AGRON 183: Photosynthesis

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Introduction

The process of photosynthesis, as described by the following chemical equation, is perhaps *the* essential aspect of agronomy.

$$\mathrm{CO_2} + \mathrm{H_2O} + \text{light} \rightarrow \text{carbohydrate} + \mathrm{O_2} \tag{1}$$

Photosynthesis makes plants special. As Dr. Lamkey, our department chair, likes to say:

> I got hungry and went outside and stood in the sun for a while, but didn't get full. So I went and found some plants to eat!

Plants *can* make their own food from sunlight! This is really quite a feat, and when you think about it, perhaps the primary reason why life exists on our planet. Agronomists have the important task of managing these amazing plants that use sunlight, carbon dioxide, and water to provide us with food, feed for livestock, fiber for clothing and building materials, and fuel for vehicles and other machinery. And oxygen to breathe! And carbon dioxide, a greenhouse gas, is removed from the atmosphere!

While the process of photosynthesis is likely familiar to everyone, there are some details and technical terms that are often misunderstood. Here are three of them.

assimilation The word *assimilate* means "to take in." Hence we use the term *assimilation* for the uptake of $\mathrm{CO_2}$ by a plant in order to perform photosynthesis according to (1). Carbon dioxide enters into a leaf via small holes called stomata. We will use the variable A to quantify assimilation with the units of micromoles of $\mathrm{CO_2}$ per square meter per second, or $\frac{\mu\text{mol } \mathrm{CO_2}}{\mathrm{m^2 \cdot s}}$.

photosynthetically–active radiation Not all sunlight is used in photosynthesis. In (1), "light" is actually just photosynthetically–active radiation (PAR). Our eyes see the same wavelengths of light that correspond to PAR, about 400 to 700 nm. Recall that we can think of light as discrete packets of energy called photons. We will use units of micromoles of PAR photons per square meter per second, or $\frac{\mu\text{mol quanta}}{\mathrm{m^2 \cdot s}}$. (PAR photons are called "quanta" when used in calculations.) The amount of PAR is normally called the photosynthetic photon flux density (PPFD). In full sunlight on a summer day in Iowa, the PPFD would be about 2000 $\mu\text{mol quanta} \cdot \mathrm{m^{-2}} \cdot \mathrm{s^{-1}}$.

transpiration The loss of H_2O from a plant. Water taken by the plant from the soil via the roots makes its way to the leaves via the plant's vascular system. Some water is used in photosynthesis according to (1). However, when the stomata open to take in carbon dioxide, water "hanging around" within leaf tissue evaporates and leaks out. This process, called *transpiration*, is *not* in (1)! However, it is a consequence of photosynthesis (if the stomata are open to take in CO_2, H_2O will be lost), and more water is actually lost via transpiration than needed for photosynthesis. We will use the variable T to quantify transpiration.

In this data collection activity we will make measurements relevant to photosynthesis, both at the scale of an individual leaf, as well as for an entire plant canopy (collection of many plants).

Objectives

There are two objectives for this laboratory.

1. Measure assimilation, A, while varying incident PAR.
2. Measure the area and dimensions (length and width) of various leaves.

We will use a special instrument called the LI-6800 Portable Photosynthesis System to measure A, along with two different methods to measure leaf area. Leaf area is important because the more leaves you have, the more photosynthesis that can occur (at least until all the incident PAR is used up!). In addition, you'll get to see an instrument that measures canopy leaf area (not just individual leaves) and PAR. This equipment belongs to the crop production and plant physiology group in our department, and is used by many to collect data for research projects.

The data we collect will enable you to answer questions like the following.

How does assimilation change as the amount of incident PAR changes?

Do two methods of leaf area measurement give the same answer?

Can measurements of leaf length and width be used to estimate leaf area?

Some Background (If Interested)

How can an instrument like the LI-6800 measure A? Consider Figure 1. Think of the box labeled "control volume" as an imaginary boundary surrounding a leaf. It is called a control volume because we will keep track of what goes into the box, what goes out of the box, and use the principle of the conservation of mass (mass is neither created nor destroyed) to determine A, T, and also O, the release of O_2 (created through photosynthesis) from the stomata as shown in (1).

First, think about all of the air going in and out of the control volume. The air contains many types of gases. We are primarily concerned with three of them: H_2O, CO_2, and O_2.

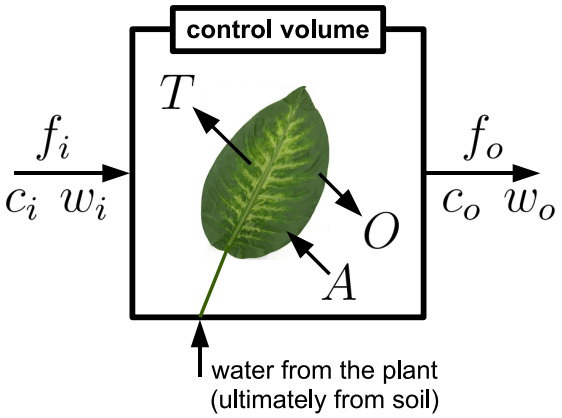

Figure 1: The LI-6800 is able to measure assimilation, A, by keeping track of what goes into the control volume, and what goes out of the control volume.

If f_i is the flow rate of air into the control volume with units $\frac{\text{mol air}}{\text{s}}$, and f_o is the flow rate of air out of the control volume also with units $\frac{\text{mol air}}{\text{s}}$, then:

$$f_o = f_i + s\,T \tag{2}$$

where s is the area of the leaf that is transpiring. Assuming the units of s are m^2, then the quantity $s\,T$ has units of $\frac{\text{mol } H_2O}{\text{s}}$. What (2) says is that the rate at which moles of air (particularly H_2O, CO_2, and O_2) are coming into the control volume must equal the rate at which moles of air are going out. Note that H_2O comes into the control volume in *two* ways. The first is with the flow of air associated with f_i (assuming the air is not perfectly dry). The second is through the stem of the leaf. This water entering through the stem is released into the control volume via T and adds to the moles of gas inside the control volume.

Why don't we consider A and O from Figure 1 in (2)? It's because the same amount of gas taken up by the leaf (moles of CO_2) is released by the leaf (moles of O_2): for every molecule of CO_2 assimilated, a molecule of O_2 is produced according to (1). So the net effect of photosynthesis, in terms of gas molecules, is only to add water vapor (via transpiration) to the control volume.

Next, think about the moles of H_2O going into and out of the control volume in Figure 1. If w_i is the mole fraction of water vapor coming in with units $\frac{\text{mol } H_2O}{\text{mol air}}$, and w_o is the mole fraction of water vapor going out also with units $\frac{\text{mol } H_2O}{\text{mol air}}$, then we can write the following.

$$f_o\,w_o = f_i\,w_i + s\,T \tag{3}$$

Each term in (3) has the units $\frac{\text{mol air}}{\text{s}} \times \frac{\text{mol } H_2O}{\text{mol air}} = \frac{\text{mol } H_2O}{\text{s}}$.

Finally, consider the moles of CO_2 coming in and out of the control volume in Figure 1. If c_i is the mole fraction of carbon dioxide coming in with units $\frac{\text{mol } CO_2}{\text{mol air}}$, and c_o is the mole fraction of carbon dioxide going out also with units $\frac{\text{mol } CO_2}{\text{mol air}}$, then we can write the following.

$$f_o\,c_o = f_i\,c_i - s\,A \tag{4}$$

Each term in (4) has the units $\frac{\text{mol air}}{\text{s}} \times \frac{\text{mol } CO_2}{\text{mol air}} = \frac{\text{mol } CO_2}{\text{s}}$. Also notice the minus sign in (4): in this case the leaf is *removing* CO_2 from the air inside the control volume.

Figure 2: To get transpiration or assimilation for an entire plant canopy (collection of plants), you need to know how many leaves are conducting photosynthesis, and their area.

Combining (2) with (3) yields the following expression for transpiration from the leaf inside the control volume.

$$T = \frac{f_i \, (w_o - w_i)}{s \, (1 - w_o)} \tag{5}$$

And combining (2) with (4) yields the following expression for assimilation inside the control volume.

$$A = \frac{f_i}{s} \, (c_i - c_o) - T \, c_o \tag{6}$$

So the LI-6800 forms a control volume around a leaf, to define s, and measures f_i, w_o, w_i, c_i, and c_o. Then (5) and (6) can be used to find T and A, respectively. Additionally, the LI-6800 can change the amount of PAR incident on s, and the CO_2 concentration within the control volume, to see how T and A change as a function of PAR and/or CO_2 concentration.

Scaling Up to a Canopy

The LI-6800 can measure A for individual leaves. But how much CO_2 is being taken up by a canopy of many plants? Look at Figure 2. To scale up A from a single leaf to a canopy, you must determine the total area of leaves conducting photosynthesis. Therefore it is important to measure leaf area. We will be using two methods to determine leaf area.

- An instrument able to measure the area of leaves that have been detached from a plant (a *destructive* measurement).
- A manual measurement in which grid paper will be used to find the area of individual leaves (normally also requiring leaves to be detached).

There are also instruments able to measure the total leaf area per ground area of an entire crop canopy *nondestructively*, that is, without having to remove leaves from plants. This

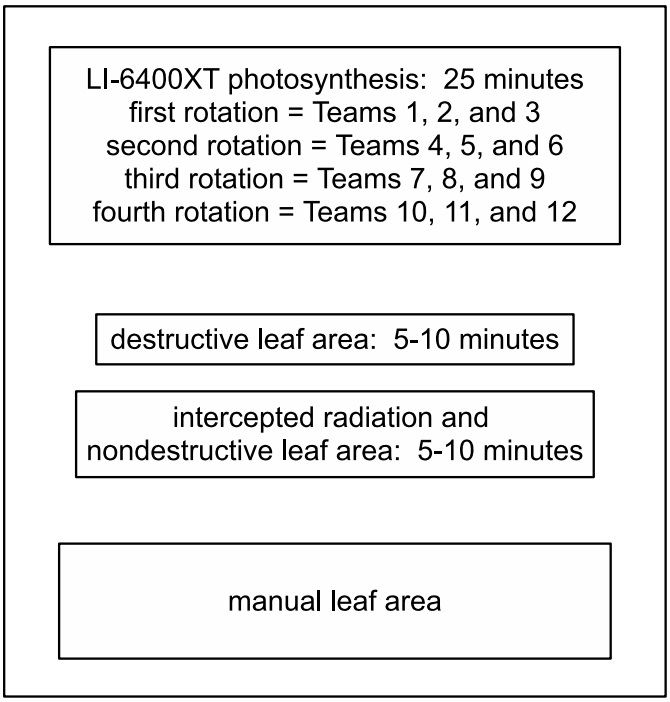

Figure 3: Data collection centers.

quantity is called the leaf–area index (LAI), and defined as the one–sided area of canopy leaves per ground area. LAI is normally expressed in units of $m^2 \cdot m^{-2}$.

General Instructions

Each team will visit four data collection centers. See Figure 3.

- When at the photosynthesis center, use the data sheets provided on Canvas. Follow the schedule in Figure 3.
- After all of your leaves have been cut, visit the destructive–leaf–area center to measure the area of each leaf in your team's set.
- After visiting the destructive–leaf–area center, go to the nondestructive–leaf–area–and–intercepted–radiation center. There you will learn how to measure canopy LAI nondestructively, as well as the PAR incident on, and intercepted by, a crop canopy.
- When not visiting the other three centers, teams will work in the manual–leaf–area center and follow these directions.
    1. Cut out one complete set of "leaves" (paper leaves).
    2. Label each leaf of your team's set using the naming convention on Canvas.
    3. Measure the length and width of each leaf of your team's set. We will use this data to create simple models that estimate leaf area using only leaf length and width.

4. Pick one small leaf, one medium–sized leaf, and one large leaf from your set. Then have each team member find the area of each of these three leaves using the graph paper by drawing an outline and counting the number of 1 mm^2 grid squares inside. You will then have either three or four estimates of a small leaf, a medium–sized leaf, and a large leaf depending on how many people are on your team. We will use these area measurements to validate the destructive leaf area measurements.

Equipment

Your team will check out the following equipment.

1. A set of artificial (paper) leaves.
2. Two sheets of graph paper for each team member.
3. Scissors for each team member.
4. A ruler.
5. A tablet computer to record data, if so desired.

Minimum Set of Measurements

Follow the instructions and record the data as directed at the photosynthesis center. Measure *each* leaf in your team's set at the destructive–leaf–area center. Measure the length and width of *each* leaf in your team's set and have *each* team member find the area of the same three leaves using the graph paper at the manual–leaf–area center.

Location

We will meet in G533 Agronomy Hall (*not* our normal classroom at the Hansen Agriculture Student Learning Center).

Tentative Timeline

9-9:30 Determine team roles. Managers check out tablet computer, if you would like, and your group's leaves. Brief overview of data collection activities. Review instructions and ask questions through your Communicator.

9:30-11:30 Measurement period.

11:30-11:50 Recorders upload data to CyBox. Managers return equipment.