ROLE OF MINERAL NUTRITION IN ALLEVIATING DETRIMENTAL EFFECTS OF ENVIRONMENTAL STRESSES ON CROP PRODUCTION

by

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HUGE INCREASES IN WORLD POPULATION

FOOD SECURITY

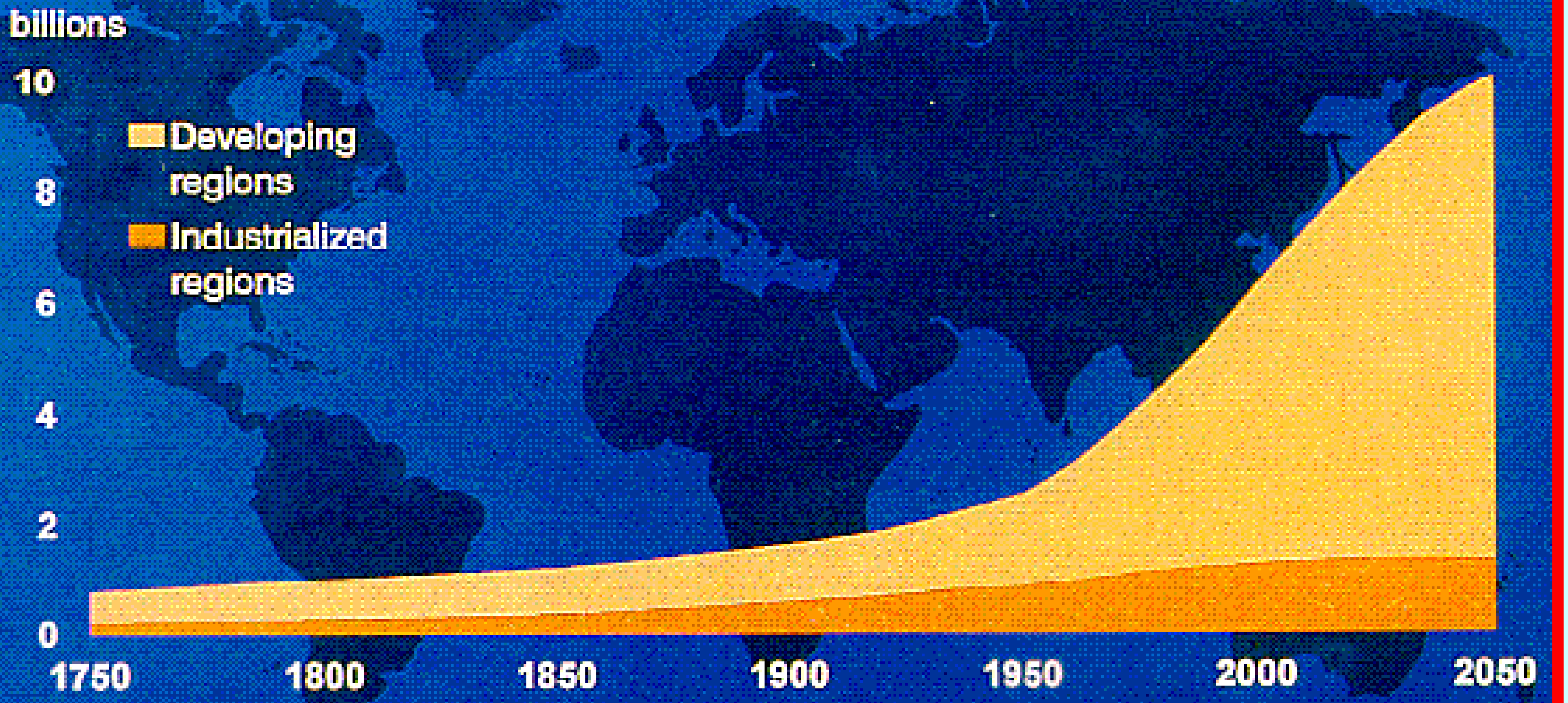
The world population is expanding rapidly and will likely be 10 billion by the year 2050. Limited availability of additional arable land and water resources, and the declining trend in crop yields globally make food security a major challenge in the 21st century.

According to the projections, food production on presently used land must be doubled in the next two decades to meet food demand of the growing world population.

> **“1 out of 4 people in line at a soup kitchen is a child.”**
> *From Hunger in America 2001*

The projected increase in food production must be accomplished on the existing cultivated areas because the expansion of new land is limited.

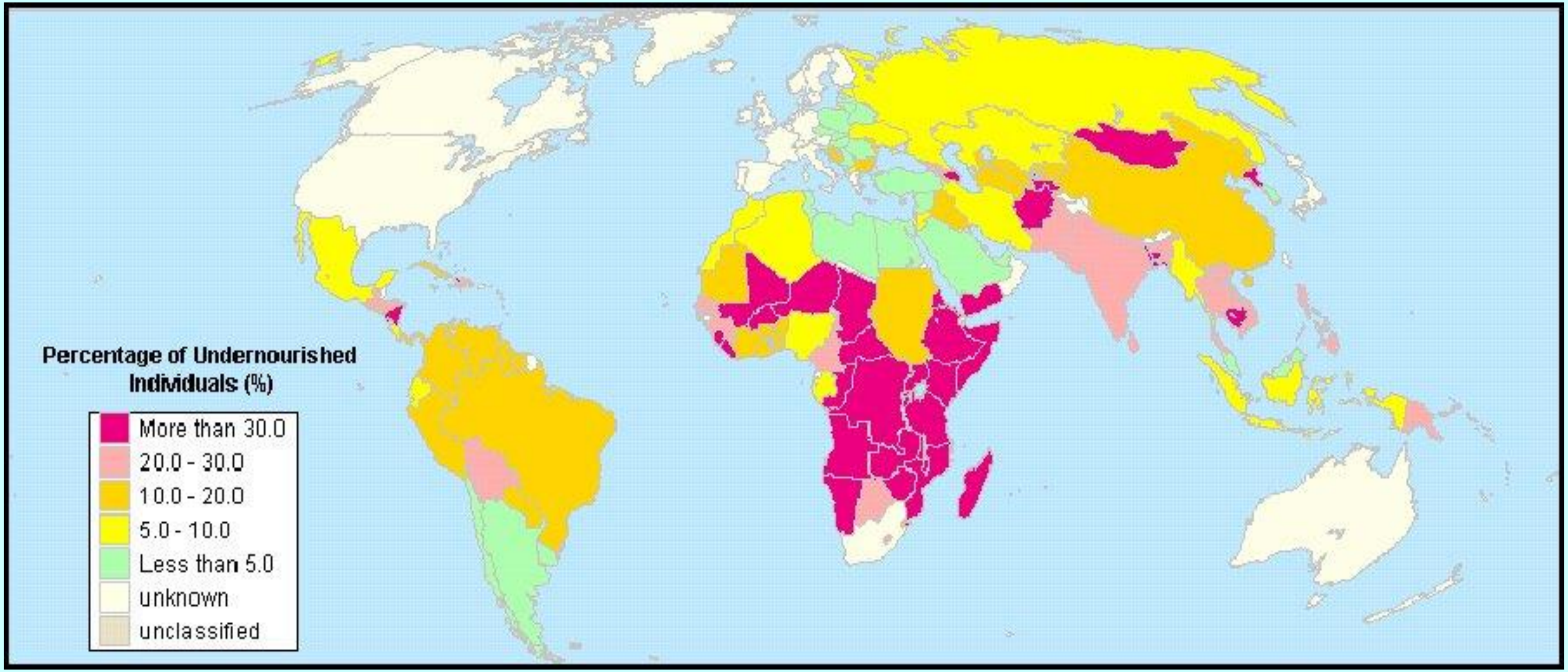
World Population Growth



Sources: United Nations Population Division and Population Reference Bureau, 1993.

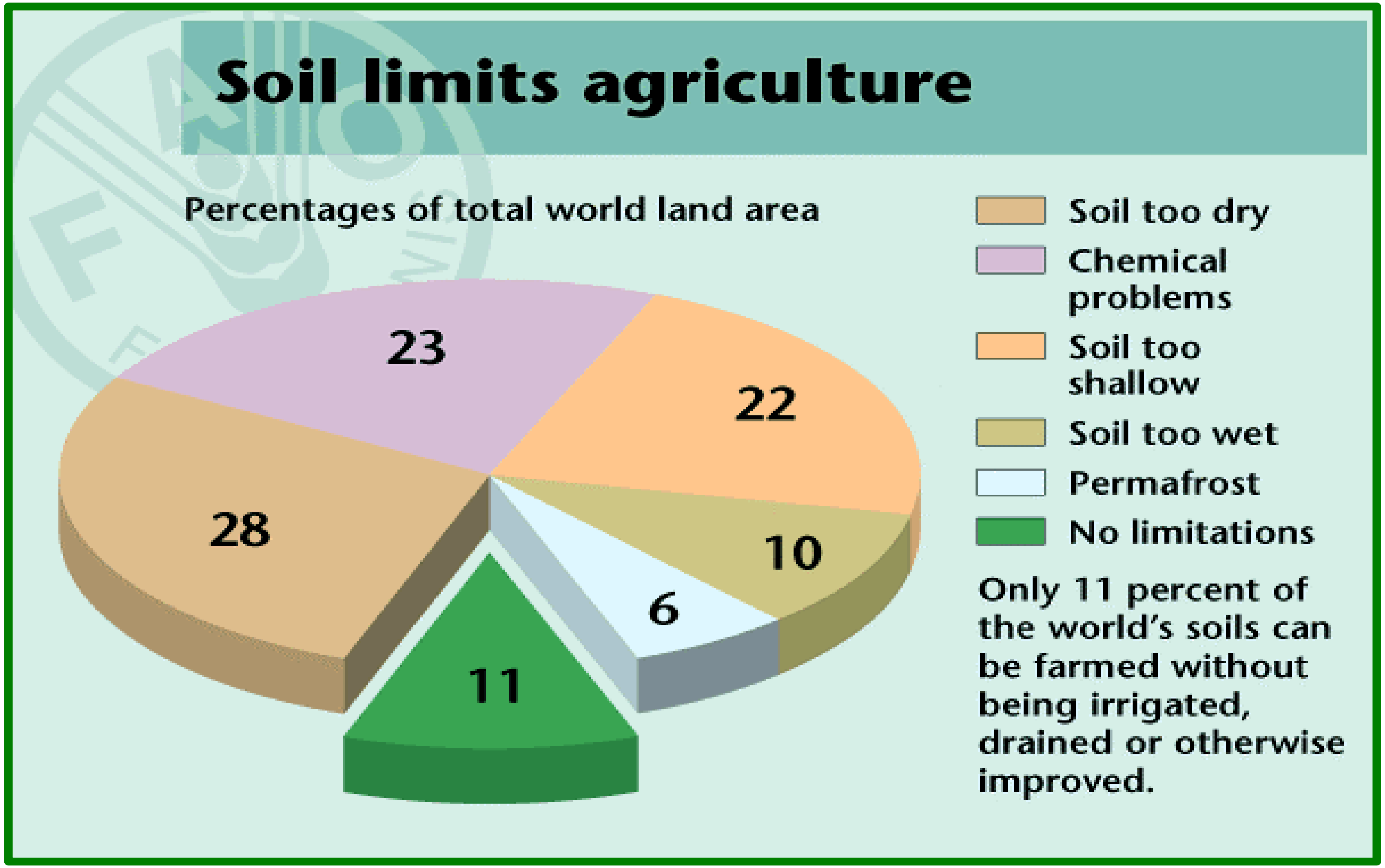
World
Resources
Institute

WORLD HUNGER



http://www.feedingminds.org/level1/lesson1/worldhungermap.htm

SOIL DEGRADATION INCREASES GLOBALLY



Soil limits agriculture

Percentages of total world land area

Only 11 percent of the world's soils can be farmed without being irrigated, drained or otherwise improved.

Source: FAO, 1998

ABIOTIC STRESS

NUTRIENT DEFICIENY

SALINITY

DROUGHT

OZONE

FLOODING

HIGH LIGHT/UV

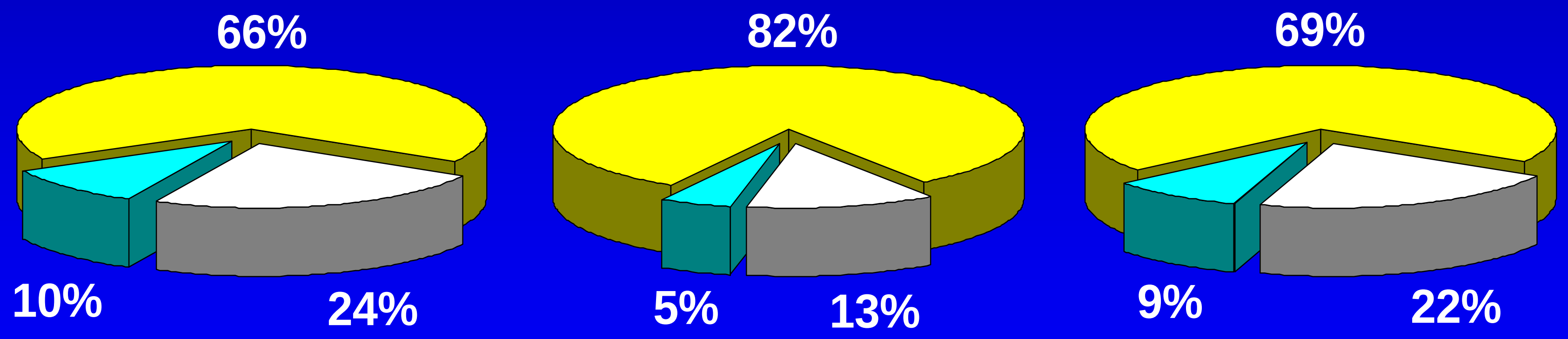
HEAT

CHILLING

Decreases in Record Yield Capacity of Crop Plants by Abiotic and Biotic Stress Factors

- 🟨 Losses by abiotic stress
- ⬜ Present average yield
- 🟦 Losses by biotic stress

CORN **WHEAT** **SOYBEAN**



Record Yield: **19.3** **14.5** **7.4**
(tons ha^{-1})

Source: Bray et al., 2000, In Molecular Biology and Biochemistry of Plants, ASPP

Photooxidative

stress

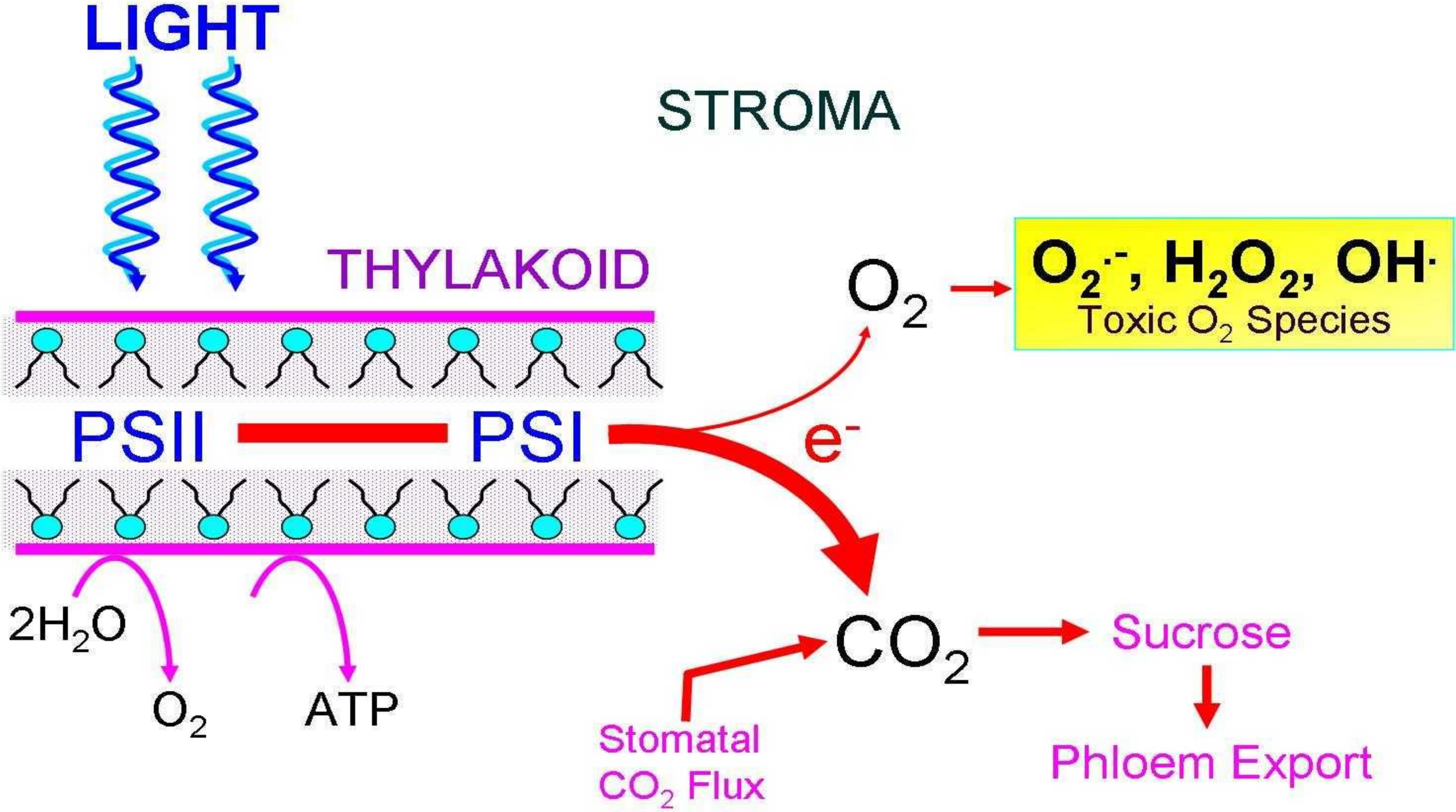
Photooxidative Damage

a key process involved in cell damage and cell death in plants exposed to environmental stress factors

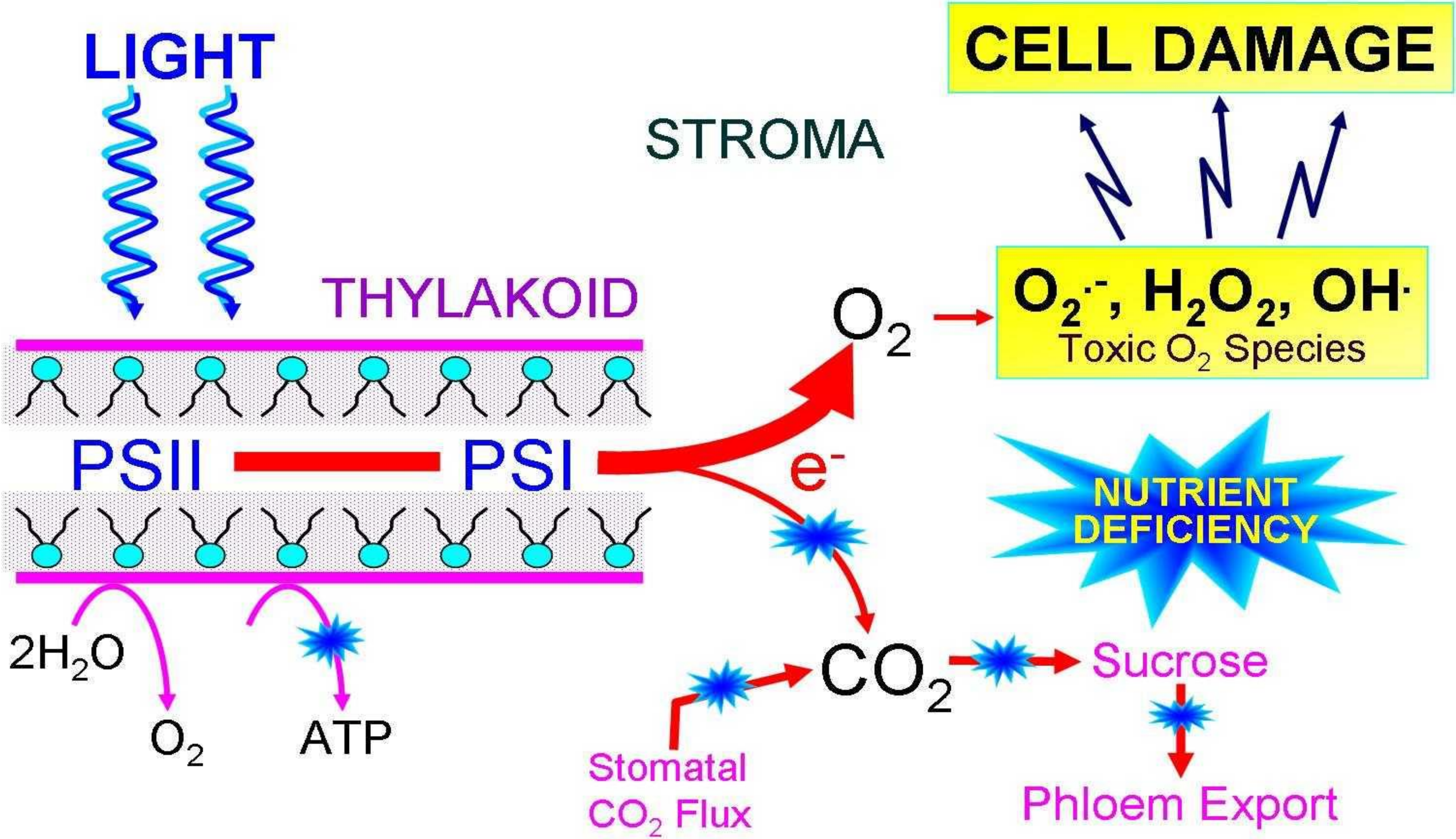
- Mineral nutritional status of plants greatly influences occurrence of photooxidative damage in plants by causing impairments in photosynthetic electron transport and CO_2 fixation in various ways.

- **Photooxidative damage in nutrient deficient plants can be more serious when plants are simultaneously exposed to an environmental stress.**

Photosynthetic Electron Transport and Superoxide Radical Generation



Photosynthetic Electron Transport and Superoxide Radical Generation



LIGHT

STROMA

CELL DAMAGE

THYLAKOID

O_2

$O_2^{\cdot -}$, H_2O_2, $OH\cdot$

Toxic O_2 Species

PSII

PSI

e^-

NUTRIENT DEFICIENCY

$2H_2O$

O_2

ATP

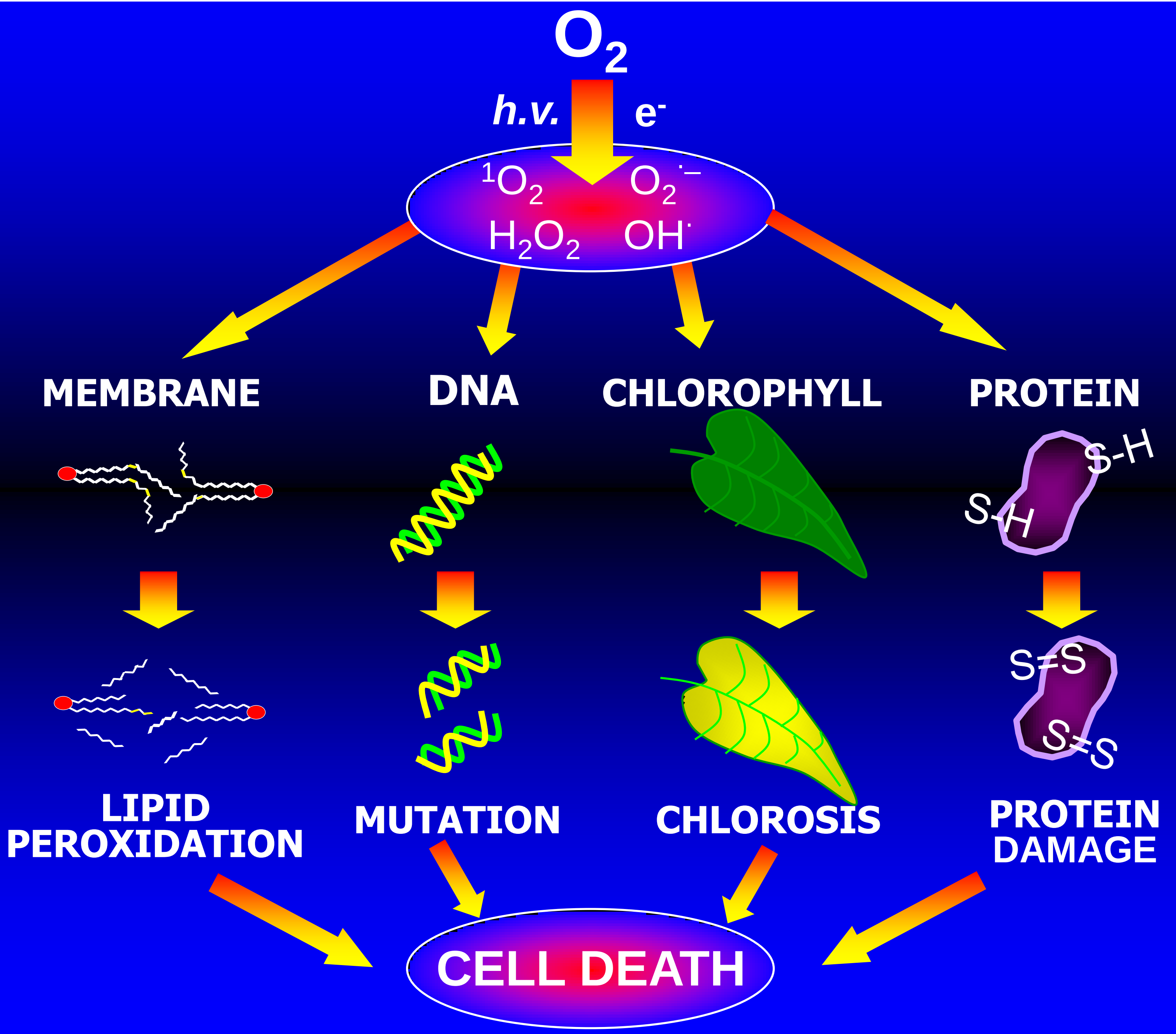
CO_2

Sucrose

Stomatal CO_2 Flux

Phloem Export

FREE RADICAL DAMAGE TO CRITICAL CELL CONSTITUENTS



O_2

h.v. e^-

$^1O_2$ $O_2^{\cdot -}$

H_2O_2 $OH^{\cdot}$

MEMBRANE **DNA** **CHLOROPHYLL** **PROTEIN**

LIPID PEROXIDATION **MUTATION** **CHLOROSIS** **PROTEIN DAMAGE**

CELL DEATH

- Of the mineral nutrients **nitrogen** plays a major role in utilization of absorbed light energy and photosynthetic carbon metabolism.

- In N-deficient leaves an excess of non-utilized light energy can be expected leading to high risk for occurrence of photooxidative damage.

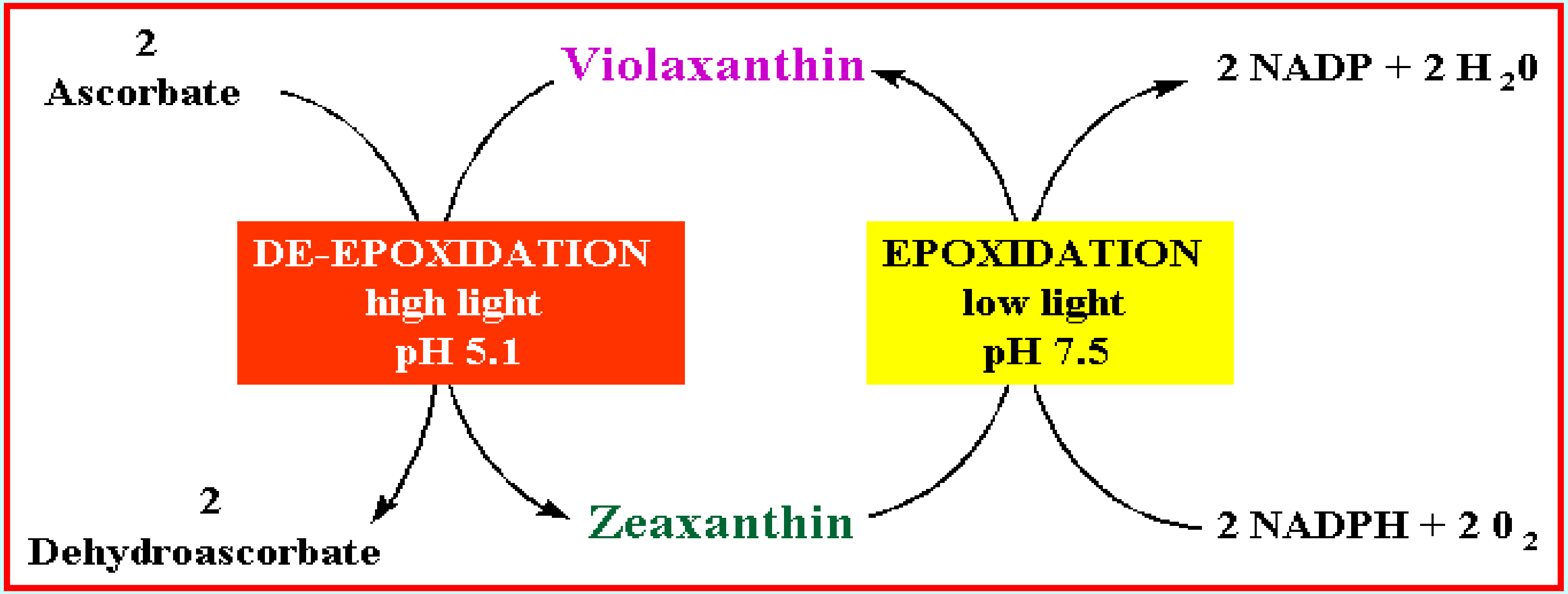
Photosynthetic characteristics in *C. album* leaves grown at high light

Growth conditions	Chl (mmol m^{-2}	Photosynthetic rate (μmol m^{-2}s^{-1})	Electron transport rate (μmol m^{-2} s^{-1})
Deficient N	0.47	13	124
Adequate N	0.90	29	254

Kato et al., 2003, Plant Cell Physiol. 44:318-325

To avoid occurrence of photooxidative damage in response to excess light energy, thylakoid membranes has a protective mechanism by which excess energy is dissipated as heat.

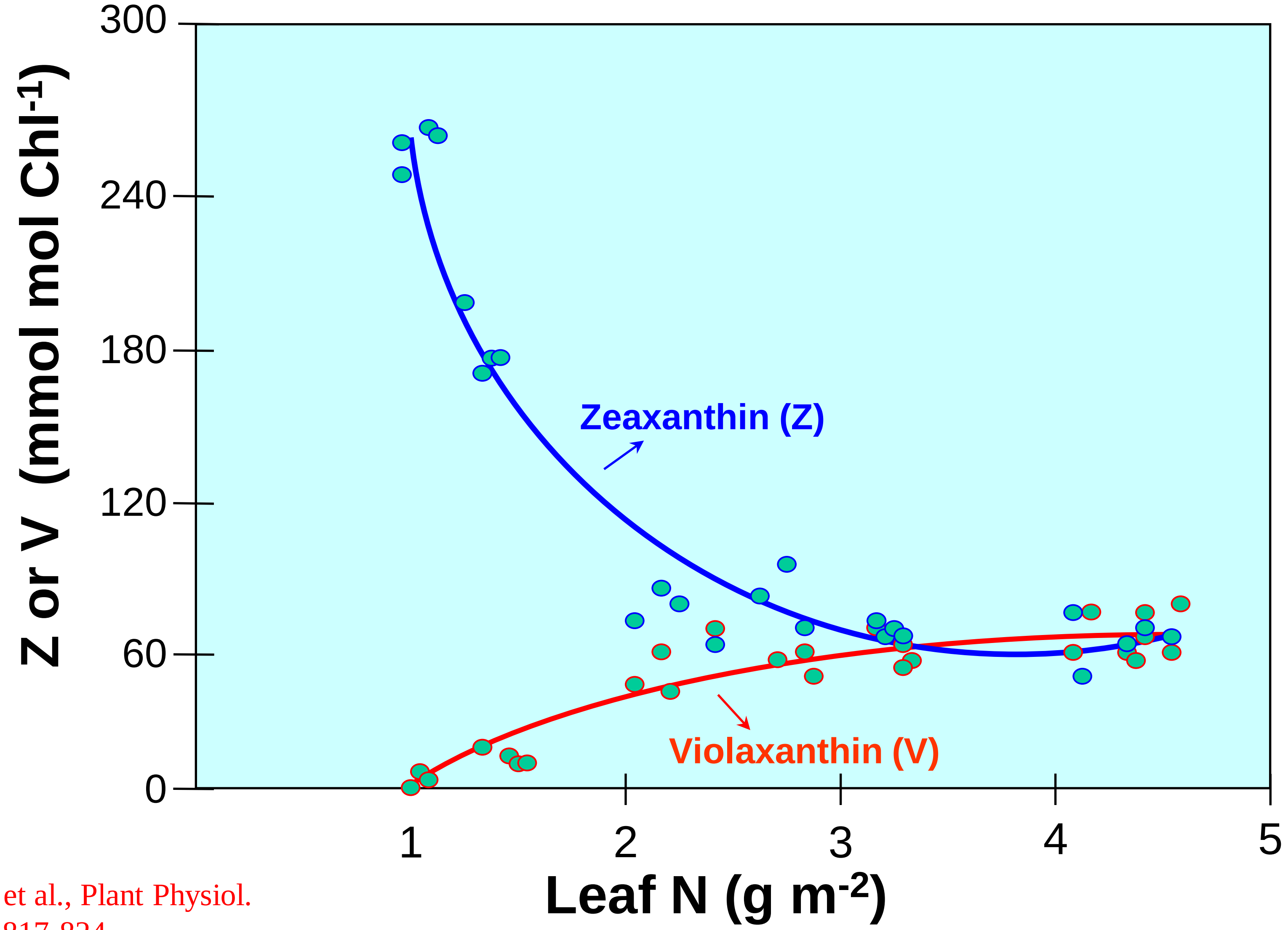
Dissipation of excess light energy is associated with enhanced formation of xanthophyll pigment **zeaxanthin.**



Zeaxanthin is synthesized from violaxanthin in the light-dependent xanthophyll cycle to avoid excess energy

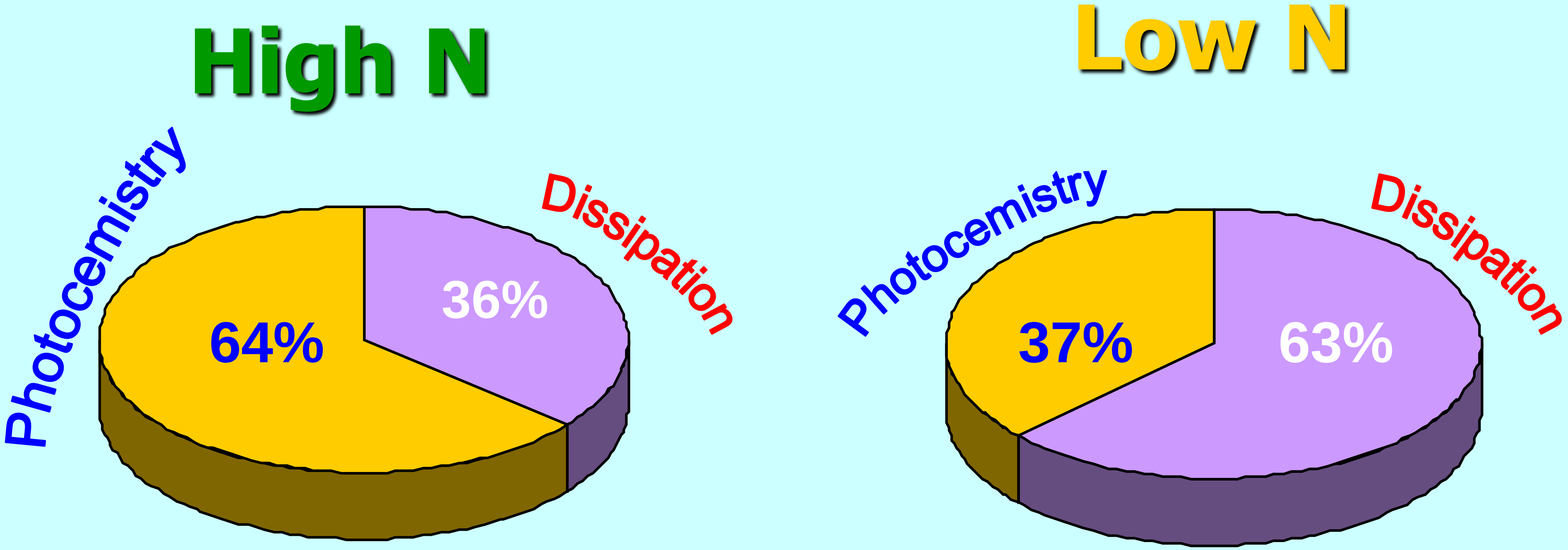
$$\boxed{\text{Violaxanthin}} \underset{\text{low light}}{\overset{\text{high light}}{\rightleftharpoons}} \boxed{\text{Antheraxanthin}} \underset{\text{low light}}{\overset{\text{high light}}{\rightleftharpoons}} \boxed{\text{Zeaxanthin}}$$

Xanthophyll Cycle Composition in Relation to Leaf N of Fuji/M.26 Trees at Noon Under an Incident PFD of 1500 µmol m^{-2} s^{-1}



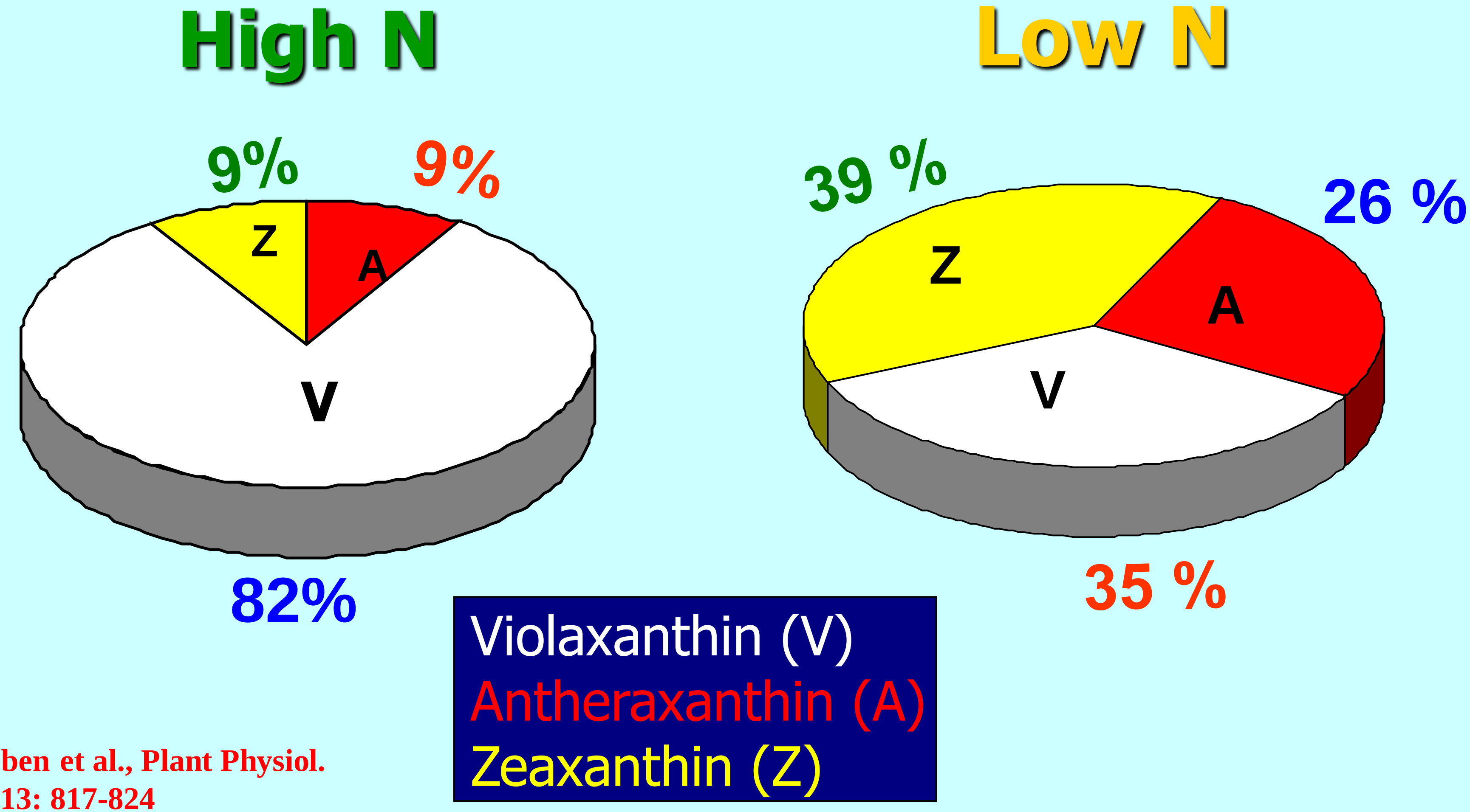
Verhoeben et al., Plant Physiol. 1997, 113: 817-824

Use of Absorbed Light Energy for Photochemistry



Verhoeben et al., Plant Physiol. 1997, 113: 817-824

Conversion State of Xantophyll Cycle Pigments at Growth Irradiance in Spinach Leaves



Verhoeben et al., Plant Physiol.
1997, 113: 817-824

- In plants suffering from N deficiency the conversion state of the xanthophyll cycle pigments zeaxanthin was enhanced together with chlorophyll bleaching particularly under high light intensity.

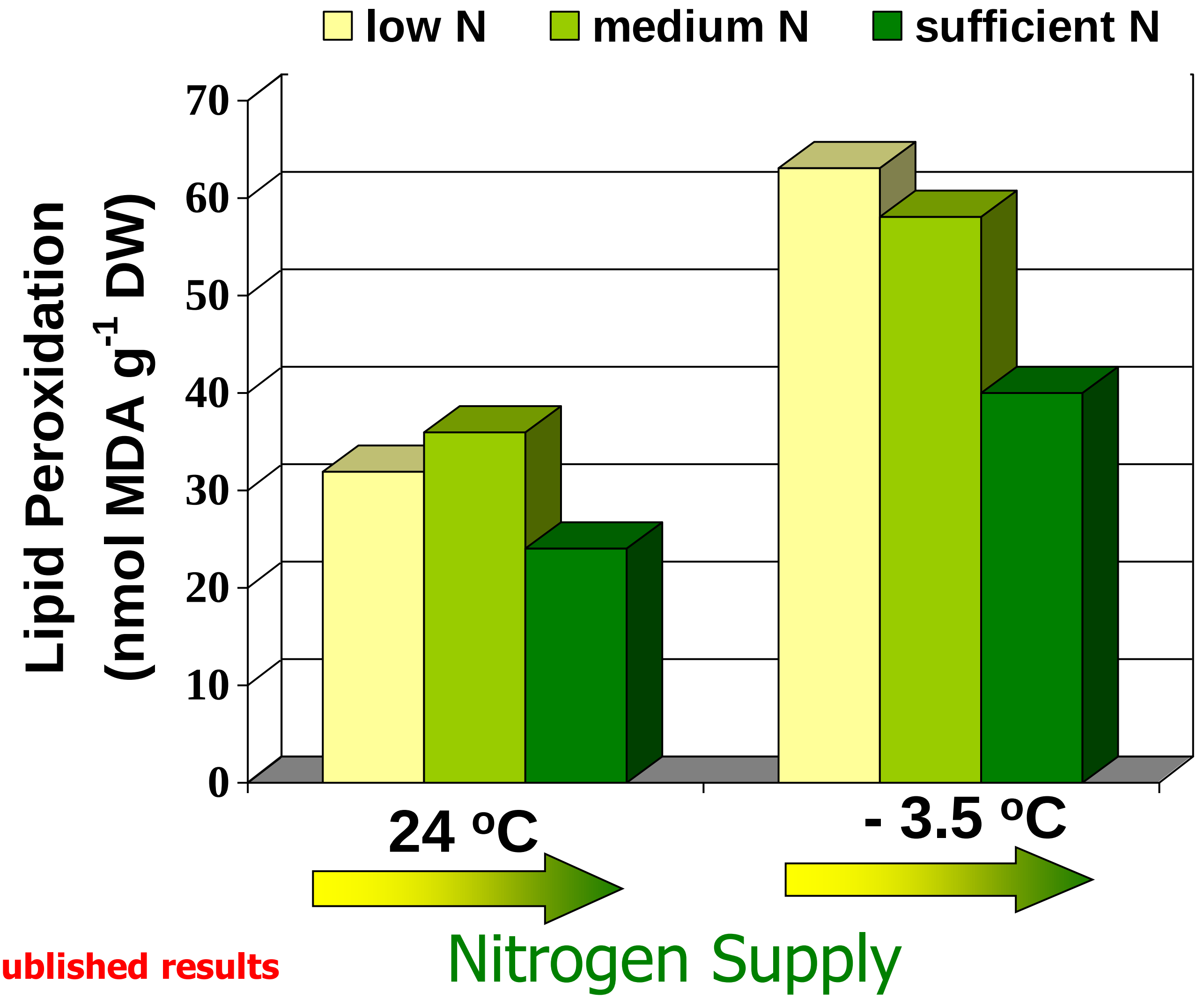
- These results indicate impaired use of absorbed light energy in photosynthetic CO_2 fixation and thus enhanced demand for protection against excess light energy in N-deficient plants.

Nitrogen is involved in protection of plants from chilling stress

In studies with *Eucalyptus* seedlings it has been shown that seedlings with impaired N nutritional status were less susceptible to photooxidative damage in winter months.

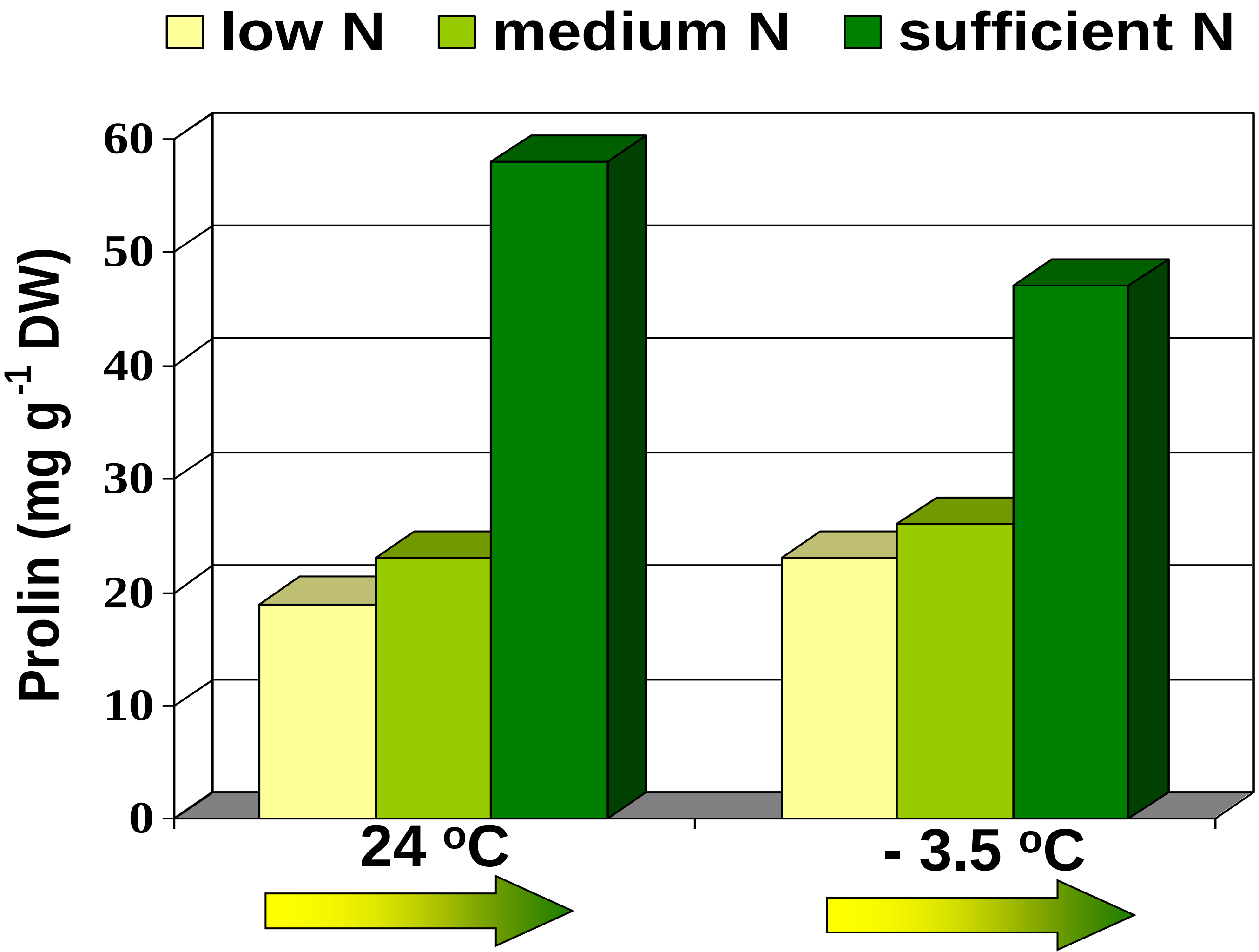
Experiments were carried out to study the effect of low temperature stress on lipid peroxidation, antioxidants and defense enzymes in lemon that is very sensitive to low temperature.

Effect of Increasing Nitrogen Supply on Lipid Peroxidation at Normal and Low Temperature in Lemon



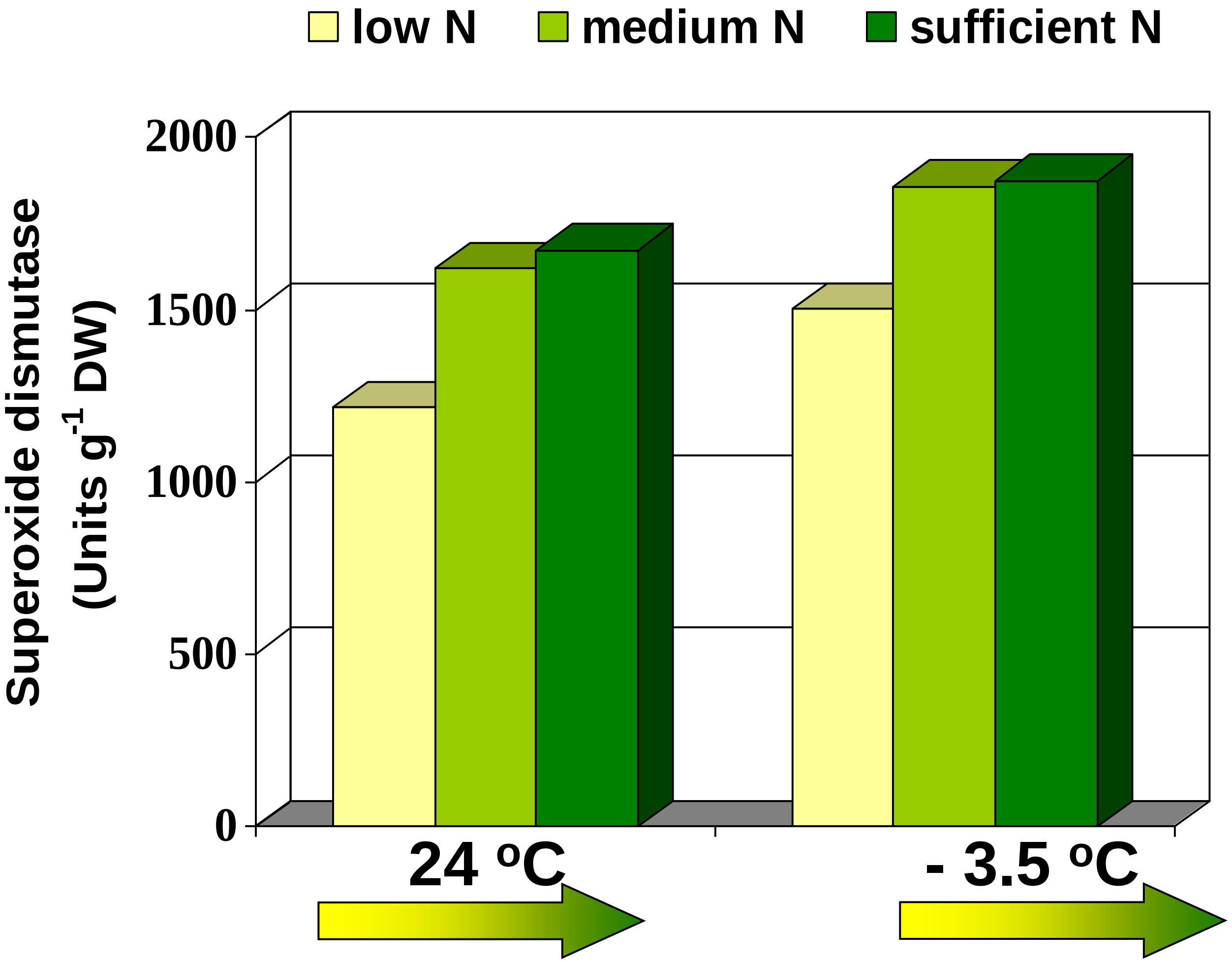
S. Eker, unpublished results

Effect of Increasing Nitrogen Supply on Prolin Concentration at Normal and Low Temperature in Lemon



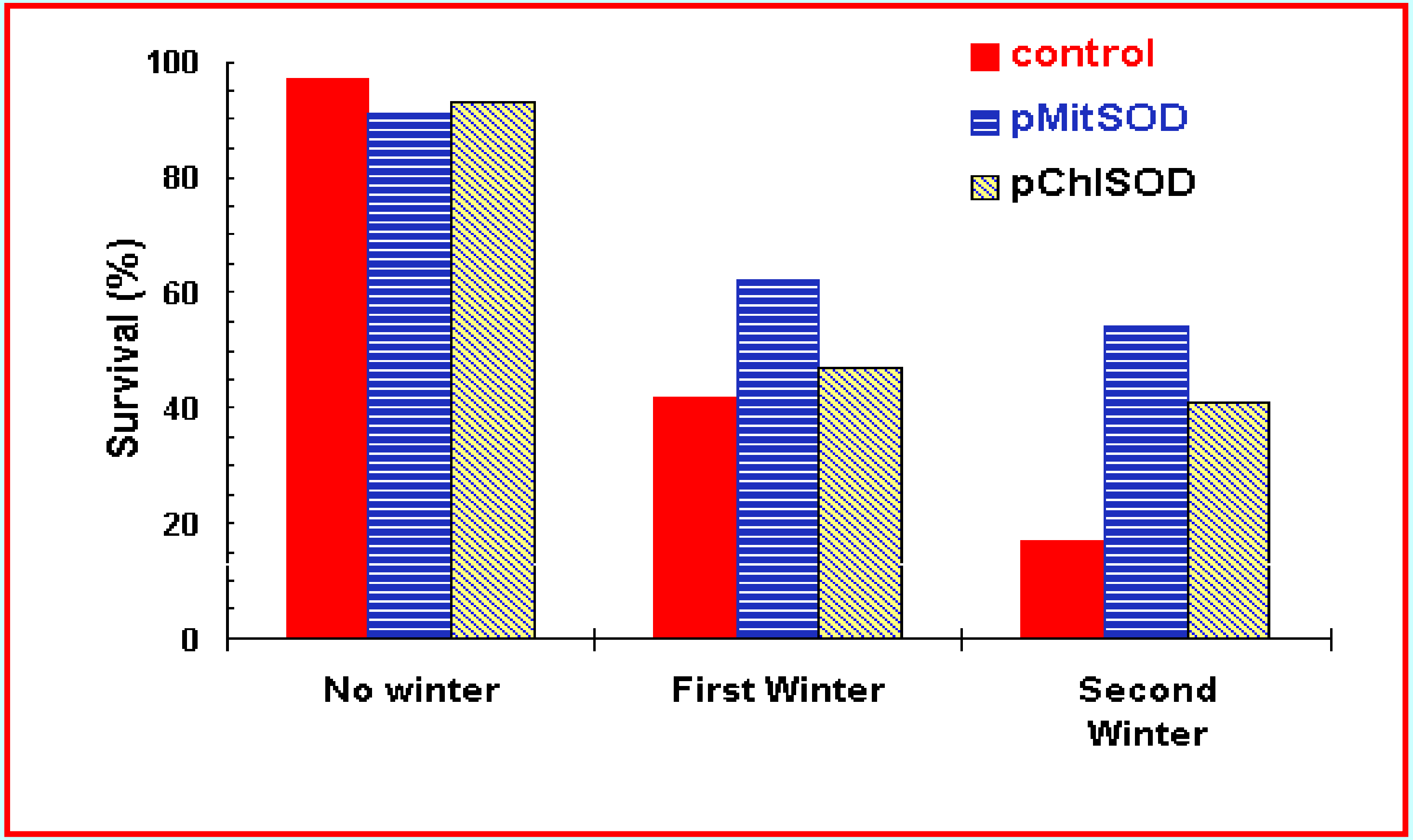
S. Eker, unpublished Results

Effect of Increasing Nitrogen Supply on Superoxide Dismutase at Normal and Low Temperature in Lemon



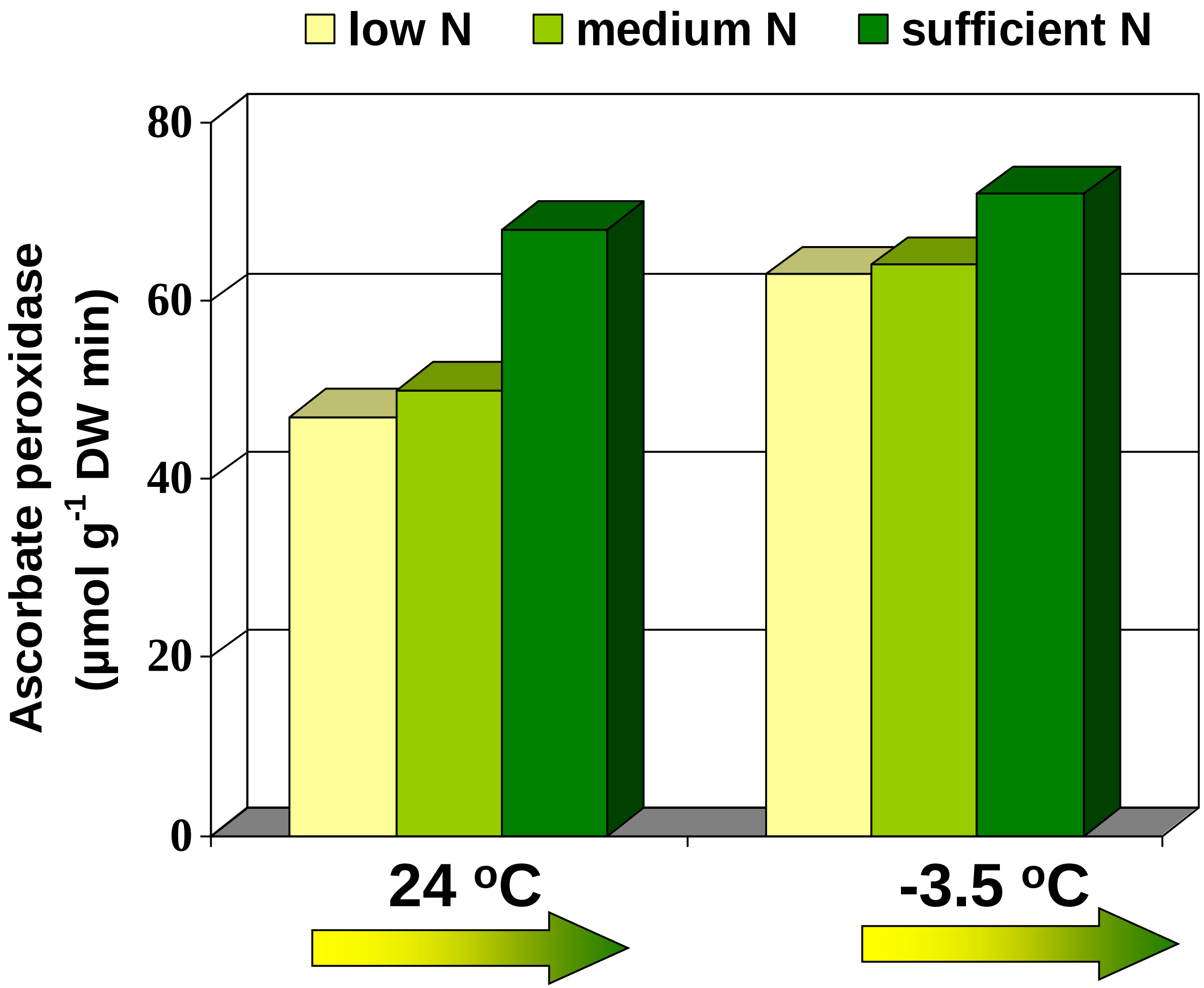
S. Eker, unpublished Results

Nitrogen Supply



Yield of transgenic alfalfa in 3 years of field trials. Cuttings were planted in 1x3 m plots in replicated trials in spring 1992.

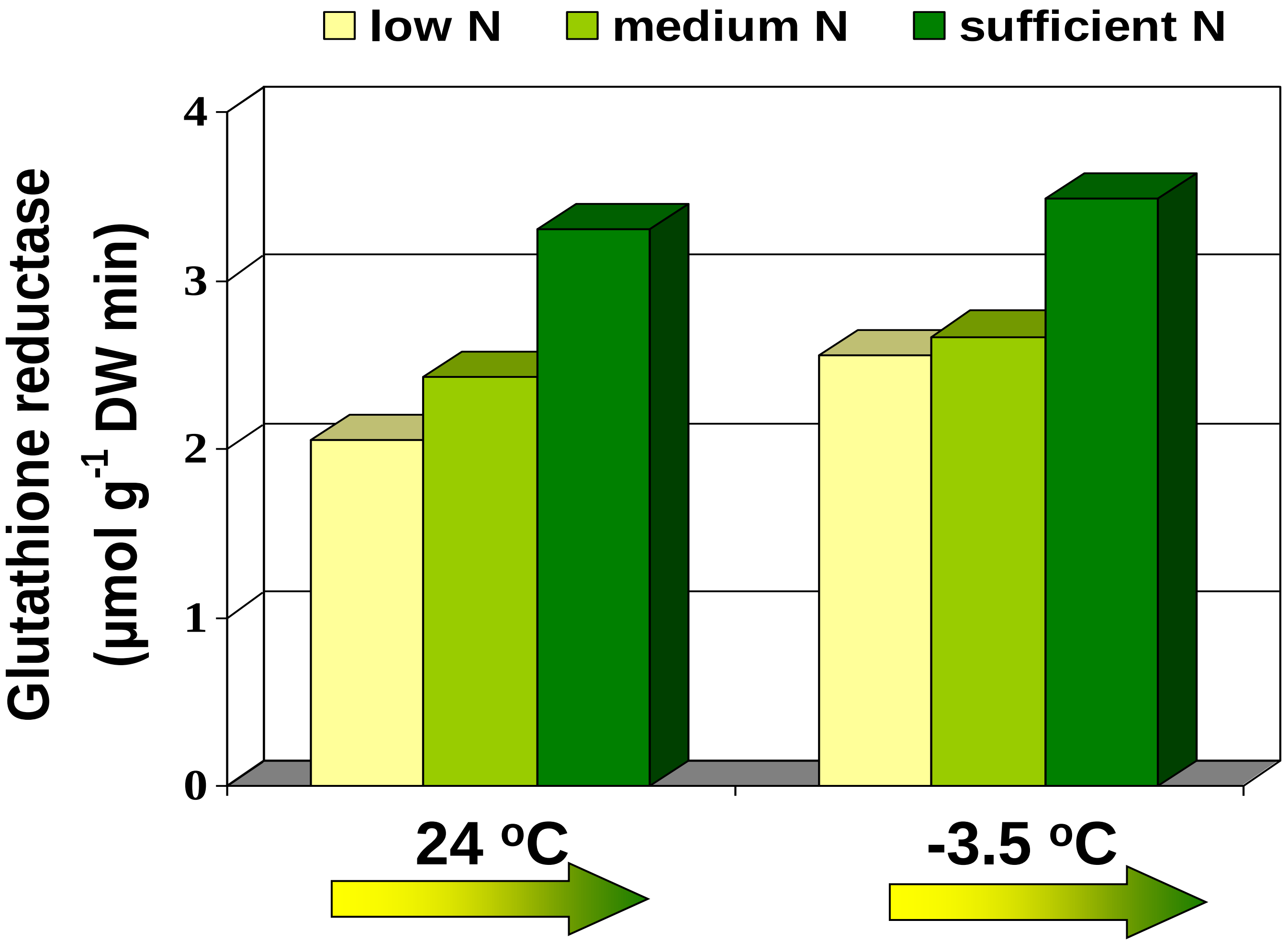
Effect of Increasing Nitrogen Supply on Ascorbate Peroxidase at Normal and Low Temperature in Lemon



S. Eker, unpublished Results

Nitrogen Supply

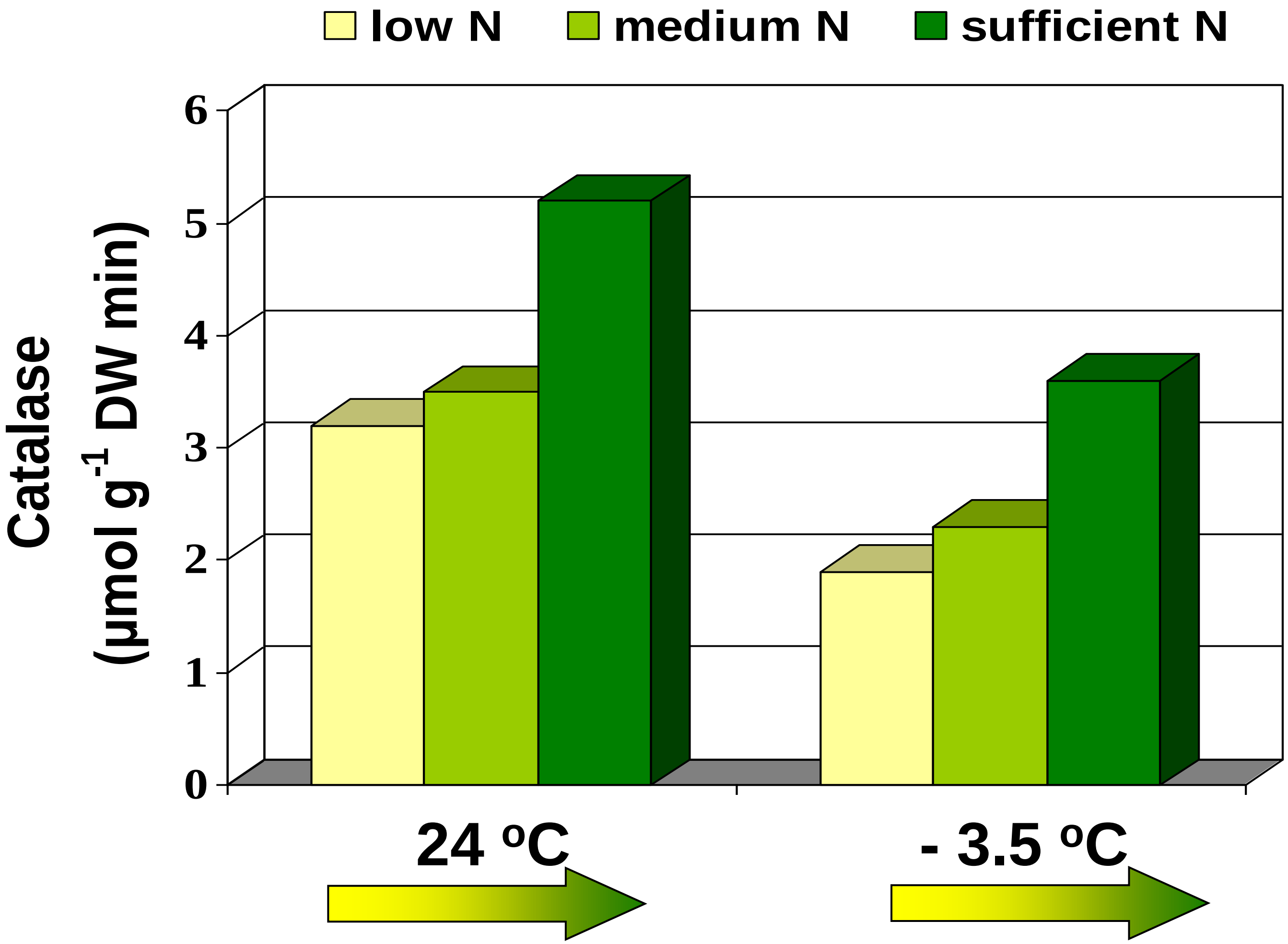
Effect of Increasing Nitrogen Supply on Glutathione Reductase at Normal and Low Temperature in Lemon



Nitrogen Supply

S. Eker, unpublished Results

Effect of Increasing Nitrogen Supply on Catalase at Normal and Low Temperature in Lemon



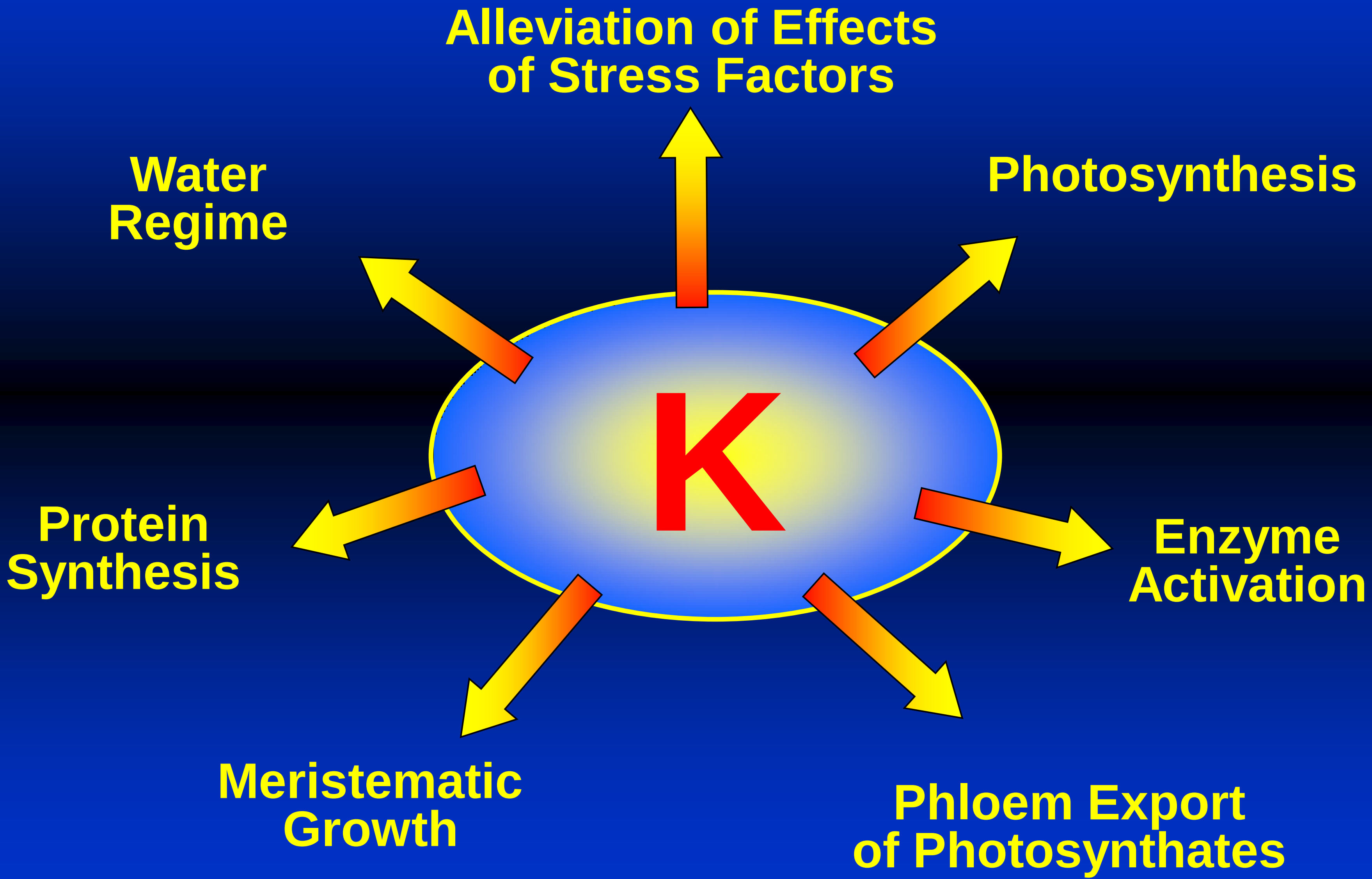
Nitrogen Supply

S. Eker, unpublished Results

- Catalase enzyme is highly sensitive to low temperature. Improved N nutrition protects catalase from inhibition/inactivation by low temperature stress.

- The activity of most antioxidant enzymes is increased by low N supply, especially at low temperature. This lead to suggestion that N deficiency promotes increased production of reactive oxygen species.

POTASSIUM IN CROP PRODUCTION



K

Alleviation of Effects of Stress Factors

Photosynthesis

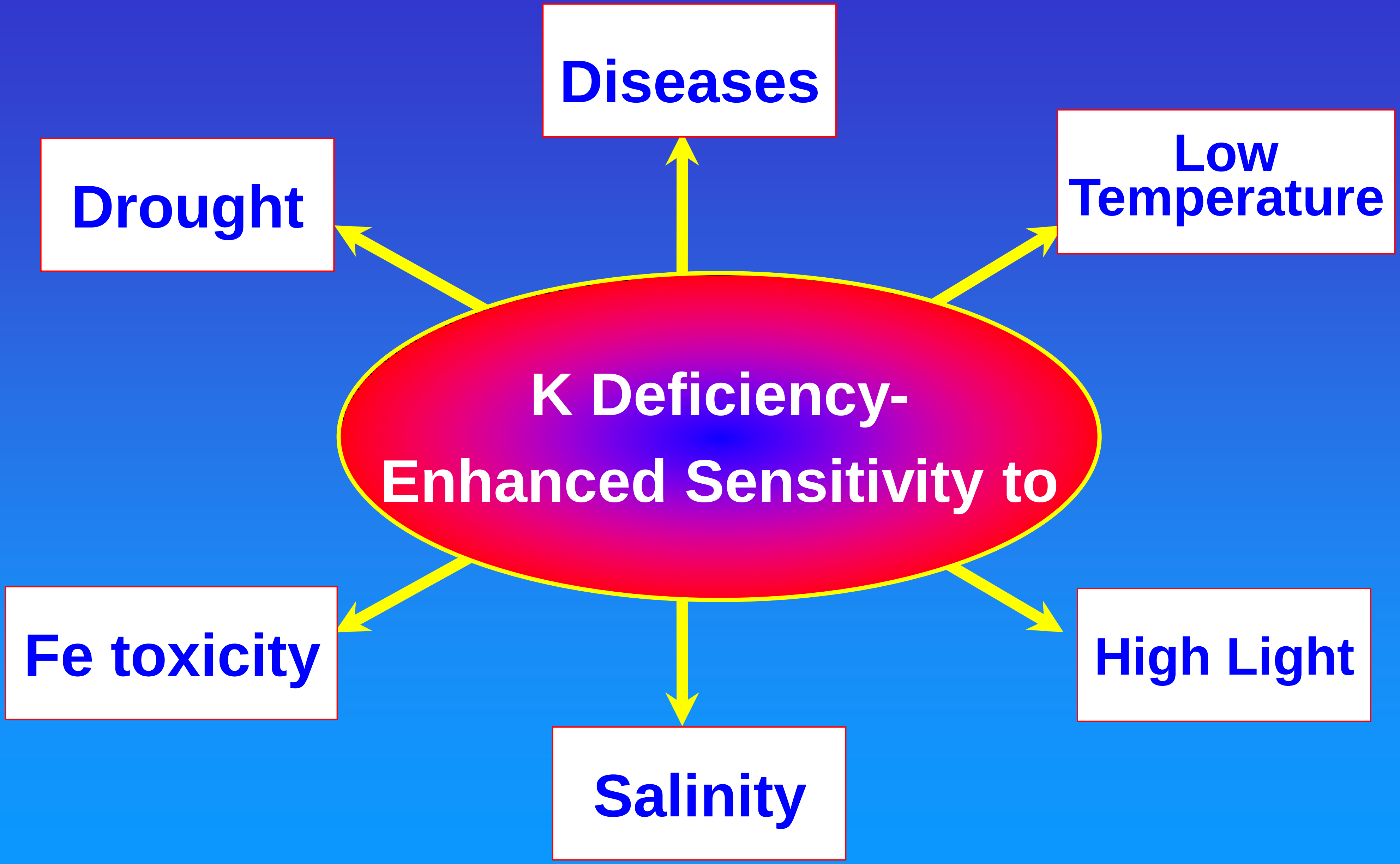
Enzyme Activation

Phloem Export of Photosynthates

Meristematic Growth

Protein Synthesis

Water Regime



K Deficiency-
Enhanced Sensitivity to

Diseases

Low Temperature

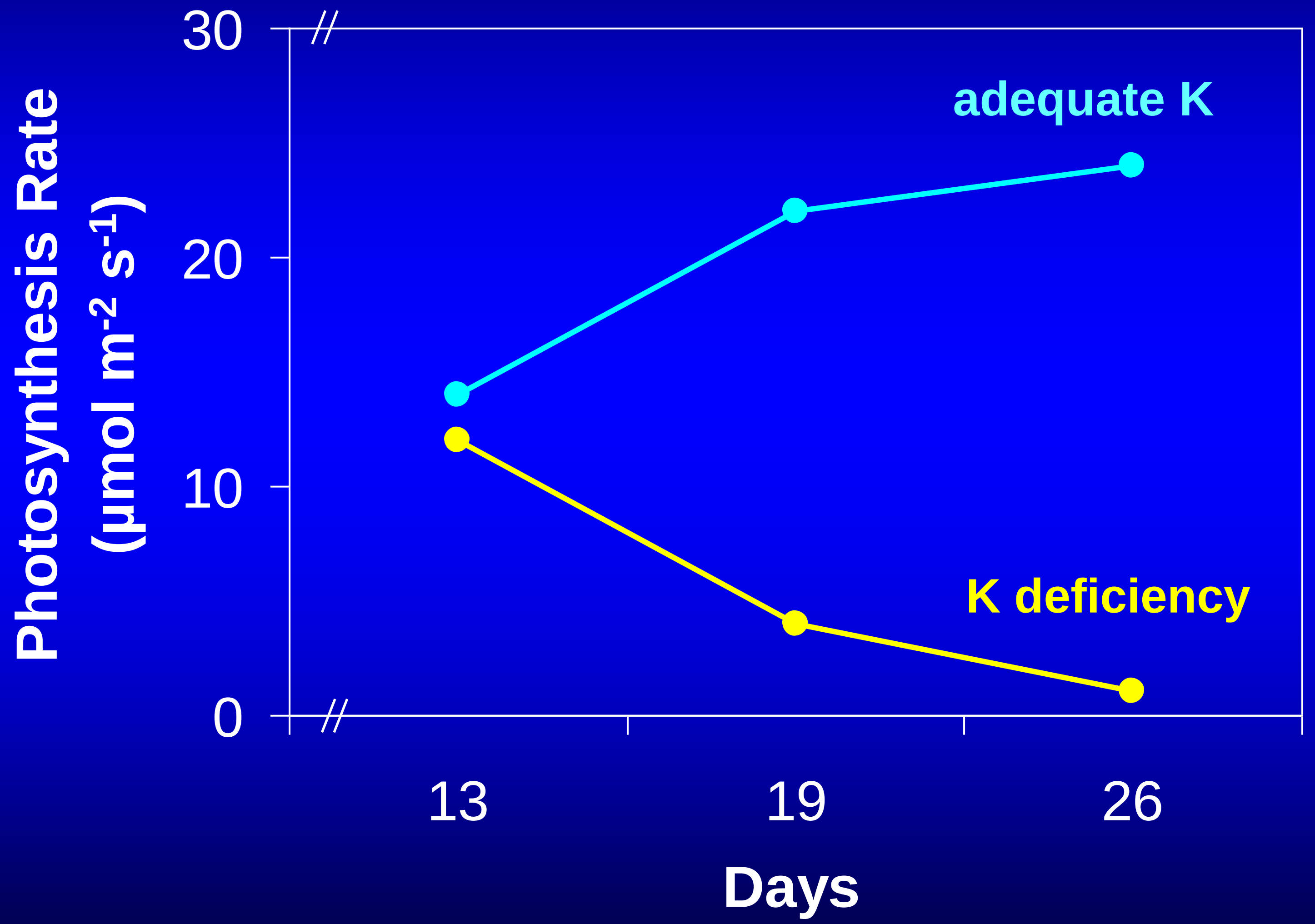
High Light

Salinity

Fe toxicity

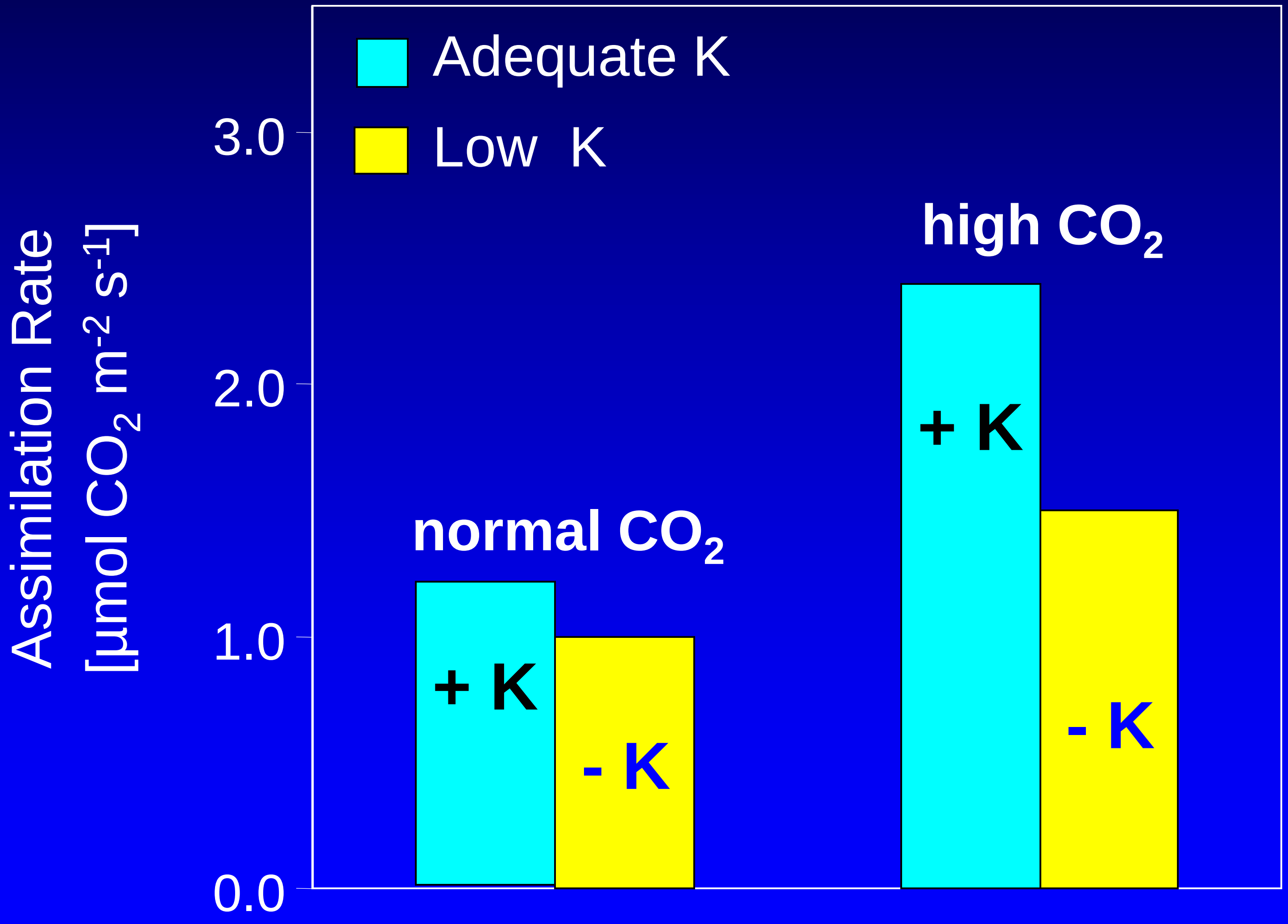
Drought

Effect of Varied K Supply on Photosynthesis in Cotton



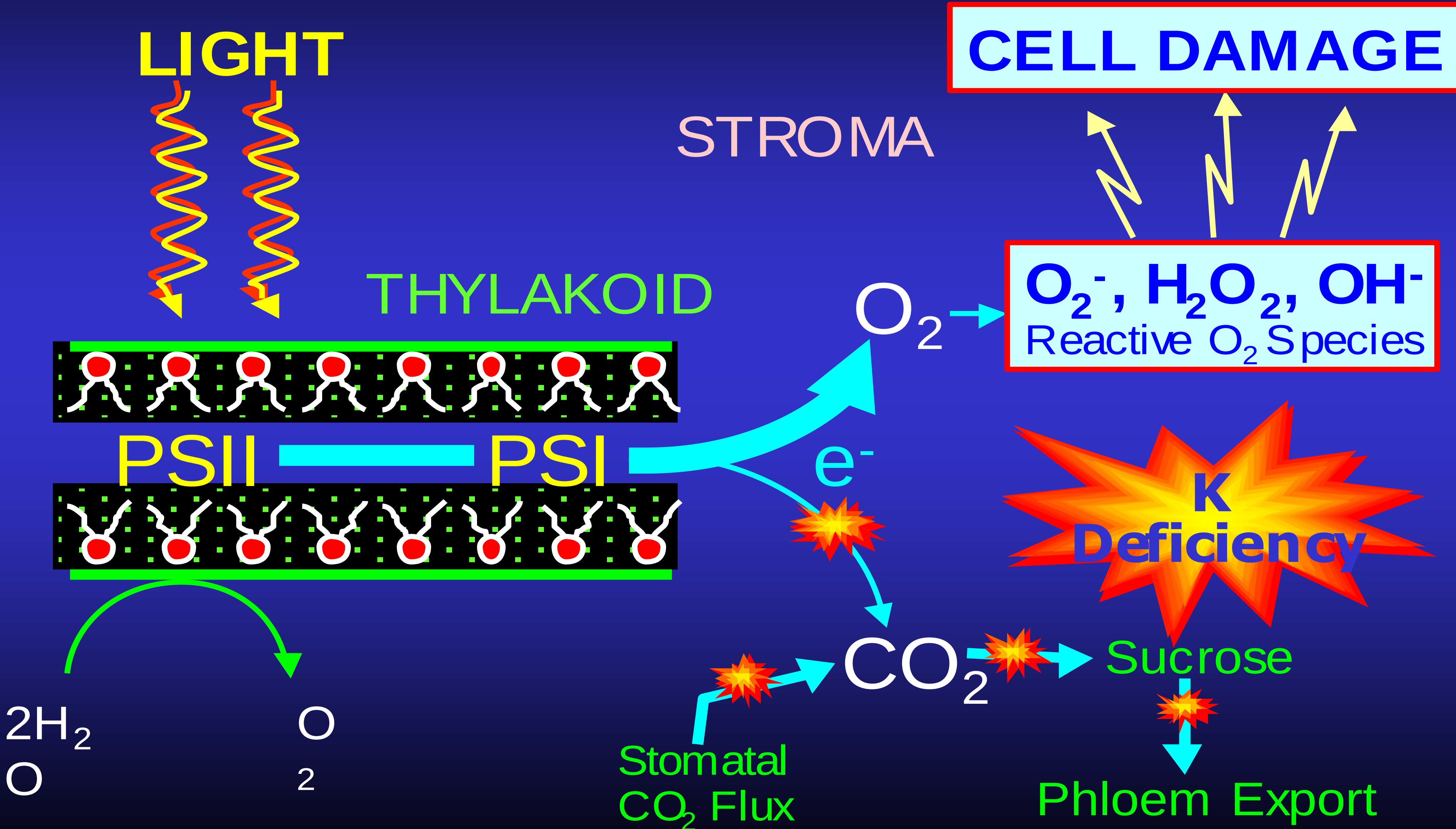
Bednarz and Oosterhuis, 1999 ; J. Plant Nutr.

Effect of Elevated CO_2 on Photosynthesis at Varied K Supply



Barnes et al., 1995, Plant Cell Environ.

Photosynthetic Electron Transport and Superoxide Radical Generation



CELL DAMAGE

STROMA

LIGHT

THYLAKOID

O_2^-, H_2O_2, OH^-

Reactive O_2 Species

O_2

PSII — PSI

e^-

K Deficiency

CO_2

Sucrose

Phloem Export

Stomatal CO_2 Flux

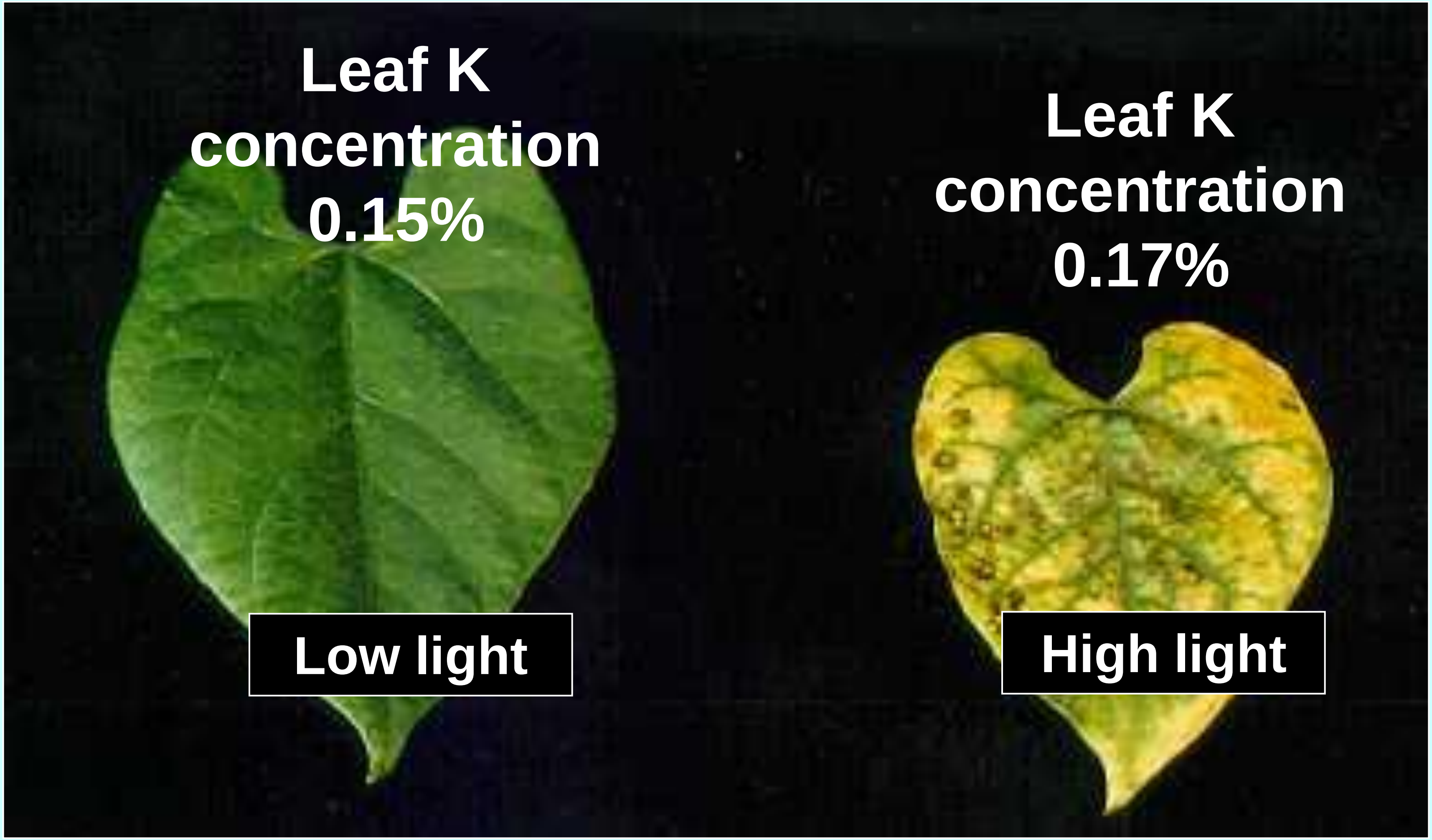
$2H_2O$

O_2

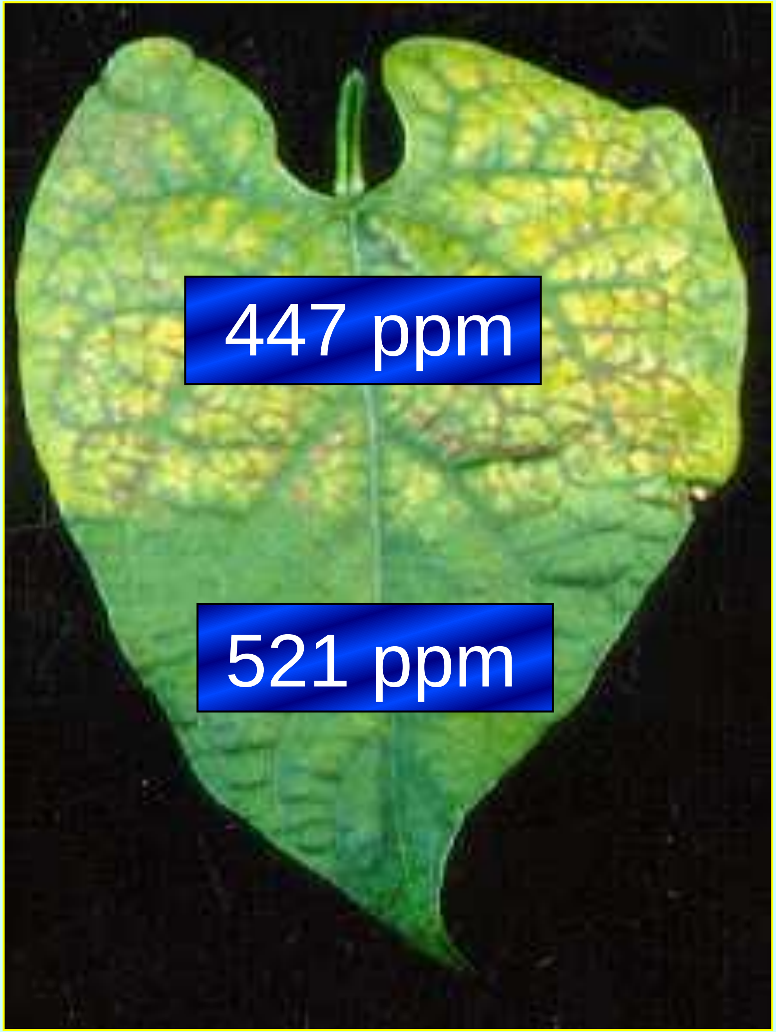
Growth of bean plants with low K supply under low and high light intensity

Marschner and Cakmak, 1989, J. Plant Physiol.

Enhancement of leaf chlorosis by high light intensity is not related to differential K concentration in leaves



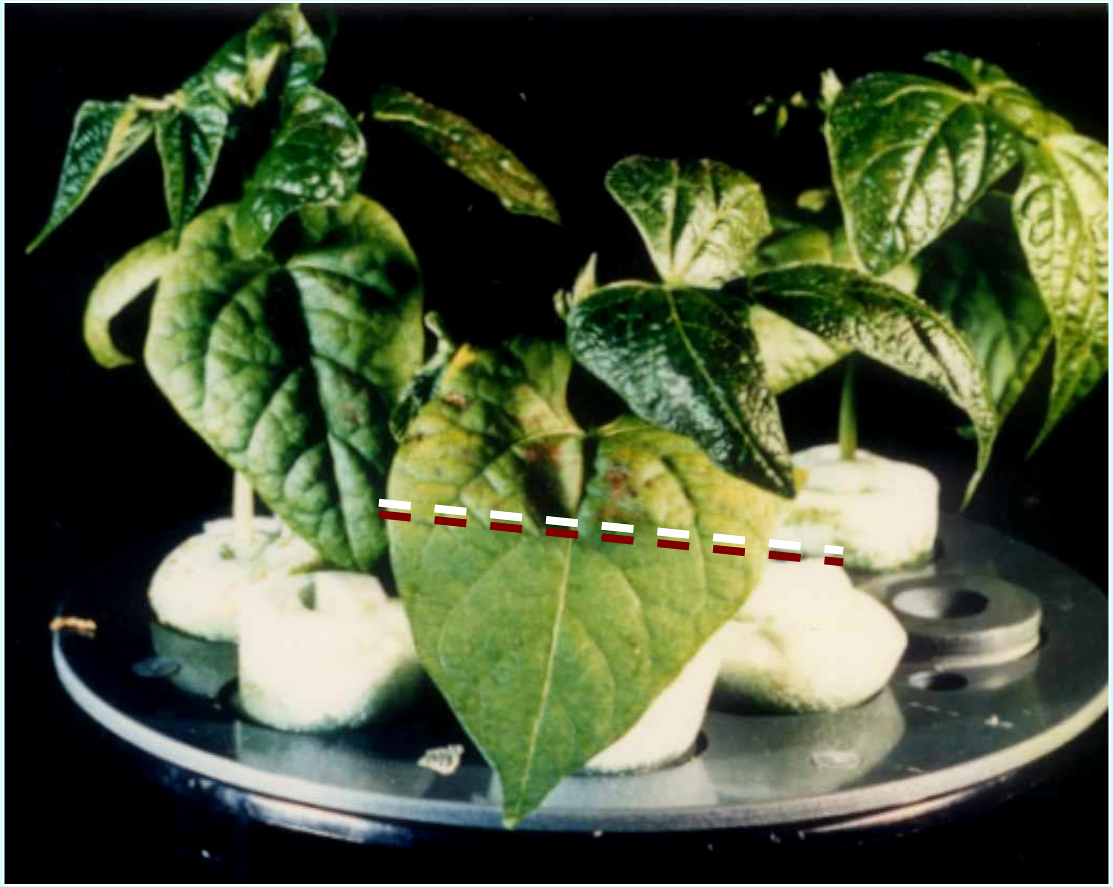
Enhancement of leaf chlorosis in Mg-deficient leaves by high light intensity is not related to Mg concentration in leaves



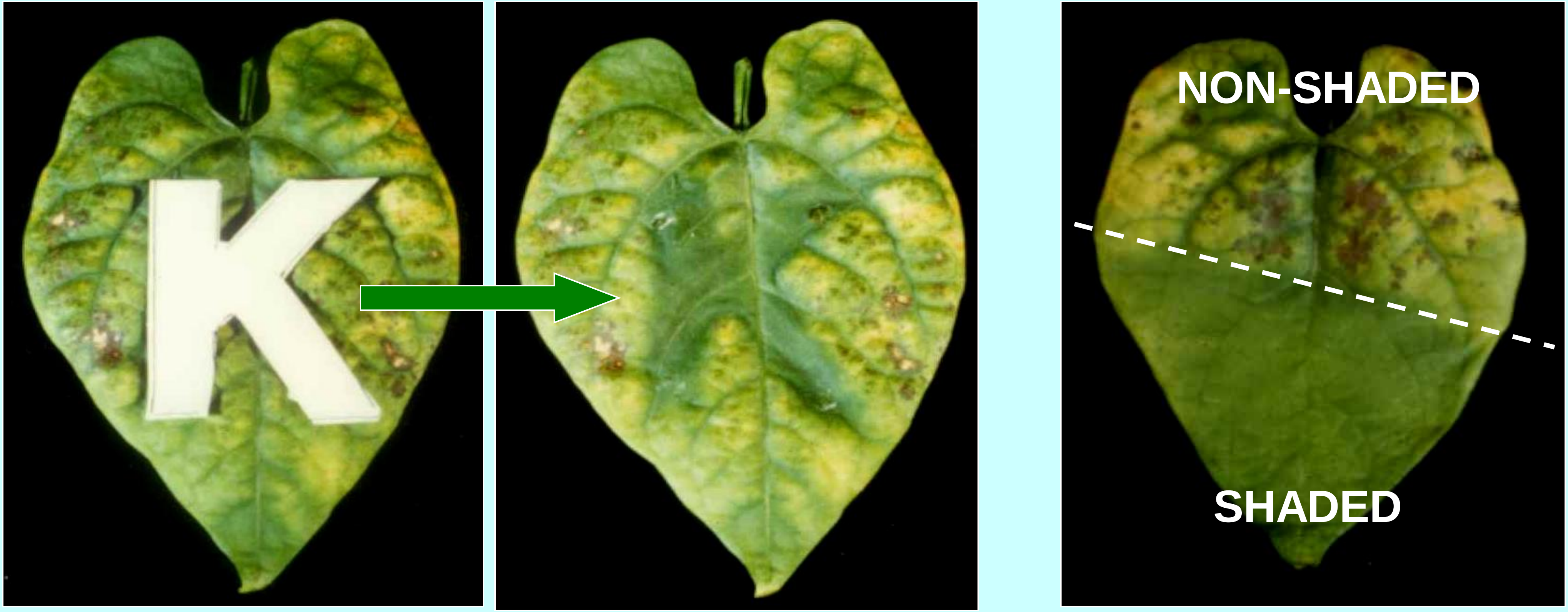
Partially shaded bean leaf at low Mg

- **Photooxidative damage to chloroplasts is a major contributing factor in development of K deficiency symptoms on leaves**

- **Plants grown under high light intensity require more K than plants grown under low light**



Enhancement of photooxidative damage in K-deficient leaves



Partially shaded K-deficient bean leaves

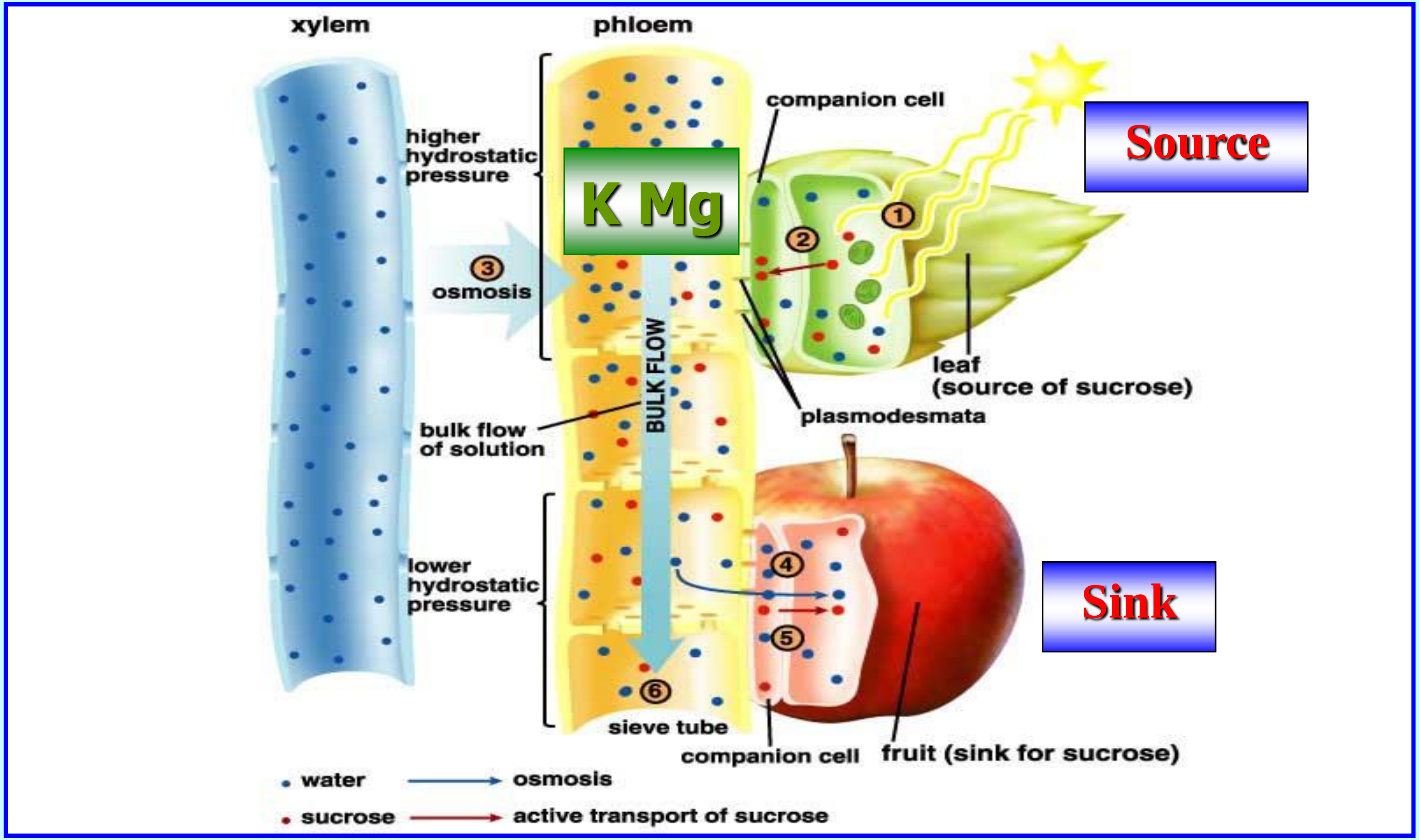
CARBOHYDRATE ACCUMULATION AND CHLOROSIS IN NUTRIENT-DEFICIENT LEAVES

Inhibitions in photosynthetic CO_2 reduction and phloem loading of sucrose play an important role in O_2 activation and occurrence of photooxidative damage, especially in Mg or K deficient leaves

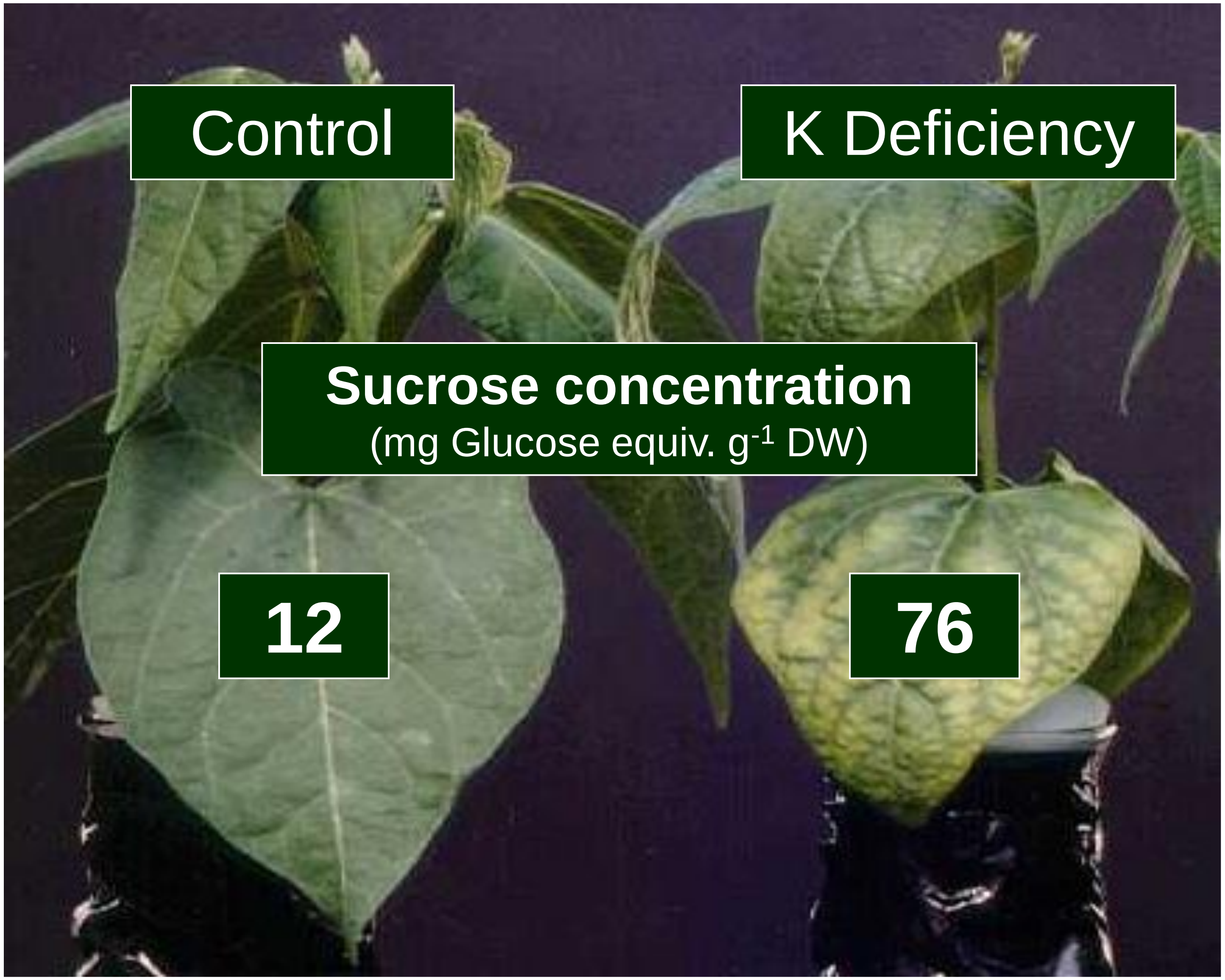
Leaf chlorosis and necrosis is common in Mg and K deficient leaves, but not in P deficient leaves

PHLOEM TRANSPORT

K and Mg play critical role in phloem transport

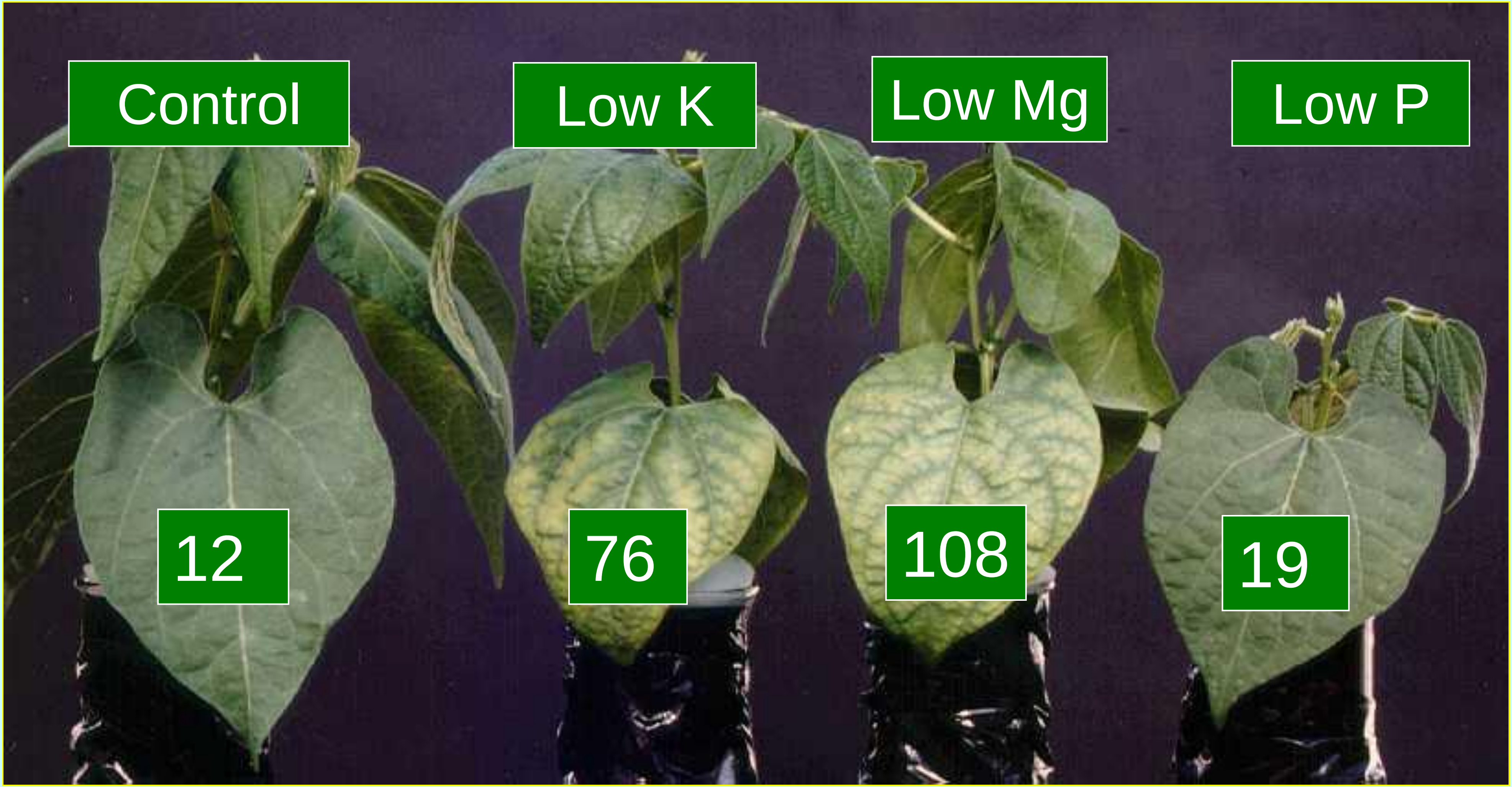


Accumulation of Phosynthates in K-Deficient Source Leaves

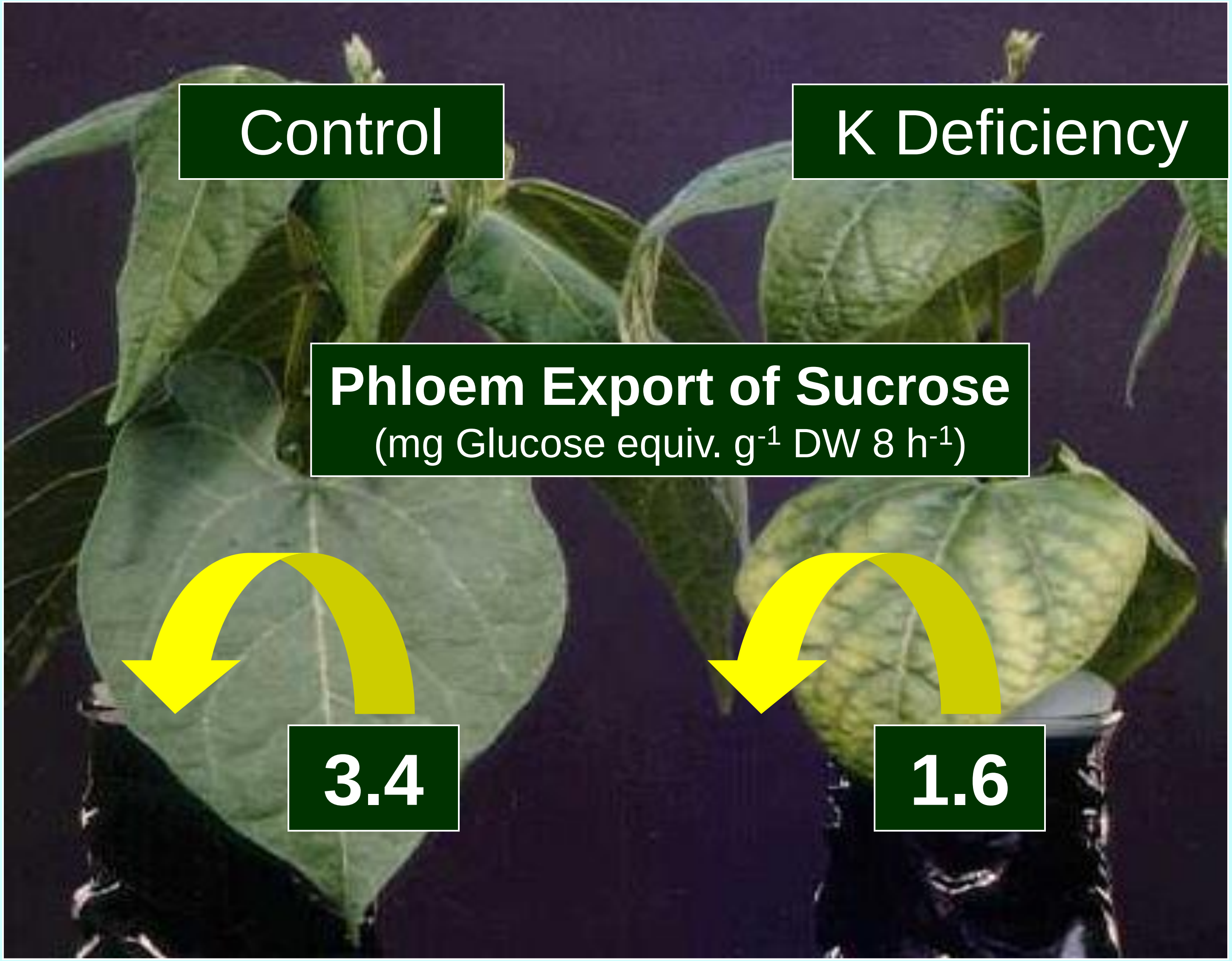


Sucrose concentration in source leaves

(mg Glucose equiv. g^{-1} DW)

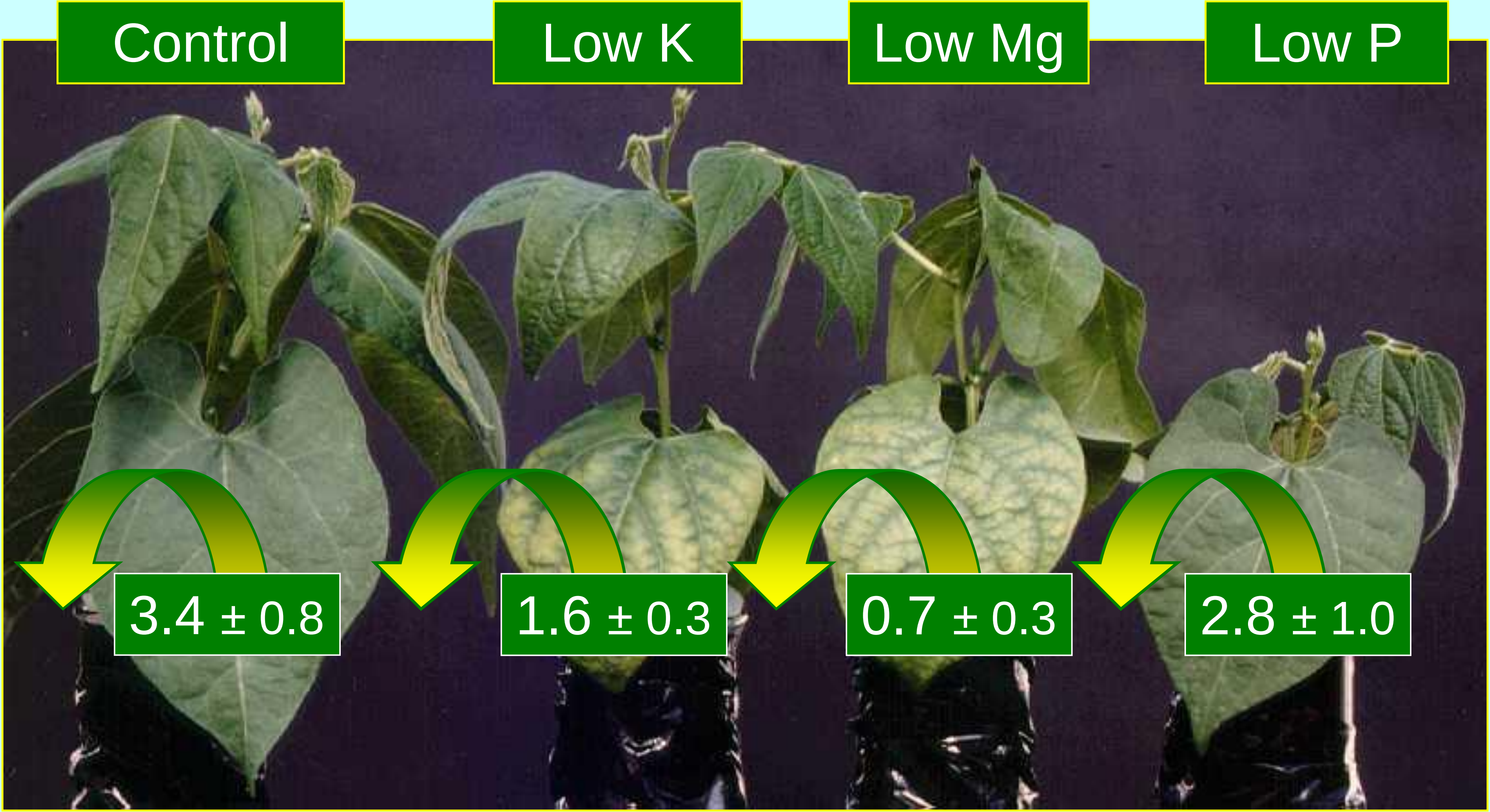


Decrease in Phloem Export of Sucrose by K-Deficiency



Export of sucrose from bean leaves

(mg Glucose equiv · g^{-1} DW · 8h^{-1})



Control

3.4 ± 0.8

Low K

1.6 ± 0.3

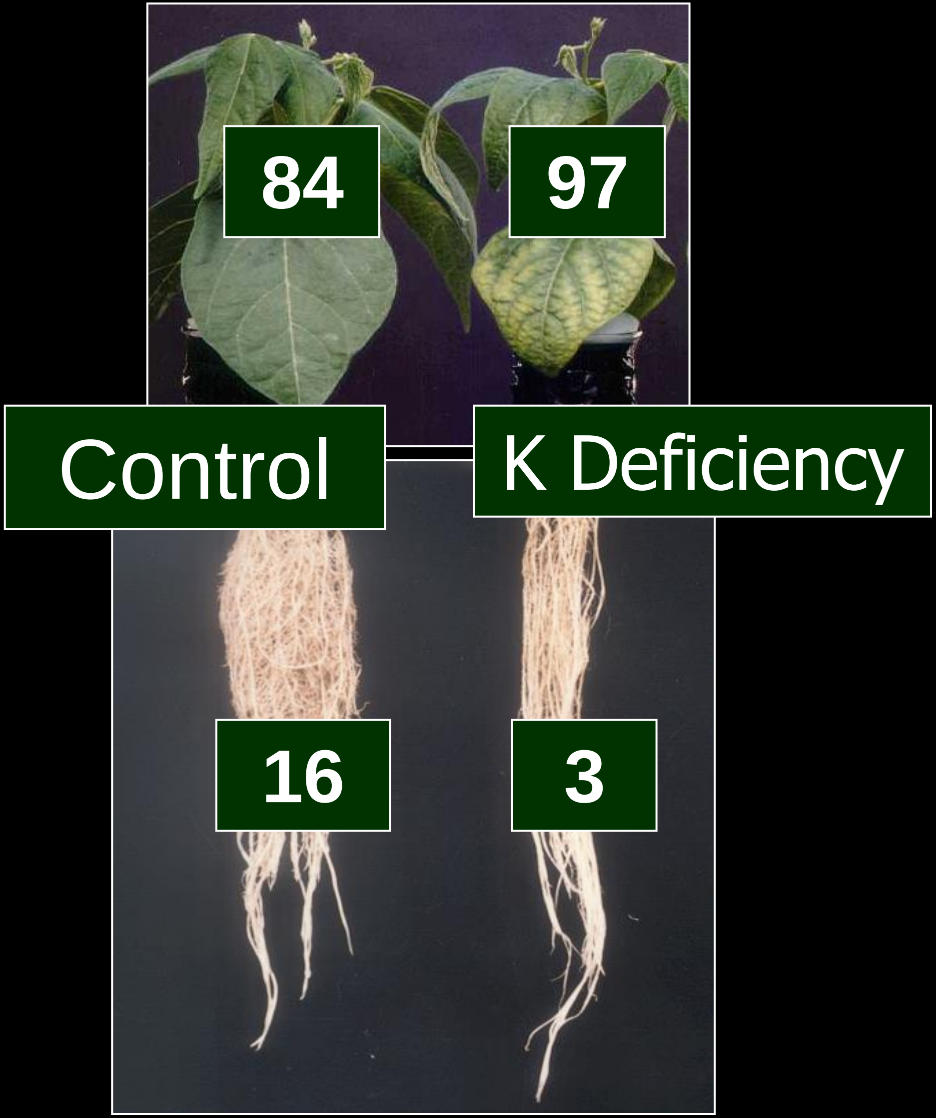
Low Mg

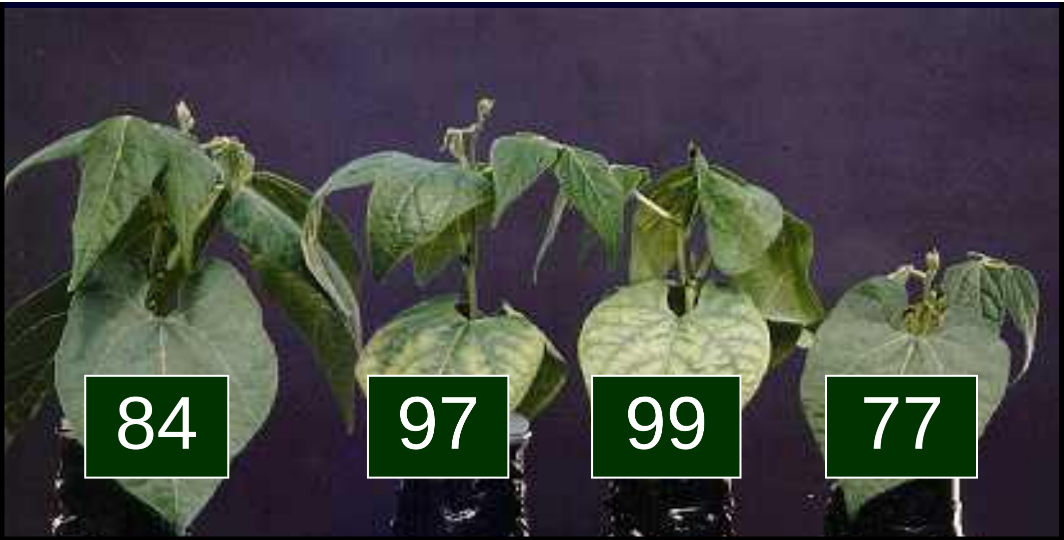
0.7 ± 0.3

Low P

2.8 ± 1.0

Relative distribution of total carbohydrates between shoot and roots (%)





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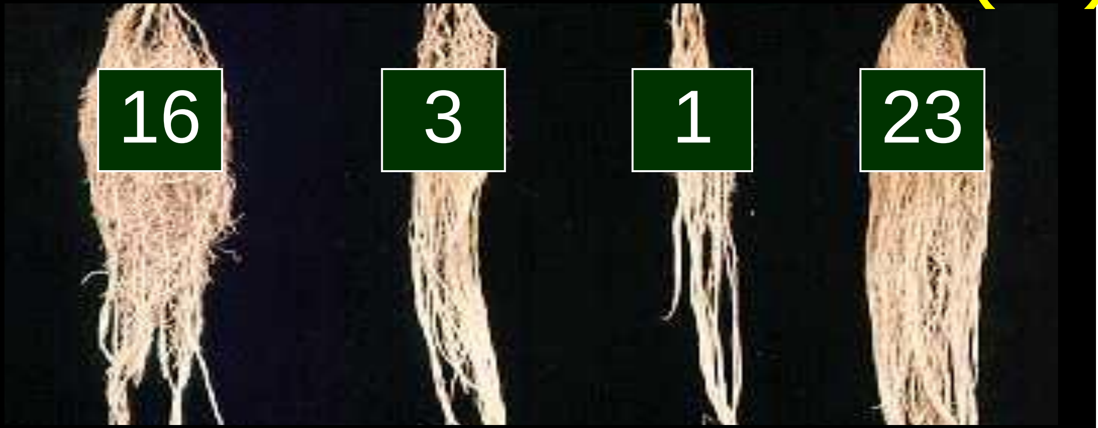


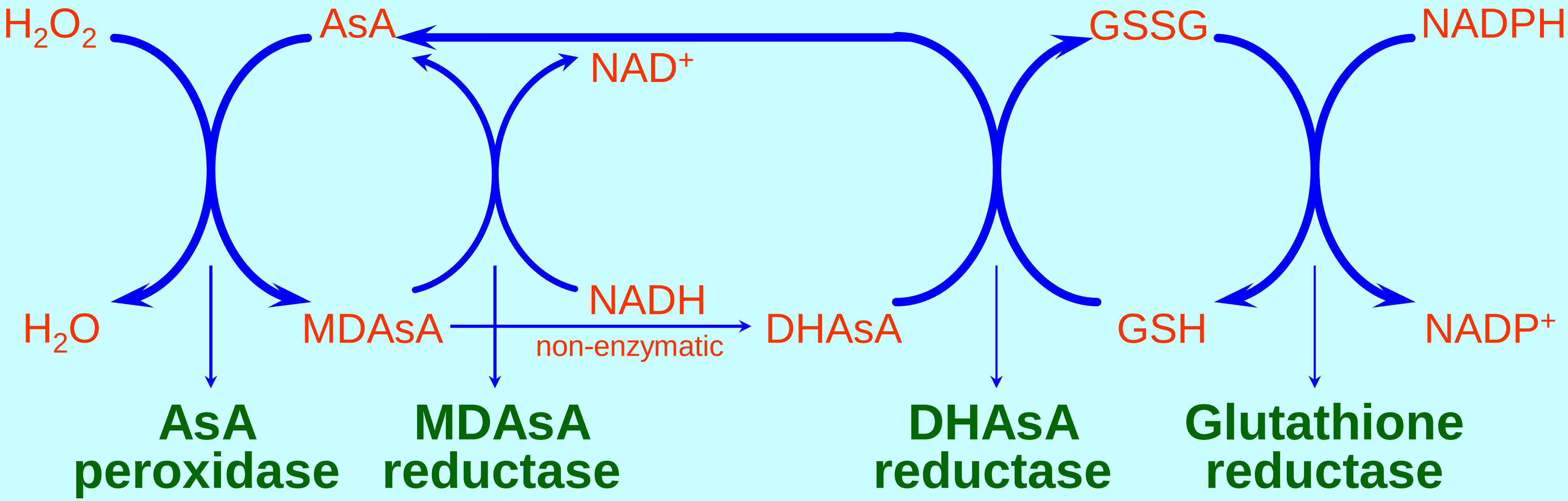
Control

Low K

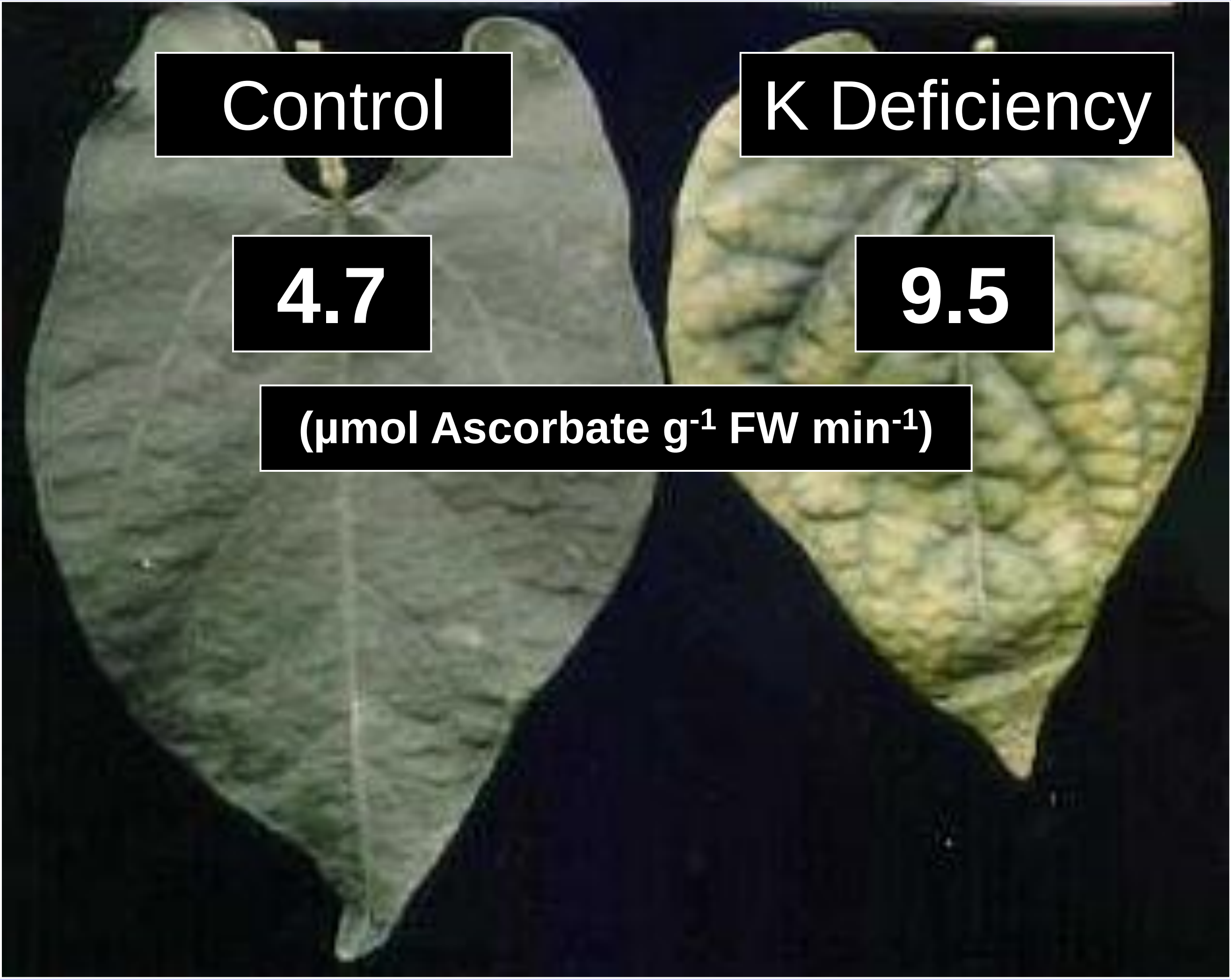
Low Mg

Low P

Enzymes involved in H_2O_2 detoxification in chloroplasts



Ascorbate Peroxidase Activity of Source Leaves



Control

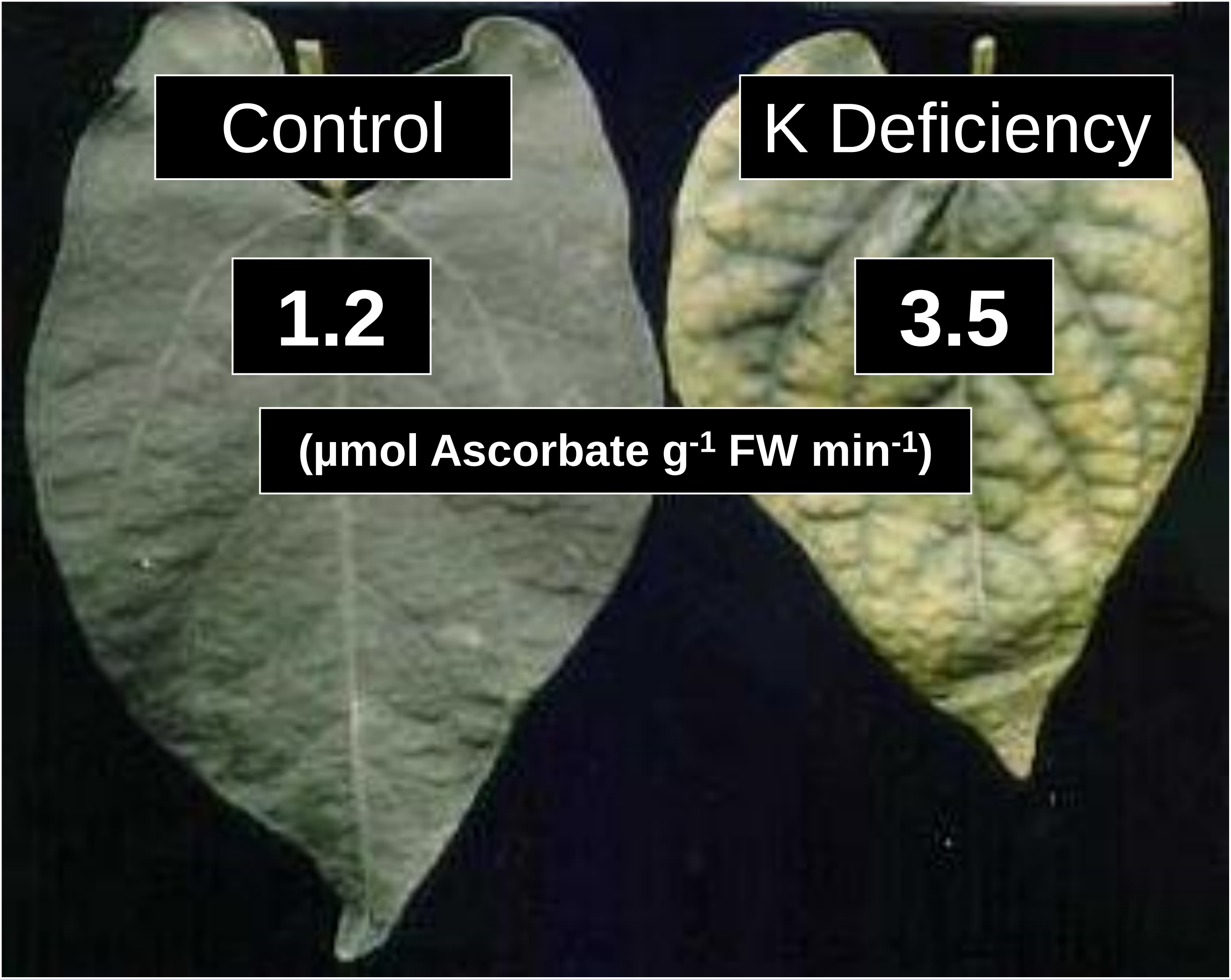
K Deficiency

4.7

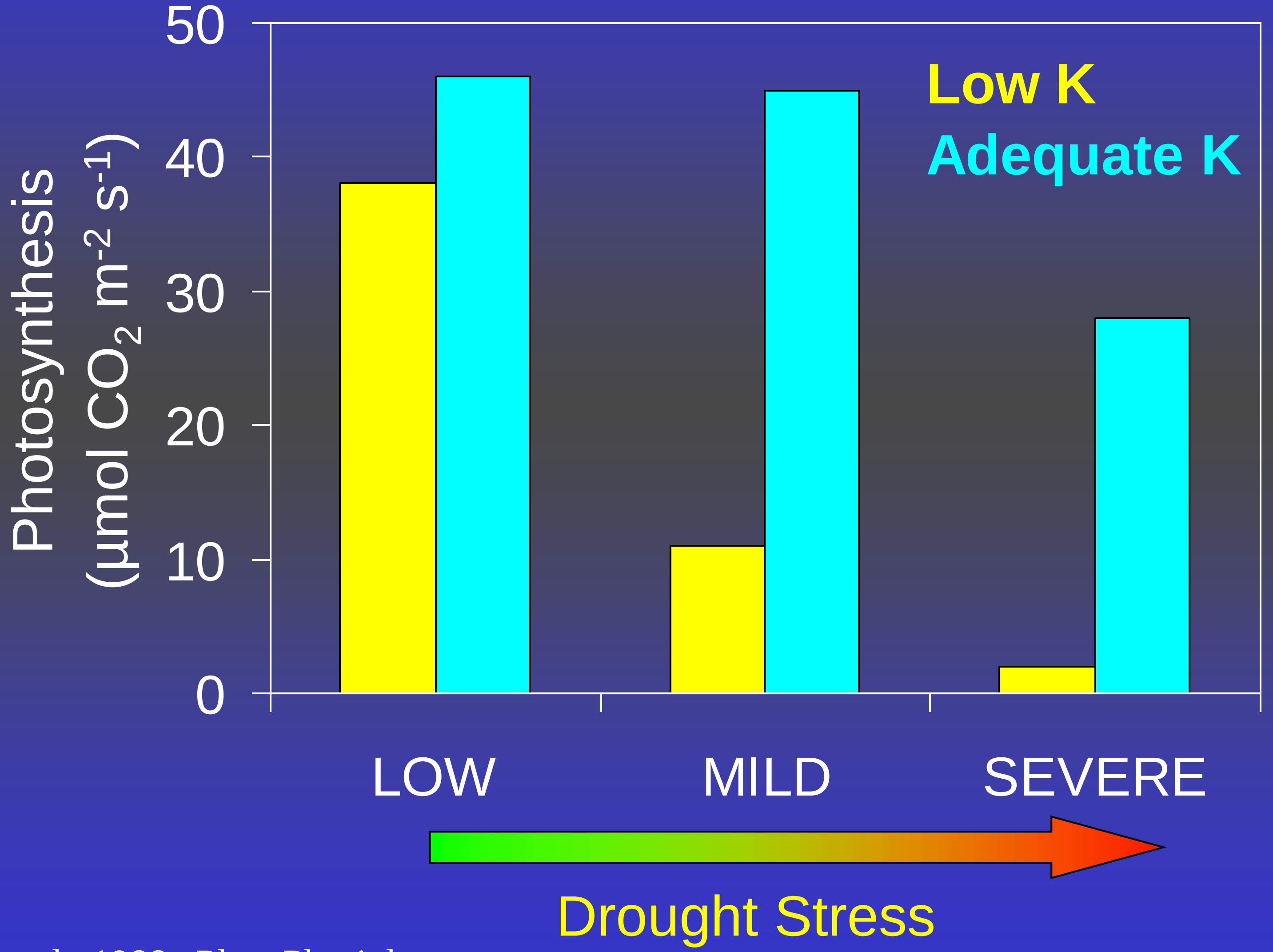
9.5

(µmol Ascorbate g^{-1} FW min^{-1})

Monodehydroascorbate Reductase Activity of Source Leaves

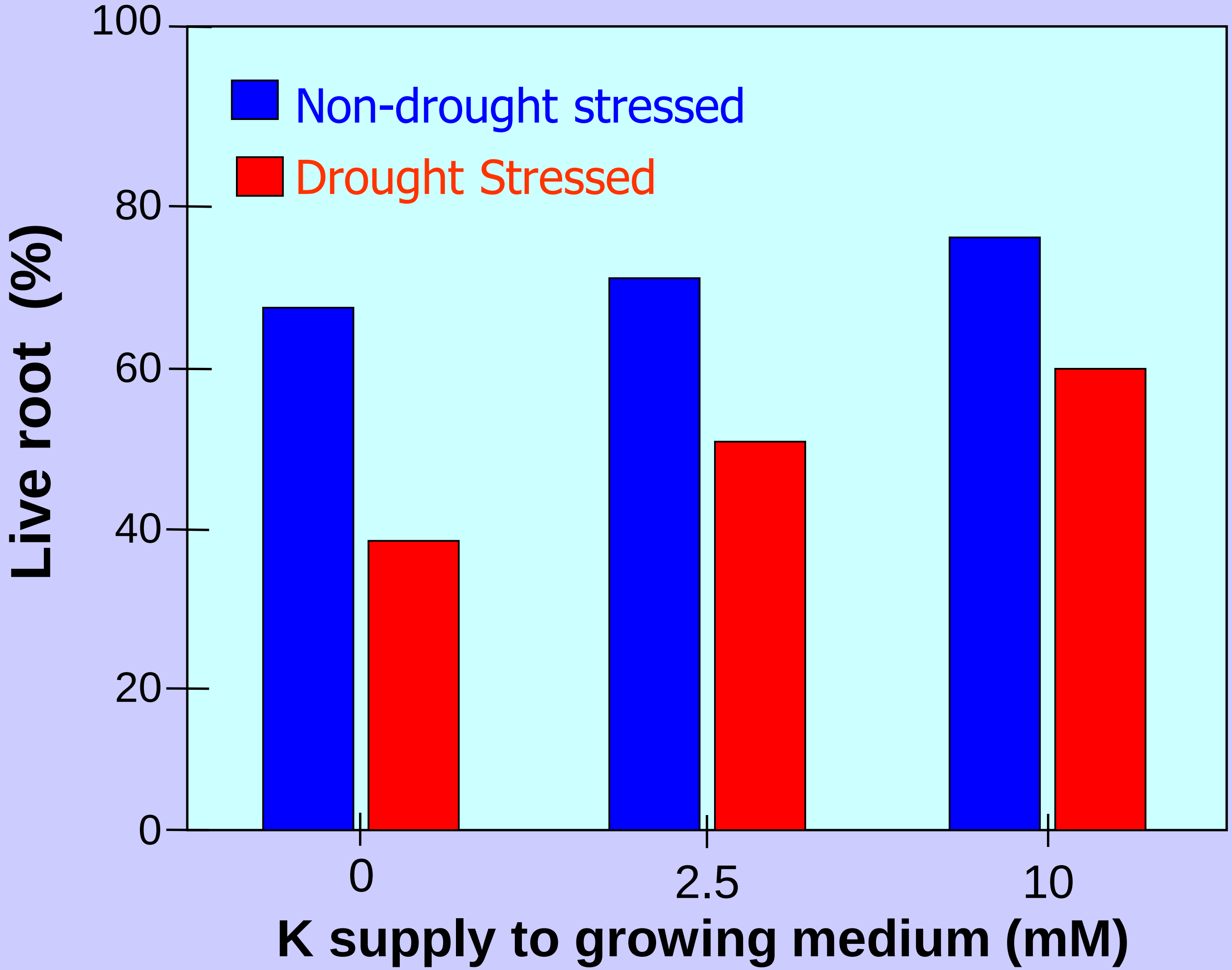


Potassium Improved Photosynthesis Under Drought Stress

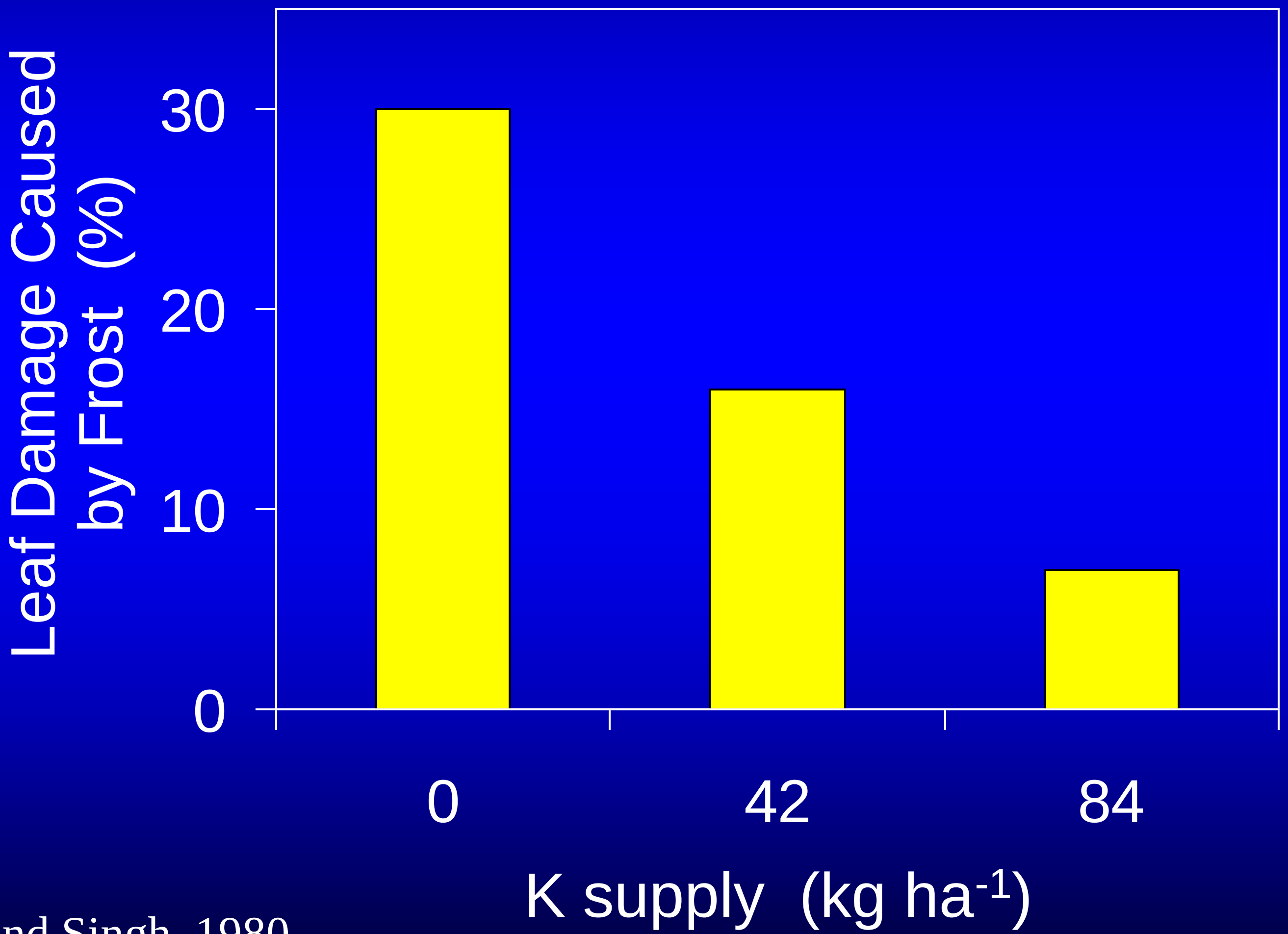


Sen Gupta et al., 1988, Plant Physiol.

Effect of increasing K Supply on Percentage of Live Roots Under Varied Drought Treatments

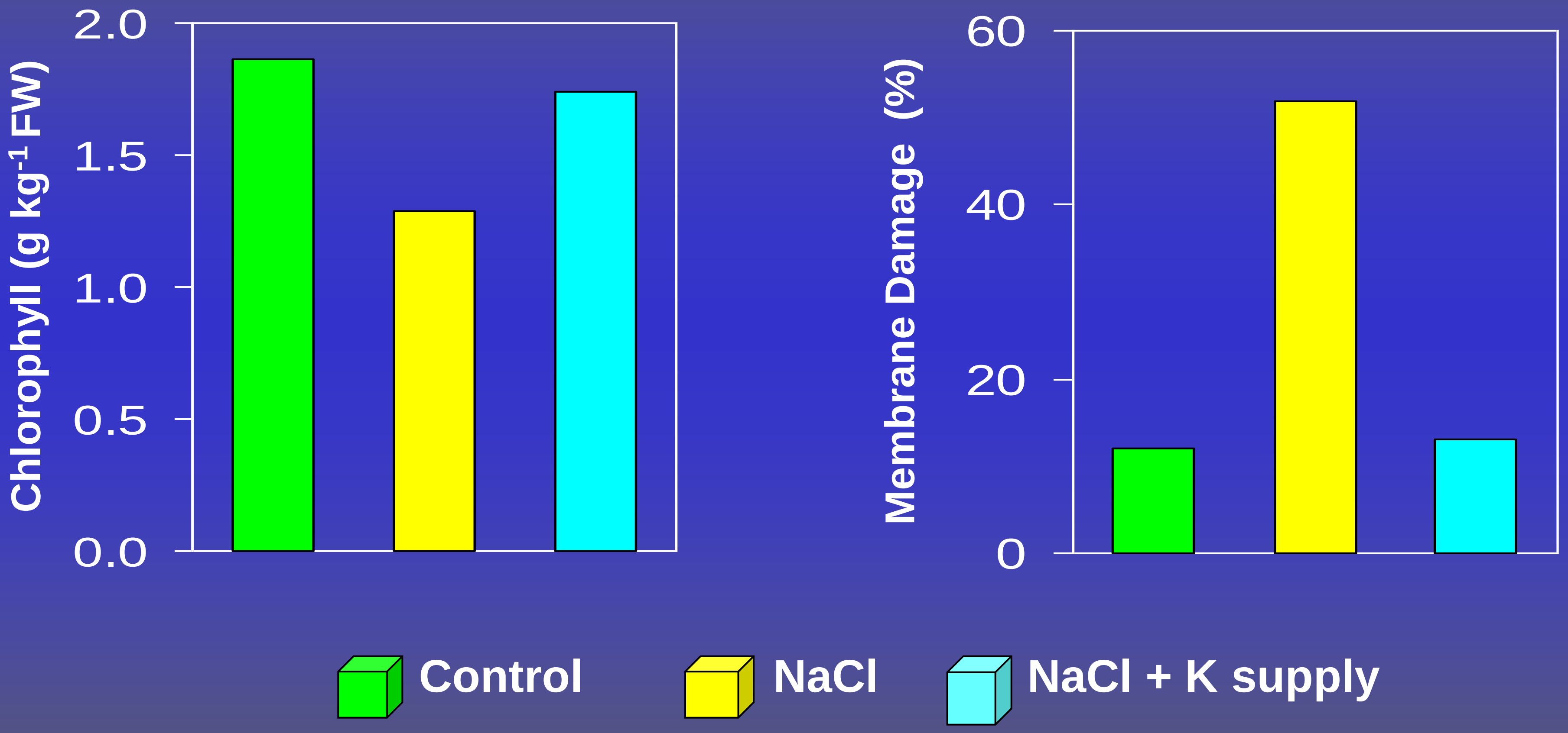


Alleviation of Frost Damage by K Supply in Potato



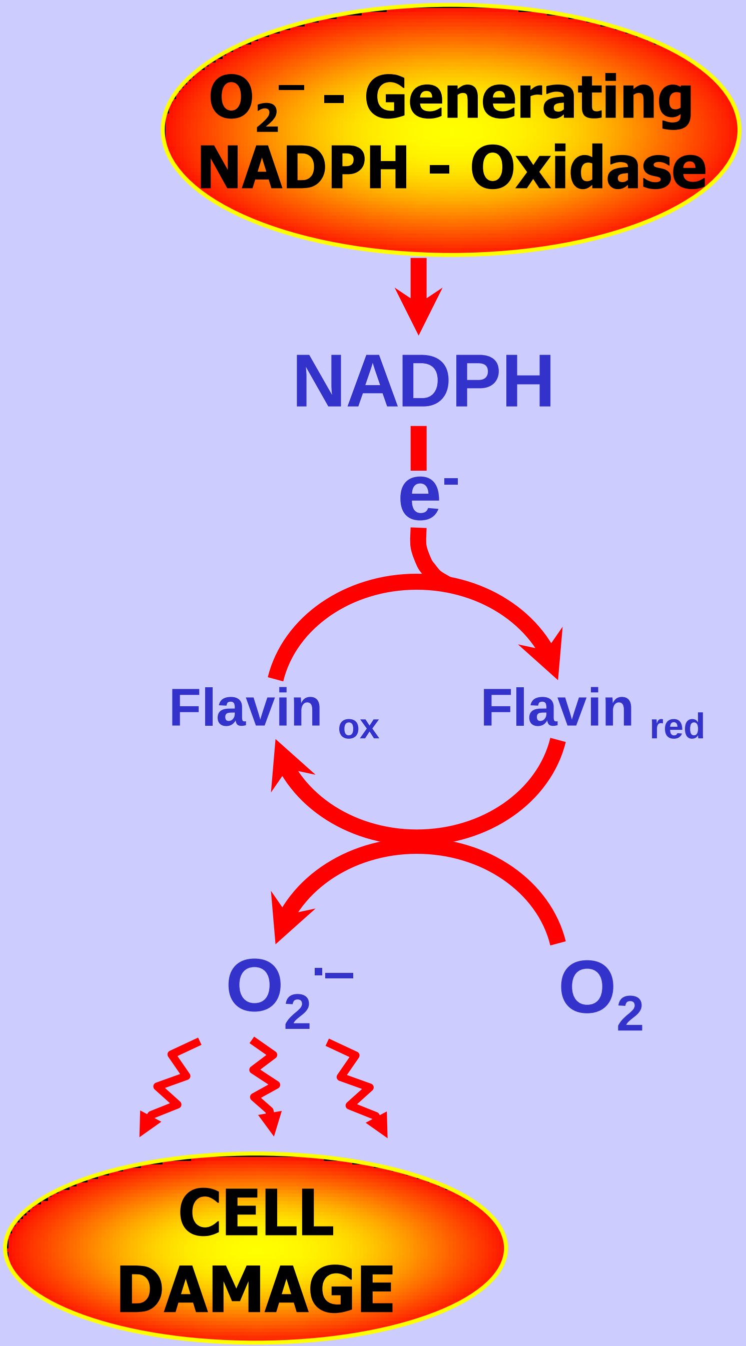
Grewal, and Singh, 1980

Alleviation of Salt Stress by K Supply



Kaya et al., 2001, J. Plant Nutr.

Activity of **NADPH-oxidizing enzymes** play an important role in generation of superoxide radical production under drought, chilling, Zn deficiency, UV light, wounding, pathogenic infection, etc.



O_2^{-} - Generating NADPH - Oxidase

NADPH

e^-

Flavin $_{ox}$

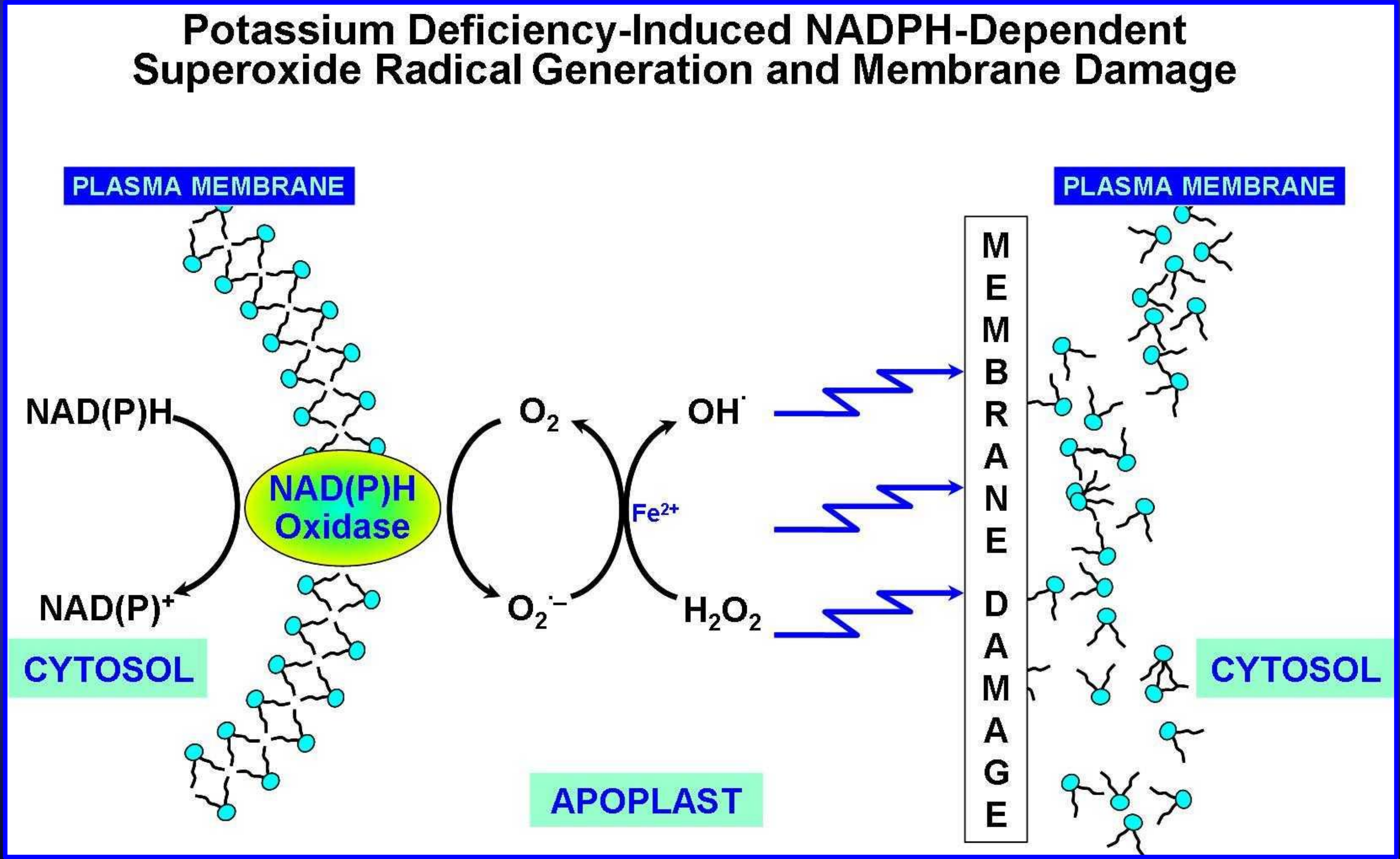
Flavin $_{red}$

$O_2^{\cdot -}$

O_2

CELL DAMAGE

Stress stimulated NADPH oxidase and NADPH-dependent superoxide radical generation



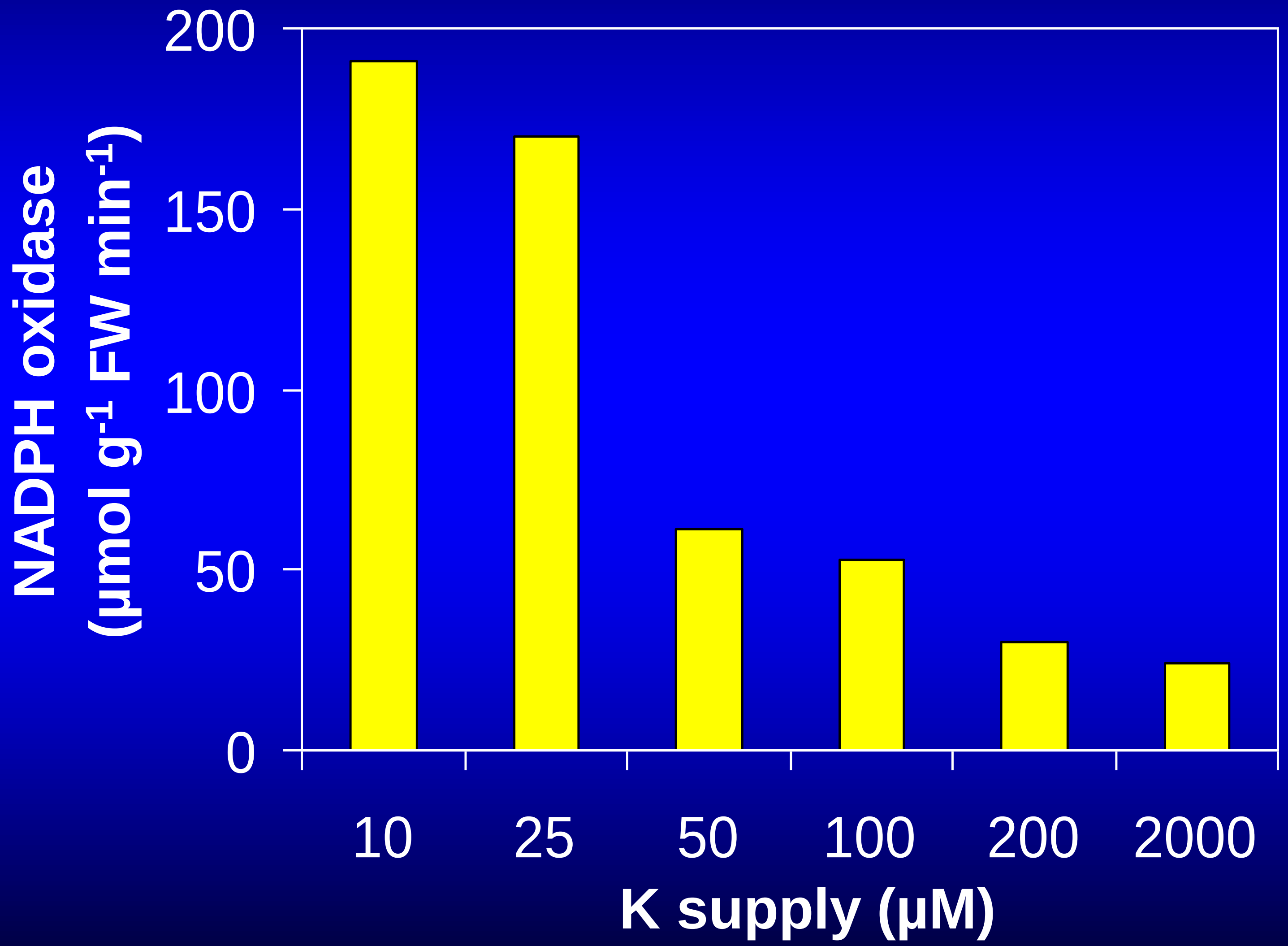
Cakmak, 2003, in press

Increases in NADPH-Dependent O_2^- Generation by K Deficiency in Bean Roots

K supply	$O_2^{\cdot -}$ generation
(µmol)	(nmol $O_2^{\cdot -}$ FW min^{-1})
10	45 (124)
25	42 (117)
50	50 (139)
100	49 (136)
200	44 (122)
2000 (control)	36 (100)

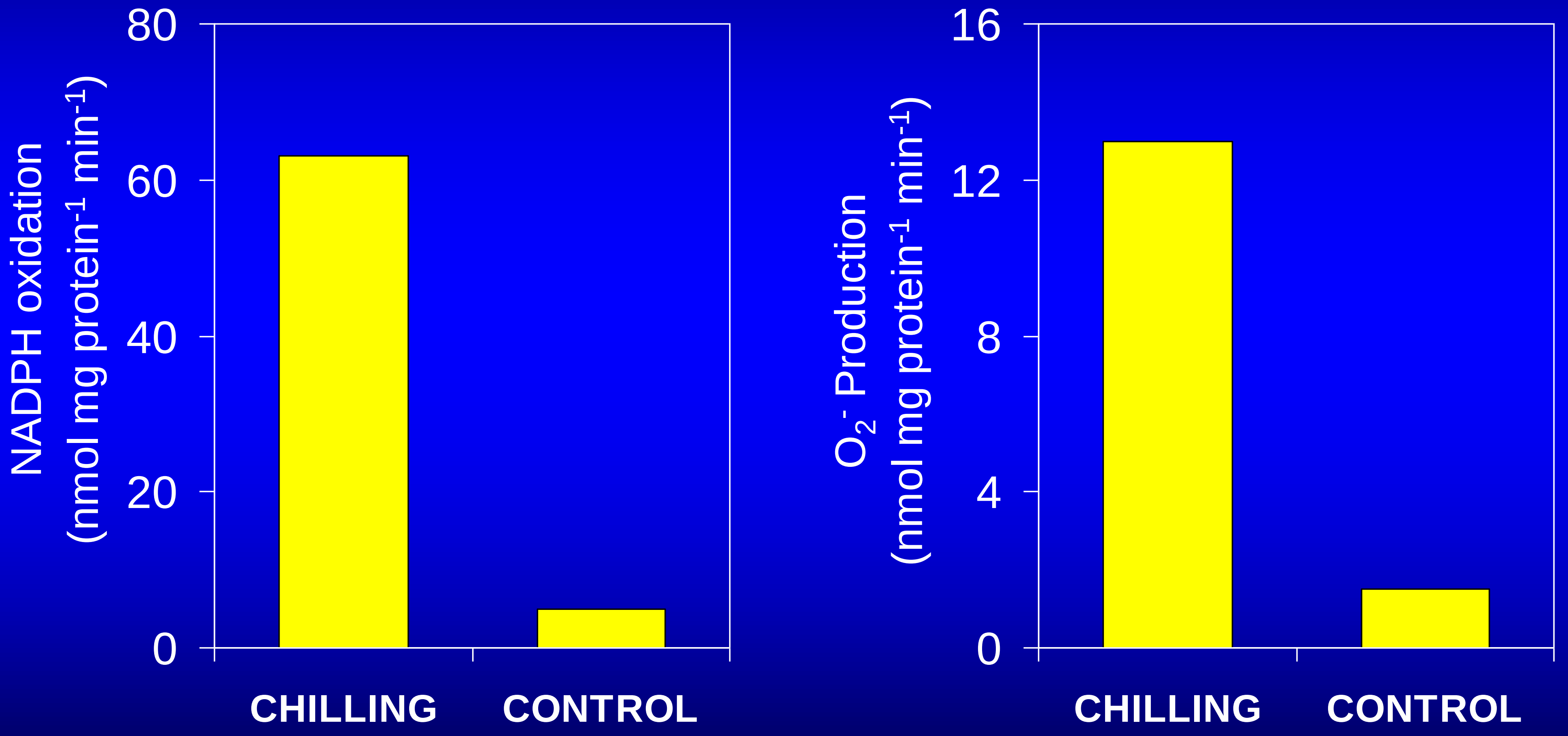
S. Eker, unpublished results

K Deficiency-Induced Marked Increases in NADPH Oxidase Activity of Bean Roots



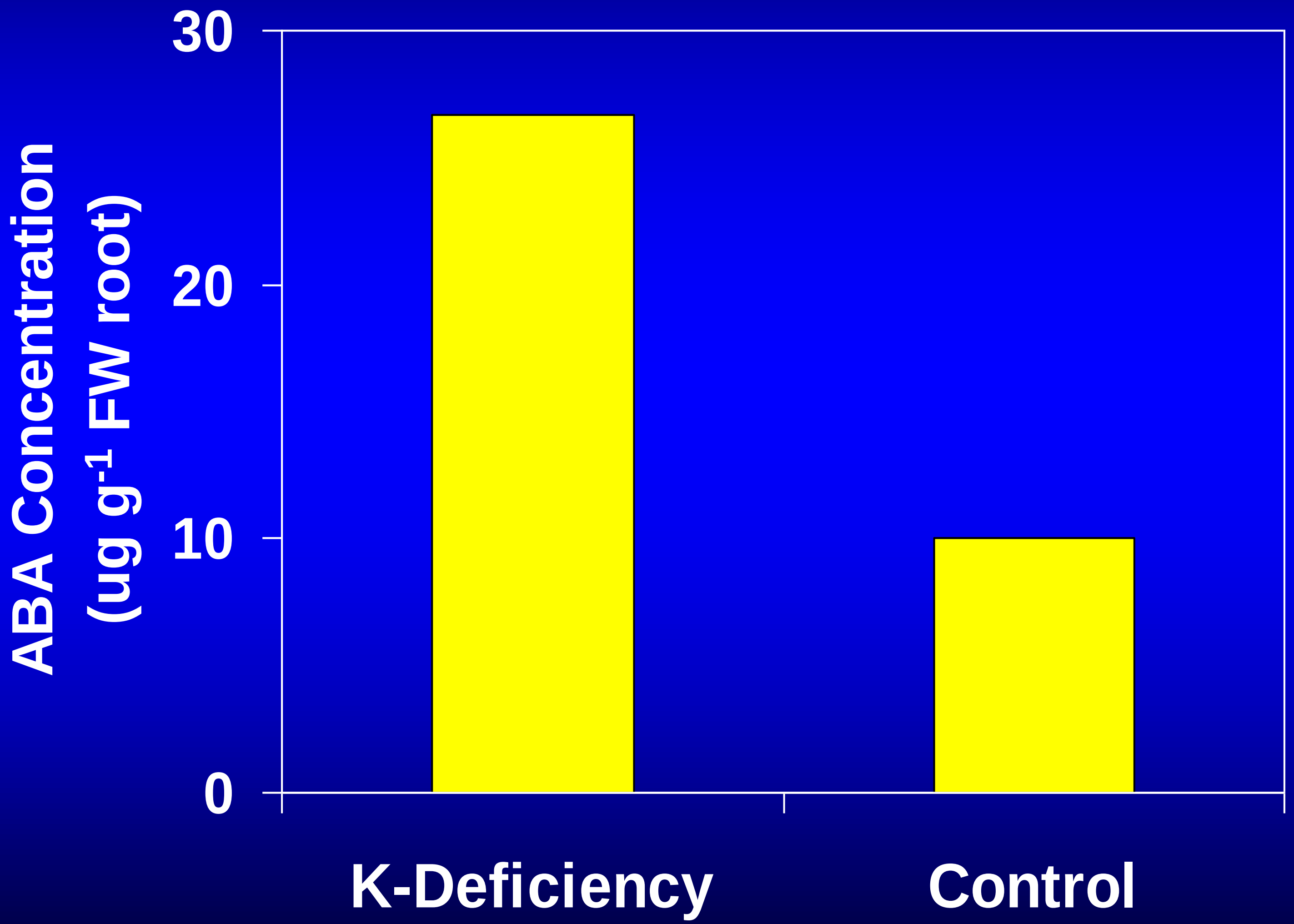
S. Eker, unpublished results

Chilling-Induced NADPH-Oxidation and NADPH-Dependent O_2^- Generation in Leaves of Cucumber



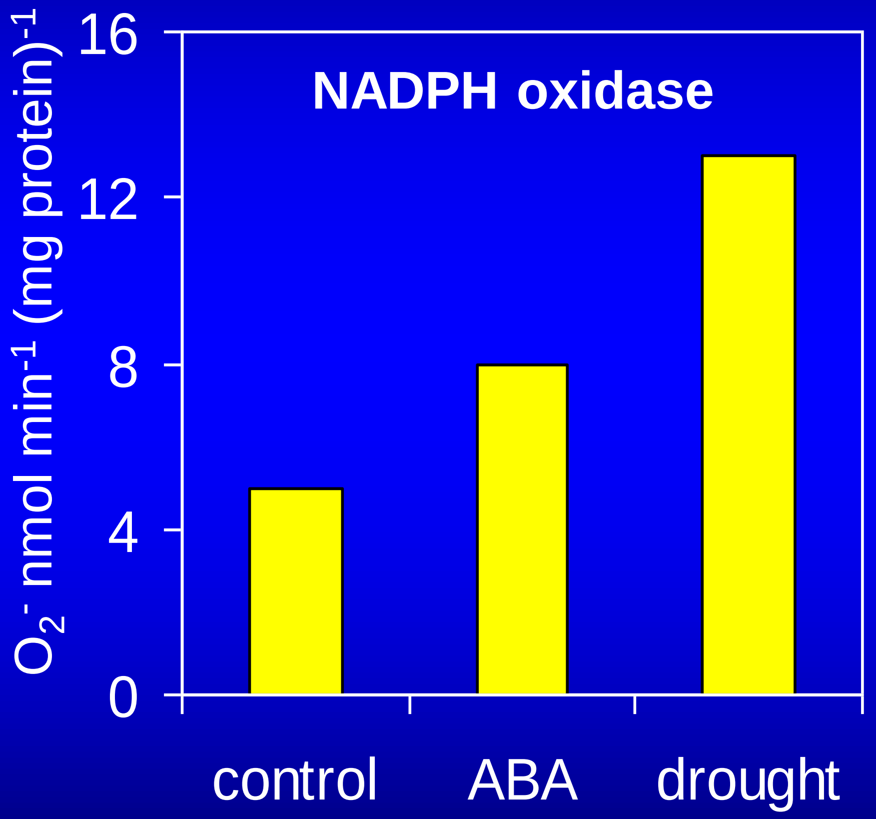
Shen et al., 2000; Plant Physiol.

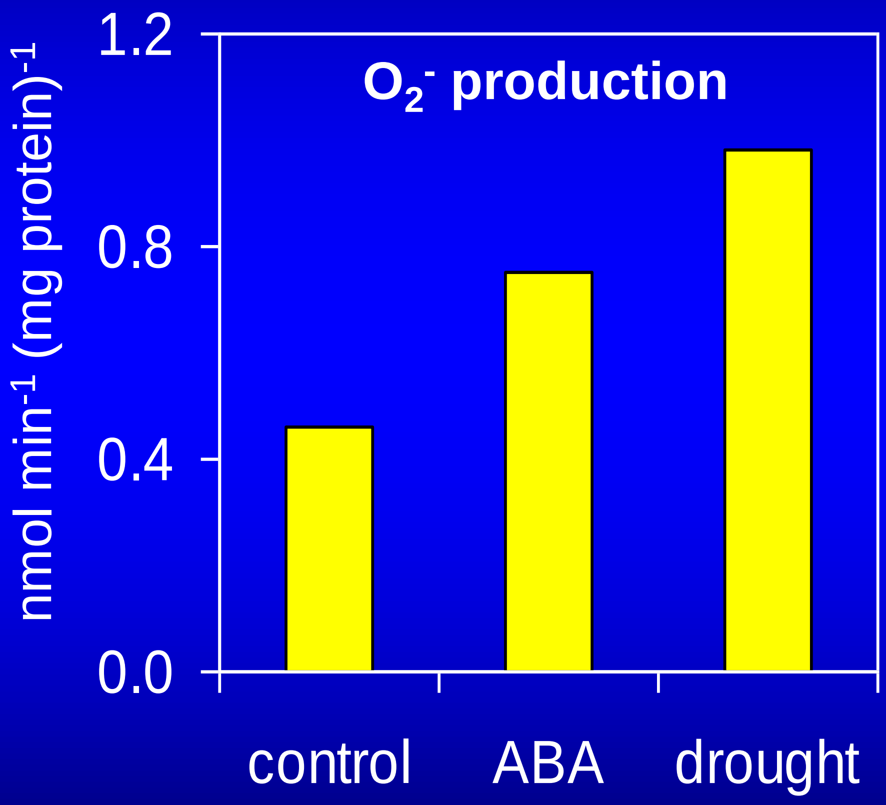
K Deficiency-Induced Biosynthesis of ABA (Abscisic Acid) in Roots



Peuke et al., 2002, J. Exp. Botany

NADPH oxidase and O_2^- Production in Plants Treated with ABA and Drought





ABA: Abscisic Acid

Jiang and Zhang, 2002; Planta

Zn and B deficiencies also affect photosynthetic activities of plants in various ways.

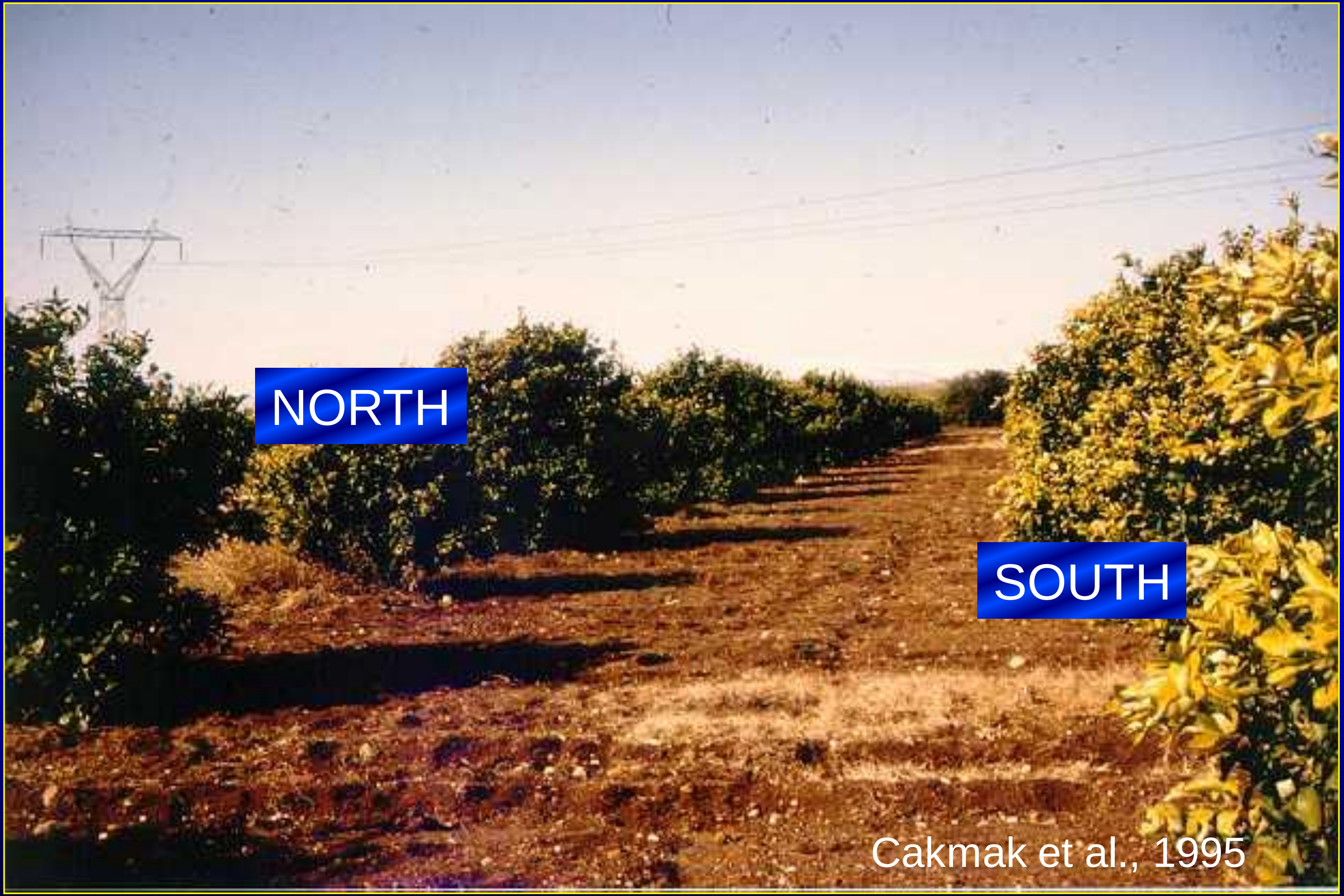
- Both micronutrients exert marked influences on photosynthetic CO_2 fixation and translocation of photosynthates.

- Any disturbance in the adequate supply of plants with Zn and B is, therefore, potentially capable of inducing photooxidative damage

ALSO ZINC-DEFICIENT PLANTS ARE HIGHLY PHOTOSENSITIVE

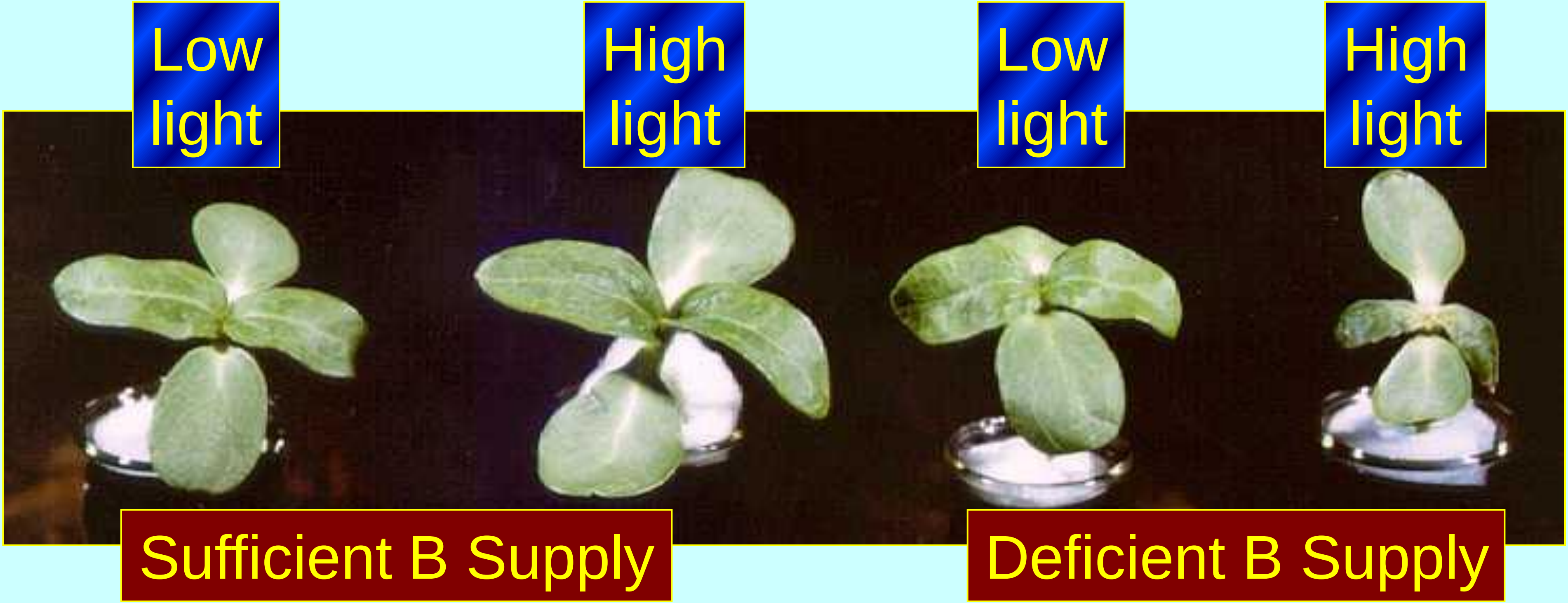
Increases in light intensity rapidly cause development of chlorosis and necrosis in Zn-deficient plants

Growth of Citrus Trees on a Zn-Deficient Soil

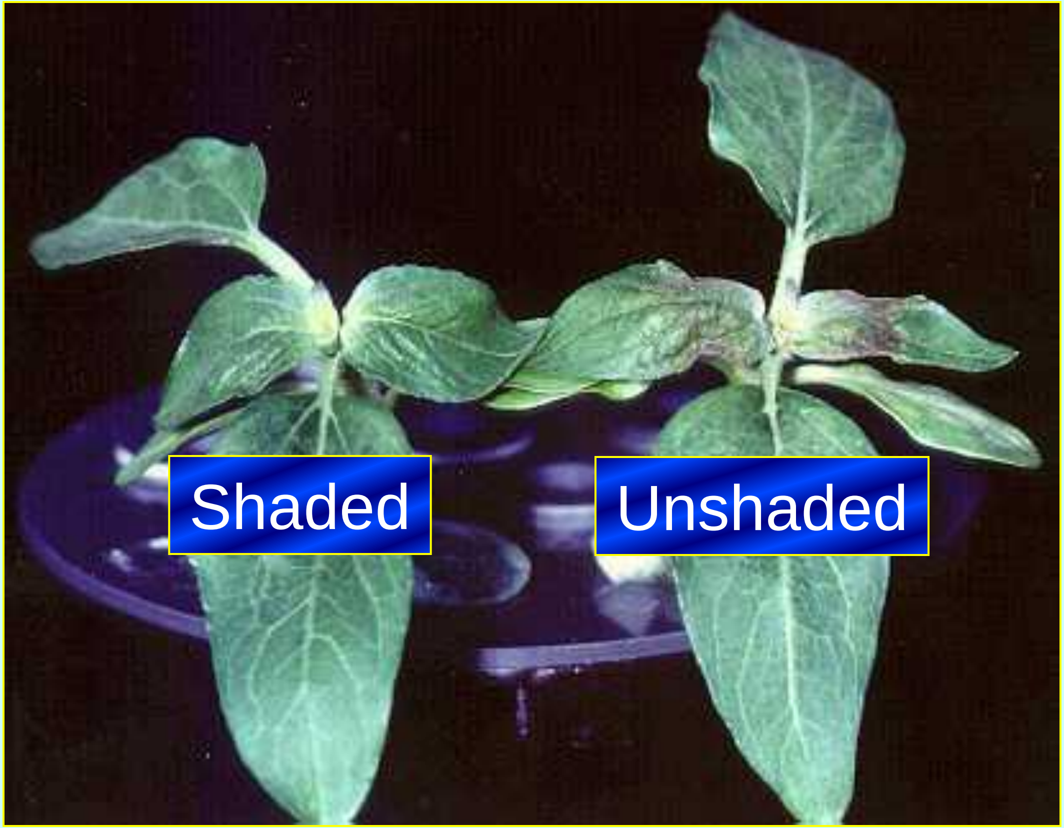


Cakmak et al., 1995

High light-induced damage in **B-deficient plants**

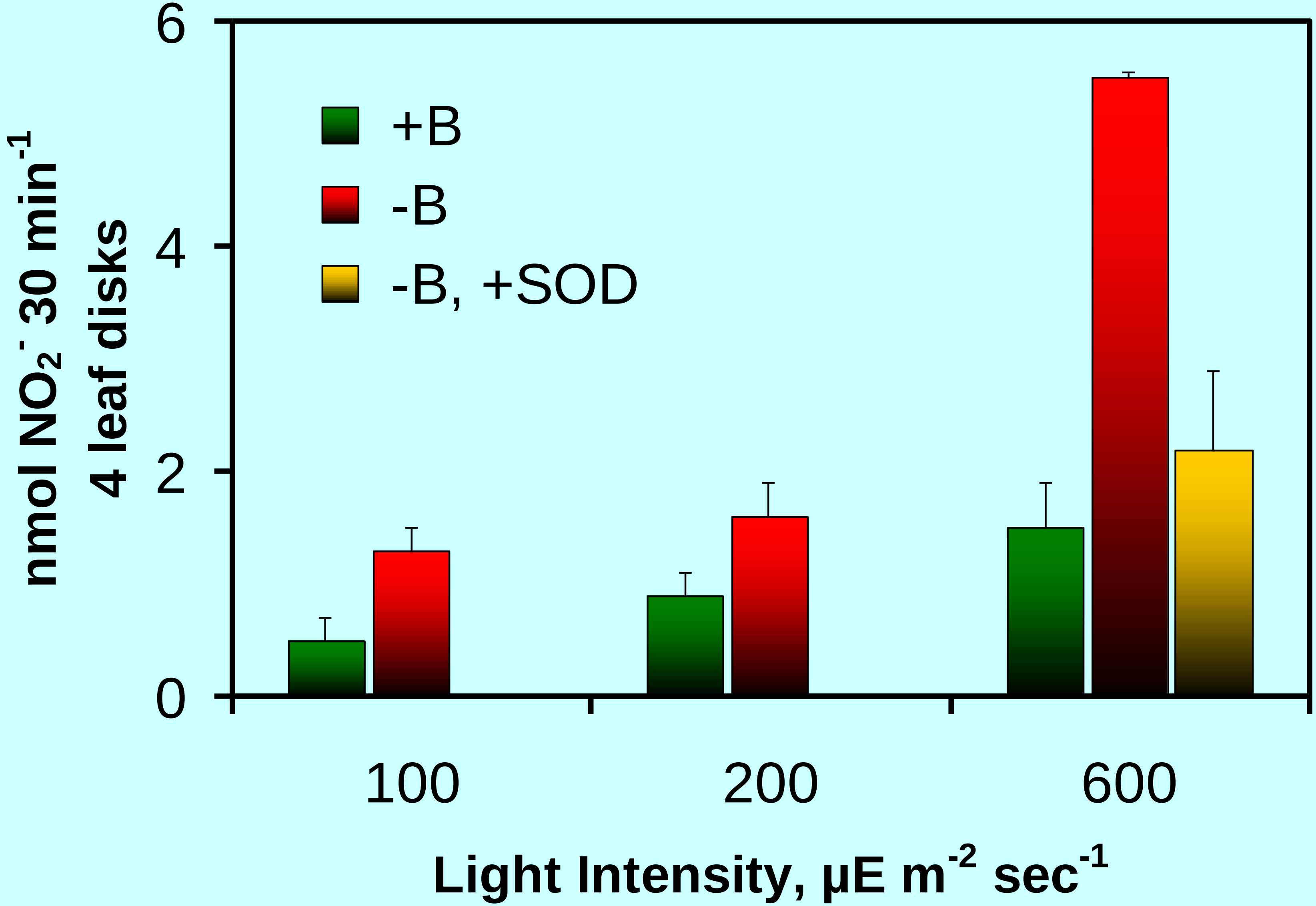


Superoxide Generation and Photooxidative Damage

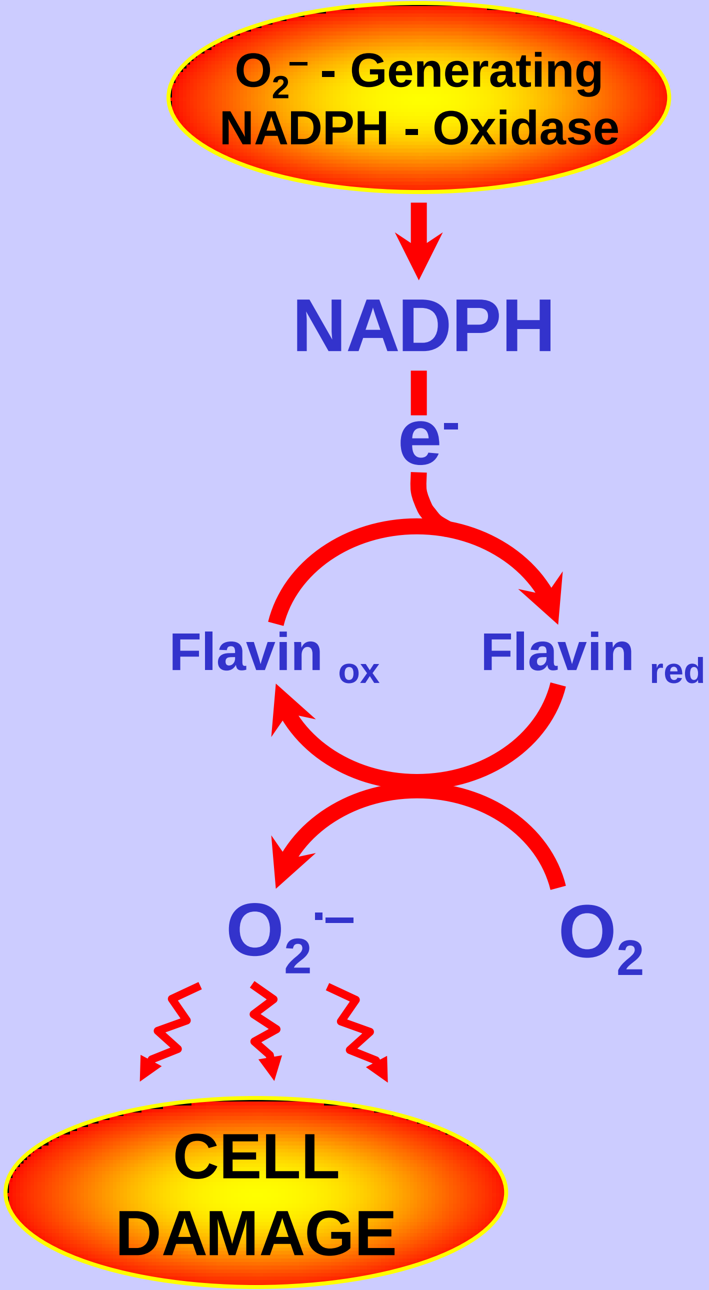


Photooxidative damage to membrane and chlorophyll can be expected in B-deficient leaves as a result of enhanced photogeneration of toxic oxygen free radicals caused by impaired utilization of light energy in photosynthesis

O_2^- - Production in Leaf Disks from B-Deficient Plants



Activity of NADPH-oxidizing enzymes play an important role in generation of superoxide radical under drought, chilling, Zn deficiency, UV light, wounding, pathogenic infection, etc.



O_2^{-} - Generating NADPH - Oxidase

NADPH

e^-

Flavin $_{ox}$

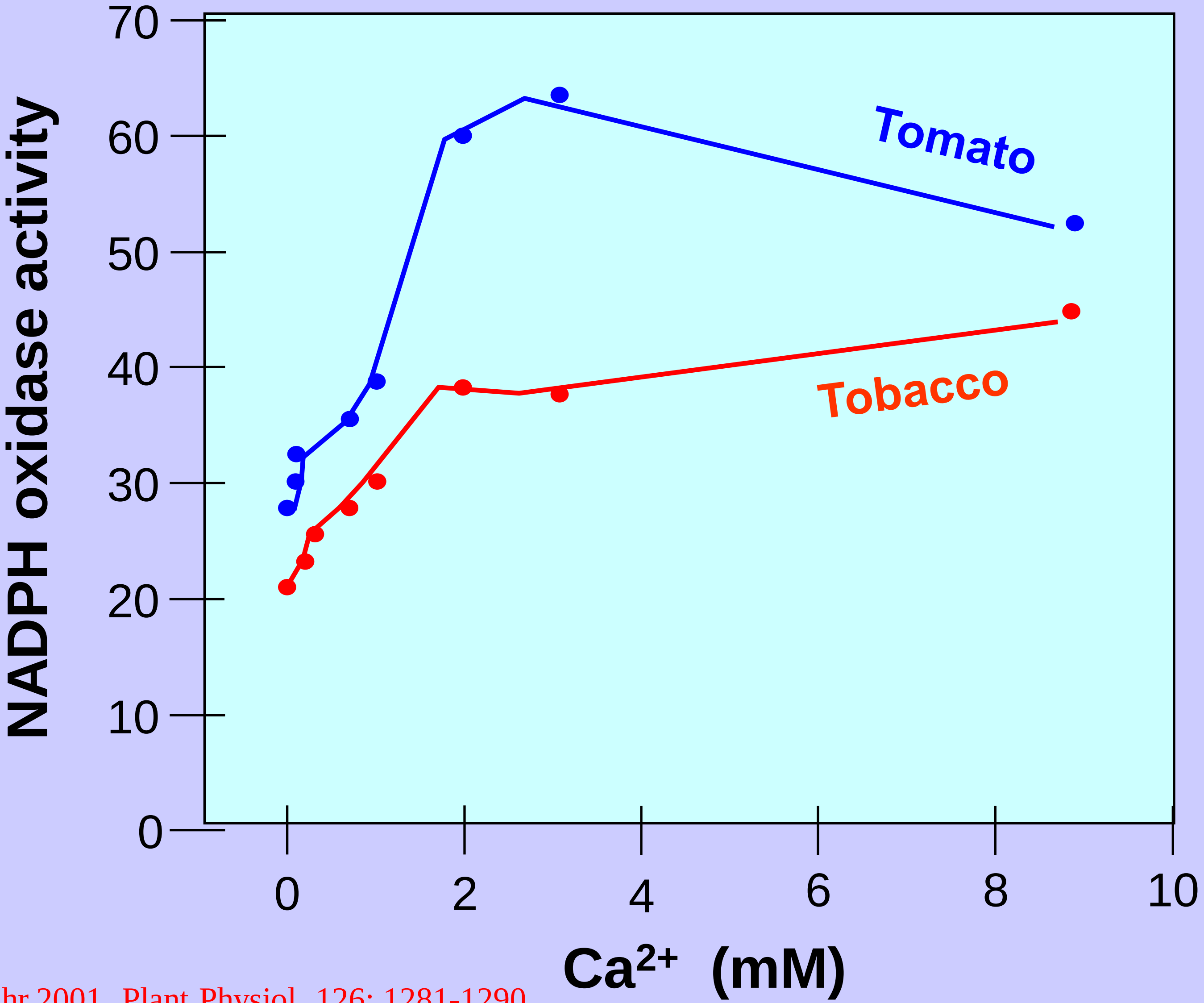
Flavin $_{red}$

$O_2^{\cdot -}$

O_2

CELL DAMAGE

NADPH Oxidase Activity in Isolated Tomato and Tobacco Membranes



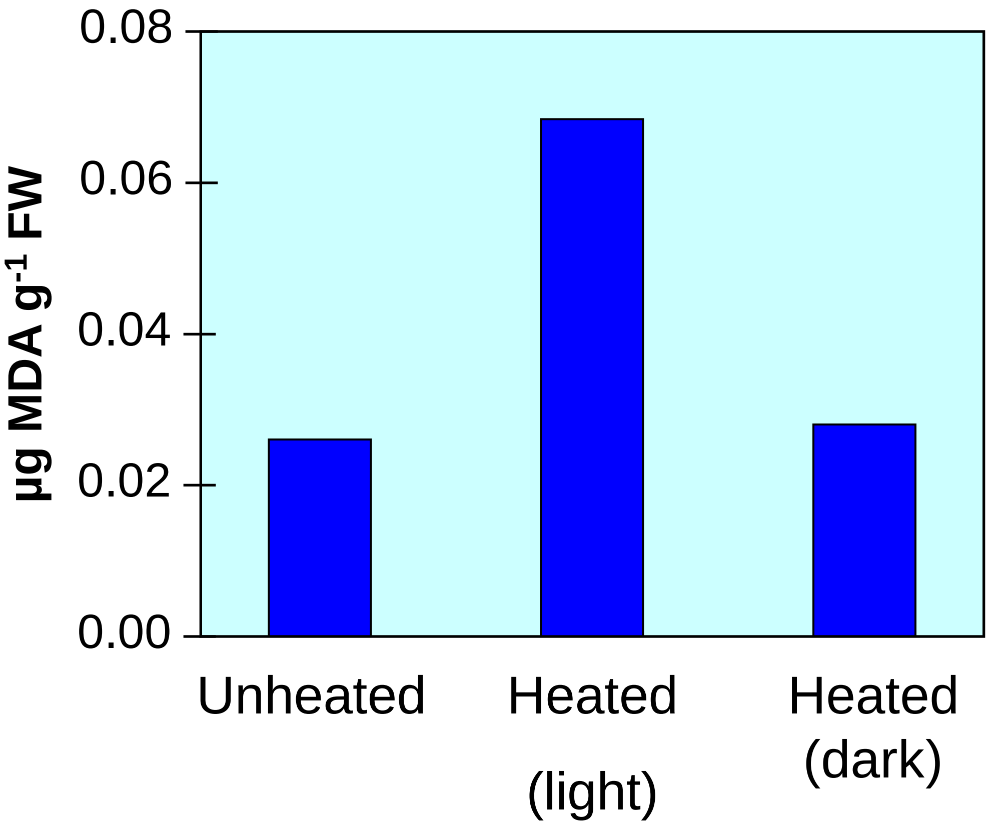
Sagi and Fluhr,2001, Plant Physiol. 126: 1281-1290

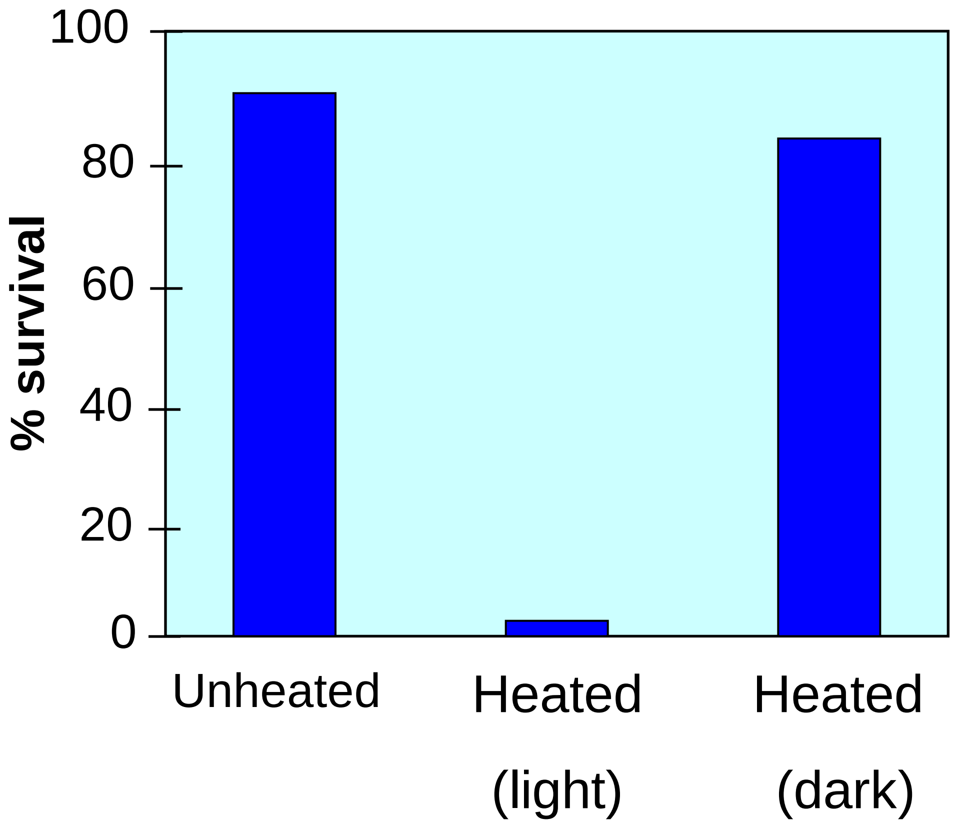
There is increasing evidence suggesting that Ca is involved in expression of high tolerance to heat stress in plants.

- Jiang and Huang (2001) showed that Ca treatment protects cool-season grass species from heat injury expressed as increased lipid peroxidation and chlorophyll degradation.

- Exposure of seedlings to heat stress at 40 ^{o}C induced lipid peroxidation and reduced survival of seedlings, and these effects of heat stress could be inhibited very significantly by Ca treatment.

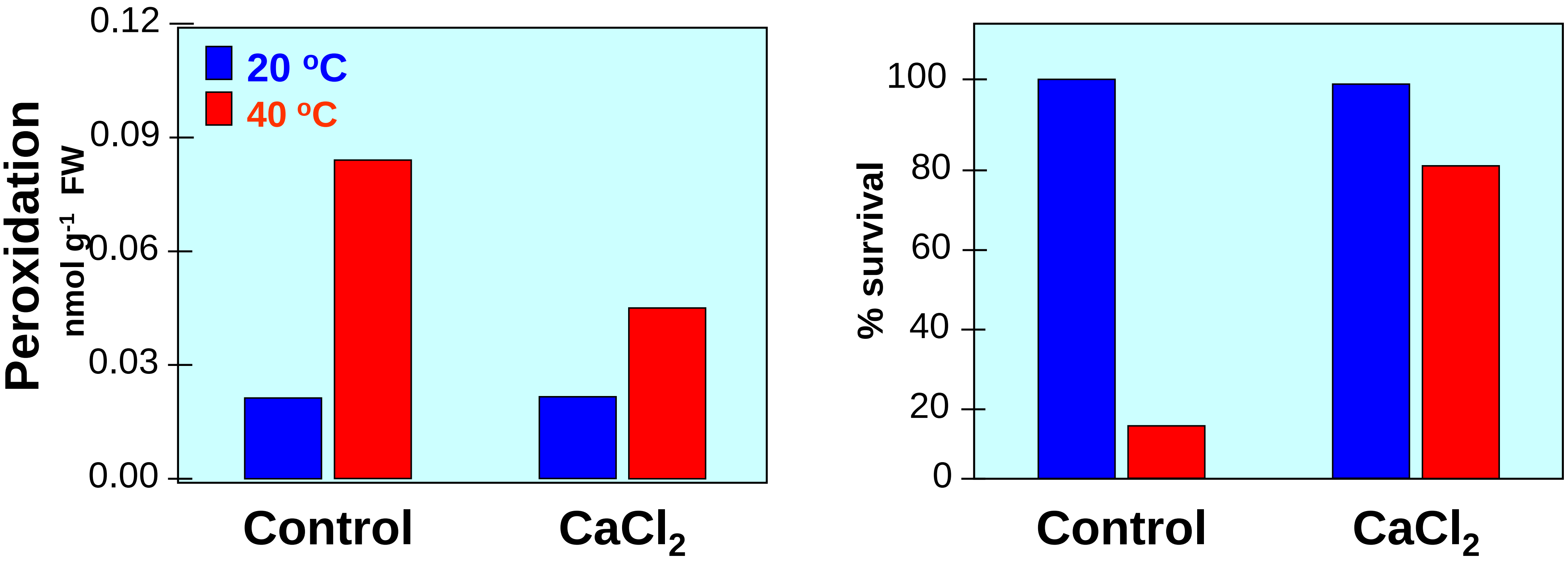
Oxidative Damage and Survival in Response of Heating in Arabidopsis





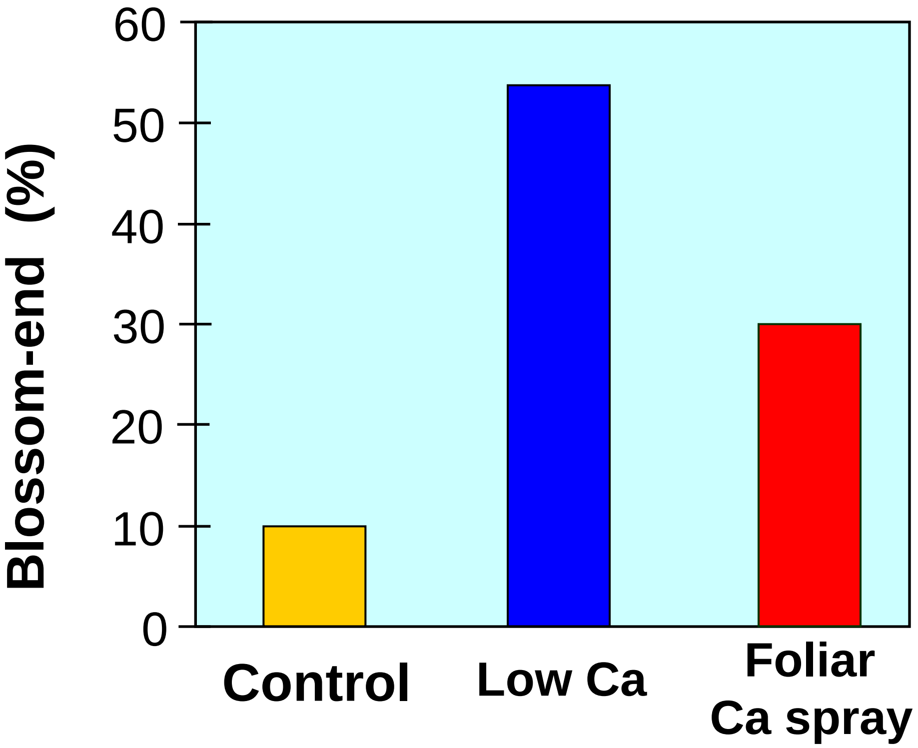
Larkindale er al., Plant Physiol. 2002, 128: 682-695

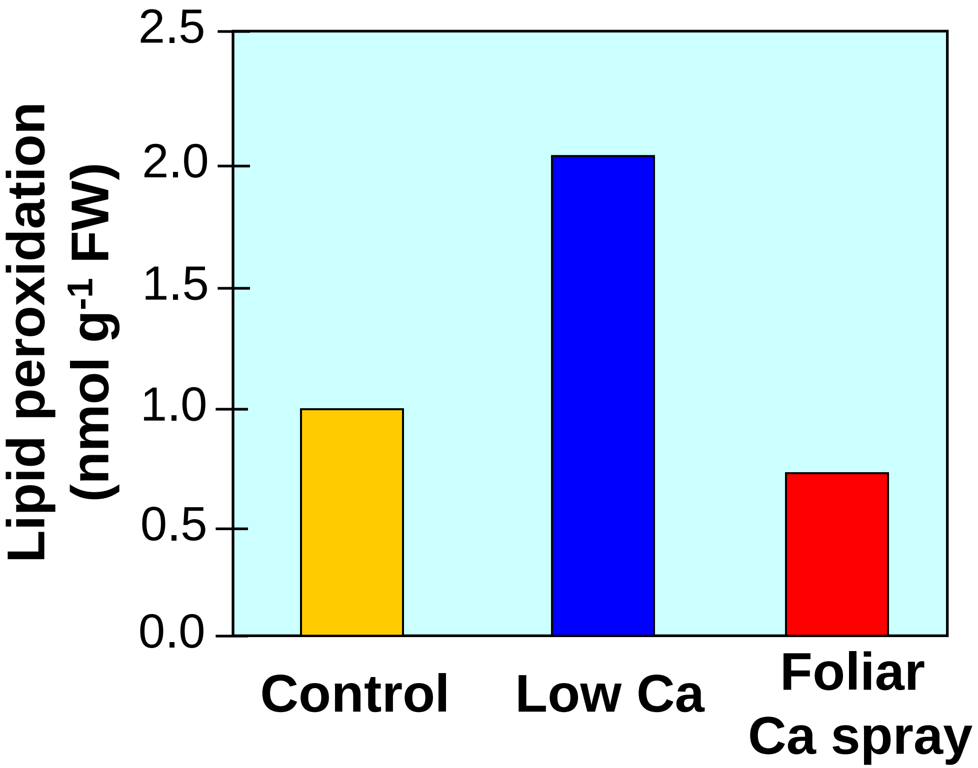
Oxidative Damage and Survival in Response of Heating in Arabidopsis with and without Ca supply



Larkindale er al., Plant Physiol. 2002, 128: 682-695

Effect of Foliar Application of Ca on Lipid Peroxidation and Blossom-end





Schmitz-Eiberger et al., J. Plant Physiol. 2002, 159: 733-742

CONCLUSIONS

- The existing data indicate that improving mineral nutritional status of plants under marginal environmental conditions is indispensable for sustaining survival and high yield.

- Impairment in mineral nutritional status of plants, therefore, exacerbates adverse effects of environmental stress factors on plant performance.

- **Mineral at adequate levels nutrients supplied are essentially required for maintaining photosynthetic activities and utilization of light energy in CO_2 fixation.**

- **Improving mineral nutrition of plants is, therefore, a major contributing factor to the protection of plants from photooxidative damage under marginal environmental conditions.**

Remaining challenges include the better understanding the roles of mineral nutrients in

i) ROS formation during photosynthesis and plasma membrane-bound NADPH oxidase,
ii) signaling pathways affecting adaptive response of plants to environmental stresses and
iii) expression and regulation of genes induced by mineral nutrient deficiency.