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 (CO₂) from the air with water to make carbohydrates plus oxygen.

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

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

Year
Atmospheric CO2, ppm
310 320 330 340 350 360 370 380

South Pole
Mauna Loa, HI

Radiation Conditions - Seasonal Trends
Bakersfield, CA, Corpus Christi, TX and Stoneville, MS

Time of the Day (Central Standard Time)
02 46 8 1 0 1 2 1 4 1 6 1 8 2 0 2 2 2 4
CO2 Concentration, ppm
340 360 380 400 420 440

23 July 1999
Month of Year
CO2 Concentration, ppm
350 351 352 353 354 355 356 357 358 359

1990 at Mauna Loa, HI
High
Low

Seasonal Trends - Midday Leaf Water Potential
Irrigated and rainfed cotton, MSU North Farm -1995
Midday Leaf Water Potential, bars
-25 -20 -15 -10 -5 0 5 10 15 20 25 30 35 40
Days after Emergence
40 60 80 100 120
Seasonal Trends Solar and UV-B Radiation
Mississippi State - 2001
Days
0 100 200 300 400
Solar Radiation, MJ m⁻² d⁻¹
0 20 40 60
0.00 0.01 0.02 0.03 0.04 0.05
UV-B Radiation, kJ m⁻² d⁻¹
0.00 0.01 0.02 0.03 0.04 0.05
UV-B/Solar Ratio: 0.00023323
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 Potassium and Phosphorus Concentration

Leaf K, %

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 an actively growing canopy, no aging effect).

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.

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) CO₂ conditions.
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 - Growing Season
Accounting for environmental factors using EPI concept

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 - Response to Solar Radiation
Maize, DAE 37

Carbon Exchange Rate, mg CO2 m-2 s-1

Solar Radiation, MJ m-2 d-1

Photosynthesis, g CO2 m-2 d-1

y = 10.7803*X - 0.1767 * X^2; r² = 0.73

The Potential PHS (at 25 MJ) = 159.07 CO2 m-2 d-1
Canopy Photosynthesis and Environment
Response to Solar Radiation

Environmental Productivity Index
Solar Radiation, MJ m$^{-2}$ d$^{-1}$

\[ y = 0.0078x - 0.001111x^2, \quad r^2 = 0.73 \]

Canopy Photosynthesis
Response to Atmospheric Carbon Dioxide

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

\[ y = 0.01235x - (0.00001222x^2) + (0.000000003976x^3) \]

Canopy Photosynthesis - Environment
Response to Atmospheric Carbon Dioxide

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

\[ y = 0.004050x - (0.000004006x^2) + (0.000000001303x^3) \]

Canopy Photosynthesis - Environment
Response to Temperature

Environmental Productivity Index
Temperature °C

\[ y = -10.286 + 1.087x - 0.0192x^2, \quad r^2 = 0.99 \]

Canopy Photosynthesis - Environment
Response to Water Deficits

Environmental Productivity Index
Midday Leaf Water Potential, MPa

\[ y = 6.0581 + (1.20327x), \quad r^2 = 0.64 \]
Canopy Photosynthesis - Environment
Response to Water Deficits

Environmental Productivity Index
for Water Deficits

Midday Leaf Water Potential, MPa

Environmental Productivity Index
for Water Deficits

Response to Solar Radiation
Response to UV-B Radiation

UV-B Radiation, kJ m\(^{-2}\) d\(^{-1}\)

Canopy Photosynthesis - Environment
Response to UV-B Radiation

Environmental Productivity Index
for UV-B radiation

y = 0.9835 - 0.0002563*X - 0.002163*X\(^2\); r\(^2\) = 0.86

Canopy Photosynthesis - Environment
Response to Fertilization - Nitrogen

Leaf N, %

Environmental Productivity Index
for Nitrogen

y = -0.4029 + (0.5954 * X) - (0.0630 * X\(^2\)); r\(^2\) = 0.79

Canopy Photosynthesis - Environment
Response to Fertilization - Nitrogen

Canopy Photosynthesis - Environment
Response to Fertilization - Potassium

Leaf K, %

y = a*(1-exp(-b*x))
a = 2.5994, b = 1.7773
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).

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 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
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.
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 CO₂ 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.

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>
</tr>
</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>
</tr>
<tr>
<td>Int. R * W</td>
<td>9783 (14%)</td>
</tr>
<tr>
<td>Int. R * N</td>
<td>8986 (21%)</td>
</tr>
<tr>
<td>Int. R * K</td>
<td>10841 (5%)</td>
</tr>
</tbody>
</table>

### Photosynthesis – EPI Concept
#### Accounting for Multiple Factors

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