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

Photosynthesis

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A Land-Grant Institution
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 (CO₂) from the air with water to make carbohydrates plus oxygen.

\[
6 \text{ CO}_2 + 6 \text{ H}_2\text{O} \rightarrow \text{ C}_6\text{H}_{12}\text{O}_6 + 6 \text{ O}_2
\]

Light, Plant

Water, Nutrients
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

<table>
<thead>
<tr>
<th>Year</th>
<th>Atmospheric CO2, ppm</th>
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<tbody>
<tr>
<td>1958</td>
<td>310</td>
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<tr>
<td>1963</td>
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<td>1988</td>
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<td>1993</td>
<td>380</td>
</tr>
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<td>1998</td>
<td>390</td>
</tr>
<tr>
<td>2003</td>
<td>400</td>
</tr>
</tbody>
</table>

*CO2 Concentration, ppm*

- **South Pole**
- **Mauna Loa, HI**

**Month of Year**

- Jan.
- Feb.
- Mar.
- Apr.
- May
- June
- July
- Aug.
- Sept.
- Oct.
- Nov.
- Dec.

**CO2 Concentration, ppm**

- 350
- 351
- 352
- 353
- 354
- 355
- 356
- 357
- 358
- 359
- 360

*23 July 1999*

*1990 at Mauna Loa, HI*

- High
- Low

**Time of the Day (Central Standard Time)**
Radiation Conditions - Seasonal Trends
Bakersfield, CA, Corpus Christi, TX and Stoneville, MS

Day of Year

Solar Radiation, Langleys

0 60 120 180 240 300 360
0 100 200 300 400 500 600 700 800

Bakersfield, CA
Corpus Christi, TX
Stoneville, MS
Long-term Average Temperatures for Four US Cotton Producing Areas

- **Corpus Christi, Texas**: Days above Optimum = 85
- **Stoneville, Mississippi**: Days above Optimum = 0
- **Phoenix, Arizona**: Days above Optimum = 111
- **Bakersfield, California**: Days above Optimum = 36
Precipitation - Seasonal Trends
Bakersfield, CA and Florence, SC - 1991
Seasonal Trends - Midday Leaf Water Potential
Irrigated and rainfed cotton, MSU North Farm - 1995

Days after Emergence
40 60 80 100 120

Midday Leaf Water Potential, bars
-25 -20 -15 -10 -5

-10 -15 -20 -25

-5

Irrigated
Rainfed

Days after Emergence
40 60 80 80 100 110 120
Seasonal Trends Solar and UV-B Radiation
Mississippi State - 2001

UV-B/Solar Ratio: 0.00023323
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

Leaf N (g kg\(^{-1}\))

Days after planting

N study (2001)

N study (2002)
Cultural and Environmental Factors
Seasonal Trends – Leaf Potassium and Phosphorus Concentration

![Graph showing seasonal trends in leaf potassium and phosphorus concentration.](image-url)
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:

\[
\text{Actual (Photosynthesis)} = \text{Potential} \times \text{Solar Radiation Index} \times \text{Water Index} \times \text{Temperature Index} \times \text{Nutrient Indices (C, N, P, K)} \times \text{UV-B Index and Ozone Index, etc.,}
\]

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

Naturally-lit Plant Growth Chambers
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

CO₂ concentration, µL L⁻¹

Time of day

CO₂ = 720 µL L⁻¹
CO₂ = 360 µL L⁻¹
CO₂ = 180 µL L⁻¹
Soil-Plant-Atmosphere-Research (SPAR) Facility

Measuring Gas Exchanges
Carbon [CO$_2$] Fluxes
Carbon Fluxes: Mass balance approach

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

\[
\text{Net photosynthesis} = \text{Amount of CO2 injected} - \text{leak rate}
\]

\[
\text{Gross Photosynthesis} = \text{Net photosynthesis} + \text{Respiration}
\]
Canopy Photosynthesis
Response to Solar Radiation

Carbon Exchange Rate, mg CO₂ m⁻² s⁻¹

Time of the Day (Central Standard Time)

PPFD, µmol m⁻² s⁻¹

360 µL L⁻¹
Solar Radiation

Maize, DAE 37
Estimating Potential Photosynthesis for Cotton as a Function of Solar Radiation

Solar Radiation, MJ m\(^{-2}\) d\(^{-1}\)

Photosynthesis, g CO\(_2\) m\(^{-2}\) d\(^{-1}\)

\[ y = 10.7803X - 0.1767X^2; r^2 = 0.73 \]

The Potential PHS (at 25 MJ) = 159.07 CO\(_2\) m\(^{-2}\) d\(^{-1}\)
Canopy Photosynthesis - Growing Season
Accounting for environmental factors using EPI concept

Days after Emergence

If the crop can intercept all the radiation

Incoming Solar

Intercepted Solar

Photosynthesis, g CO₂ m⁻² d⁻¹

Days after Emergence
Canopy Photosynthesis and Environment
Response to Solar Radiation

Environmental Productivity Index
for Photosynthesis

Solar Radiation, MJ m\(^{-2}\) d\(^{-1}\)

\[y = 0.0678X - 0.001111X^2, \quad r^2 = 0.73\]
Canopy Photosynthesis
Response to Atmospheric Carbon Dioxide

Canopy Photosynthesis, mg CO$_2$ m$^{-2}$ s$^{-1}$

Carbon Dioxide Concentration, µL L$^{-1}$

\[ y = 0.01235 \times X - (0.00001222 \times X^2) + (0.000000003976 \times X^3) \]
Canopy Photosynthesis - Environment Response to Atmospheric Carbon Dioxide

Environmental Productivity Index for CO\textsubscript{2} (CO\textsubscript{2} = 360)

\[ y = 0.004050 \times X - (0.000004006 \times X^2) + (0.00000001303 \times X^3) \]

Carbon Dioxide Concentration, µL L\textsuperscript{-1}
Canopy Photosynthesis - Environment Response to Temperature

Canopy Photosynthesis, mg CO$_2$ m$^{-2}$ s$^{-1}$

Temperature, °C

$y = -10.286 + 1.087 \times X - 0.0192 \times X^2$, $r^2 = 0.99$
Canopy Photosynthesis - Environment Response to Temperature

Environmental Productivity Index for Temperature (T=27°C)

\[ y = -2.0247 + (0.2141 \times X) - (0.003779 \times X^2); \quad r^2 = 0.99 \]
Canopy Photosynthesis - Environment

Response to Water Deficits

Photosynthesis, mg CO₂ m⁻² s⁻¹

Midday Leaf Water Potential, MPa

y = 6.0581 + (1.20327 * X); r² = 0.64
Canopy Photosynthesis - Environment

Response to Water Deficits

Environmental Productivity Index

for Water Deficits

-4.0 -3.5 -3.0 -2.5 -2.0 -1.5 -1.0

Midday Leaf Water Potential, MPa

0.0 0.2 0.4 0.6 0.8 1.0 1.2

Environmental Productivity Index

for Water Deficits

350 μmol mol$^{-1}$ CO$_2$

PPFD, 1600 μmol m$^{-2}$ s$^{-1}$

$y = 1.3129 + (0.2608 \times X); r^2 = 0.64$
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

Environmental Productivity Index
for UV-B radiation

\[ y = 0.9835 - 0.0002563 \times X - 0.002163 \times X^2, \quad r^2 = 0.86 \]
Canopy Photosynthesis - Environment
Response to Fertilization - Nitrogen

360 µL L⁻¹ CO₂
PPFD = 1200

y = -1.9788 + (2.9243 * X) - (0.3096 * X²); r² = 0.79
Canopy Photosynthesis - Environment Response to Fertilization - Nitrogen

Environmental Productivity Index for Nitrogen

360 µL L⁻¹ CO₂
PPFD = 1200

\[ y = -0.4029 + (0.5954 \times X) - (0.0630 \times X^2); \quad r^2 = 0.79 \]
Canopy Photosynthesis - Environment

Response to Fertilization - Potassium

\[ y = a^{1 - \exp(-b\times)} \]

\[ a = 2.5994, \ b = 1.7773 \]

\[ R^2 = 0.96 \]
Environmental Productivity Index for Potassium

$y = a(1 - \exp(-b \cdot x))$

$a = 1.0028$, $b = 1.4577$

$R^2 = 0.96$
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 \((159.07 \, \text{g CO}_2 \, \text{m}^{-2} \, \text{d}^{-1}) \times \text{EPI}\)

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 Solar Radiation - 18 May = 0

Solar Radiation, MJ per day

Days after Emergence

Square   Flower   Open Boll   Maturity
Impact of Weather on Plant Growth - Mississippi State - 1992

Temporal Trends in Mainstem Nodes - Simulated and Observed

Days after Emergence

Mainstem Nodes, no. per plant

0 25 50 75 100 125 150

Simulated

Observed

Square Flower Open Boll Maturity

0 5 10 15 20 25 30 35
Impact of Weather on Plant Growth - Mississippi State - 1992

Temporal Trends in Plant Height - Simulated and Observed

Days after Emergence

0 25 50 75 100 125 150

Plant Height, cm

0 25 50 75 100 125 150

Simulated

Observed

Days after Emergence

0 25 50 75 100 125 150

Square  Flower  Open Boll  Maturity
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.
Temporal Trends in Solar Radiation - 18 May = 0

Weather Variables - Mississippi State - 1992

Days after Emergence

Solar Radiation, MJ per day

Square Flower Open Boll Maturity

Days after Emergence
Temporal Trends in Light Interception - 18 May = 0
Canopy Photosynthesis - Growing Season
Accounting for environmental factors using EPI concept

If the crop can intercept all the radiation

Incoming Solar

Intercepted Solar

Photosynthesis, g CO₂ m⁻² d⁻¹

Days after Emergence
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

Days after Emergence

EPI Indices for Various Environmental Factors

UV-B, W, SR, T, K, N
Canopy Photosynthesis - Growing Season

Accounting for environmental factors using EPI concept

![Graph showing photosynthesis over days after emergence with intercepted and incoming solar radiation.]
Canopy Photosynthesis - Growing Season
Accounting for environmental factors using EPI concept

If the crop can intercept all the radiation

Incoming Solar

Incoming Solar

Intercepted Solar (Potential)

Potential * UV-B

Potential * UV-B * T

Potential * UV-B * T * LWP

Potential * UV-B * T * LWP * N

Potential * UV-B * T * LWP * N * K
Radiation Totals for the 1992 Growing season
Mississippi State – North Farm

<table>
<thead>
<tr>
<th>Variable</th>
<th>Amount, MJ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Incoming Radiation</td>
<td>2842</td>
</tr>
<tr>
<td>Intercepted Radiation</td>
<td>1551</td>
</tr>
<tr>
<td>Percent Intercepted</td>
<td>55</td>
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</tbody>
</table>


### Photosynthesis – EPI Concept

**Accounting for Individual factors**

<table>
<thead>
<tr>
<th>Variable</th>
<th>Amount, g CO2 m(^{-2}) season(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Incoming R</td>
<td>19644</td>
</tr>
<tr>
<td>Intercepted R</td>
<td>11441 (100%)</td>
</tr>
<tr>
<td>Int. R * UV-B</td>
<td>10448 (9%)</td>
</tr>
<tr>
<td>Int. R. * T</td>
<td>10139 (11%)</td>
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<tr>
<td>Int. R. * W</td>
<td>9783 (14%)</td>
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<tr>
<td>Int. R. * N</td>
<td>8986 (21%)</td>
</tr>
<tr>
<td>Int. R * K</td>
<td>10841 (5%)</td>
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</table>
## Photosynthesis – EPI Concept
Accounting for Multiple Factors

<table>
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<tr>
<th>Variable</th>
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</tr>
<tr>
<td>Int. R* UV-B</td>
<td>10448 (9%)</td>
</tr>
<tr>
<td>Int. R* UV-B*T</td>
<td>9153 (20%)</td>
</tr>
<tr>
<td>Int. R* UV-B<em>T</em>W</td>
<td>7551 (34%)</td>
</tr>
<tr>
<td>Int. R<em>UV-B</em>T<em>W</em>N</td>
<td>6292 (55%)</td>
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<tr>
<td>Int. R<em>UV-B</em>T<em>W</em> K</td>
<td>4576 (60%)</td>
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