Tweaking Photosynthesis – Recent Advances & Implications

Breakthrough Institute Ecomodernism 2019

L. Val Giddings, Ph.D.
Senior Fellow

September 24, 2019

ITIF | INFORMATION TECHNOLOGY & INNOVATION FOUNDATION

@ITIFdc @prometheusgreen

About ITIF

- Independent, nonpartisan research and education institute focusing on intersection of technological innovation and public policy, including:
  - Innovation and competitiveness
  - IT and data
  - Telecommunications
  - Trade and globalization
  - Life sciences, agricultural biotech, and energy
- Formulates and promotes policy solutions that accelerate innovation and boost productivity to spur growth, opportunity, and progress
- World's top think tank for science and technology policy, according to the University of Pennsylvania's authoritative *Global Go To Think Tank* Index

ITIF | INFORMATION TECHNOLOGY & INNOVATION FOUNDATION

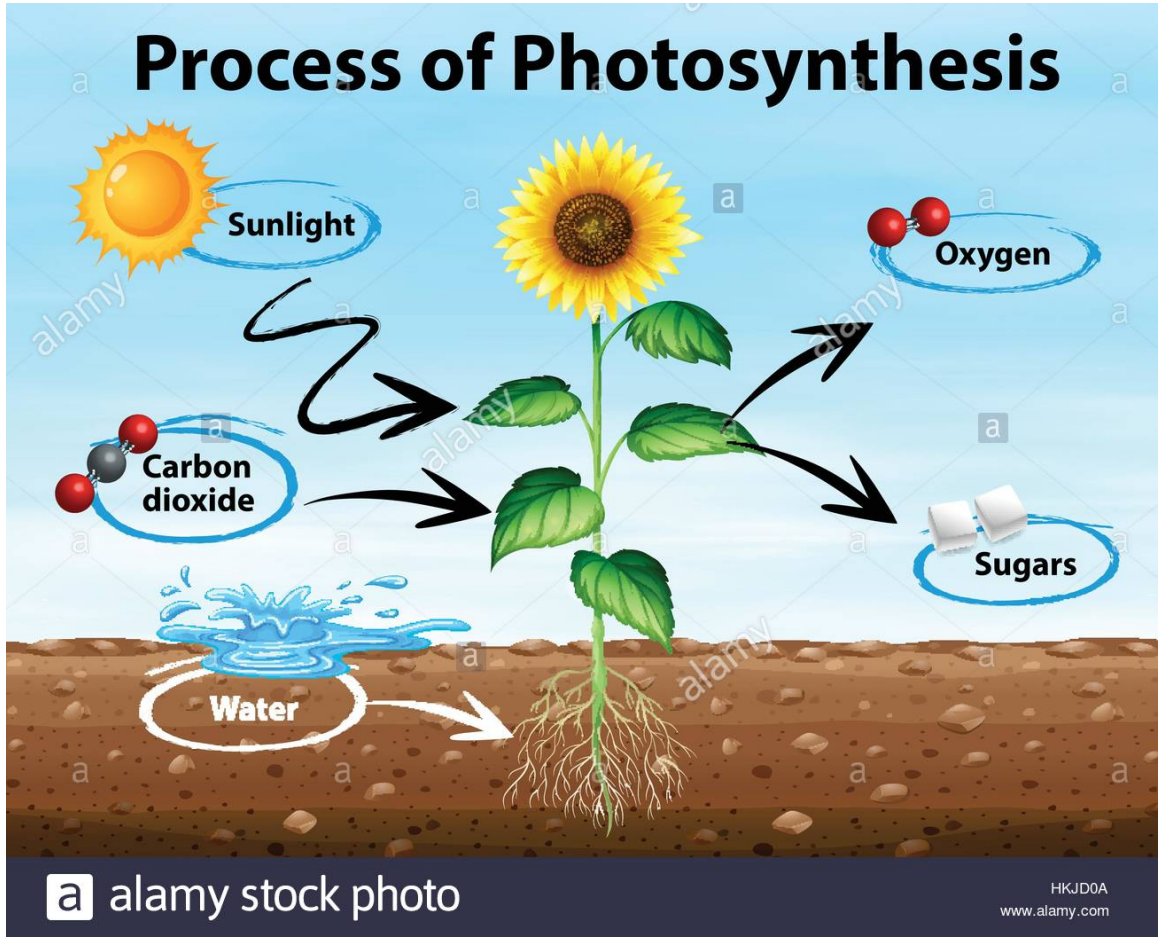
Global Take-Home Messages:

1. Photosynthesis is a complicated process influenced by myriad factors.
2. As we observe it in nature, it is not efficient.
3. Our understanding is now detailed enough we can envision many ways to improve it.
4. Recent advances in recombinant DNA techniques (“GMOs”, gene editing…) means we now have powerful tools to tune photosynthesis in many different ways.
5. The potential economic impacts promise to re-shape every aspect of the relationships between humans and the biosphere.
6. Significant Climate mitigation potential through improved carbon sequestration etc.
7. Everyone but a handful of science fiction writers underestimates this potential.

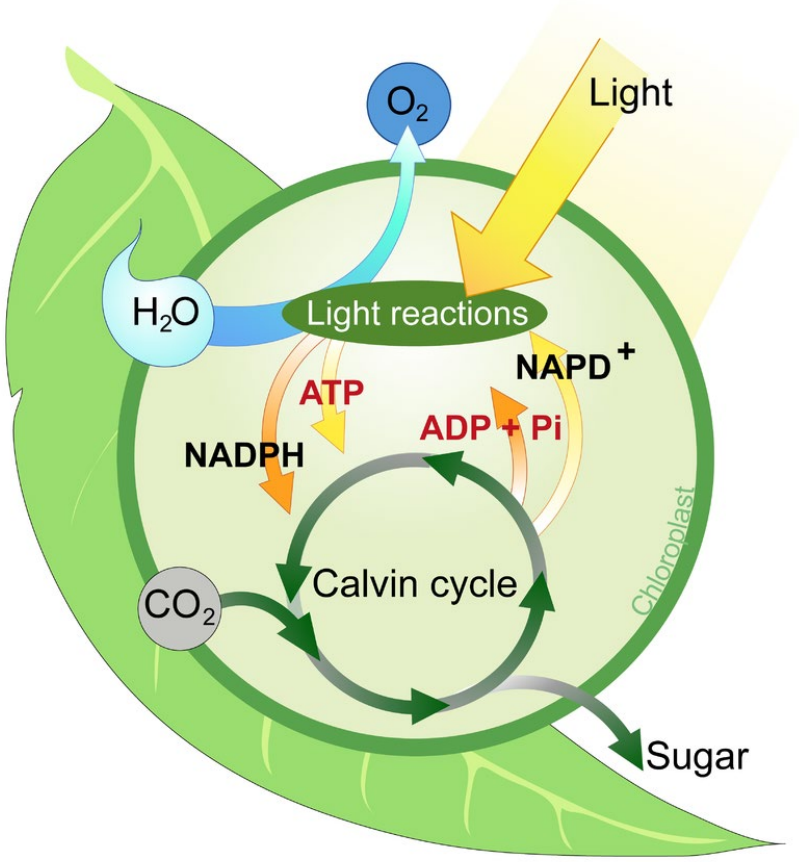
What is photosynthesis & why does it matter?

1. A series of chemical reactions through which sunlight is converted to biomass.
2. carbon dioxide + water + light → glucose + oxygen.
3. The basis of life on earth.*

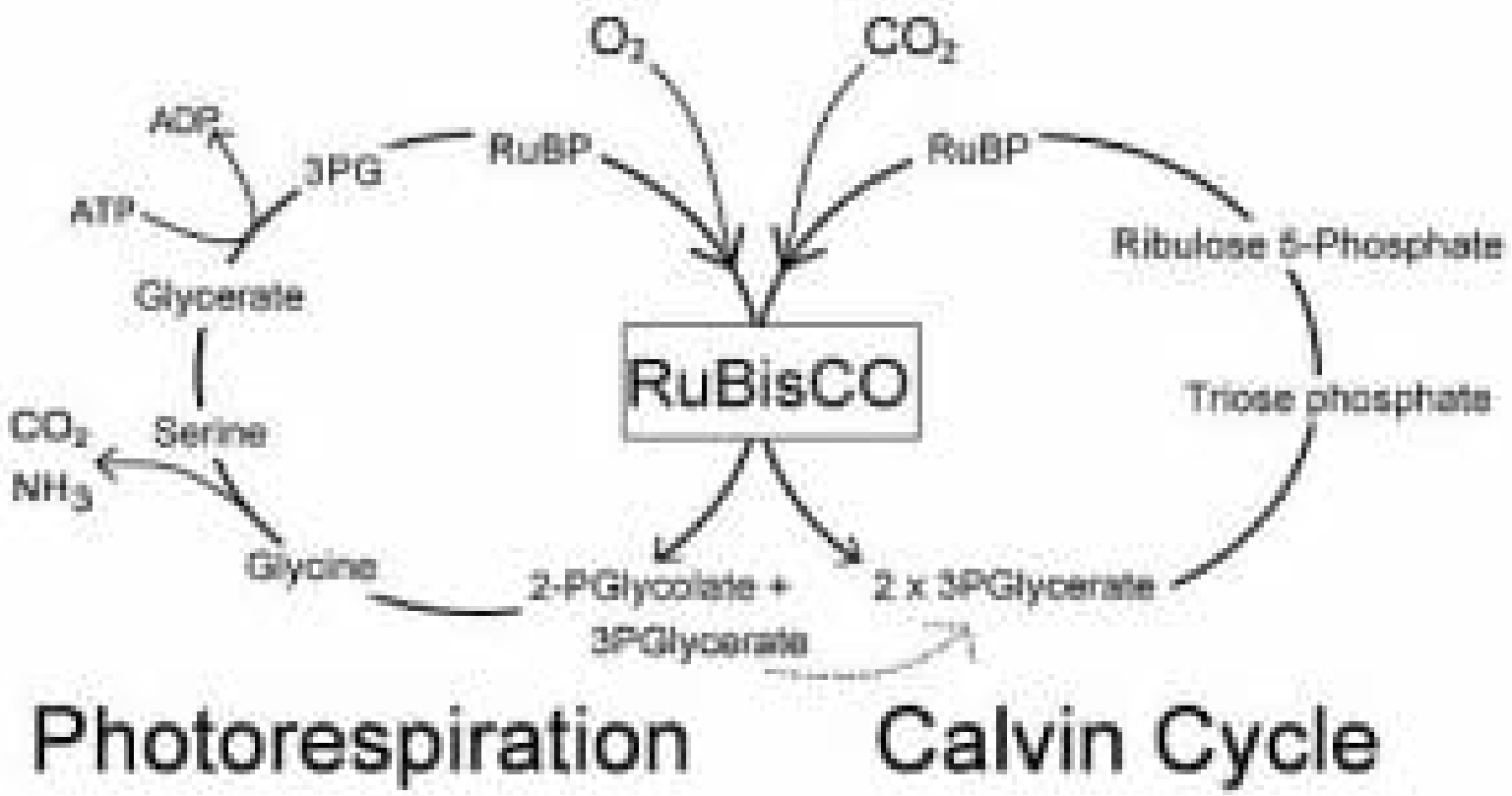
Reduced to the basics…



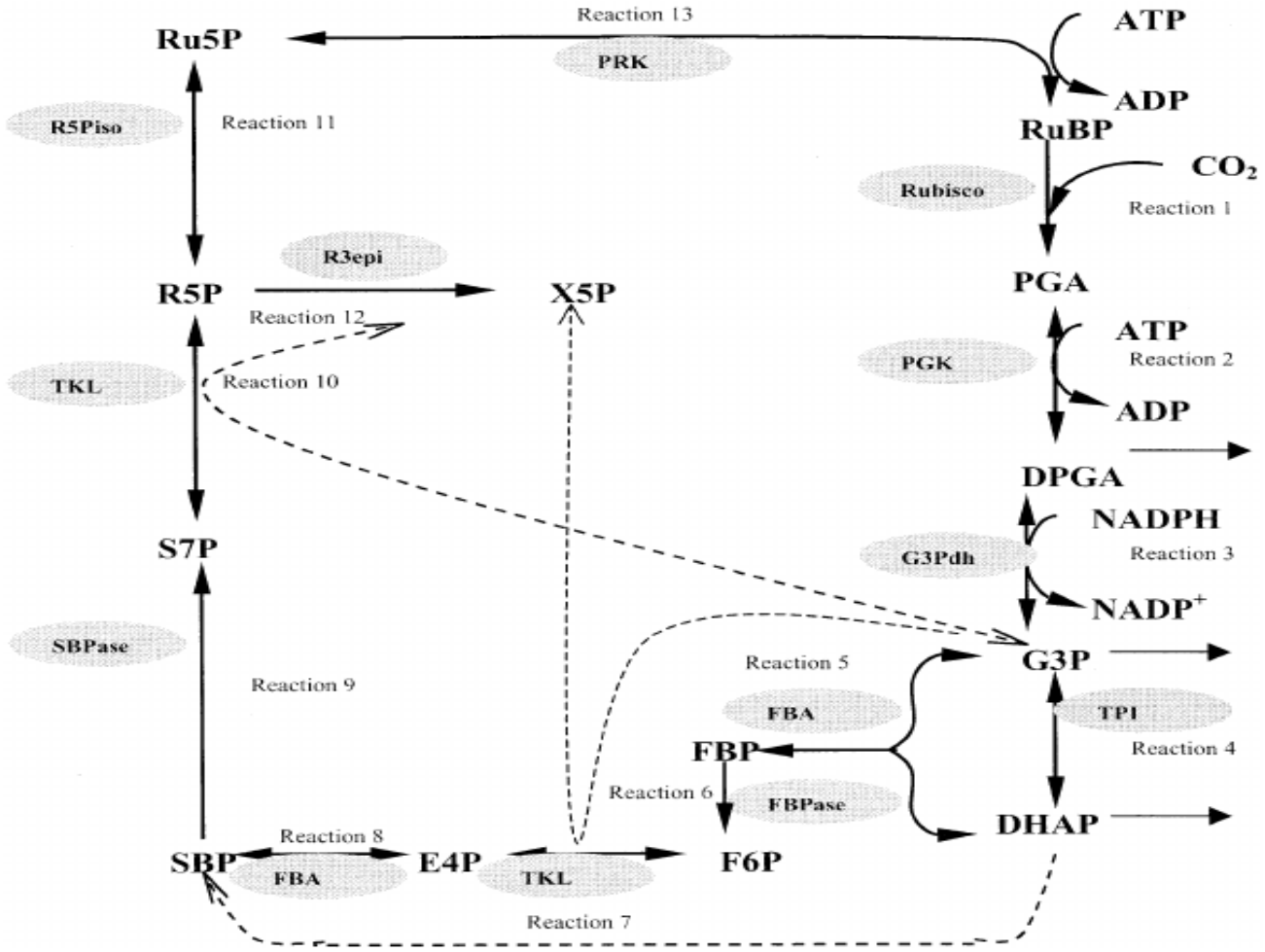
The details…


O_2
Light
H_2O
Light reactions
NAPD+
ATP
ADP + Pi
NADPH
Calvin cycle
CO_2
Chloroplast
Sugar

More details...



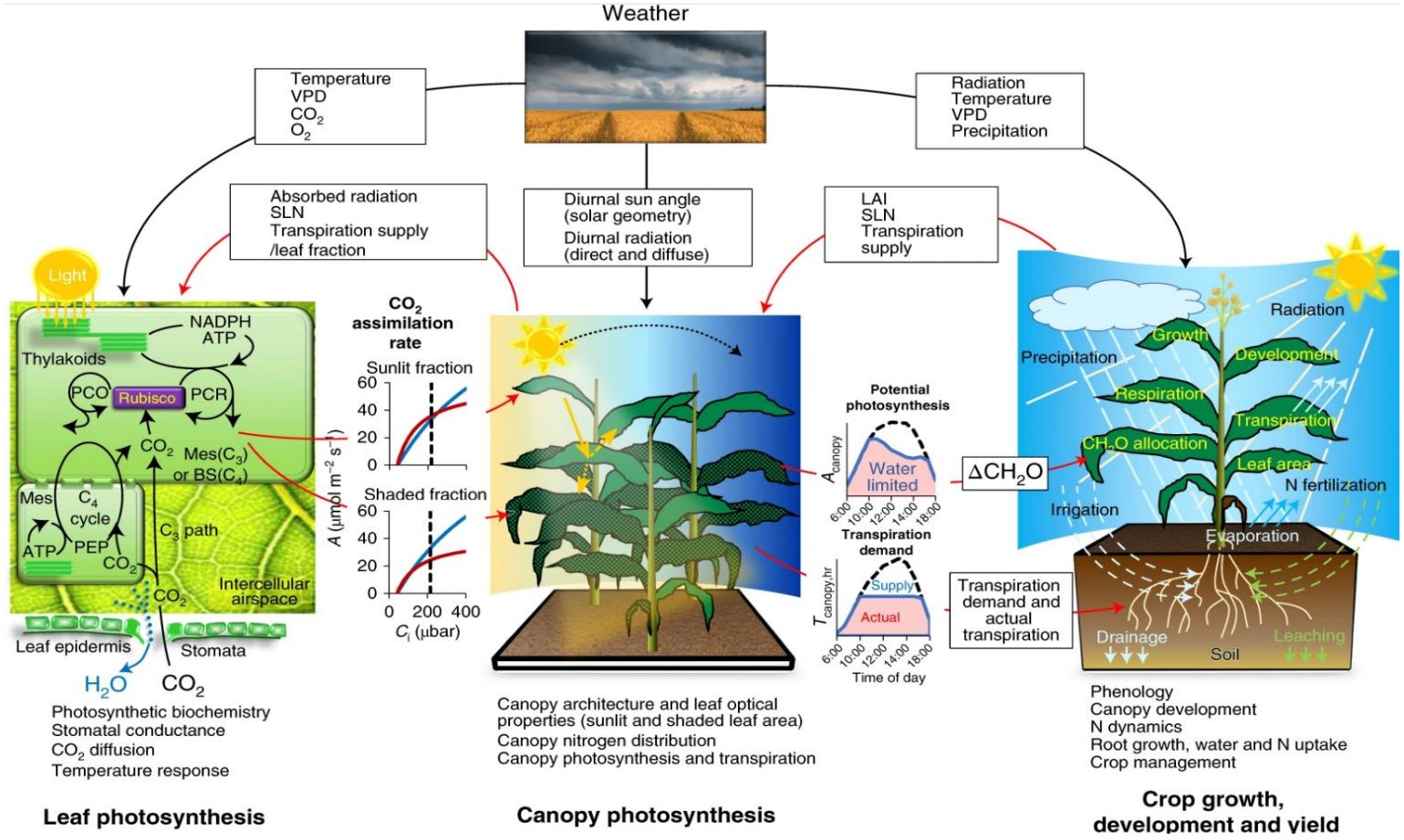
Even more details…



The Calvin cycle has 13 reactions starting at Ribulose and ending with phosphoribulokinase. There are 11 enzymes to catalyze the 13 reactions…

Ligeng Ma et al. Plant Molecular Biology 53(4):467-78 · December 2003

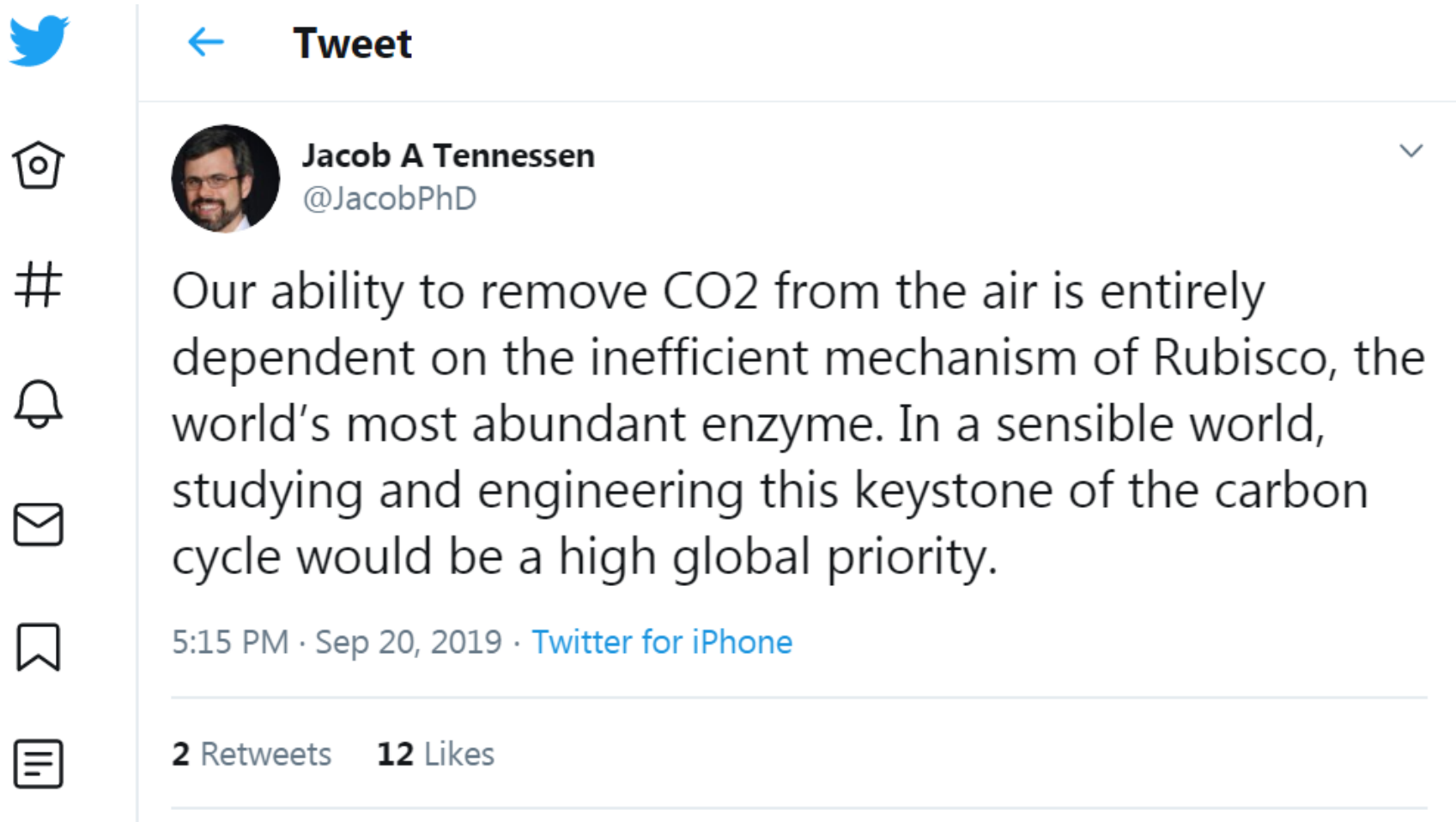
The Big Picture with yet more details…



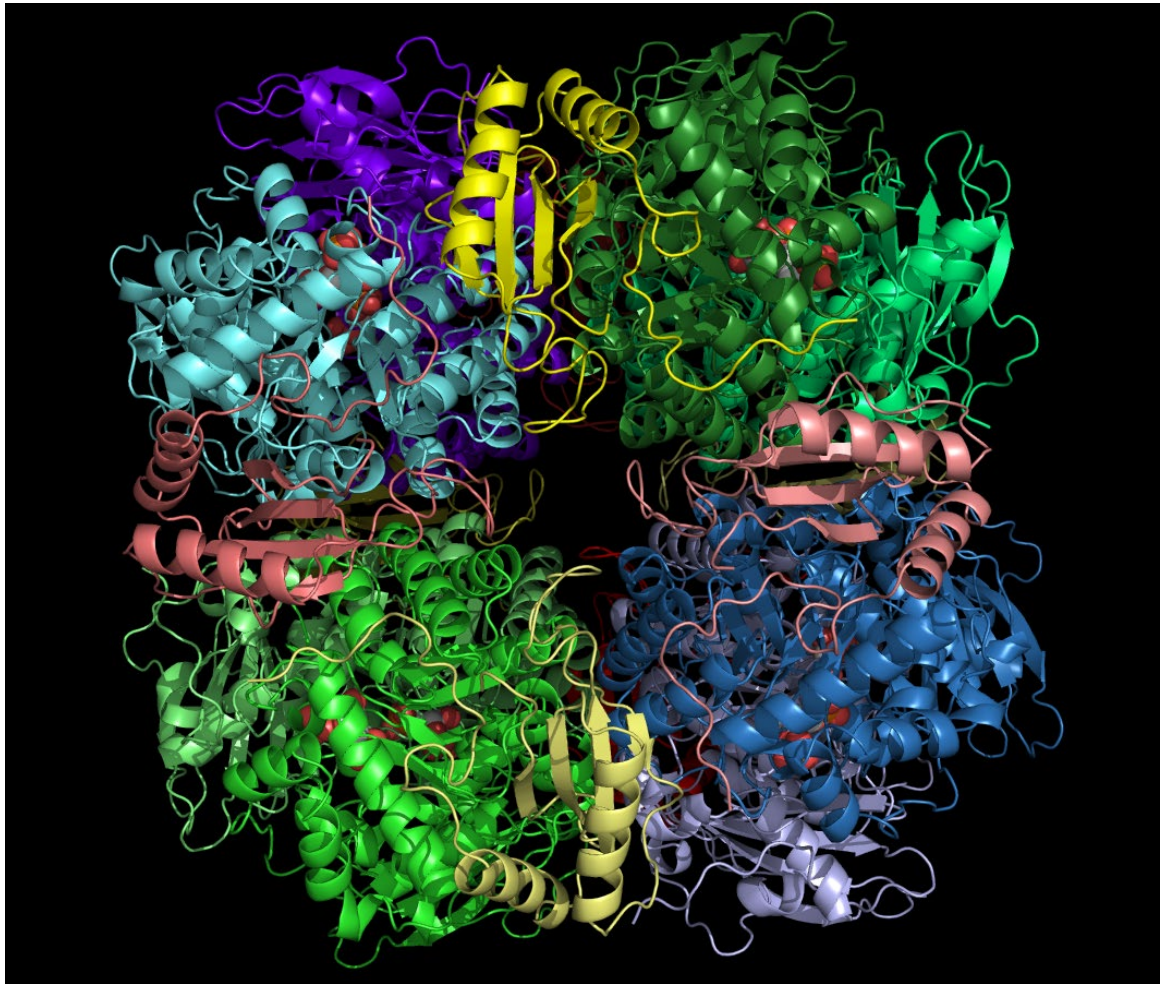
Wu, Hammer & Doherty, Nature Plants 5:380–388 (2019)

The important details…

1. Plants can harness less than 50% of incident sunlight.
2. Not very efficient – typical crops ~1-2% (theoretical max ~11%); photovoltaic efficiency ~11-15%).
3. Most plants (~85%) use C3 photosynthesis; better in cool/moist conditions (wheat, rice, barley, oats, peanuts, cotton, sugar beets, trees…).
4. C4 is more efficient; better in hot/dry conditions (maize, sorghum, switchgrass…).
5. It's ALL about electron transport.


Tweet
Jacob A Tennessen
@JacobPhD
Our ability to remove CO2 from the air is entirely dependent on the inefficient mechanism of Rubisco, the world's most abundant enzyme. In a sensible world, studying and engineering this keystone of the carbon cycle would be a high global priority.
5:15 PM · Sep 20, 2019 · Twitter for iPhone
2 Retweets
12 Likes

(RuBisCo = Ribulose-1,5-bisphosphate carboxylase/oxygenase)



Turns out we have a medley of [photosynthesis] enhancements in the pipeline."

--Tim Durham, "Plant MD"

https://www.agdaily.com/crops/durham-photosynthesis-biohacking-ftw/

Opportunities for improving photosynthetic efficiency

- **Modifying 3D structure of enzymes to make them more efficient at electron transfer** (Qin, Suga & Shen, et al., 2015. Structural basis for energy transfer pathways in the plant PSI-LHCI supercomplex https://science.sciencemag.org/content/348/6238/989; Overexpression of the Rieske FeS protein of the Cytochrome b_6f complex increases C_4 photosynthesis in *Setaria viridis,* 2019. https://www.nature.com/articles/s42003-019-0561-9)
- **Improving RuBisCo performance – fixing photosynthetic inefficiencies** (~+20% South et al., 2019. Synthetic glycolate metabolism pathways stimulate crop growth and productivity in the field https://science.sciencemag.org/content/363/6422/eaat9077)
- **Decreasing lag time in photoprotective response** (+13-20%; Kromdijk et al. 2016. Improving photosynthesis and crop productivity by accelerating recovery from photoprotection https://science.sciencemag.org/content/354/6314/857)
- **Improving CO2 flow within plant tissues** (Evans, J. R. 2013. Improving photosynthesis. Plant Physiol. 162, 1780–1793 http://www.plantphysiol.org/content/162/4/1780.)
- **Bionic LEAF 2.0 – Artificial Photosynthesis** (10% Liu, Colón, Ziesack, Silver & Nocera, 2016. Water splitting–biosynthetic system with CO_2 reduction efficiencies exceeding photosynthesis https://science.sciencemag.org/content/352/6290/1210)

Bionic Leaf 2.0 – “artificial photosynthesis”

- a silicon solar cell with different catalytic materials bonded onto its two sides.
- needs no external wires or control circuits to operate.
- placed in a container of water and exposed to sunlight, it generates bubbles of O2 and H2.

So…. Where is this “Bionic Leaf?”

- Sun Catalytix, Lockheed, and the “MIT curse”

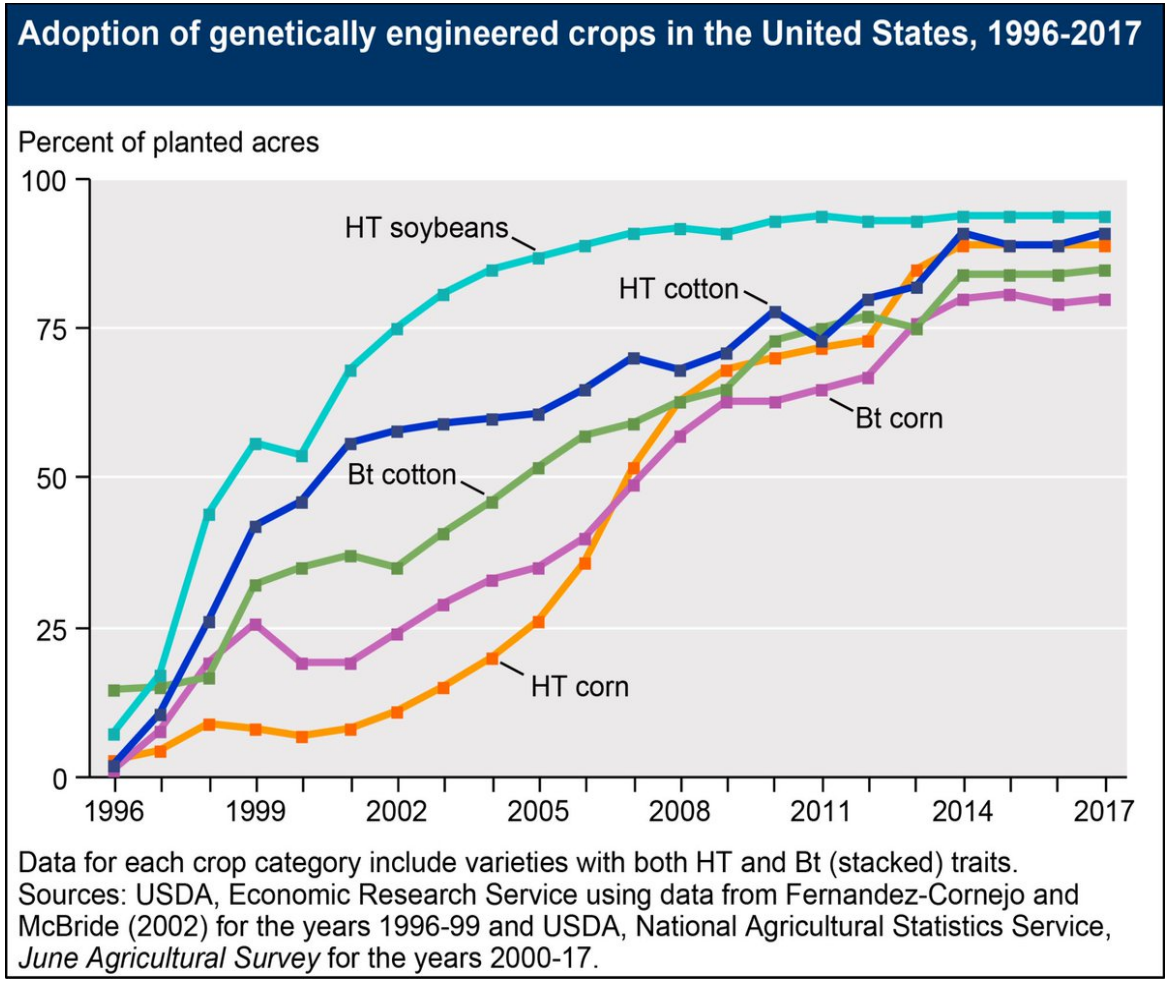
Some of the key players to watch:

- Realizing Increased Photosynthetic Efficiency (RIPE) https://ripe.illinois.edu/ (Gates, FFAR, UKaid)
- Joint Center for Artificial Photosynthesis https://solarfuelshub.org/ (Caltech, Berkeley, Irvine, UCSD, SLAC, DOE…)
- Pamela Silver & Daniel Nocera labs, Harvard; MacFarlane lab, Monash.

What could this mean?

1. A new (“greener”) way to replace fossil fuels with biofuels
2. A new source of organic/biological compounds (isobutanol, methane, etc.)
3. A novel source of cheap energy in remote areas w/ minimal infrastructure
4. A new source for pure water in remote areas w/ minimal infrastructure
5. A new way to scrub CO2 emissions from power plants
6. New paths to carbon sequestration

History suggests such innovations can be deployed very rapidly



What policy changes will accelerate progress?

1. Increased support for basic research
2. Increased support for applied research – we need an ARPA-E Manhattan Project on Photosynthesis
3. Science-based regulations – the critical limiting factor

Further reading…

- Basic Biology: Photosynthesis https://basicbiology.net/micro/biochemistry/photosynthesis
- June 29, 2015. D.R. Ort et al., Redesigning photosynthesis to sustainably meet global food and bioenergy demand https://www.pnas.org/content/early/2015/06/24/1424031112.abstract?sid=654b5c71-86fc-4488-ac17-5de96b159cf8
- April 16, 2015. Major Advance in Artificial Photosynthesis Poses Win/Win for the Environment https://newscenter.lbl.gov/2015/04/16/major-advance-in-artificial-photosynthesis/?utm_content=bufferc7ce0&utm_medium=social&utm_source=twitter.com&utm_campaign=buffer
- May 28 2015. Joel Achenbach Scientists are closing in on the ultimate secrets of plant photosynthesis https://www.washingtonpost.com/news/speaking-of-science/wp/2015/05/28/scientists-are-closing-in-on-the-ultimate-secrets-of-plant-photosynthesis-with-implications-for-solar-energy-and-agriculture/?postshare=9101432919350120
- June 3, 2016. Liu, Colón, Ziesack, Silver & Nocera, 2016. Water splitting–biosynthetic system with CO_2 reduction efficiencies exceeding photosynthesis https://science.sciencemag.org/content/352/6290/1210
- Nov 17 2016. Justin Gillis With an Eye on Hunger, Scientists See Promise in Genetic Tinkering of Plants https://www.nytimes.com/2016/11/18/science/gmo-foods-photosynthesis.html
- 8 April, 2019 Wu, Hammer & Douherty, et al. Quantifying impacts of enhancing photosynthesis on crop yield https://www.nature.com/articles/s41477-019-0398-8 & https://www.agdaily.com/technology/just-much-enhancing-photosynthesis-improve-crop-yield/
- 16 August, 2019. Ermakova, Lopez-Calcagno, Raines, et al. Overexpression of the Rieske FeS protein of the Cytochrome b_6f complex increases C_4 photosynthesis in *Setaria viridis* https://www.nature.com/articles/s42003-019-0561-9
- September 5, 2019. Eshed & Lippman. Revolutions in agriculture chart a course for targeted breeding of old and new crops. https://www.nature.com/articles/s42003-019-0561-9 Science. DOI: 10.1126/science.aax0025. https://science.sciencemag.org/content/early/2019/09/09/science.aax0025.

Thank You!

Val Giddings | vgiddings@itif.org | @PrometheusGreen

"In the last 30 years, we have learnt a lot about how C4 plants work by making them worse—by breaking them as part of the process of discovery. However, this is the first example in which we have actually improved the plants…"

– Robert Furbank,

https://phys.org/news/2019-08-discovery-bottleneck-relief-photosynthesis-major.html

https://www.nature.com/articles/s42003-019-0561-9