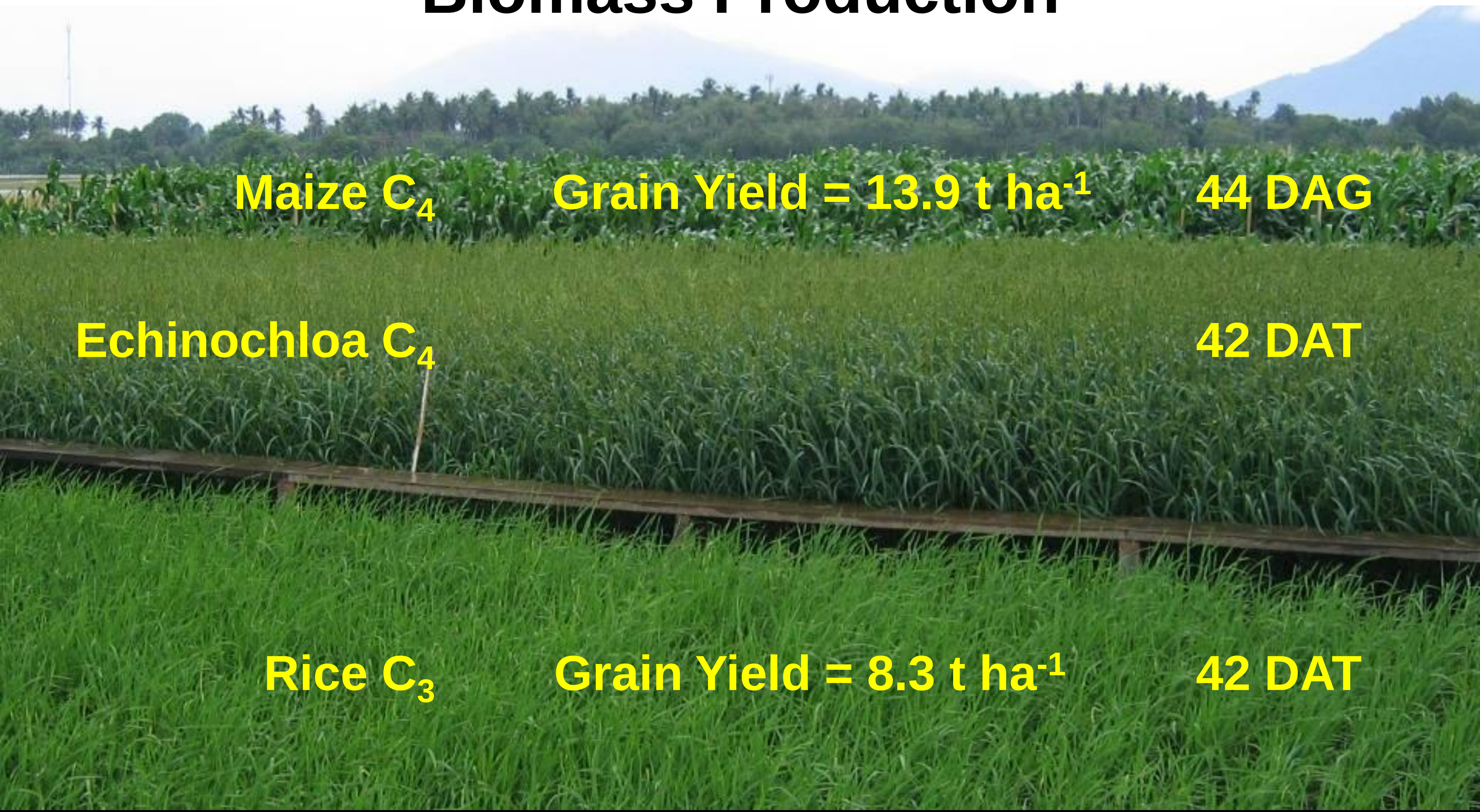
Mechanisms Controlling the Temperature Response of C_4 Photosynthesis

Rowan Sage
Department of Ecology and Evolutionary Biology, University of Toronto, Toronto ON M5S3B2

C_4 Photosynthesis Supercharges Biomass Production

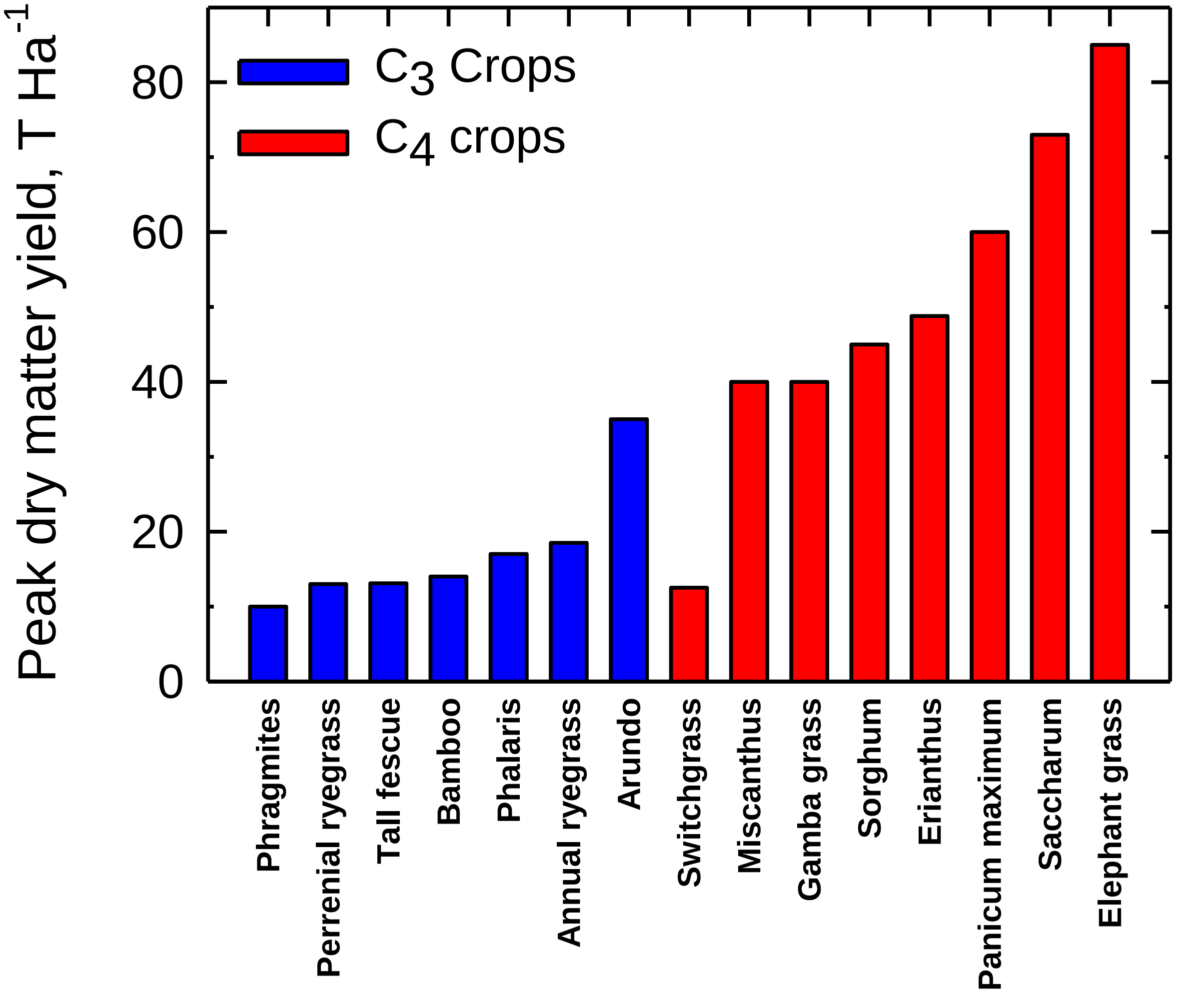


DAG = Days after germination
DAT = Days after transplanting

Slide courtesy of John Sheehy, International Rice Research Institute

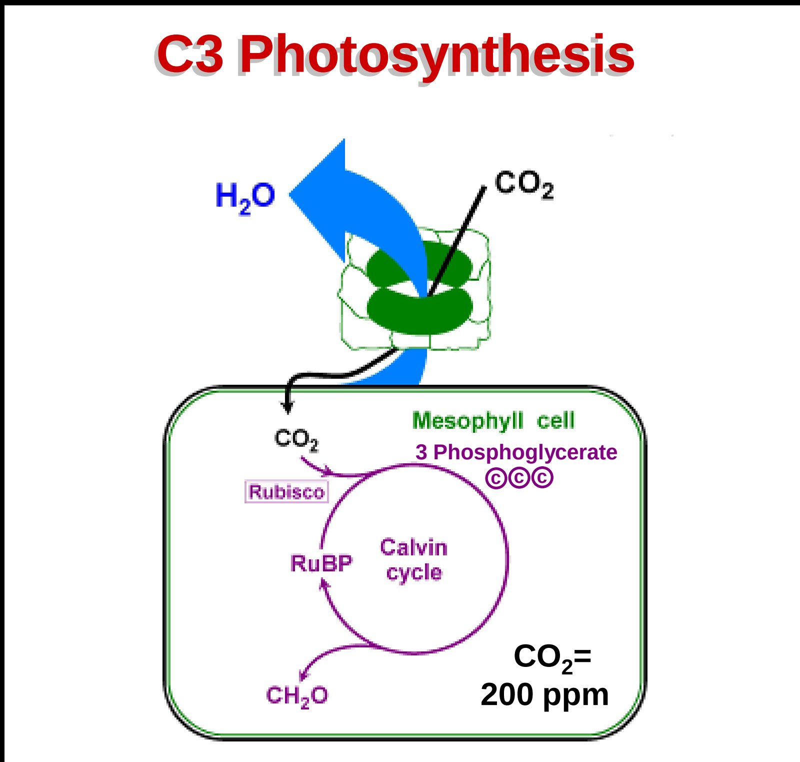
Maximum Dry Matter Yields Reported for Biofuel Crops

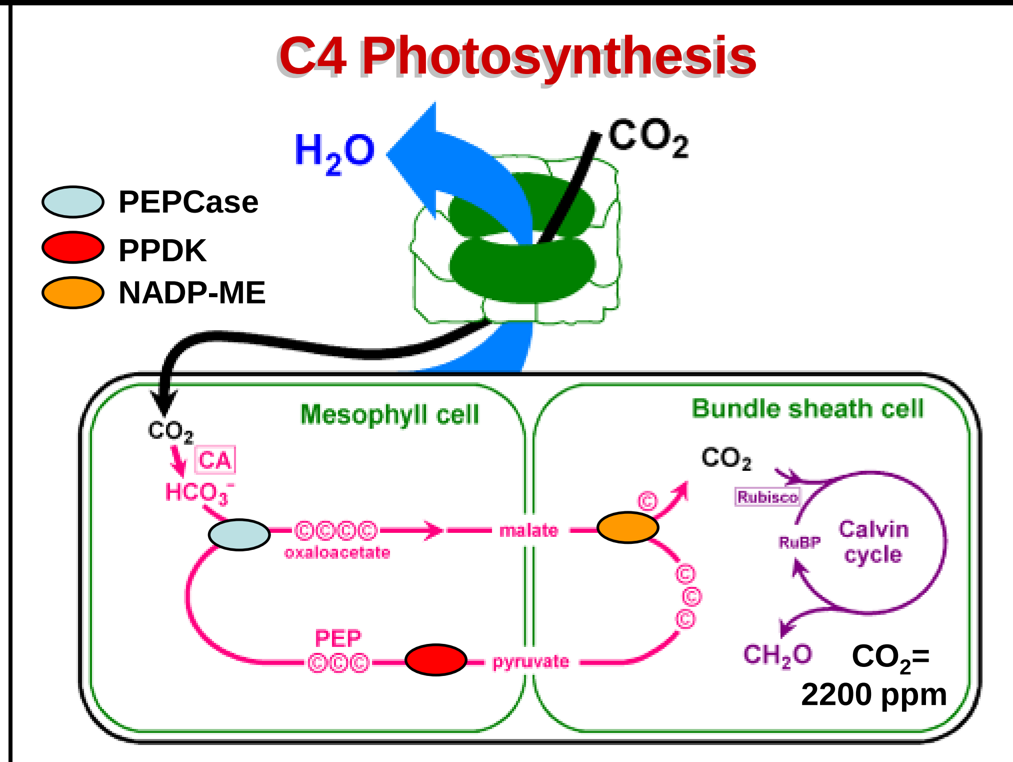
from El Bassam (1997) *Energy Plant Species*

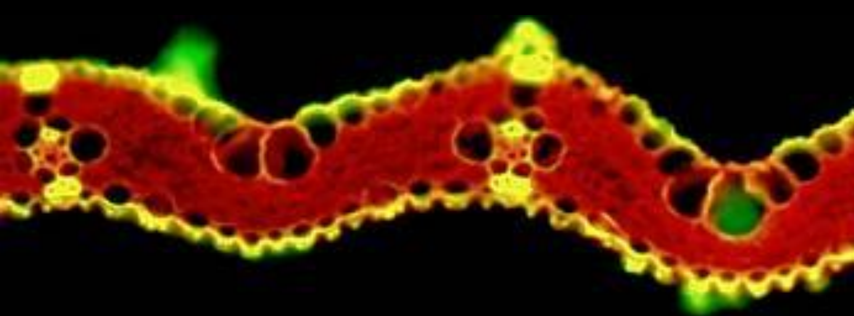


C_4 Supercharges Photosynthesis Using A Two Compartment CO_2 Concentrating Mechanism

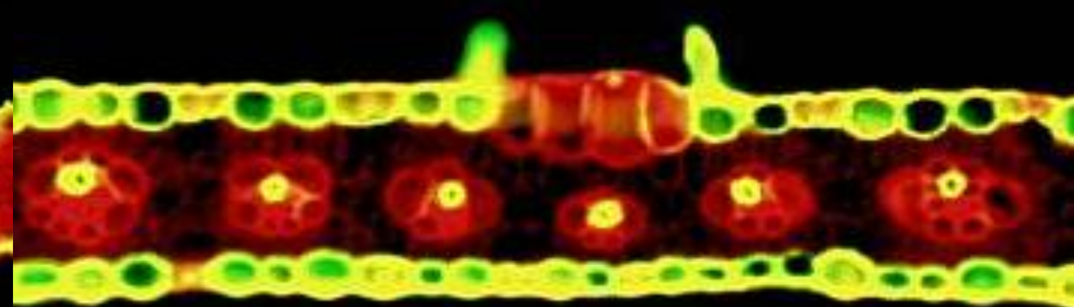
Slide courtesy of John Sheehy, International Rice Research Institute



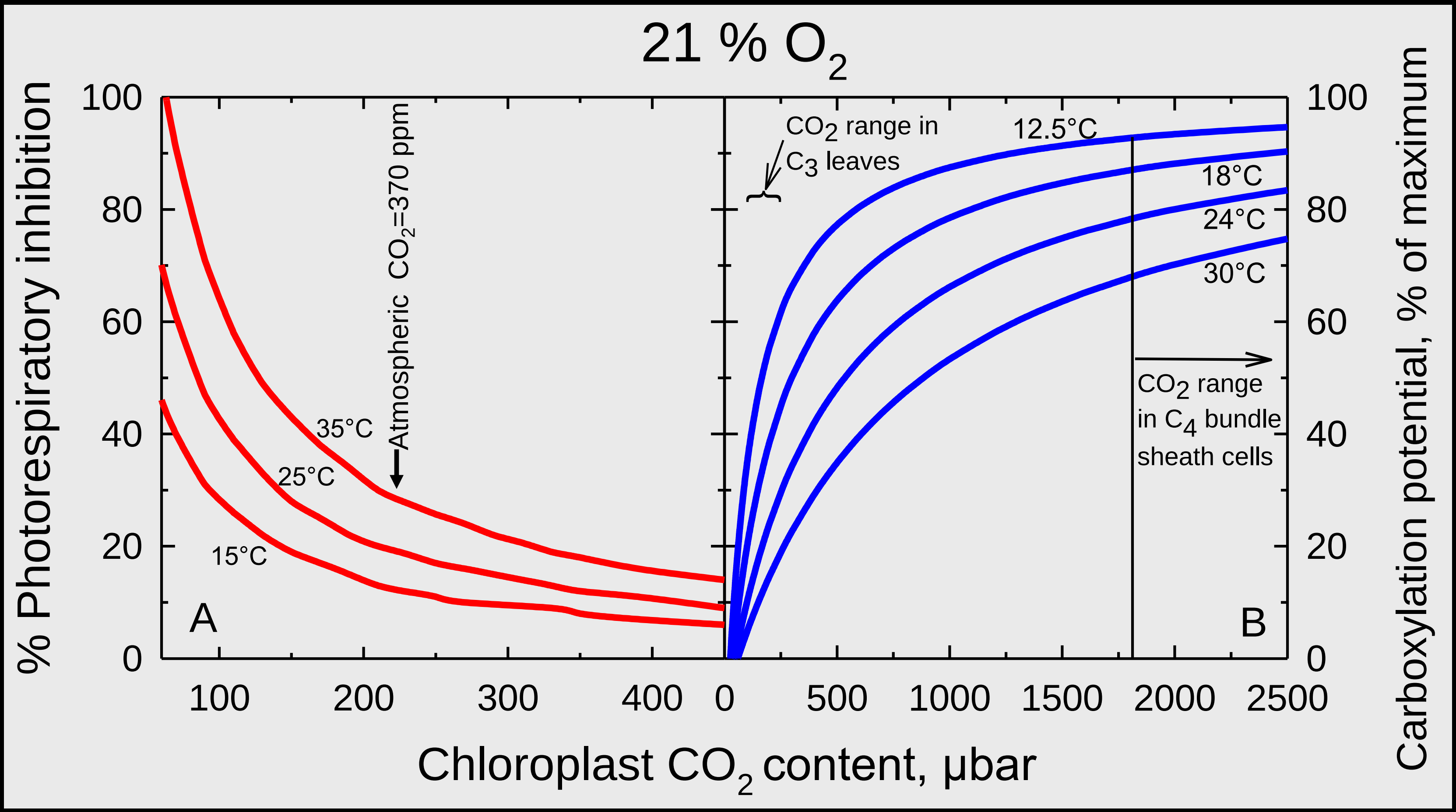




C_3 Anatomy

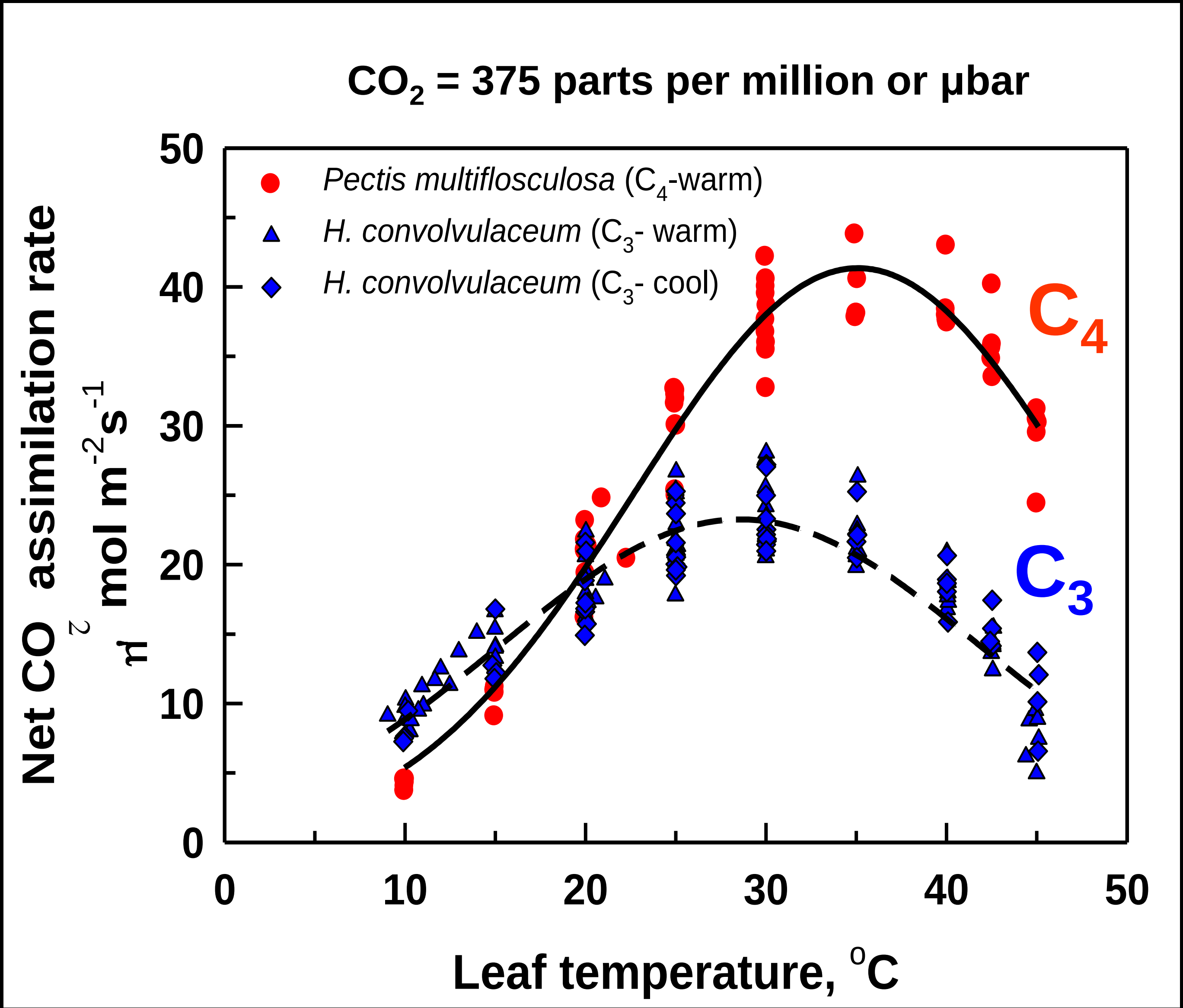


C_4 “Kranz” Anatomy

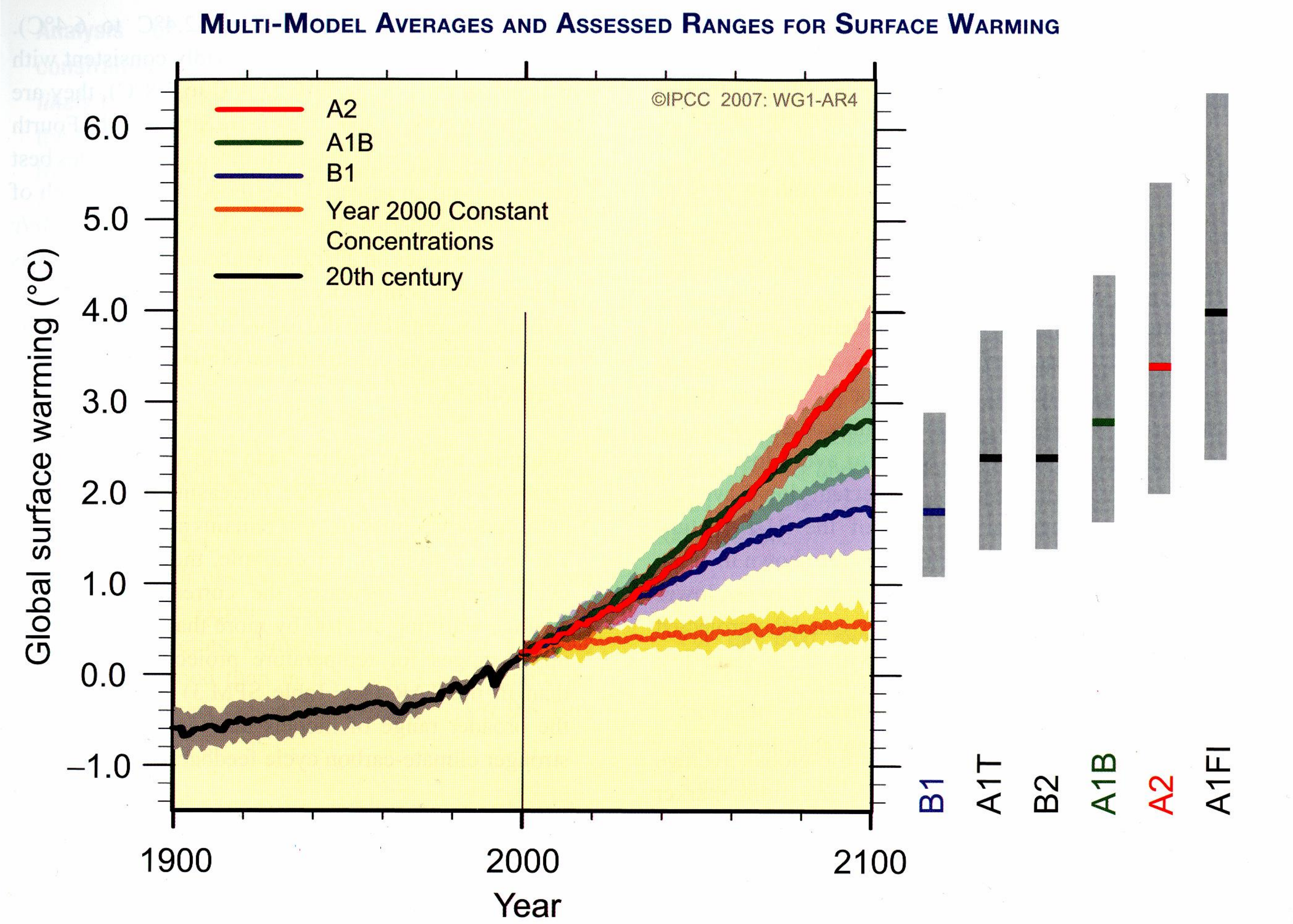


from Sage (2000) in *Redesigning Rice Photosynthesis to Increase Yield. Sheehy, Mitchell and Hardy, eds. Elsevier.*

Typical C_3 and C_4 Photosynthetic Temperature Responses

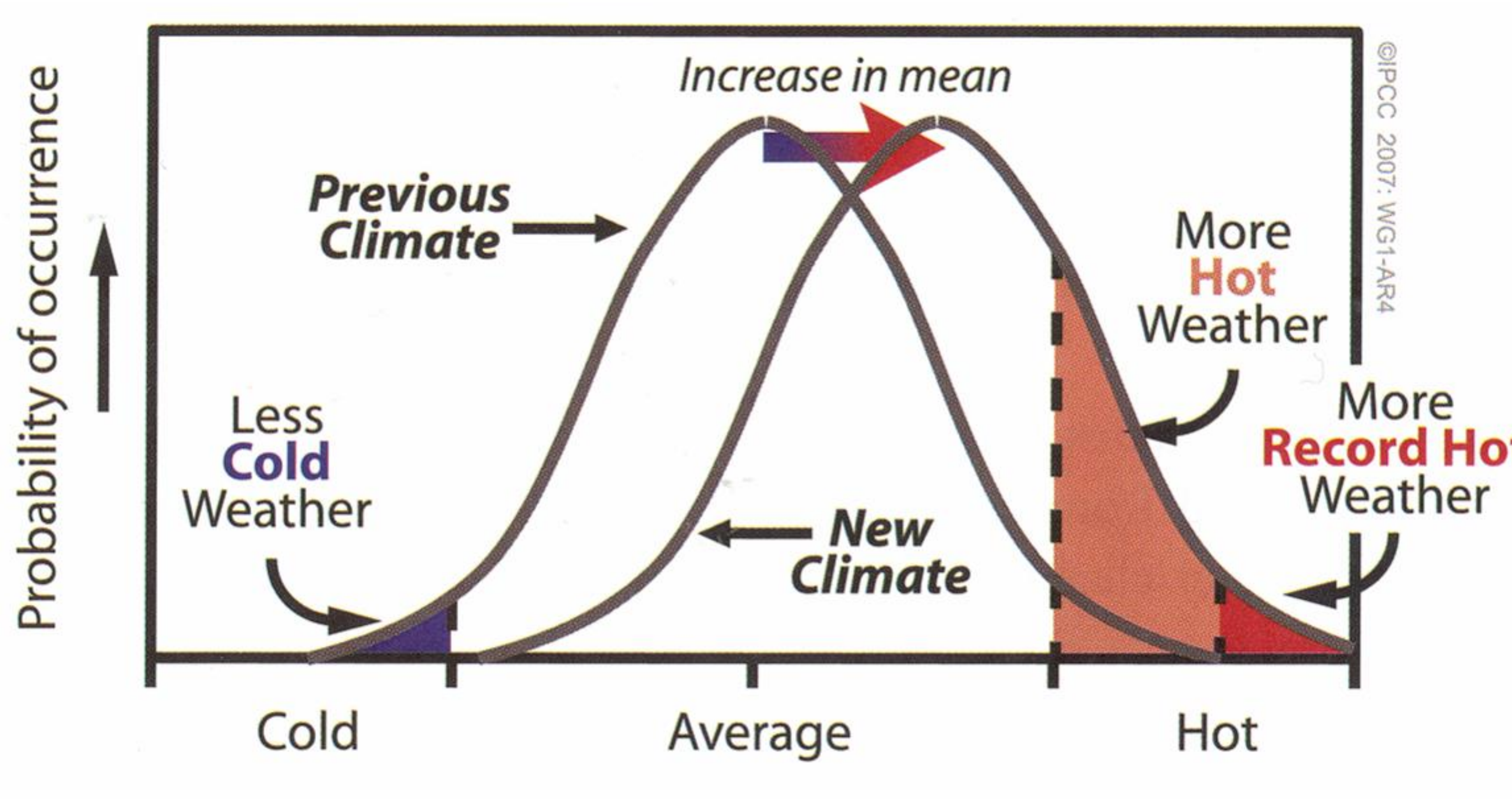


Global Temperature Change and Modeled Predictions: 1900 to 2100



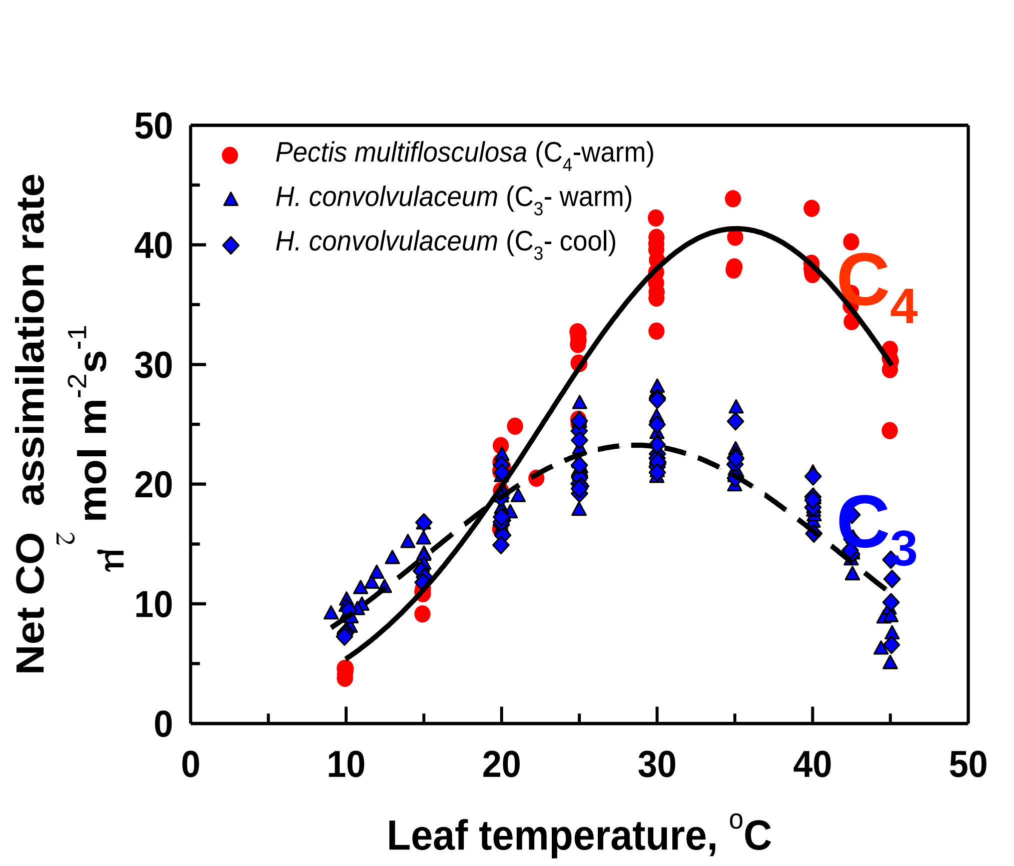
Source: Intergovernmental Panel on Climate Change (2007)
Climate Change 2007: The Physical Basis. Cambridge Univ. Press

A Schematic of How Warming Affects Climate



Source: Intergovernmental Panel on Climate Change (2007):
Climate Change 2007: The Physical Basis. Cambridge Univ. Press

Typical C_3 and C_4 Photosynthetic Temperature Responses



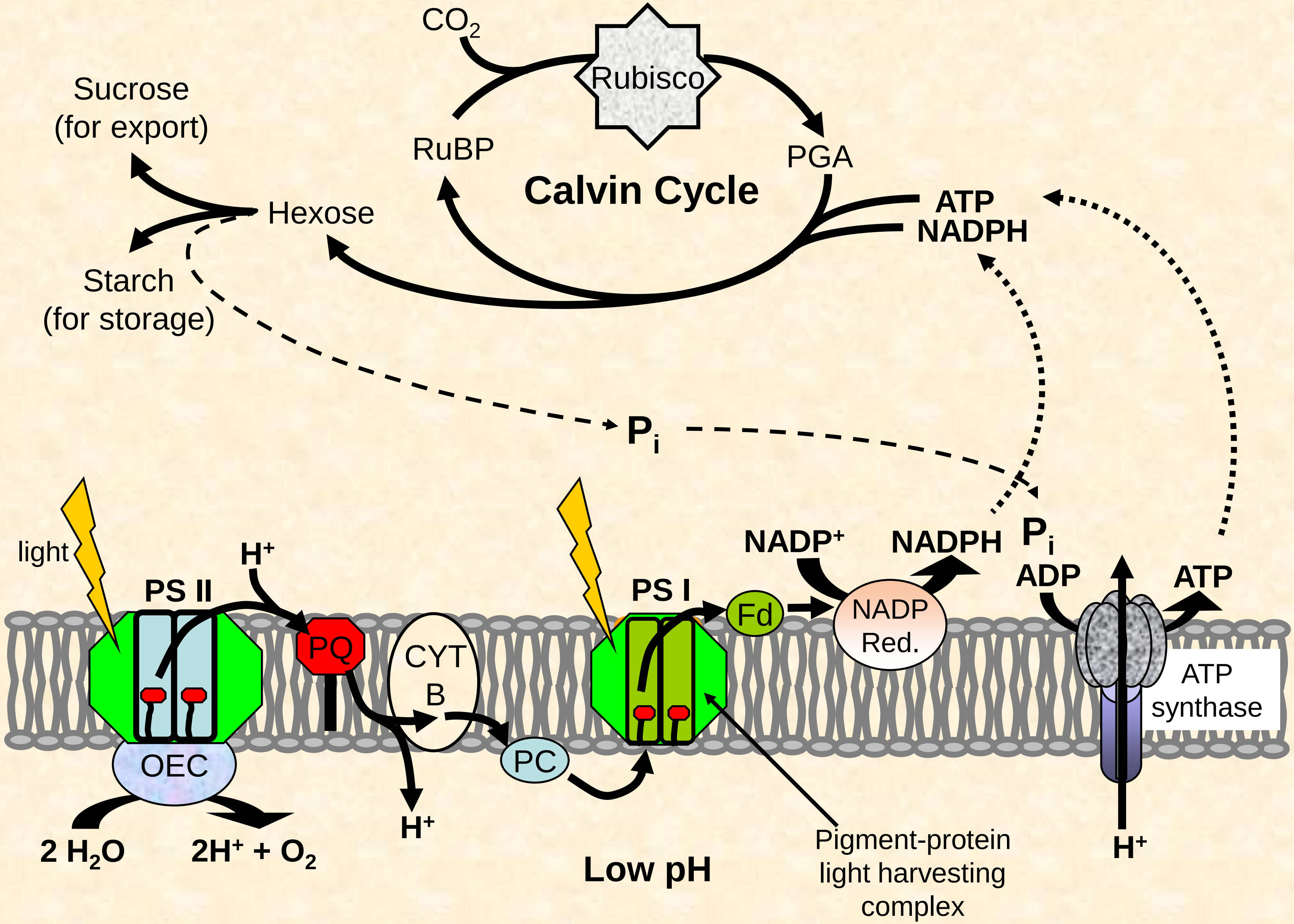
Strategies to Improve the C_4 Response to Climate Warming

1. Exploit moderation of the cool season
2. Exploit warmer summers
3. Exploit warmer temperature and elevated CO_2 to enhance WUE and NUE.

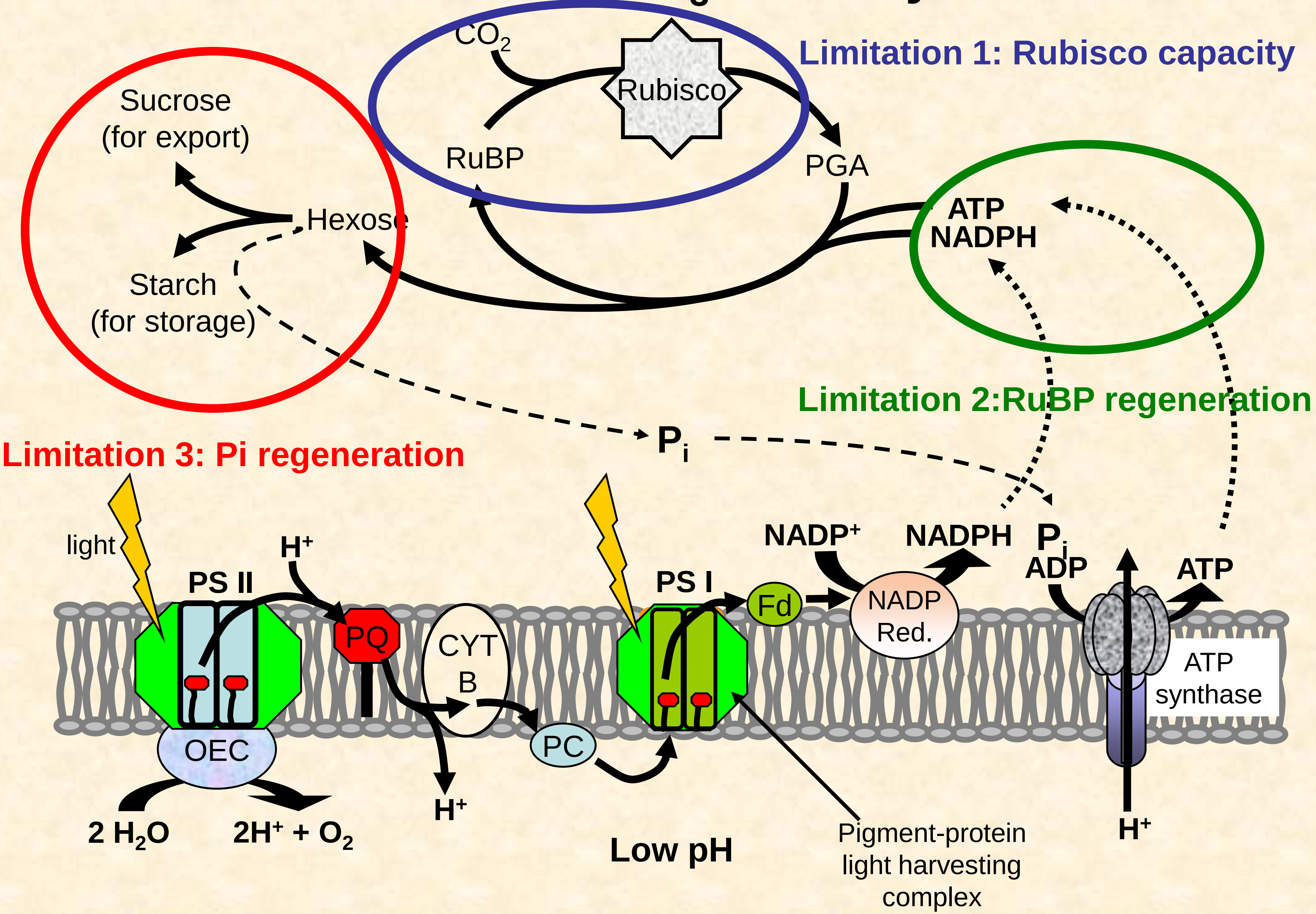
Improving C_4 Photosynthesis

To improve C_4 photosynthetic capacity in a crop plant, one should understand the biochemical processes that limit C_4 photosynthesis in the environment of interest.

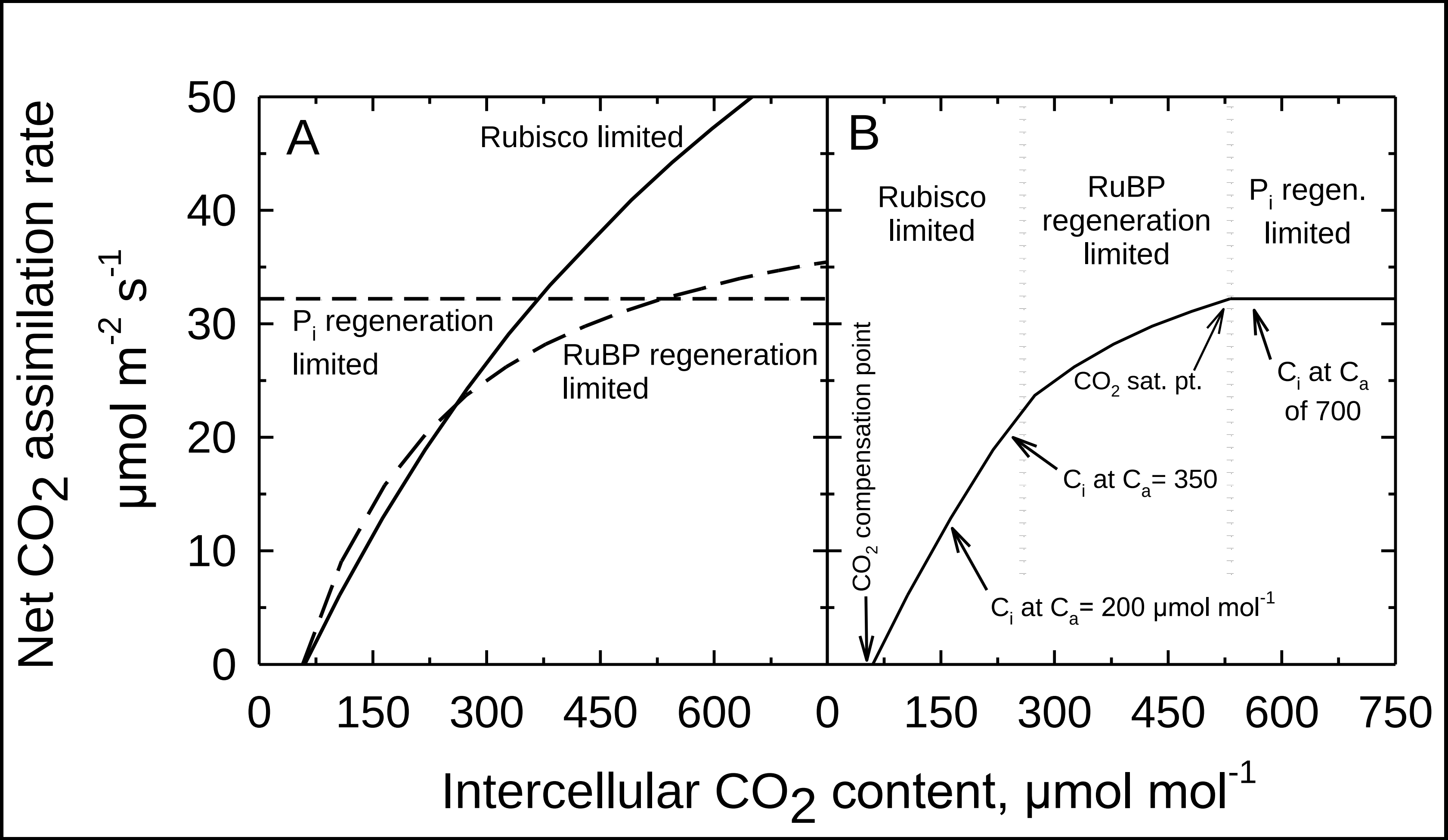
A Schematic of C_3 Photosynthesis



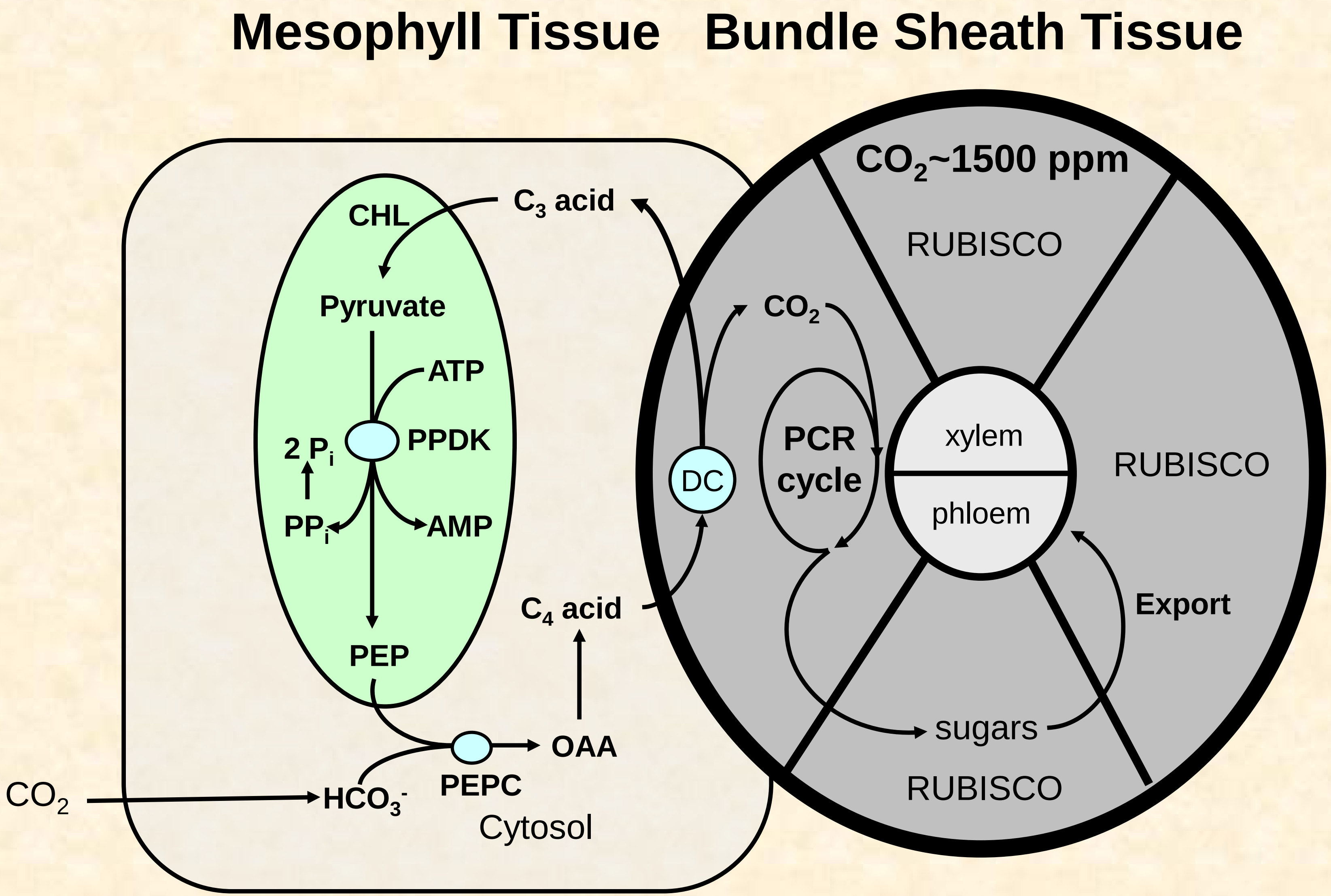
A Schematic of C_3 Photosynthesis



Theoretical Controls Over C_3 Photosynthesis

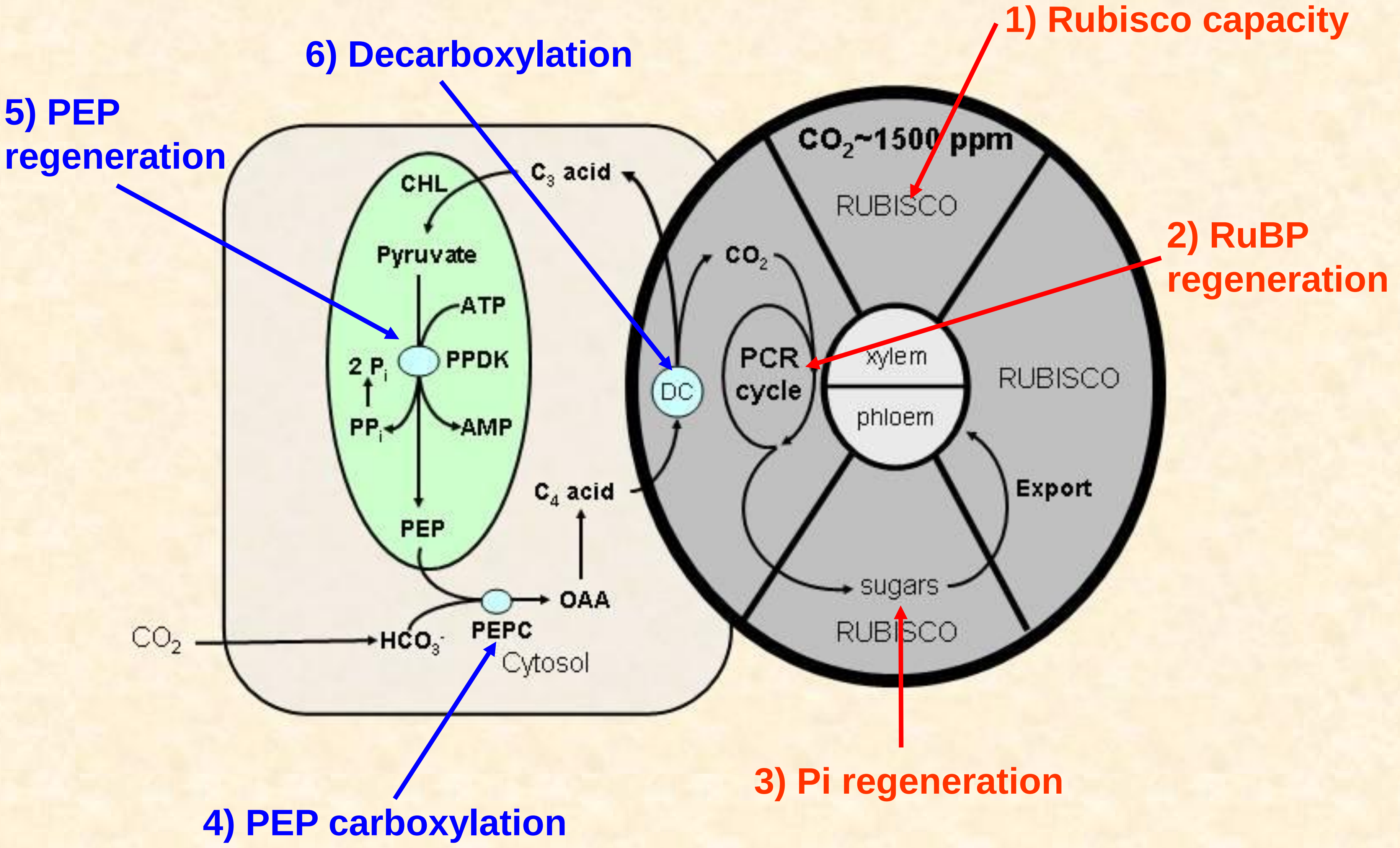


A Schematic of C_4 Photosynthesis



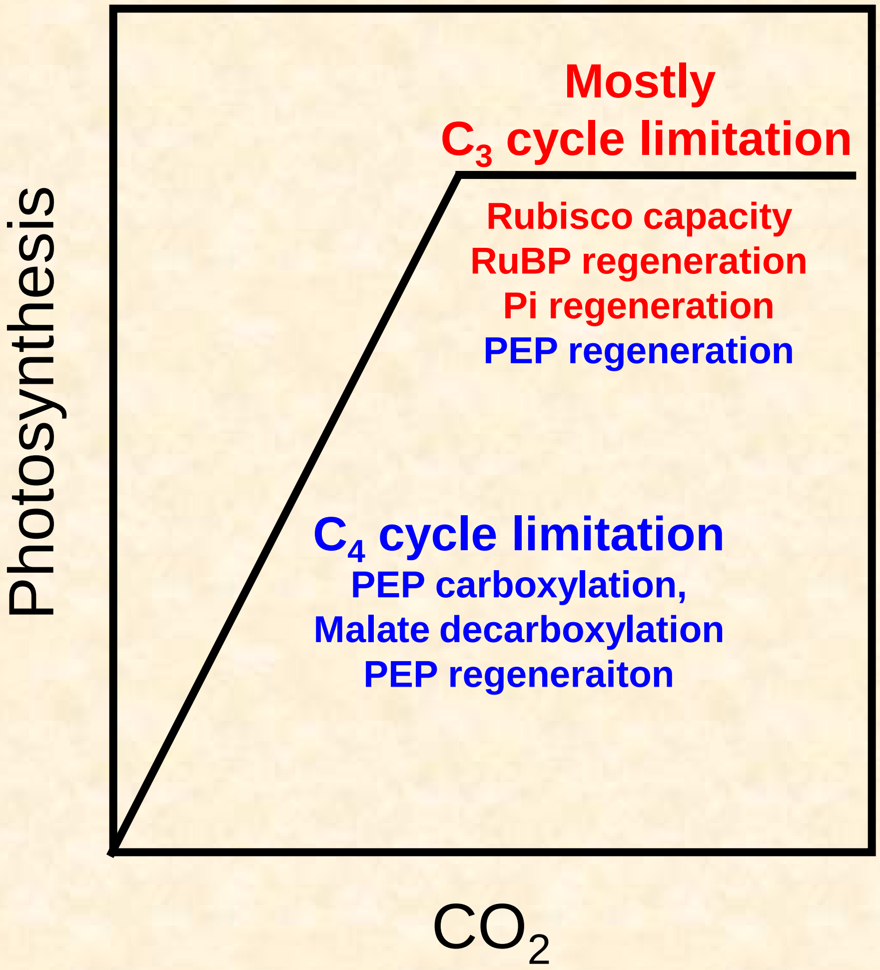
Potential Limitations on C_4 Photosynthesis

C_4 cycle limitations in blue, C_3 cycle limitations in red



Limitations of C_4 Photosynthesis

(after von Caemmerer and Furbank (1999) *C_4 Plant Biology*



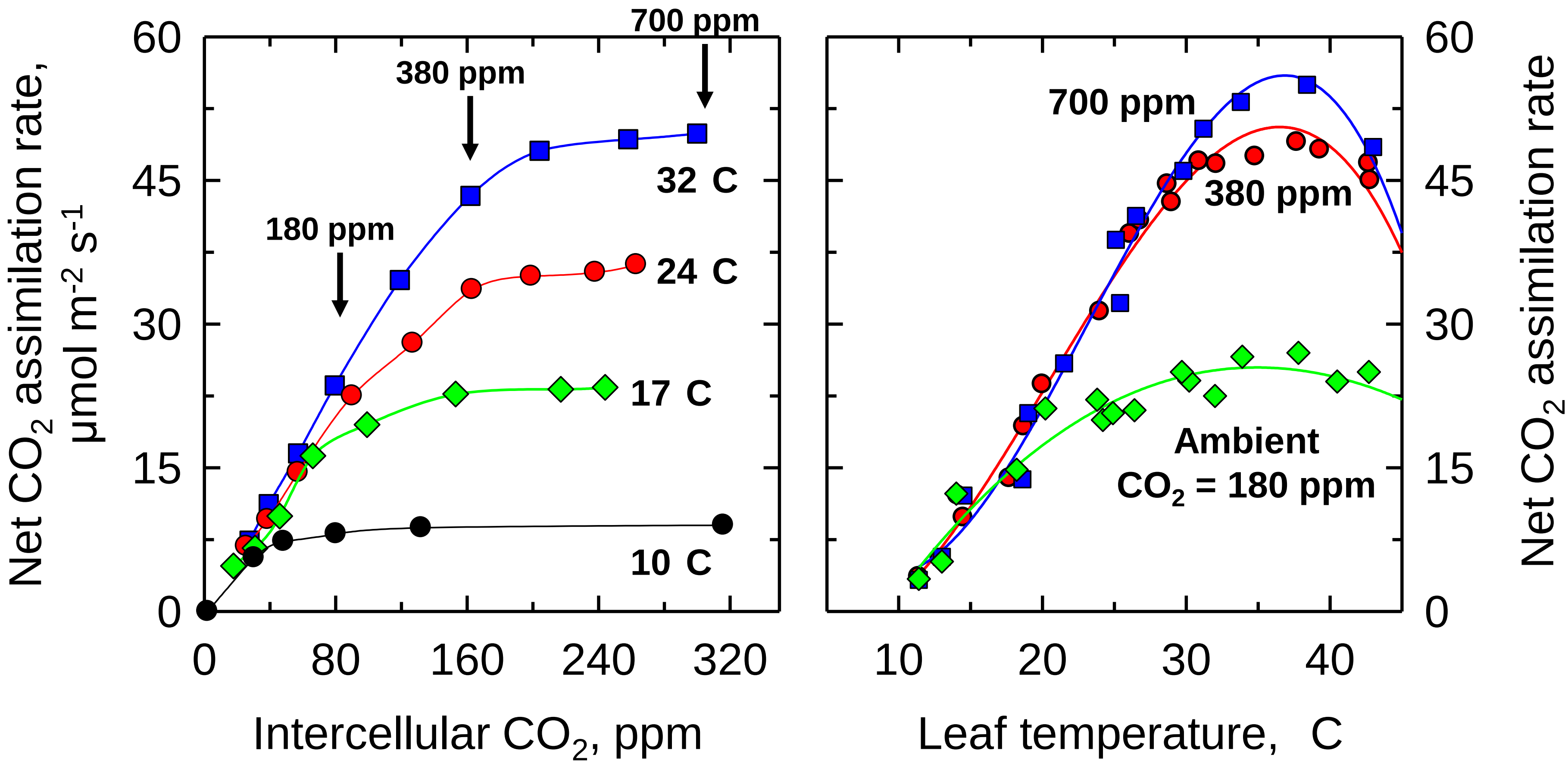
Biochemical models of C_4 photosynthesis predict

1) The initial slope of the CO_2 response of photosynthesis generally reflects the strength of the C_4 metabolic pump.

2) The CO_2 saturated plateau mainly reflect the strength of the C_3 cycle.

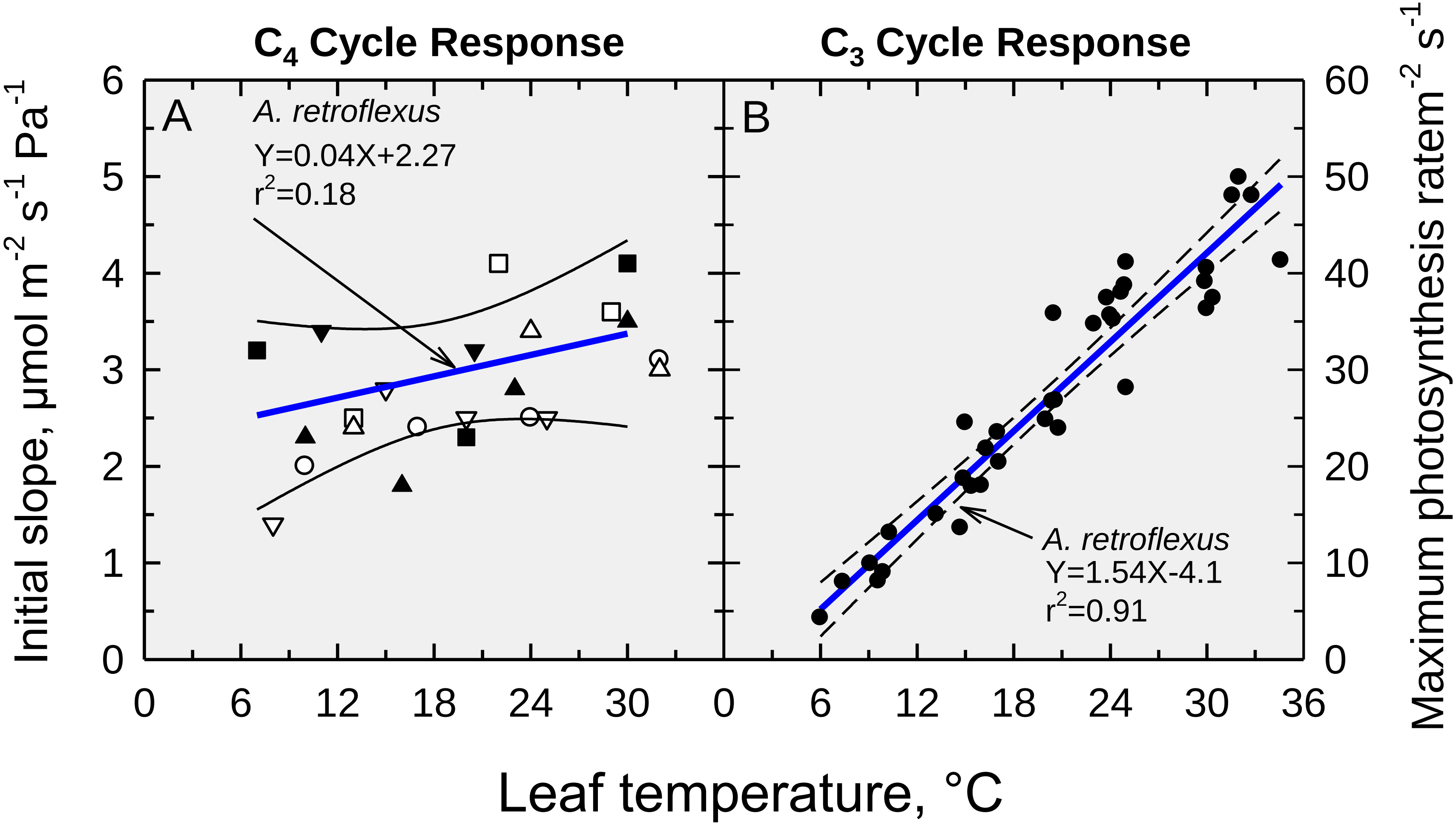
C_4 Photosynthetic Response to CO_2 and Temperature

Amaranthus retroflexus

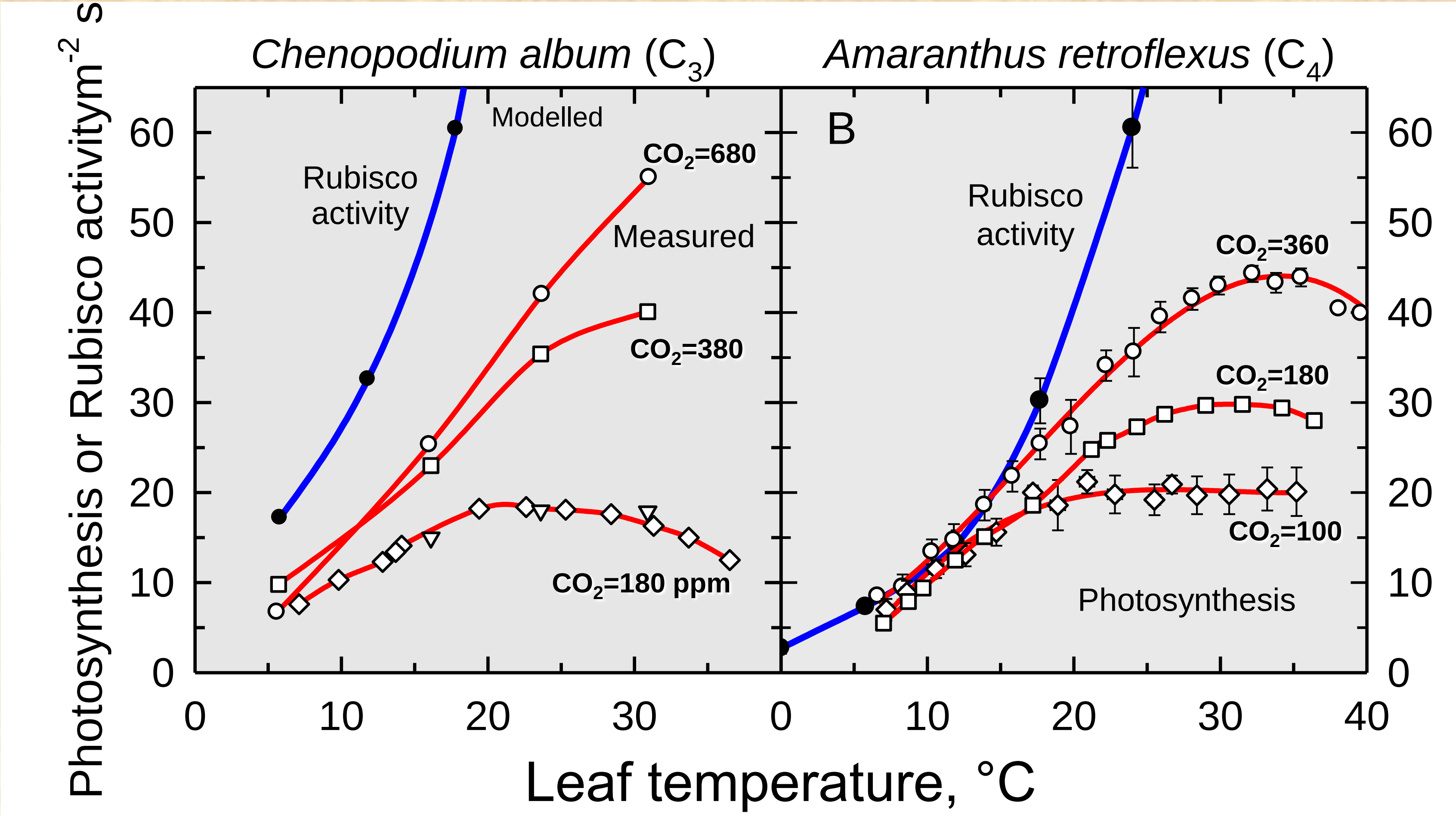


From Sage 2002 J. Exp Bot. 53:609; Sage and Pearcy 2000 Adv. Photosynthesis 9: 497.

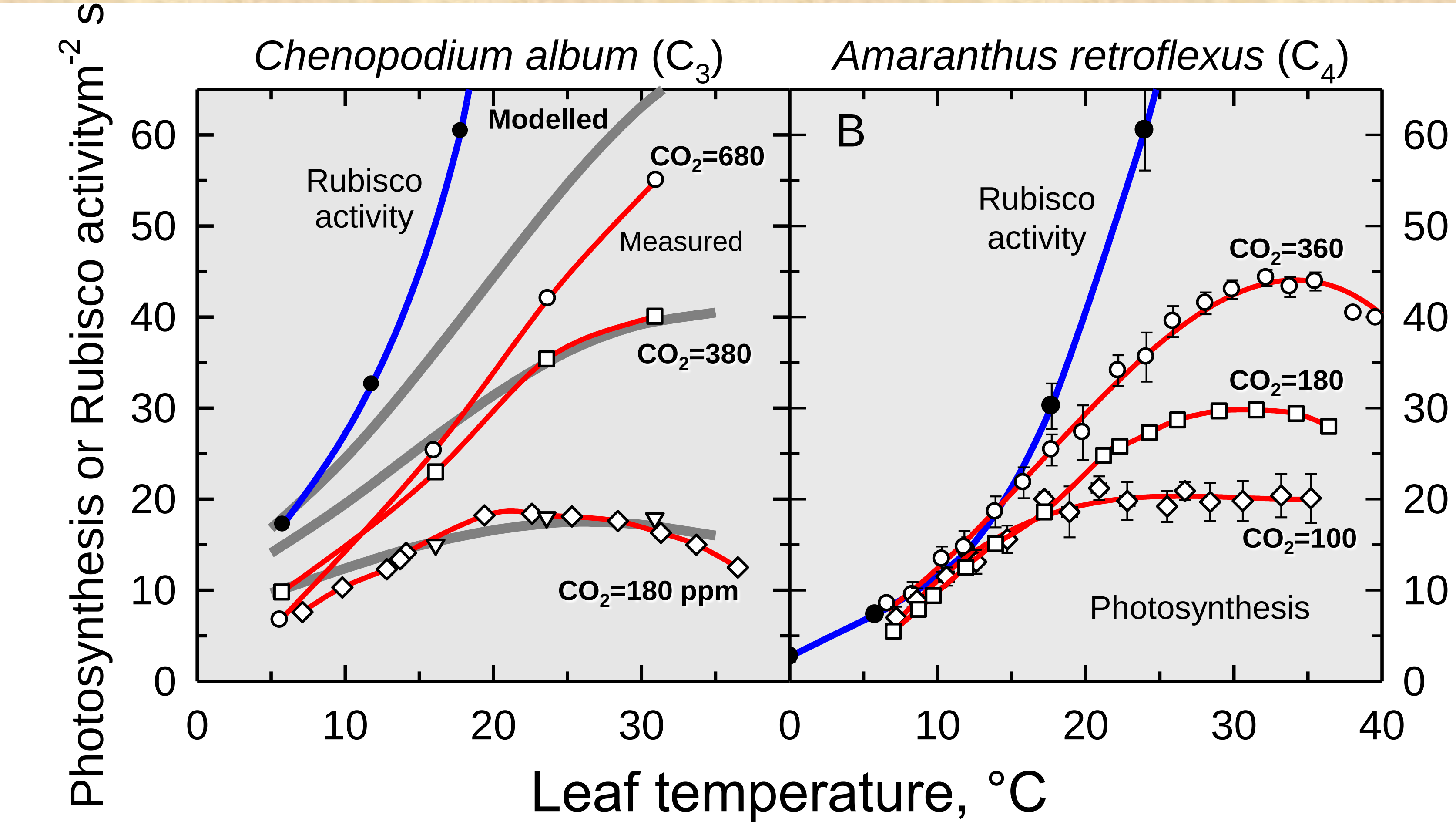
The Effect of Temperature on the Initial Slope and CO_2 Saturated Rate of C_4 Photosynthesis in *Amaranthus retroflexus*



Sage (2002) J. Exp. Bot 53:609

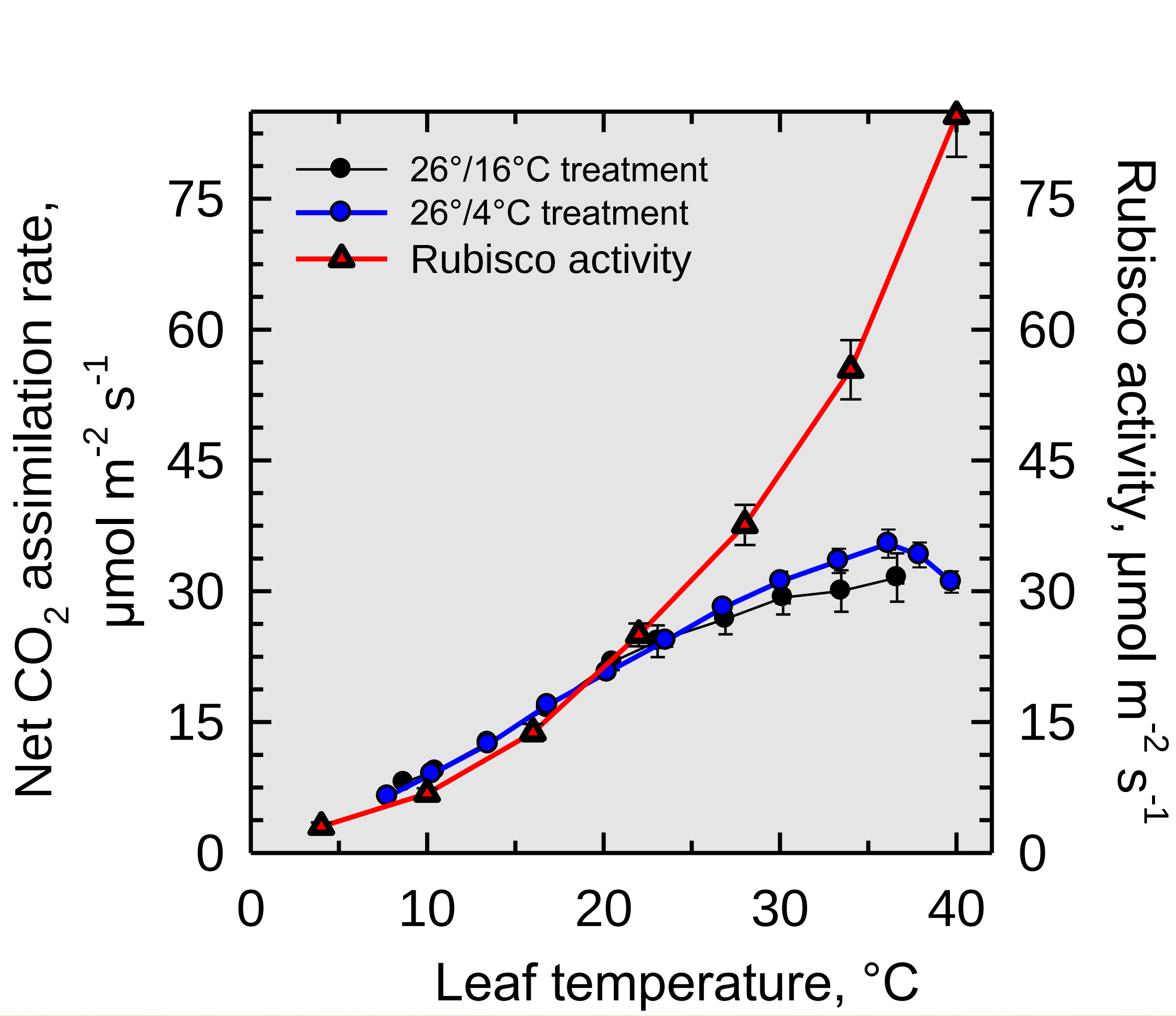


Sage (2002) J. Exp. Bot 53:609 -620



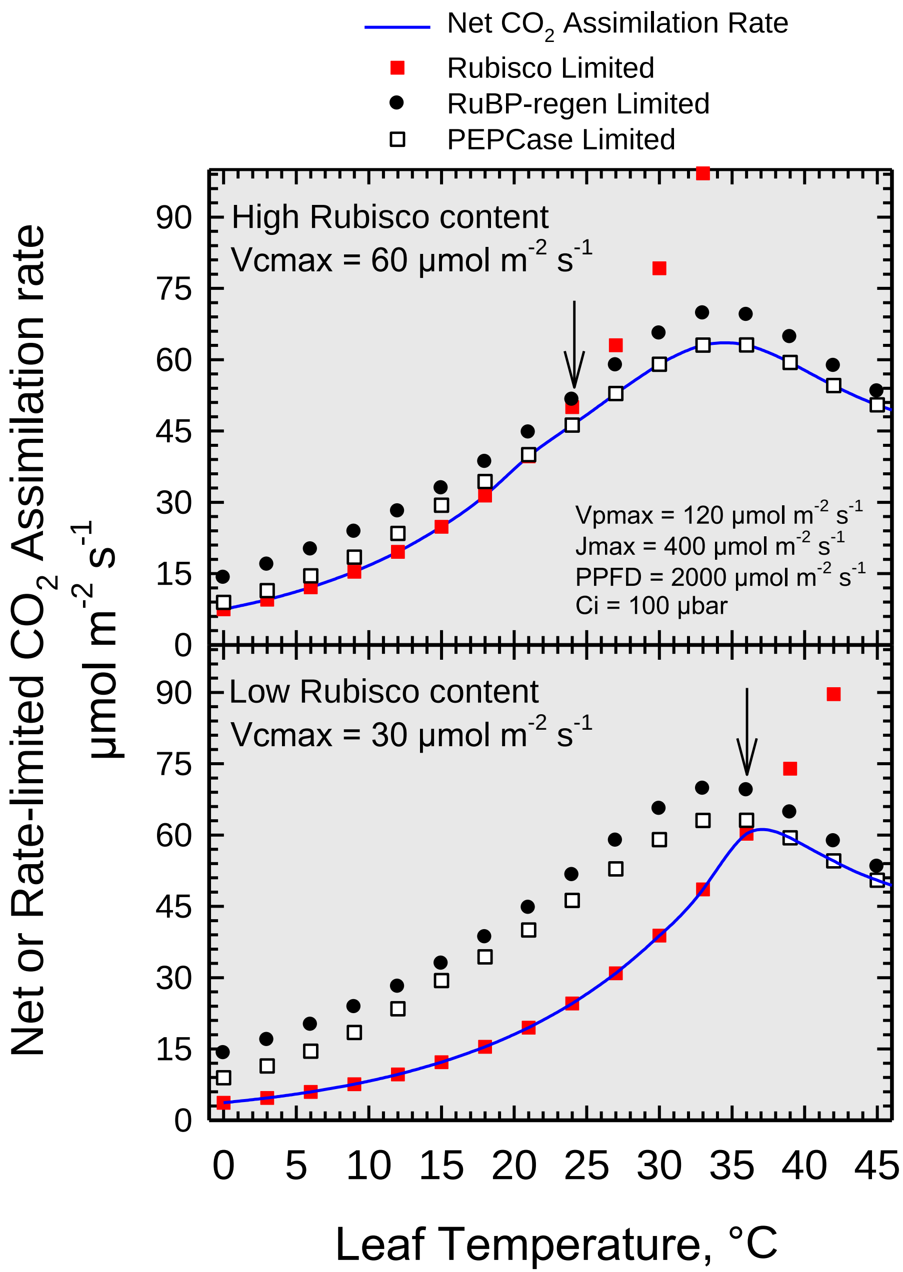
Sage (2002) J. Exp. Bot 53:609 -620

Photosynthetic Acclimation to Temperature in *Muhlenbergia montanum* A cold adapted C_4 grass from High Elevation



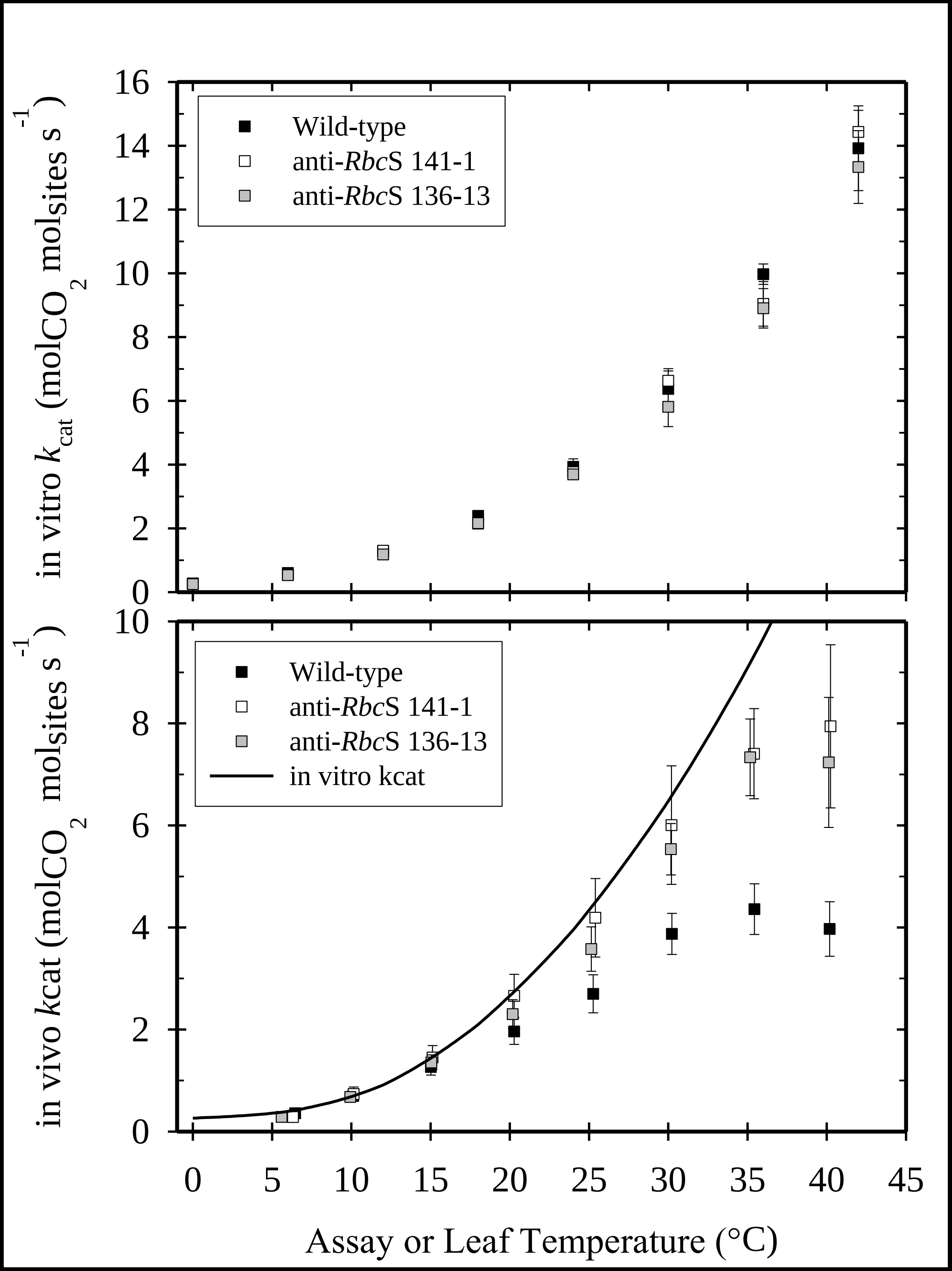
Pittermann and Sage (2001) J. Exp. Bot. 52:829-838

Modelled Temperature Response of C_4 Photosynthesis



Measured and Modelled Results from *Flaveria bidentis*

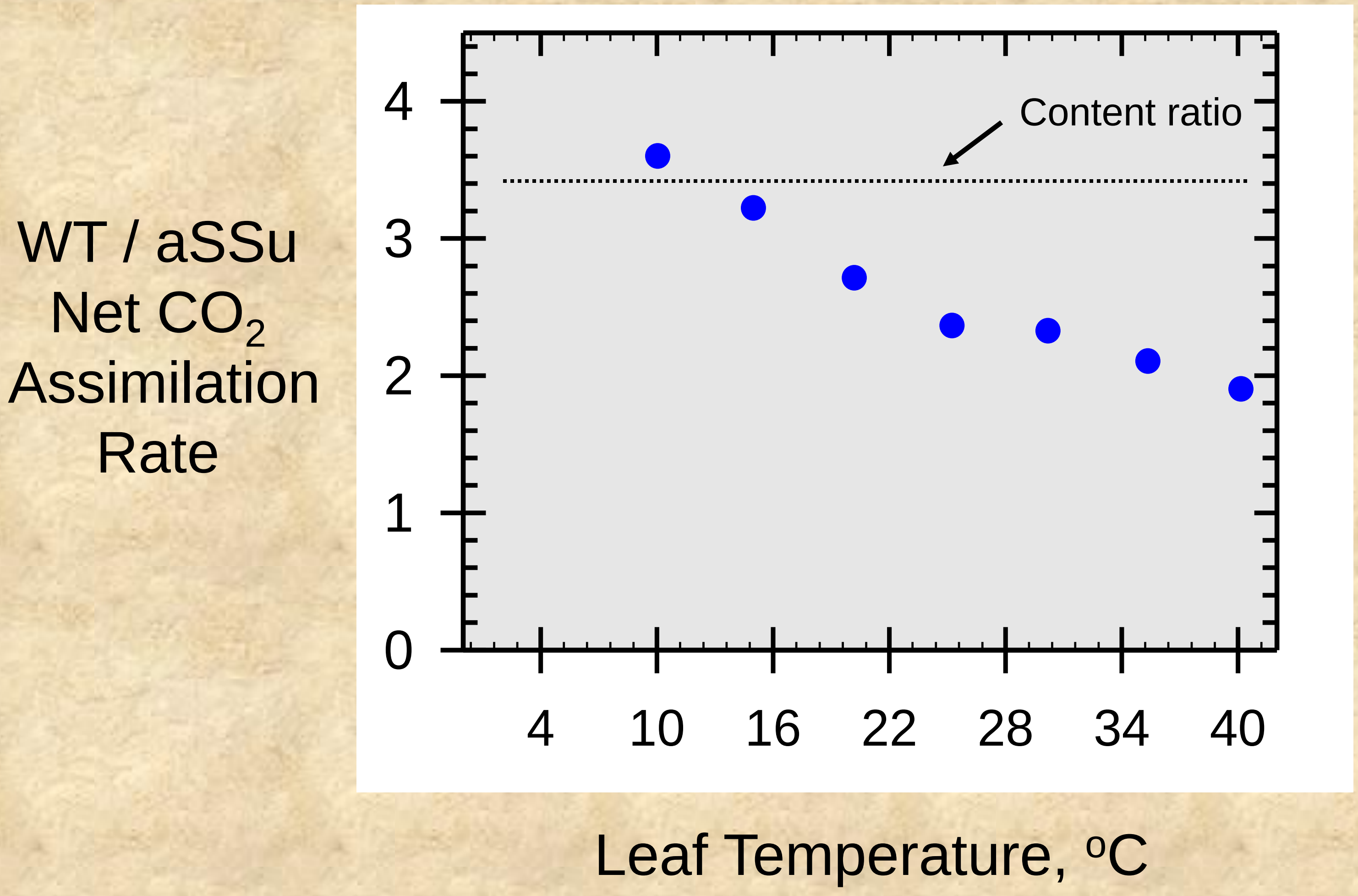
From Kubien, von Caemmerer, Furbank and Sage (2003) Plant Physiology 132: 1577

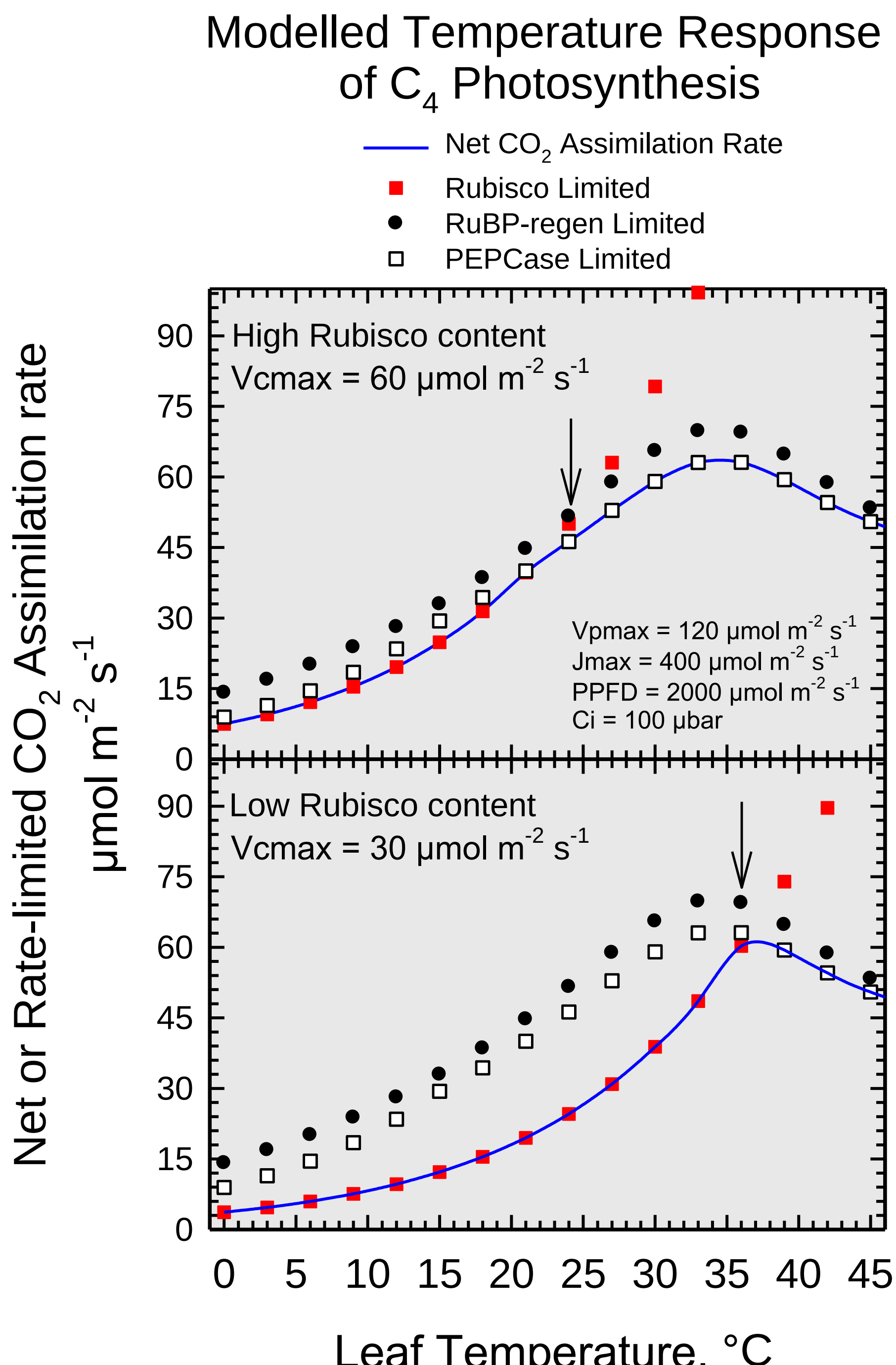


In vitro Rubisco K_{cat} equals in vivo Rubisco K_{cat} (gross CO_2 assimilation/Rubisco sites) rate in *Flaveria bidentis* at low temperature

From Kubien, von Caemmerer, Furbank and Sage Plant Physiology (in press)

The Net CO_2 Assimilation Rate of Wild type Relative to Rubisco-Antisense *Flaveria bidentis*





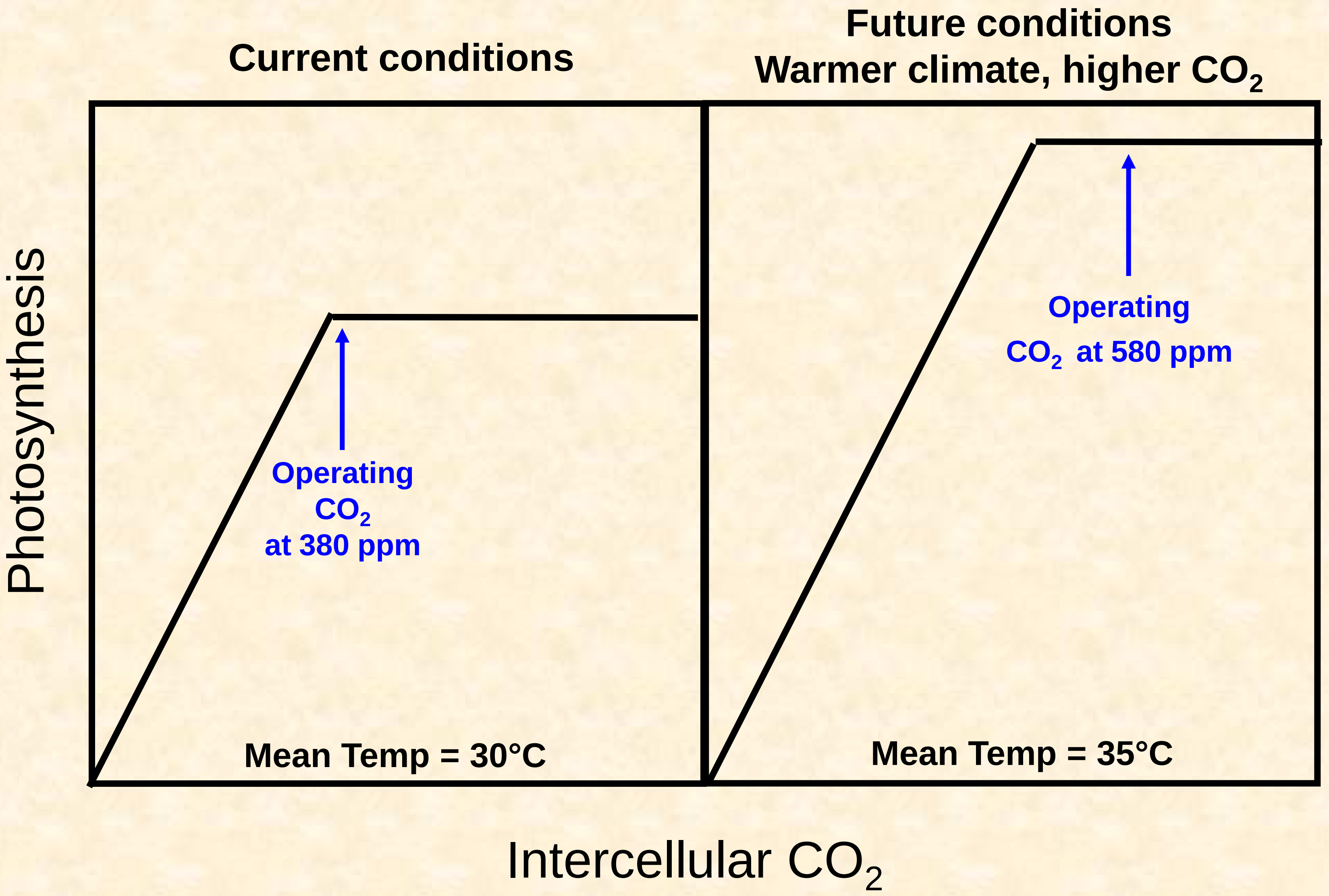
The Limitations on C_4 Photosynthesis Above the Thermal Optimum Are Not Clear.

Leading Proposals:

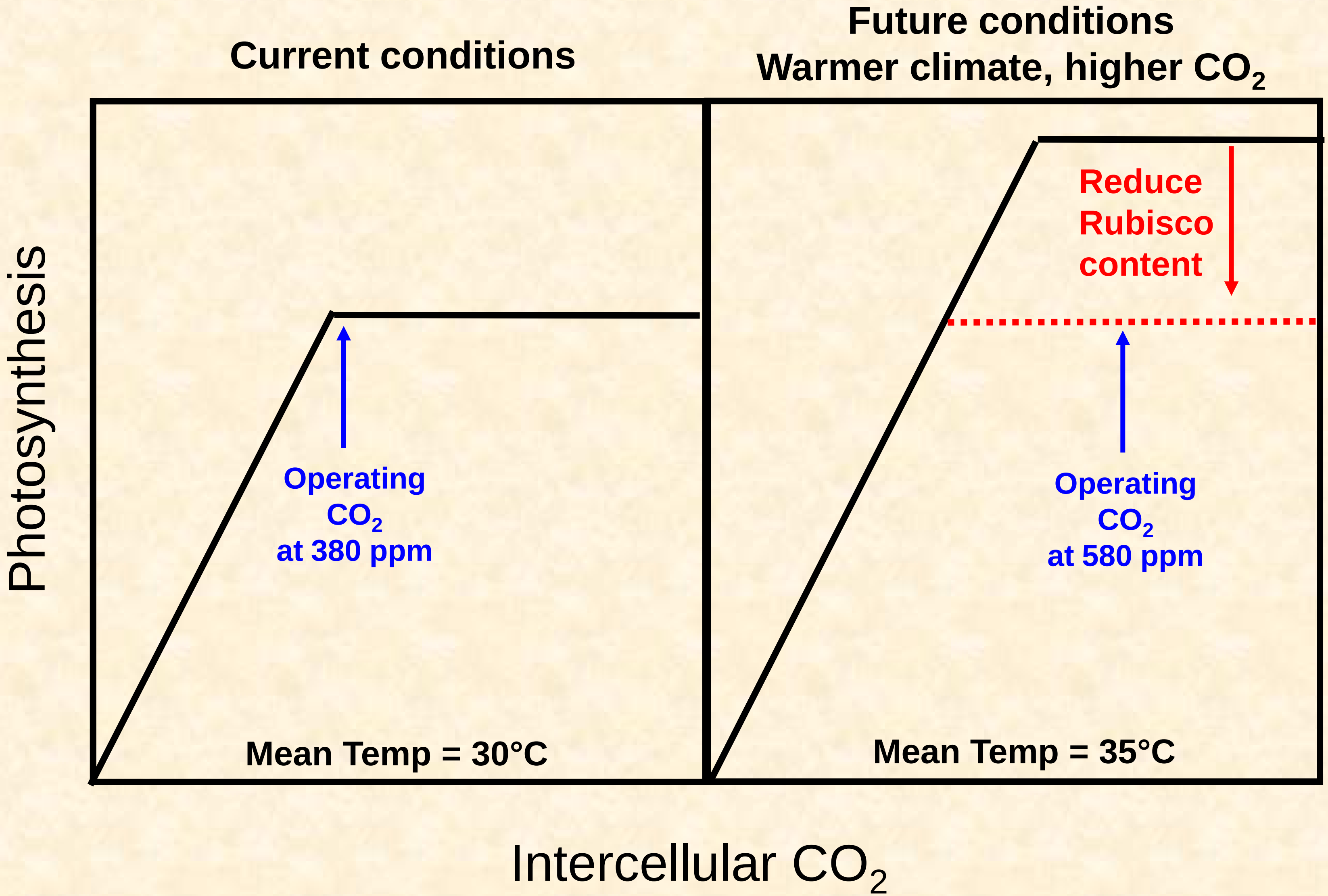
1) PEP carboxylation Capacity
2) Electron Transport
3) Rubisco activation state
4) PEP regeneration

It is not the capacity of Rubisco to consume RuBP.

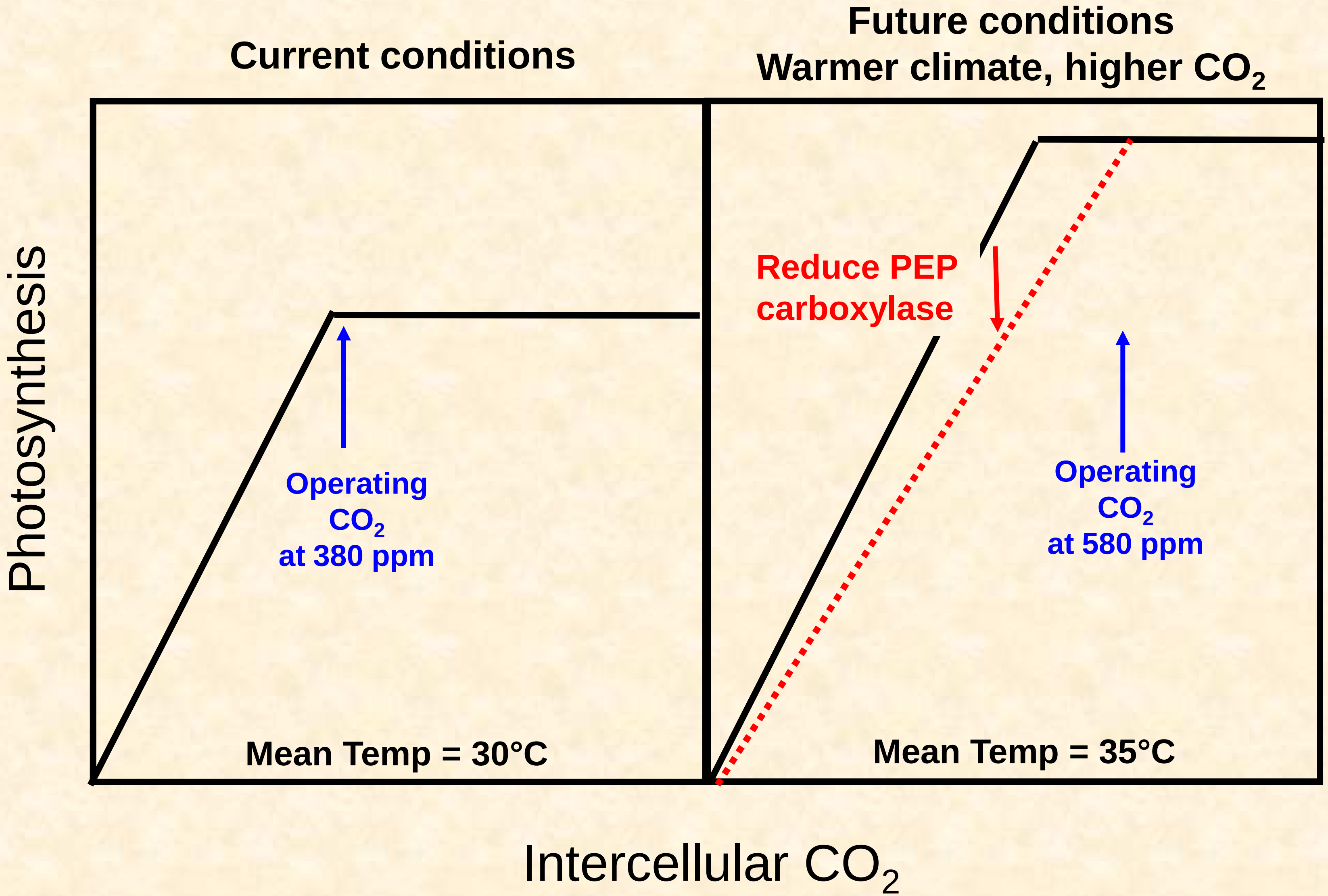
C_4 Photosynthesis Provides Many Options for Responding to Global Climate Change



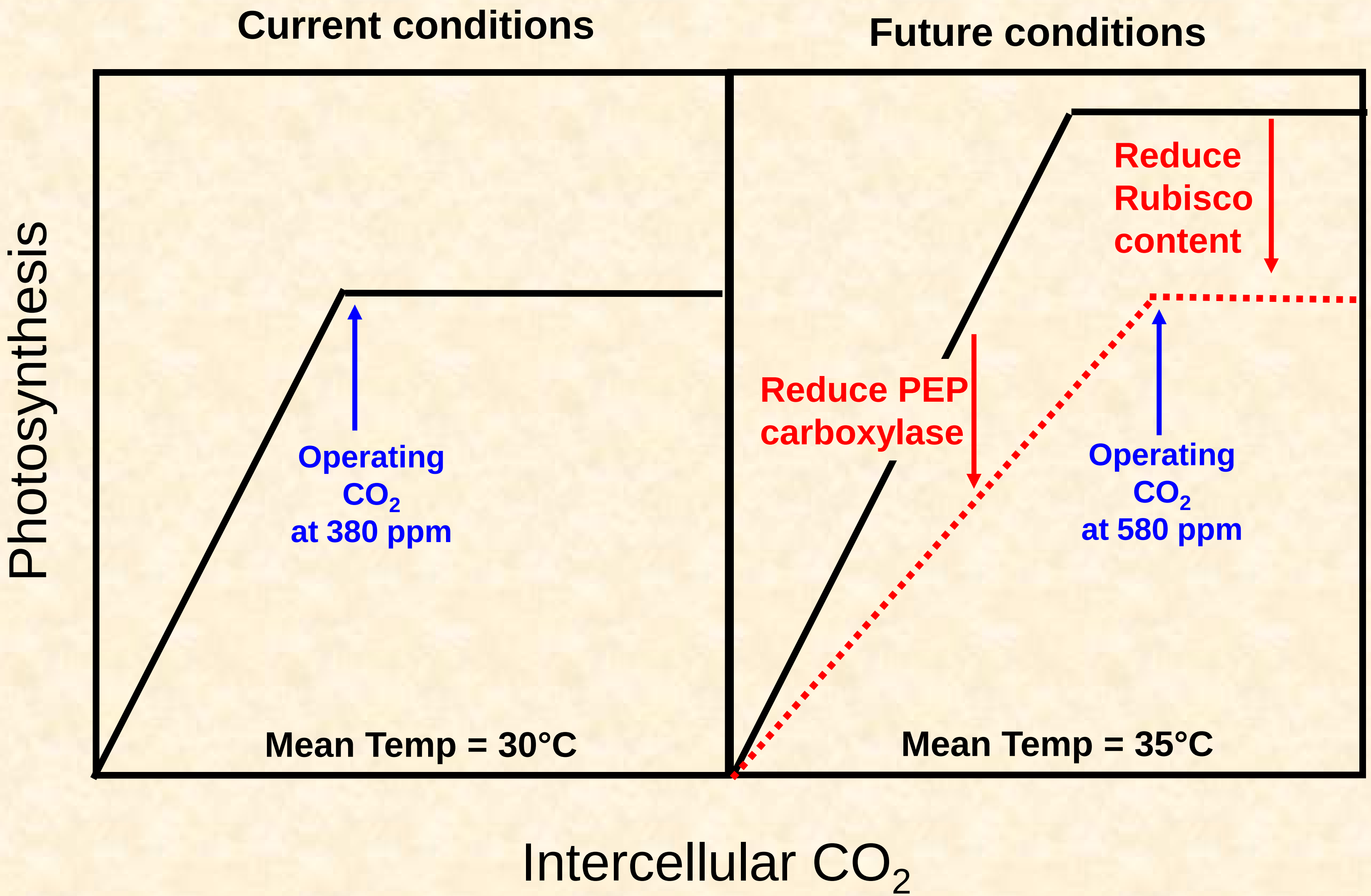
Scenario 1: Improve Nitrogen Use Efficiency by Reducing Rubisco Investment



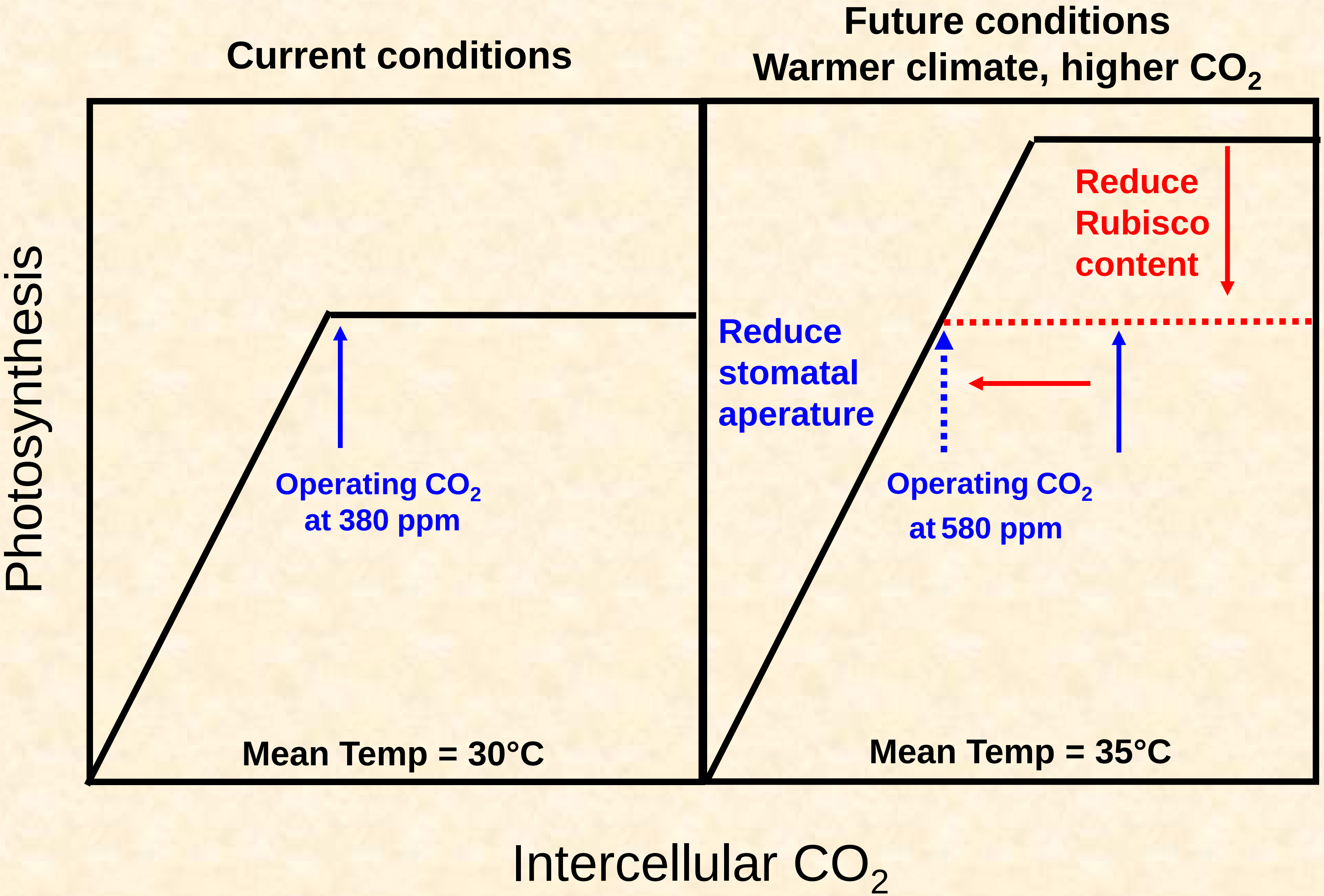
Scenario 2: Improve Nitrogen Use Efficiency by Reducing PEP Carboxylase Investment

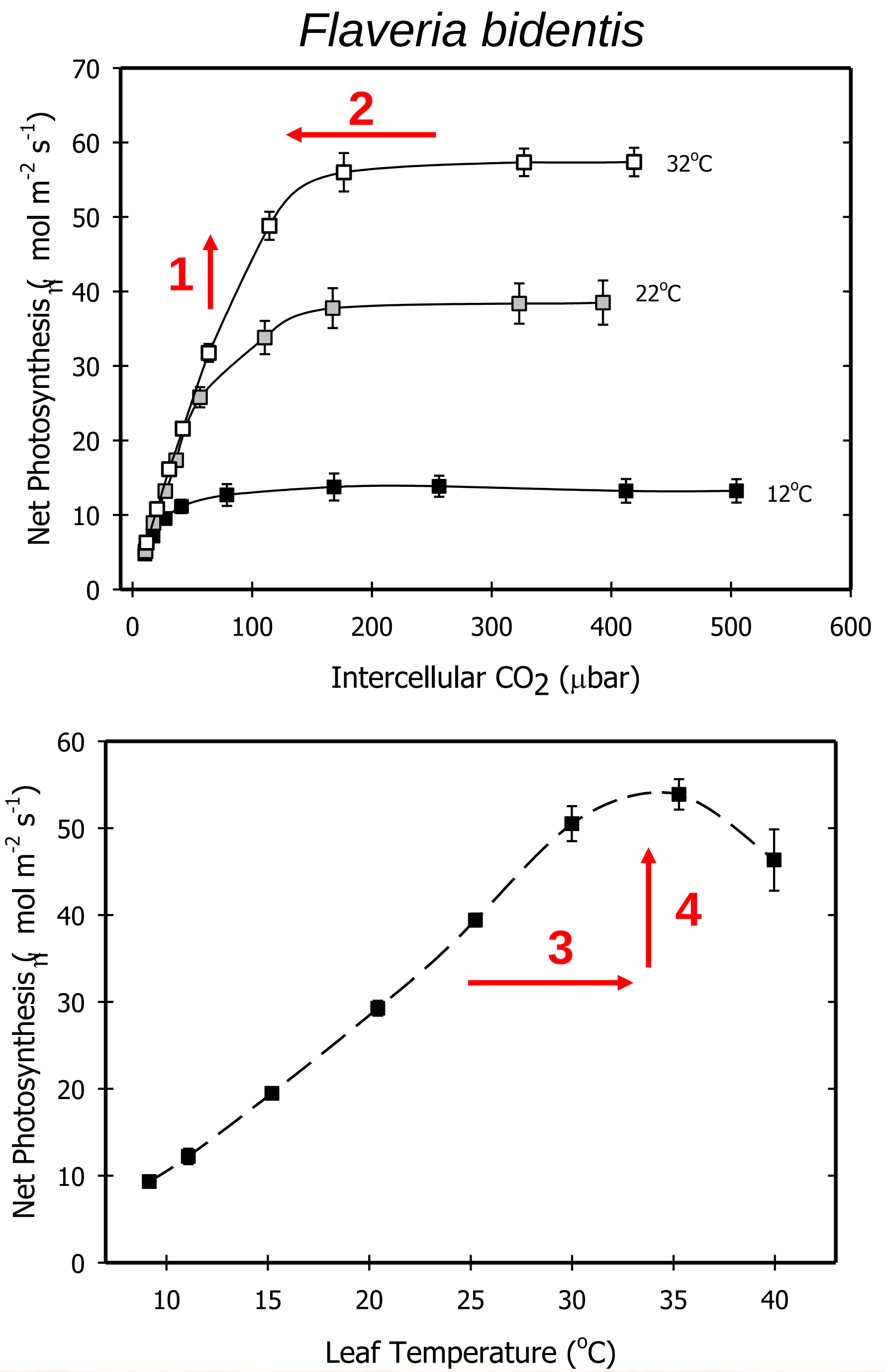


Scenario 3: Improve Nitrogen Use Efficiency by Reducing Both Carboxylases



Scenario 4: Improve Nitrogen Use Efficiency and Water Use Efficiency

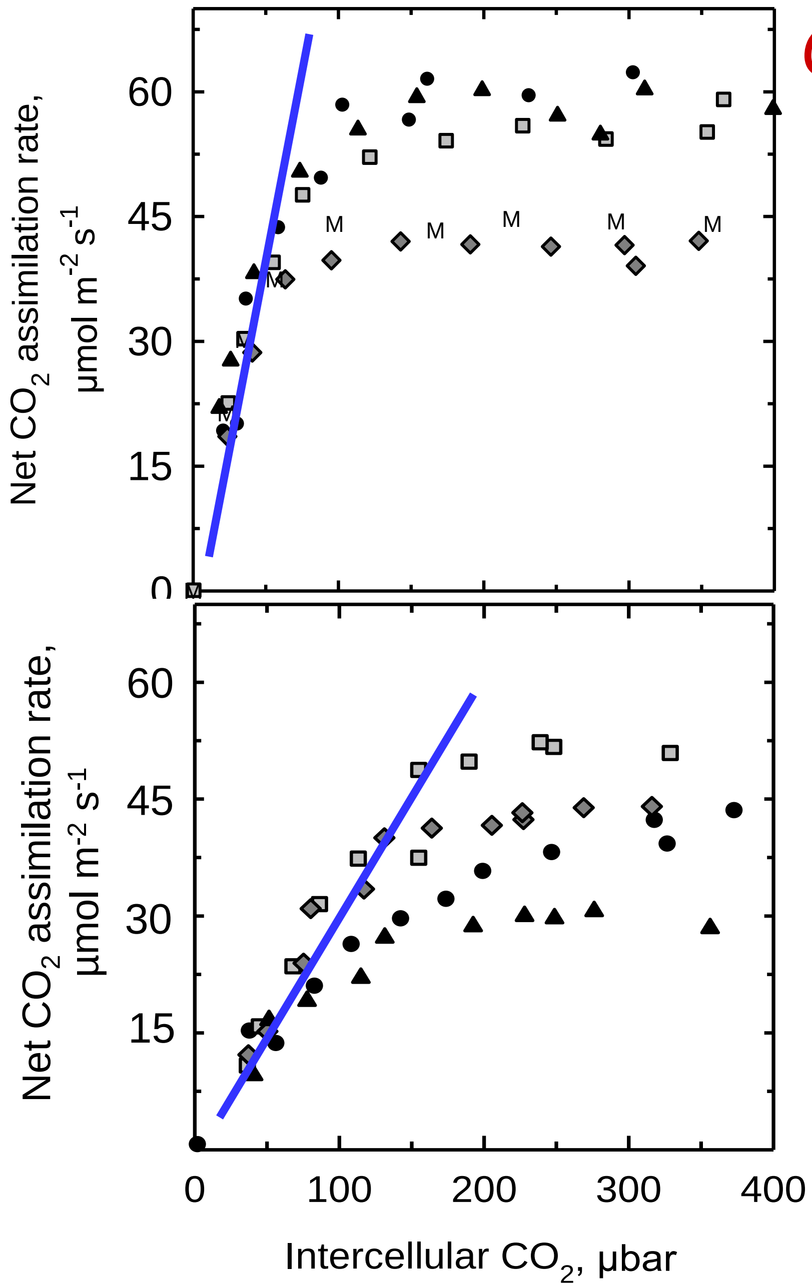




Scenario 5: Improve WUE and Photosynthesis

1. Increase the strength of the C_4 pump
2. Selectively reduce stomatal conductance and the operational CO_2
3. Lower transpiration saves water and increases canopy temperature
4. A warm canopy stimulates C_4 gas exchange
5. High photosynthesis maximizes light use efficiency

Gas Exchange Responses



Calligonum caput-medusae

Carboxylation efficiency (CE) 0.78 µmol m^{-2} s^{-1} $µbar^{-1}$

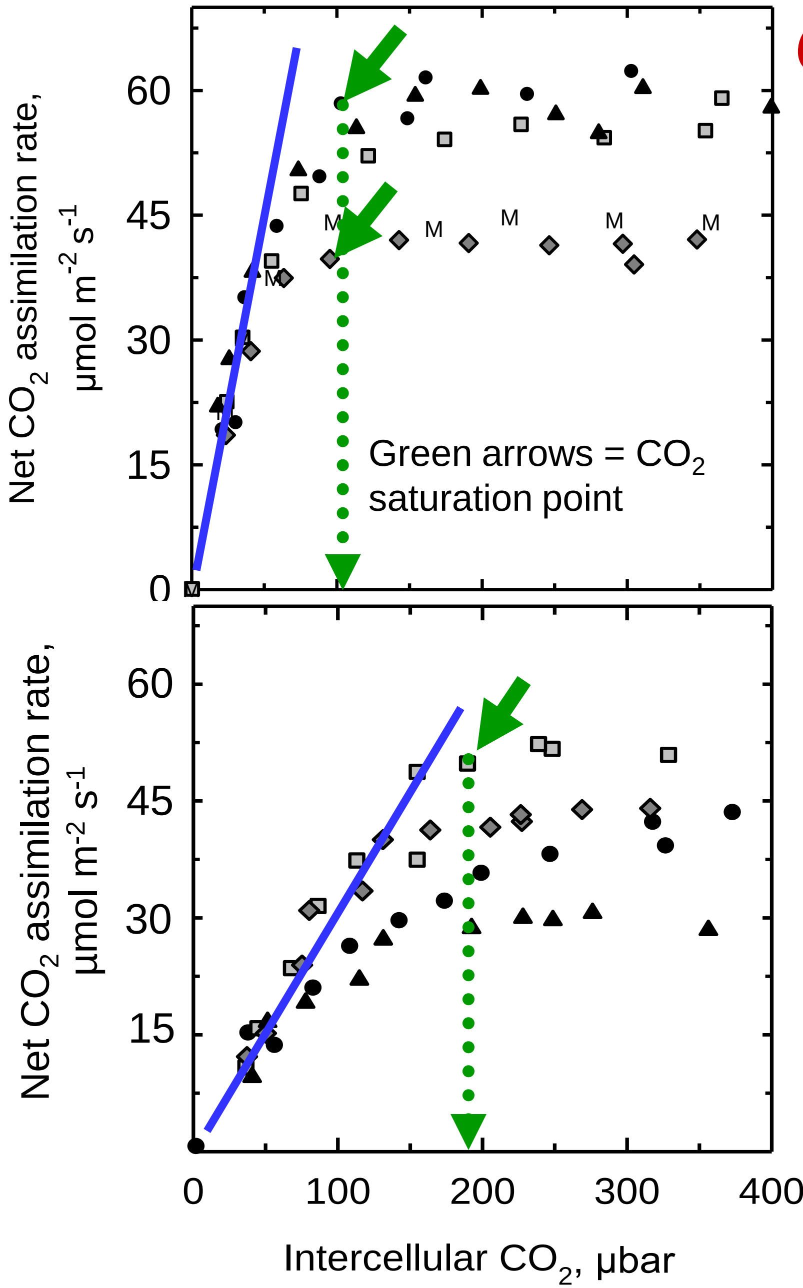
* Each symbol represents a separate individual, **M =** *C. microcarpum*

Haloxylon aphyllum

Carboxylation efficiency (CE) 0.31 µmol m^{-2} s^{-1} $µbar^{-1}$

Muhaidat, Dengler and Sage, in prep

RESULTS: A. Gas-exchange:



Calligonum caput-medusae

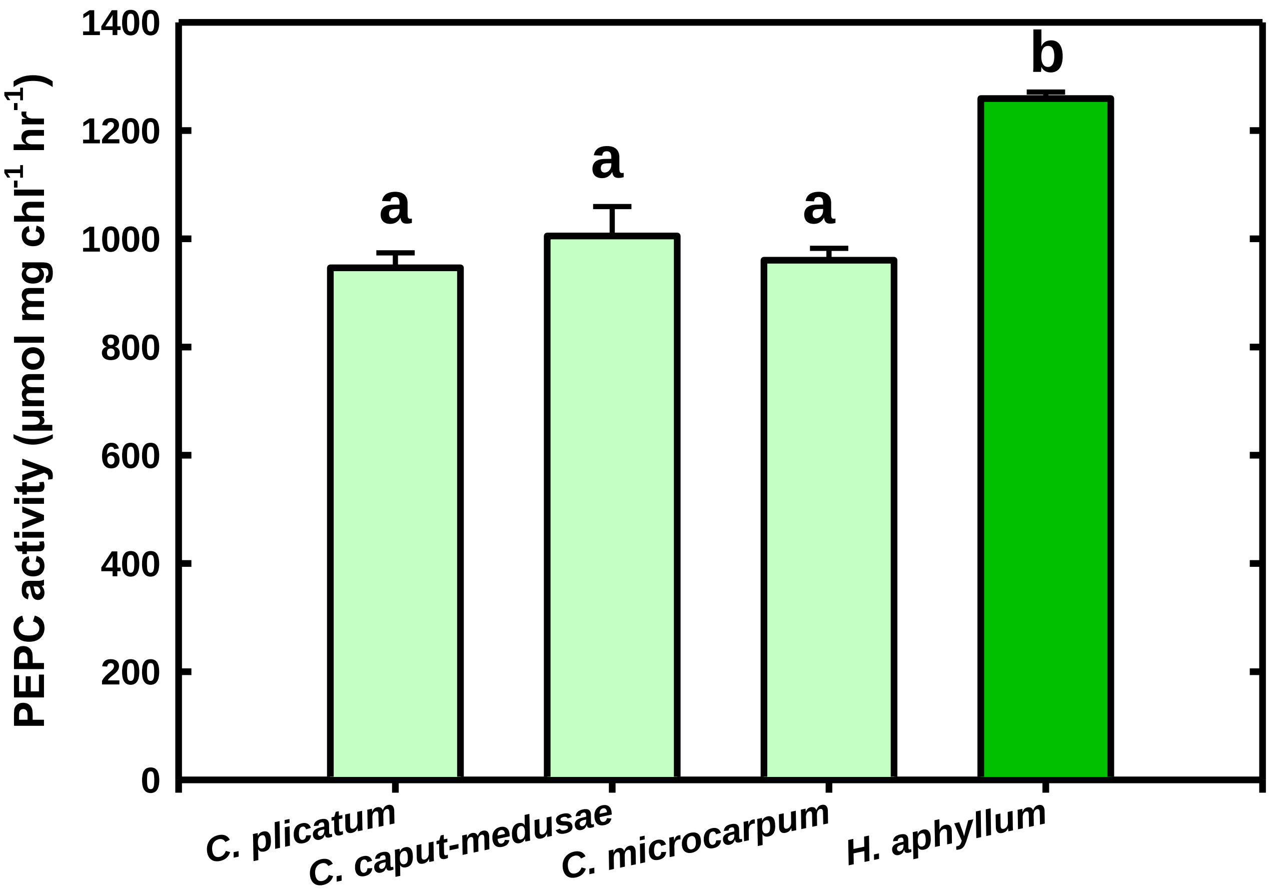
Calligonum is more effective than *Haloxylon* in concentrating CO_2 around Rubisco at limiting CO_2 levels

What might contribute to these differences?

Haloxylon aphyllum

(Muhaidat et al., in prep.)

PEP Carboxylase activity



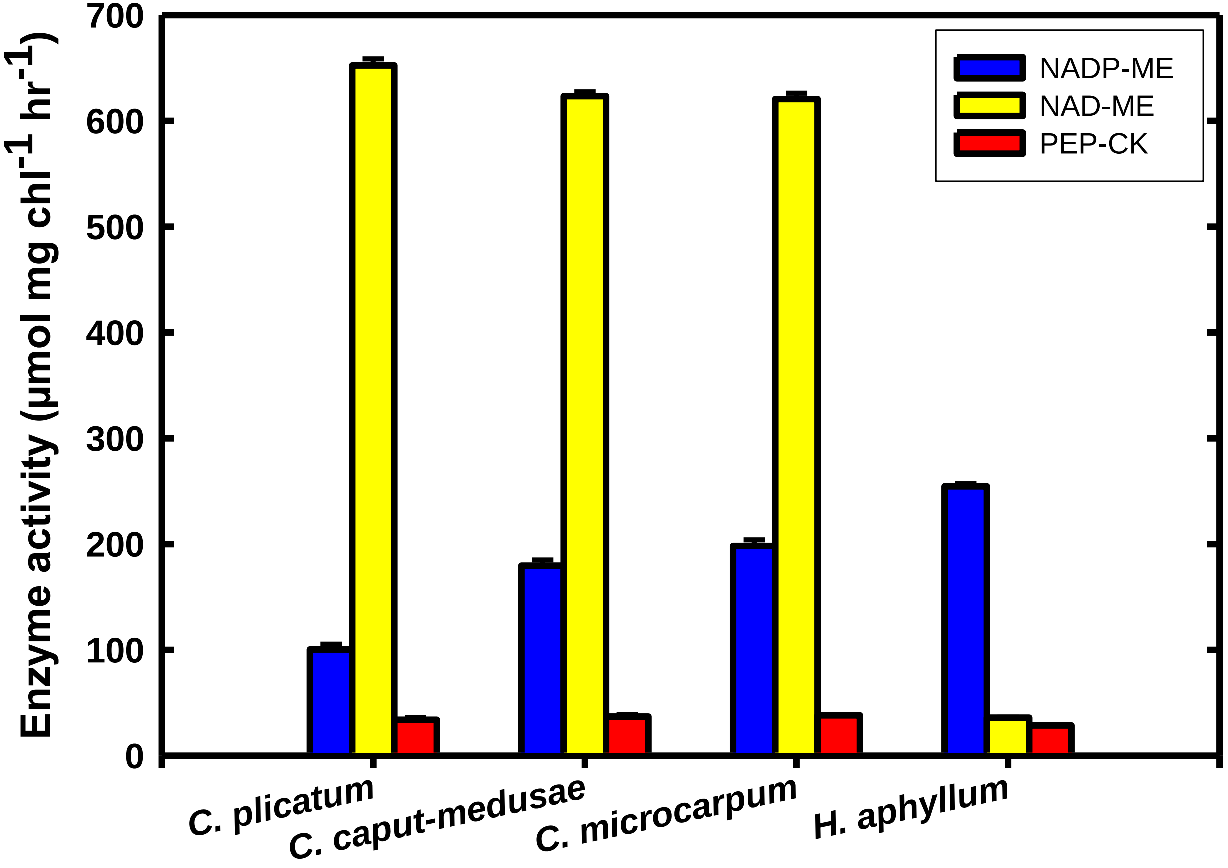
Calligonum **- light green**

CE = 0.78 µmol m^{-2} s^{-1} μbar^{-1}

Haloxylon **- Dark green**

CE = 0.31 µmol m^{-2} s^{-1} μbar^{-1}

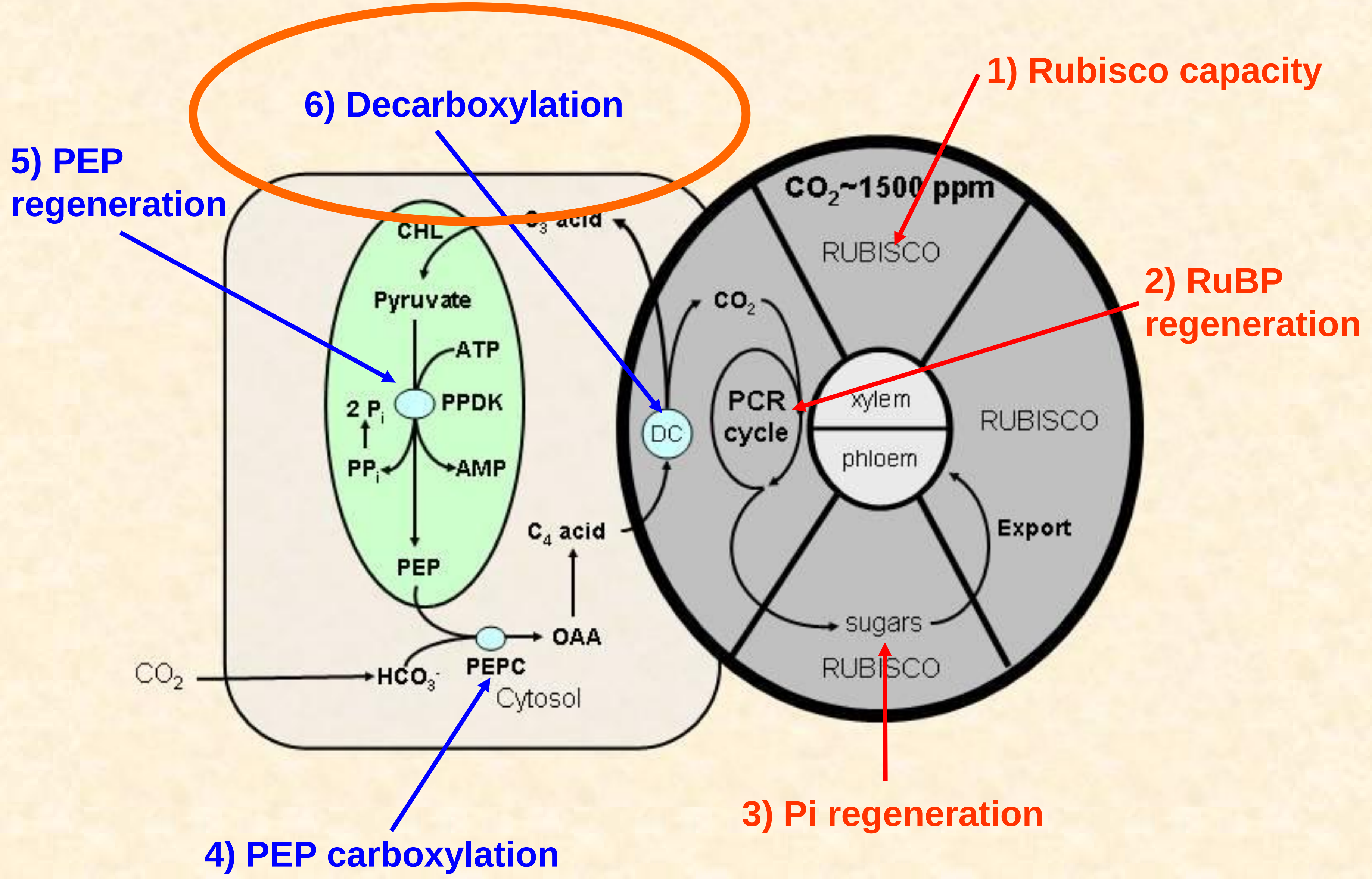
Activities of Decarboxylating Enzymes



(Muhaidat, Dengler and Sage, In prep

Potential Limitations on C_4 Photosynthesis

C_4 cycle limitations in blue, C_3 cycle limitations in red



Summary

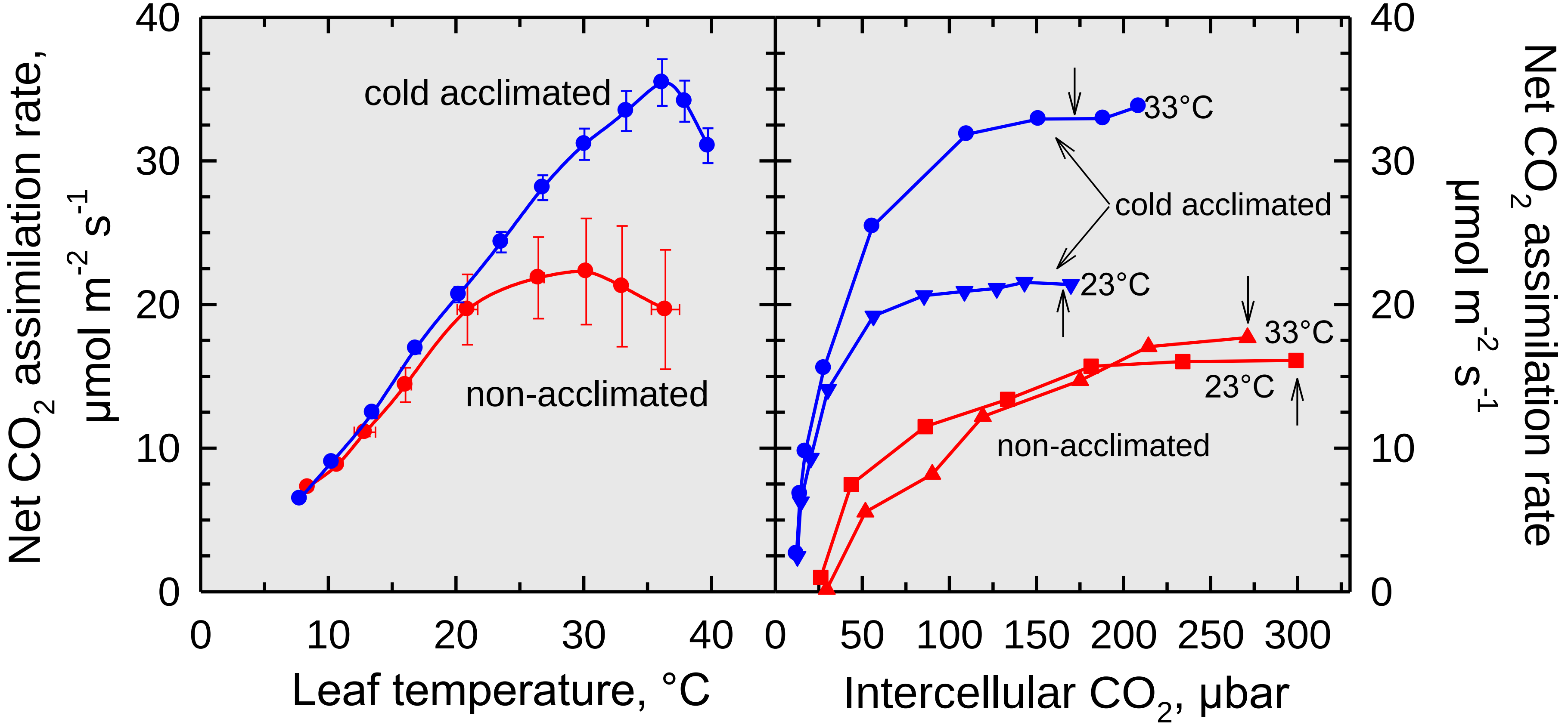
- C_4 photosynthesis is limited by Rubisco capacity at cooler temperatures, although short-term cold exposure can also impair PPDK.

- The limitation on C_4 photosynthesis at elevated temperature remains unclear.

- In a warmer, high CO_2 world, it is possible to improve WUE and NUE without impairing photosynthesis by manipulating enzyme contents in the C_3 and C_4 cycles of a C_4 crop such as sugar cane.

Many Thanks to David Kubien (on the left), my PhD student who worked on *Flavaria bidentis*

Photosynthetic Response following Transfer to Night Cold (4°C)
Muhlenbergia montanum



Pittermann and Sage (2001) J. Exp. Bot. 52:829-838

Cold-acclimation in *Miscanthus x giganteus* and cold-stress in *Zea mays*

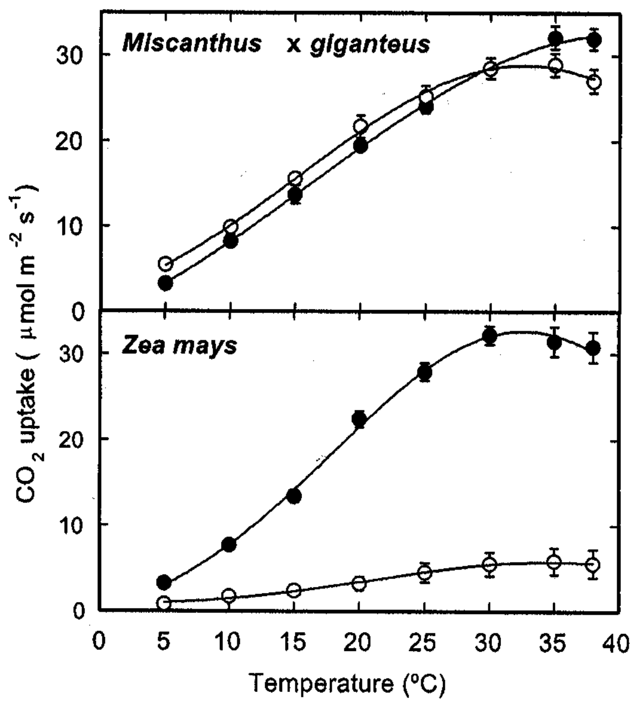


Figure 1. Temperature response of photosynthetic CO_2 uptake per unit leaf area for *M.* × *giganteus* and maize grown at 25°C/20°C or 14°C/11°C day/night temperatures. Error bars (±1 SE) of the mean (n = 8–15) are shown, except when smaller than the symbol size.

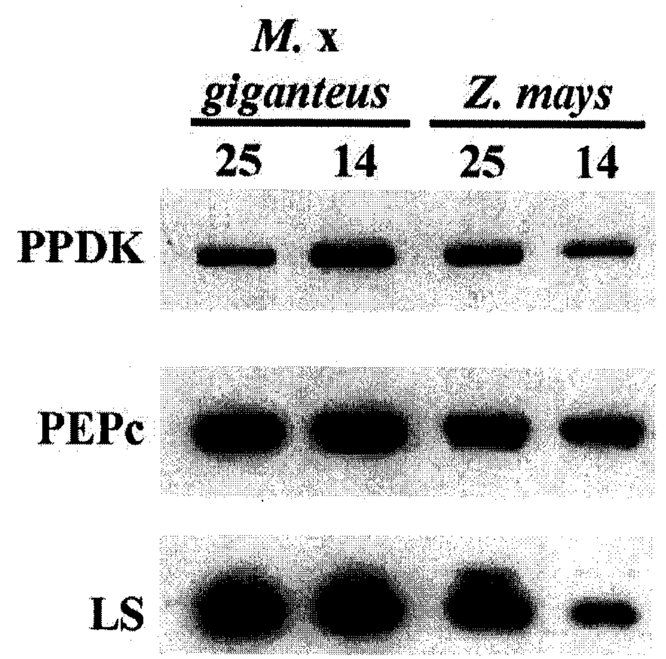
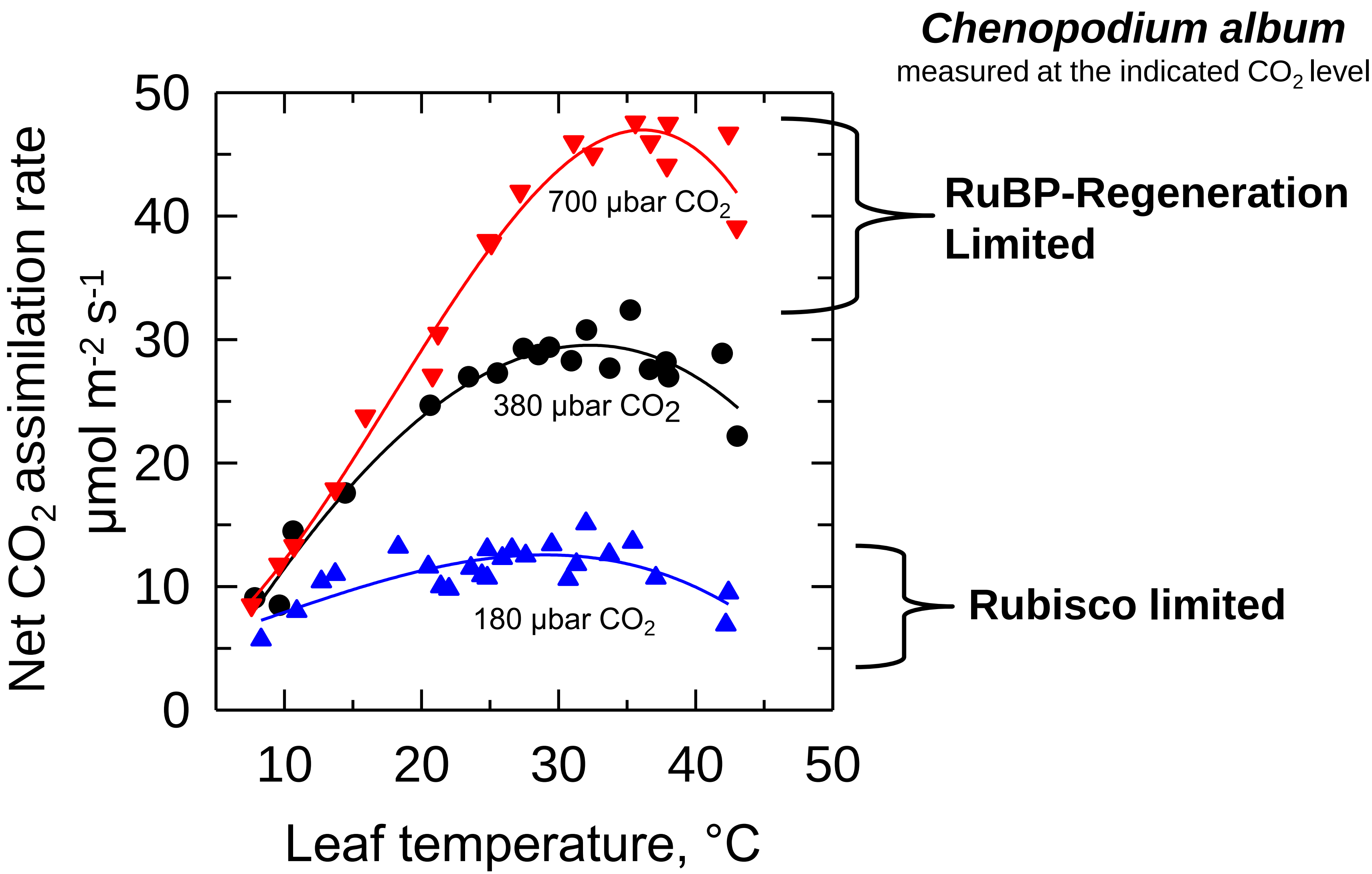
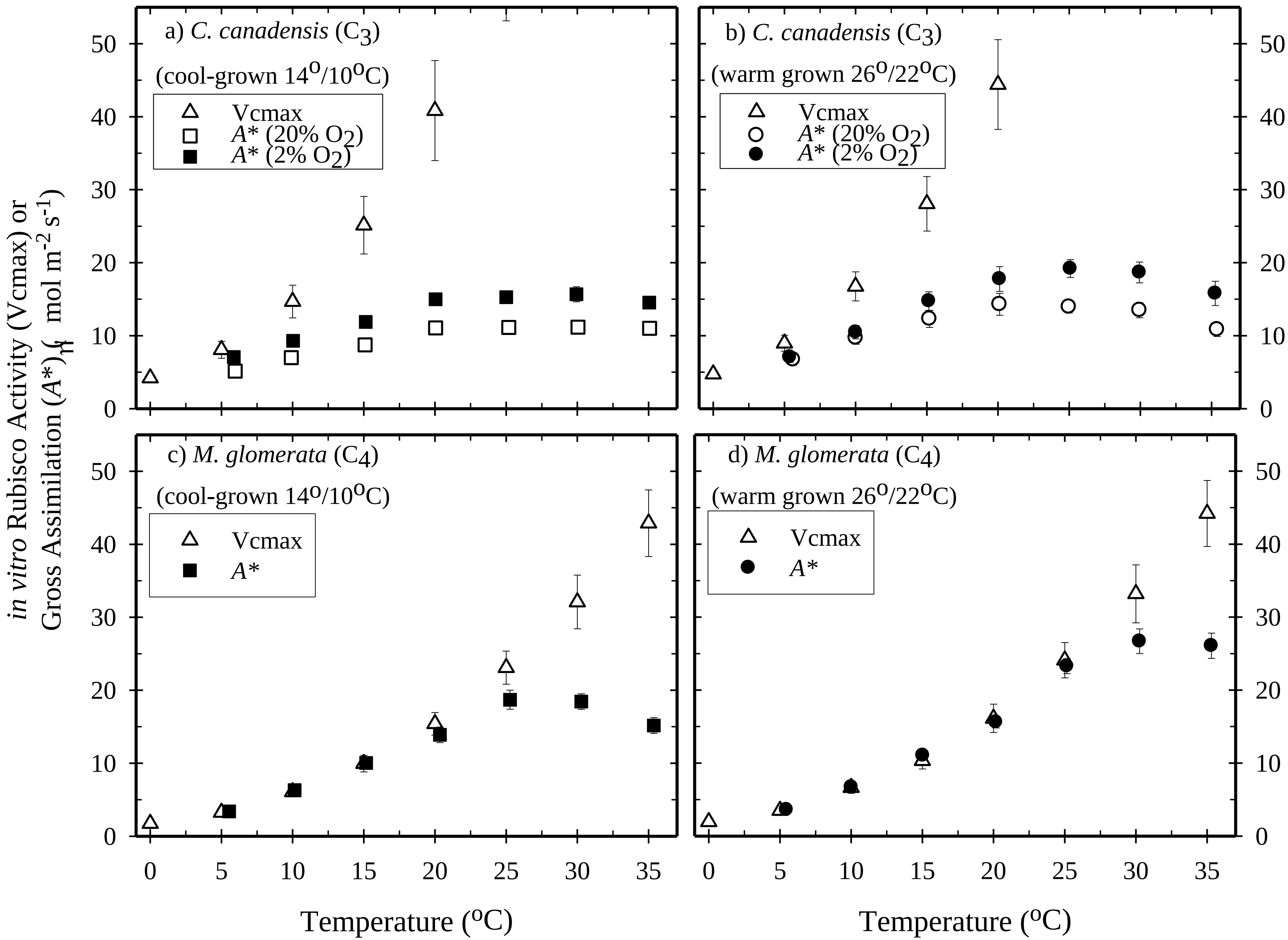


Figure 2. Sample western blot of PPDK, PEPc, and the large subunit of Rubisco (LS) extracted from *M.* × *giganteus* and maize leaves grown at 25°C/20°C or 14°C/11°C day/night temperatures. Samples were loaded on an equal leaf area basis.

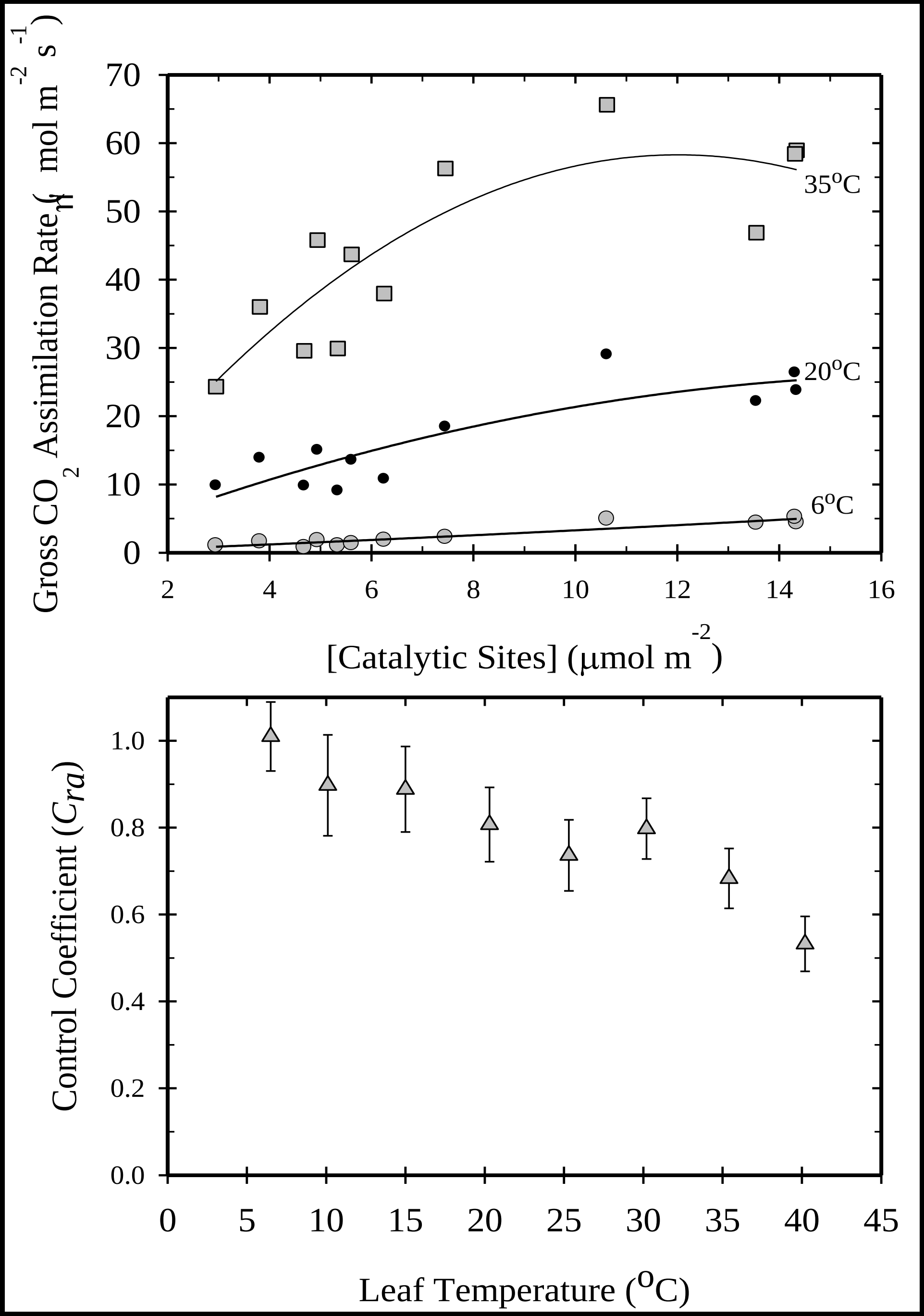
Naidu, Moose, Al-Shoaibi et al. (2003) Plant Physiol. 132:1688

Possible Limitations on C_3 Photosynthesis at High and Low CO_2



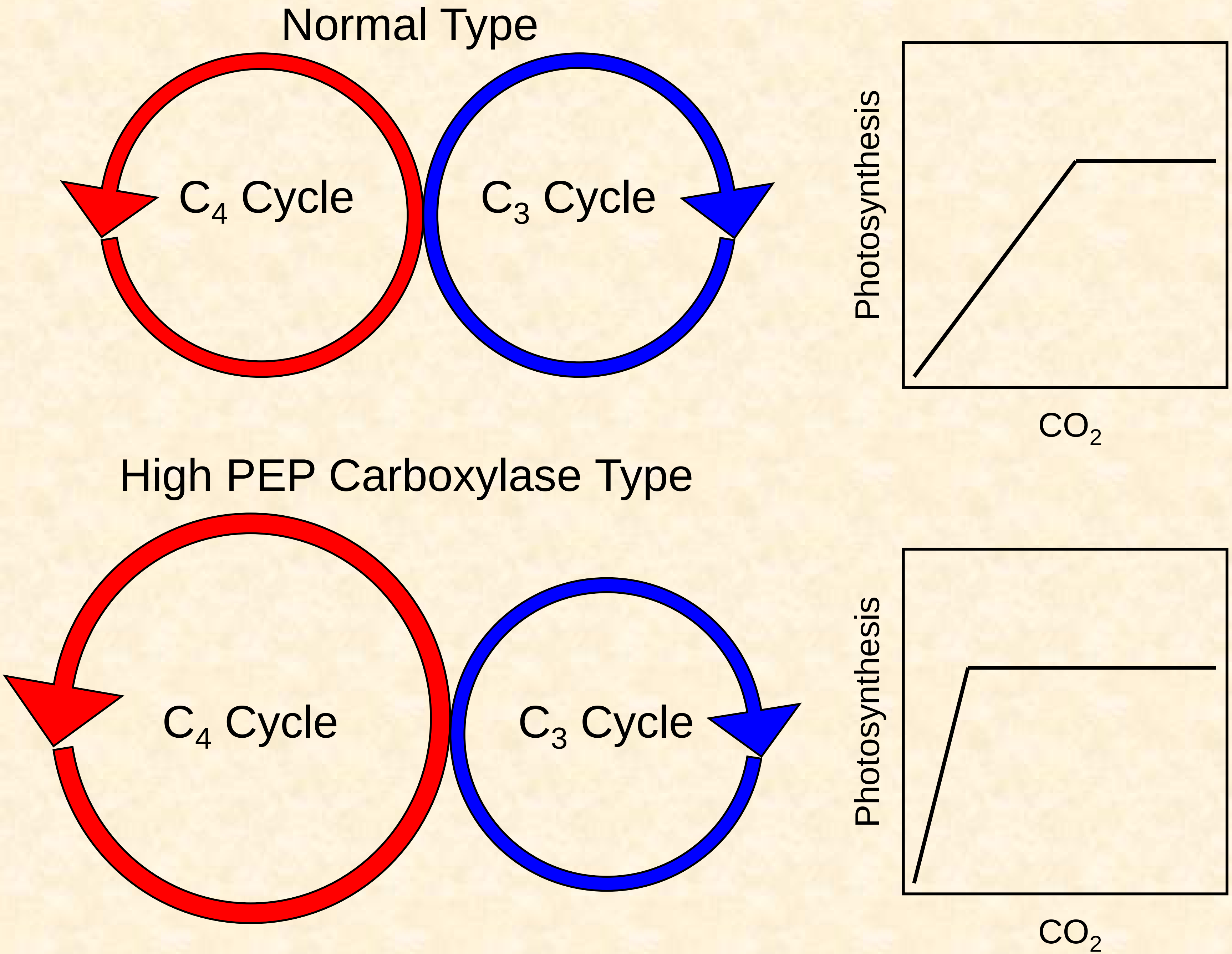


From Kubien and Sage (2004) Plant, Cell Environment 27:907



In *Flaveria bidentis*, control analysis using plants with an antisense Rubisco gene demonstrate the control Rubisco exerts over photosynthesis is great at low temperature in C_4 plants

From Kubien, von Caemmerer, Furbank and Sage (2003) Plant Physiology 132: 1577


Normal Type
C_4 Cycle
C_3 Cycle
Photosynthesis
CO_2
High PEP Carboxylase Type
C_4 Cycle
C_3 Cycle
Photosynthesis
CO_2