METER
ENVIRONMENT

SIMPLIFIED MODELS FOR CARBON ASSIMILATION BY PLANTS

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The detailed processes in photosynthesis are complicated and hard to model. In many cases, however, it's possible to simplify the model by focusing on one or more of the limitations to assimilation.

CARBON ASSIMILATION SIMPLIFIED: LIGHT AND WATER

In simplest terms, carbon assimilation involves the chemical transformation of carbon dioxide and water to carbohydrate and oxygen within the leaves of plants. The process requires energy to proceed, and that energy is supplied by light, usually coming from the sun. The CO_2 comes from the atmosphere and must diffuse into the leaf mesophyll cells to be fixed. Since the inside of the leaf is much wetter than the atmosphere, water diffuses out as CO_2 diffuses in. The amount of water used in the actual photosynthetic process is minuscule, but the water lost in connection with CO_2 uptake is substantial.

LIMITED BY LIGHT, LIMITED BY WATER: TWO SEPARATE APPROACHES

Based on this simple description, we could postulate situations where light would be the limiting factor in assimilation, and others where water would be the limiting factor. Our models, in words, might be: assimilation is proportional to the plant's ability to capture light, or assimilation is proportional to the plant's ability to capture water. Both approaches can be useful in modeling biomass production.

LIGHT-BASED MODEL

The light-based model in equation form is

$$A = efS$$

Equation 1

where A is the net dry matter assimilation, S is the total incident radiation received during the time the crop is growing, f is the average fraction of radiation intercepted by the crop, and e is a conversion efficiency. If A and S are both expressed in mol $m^{-2}s^{-1}$, then e is a dimensionless conversion efficiency. In light-limiting situations, the value of e is quite conservative for a particular species, and in the range of 0.01 to 0.03 mol CO_2 (mol photons)$^{-1}$ Campbell and Norman (1998, p. 237) give additional information and references to do a more complete analysis.

MEASURING f WITH THE ACCUPAR LP-80

It is clear that f, the fraction of incident light intercepted by the plant canopy is a critical factor in determining assimilation. This factor is directly measured with the ACCUPAR LP-80. In light-limited environments, one can predict dry matter production knowing the amount of incident PAR and the light conversion efficiency, e, and then measuring f over time with the LP-80.

WATER-BASED MODEL

In water-limited situations, a different equation applies. It is

$$A = \frac{kT}{D}$$

Equation 2

where T is transpiration, D is the atmospheric vapor deficit, and k is a constant for a particular species and atmospheric CO_2 level. Tanner and Sinclair (1983) and Campbell and Norman (1998) give derivations for this equation, but its validity has been repeatedly confirmed in experiments going back more than a century. Among other things, it predicts that humid regions will produce more dry matter per unit water used than arid areas. Thus, an irrigation project in Wisconsin, say, would produce a lot more dry matter per unit water used than one in Arizona. While there may be differences from one species to another in the amount of dry matter produced per unit water used, all dry matter production requires a substantial quantity of water. Dreams of making deserts blossom by genetically engineering plants that fix carbon without using water are just that–dreams.

INTERCEPTION IN THE WATER-BASED MODEL

The evaporation-based dry matter model also depends on light interception. The water lost by a crop includes water transpired by the plants and water evaporated from the soil. Only the water lost by transpiration relates to carbon assimilation. It usually isn't practical to measure T in Equation 2, but we can make a simple computer model that will compute it each day if we know the rain or irrigation and some soil and environmental variables. For the model, we need to define a quantity called potential evapotranspiration, which is the rate of water loss when water supply limits neither evaporation nor transpiration. Potential transpiration is computed from

$$T_p = f E_{tp}$$

Equation 3

Since evaporation from the soil surface also uses up water, we need to compute it as well. Potential evaporation is computed from

$$E_p = (1-f)\, E_{tp}$$

Equation 4

where E_{tp} is potential evapotranspiration. As before, f is the fraction of radiation intercepted by the canopy and can be measured with the LP-80. Campbell and Diaz (1988) give a simple computer model for computing E_{tp} as well as algorithms for computing actual evaporation and transpiration from the potential quantities given by Equations 3 and 4.

KNOWING WHICH MODEL TO USE IS EASY

The most efficient way to determine whether light or water is the limiting factor is to simply run both mathematical models daily to see which one predicts the lowest value. That value is the best predictor of dry matter production for the particular day on which it is run.

BASIC COMPUTER MODELING

The light-limited and water-limited mathematical models are hard to manipulate by hand but easy to program on a computer. They run from easily obtained climatic data and can be quite accurate predictors of crop dry matter production, particularly for annual crops. They have been especially useful for assessing production potential for particular environments and cultural practices (Campbell and Diaz, 1988; Kunkel and Campbell, 1987).

COMPUTING FRACTIONAL INTERCEPTION

The fractional interception, f used in both of these models is the value averaged over whole days. The measurement by the LP-80 typically is made at a particular time of day and is not the average over the day. The LP-80 manual gives equations and an example (p. 57) to convert from the single observation to the daily average. The LP-80 measures transmission of radiation by taking the ratio of PAR measured below the canopy to PAR measured above. This is the transmission at a particular sun zenith angle, ?(θ). The transmission averaged over whole days is the same as the transmission for diffuse radiation, and is given by

$$\tau_d = \tau(\theta)^q$$

Equation 5

where q depends on leaf area index (LAI), leaf angle distribution, and sun zenith angle, as shown in the manual. The fractional interception for these models is:

$$f = 1 - \tau_d$$

Equation 6

REFERENCES

Campbell, G. S., and R. Diaz. "Simplified soil-water balance models to predict crop transpiration." *Drought research priorities for the dryland tropics. ICRISAT, India* (1988): 15-26. Article link (open access).

Campbell, G. S., and J. M. Norman. *An Introduction to Environmental Biophysics (2nd Ed.)*. New York: Springer,1998. Article link.

Kunkel, Robert, and Gaylon S. Campbell. "Maximum potential potato yield in the Columbia Basin, USA: Model and measured values." *American potato journal 64, no. 7* (1987): 355-366. Article link.

QUESTIONS?

Explore questions and ideas with a canopy expert. METER scientists have over 100 years combined experience measuring the soil-plant-atmosphere continuum. Learn more about canopy measurement in the video here. Dr. Steve Garrity discusses Leaf Area Index (LAI). Topics covered include the theory behind the measurement, direct and indirect methods, variability among those methods, things to consider when choosing a method, and applications of LAI.

GET THE COMPLETE PICTURE

Learn more about measuring canopy. Get everything you need to know about measuring leaf area index, all in one place.

Download the "Researcher's complete guide to leaf area index (LAI)"