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

Xiaohan Yang
Senior Staff Scientist
Biosciences Division, Oak Ridge National Laboratory
Oak Ridge, TN 37831
E-mail: yangx@ornl.gov
https://www.ornl.gov/staff-profile/xiaohan-yang

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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

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

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

0.17% - 0.50%  
*Agave spp.*

0.19%  
*Zea mays*

0.077% - 0.17%  
*Populus spp.*

0.24% - 0.64%  
*Miscanthus x giganteus*

Davis *et al.* 2014. Journal of Experimental Botany
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!
How to covert C₃ photosyn into CAM?

**Answer: Accelerated convergent evolution**

- **C₃ photosynthesis ancestors**
  - Extant C₃ species
  - Synthetic biology (Practice)
  - CAM/C₃ hybrid
  - CAM
  - Drought

- Extant CAM species
  - Molecular basis of convergent evolution (Theory)

- Accelerated convergent evolution
- Natural convergent evolution

- This is a very ambitious goal.
- What’s the plan to achieve this goal?
A roadmap for research on crassulacean acid metabolism (CAM) to enhance sustainable food and bioenergy production in a hotter, drier world

Yang et al. 2015. New Phytologist
Genes found in drought-resistant plants could accelerate evolution of water-use efficient crops

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

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

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Building blocks of CAM pathway

Yang et al. 2017. Nature Communications
Strategy for engineering of CAM into C₃ plants

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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