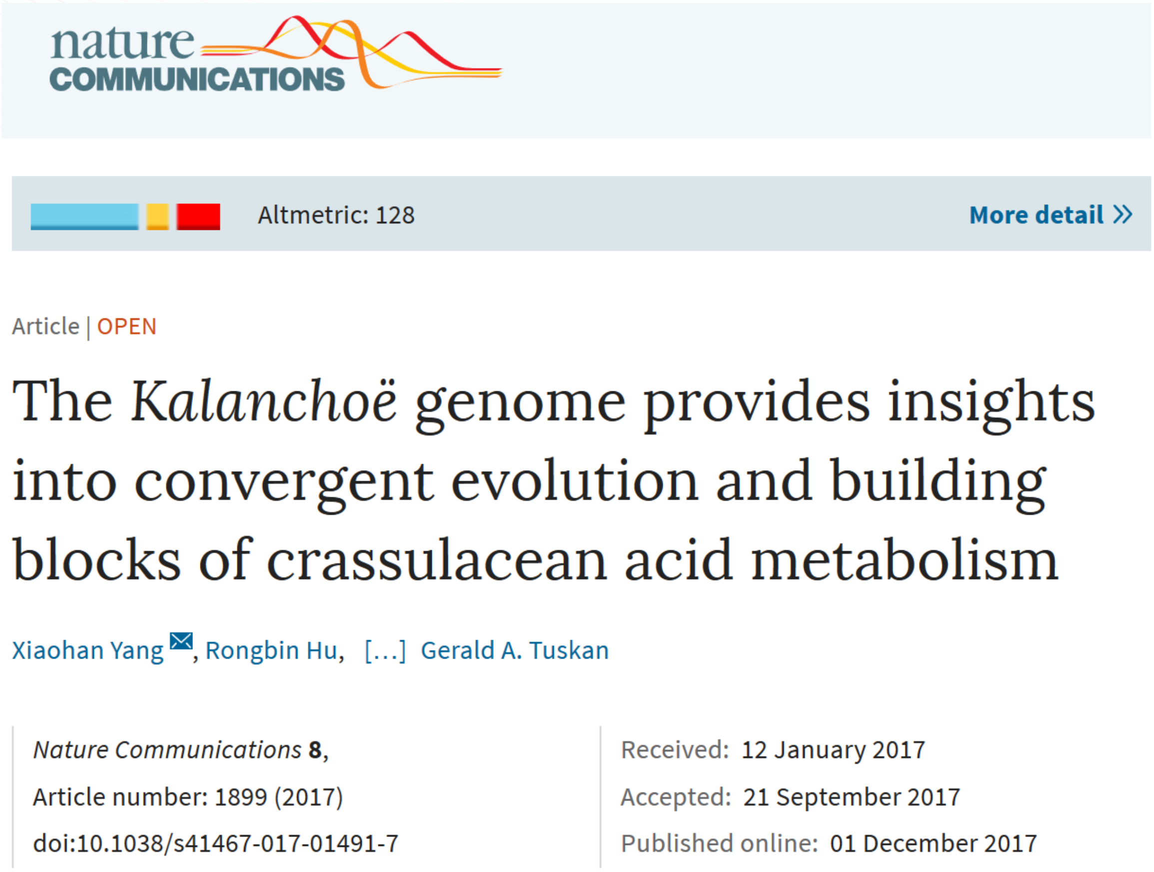
Yang *et al*. 2015. New Phytologist

CAM research roadmap



Yang *et al*. 2015. New Phytologist 207: 491-504

Genes found in drought-resistant plants could accelerate evolution of water-use efficient crops



nature COMMUNICATIONS

Altmetric: 128 **More detail »**

Article | OPEN

The *Kalanchoë* genome provides insights into convergent evolution and building blocks of crassulacean acid metabolism

Xiaohan Yang ✉, Rongbin Hu, […] Gerald A. Tuskan

Nature Communications **8**,
Article number: 1899 (2017)
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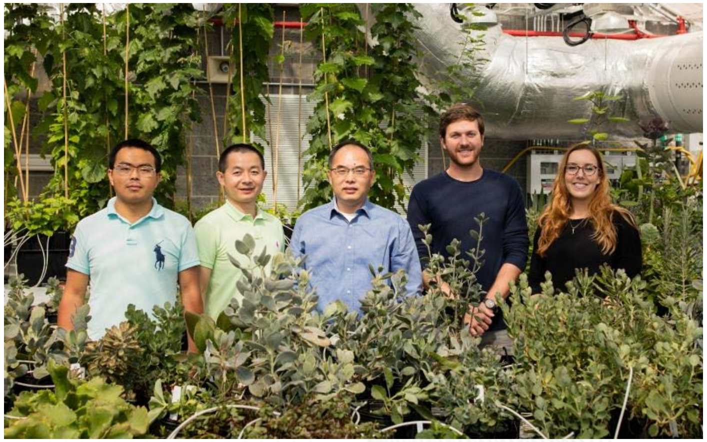

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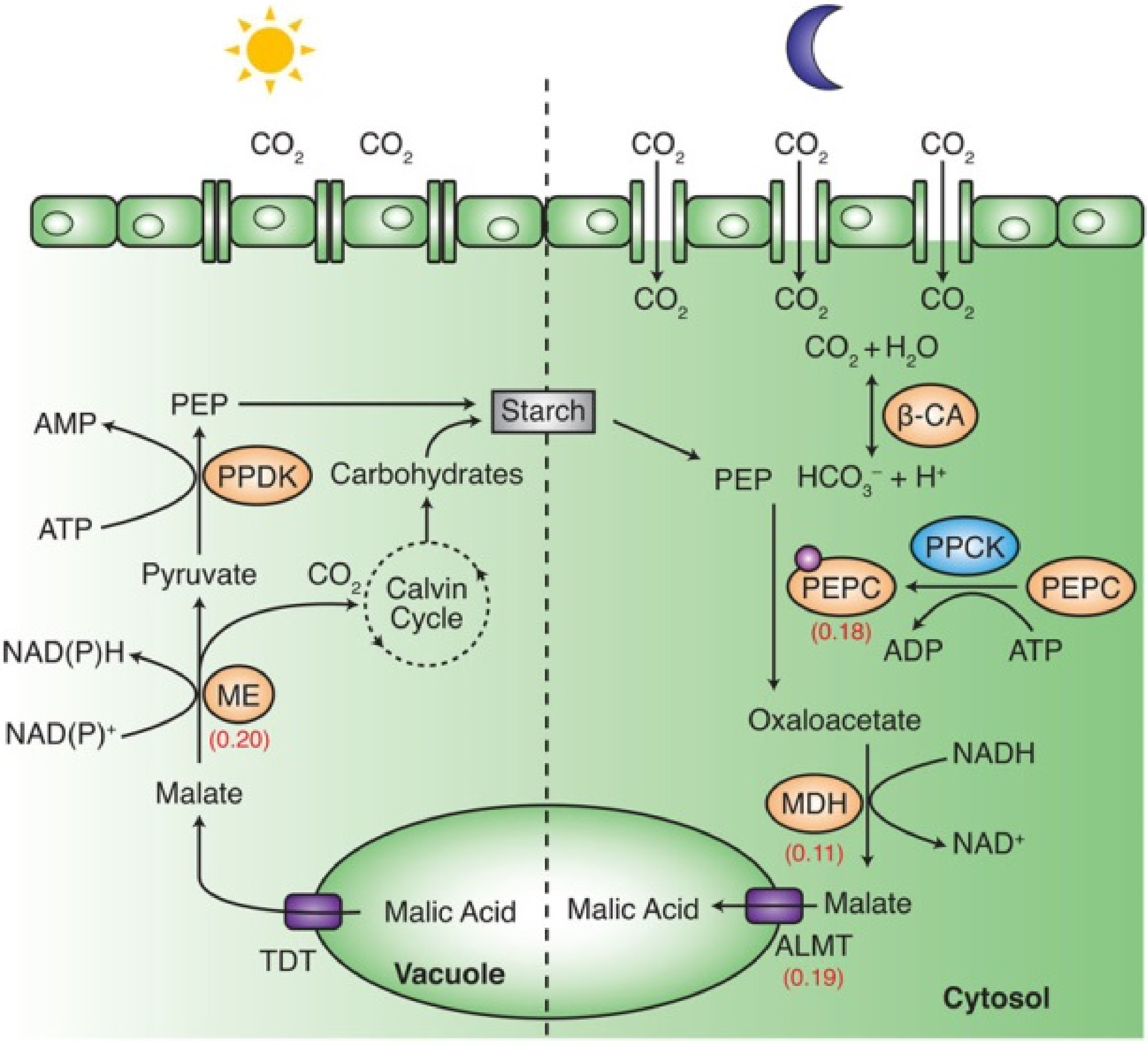
Building blocks of CAM pathway

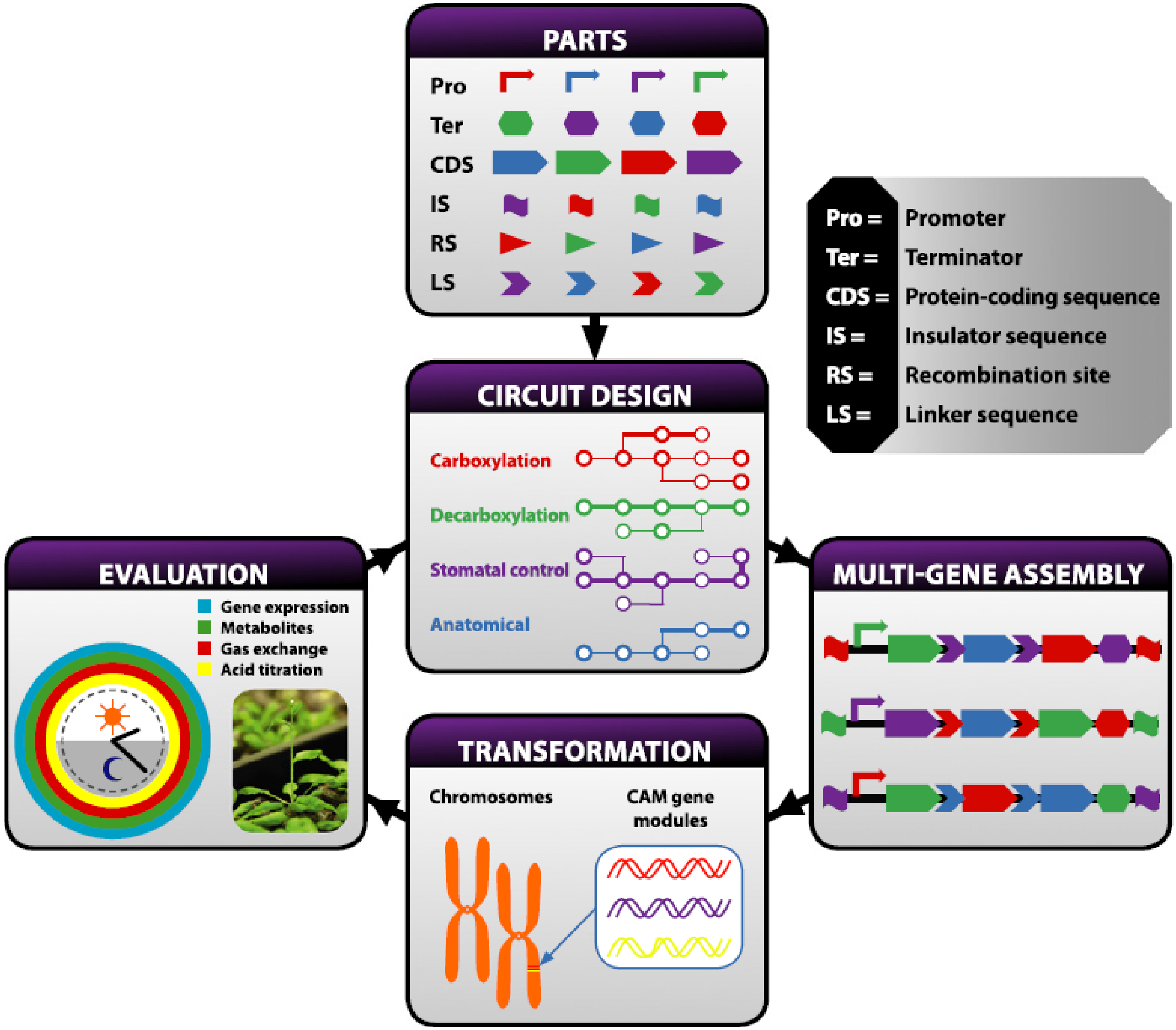
Kalanchoë fedtschenkoi

Agave americana



Abraham *et al*. 2016. Nature Plants
Yang *et al*. 2017. Nature Communications

Strategy for engineering of CAM into C_3 plants



Pro = Promoter
Ter = Terminator
CDS = Protein-coding sequence
IS = Insulator sequence
RS = Recombination site
LS = Linker sequence

Yang *et al*. 2015. New Phytologist

Summary

Genetic engineering of CAM photosynthesis in existing crops can increase water-use efficiency and biomass yield

Development of CAM plants (e.g., Agave and cactus) as new emerging crops has a great potential for bioenergy and food production on marginal and non-arable lands

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