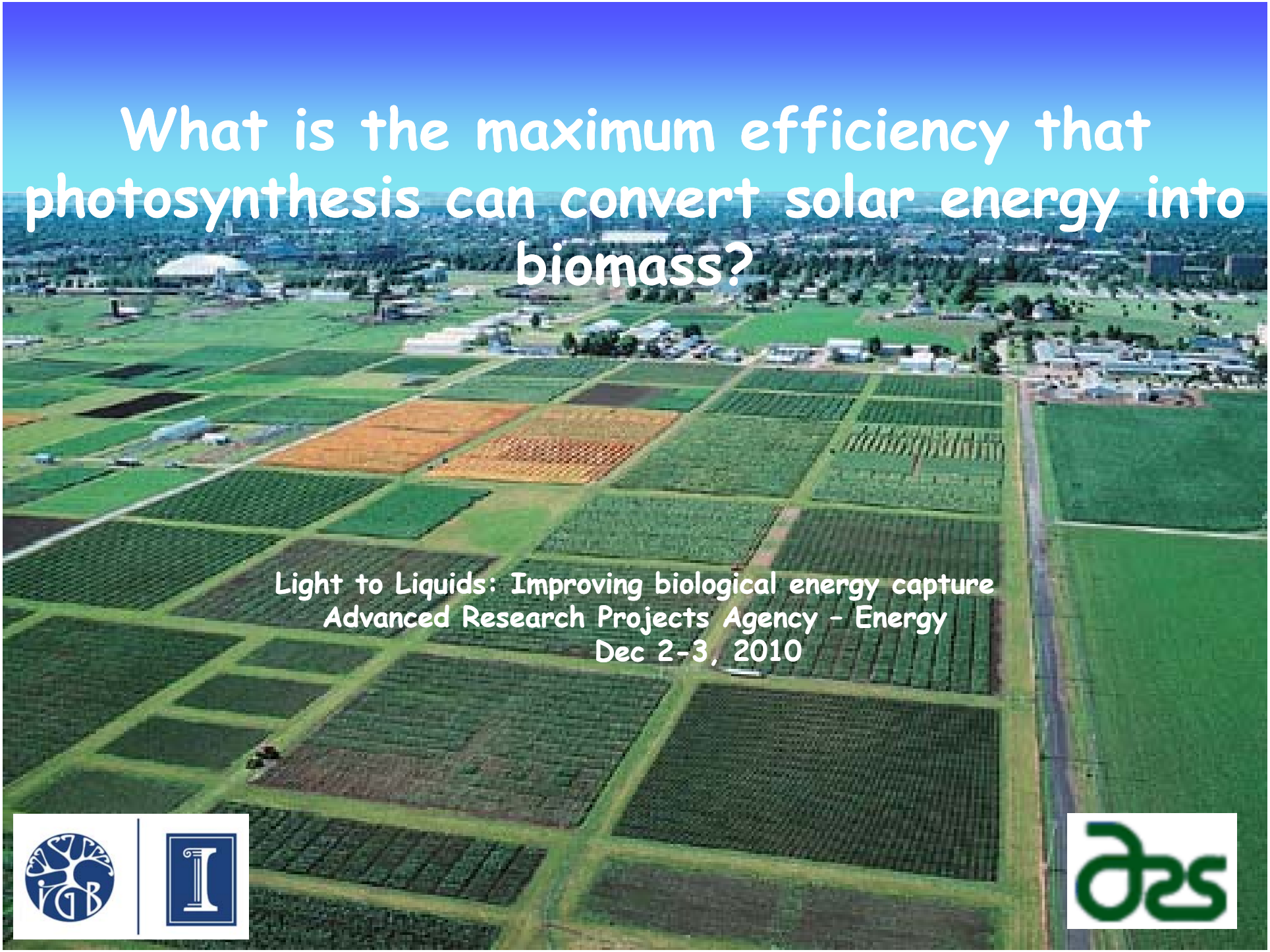
What is the maximum efficiency that photosynthesis can convert solar energy into biomass?



Light to Liquids: Improving biological energy capture
Advanced Research Projects Agency – Energy
Dec 2-3, 2010

Total solar energy

Conversion efficiency

$$W_h = S\,\varepsilon_i\,\varepsilon_c\,\eta$$

Harvested yield

Interception efficiency

Partitioning efficiency (Harvest index)

ε_i is determined by speed of canopy closure, and canopy size & architecture

- top performing crops achieve ε_i = 0.9

- little potential for further improvement

Partitioning efficiency (η)

- for some crops, yield increase has been due in large part to improved η
- Harvest index (η) for corn grain in modern cultivars is ~55% of above ground biomass (i.e. η = 0.55)
- little room for improvement in major grain crops

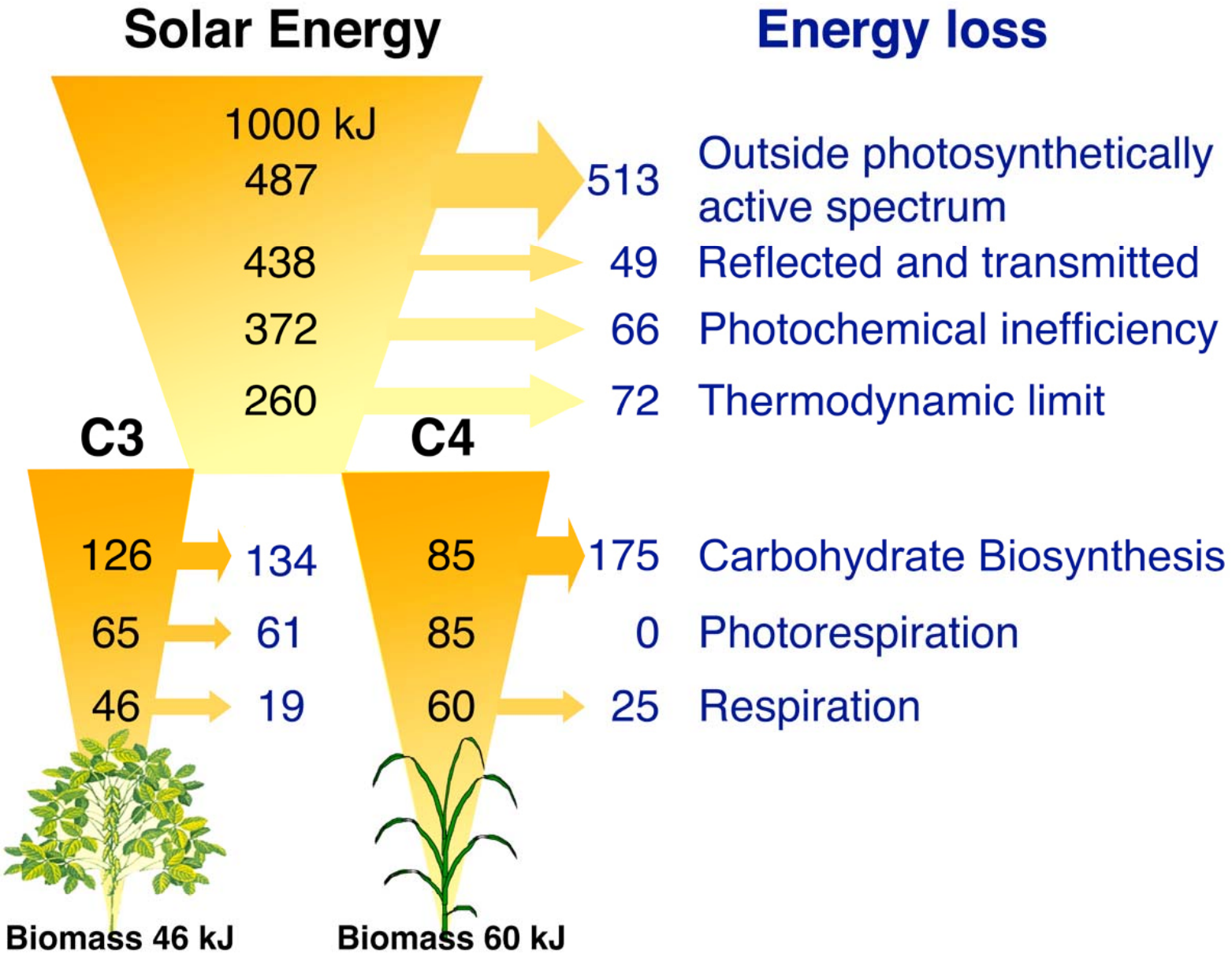
Lignocellulosic Feedstock Harvest Index

Feedstock	Cellulose	Hemicellulose	Lignin	Ash	Other	HI
Hardwoods	39-50%	18-28%	15-28%	0.3-1 %	3-6%	0.65-0.82
Softwoods	41-57%	8-12%	24-27%	0.1-0.4%	5-9%	0.63-0.69
Miscanthus	43-48%	23-27%	9-22%	1.7-2.1%	?	0.78-0.89

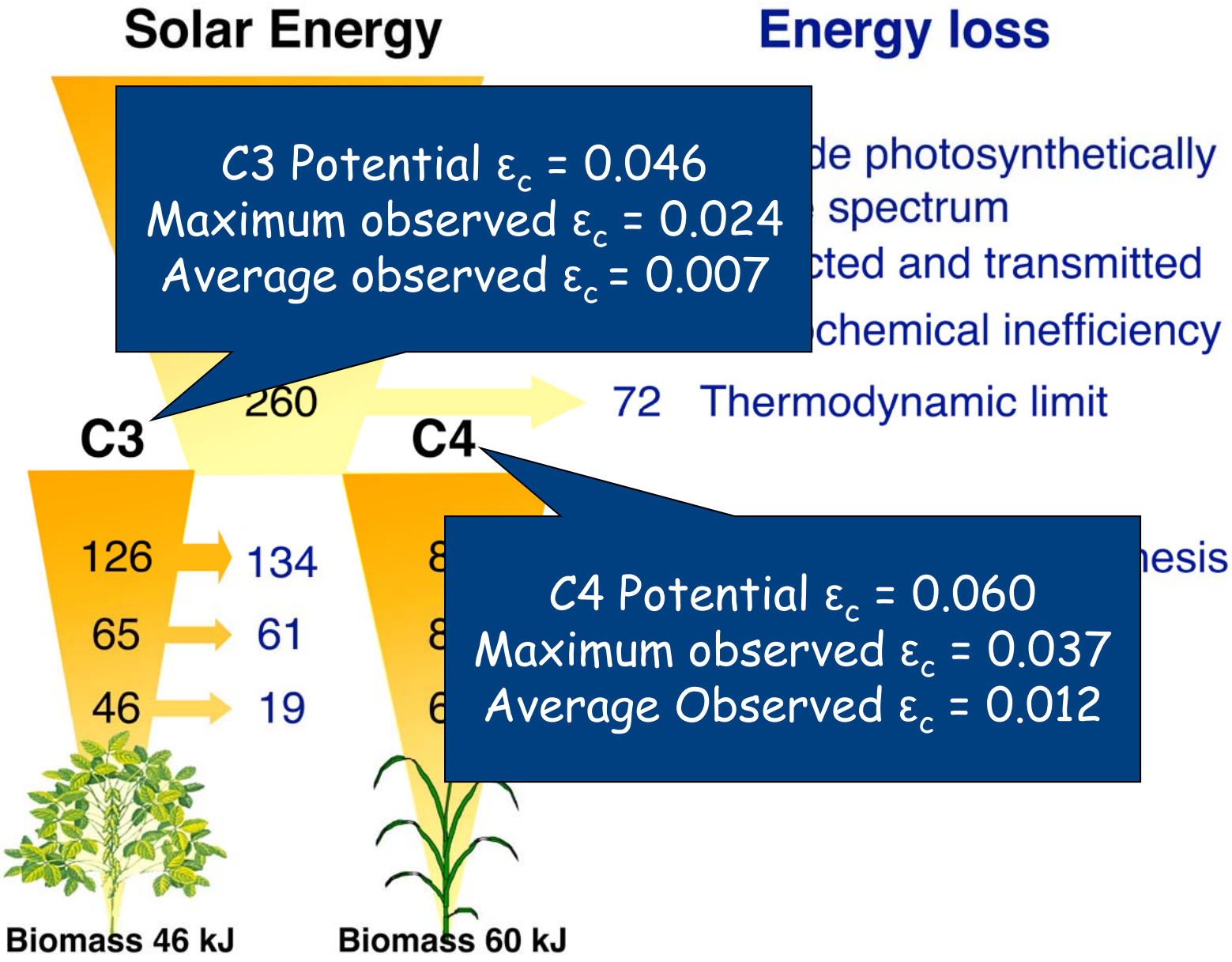
ε_c is determined by combined photo-synthetic rate of leaves in the canopy corrected for respiratory loses.

Annual solar energy conversion efficiencies of C3 and C4 agricultural crops.

Crop	Type	Yield ($t\ ha^{-1}y^{-1}$)	Efficiency (%)
Pennisetum purpureum	*C4*	*88*	*0.8*
Saccharum officaarum	*C4*	*66*	*0.6*
Zea mays	*C4*	*27*	*0.4*
Beta vulgaris	*C3*	*32*	*0.5*
Lolium perenne	*C3*	*23*	*0.7*
Solanium tuberosum	*C3*	*11*	*0.3*
Triticum aestivum	*C3*	*12*	*0.2*

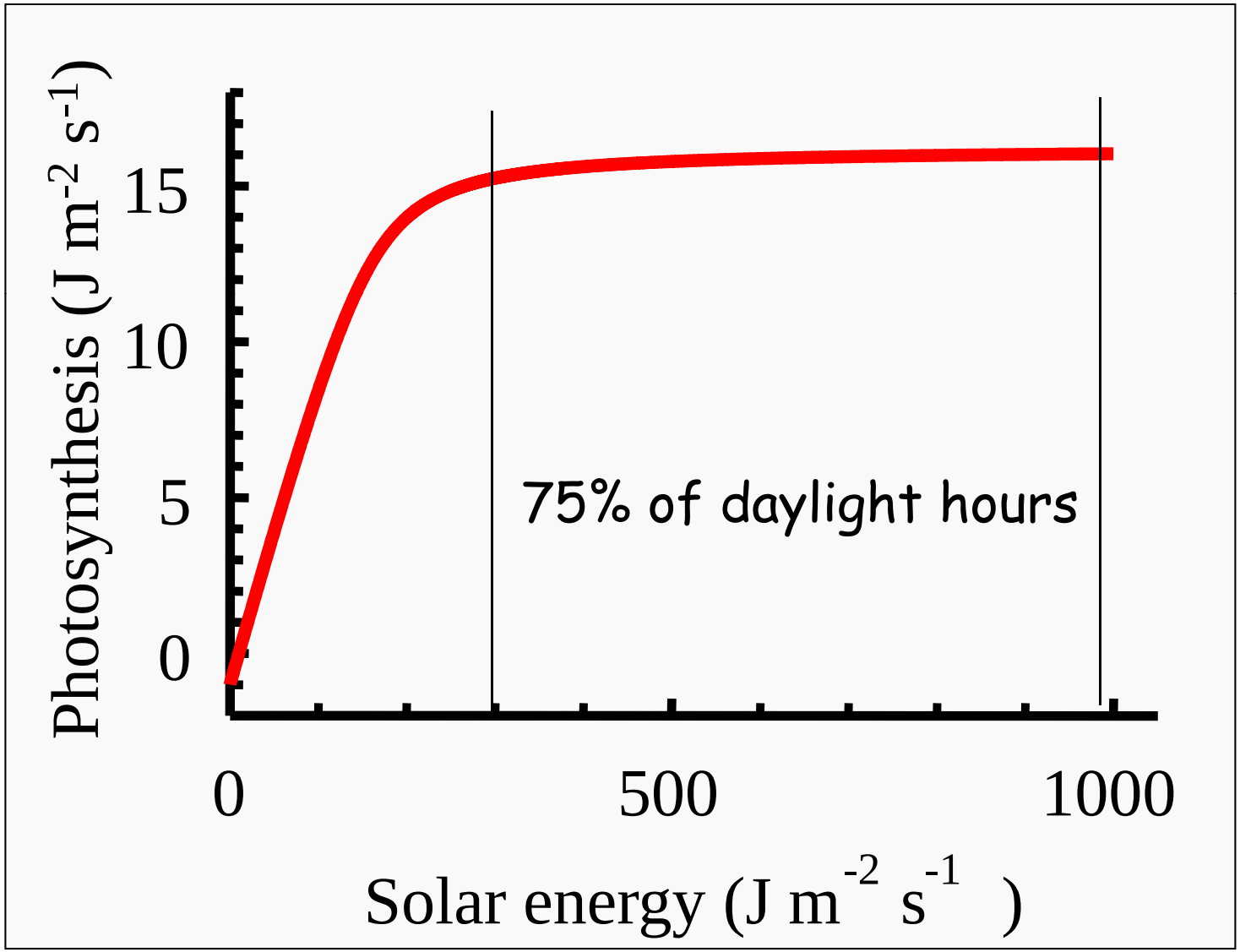


Modified from Zhu et al. 2008 Current Opinion in Biotechnology. 19:153-159.

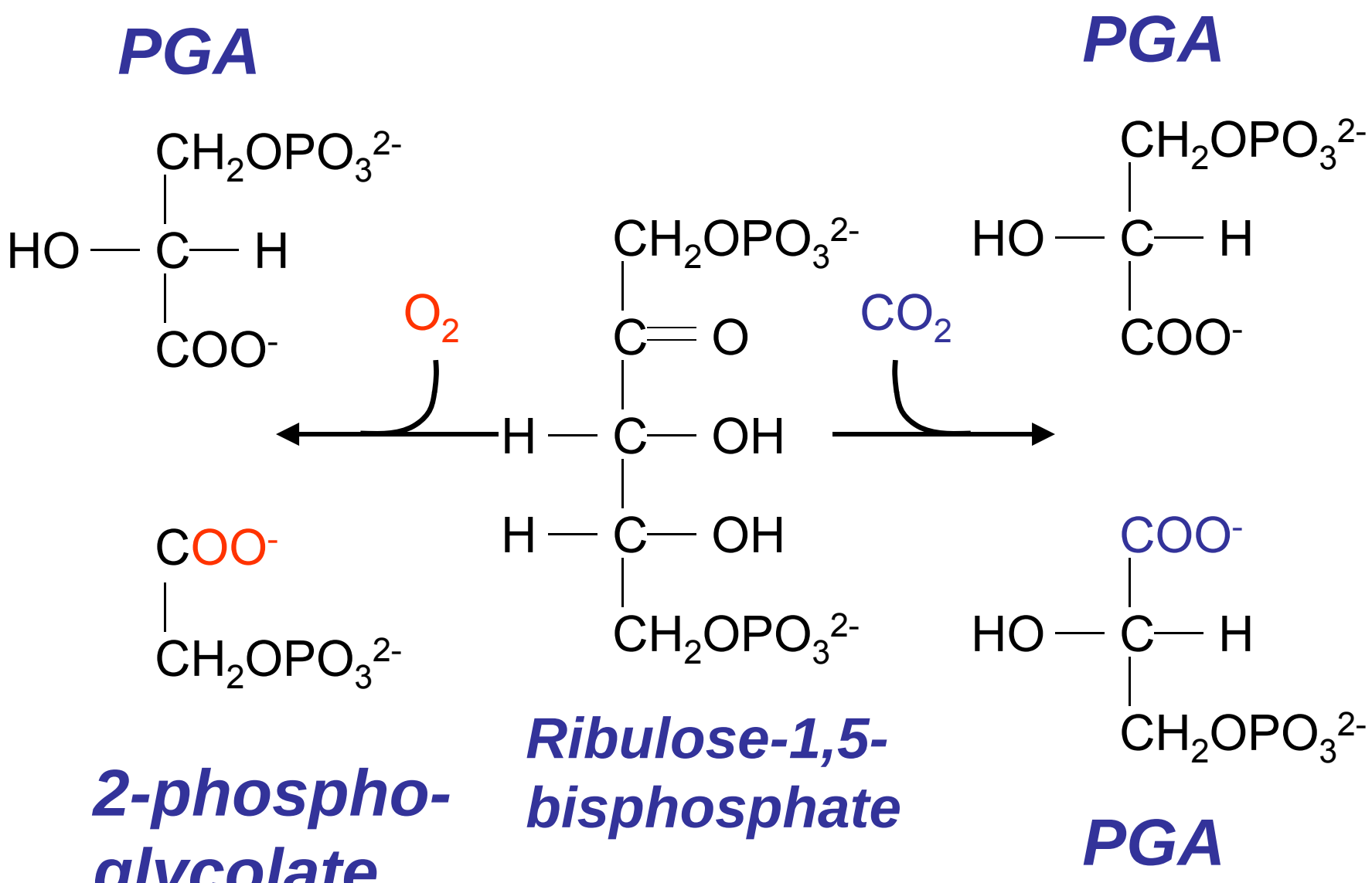


Modified from Zhu et al. 2008 Current Opinion in Biotechnology. 19:153-159.

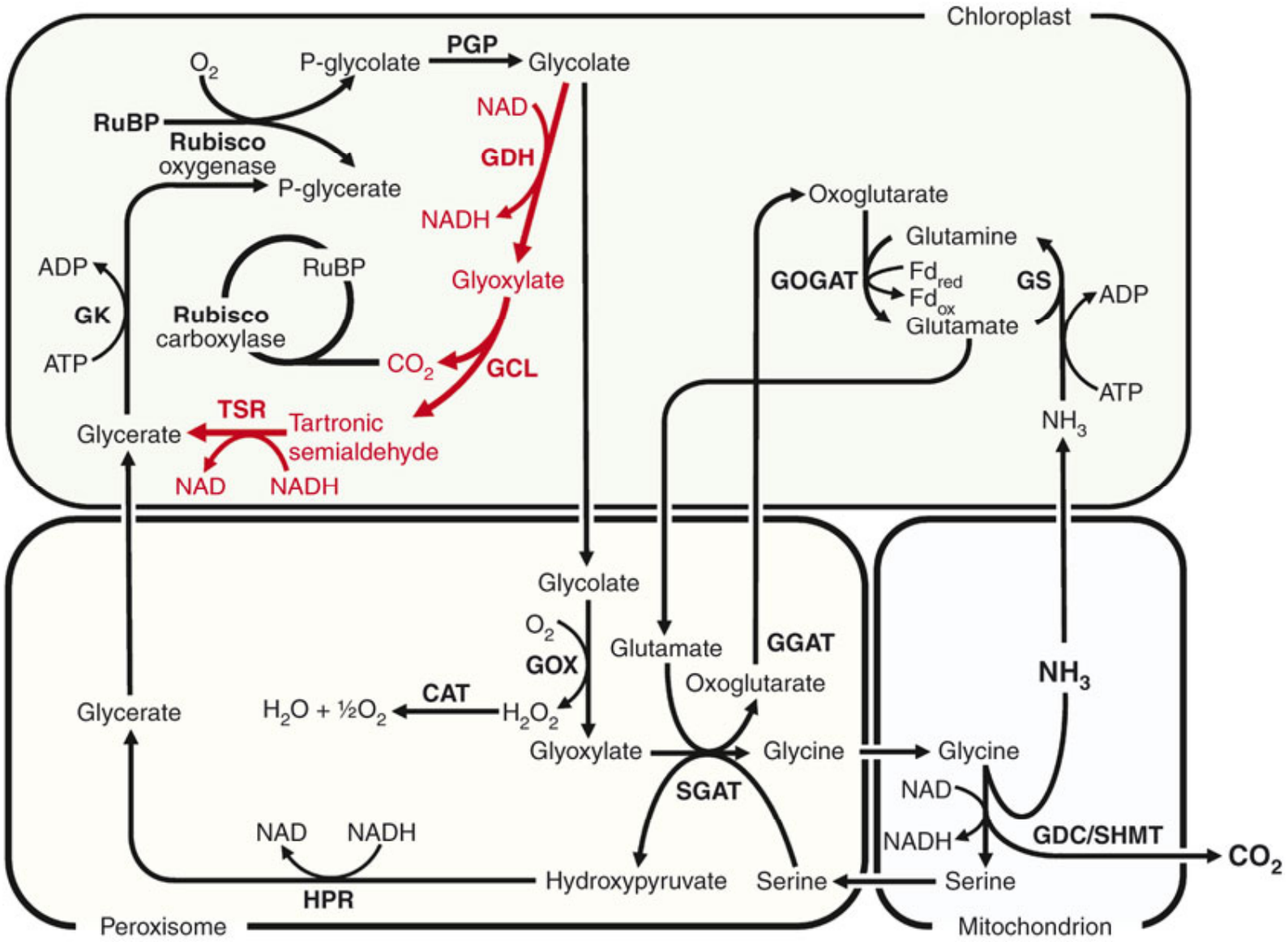
Why is maximum observed below theortical ε_c?



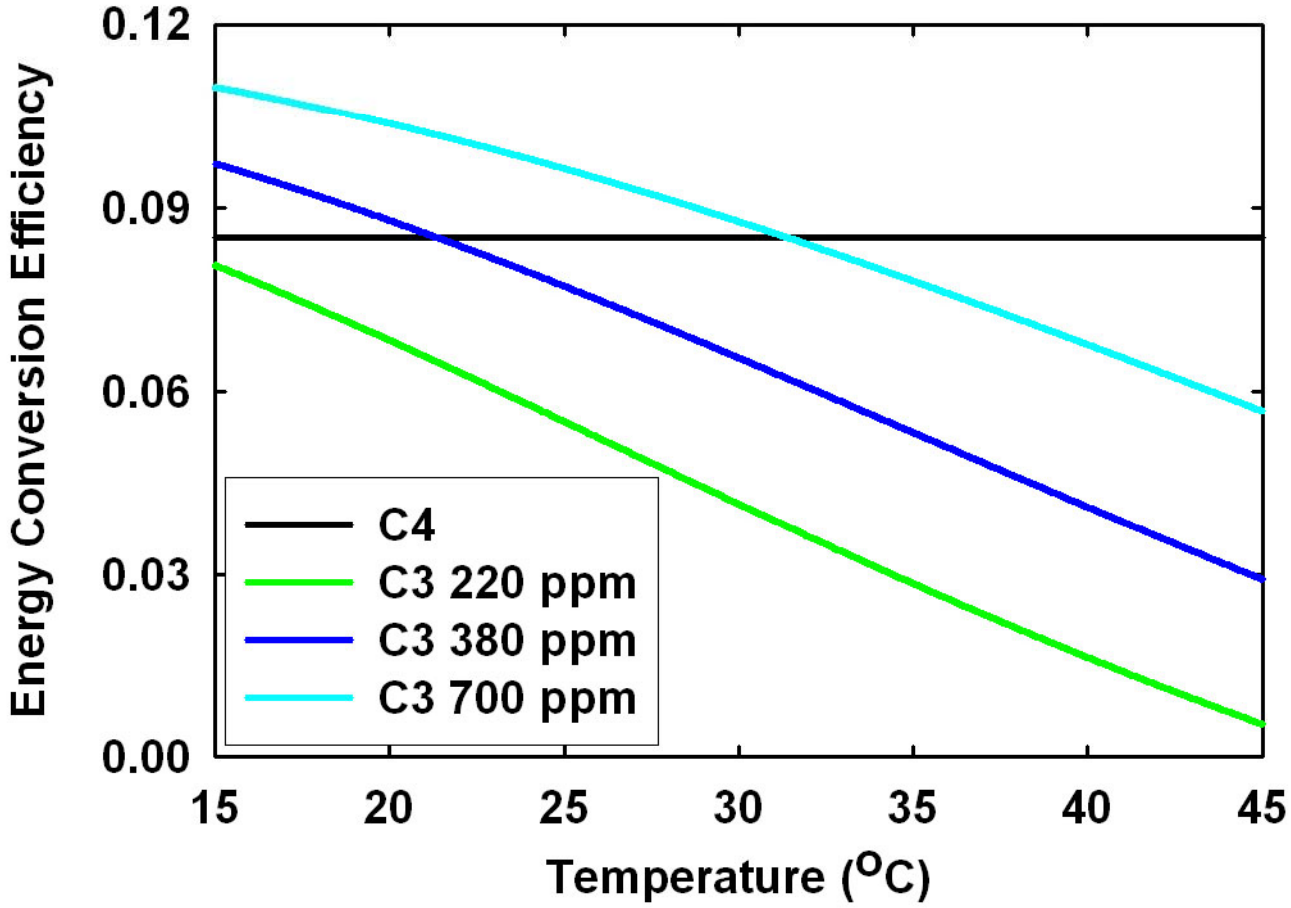
Raising the theoretical upper limit of photosynthetic efficiency.


PGA
PGA
$CH_2OPO_3^{2-}$
HO — C — H
COO^-
O_2
CO_2
$CH_2OPO_3^{2-}$
C = O
H — C — OH
H — C — OH
$CH_2OPO_3^{2-}$
COO^-
$CH_2OPO_3^{2-}$
$CH_2OPO_3^{2-}$
HO — C — H
COO^-
COO^-
HO — C — H
$CH_2OPO_3^{2-}$
2-phospho-glycolate
Ribulose-1,5-bisphosphate
PGA

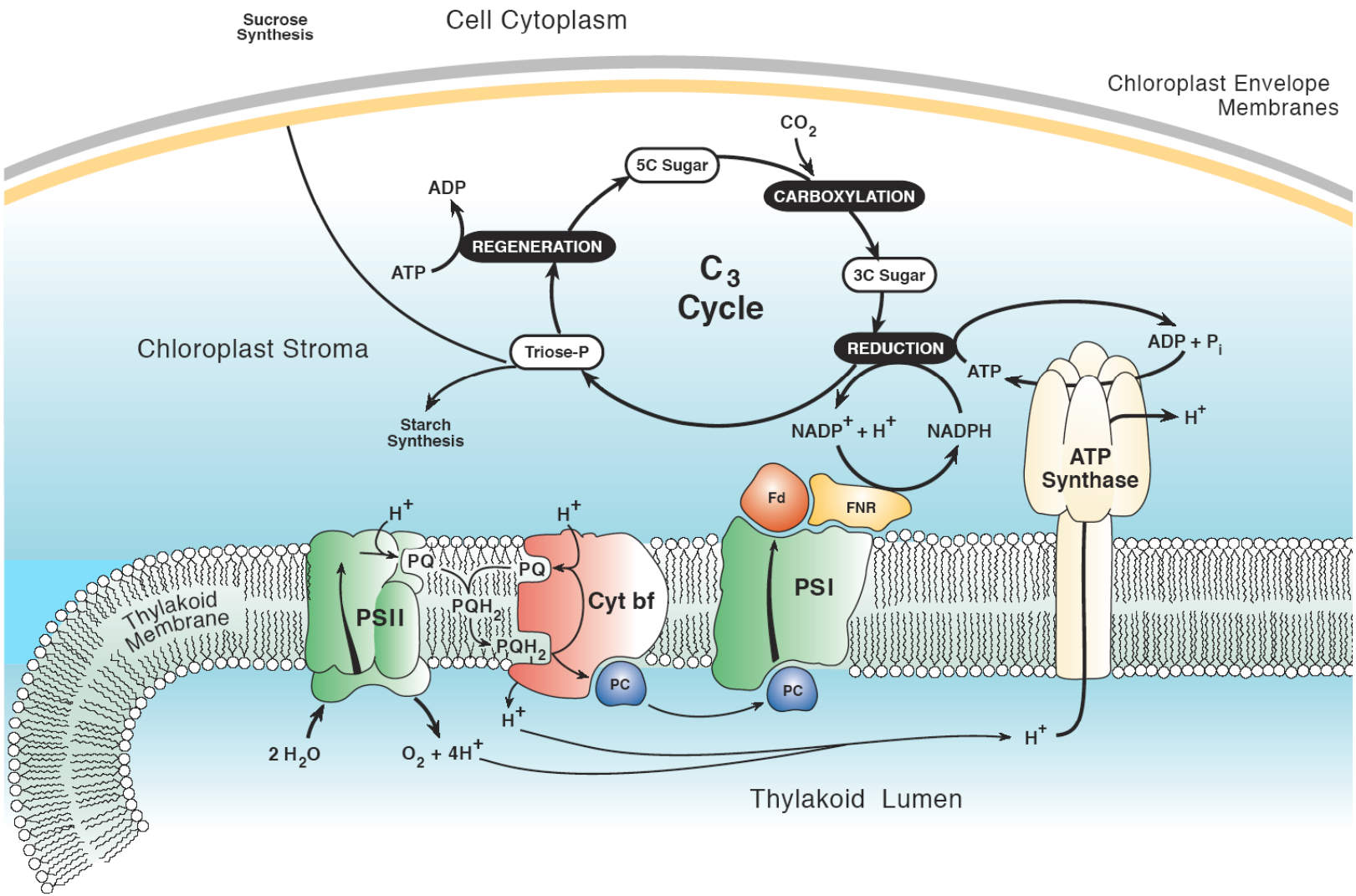
Photorespiratory "by-pass"



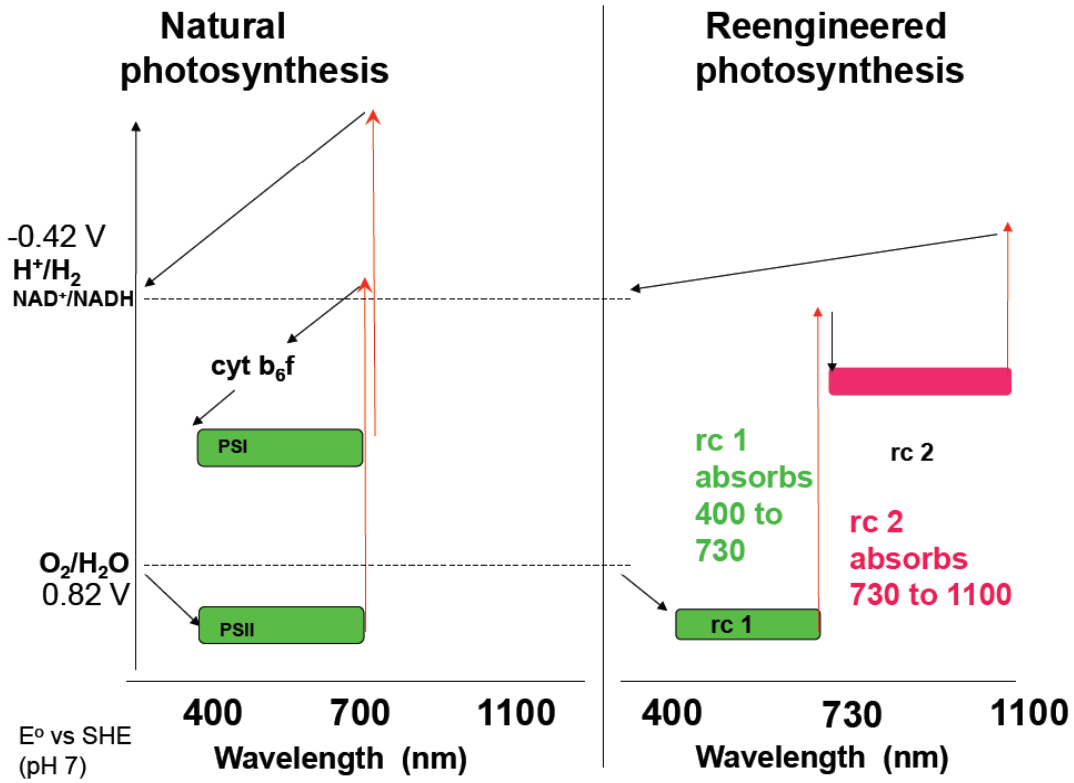
Effects of temperature and [CO_2] on ε_c of C3 vs C4 photosynthesis



Zhu , Long, and Ort (2008) Current Opinion in Biotechnology 19, 153-159


Sucrose Synthesis
Cell Cytoplasm
Chloroplast Envelope Membranes
CO_2
5C Sugar
CARBOXYLATION
ADP
REGENERATION
ATP
C_3 Cycle
3C Sugar
Chloroplast Stroma
Triose-P
REDUCTION
$ADP + P_i$
ATP
H^+
Starch Synthesis
$NADP^+ + H^+$
NADPH
ATP Synthase
Fd
FNR
H^+
H^+
PQ
PQ
PQH_2
PQH_2
Cyt bf
PSII
PSI
Thylakoid Membrane
PC
PC
H^+
H^+
$2\ H_2O$
$O_2 + 4H^+$
Thylakoid Lumen

Redesigning photosystem absorption to better match energetic requirements of H_2O oxidation and carbon reduction to solar spectrum



Blankenship et al. submitted

Targets and timelines for improving photosynthetic efficiency

Time horizon	Change to be made	[a] Increase in ε_c (%)	Major obstacle(s) to implementation
Long-term[b]	Rubisco with dramatically decreased oxygenase activity	30	Determining which molecular features of Rubisco control specificity
	Increase mesophyll conductance	20	Determining which physiological factors control mesophyll conductance
	Conversion of C3 to C4	30	Identifying suite of genes that control morphological and biochemical conversion
Mid-term[c]	Increased rate of recovery from photoprotective state	15	Determining combination of components in PSII photoprotective pathway to be altered
	Introduction of Rubisco with increased carboxylation rate	25	Developing efficient transformation technologies
Near-term[d]	Photorespiration bypass	13	Maximizing bypass flux; introducing into crop plants
	Improved canopy structure	30	Identifying genetic variability
	Rebalancing of RuBP regeneration rate with increased carboxylation	30	Demonstrating proof of concept experiments in crop plants; developing efficient transformation technologies
	Optimize canopy chlorophyll content	30	Developing optimization models; determining metabolically most efficient mode of reducing chlorophyll content

[a] Percent increase in the daily integral of carbon uptake estimated for a sunny day at midlatitudes.

[b] Theoretical basis for what change to make to affect the increase is missing. Not enough is known to determine if answers can be bought.

[c] Important science regarding what components to change to affect the increase is missing. With substantial focused investment, possible in 20-year time frame.

[d] The basic science about what needs to be done is in place and the hurdles for implementation are technical. With adequate investment, possible in 10-year time frame.

Zhu, Long, Ort (2010) Annu Rev Plant Biol 61:235-261