Light Use Efficiency-based Crop Yield Modelling

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Four Pillars of Food Security

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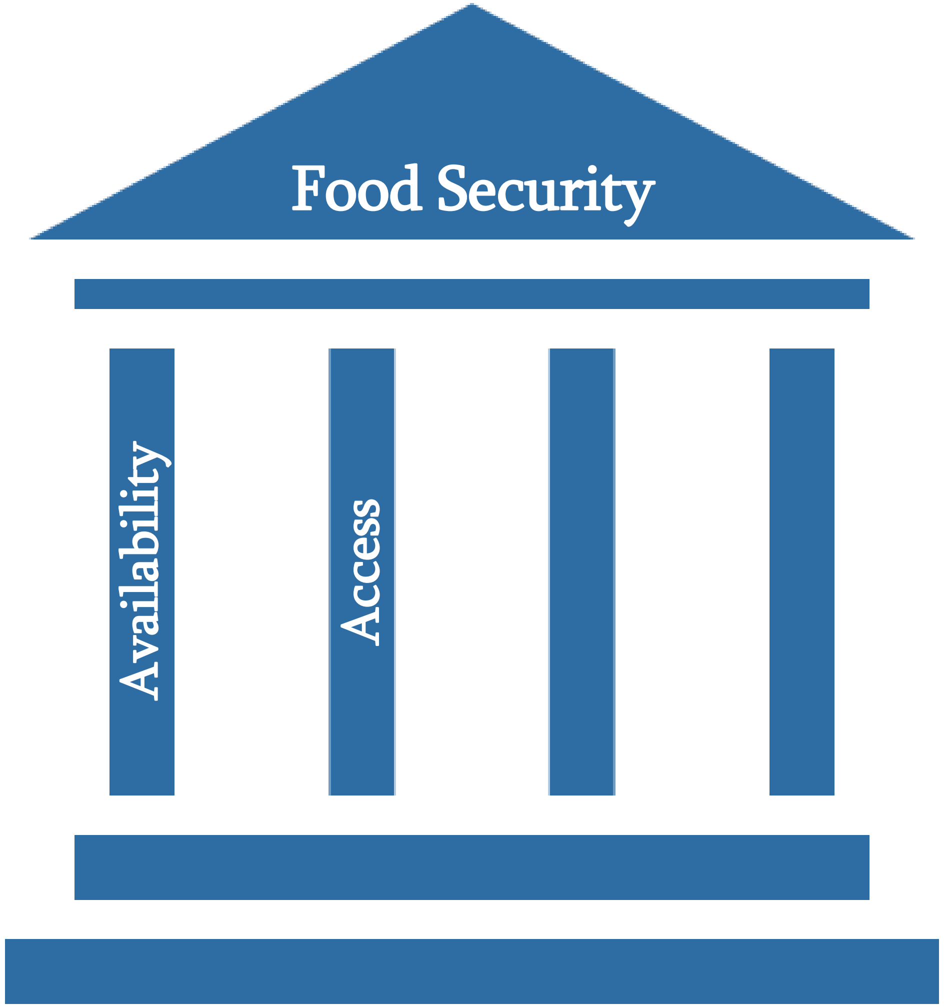
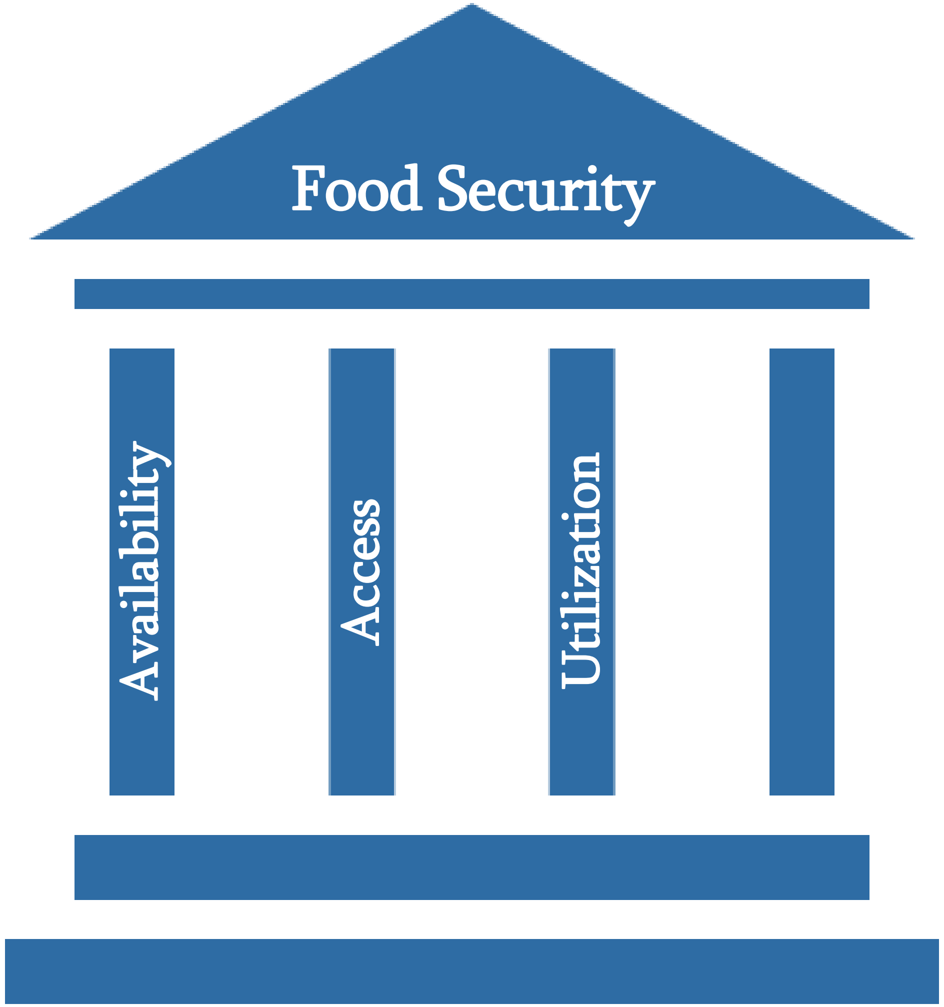


Four Pillars of Food Security



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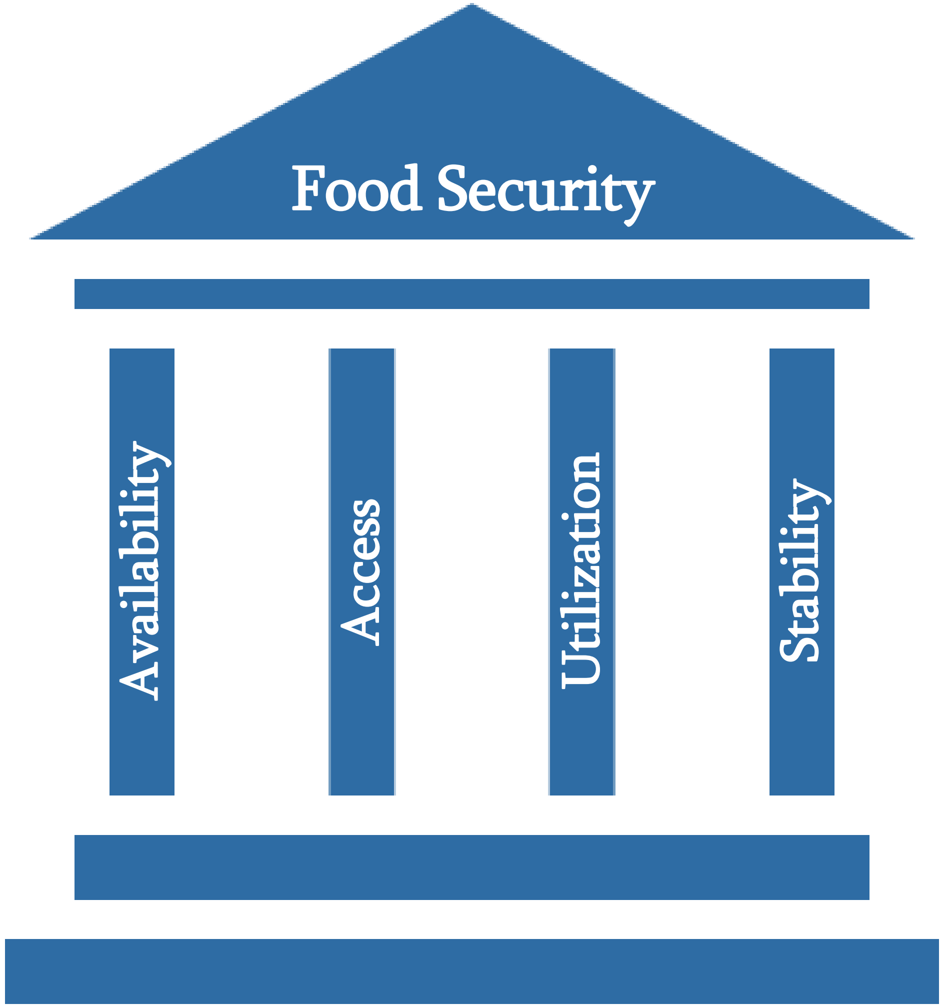


Earth Observation and Food Availability

2 ZERO HUNGER

Earth observation is almost exclusively used to estimate the amount produced:

$$\text{Food Production (kg)} = \text{Area (ha)} \times \text{Crop Yield (kg ha}^{-1}\text{)}$$

Earth observation agricultural research deals largely with cropland extent mapping. But crop yield is also widely assessed,

$$\text{Crop Yield} = \frac{\text{Production (kg)}}{\text{Area (ha)}}$$

Crop yield is the marketable fraction of aboveground biomass accumulated over a growing season for food, feed, fiber or oil

Why would you want to measure crop yield from space?

Why would you want to measure crop yield from space?

residue management
crop variety performance
irrigation
fertilizer application
planting
tillage
harvest
forecasting
drought

Learning Objectives of this Course

- Interpret problems in agricultural monitoring considering the scale of observation and information requirements
- Compare observation and remote sensing-based estimates of crop yield
- Analyze observation and remote sensing-based estimates of evapotranspiration

NPP → Yield

Crop yield can be calculated from the net biomass accumulated by crops over the growing season (net primary production: **NPP**) with the harvest index (**HI**):

$$\text{Crop Yield} = \text{NPP} \times \frac{\text{HI}}{1 + \text{RS}} \times \frac{1}{1 - \text{MC}}$$

Moisture content (**MC**) standardizes variations in grain/tuber quality depending on harvest date.

Root to shoot ratio (**RS**) standardizes variations in the allocation of biomass below ground.

Why do we measure yield with Earth observation?

Why do we measure yield with Earth observation?

$$\mathbf{Yield} = \mathbf{f}(\mathbf{G} \times \mathbf{E} \times \mathbf{M})$$

Genetics
Environment
Management

Why do we measure yield with Earth observation?

Large spatial and temporal variations

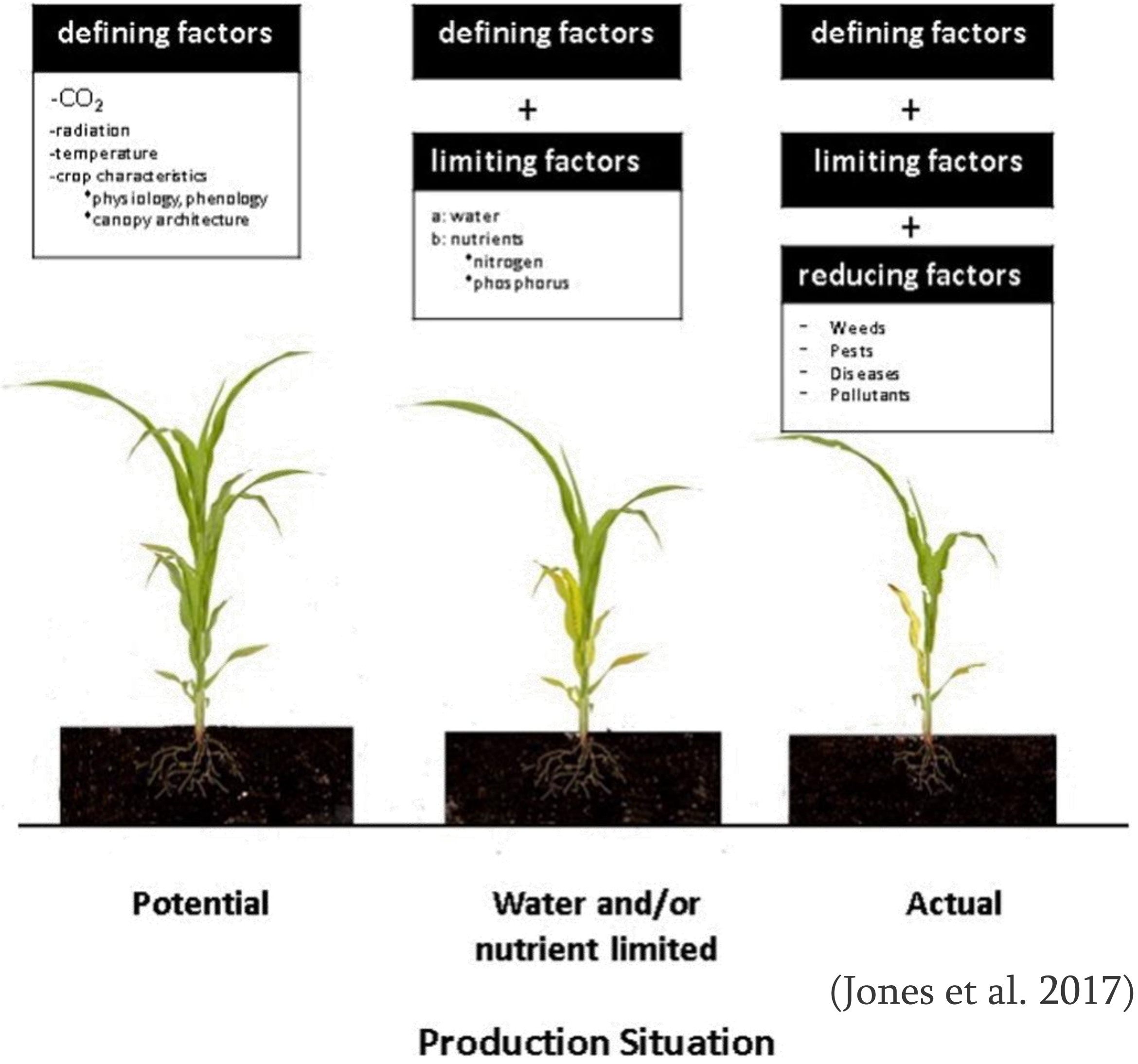
Why do we measure yield with Earth observation?

Main Goals

- Estimate size of yield gaps
- Determine main causes of yield gaps

Yield Gap Drivers (Supply-Side)

- Defining factors (potential)
- Limiting (regulated) factors
- Reducing factors
- Yield gap =
  Defining - (Limiting + Reducing)



(Jones et al. 2017)

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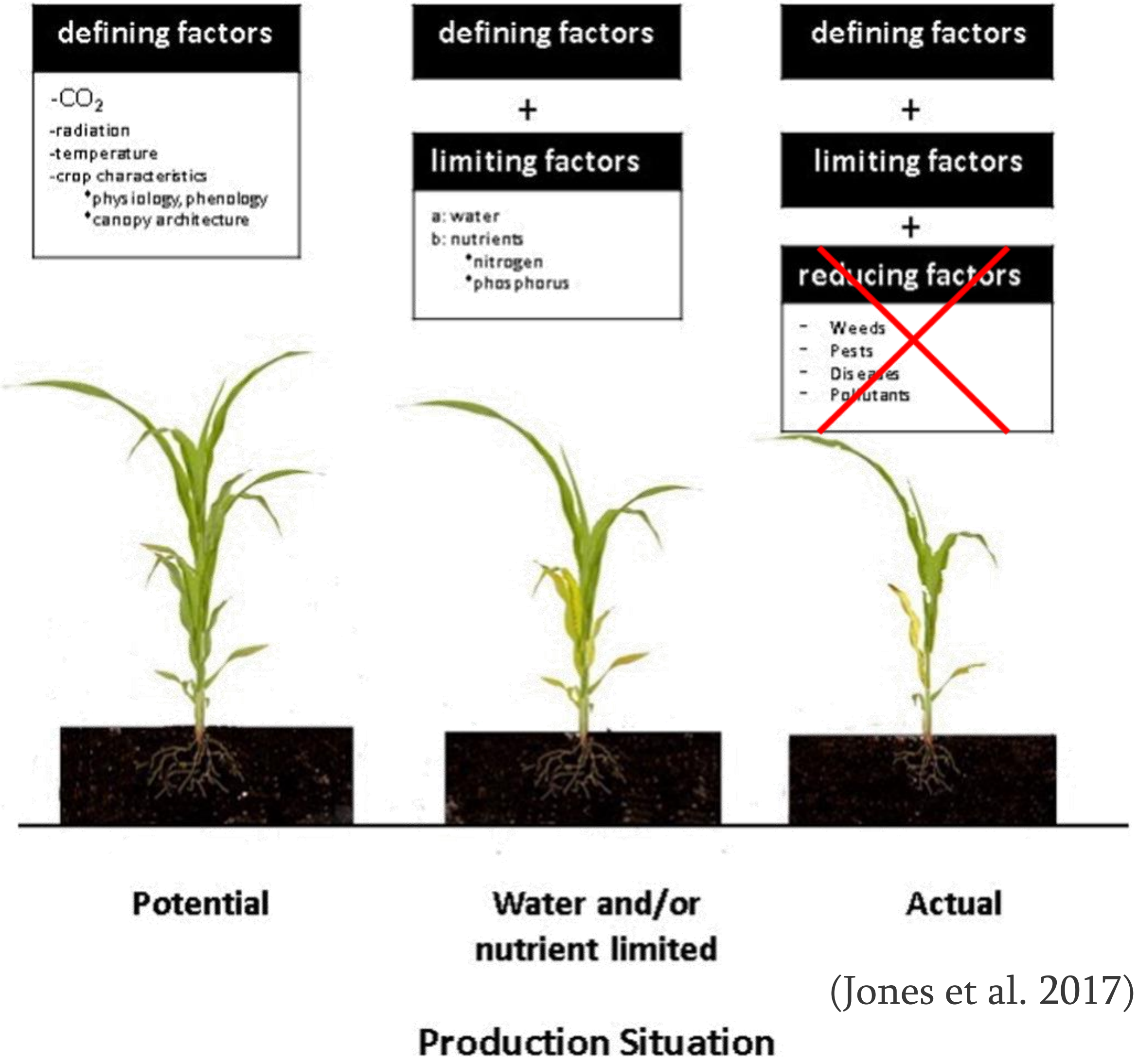
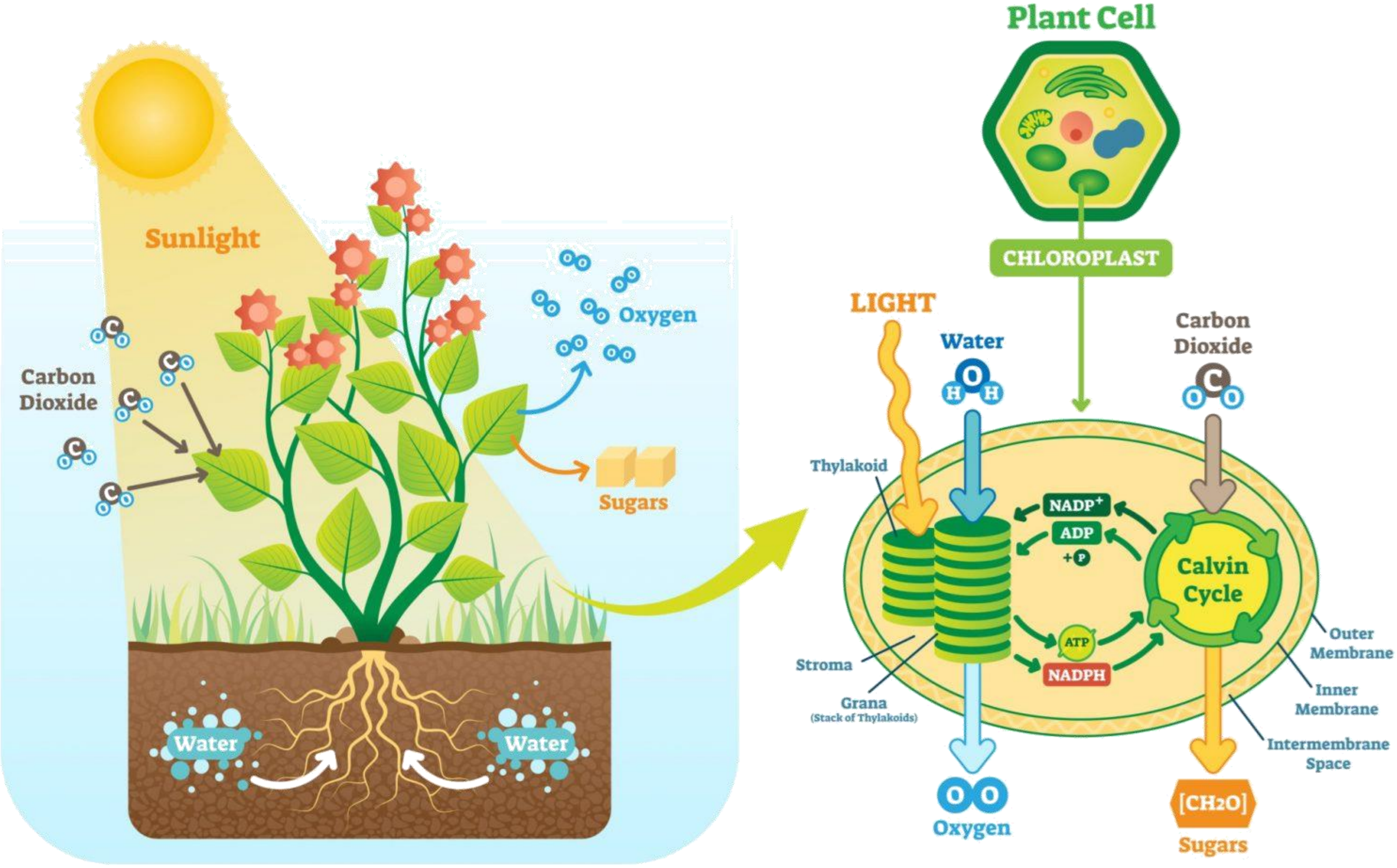
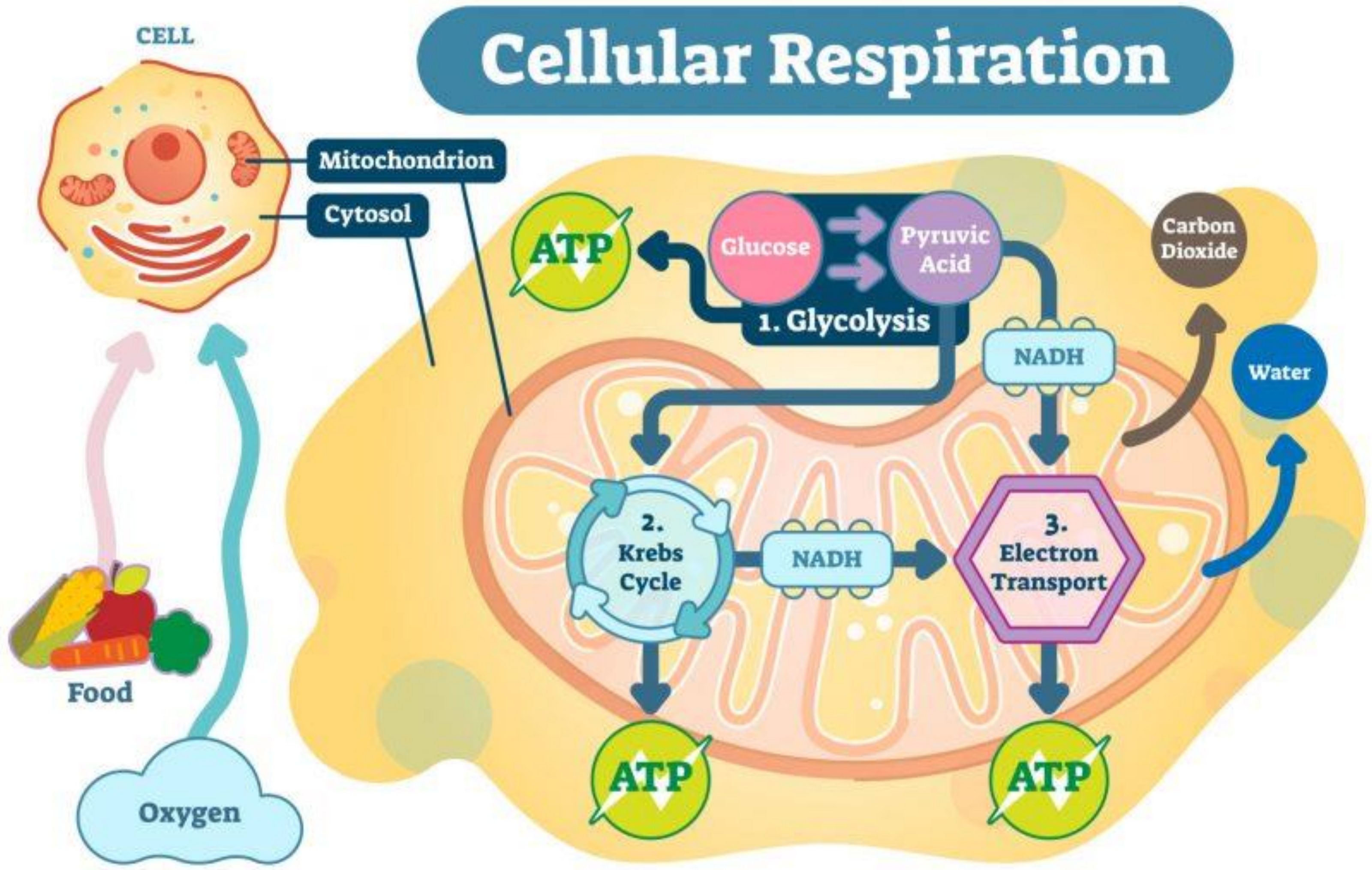
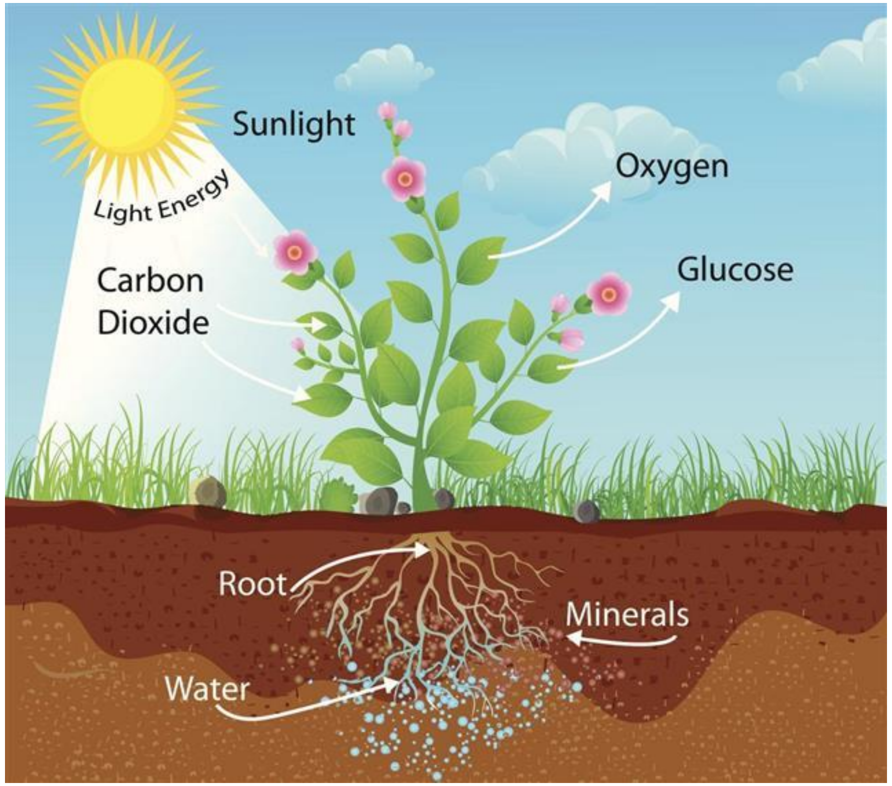


(Jones et al. 2017)

PHOTOSYNTHESIS




Cellular Respiration
CELL
Mitochondrion
Cytosol
Food
Oxygen
ATP
Glucose
Pyruvic Acid
1. Glycolysis
NADH
Carbon Dioxide
Water
2. Krebs Cycle
NADH
3. Electron Transport
ATP
ATP

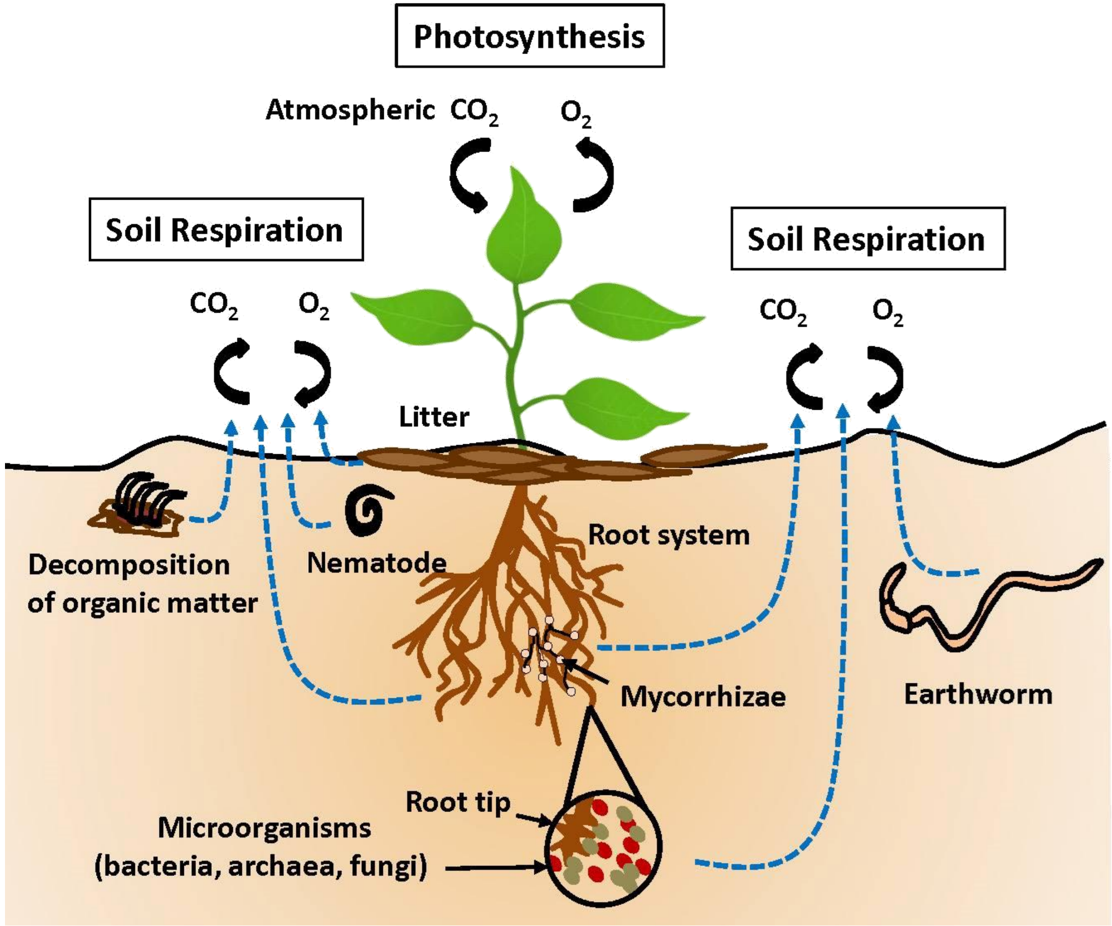


Photosynthesis	Respiration
• Sugar molecules store energy • CO_2 and H_2O absorbed • Increases biomass • Light reaction • Occurs in chloroplast • Oxygen is a by-product	• Sugar molecules release energy • CO_2 and H_2O released • Uses biomass • Light or dark reaction • Occurs in all living cells • Uses oxygen (autotrophic)

Plant and Soil Respiration

- Autotrophic respiration (R_G+ R_M)
  - Energy used from photosynthesis
  - Growth
  - Maintenance

- Heterotrophic respiration (R_H)
  - Organic material consumed



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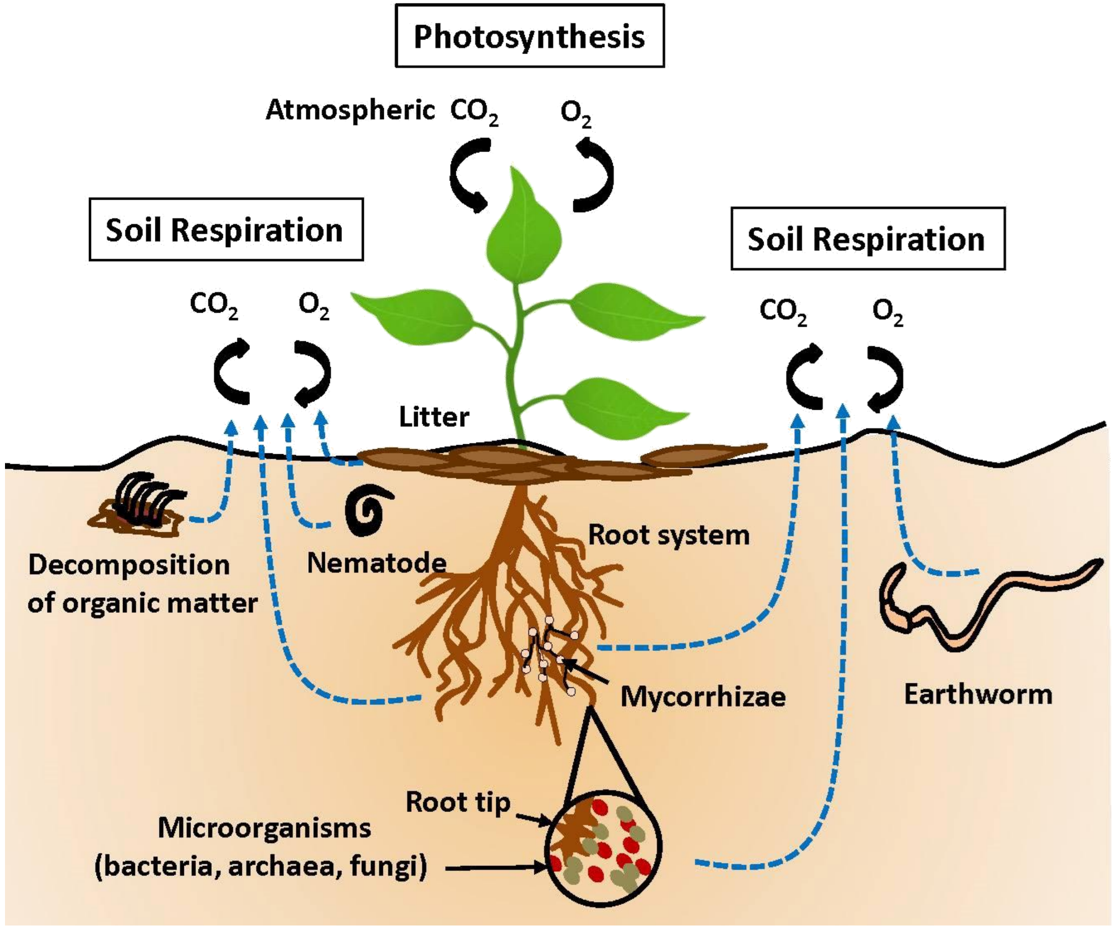


GPP $\rightarrow$ NPP

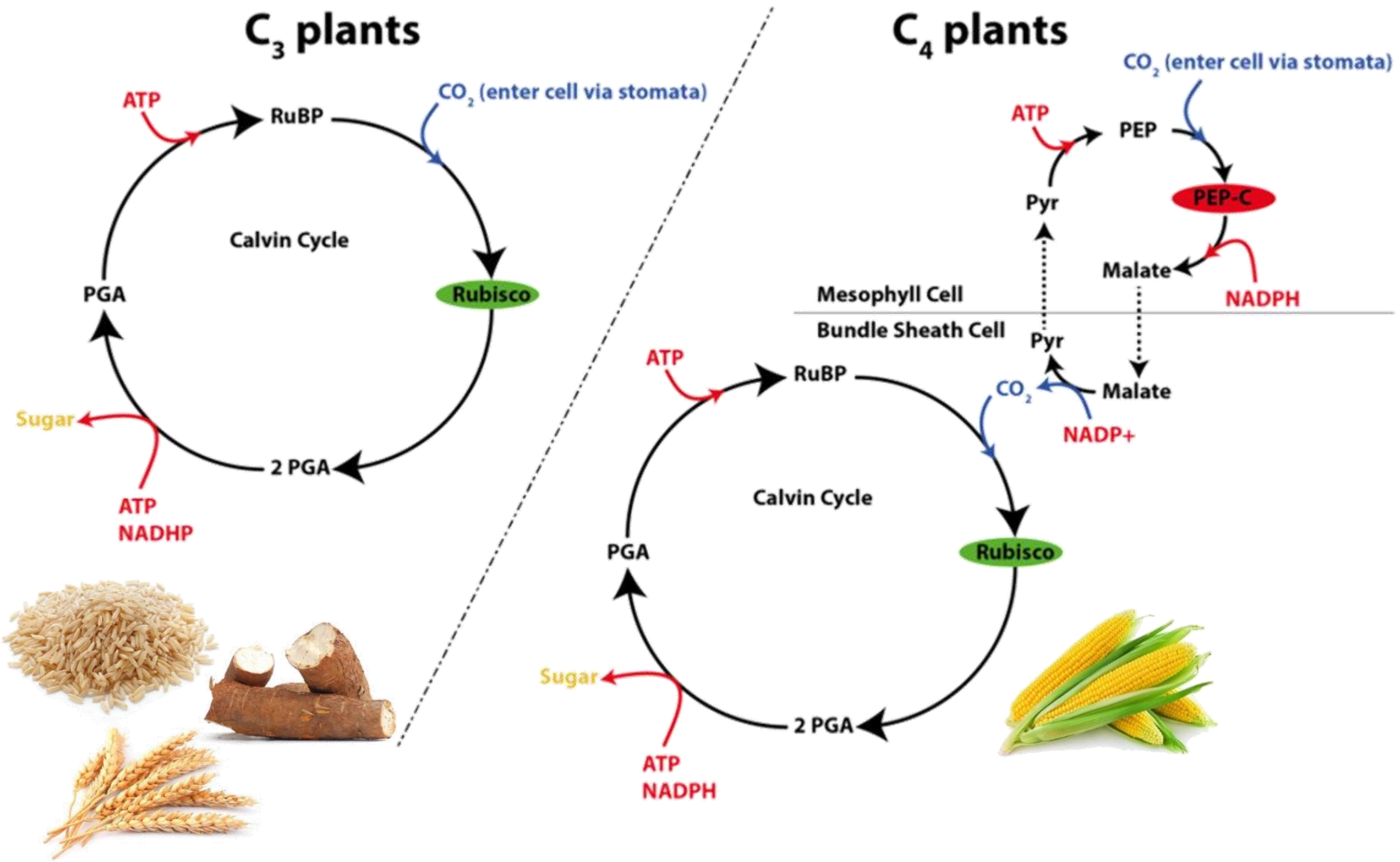
Gross Primary Production (GPP) is the daily amount of carbon gained through photosynthesis by plants per unit area.

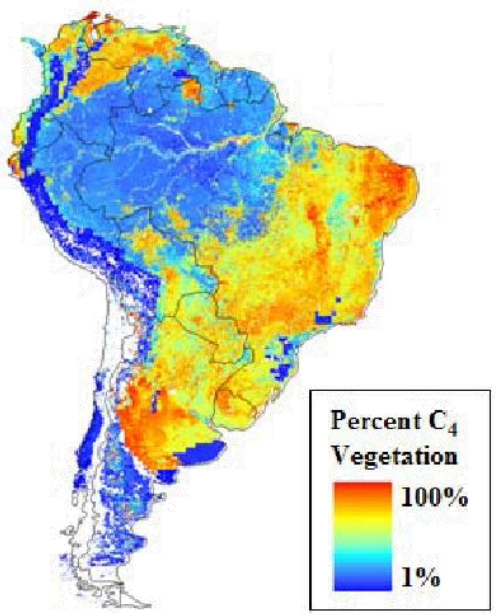
$$\mathrm{NPP} = \sum_{\mathrm{SOS}}^{\mathrm{EOS}} \mathrm{GPP} - (\mathrm{R_G} + \mathrm{R_M})$$

NPP is the sum of GPP (gain) from the start and end of growing season (SOS, EOS) minus the seasonal respiration (cost).

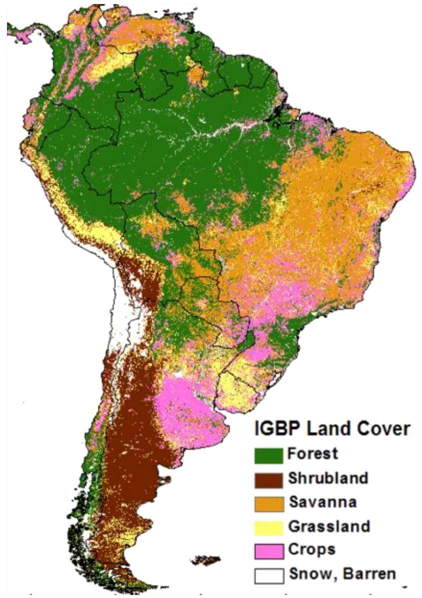
Respiration is calculated empirically from GPP and ambient air temperature

C_3 and C_4 Photosynthesis





(Powell et al. 2012)



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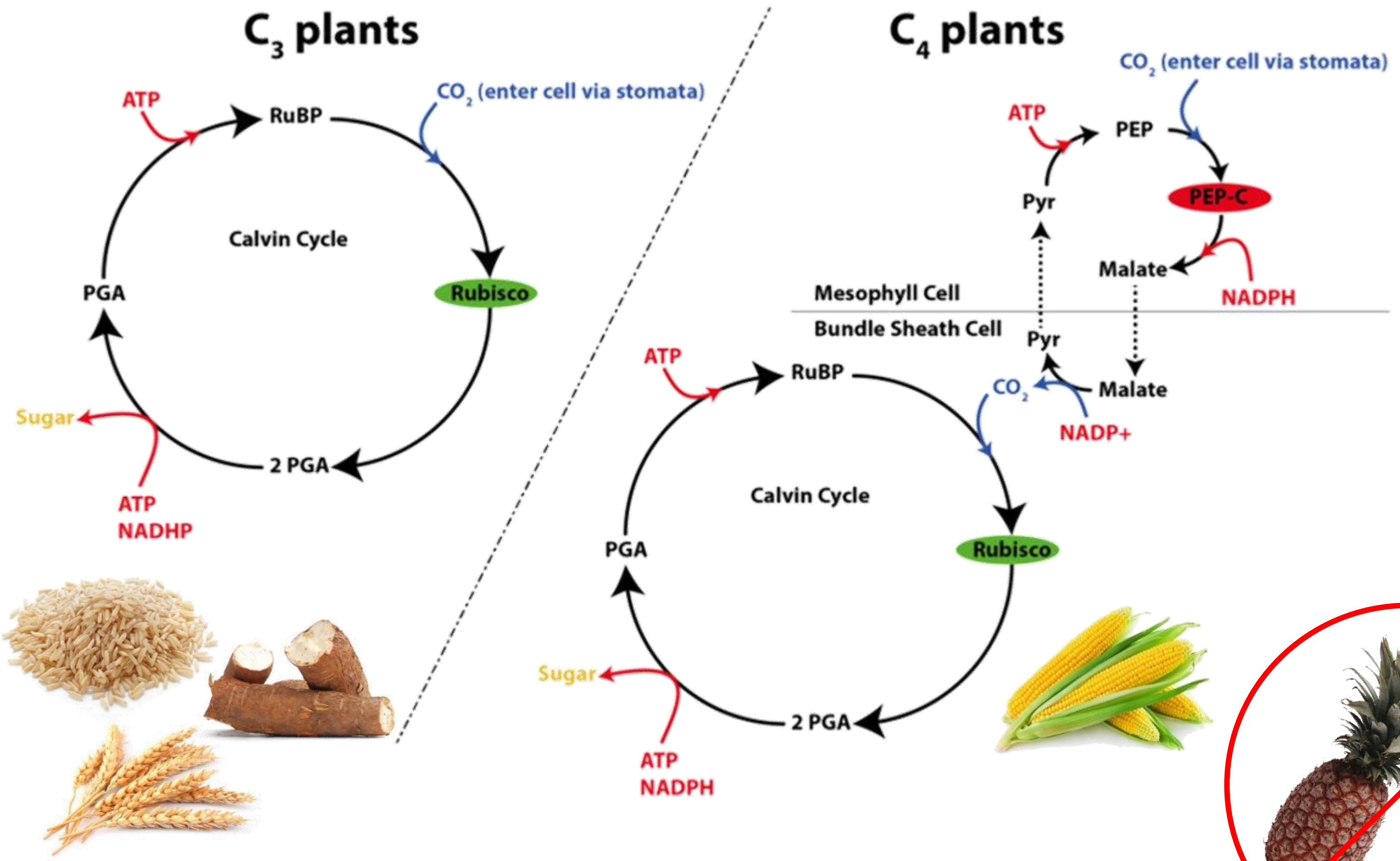

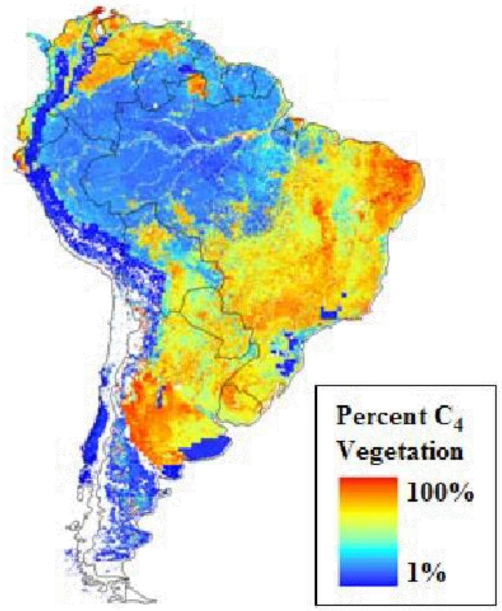

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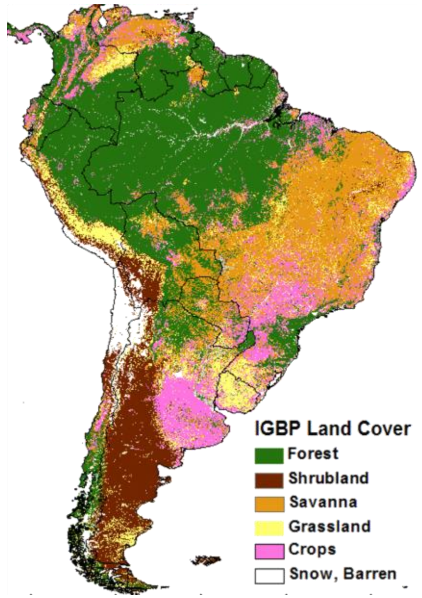
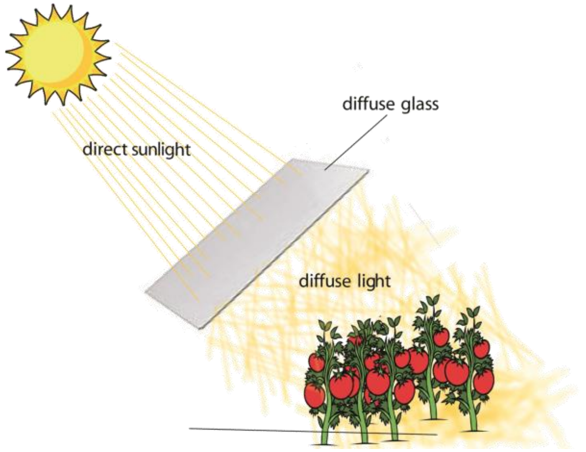
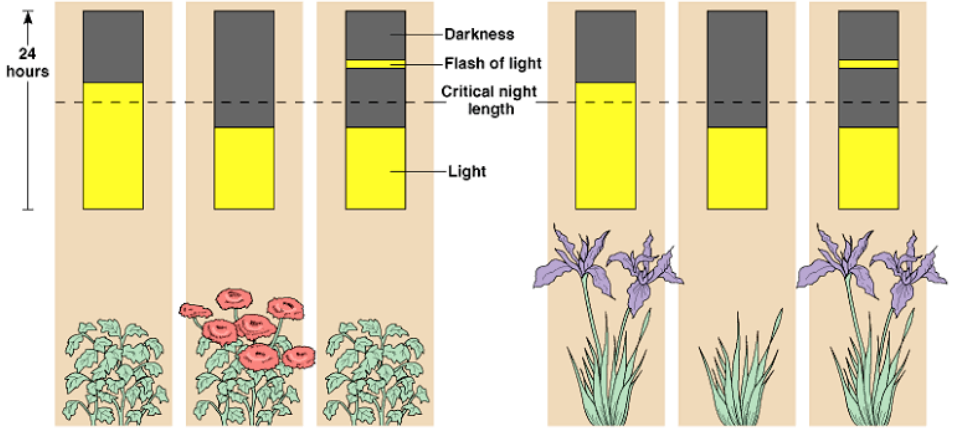


Radiation

- Quantity of light
  - Seasons
  - Direct versus diffuse light
- Quality of light
  - Vegetative growth (visible blue)
  - Flowering (visible red)
- Duration (photoperiod)
  - Critical to flowering
  - Short-day / long-night
  - Long-day / short-night
  - Day-neutral

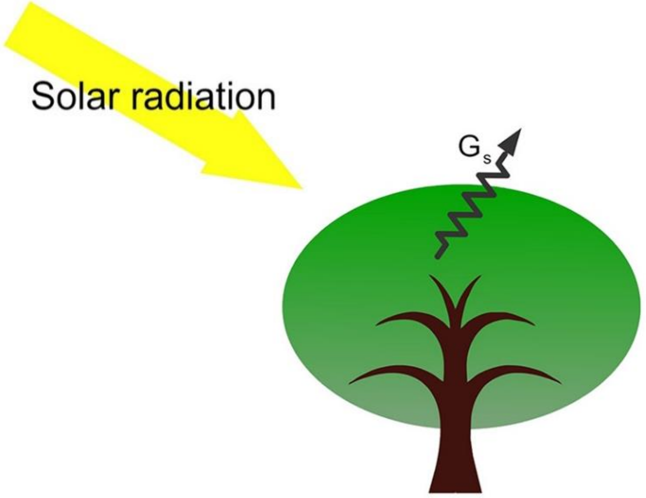


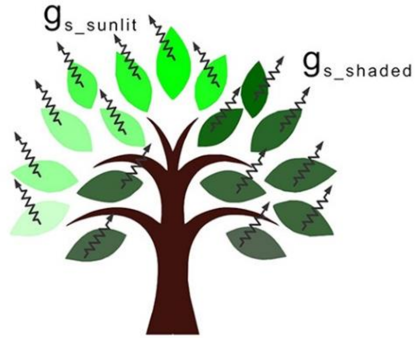


Radiation: "Big Leaf" Concept

How do we scale from the leaf to pixel level?

- Big leaf
    - o Light interactions average out
    - o Works well for homogeneous canopies
    - o Easy to implement over large areas
- Multi-leaf
    - o Works well for heterogeneous canopies
    - o Accurate with sufficient calibration data
    - o Difficult to implement over large areas





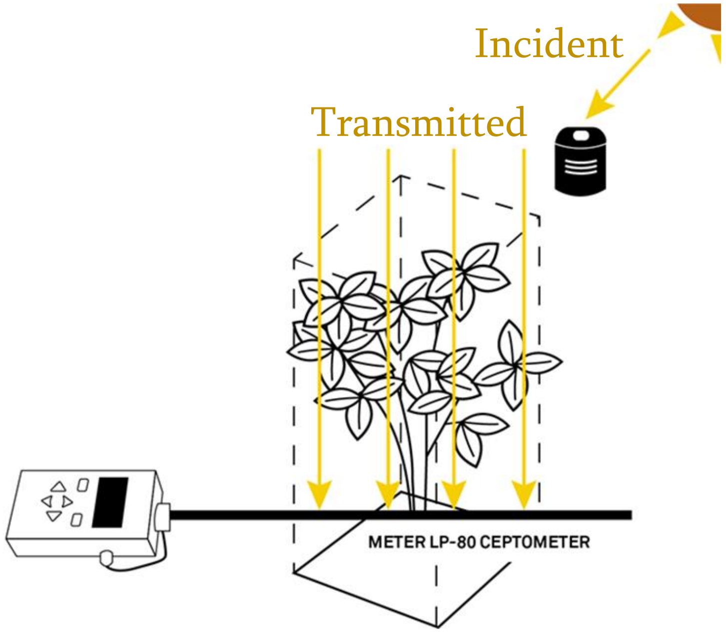
Fraction of absorbed Photo-Active Radiation (F_{PAR})

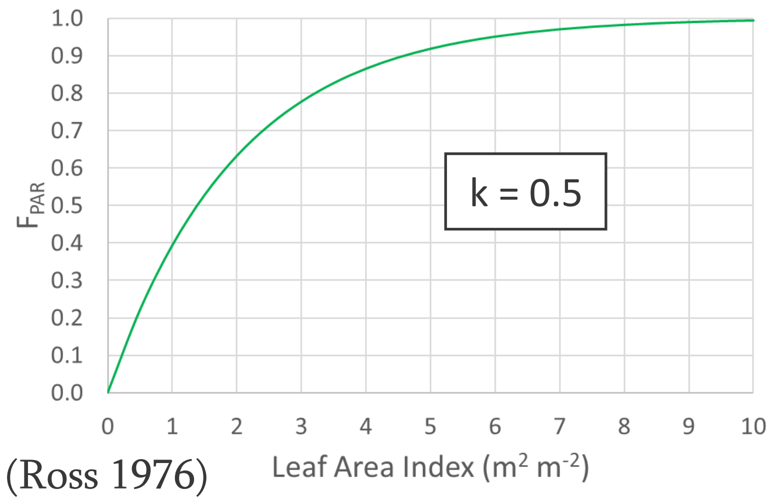
Leaf area index is the ratio of total leaf area of the canopy to the area over which the canopy grows.

Beer-Lambert Law

$$PAR_{transmitted} = PAR_{incident} e^{(-kZ)}$$

k is the extinction coefficient and **Z** is the path length—LAI for plants



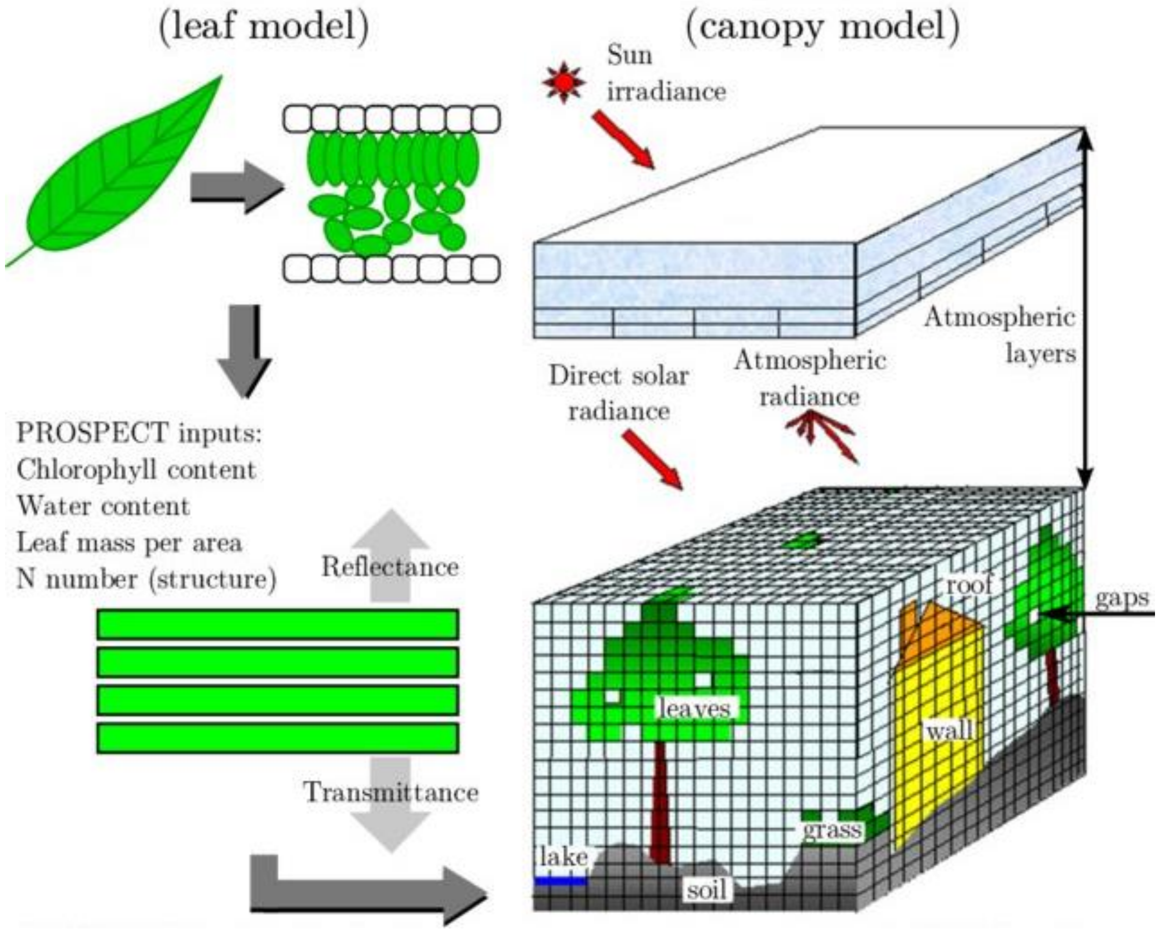


(Ross 1976)

Multi-leaf (Radiative Transfer) Models

Traces reflectance/transmittance from leaf to canopy

- Leaf model
  - Chlorophyll a+b
  - Accessory pigments
  - Leaf water
- Canopy model
  - Canopy structure (e.g. LAI)
  - Sun-sensor geometry
- Backward (inverted) mode



Which crop has the lowest Fpar?

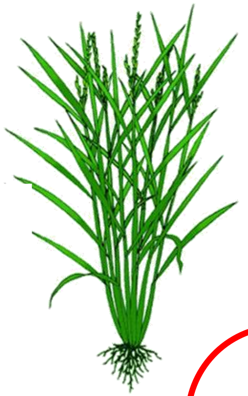
(assume full canopy and same light)

Cotton	Rice	Maize
0	0	0

Which crop has the lowest Fpar?

(assume full canopy and same light)

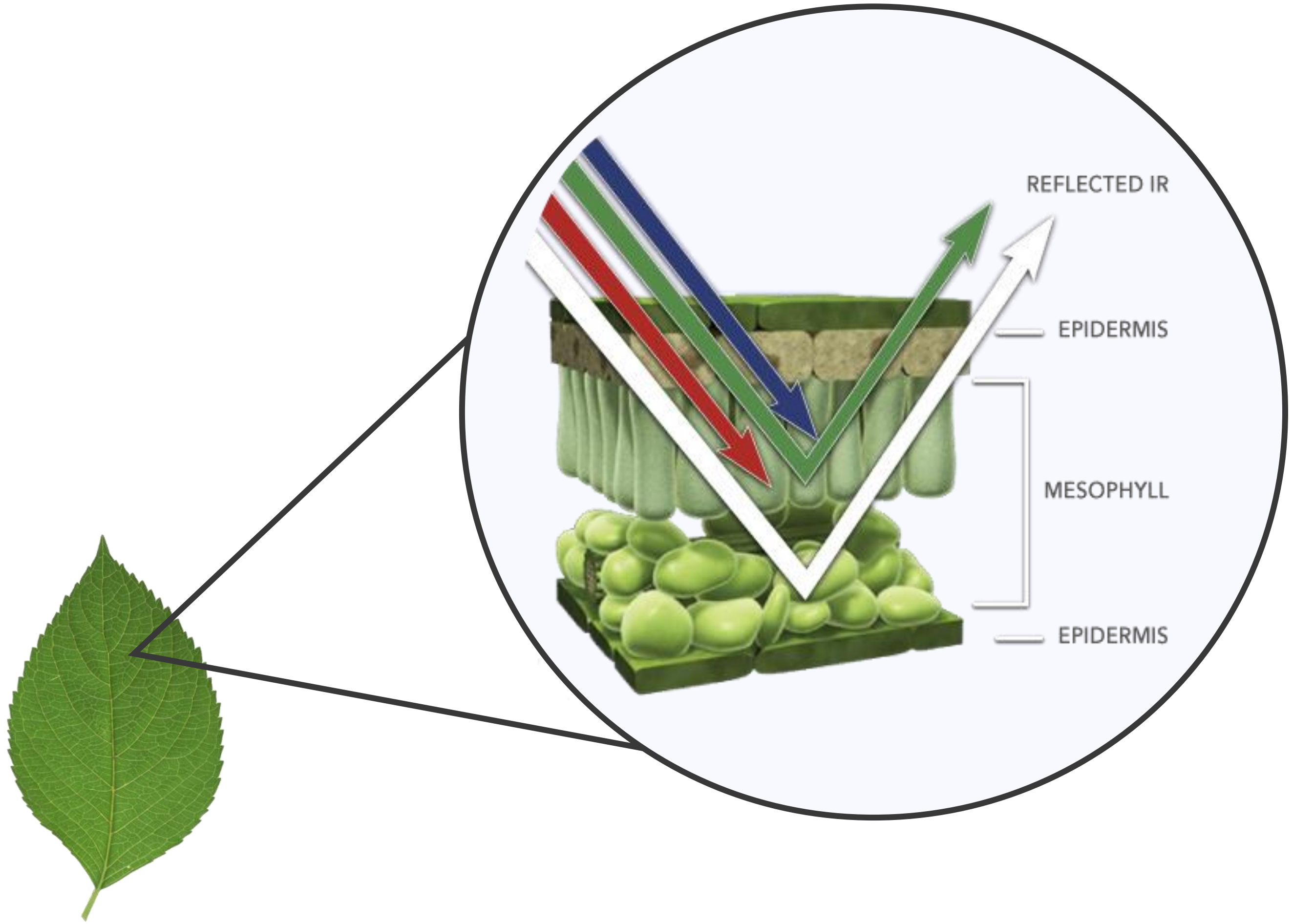
0
Cotton



0
Rice

0
Maize

Normalized Difference Vegetation Index (NDVI)



Healthy plants

- Strong scatter in the green and NIR
- Strong absorption in the blue and red

$$\mathrm{NDVI} = \frac{\mathrm{NIR} - \mathrm{red}}{\mathrm{NIR} + \mathrm{red}}$$

Tucker, C.J. 1979. Red and photographic linear combinations for monitoring vegetation, Remote Sensing of Environment, 8: 127-150.

Other Spectral Vegetation Indices

Vegetation Indices

EO-1 Hyperion Vegetation Indices Tutorial

Vegetation Indices (VIs) are combinations of surface reflectance at two or more wavelengths designed to highlight a particular property of vegetation. They are derived using the reflectance properties of vegetation. Each of the VIs is designed to accentuate a particular vegetation property.

More than 150 VIs have been published in scientific literature, but only a small subset have substantial biophysical basis or have been systematically tested. ENVI provides 27 vegetation indices to use to detect the presence and relative abundance of pigments, water, and carbon as expressed in the solar-reflected optical spectrum (400 nm to 2500 nm).

Selection of the most important vegetation categories and the best representative indices within each category was performed by Dr. Gregory P. Asner of the Carnegie Institution of Washington, Department of Global Ecology. The selections were based upon robustness, scientific basis, and general applicability. Many of these indices are currently unknown or under-used in the commercial, government, and scientific communities.

The indices are grouped into categories that calculate similar properties. The categories and indices are as follows:

- Broadband Greenness
- Narrowband Greenness
- Light Use Efficiency
- Canopy Nitrogen
- Dry or Senescent Carbon
- Leaf Pigments
- Canopy Water Content

Each category of indices typically provides multiple techniques to estimate the absence or presence of a single vegetation property. For different properties and field conditions, some indices within a category provide results with higher validity than others. By comparing the results of different VIs in a category, and correlating these to field conditions measured on site, you can assess which indices in a particular category do the best job of modelling the variability in your scene. By using the VI in any category that best models the measured field

Product **ENVI**

Version **5.5.2**

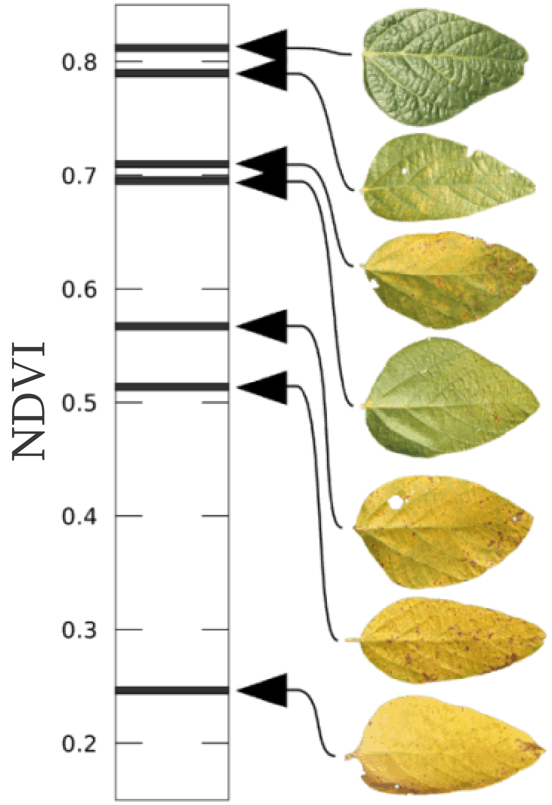
Table of Contents

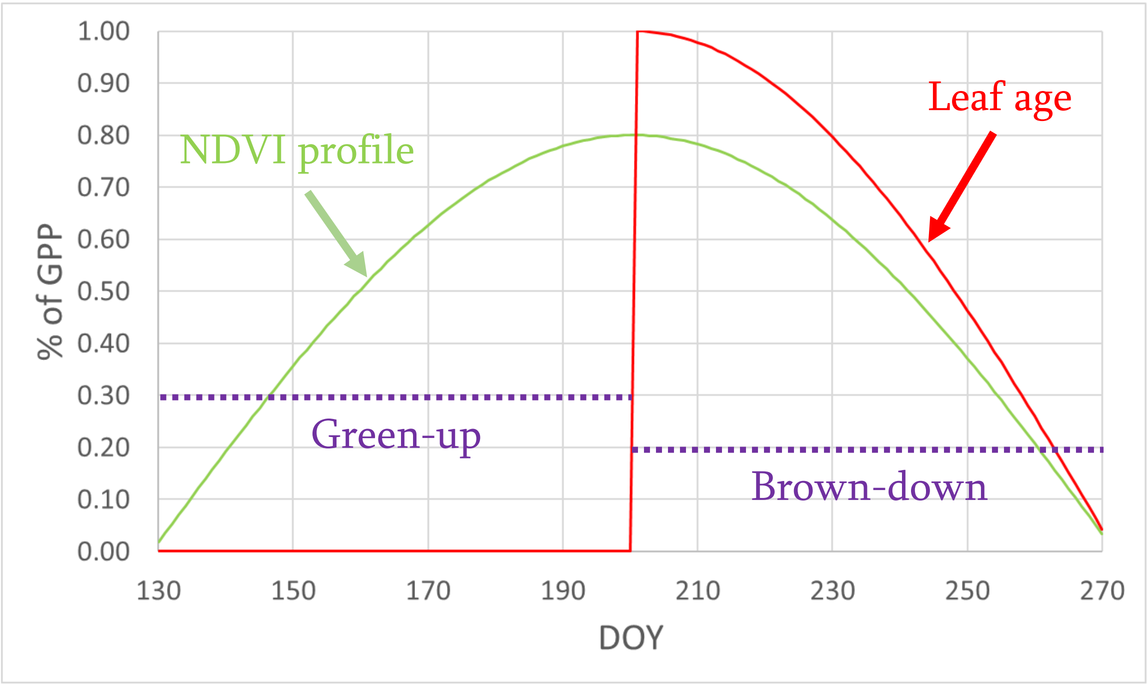
ENVI on GitHub

A collection of resources for ENVI users: custom tasks, extensions, and example models

Leaf Age

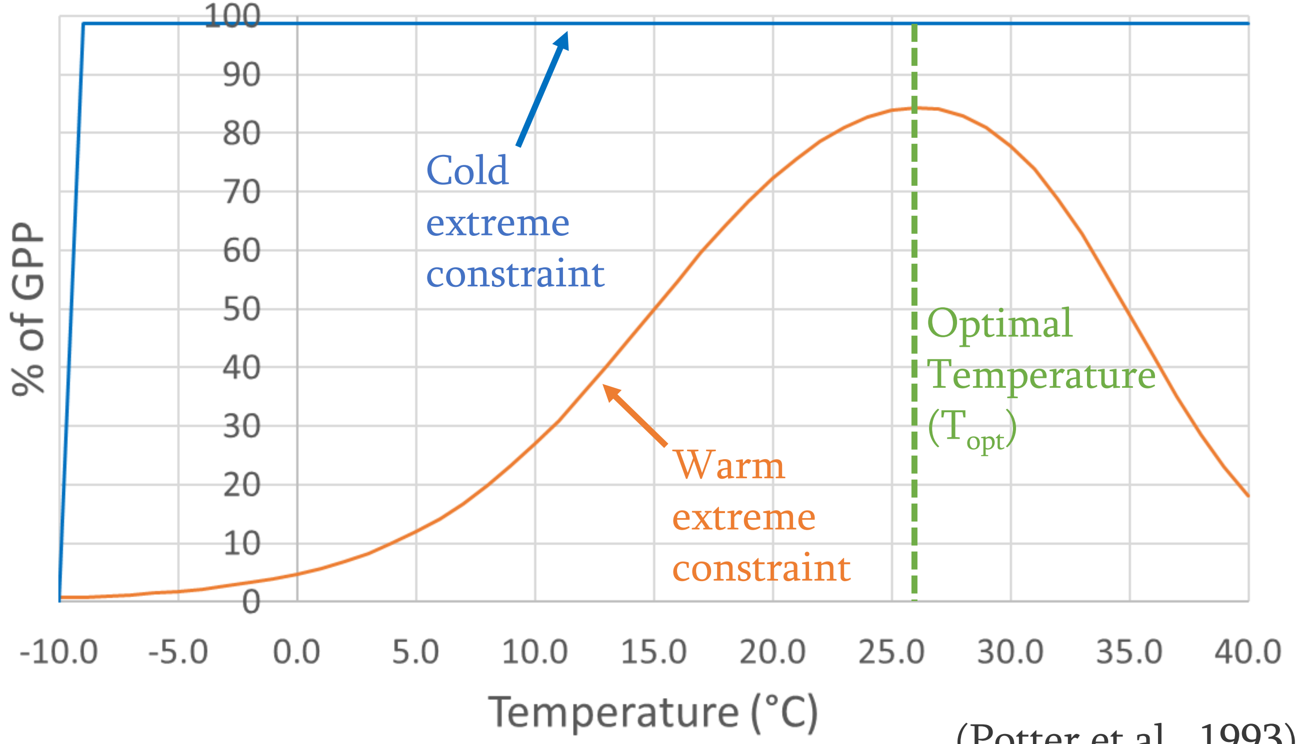
During the reproductive phase, photosynthesis slows down and leaves begin to lose their chlorophyll. Nutrients are remobilized for grain-filling.





Temperature (F_T)

- Germination
- Photoperiod / flowering
- Crop quality
- Photosynthesis
  - Cold extremes
  - Warm extremes
- Dormancy
- Hardiness



(Potter et al., 1993)

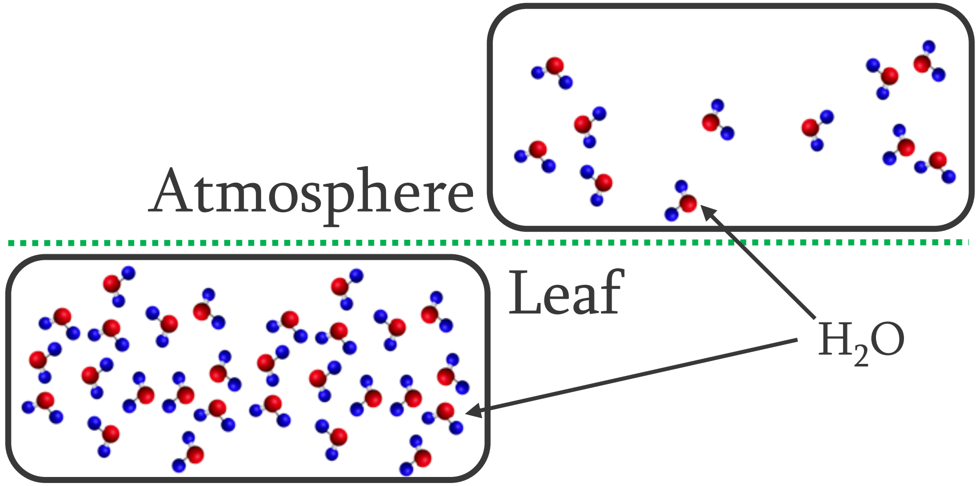
Water and Humidity (F_M)

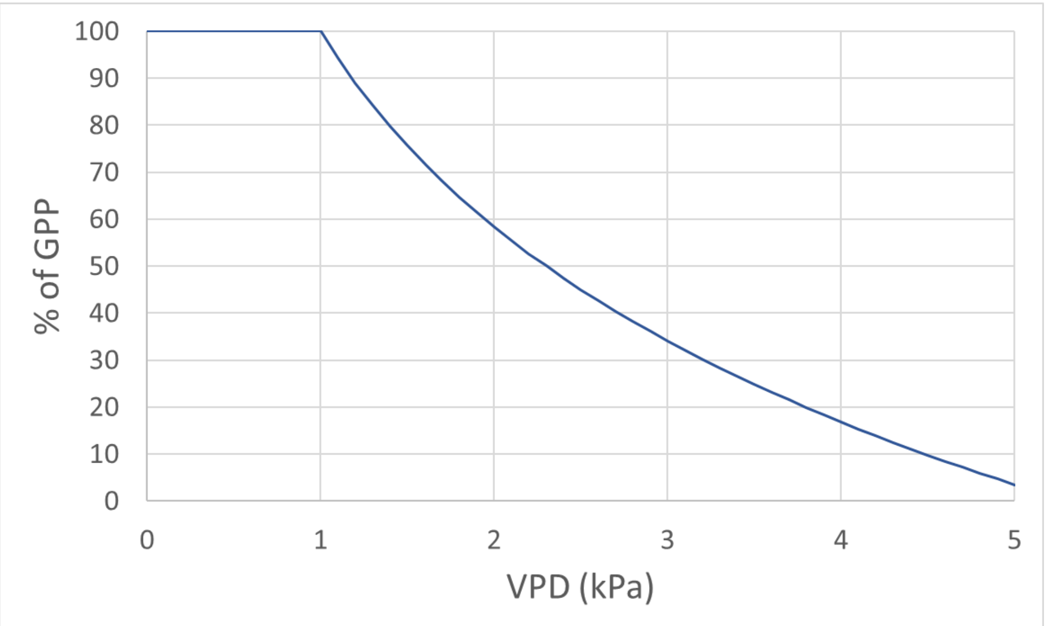
Vapor pressure deficit (**VPD**) is the difference between saturated (canopy) and actual (atmospheric) moisture pressure.

Buck's Equation

$$\mathrm{VPD} = \mathrm{VP}_{saturation} \times \left(1 - \frac{\mathrm{RH}}{100}\right)$$

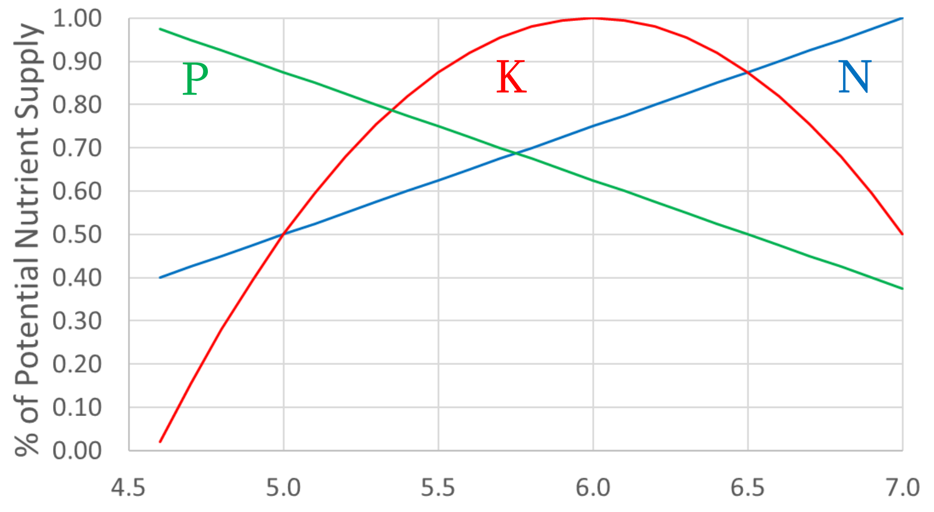
- Photolysis
- Turgor pressure
- Solvent/medium
- Transpiration
- Root elongation



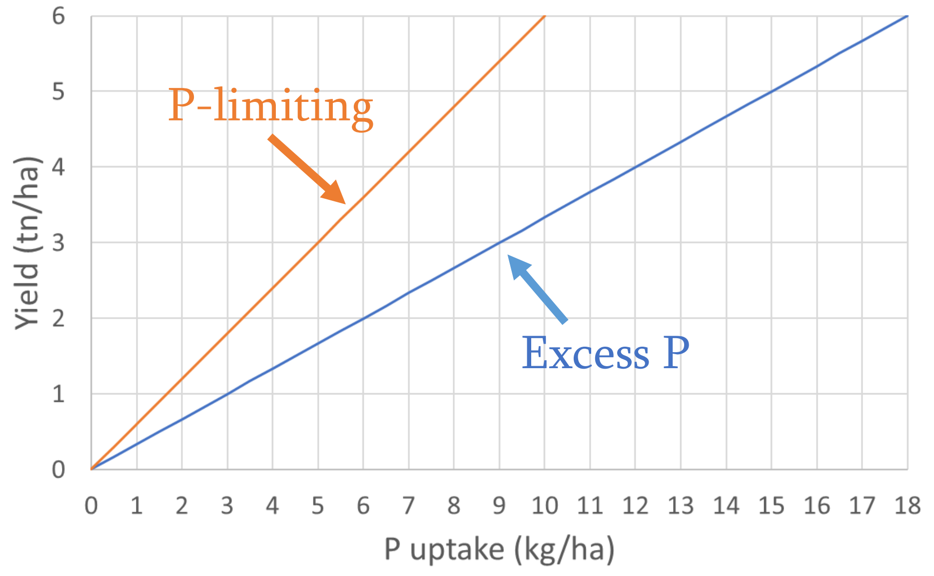


Nutrients

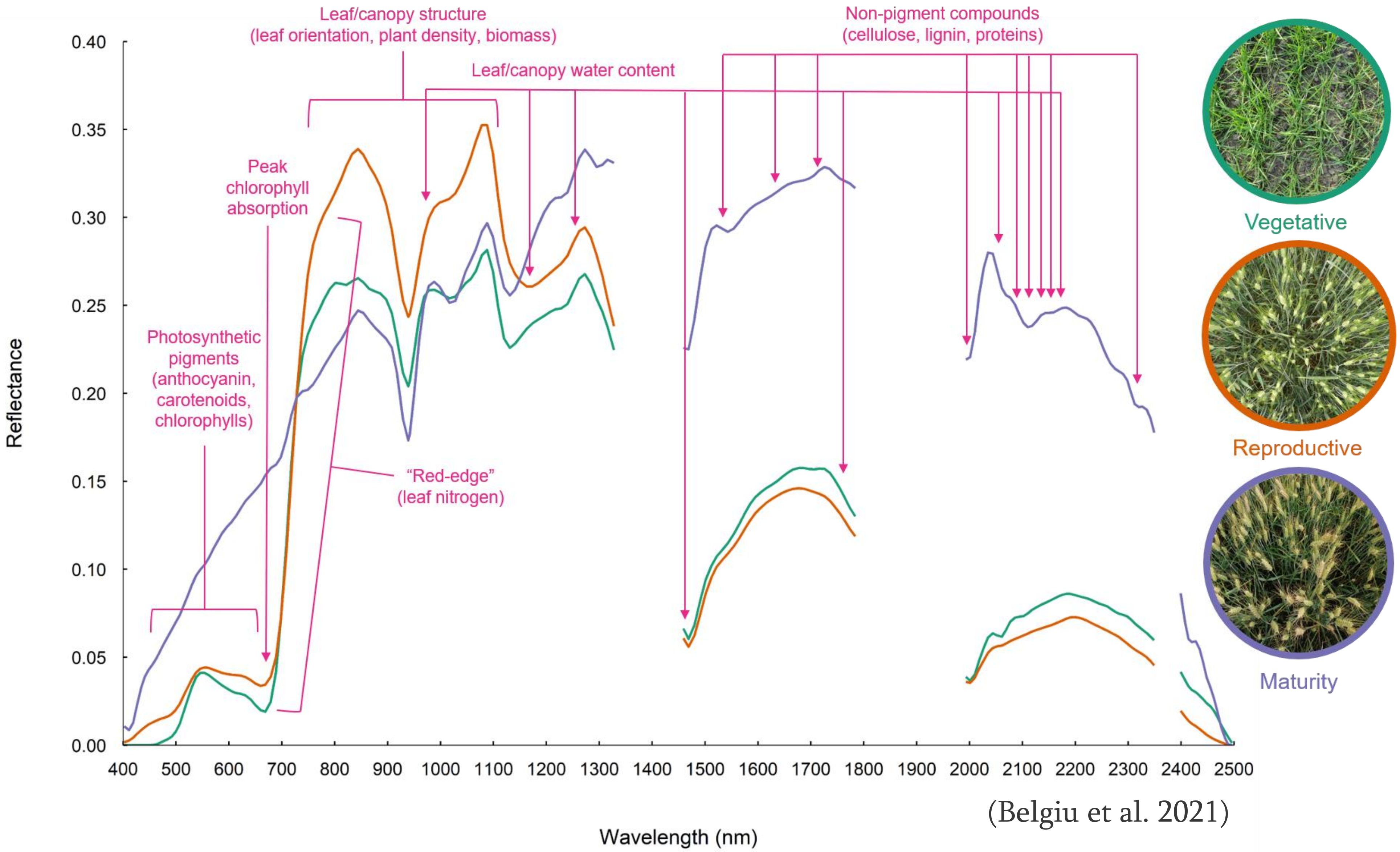
- Macro- and micro-nutrients serve a number of functions in plants
  - Nitrogen (N)
  - Phosphorus (P)
  - Potassium (K)
- Nutrient availability
  - Ph (H_2O)
  - Organic carbon
  - Olsen-P
  - Exchangeable potassium
  - Organic N
  - Total P
- Limiting factor



(Janssen et al., 1990)



Crop Growth/Development and Earth Observation



(Belgiu et al. 2021)

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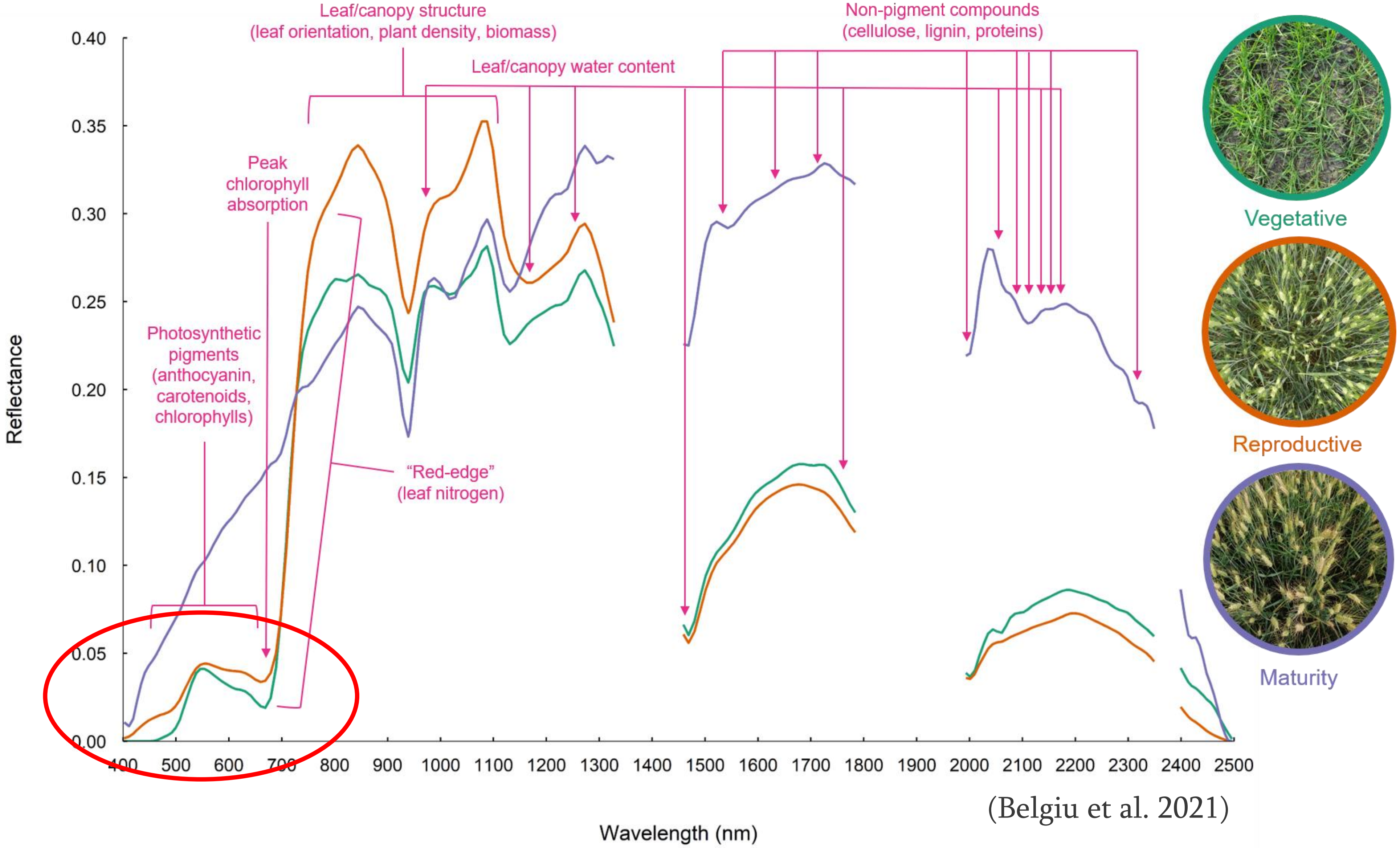
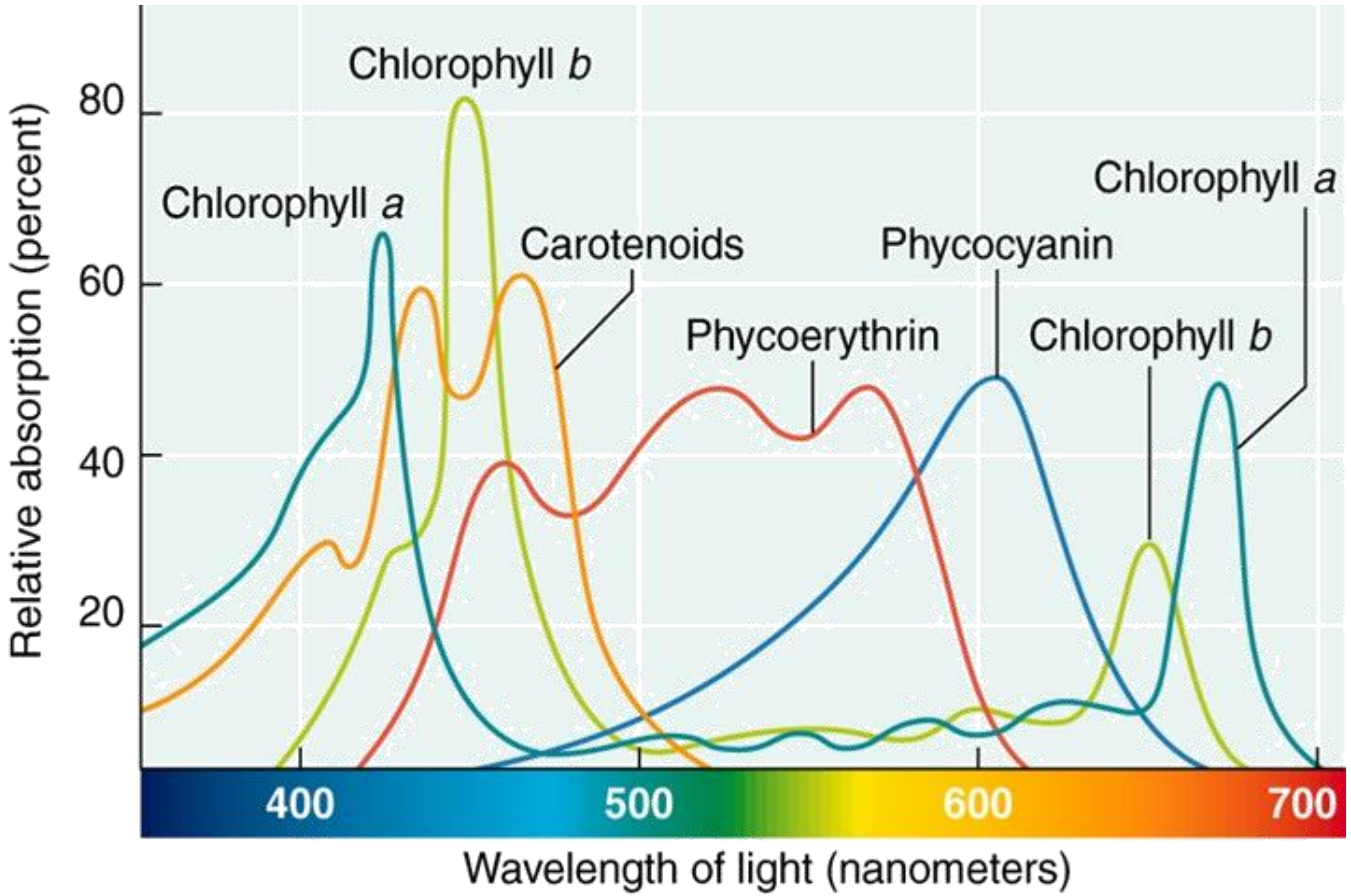
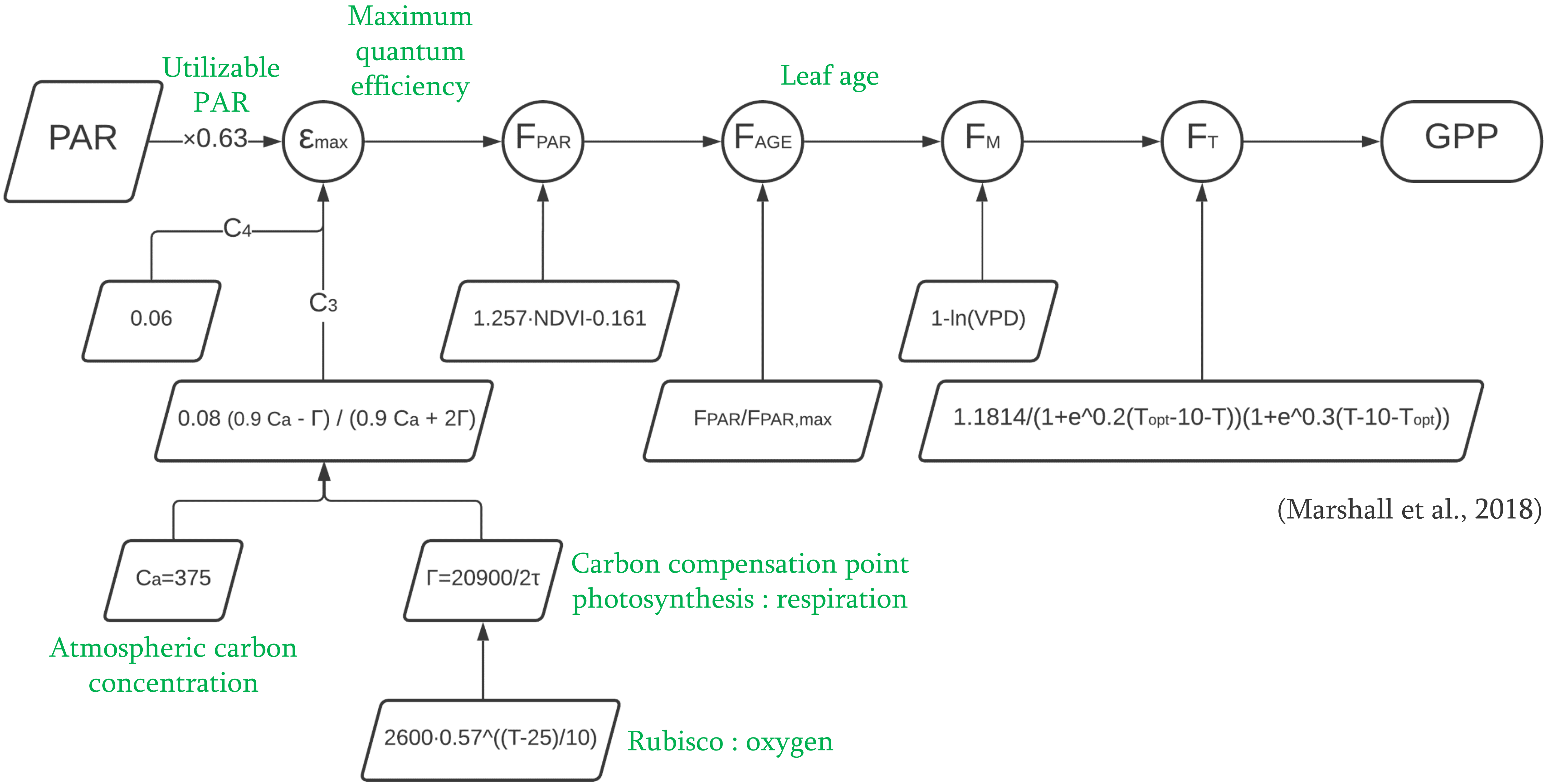


(Belgiu et al. 2021)

Photosynthesis and Earth Observation



Putting it together: PEMOC Model



(Marshall et al., 2018)

Other LUE Models

- Carnegie–Ames–Stanford approach (CASA)
- Gross Primary Production Estimates for Winter Wheat from the Vegetation Photosynthesis Model (GPP_{VPM})
- MODIS GPP/NPP (MOD17)
- Eddy Covariance-Light Use Efficiency (EC-LUE)
- Cloudiness index light use efficiency (CI-LUE)
- Copernicus dry matter productivity (DMP)

Reducing Factors

- Weeds
- Pest and disease
- Air pollution / acid rain
- Salinization
- Large number and diversity
- Non-linear relationships
- High spatial/temporal variability




What do you think are some limitations of LUE crop yield models?

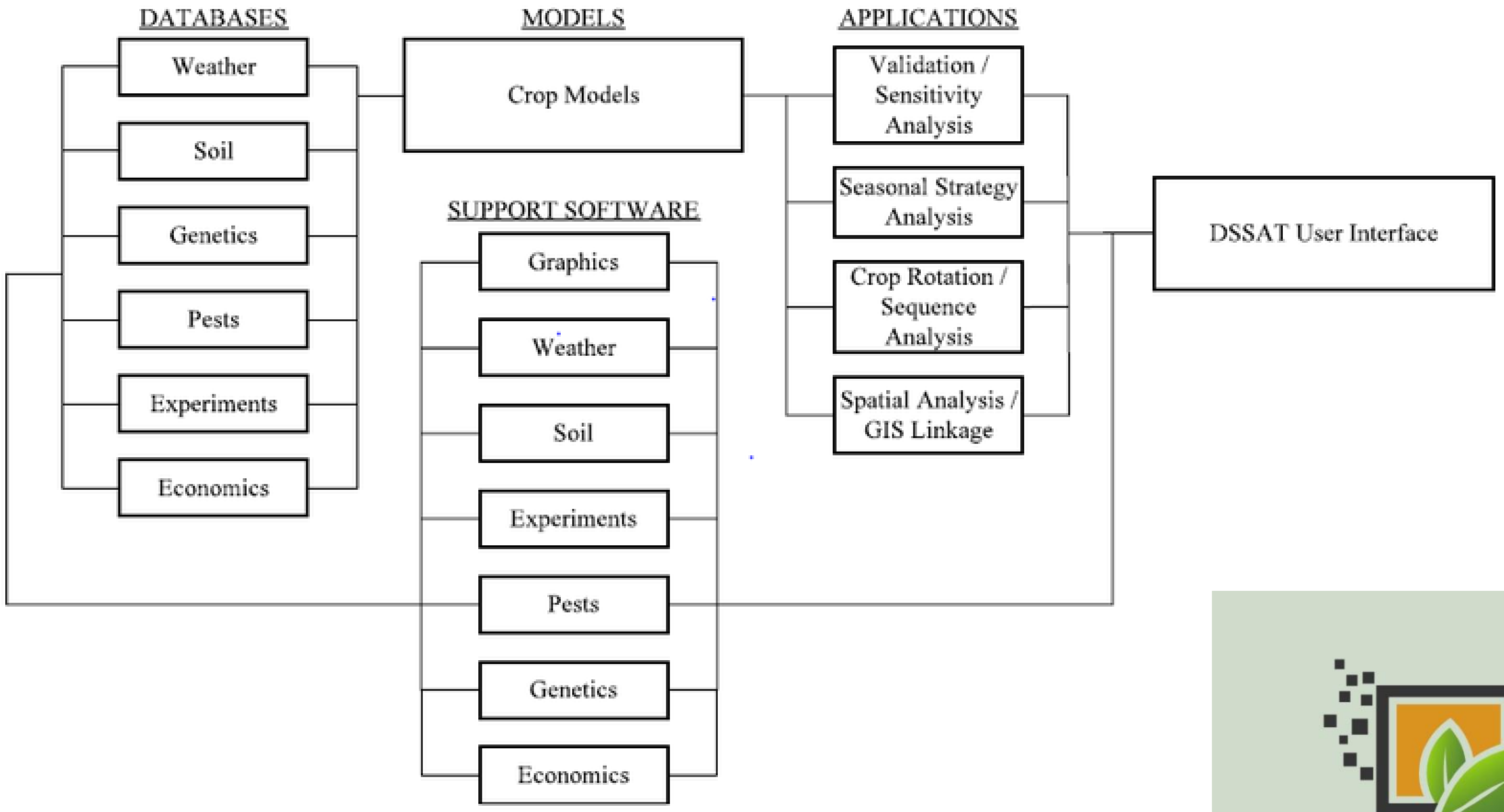
Mentimeter

What do you think are some limitations of LUE crop yield models?

Mentimeter

- They do not account for pests and disease
- They do not account for different crop types or varieties
- They do not properly account for soil moisture
- They do not properly consider management practices (fertilizer, irrigation)
- Big leaf models do not work well for complex canopies or landscapes
- Harvest index is sensitive first to variety and second to the environment
- Respiration is overly simplified
- Models are difficult to calibrate and validate
- Models are difficult to scale and transfer

Fully Processed-Based Models



DSSAT
Decision Support System for Agrotechnology Transfer

Jones J W, Hoogenboom G, Porter C H, Boote K J, Batchelor W D, Hunt L A, Wilkens P W, Singh U, Gijsman A J and Ritchie J T 2003 The DSSAT cropping system model *European Journal of Agronomy* **18** 235–65

Summary

- Crop yield is a function of incoming solar radiation
- Earth observation exploits the biophysical and biochemical constraints on light-use efficiency
- Other factors further constrain light-use efficiency
  - CO_2
  - Temperature
  - Water/humidity
- Big leaf models assume that canopy-light interactions scale linearly
  - Best for regional to global scale applications
  - Poorly suited for heterogenous canopies
  - Non-biophysical/biochemical factors are not directly considered

Practical

Building crop yield models with vegetation indices (VIs)

- Download Sentinel-2 (level 2) data
- Clear cut dry-weight crop yield
- Build statistical relationships between VIs
  - – Best single date
  - – Seasonal average
  - – Seasonal maximum (i.e., flowering)
  - – Cumulative