Environmental productivity indices for crop growth and development: Cotton as an example

Photosynthesis

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Photosynthesis and Respiration and Environment

Goals and Learning Objectives:

- To understand the effects of multiple environmental factors on photosynthesis and respiration.
  - Photosynthesis and environment and Environmental Productivity Index (EPI) concept using cotton as an example crop.
  - Photosynthesis and environment and species variability and applicability of EPI concept.
  - Leaf and canopy aging and their relationship with photosynthesis.
  - Respiration and environment

Photosynthesis and Environment

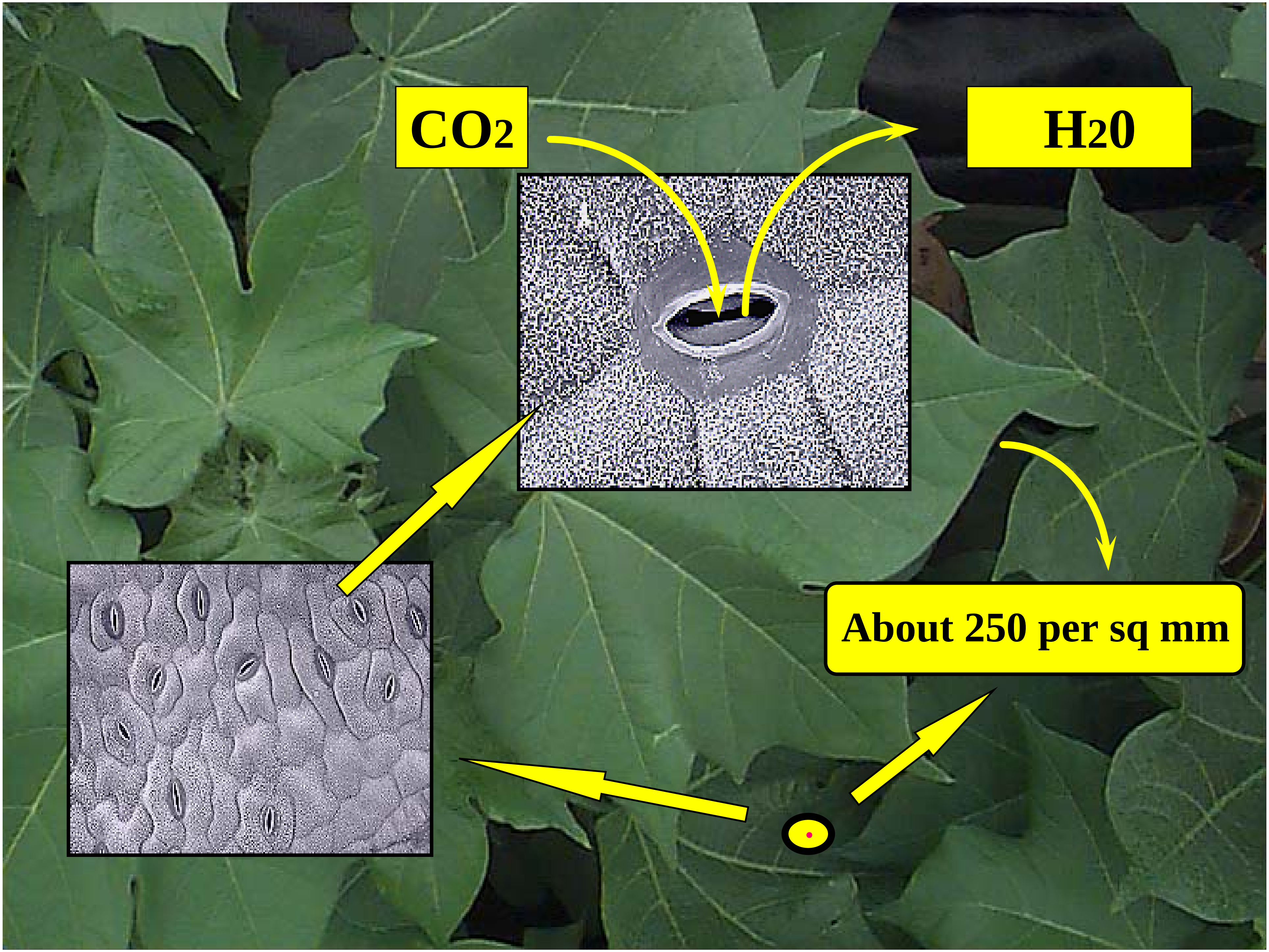
You will learn:

- Effects of environmental factors on photosynthesis
- How to quantify the effects of multiple environmental factors on photosynthesis.
- How to calculate potential photosynthesis under optimum conditions.
- How to develop environmental productivity indices for various environmental factors to decrement the potential photosynthesis and to calculate actual photosynthesis.

Photosynthesis

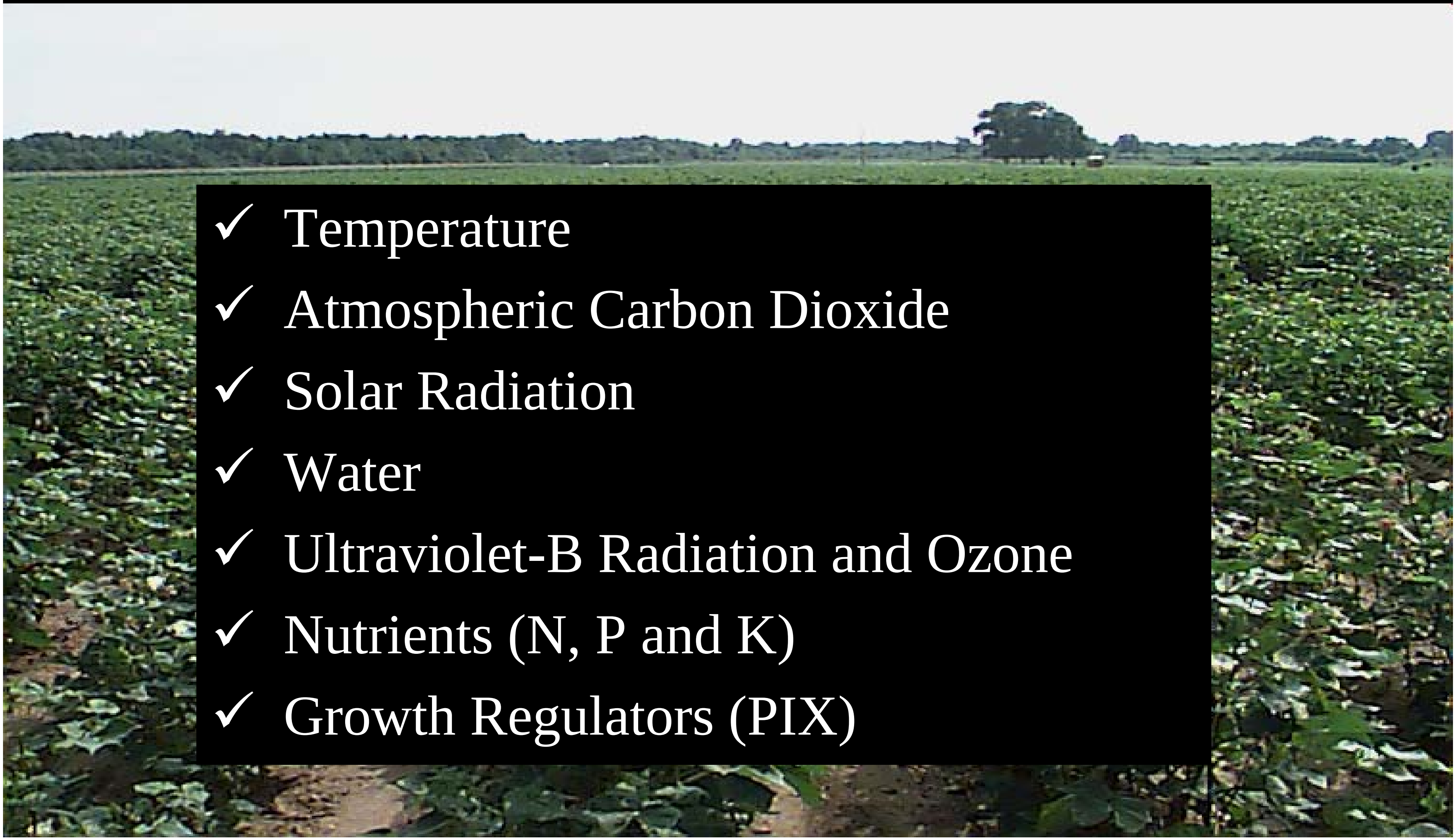
- The process in which plants uses the energy from sunlight to combine carbon dioxide (CO_2) from the air with water to make carbohydrates plus oxygen.

$$6\ CO_2 + 6\ H_2O \xrightarrow[\text{Water, Nutrients}]{\text{Light, Plant}} C_6H_{12}O_6 + 6\ O_2$$



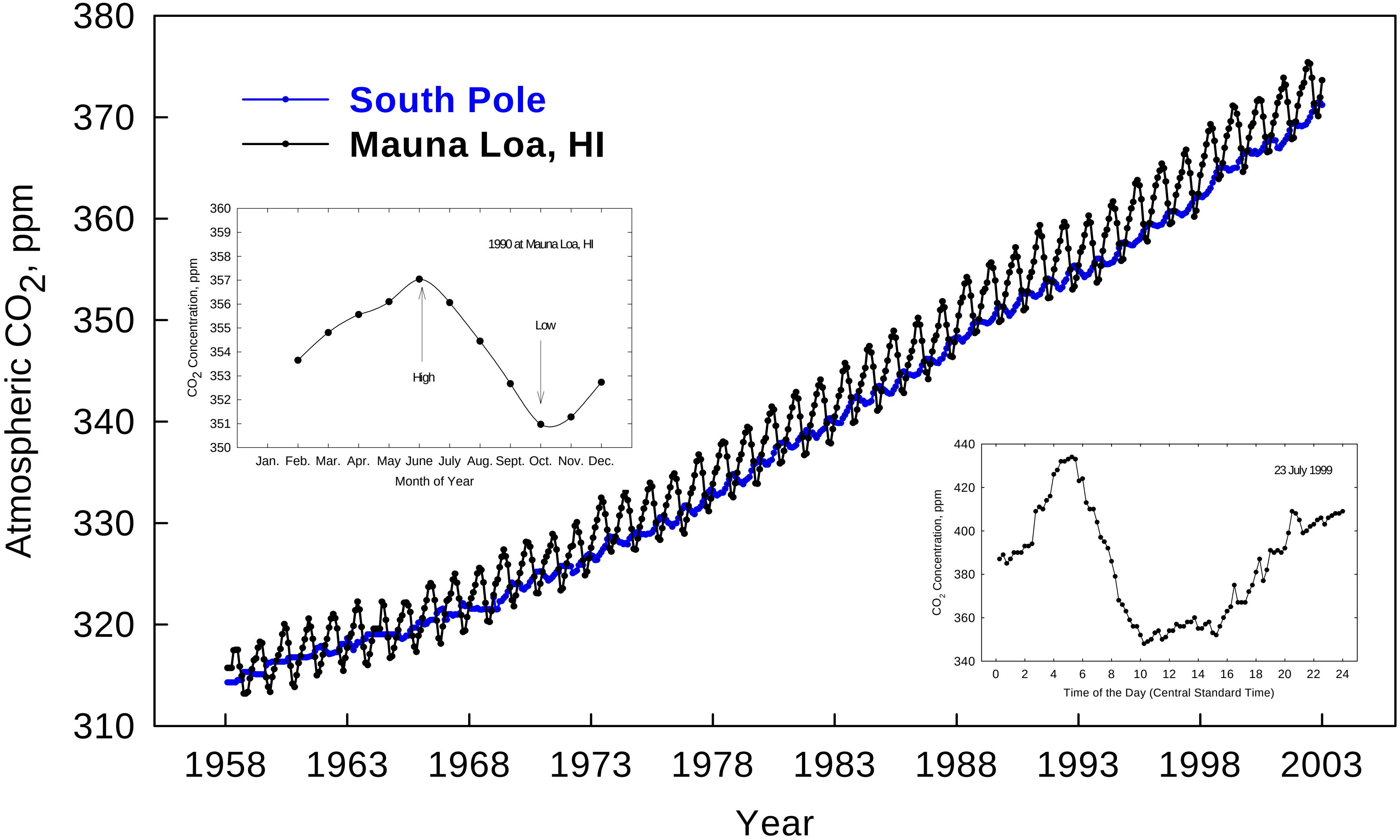
CO2
H20
About 250 per sq mm

Environmental and cultural factors affecting Cotton growth and productivity



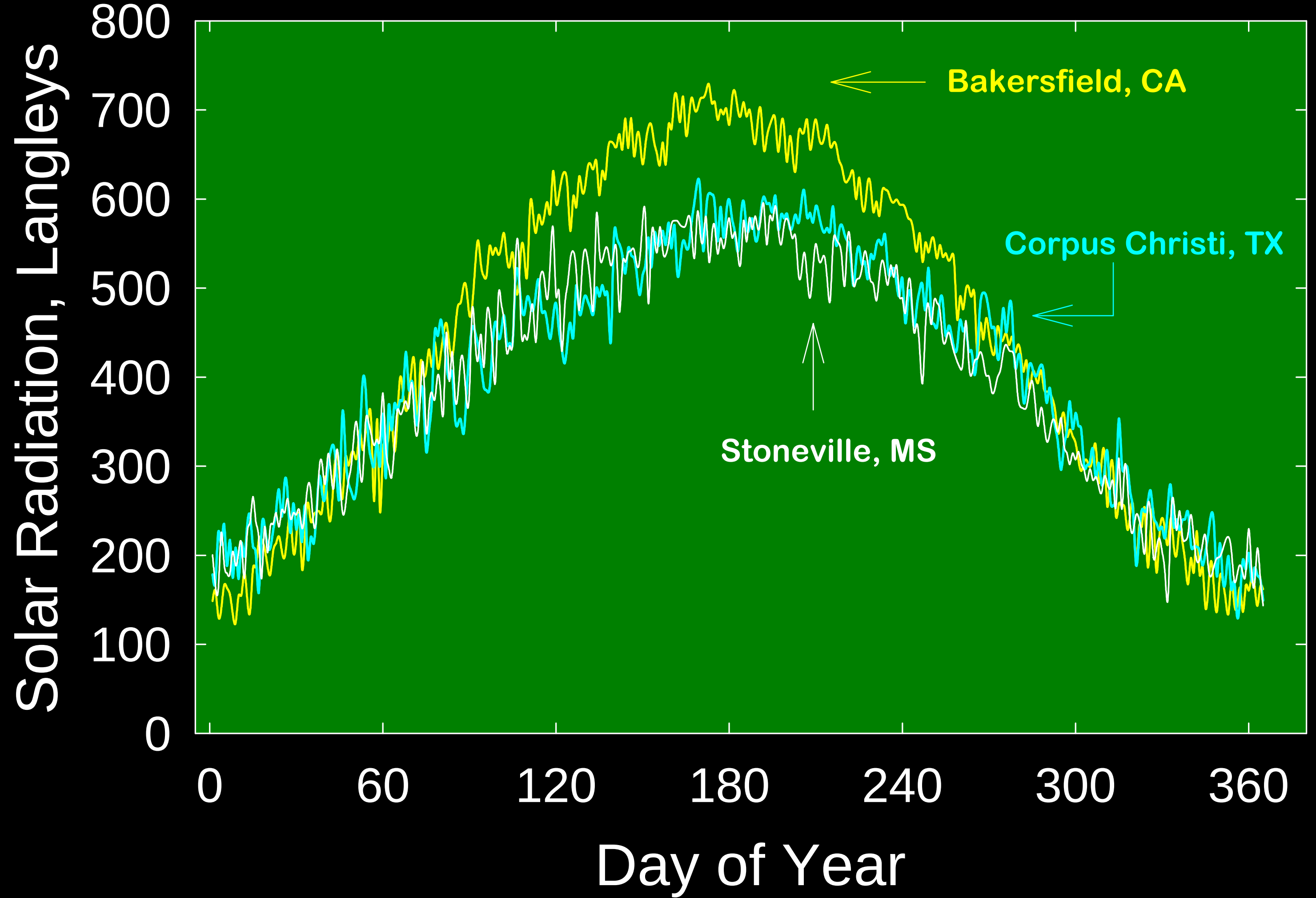
- ✓ Temperature
- ✓ Atmospheric Carbon Dioxide
- ✓ Solar Radiation
- ✓ Water
- ✓ Ultraviolet-B Radiation and Ozone
- ✓ Nutrients (N, P and K)
- ✓ Growth Regulators (PIX)

Global Atmospheric CO2 Concentrations
Mauna Loa, HI and South Pole

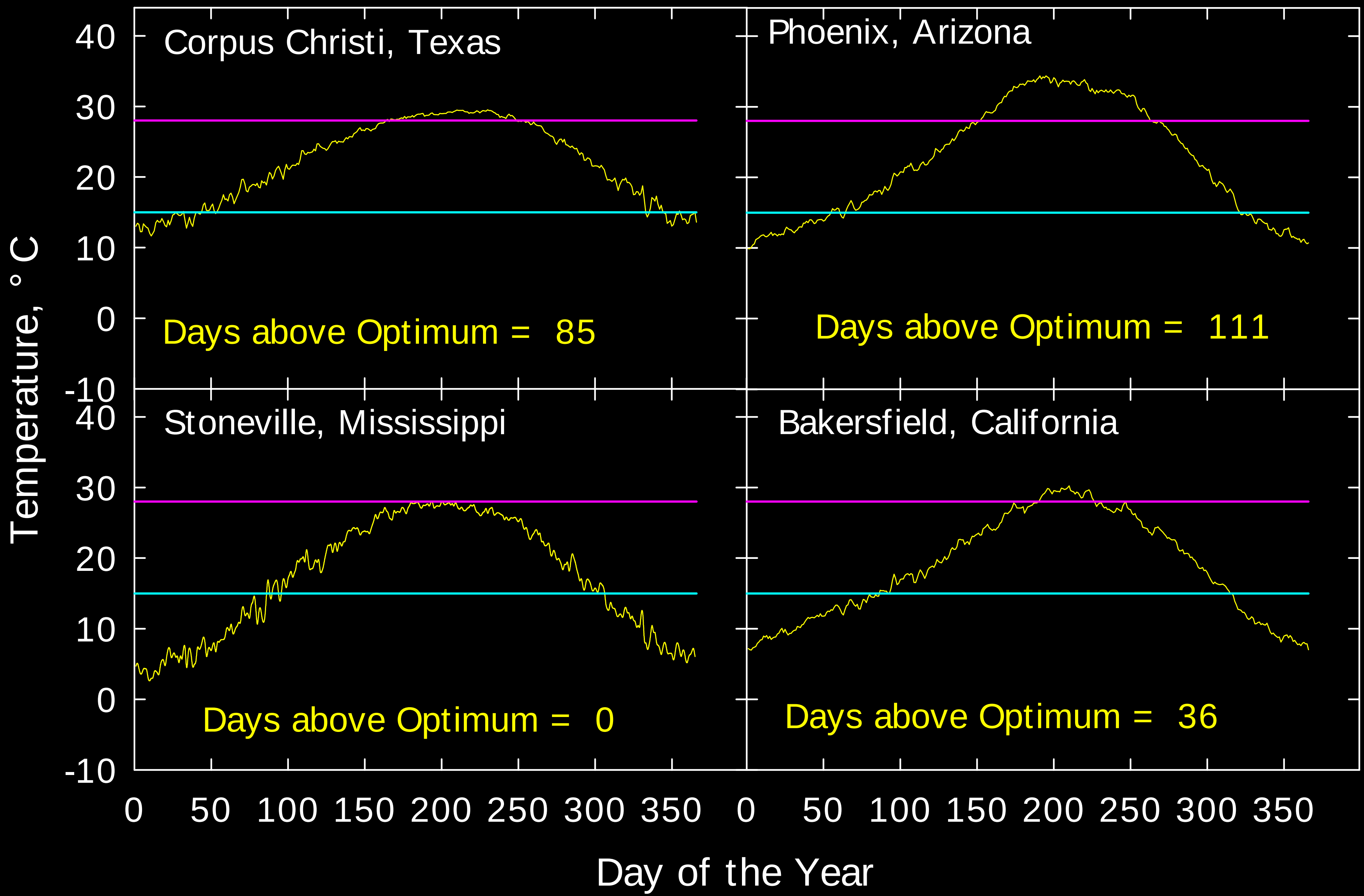


Radiation Conditions - Seasonal Trends

Bakersfield, CA, Corpus Christi, TX and Stoneville, MS

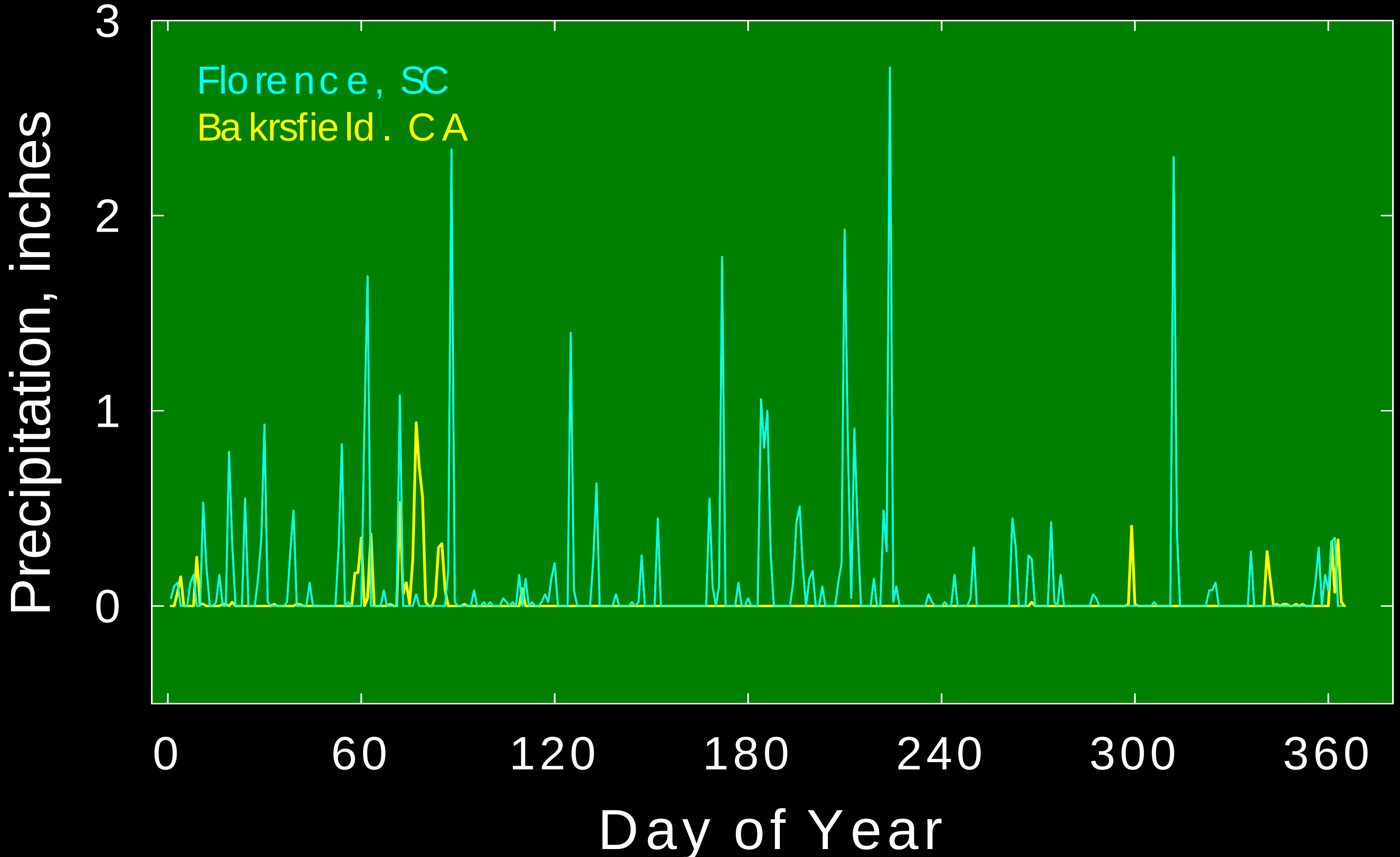


Long-term Average Temperatures for Four US Cotton Producing Areas



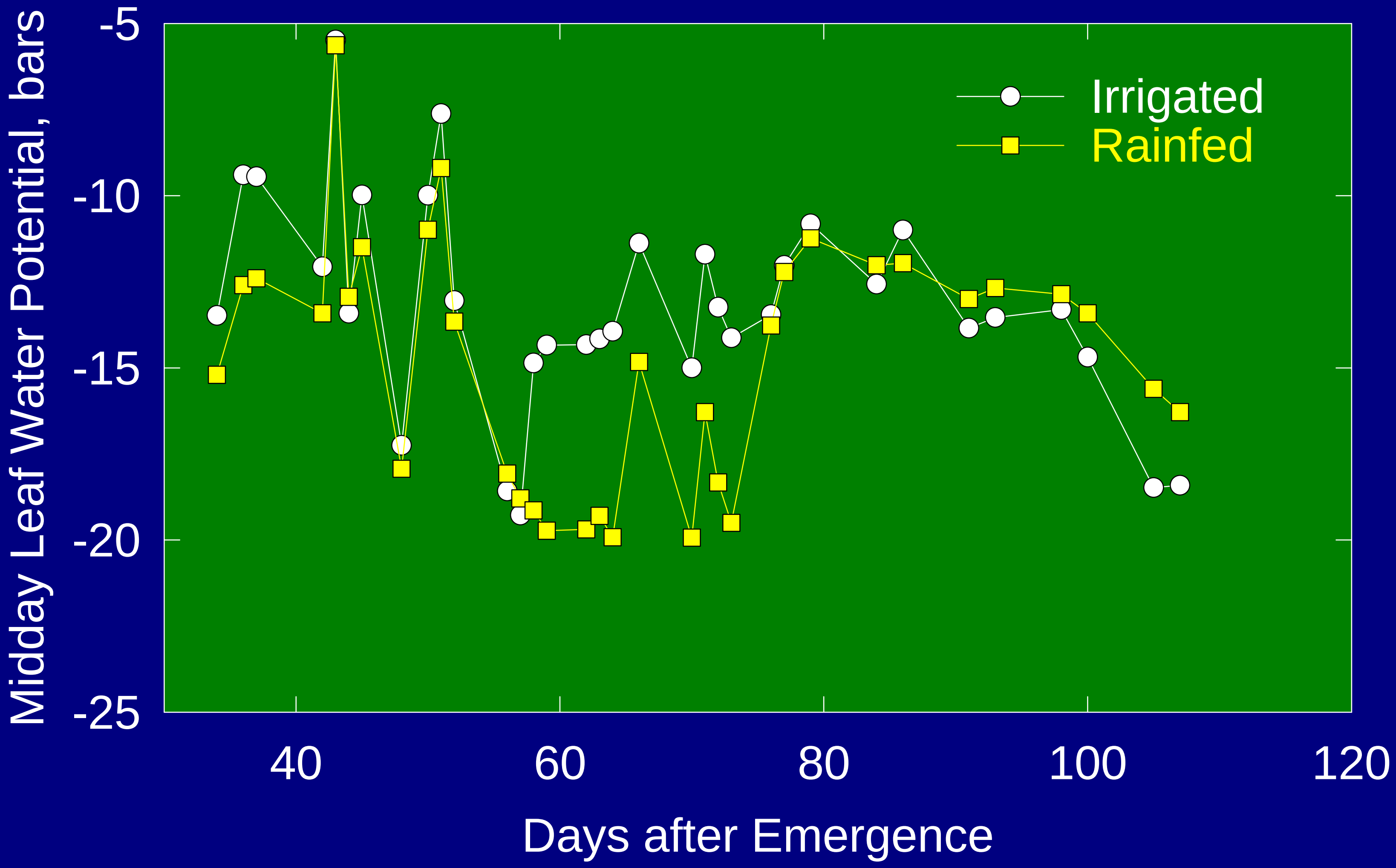
Precipitation - Seasonal Trends

Bakersfield, CA and Florence, SC - 1991



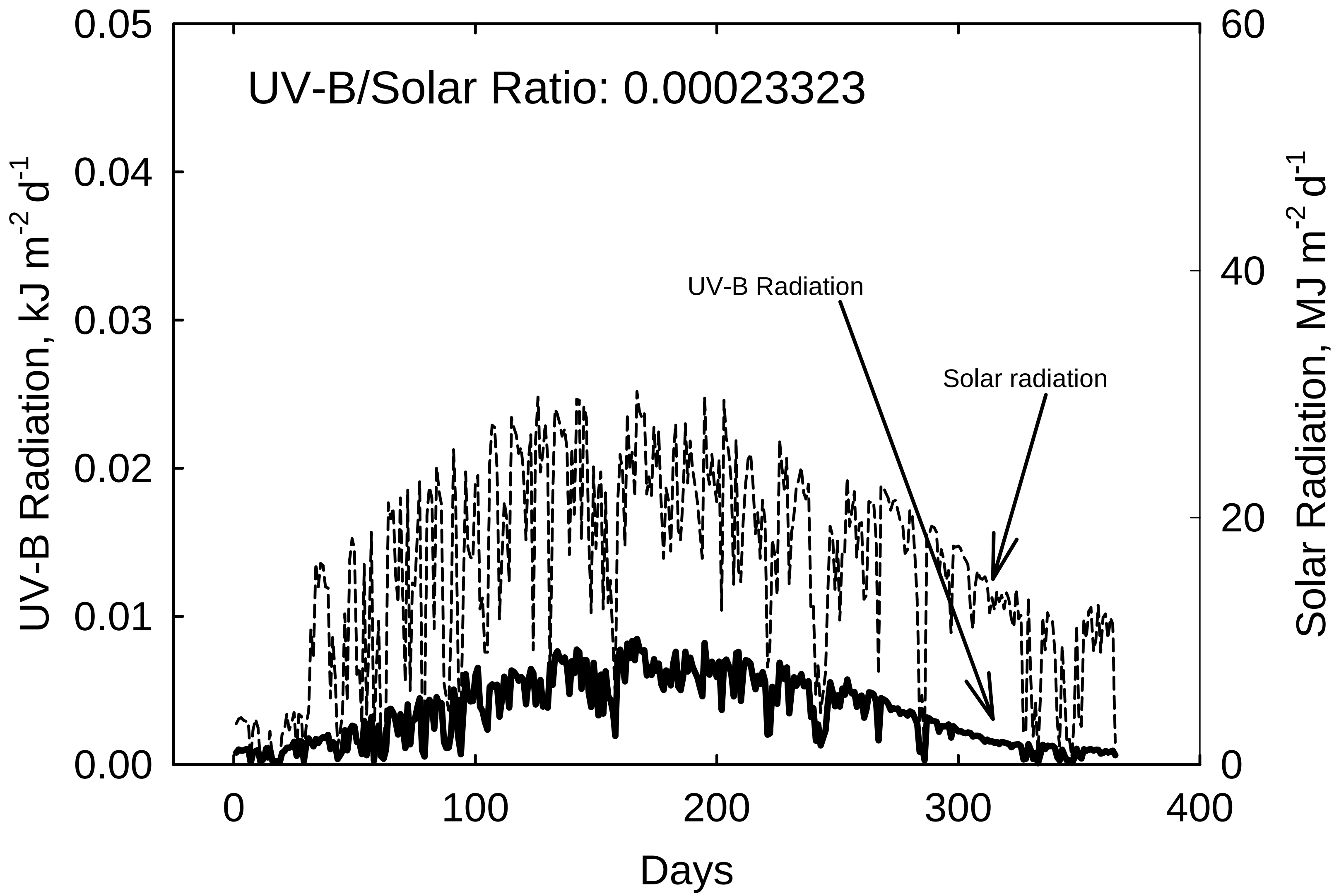
Seasonal Trends - Midday Leaf Water Potential

Irrigated and rainfed cotton, MSU North Farm -1995

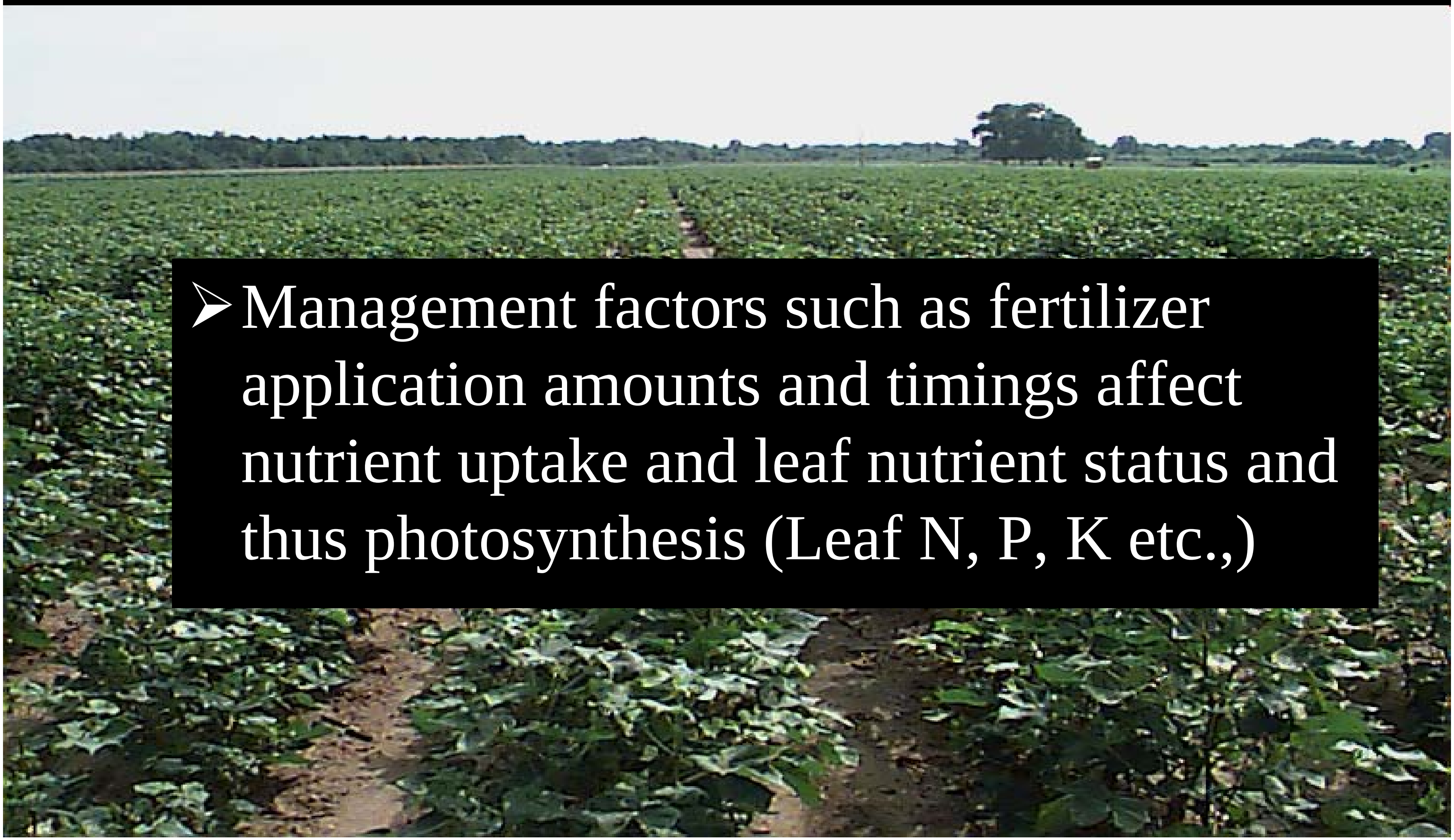


Seasonal Trends Solar and UV-B Radiation

Mississippi State - 2001

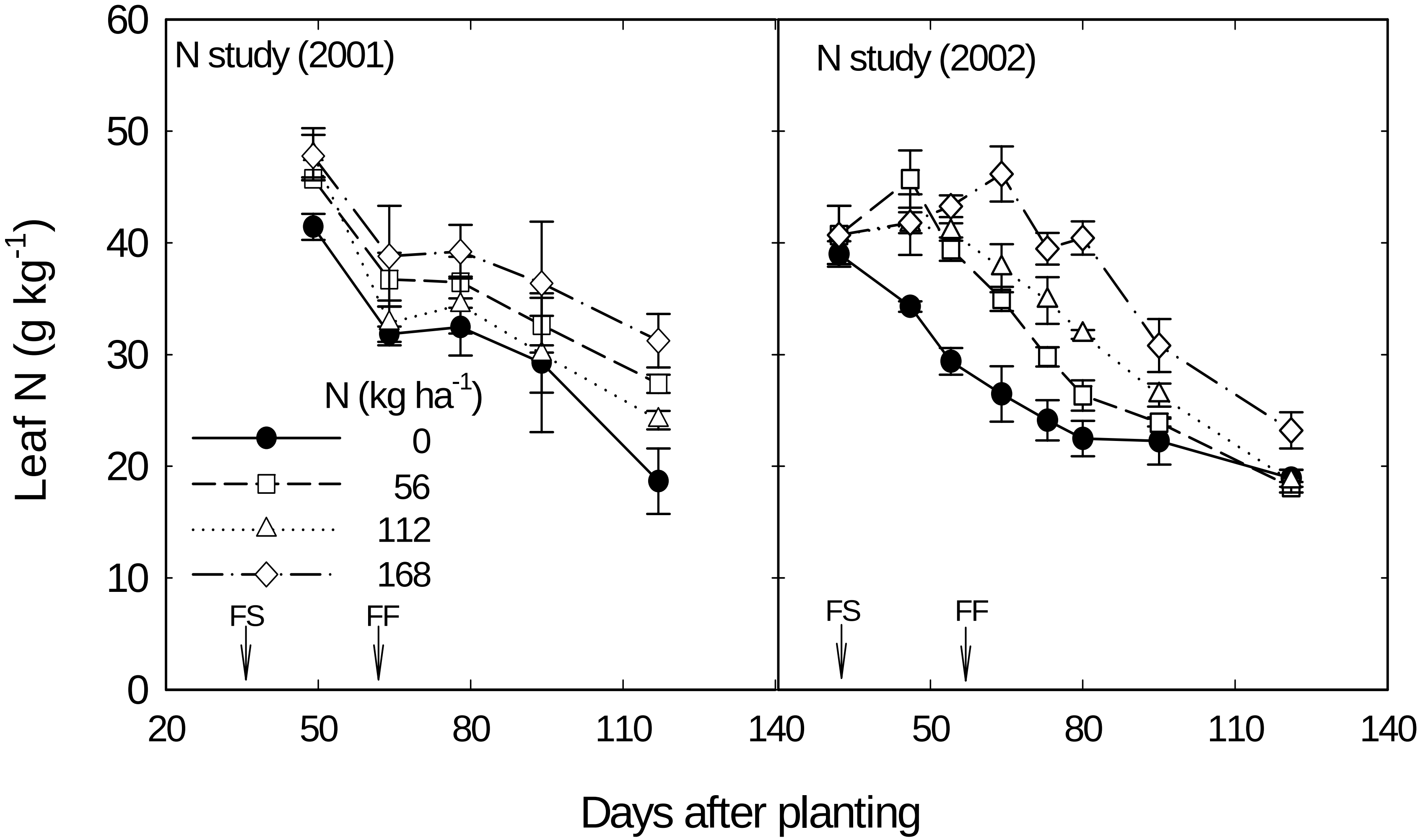


Photosynthesis - Management Factors

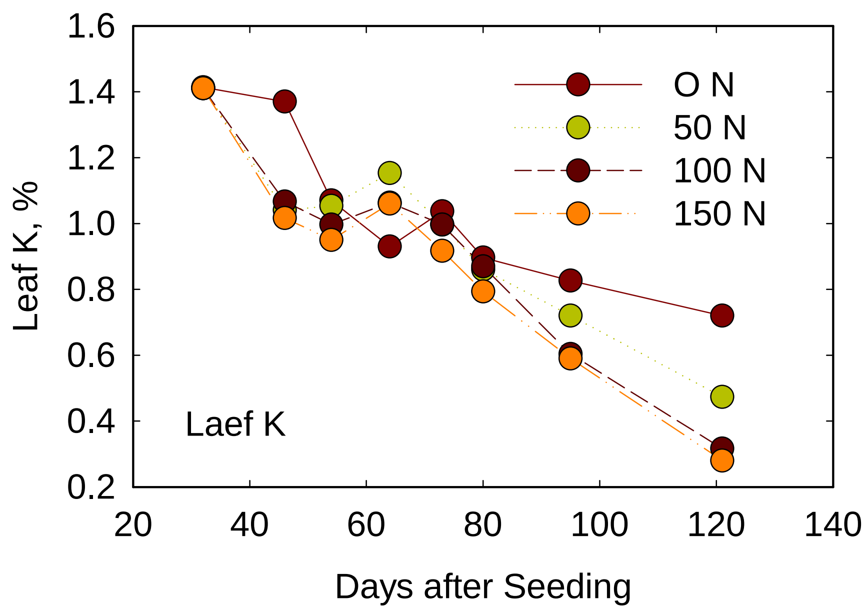


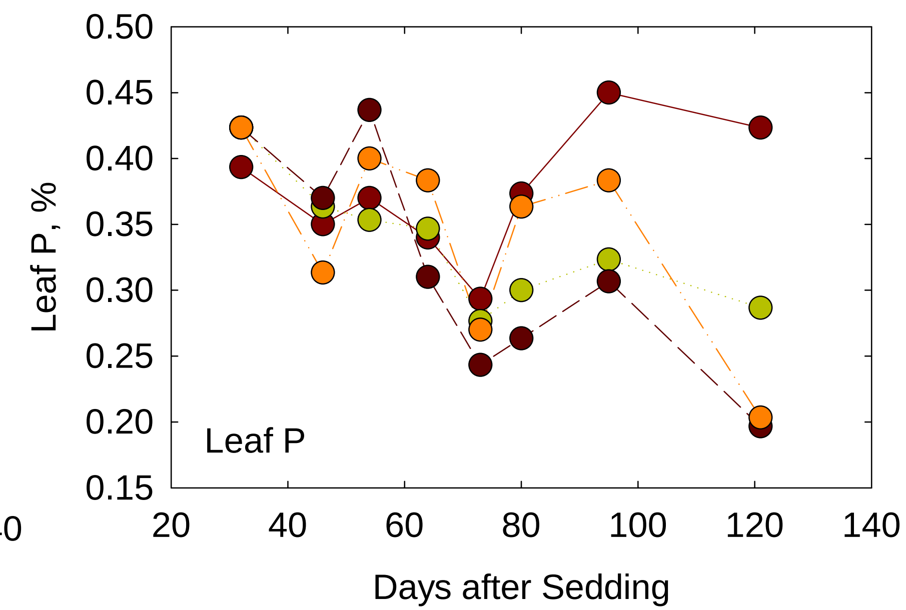
- Management factors such as fertilizer application amounts and timings affect nutrient uptake and leaf nutrient status and thus photosynthesis (Leaf N, P, K etc.,)

Cultural and Environmental Factors
Seasonal Trends – Leaf Nitrogen Concentration

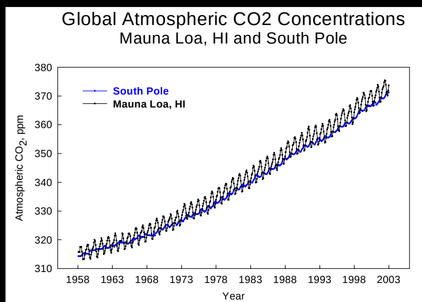


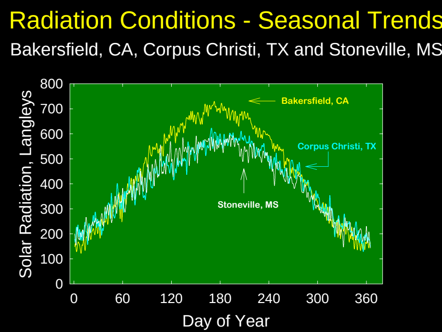
Cultural and Environmental Factors Seasonal Trends – Leaf Potassium and Phosphorus Concentration

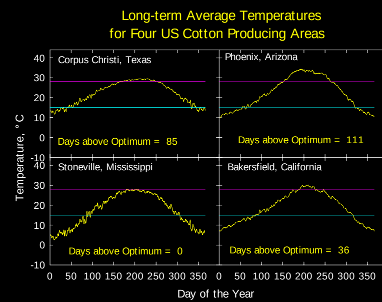


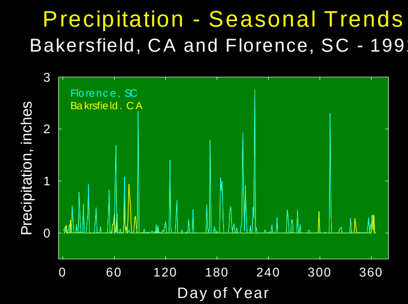


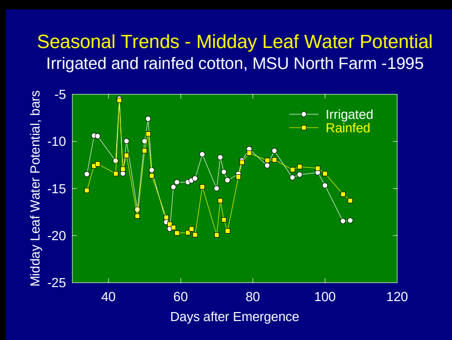
How can we quantify environmental and cultural factor effects on plant processes – Photosynthesis?

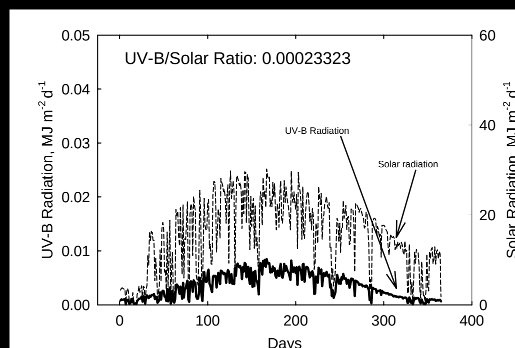


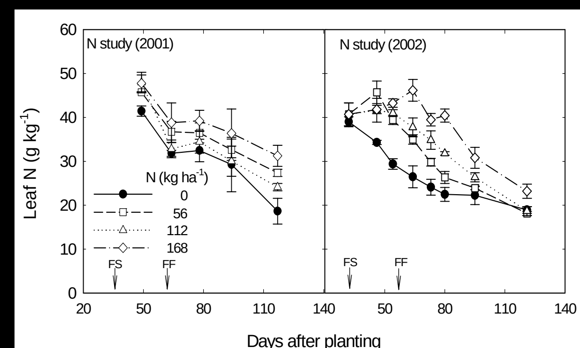




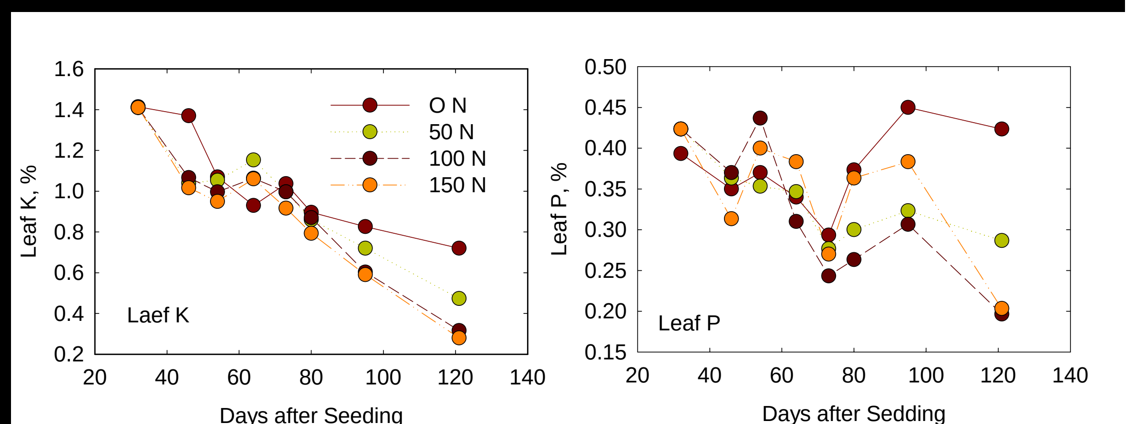








Temporal trends in crop growth as affected by environment



Quantifying the Effects of Environmental Factors on Photosynthesis

One way to quantify the effects of environmental factors on photosynthesis is to use environmental productivity Index (EPI) concept:

Actual (Photosynthesis) = Potential * Solar Radiation Index*Water Index * Temperature Index * Nutrient Indices (C, N, P, K) * UV-B Index and Ozone Index, etc.,

First, we have to calculate the potential photosynthesis for a given species or cultivar. Potential photosynthesis is defined as the amount of photosynthesis that takes place at a maximum solar radiation under optimum environmental conditions (optimum water, nutrient, zero UV-B, temperature (27 °C) and in an actively growing canopy, no aging effect).

Quantifying the Effects of Environmental Factors on Photosynthesis

Then, we have to account for all the environmental factors that limit to obtain that potential.

Individual environmental factors affect the potential photosynthesis multiplicatively, not additively. For instance, if prolonged drought causes daily stomatal opening to cease, then no photosynthesis will occur, regardless of whether or not light, temperature or other factors are optimal for photosynthesis.

All the indices, ranging from 0 when it is totally limiting photosynthesis to 1 when it does not limit photosynthesis, represent the fractional limitation due to that particular environmental factor. Therefore, photosynthesis decreases as the effect of that particular stress becomes more severe.

Quantifying the Effects of Environmental Factors on Photosynthesis

This way, we could able to quantify the effect of all environmental factors limiting crop photosynthesis in multi-stress environments or in field conditions.

Quantifying the Effects of Environmental Factors on Photosynthesis

Database and Modeling Methodologies
with Cotton as an Example Crop

Crop Responses to Environment - Tools

Soil-Plant-Atmosphere-Research (SPAR) Facility

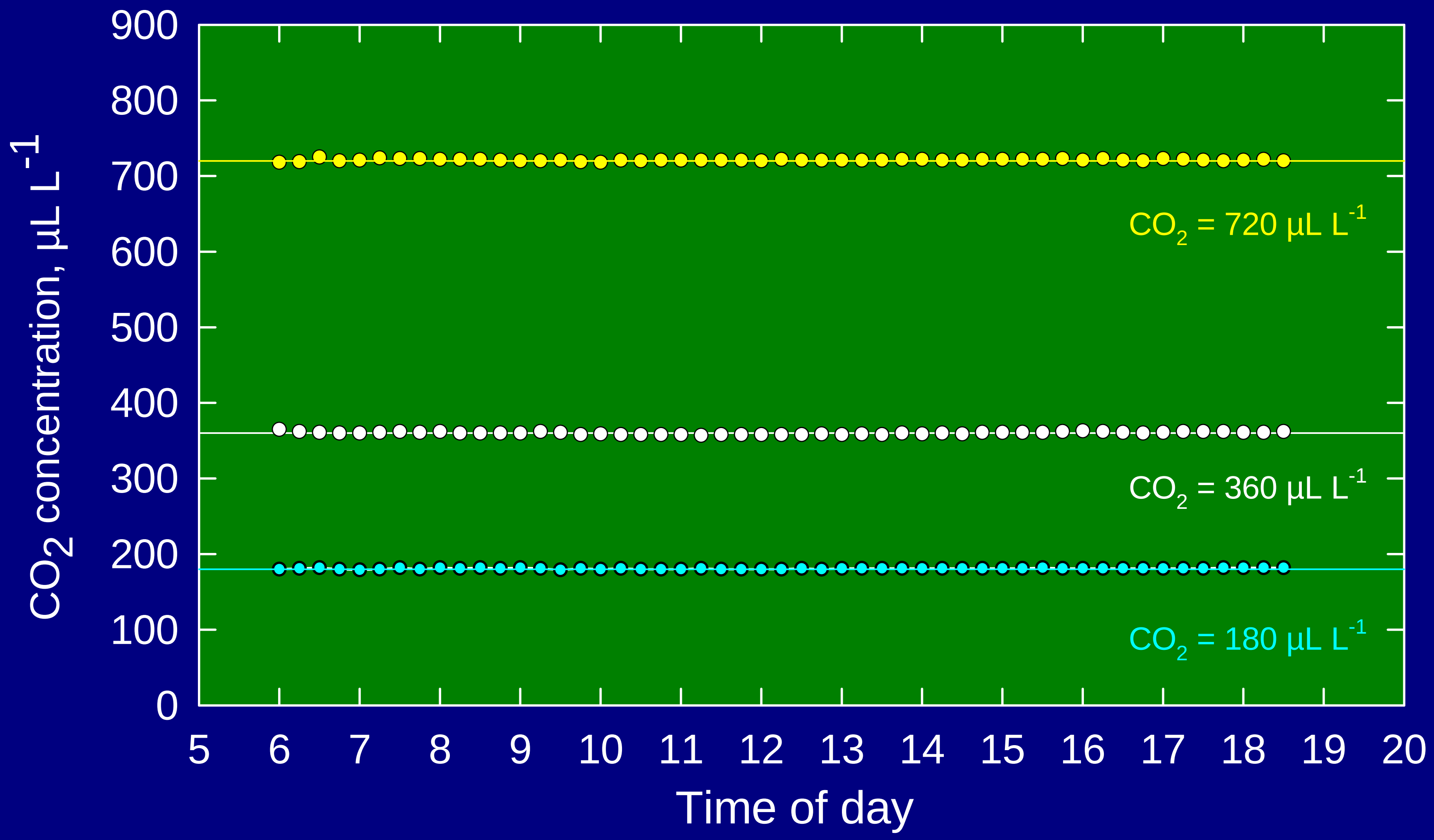
Controlling Environmental Variables

Soil-Plant-Atmosphere-Research (SPAR) Facility

Temperature = 30/22 °C (Average =27 °C) and in ambient (360 ppm) CO_2 conditions.

SPAR - Data Acquisition

Atmospheric Carbon Dioxide Control



Soil-Plant-Atmosphere-Research (SPAR) Facility

Measuring Gas Exchanges

Carbon [CO_2] Fluxes

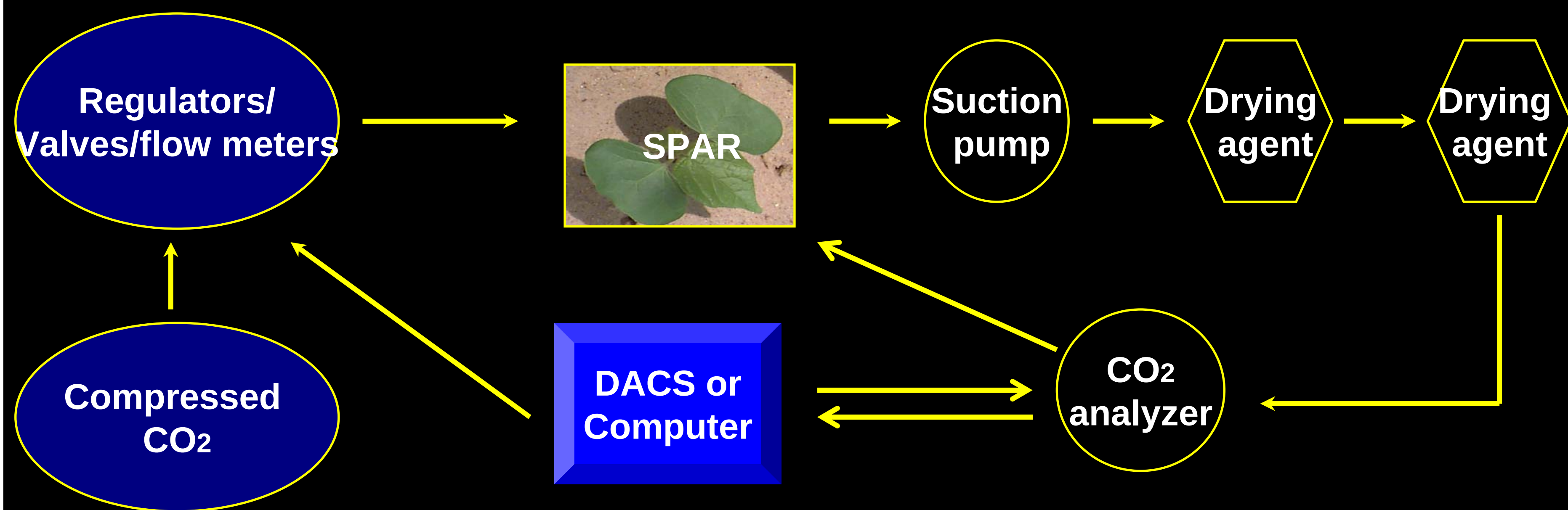
Measuring Carbon Fluxes

Carbon Fluxes: Mass balance approach

During sunlit hours, by maintaining steady or constant CO2 concentration inside the SPAR chamber, we can calculate,

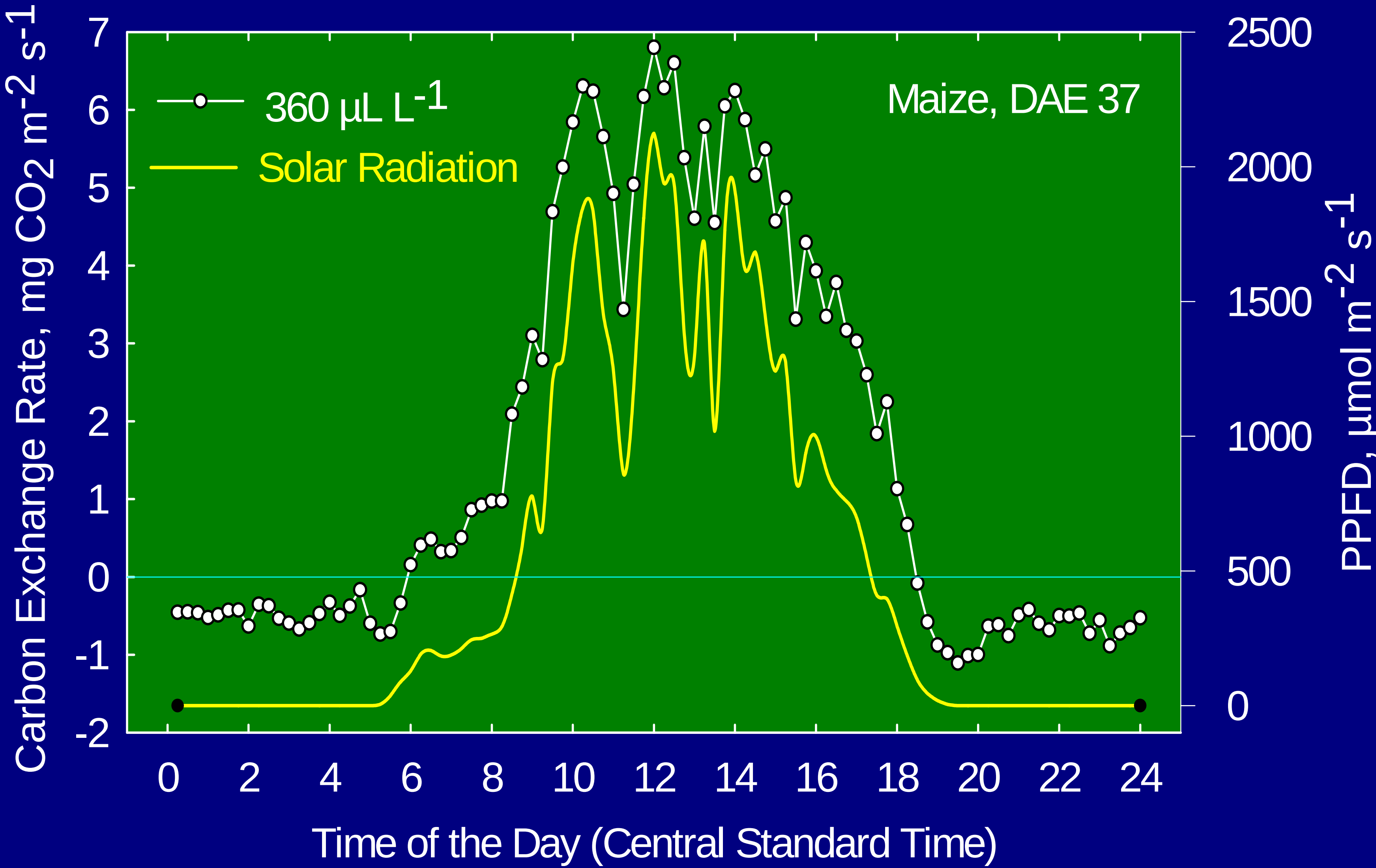
Net photosynthesis = Amount of CO2 injected – leak rate

Gross Photosynthesis = Net photosynthesis + Respiration

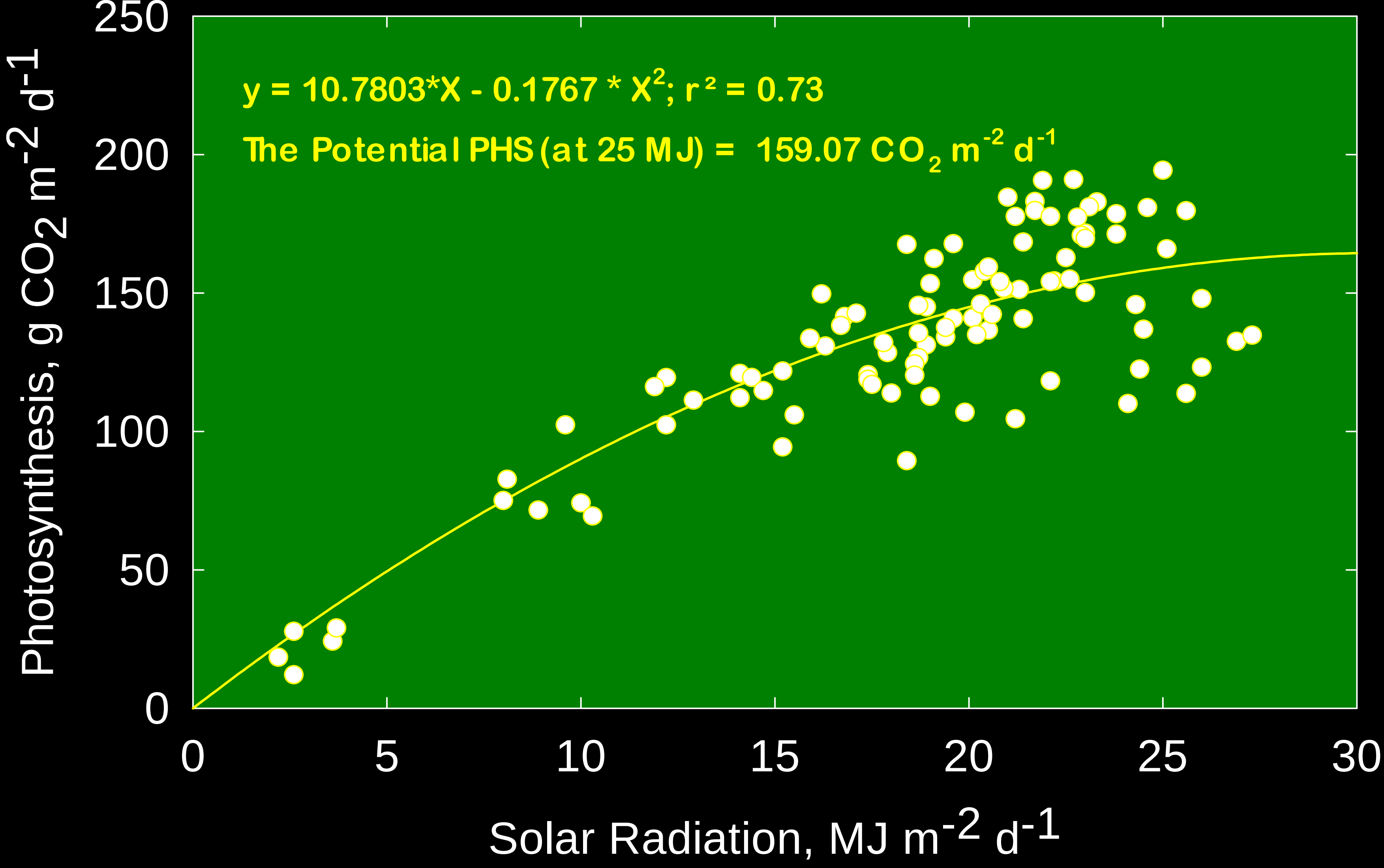


Canopy Photosynthesis

Response to Solar Radiation

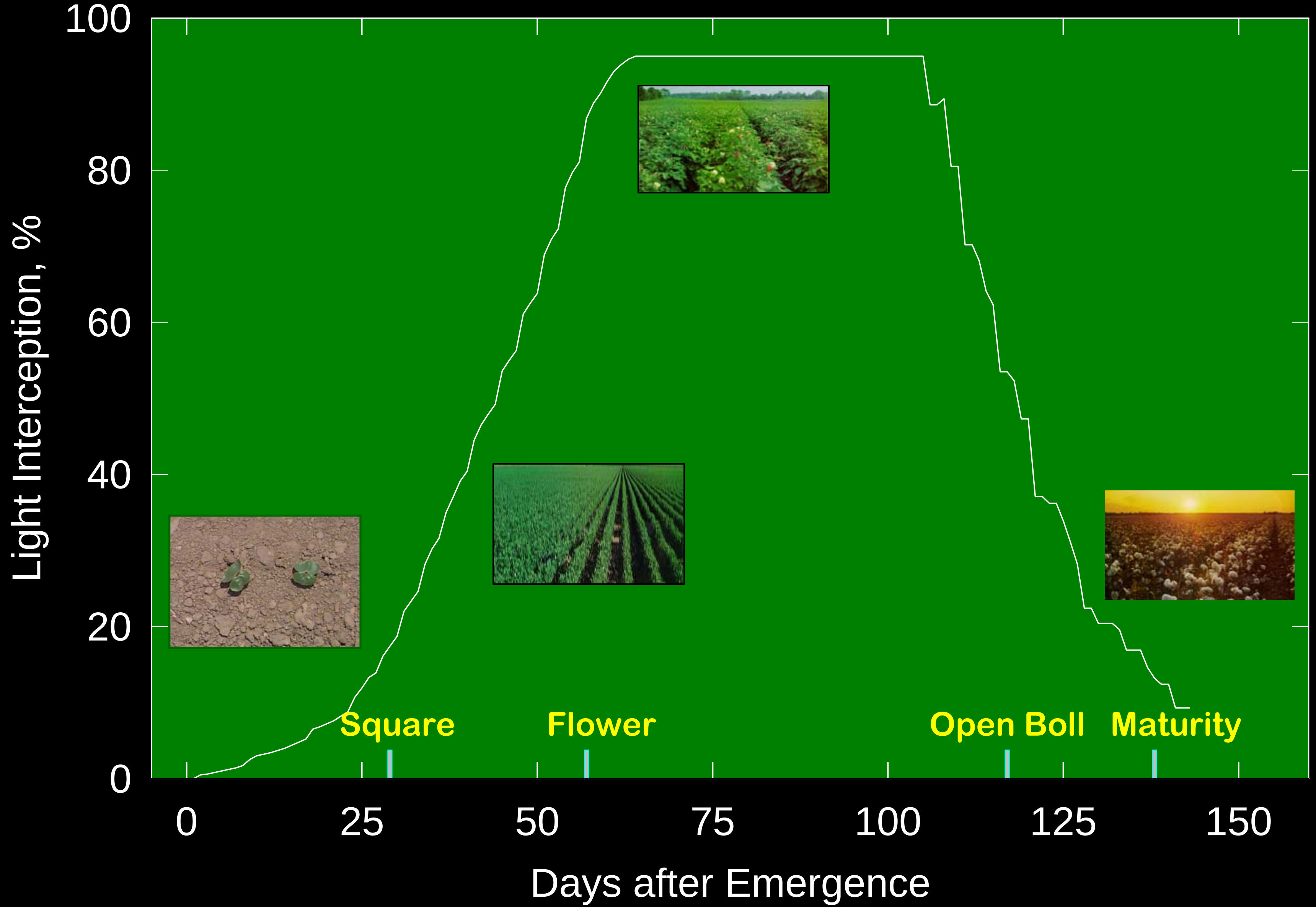


Estimating Potential Photosynthesis for Cotton as a Function of Solar Radiation



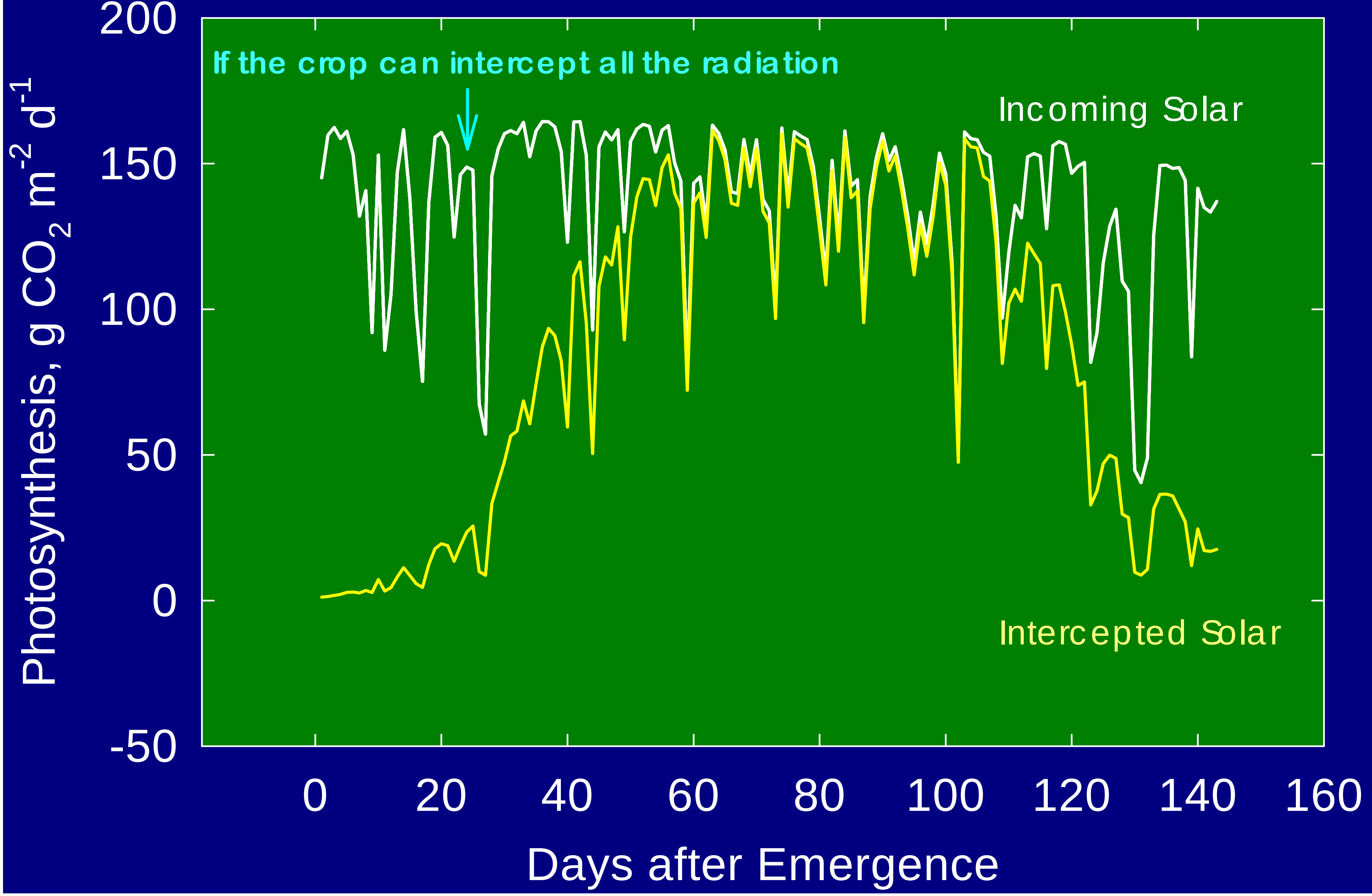
Weather Variables - Mississippi State - 1992

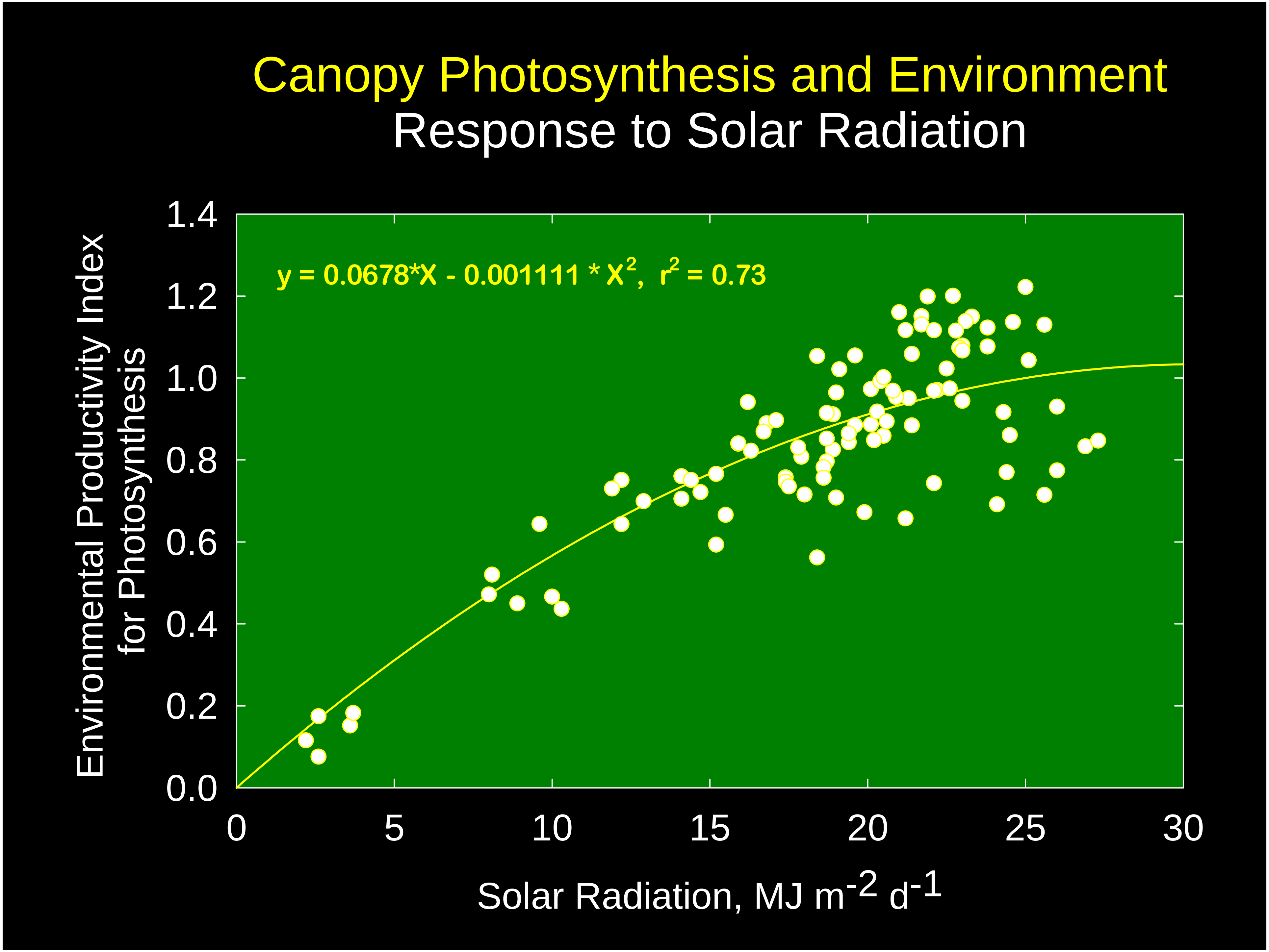
Temporal Trends in Light Interception - 18 May = 0



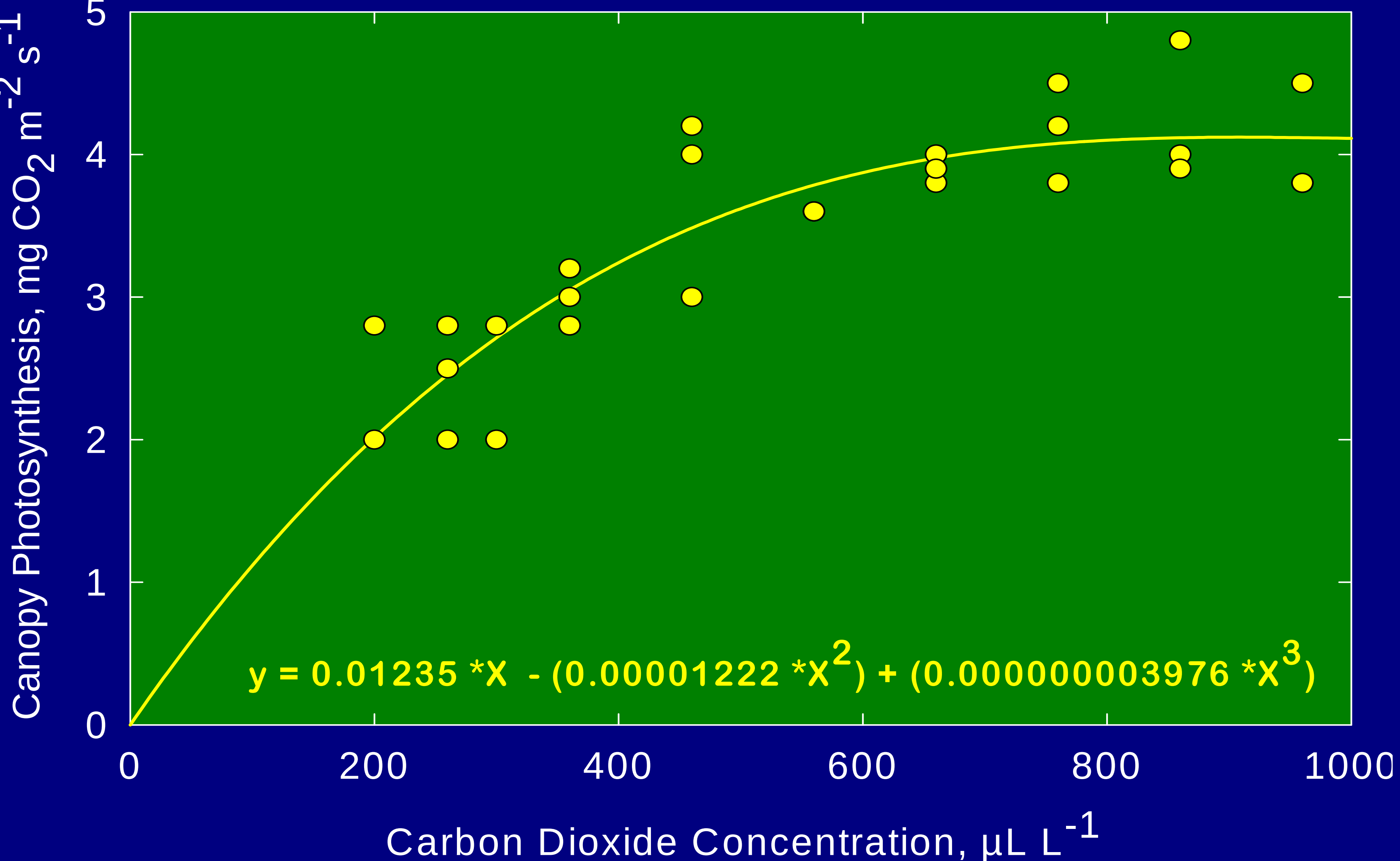
Canopy Photosynthesis - Growing Season

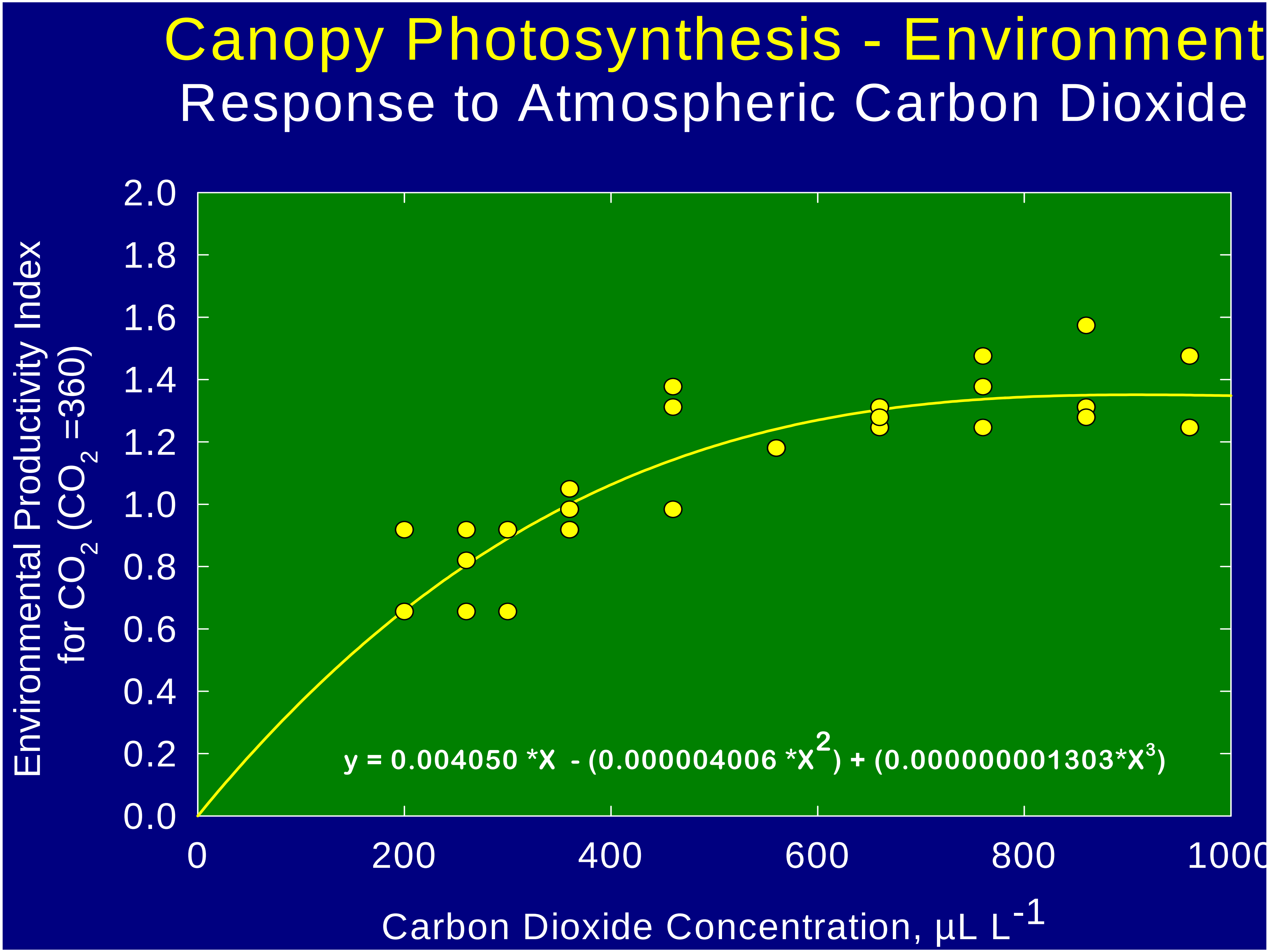
Accounting for environmental factors using EPI concept




Canopy Photosynthesis and Environment
Response to Solar Radiation
y = 0.0678*X - 0.001111 * X^2, r^2 = 0.73
Environmental Productivity Index
for Photosynthesis
Solar Radiation, MJ m^{-2} d^{-1}
0.0
0.2
0.4
0.6
0.8
1.0
1.2
1.4
0
5
10
15
20
25
30

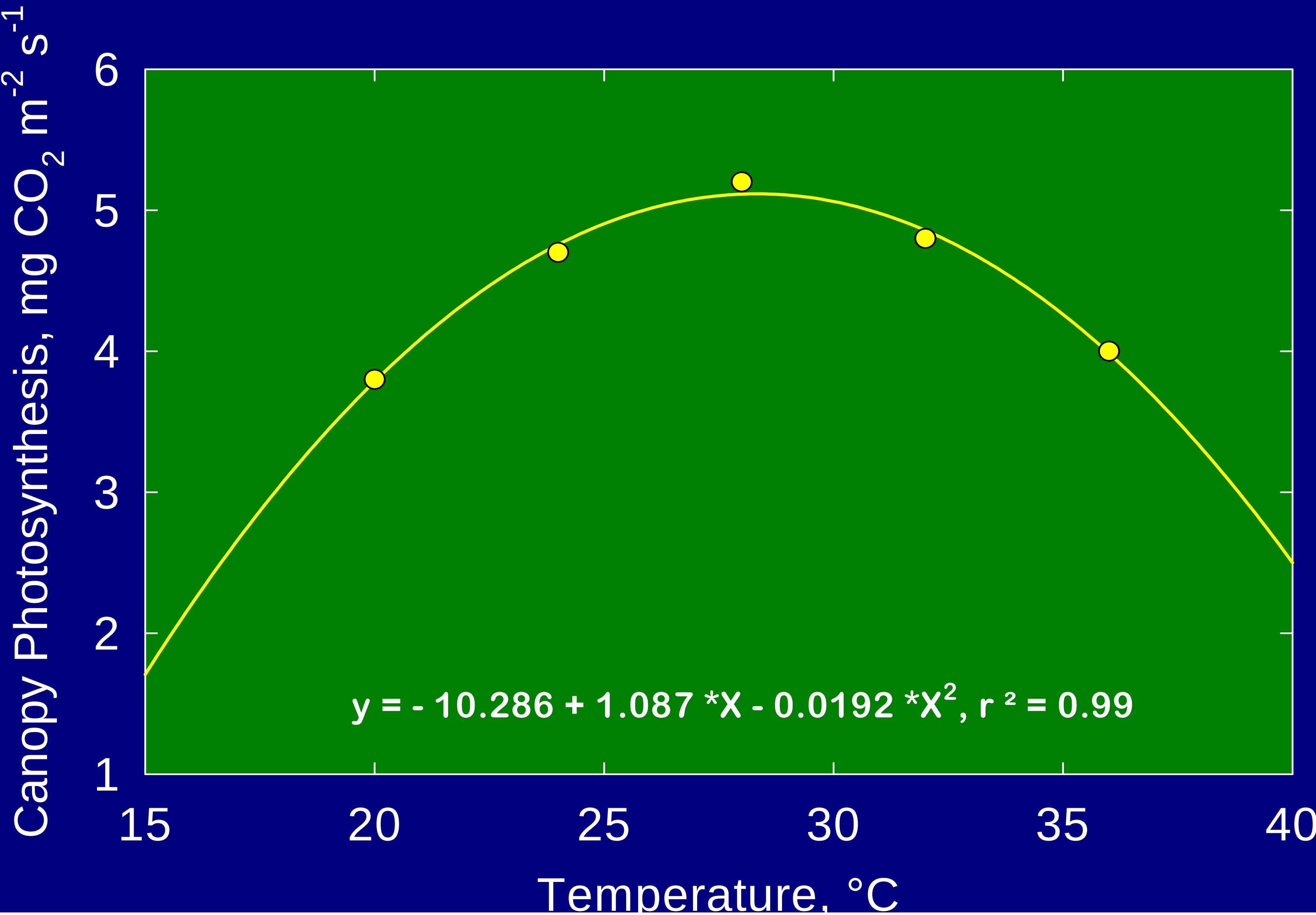
Canopy Photosynthesis
Response to Atmospheric Carbon Dioxide





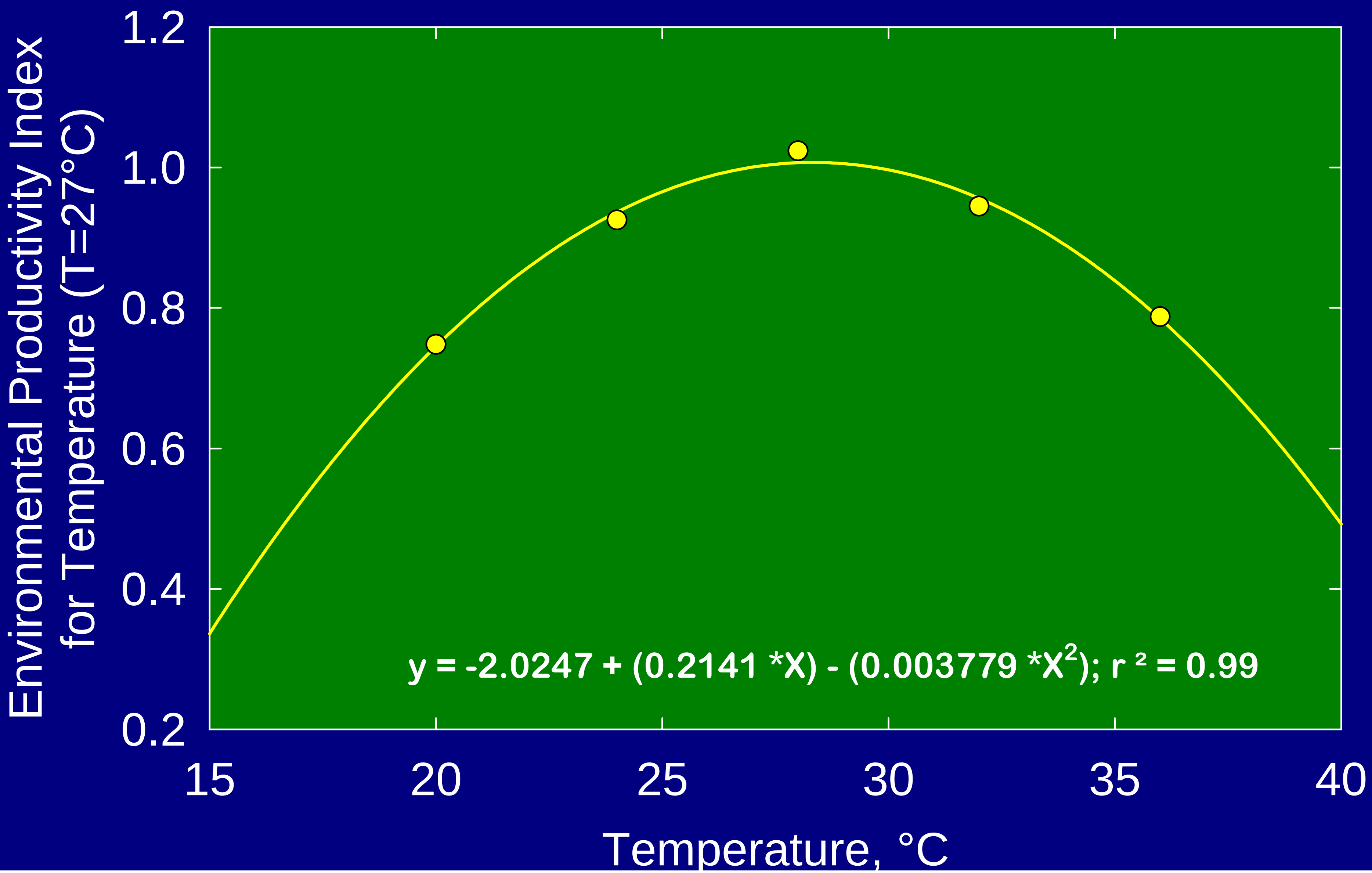
Canopy Photosynthesis - Environment
Response to Atmospheric Carbon Dioxide
Environmental Productivity Index for CO_2 (CO_2 =360)
2.0
1.8
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
200
400
600
800
1000
$y = 0.004050 * X - (0.000004006 * X^2) + (0.000000001303 * X^3)$
Carbon Dioxide Concentration, µL L^{-1}

Canopy Photosynthesis - Environment
Response to Temperature



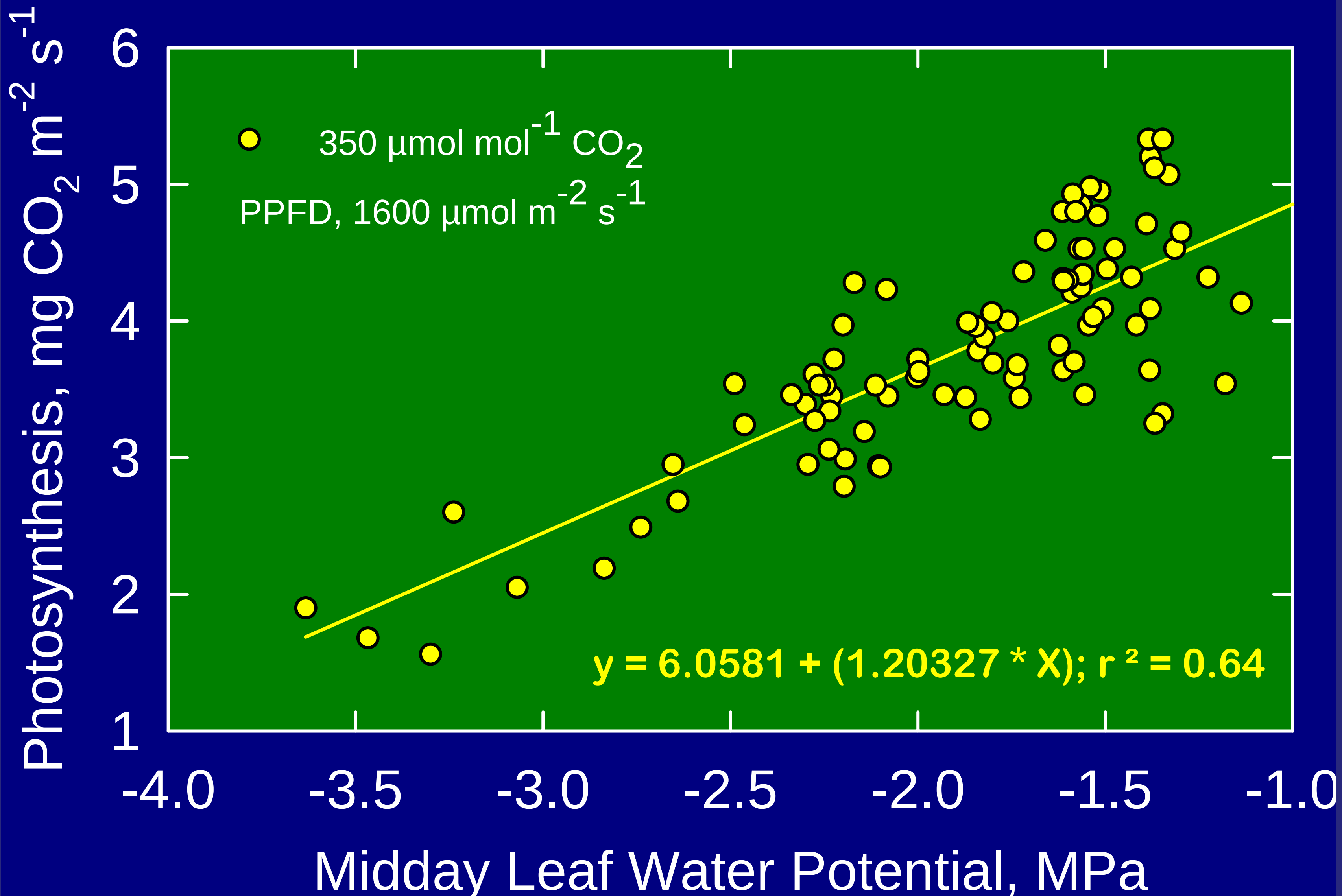
Canopy Photosynthesis - Environment

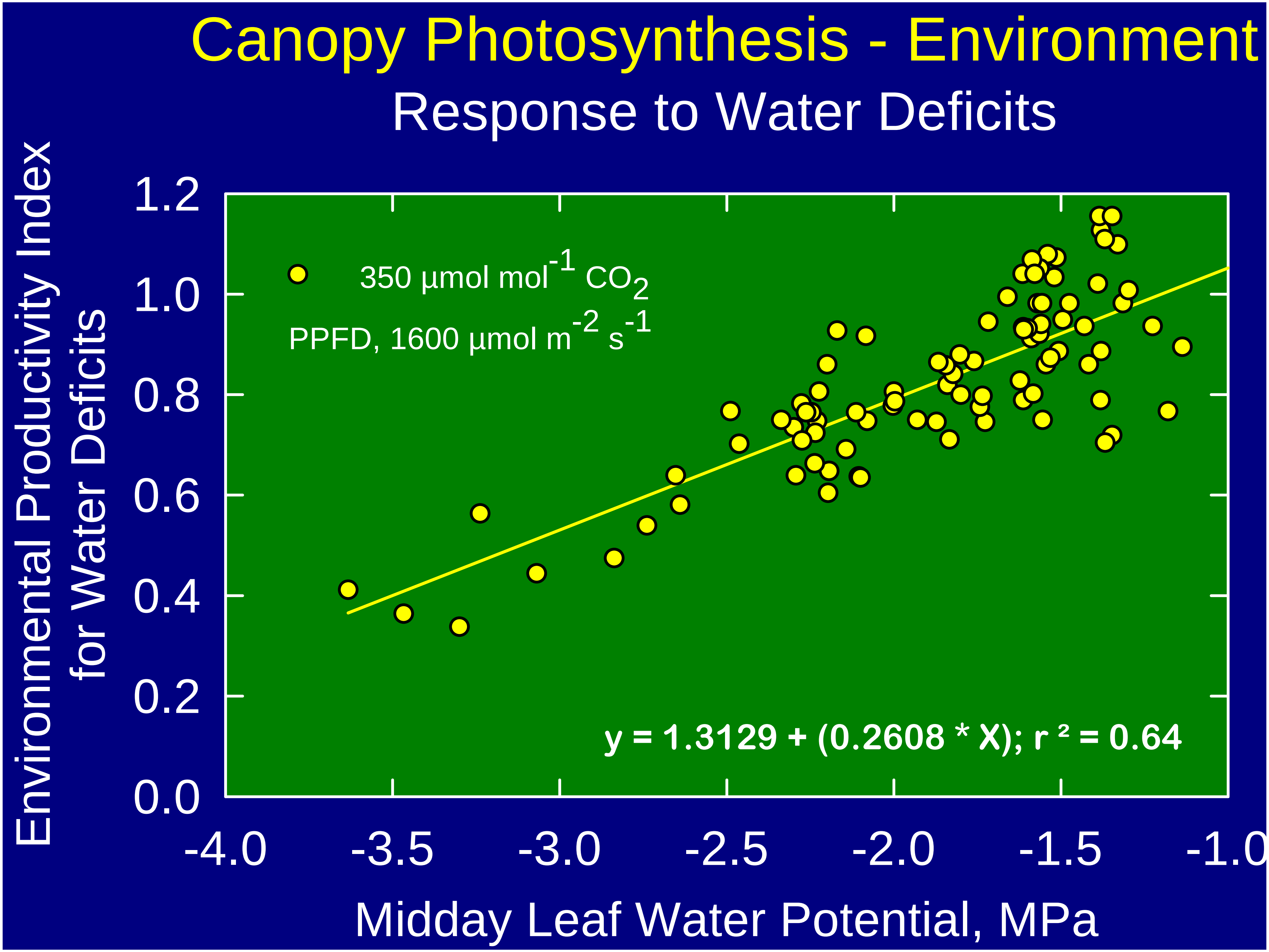
Response to Temperature



Canopy Photosynthesis - Environment

Response to Water Deficits



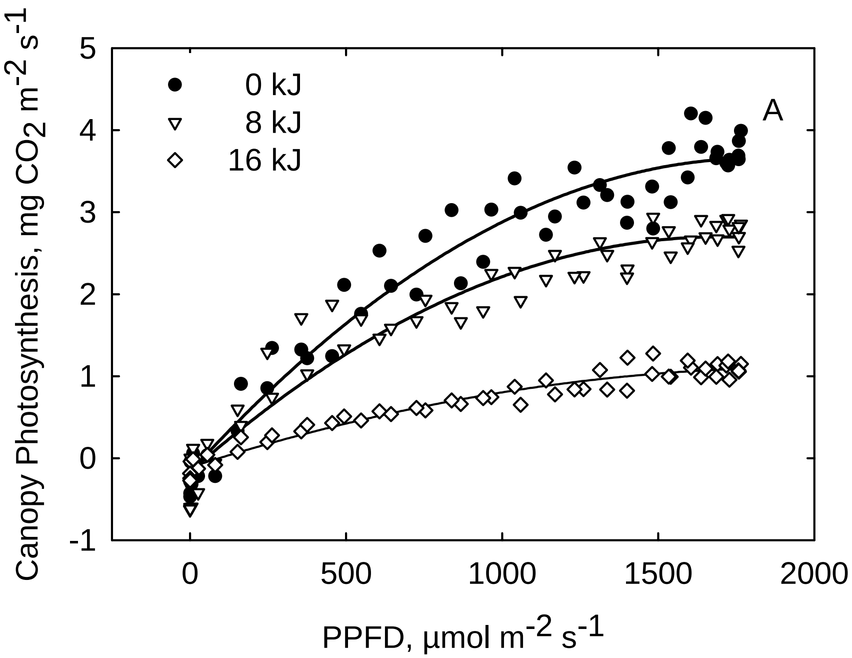


Canopy Photosynthesis - Environment
Response to Water Deficits
Environmental Productivity Index for Water Deficits
1.2
1.0
0.8
0.6
0.4
0.2
0.0
350 µmol mol-1 CO2
PPFD, 1600 µmol m-2 s-1
y = 1.3129 + (0.2608 * X); r ² = 0.64
-4.0
-3.5
-3.0
-2.5
-2.0
-1.5
-1.0
Midday Leaf Water Potential, MPa

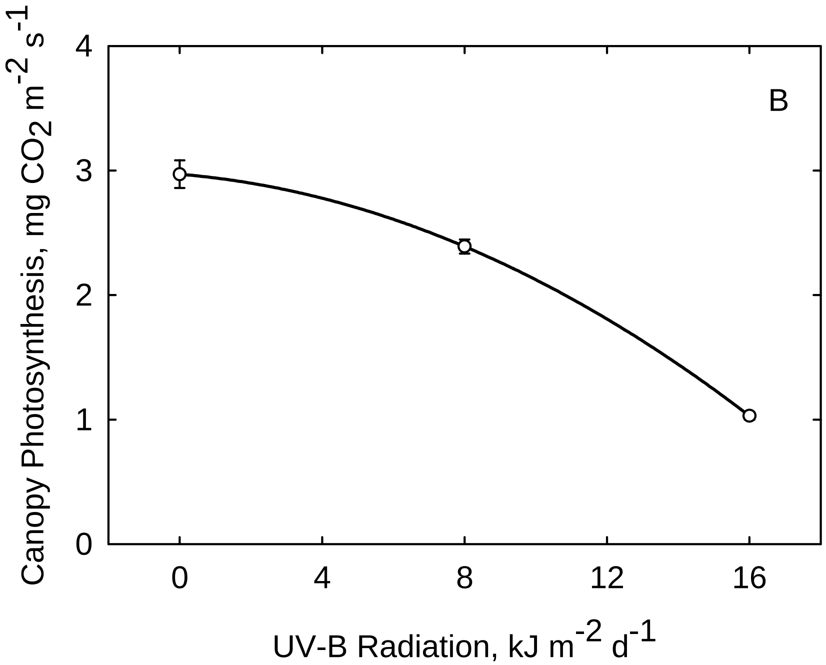
Canopy Photosynthesis – Environment

Response to UV-B Radiation

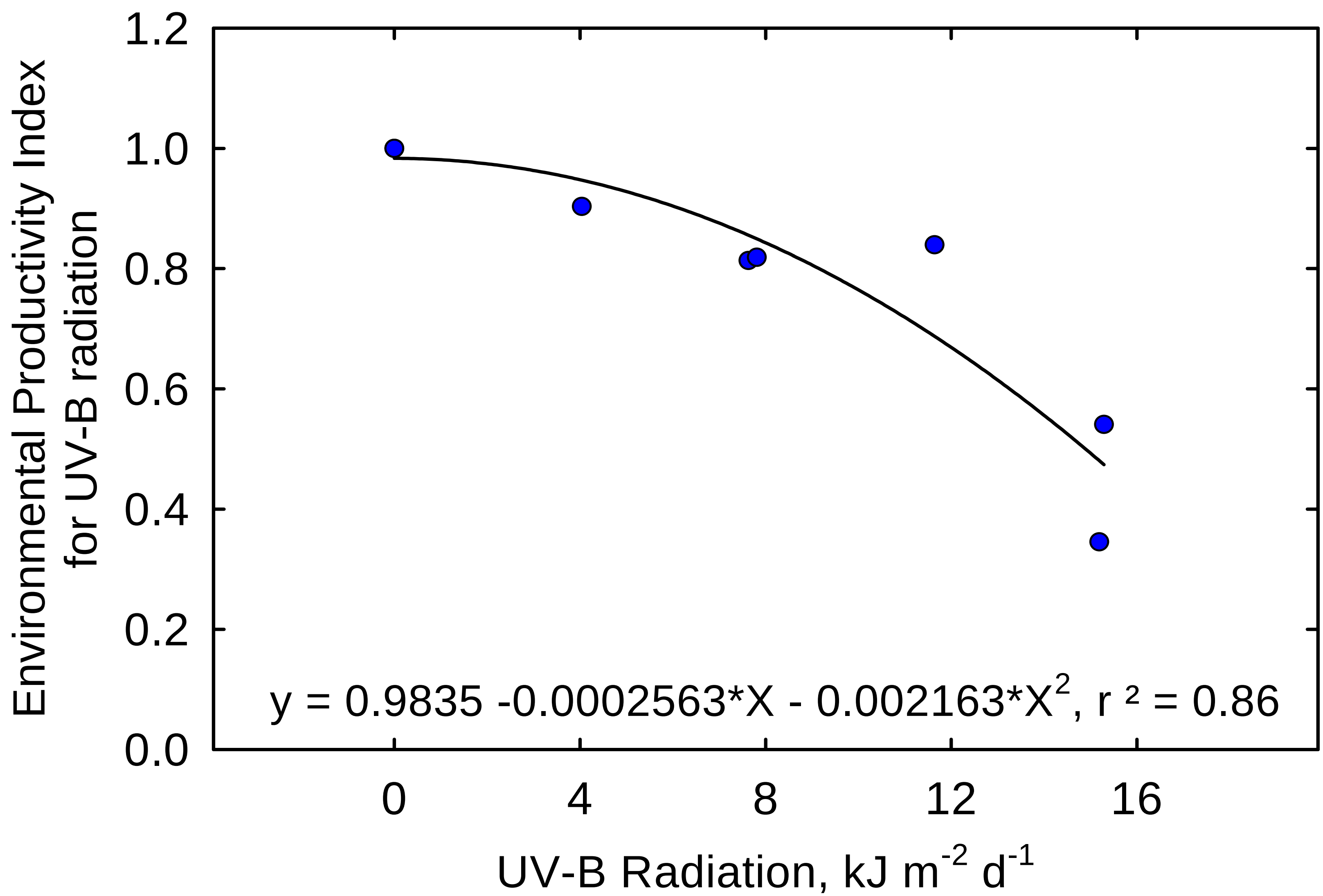
Response to Solar Radiation



Response to UV-B Radiation

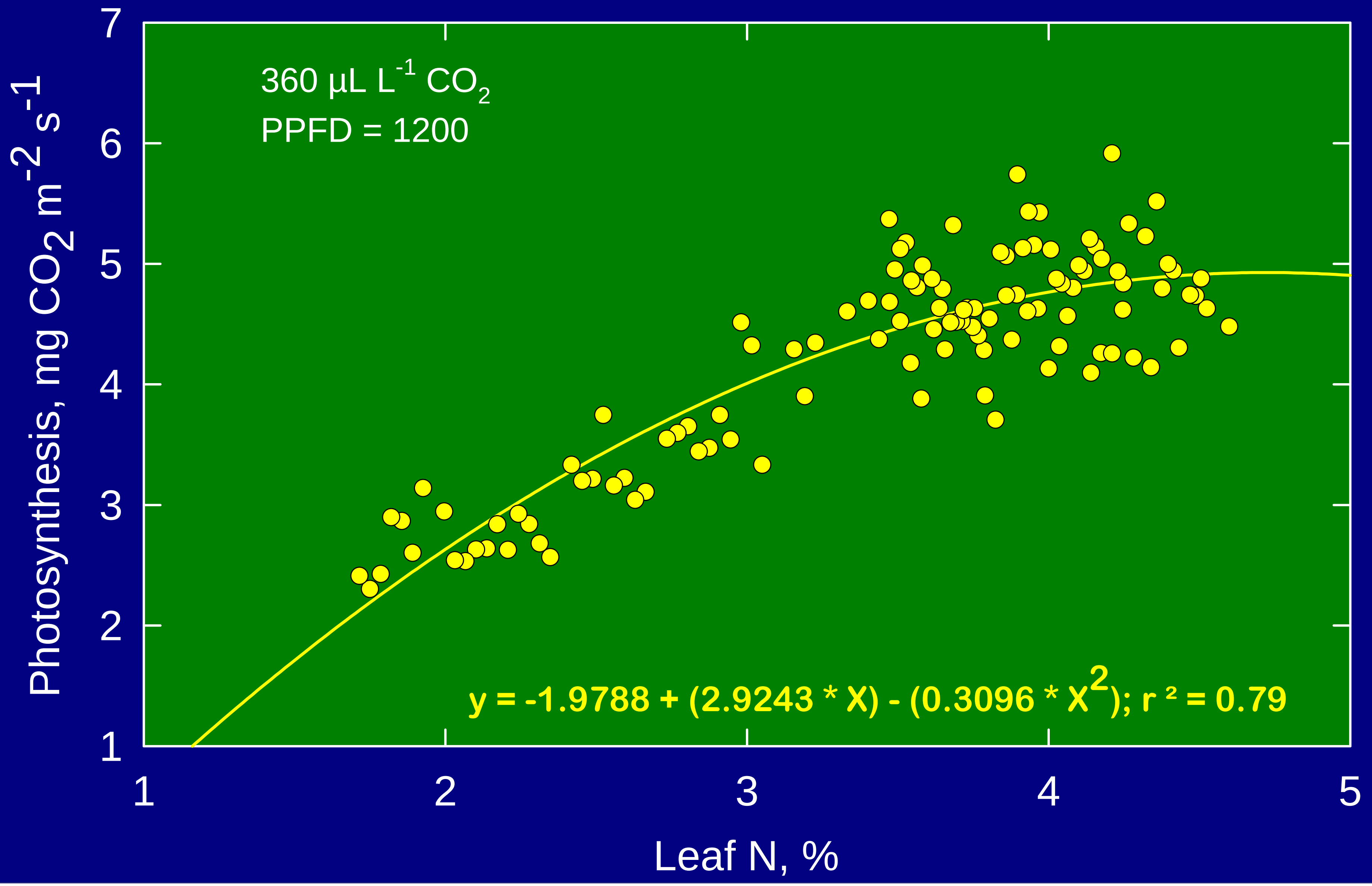


Canopy Photosynthesis - Environment
Response to UV-B Radiation



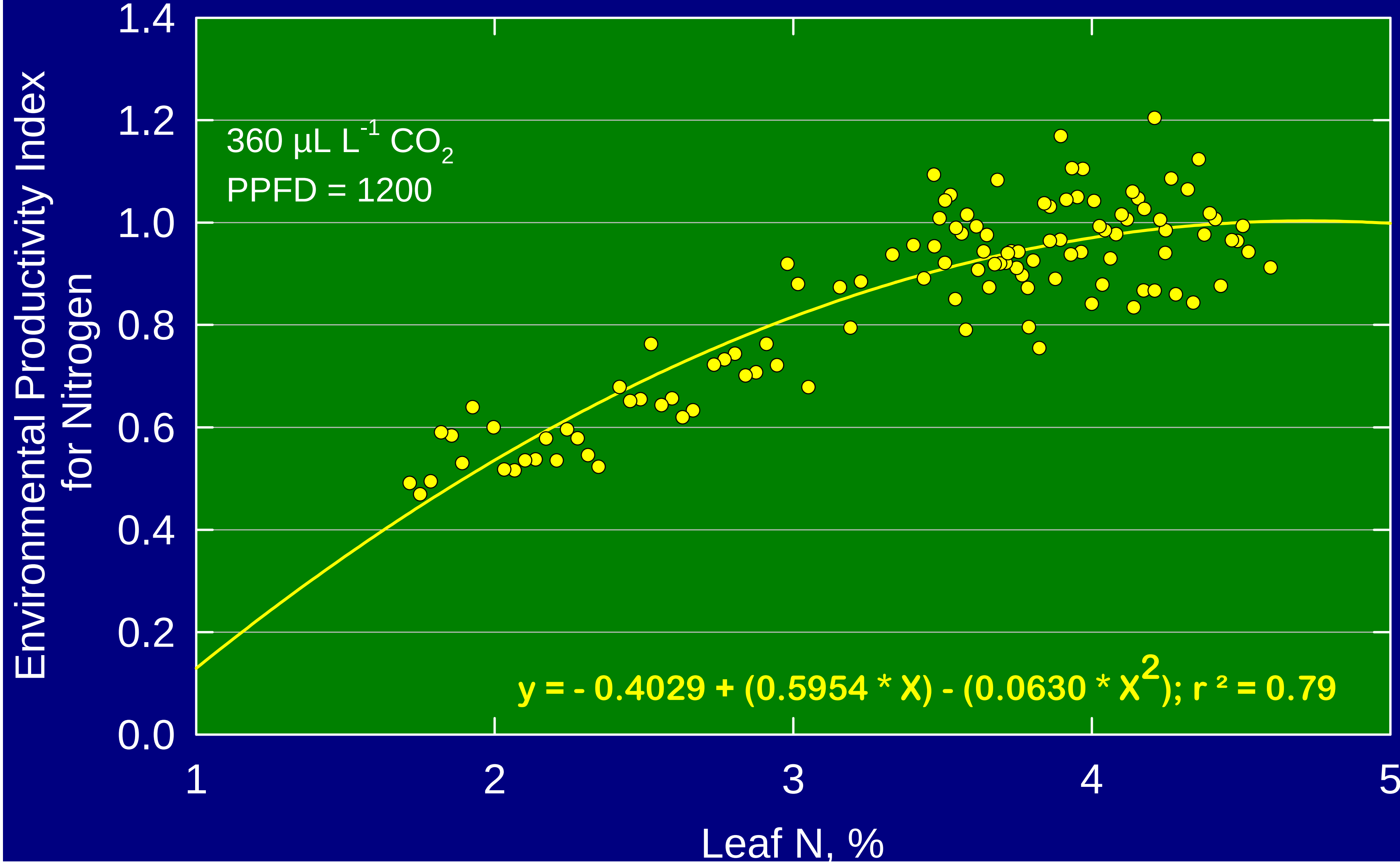
Canopy Photosynthesis - Environment

Response to Fertilization - Nitrogen



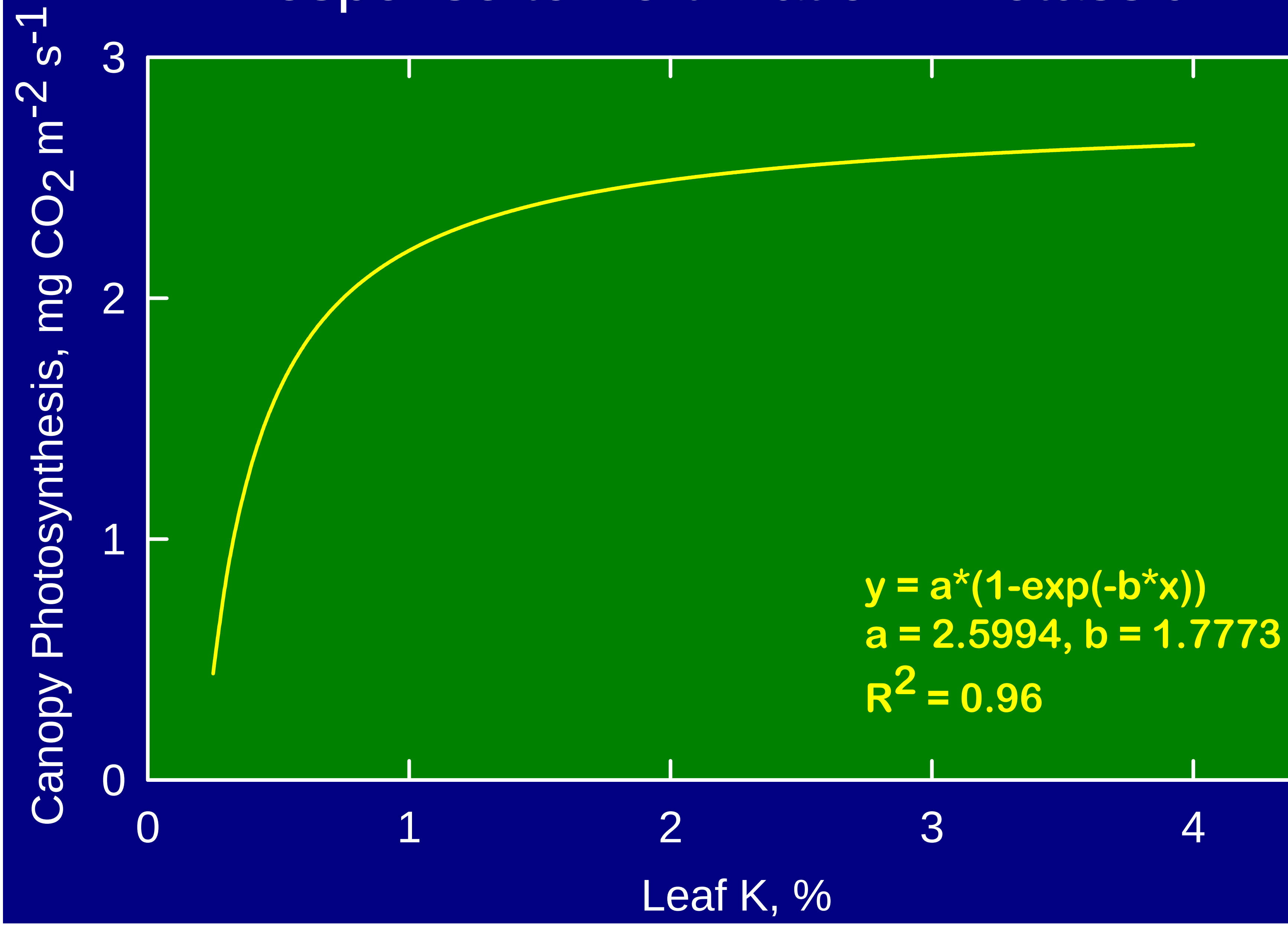
Canopy Photosynthesis - Environment

Response to Fertilization - Nitrogen

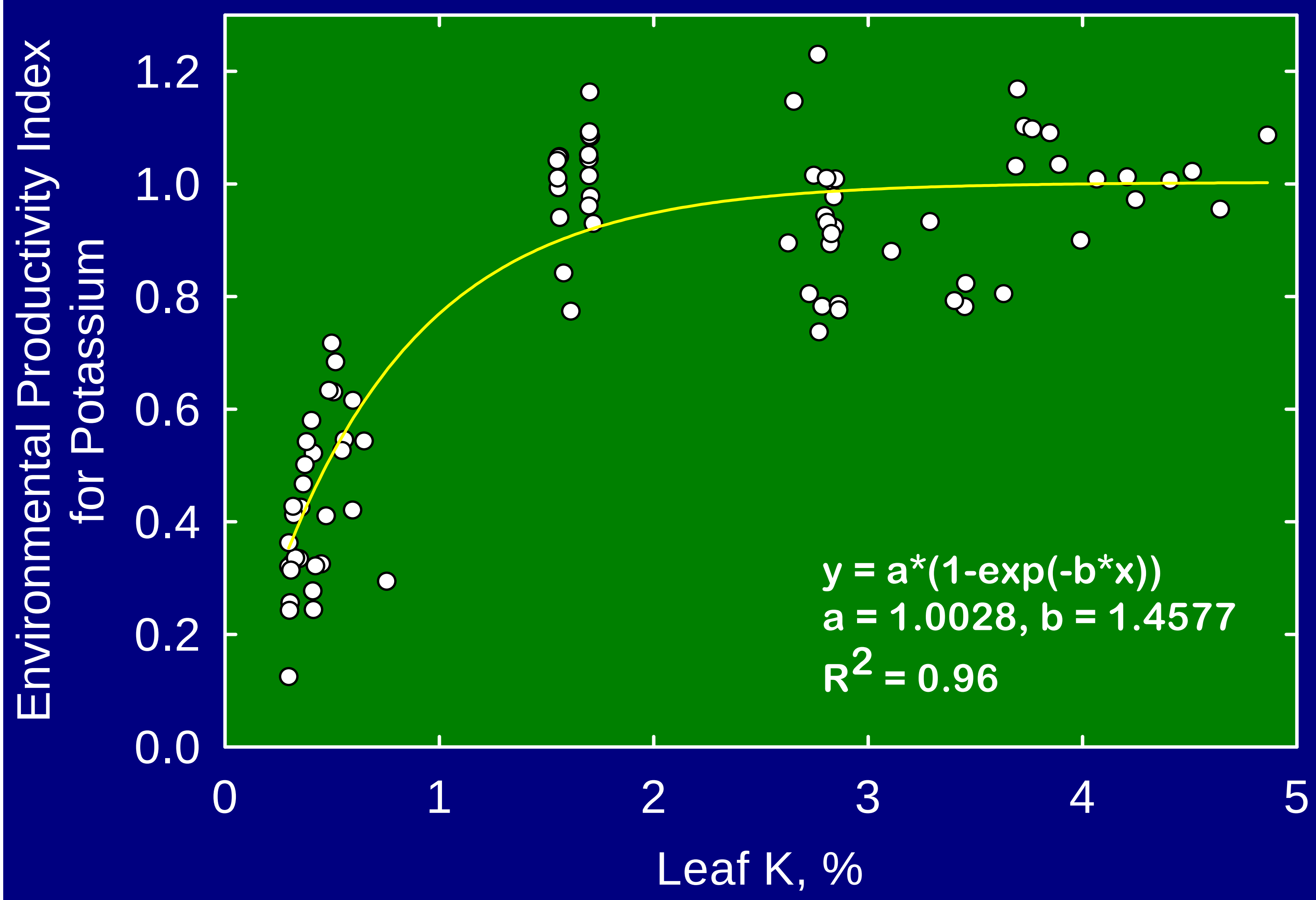


Canopy Photosynthesis - Environment

Response to Fertilization - Potassium



Canopy Photosynthesis - Environment
Response to Fertilization - Potassium



Photosynthesis and Environment

Modeling photosynthesis:

- ✓ Daily values of environmental variables such as temperature and solar radiation (total as well as UV-B) as inputs (Physical inputs).
- ✓ Daily values of light interception (A separate model for solar radiation interception).
- ✓ Daily values of leaf nutrient (N,P, K) status (Models for nutrient uptake and leaf nutrient status).
- ✓ Daily values of leaf water potential as affected by precipitation and irrigation (Model for water uptake and leaf water potential).

Photosynthesis and Respiration and Environment

Actual photosynthesis:

Potential photosynthesis (159.07 g CO_2 m^{-2} d^{-1})*EPI Indices (solar radiation, Temperature, Water stress, Nutrient stresses, UV-B radiation) for various environmental factors.

Therefore, EPI is the way to quantify the effects of environmental factors on photosynthesis and thus productivity of any crop.

Environmental Productivity Index (EPI)

- Same concept can be applied for other crop growth and developmental processes.
- The EPI concept has universal applicability and NOT location or crop-specific.
- EPI also allows one to interpret and to understand stresses in the field situations.
- If we know the factor that is limiting most at any point of time during the growing season, then we can make appropriate management decisions to correct that limitation.

Environmental Productivity Concept
Environment - Photosynthesis

Application of Environmental Productivity Index Concept to the Real-World Situation

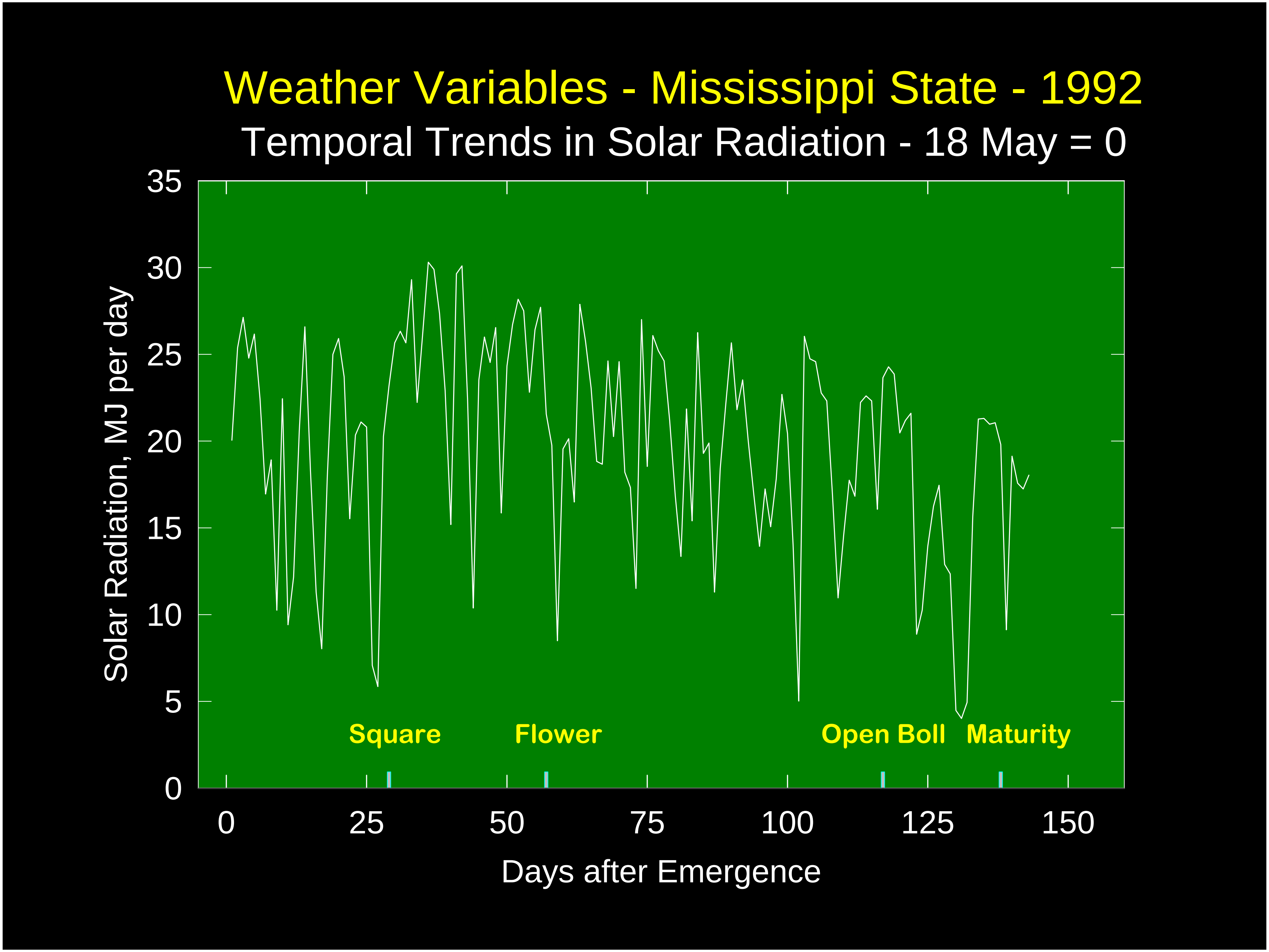
Environmental Factors Impacting Photosynthesis, Productivity and Growth of Crops in a Single Season

Let us examine the environmental variables impacting crop growth and development in a single growing Season:

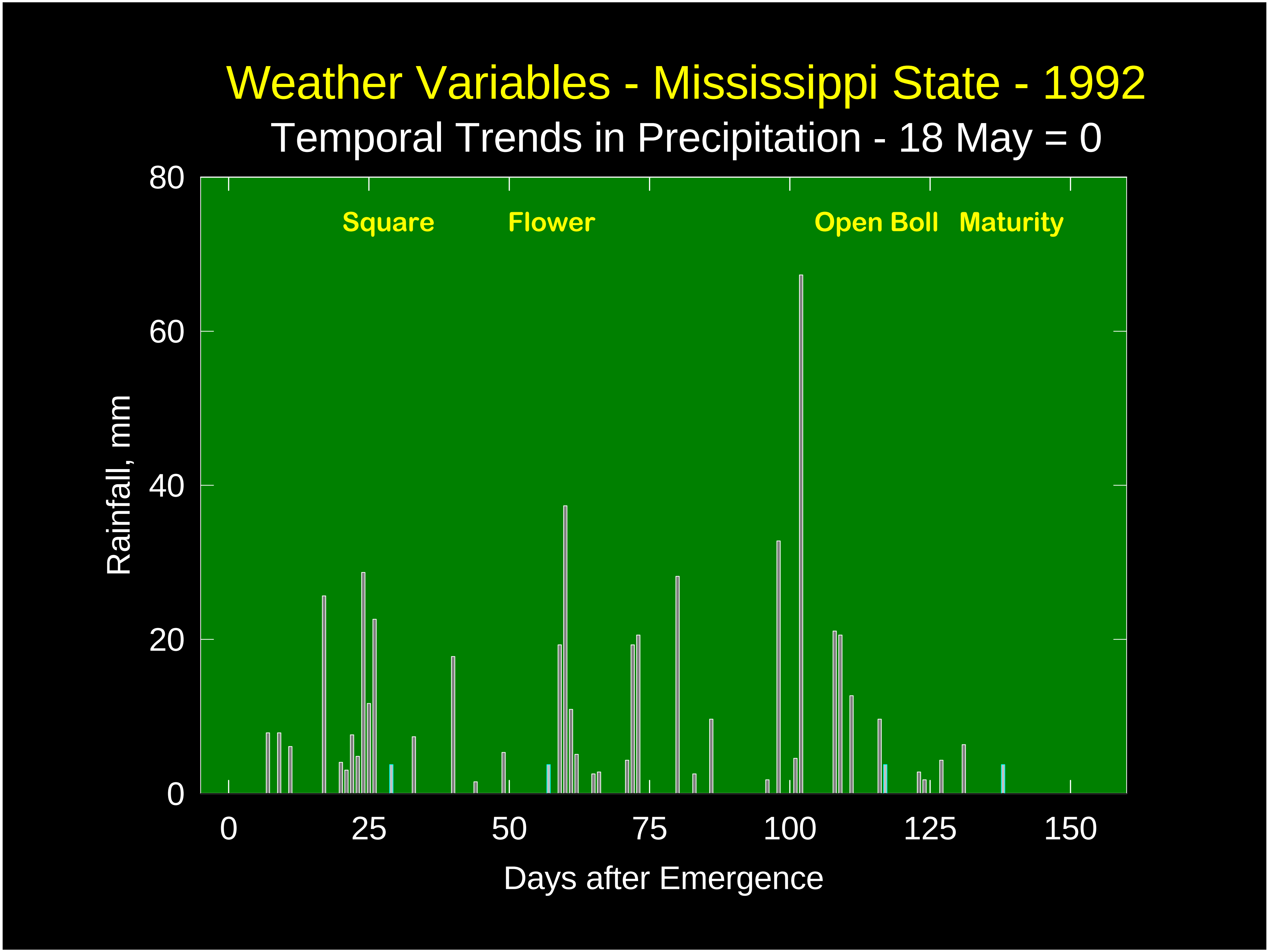
Location:	Mississippi State, North Farm
Year :	1992 cotton growing season
Cultivar:	DPL 90
Fertilizer Applications:	80 lb N prior to planting
Irrigation/rain-fed:	Rain-fed only
Pesticide and weed control:	Standard best management practices

Weather Variables - Mississippi State - 1992

Temporal Trends in Temperatures - 18 May = 0



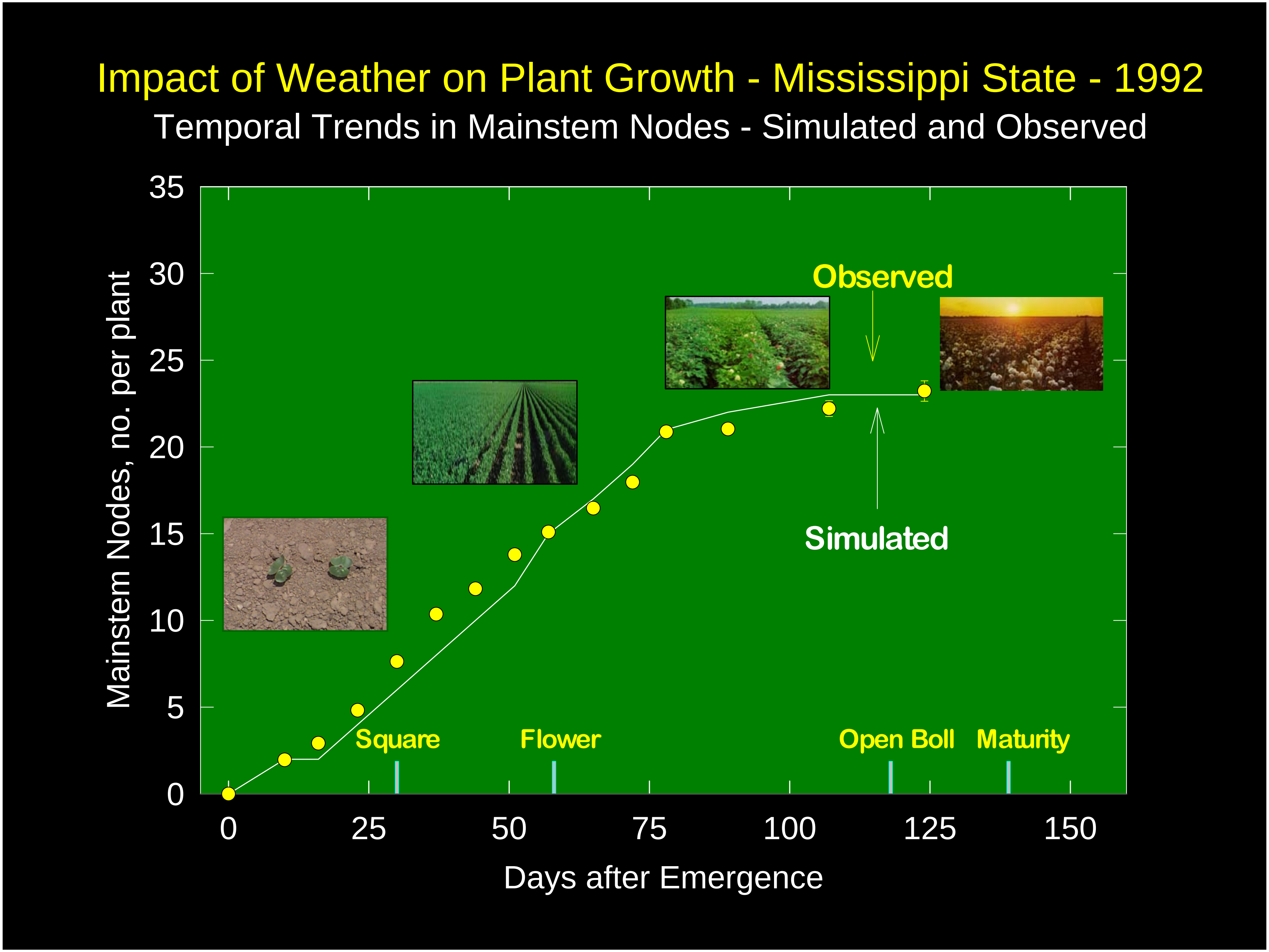
Weather Variables - Mississippi State - 1992
Temporal Trends in Solar Radiation - 18 May = 0
Solar Radiation, MJ per day
0
5
10
15
20
25
30
35
0
25
50
75
100
125
150
Days after Emergence
Square
Flower
Open Boll
Maturity



Weather Variables - Mississippi State - 1992
Temporal Trends in Precipitation - 18 May = 0
Rainfall, mm
0
20
40
60
80
Square
Flower
Open Boll
Maturity
0
25
50
75
100
125
150
Days after Emergence

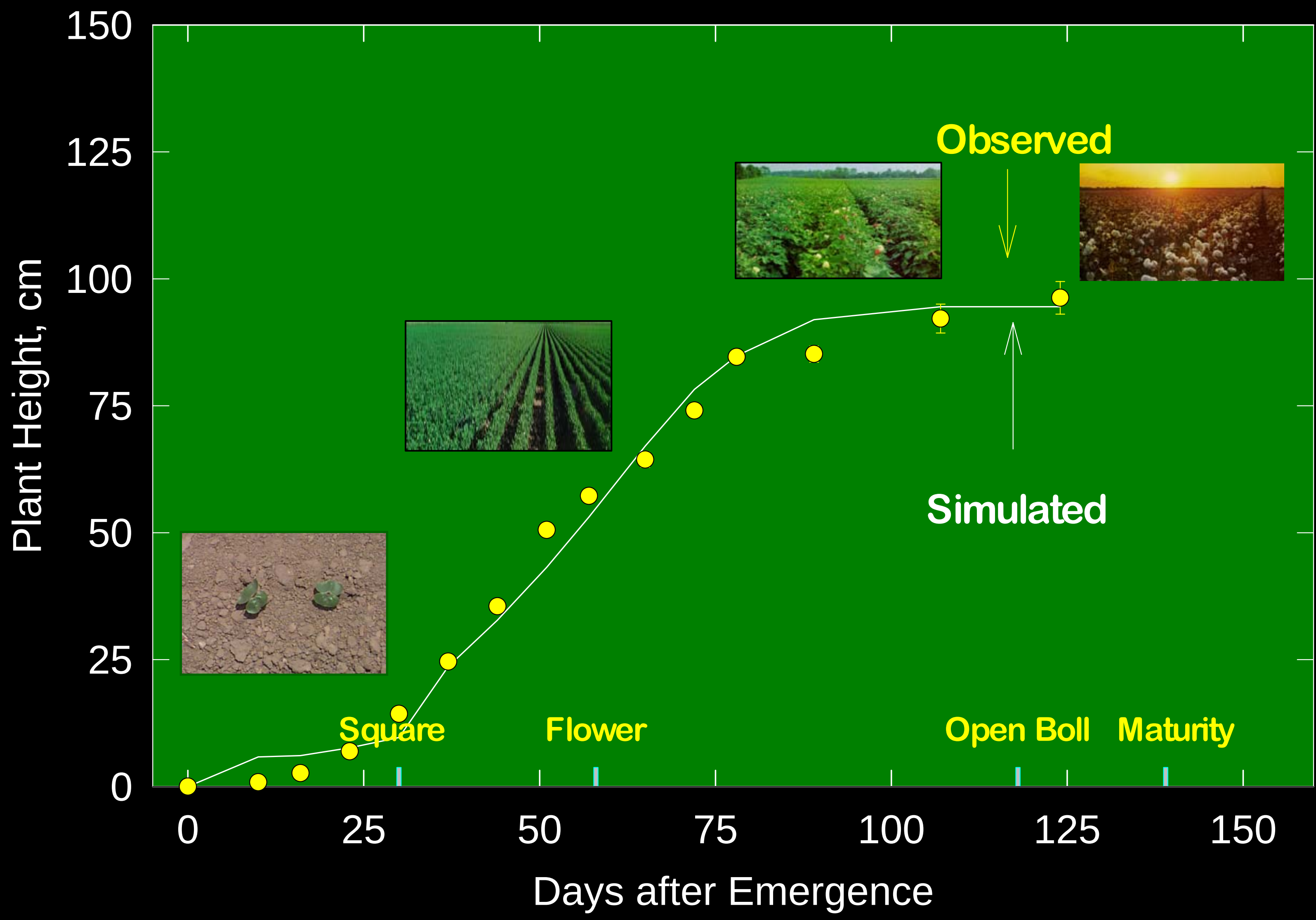
Weather Variables - Mississippi State - 1992

Temporal Trends in Wind Run - 18 May = 0


Impact of Weather on Plant Growth - Mississippi State - 1992
Temporal Trends in Mainstem Nodes - Simulated and Observed
Mainstem Nodes, no. per plant
0
5
10
15
20
25
30
35
0
25
50
75
100
125
150
Days after Emergence
Observed
Simulated
Square
Flower
Open Boll
Maturity

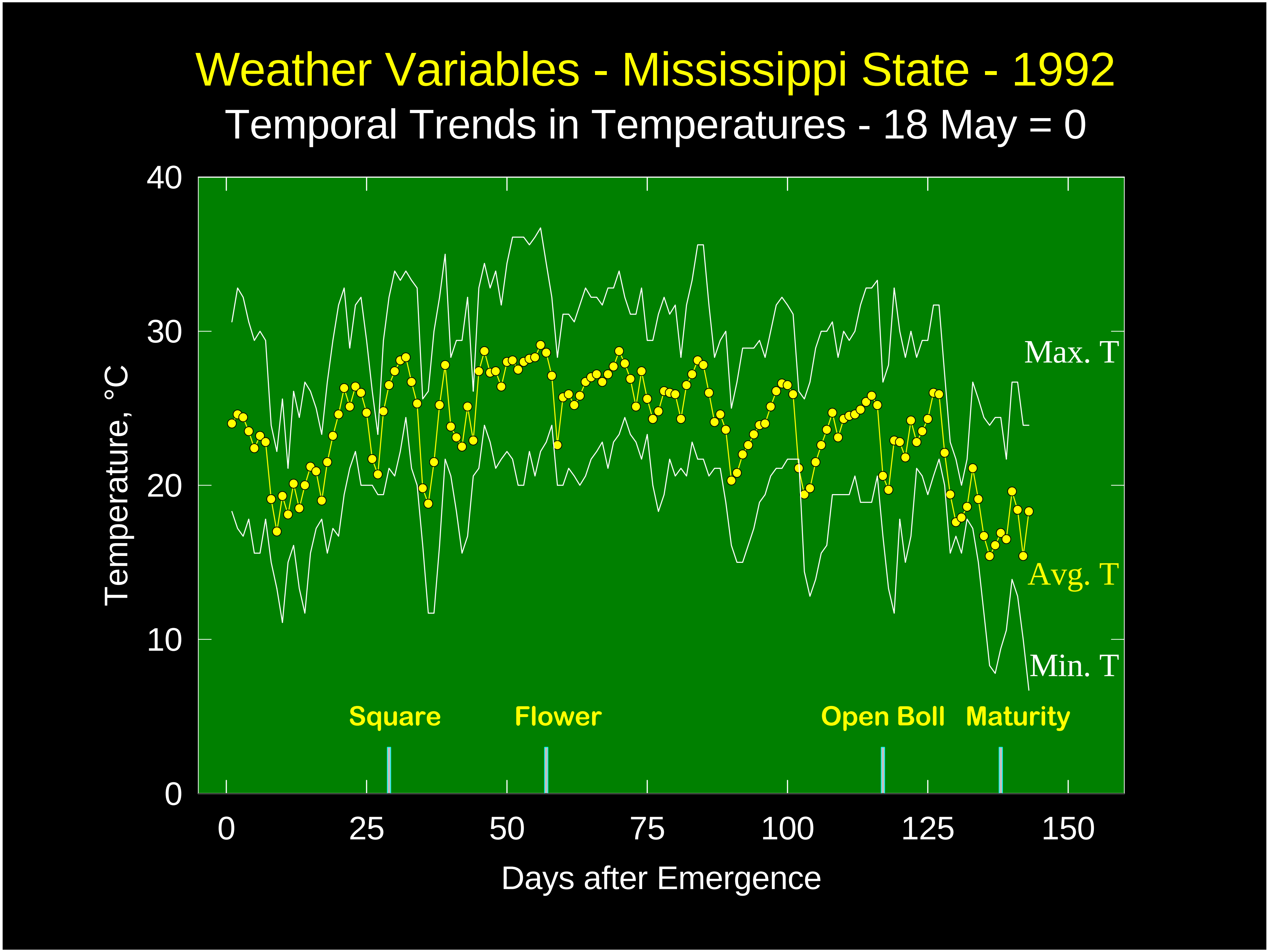
Impact of Weather on Plant Growth - Mississippi State - 1992

Temporal Trends in Plant Height - Simulated and Observed

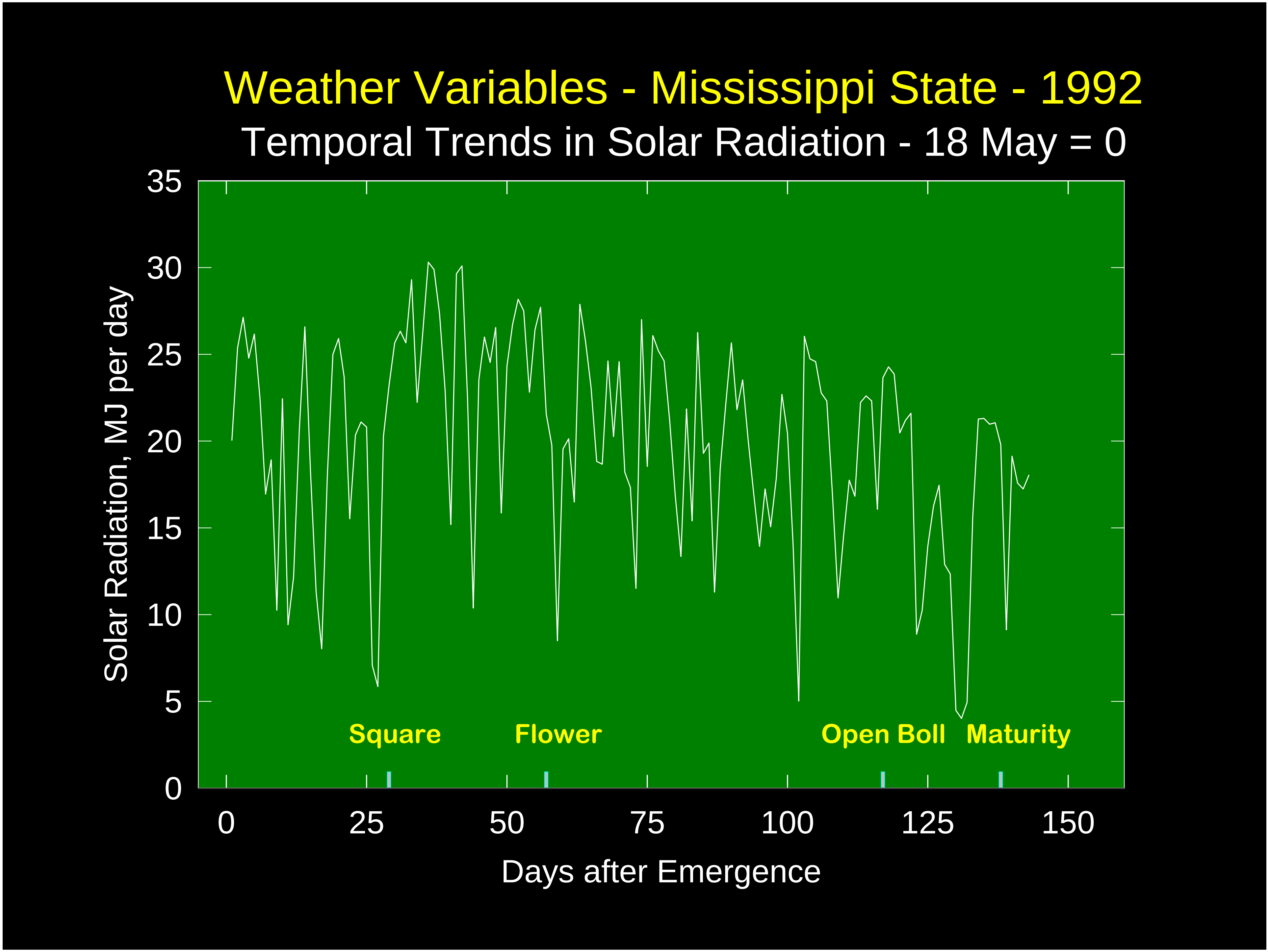


Quantifying the Effects of Environmental Factors on Photosynthesis

Let us assume the following crop conditions for leaf nitrogen, leaf K, and midday leaf water potential and weather variables such as solar radiation and use percent light interception to calculate an intercepted portion of the incoming solar radiation and temperatures for applying the EPI concept for one cotton growing season - 1992.



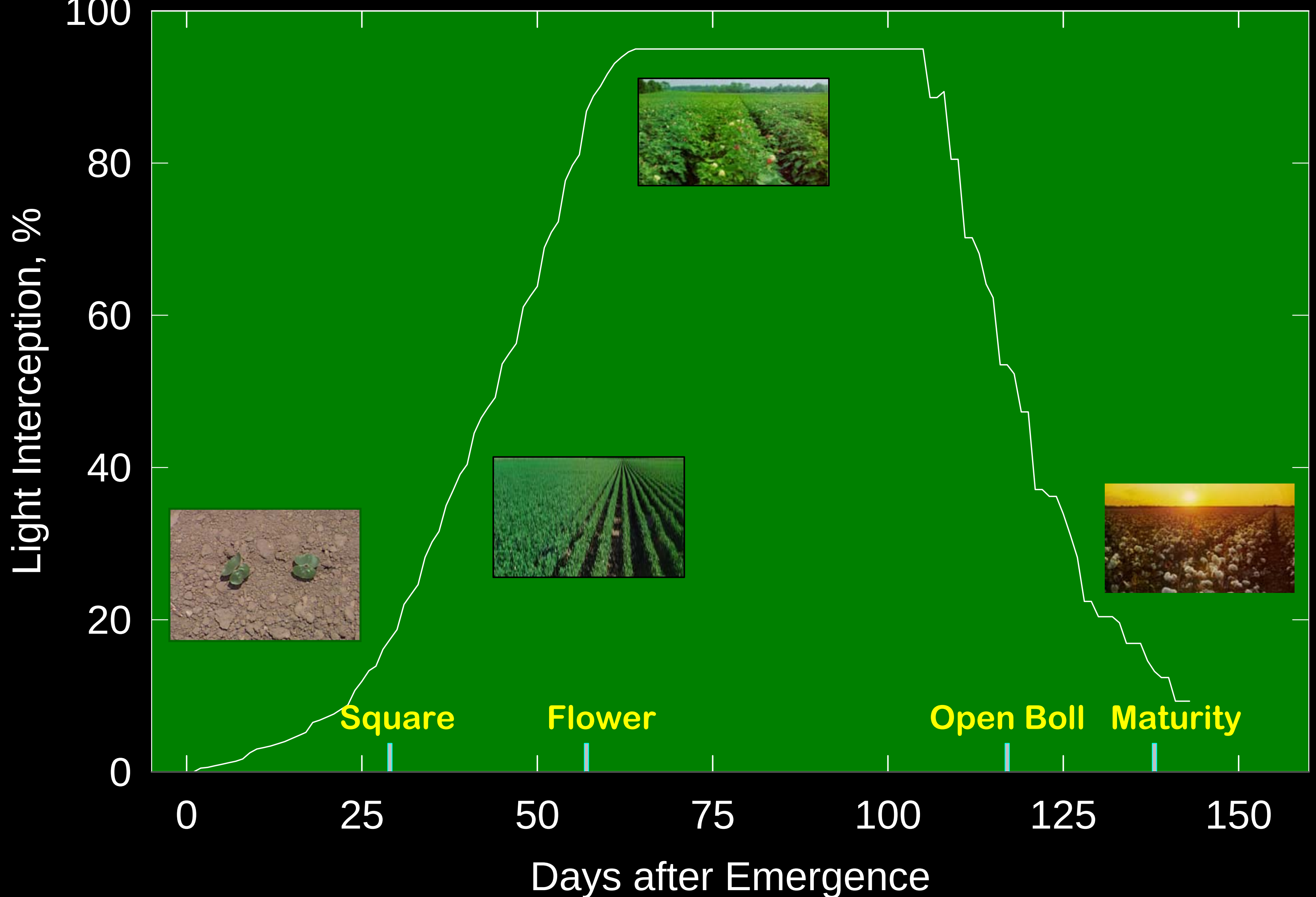
Weather Variables - Mississippi State - 1992
Temporal Trends in Temperatures - 18 May = 0
Temperature, °C
Days after Emergence
0
10
20
30
40
0
25
50
75
100
125
150
Max. T
Avg. T
Min. T
Square
Flower
Open Boll
Maturity



Weather Variables - Mississippi State - 1992
Temporal Trends in Solar Radiation - 18 May = 0
Solar Radiation, MJ per day
Days after Emergence
0
5
10
15
20
25
30
35
0
25
50
75
100
125
150
Square
Flower
Open Boll
Maturity

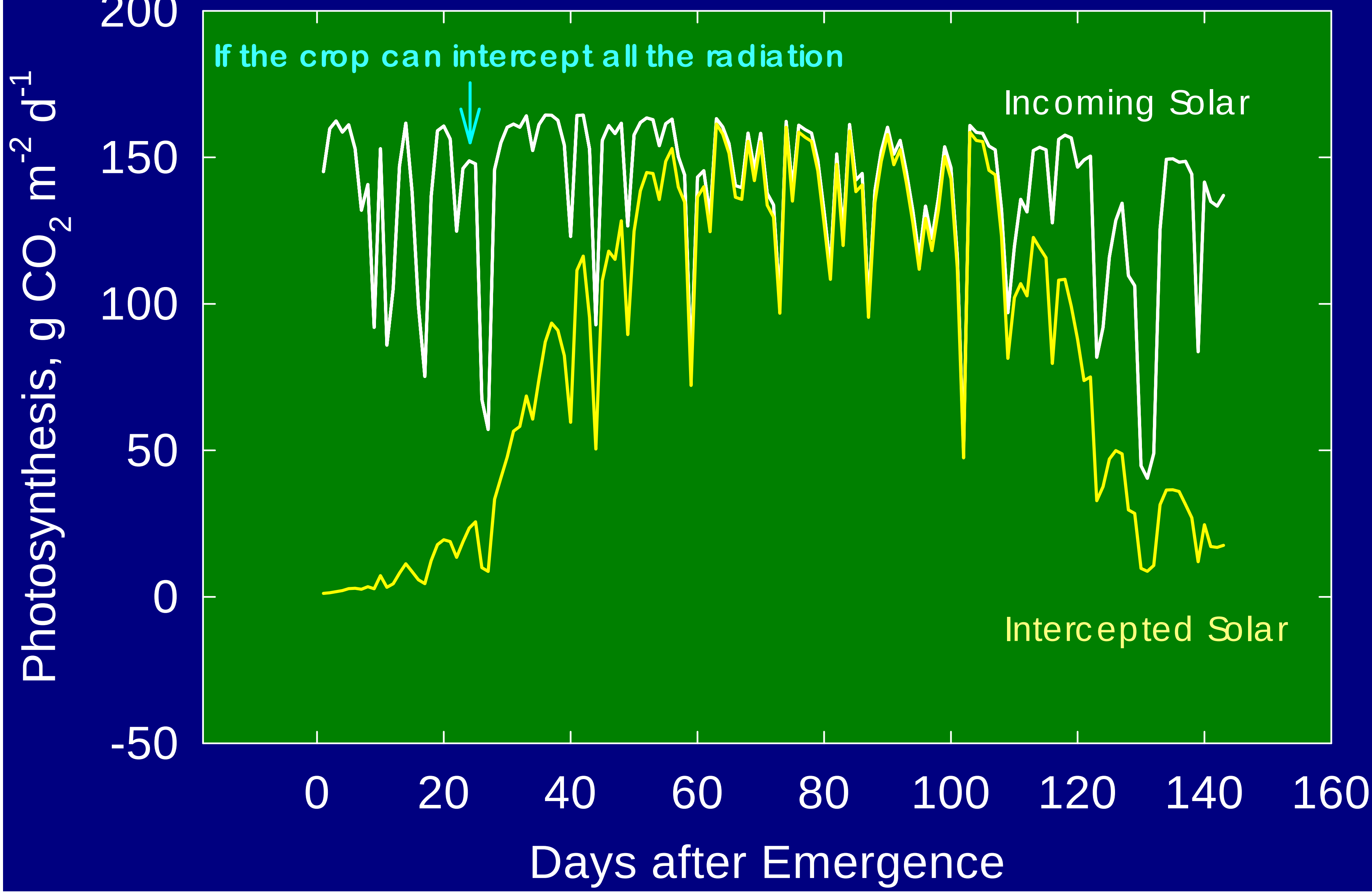
Weather Variables - Mississippi State - 1992

Temporal Trends in Light Interception - 18 May = 0



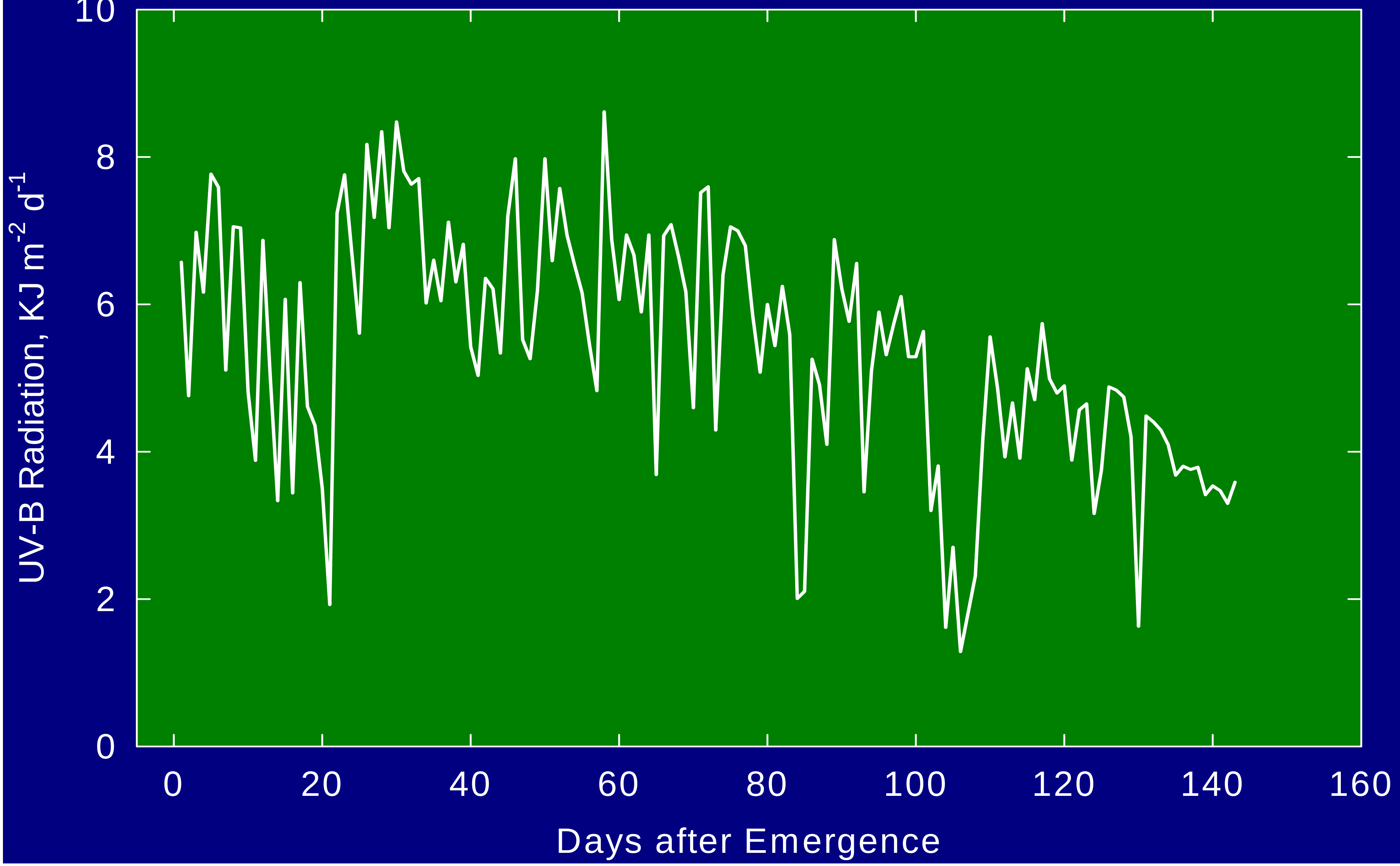
Canopy Photosynthesis - Growing Season

Accounting for environmental factors using EPI concept

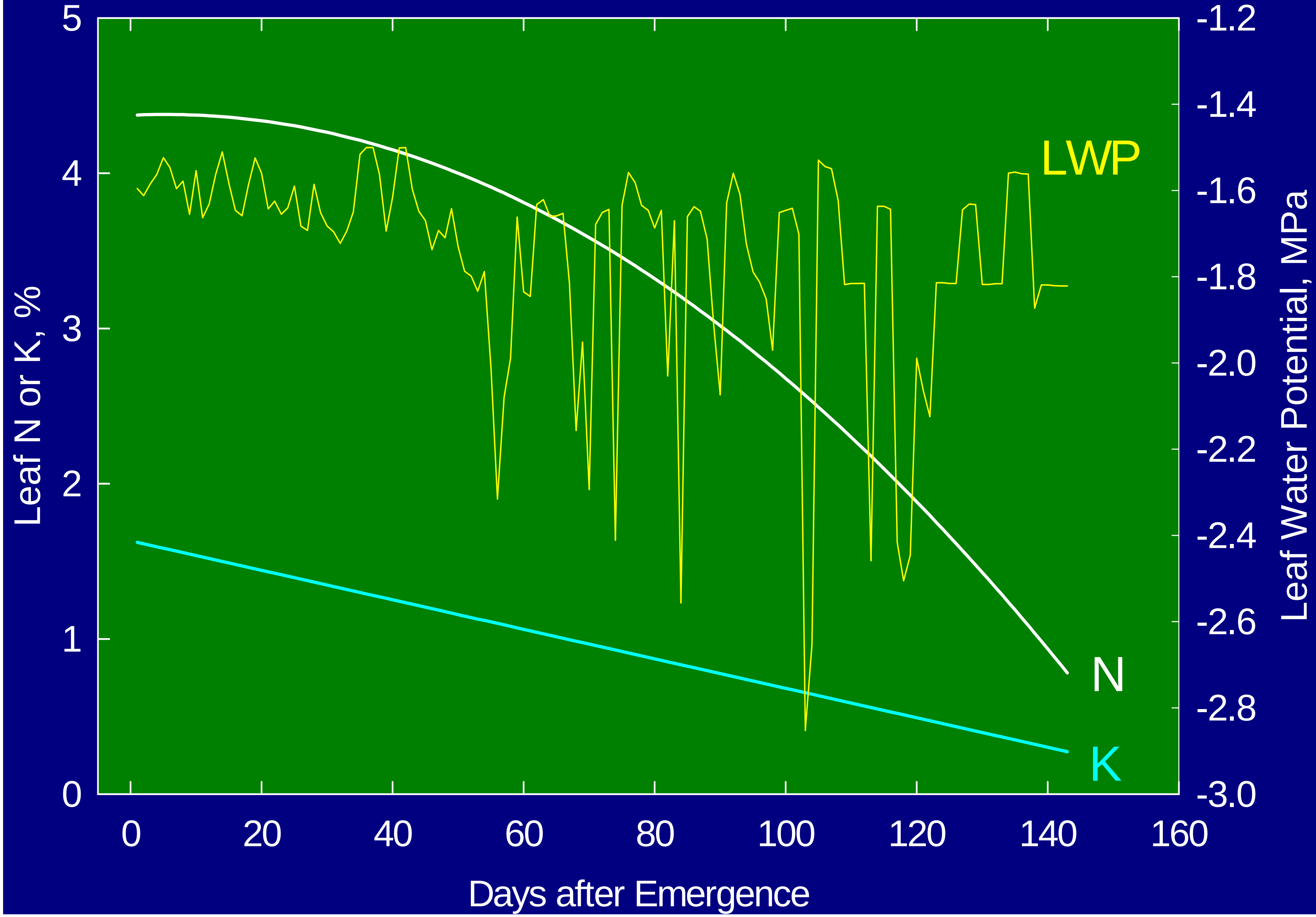


Photosynthesis and environment

Seasonal trends in Ultraviolet-B Radiation



Photosynthesis and environment
Seasonal trends in Leaf N, K and Water Potential

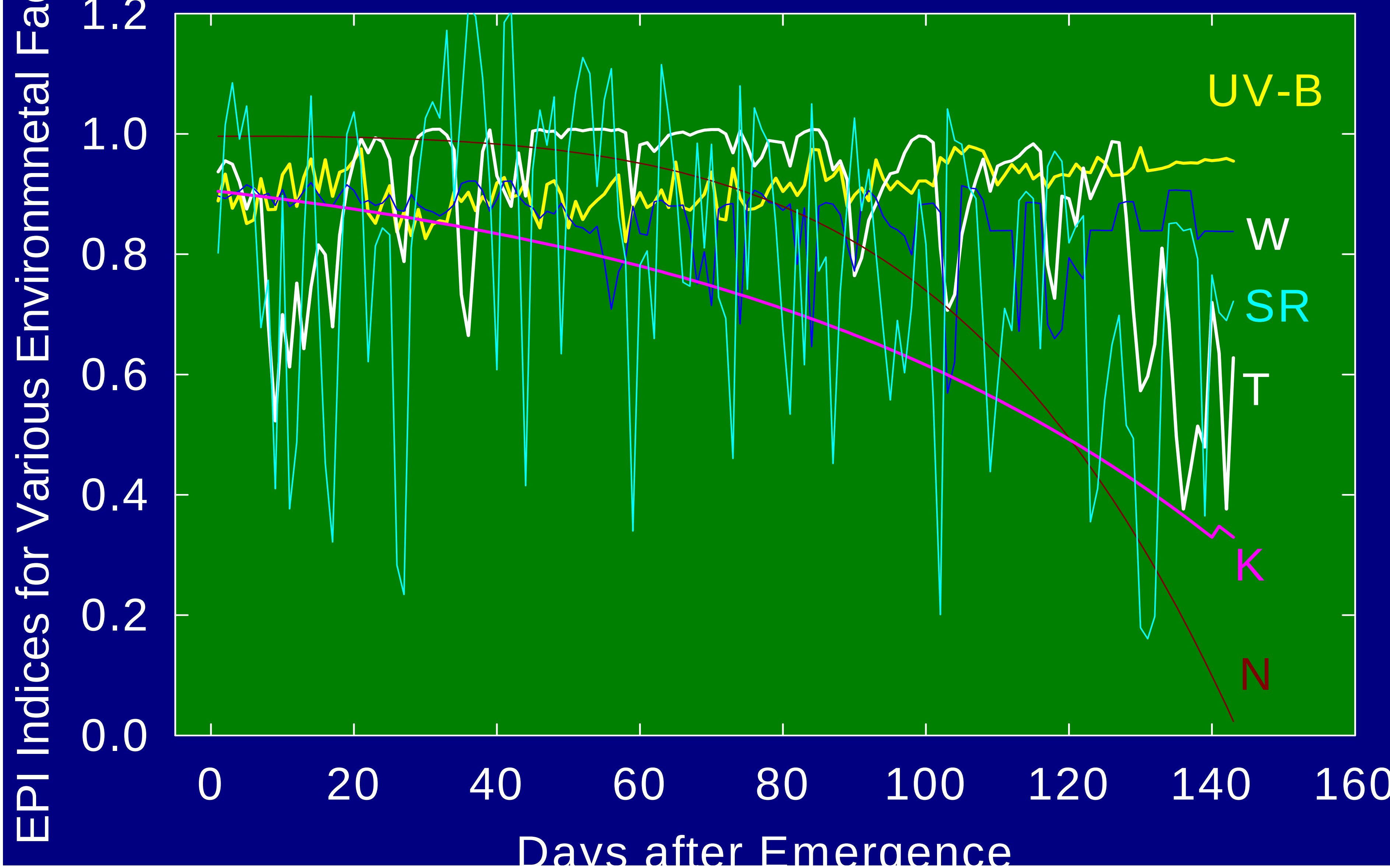


Applying EPI Concept to Real-world Situation

1. First potential photosynthesis is calculated at optimum temperature, water, and nutrient conditions and 0 UV-B and at maximum solar radiation in an actively growing canopy. That is equal to 159.07 g CO_2 m^{-2} d^{-1}.
2. Then, using the functional algorithms or equations for Solar radiation, UV-B radiation, temperature, water stress, and nutrient stresses, EPI Indices for the environmental factors are calculated.
3. Finally, actual photosynthesis is estimated = Potential *EPI indices for various environmental factors.

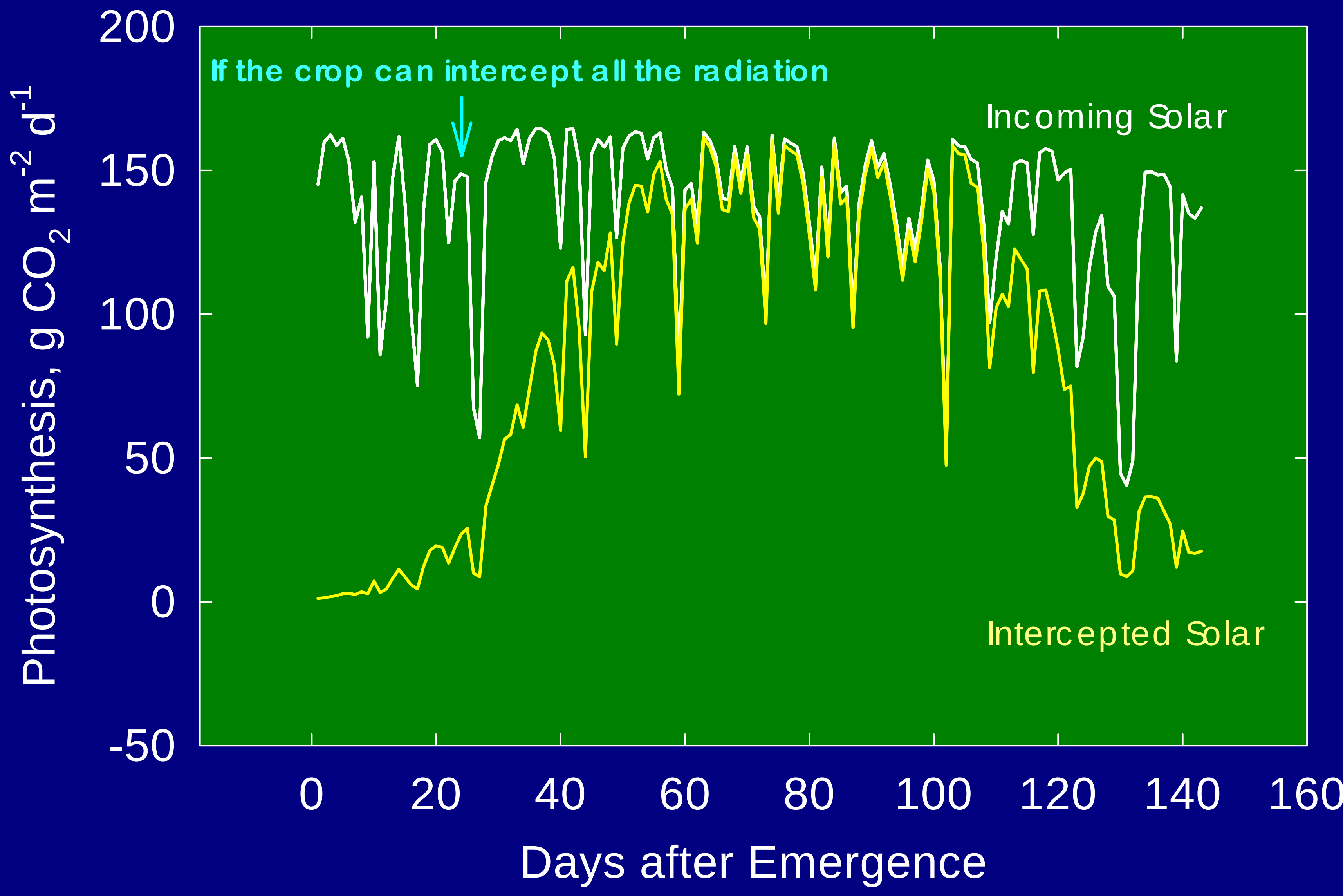
Canopy Photosynthesis - Growing Season

Accounting for environmental factors using EPI concept



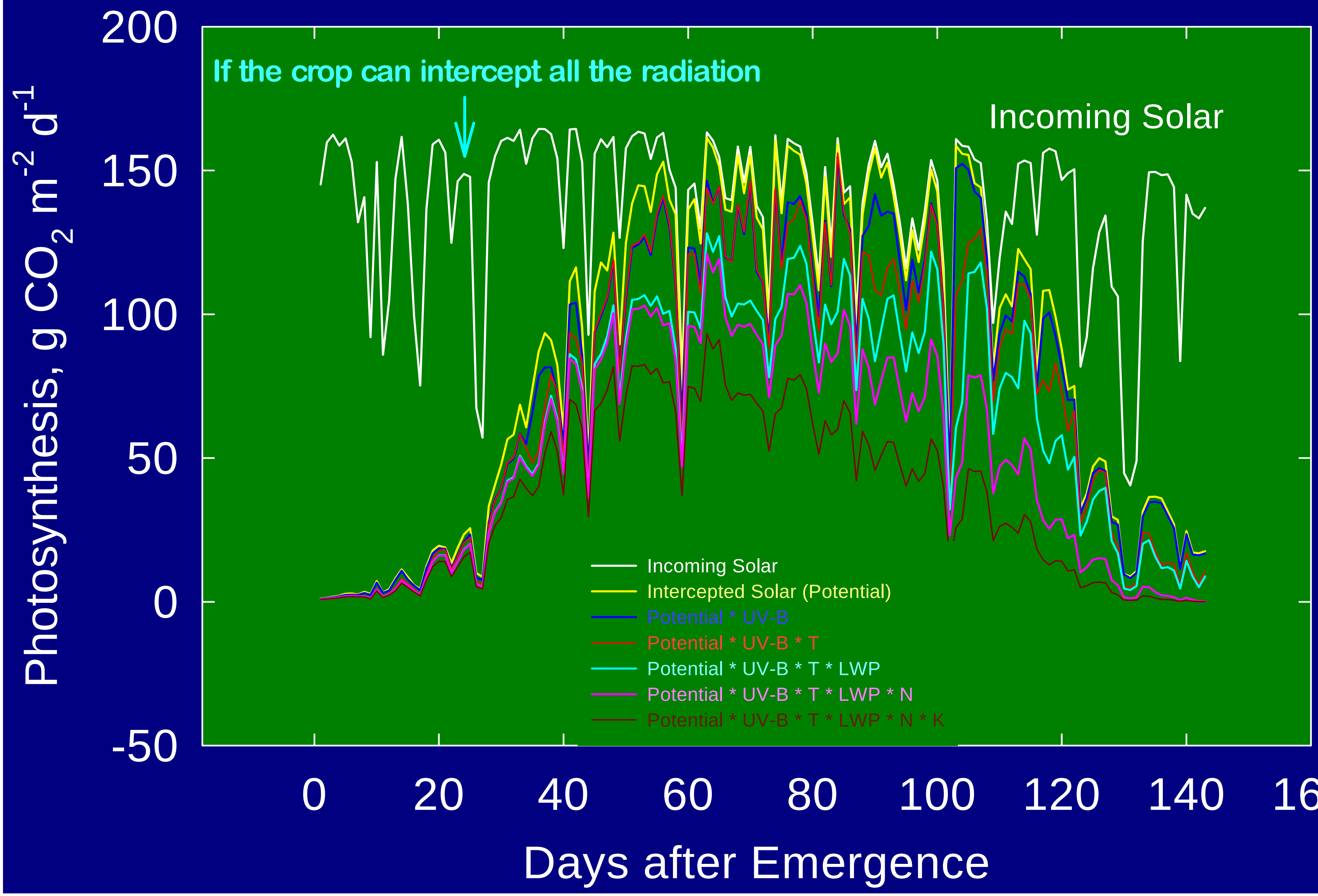
Canopy Photosynthesis - Growing Season

Accounting for environmental factors using EPI concept



Canopy Photosynthesis - Growing Season

Accounting for environmental factors using EPI concept



Radiation Totals for the 1992 Growing season Mississippi State – North Farm

Variable	Amount, MJ
Total Incoming Radiation	2842
Intercepted Radiation	1551
Percent Intercepted	55

Photosynthesis – EPI Concept
Accounting for Individual factors

Variable	Amount, g CO2 m^{-2} $season^{-1}$
Incoming R	19644
Intercepted R	11441 (100%)
Int. R * UV-B	10448 (9%)
Int. R.* T	10139 (11%)
Int. R.* W	9783 (14%)
Int. R.* N	8986 (21%)
Int. R * K	10841 (5%)

Photosynthesis – EPI Concept
Accounting for Multiple Factors

Variable	Amount, g $CO2\ m^{-2}\ season^{-1}$
Incoming R	19644
Intercepted R	11441 (100%)
Int. R* UV-B	10448 (9%)
Int. R* UV-B*T	9153 (20%)
Int. R* UV-B*T*W	7551 (34%)
Int. R*UV-B*T*W*N	6292 (55%)
Int. R*UV-B*T*W* K	4576 (60%)

Actual amount