
CONTROLS ON PHOTOSYNTHESIS AND SUGAR PRODUCTION IN C3 AND C4 PLANTS: A MODELING APPROACH

Steven K. Rice
Dept. of Biological Sciences
Union College
Schenectady, NY
12308

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Photosynthesis is a rather complicated process (Figure 1). Along the pathway, there are a series of energy transformations, redox reactions, and entry and exit points, any of which could influence the rate of the overall process. However, physiological measurements yield surprisingly simple relationships among a few environmental factors such as light and CO₂ availability and overall rates of photosynthesis measured in the short-term. How do these variables control photosynthesis? You will investigate these mechanisms in two ways. Today, you will use STELLA to simulate the process of photosynthesis to better understand how different mechanisms work together to control the photosynthetic process. In lab next week, you will explore the relationship between carbon dioxide concentration and photosynthesis in two species that differed in their CO₂ uptake pathways (C-3 and C-4 plants).

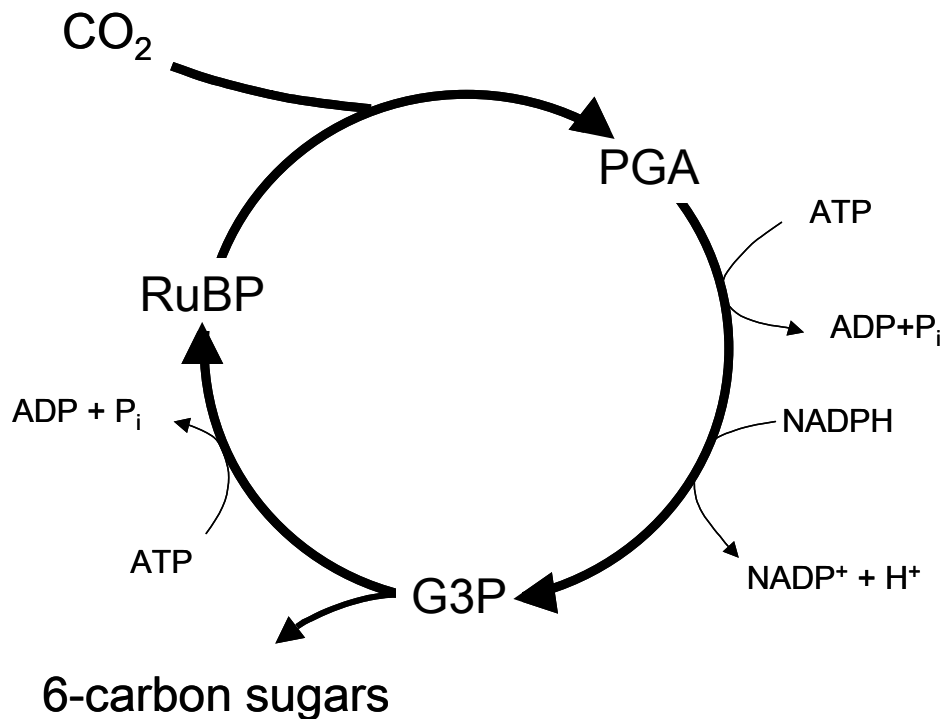
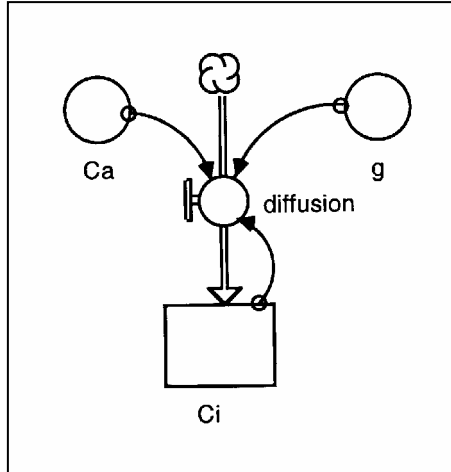


Figure 1. Abbreviated Summary of the Calvin Cycle.

BUILDING A SIMPLE MODEL OF CO₂ DIFFUSION USING STELLA

To begin your modeling effort, you must first identify the important “players”. This exercise will walk you through a simple model that can be used to predict CO₂ concentration within the intercellular air space in the leaf. Thus, the important “player” is the pool of CO₂ within the leaf (C_i). The pool will exist in what will be referred to as a “stock”. This stock retains the amount of CO₂ available for photosynthesis. Stocks can have input and output flows (diffusion into the leaf and fixation in the Calvin Cycle) and controlling variables that affect these inputs and outputs (conductance and rubisco activity, for example). The four STELLA model building blocks which you have been introduced to allow you to apply these.



Now, proceed with your modeling effort. Consider the map below that shows a model structure for a simple diffusion model (Figure 2). What does this map represent? The stock C_i represents the pools of carbon in the intercellular air space (*ias*) and C_a is the atmospheric [CO₂]. The flow labeled *diffusion* attempts to model the flow of CO₂ from the air through the stomata to the *ias*. You will model the flow as a diffusional process. The map shows that this flow is affected by C_a , C_i and g , the conductance to movement into the *ias*. This latter term is controlled principally by the size, number and opening and closing of stomata.

Figure 2. Diffusion Model.

Like all models, this map simplifies the diffusional process. *What could be added to the model to make it more realistic?*

What assumptions are made in order to represent photosynthesis in this way?

PARAMETERIZING YOUR MODEL

Your model is an abstracted version of the real process. However, if the model represents the important underlying processes, it may serve as a useful tool to explore dynamic relationships of the system. For example, we can parameterize the model by defining specific mathematical relationships among the model elements and determining how differences in conductance influence photosynthetic rates. Follow the directions below to parameterize your model.

Now that you've developed the map, it is time to use it to simulate diffusion. The STELLA software contains the framework necessary to perform dynamic simulations. You, however, have to establish the specific relationships and set the initial parameter values. To begin, click on the globe icon on the left-side of the screen and it will put you into modeling mode. Consider the *diffusion* flow that controls C_i . Double click on the *diffusion* flow regulator (the circle attached to the pipe). Notice that g (conductance), C_a and C_i appear in the **Required Inputs** list. The software recognizes that they belong there because you used connectors to indicate that these variables serve as input to C_i . The software requires that they be used as input.

Define the *diffusion* flow as: $1.56 * g * (C_a - C_i)$.

This equation is derived from Fick's First Law of Diffusion that states that flux is related to the product of the concentration difference (C_a minus C_i), the diffusivity ($1.56 \text{ m}^2/\text{s}$) and the conductance (variable, with high values equal to $1 \text{ mol}/\text{m}^2/\text{s}$). Set C_a to equal $360 \text{ } \mu\text{mol CO}_2 \text{ mol}^{-1}$ and set the initial value of C_i at 300, a value that represents a plant with a high photosynthetic rate.

RUNNING THE SIMULATION

Now that the model is constructed, you can explore its dynamics. First you must create a graph to view the results. Click on the graph icon in the tools menu. Then click on the map workspace to place a graph there. Double-click on the graph and move C_i to the selected column to serve as the y-axis. Click on the run icon in the lower left-hand corner of the screen (shows a person running). Change the "Time Specs" to run for 10 time units (seconds in the model). Click on the forward arrow to run the model.

What is the final concentration of carbon in the intercellular air space?

How long does it take for C_i to reach an equilibrium level?

What would happen to C_i if you increased the conductance to CO_2 ? Why?

Consider photosynthesis and other possible control points on the process. What control mechanisms might exist that are not contained within the model shown?

This simple model has introduced you to some of the features of the STELLA software. Now, continue with the exercise below to build a more realistic model of photosynthesis

INCORPORATING REALISM

The model you constructed simulates one important process that can limit the rate of photosynthesis: diffusion of CO₂. However, the photosynthetic process is affected by many other factors, for example, light. You will apply your understanding of photosynthesis, particularly of the Calvin Cycle, to develop a more sophisticated and realistic model of the photosynthetic process that combines the potential influences of conductance and light on photosynthesis. With this model you can begin to explore how different control process may interact to determine overall photosynthetic rates in plants.

Use Figure 1, your textbook, and/or your notes to refresh your understanding of the Calvin Cycle. Notice that there are many intermediates within this catabolic pathway, but there are several essential molecules that we can represent as stocks. In your model, you may want to consider using the following: PGA, G3P, and RuBP. What controls the conversion from one of these pools to the other? It is often useful to begin with a simple model and work toward complexity. How and where does light influence the process? What enzymes control the process? Generate a model map of the Calvin Cycle and use the modeling tools to show how steps in the process are controlled. Show this to your instructor and discuss.

mapping workspace

The mapping process you just performed has you thinking about controls to photosynthesis. In order to relate the results of your modeling to experimental data, you will need to parameterize it in a meaningful way. Consequently, we will all construct similar model maps, parameterize them similarly and explore the model dynamics as a class. To begin, construct the model map shown in Figure 3 and parameterize it with the equations indicated. This model is based on a one presented in Collatz et al. 1991 (*Agric. For. Meteorol.* 54: 107-136).

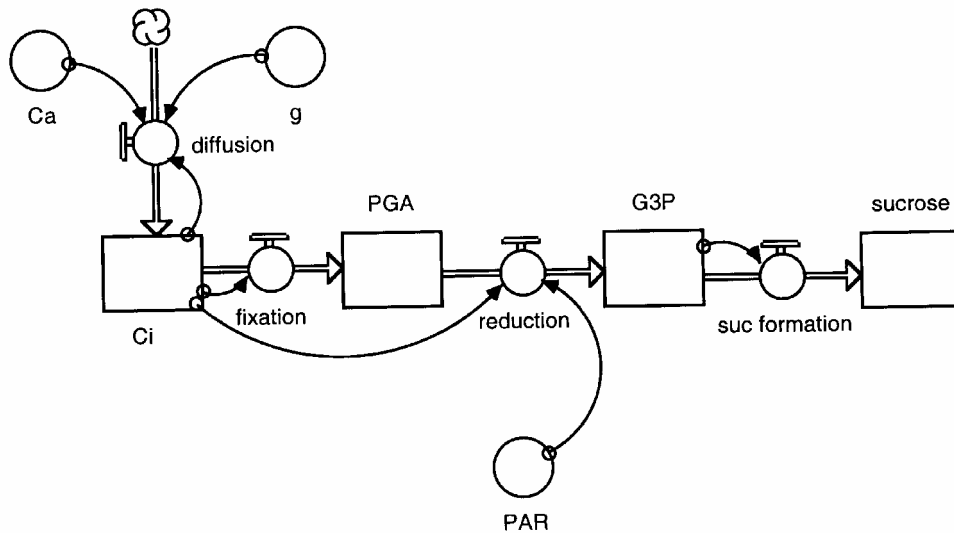


Figure 3. Photosynthesis Model Structure.

Model Parameters:

- *PAR* is the Photosynthetically Active Radiation; the amount of light energy in the wavelengths used for PS
- *PGA*, *G3P* and sucrose all begin with 0.
- *fixation* receives equation: $(100*(C_i-40.4))/(C_i+300*(1.7))$; this represents the performance of rubisco at the given $[CO_2]$.
- *reduction* receives equation: $(0.064*PAR*(C_i-40.4))/(C_i+80.8)$; this represents the limitation by light availability.
- *suc formation* receives equation: $MIN(50,G3P)$; this represents the limitation by enzymes responsible for sucrose formation

We will discuss the origin of these equations. Use this model to explore how light and CO_2 availability influence sucrose formation in C3 and C4 species. Begin with a C3 plant (the model you have developed is parameterized for a C3 plant). Employ the parameters in the table below and record the amount of sucrose formed at 10 s. Graph the results in the graph provided.

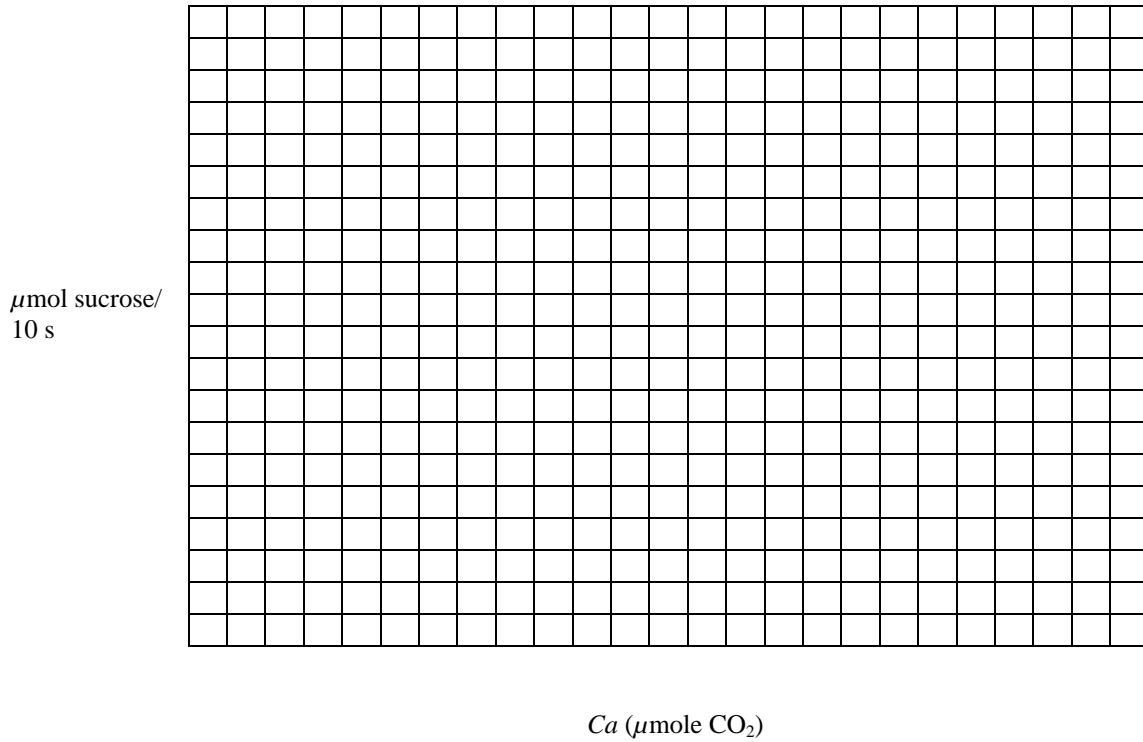
C3 Plant

@PAR = 300

@PAR = 800

<i>Ca</i>	sucrose at 10 s	<i>Ca</i>	sucrose at 10 s
50		50	
200		200	
400		400	
600		600	
800		800	
1000		1000	

C3 Plant Results:



Now, consider the differences between C3 and C4 plants. How could you adapt your model to simulate sucrose formation in a C4 plant? *Describe which parameters you change and why--make sure you can justify this and discuss your alterations with your instructor before continuing.*

Once you have adapted your model, run it for the same conditions as the C3 plant and record the results in the table below and construct a similar graph to the one you made for the C3 plant.

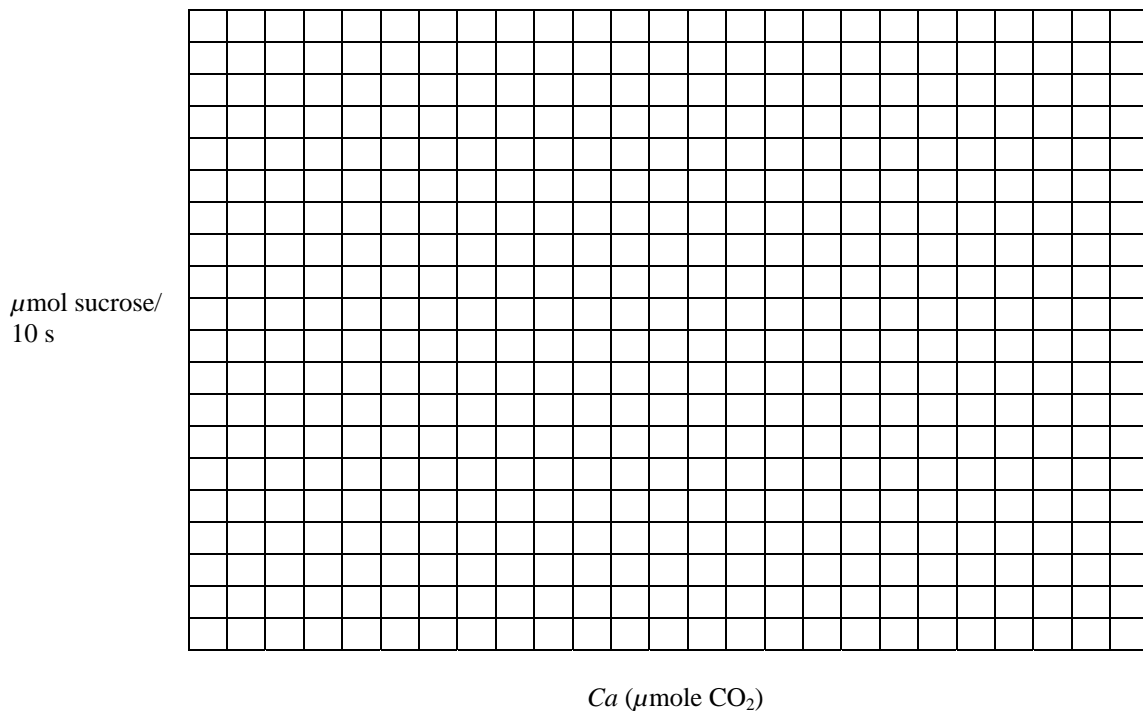
C4 Plant

@PAR = 300

@PAR = 800

C_a	sucrose at 10 s	C_a	sucrose at 10 s
0		0	
200		200	
400		400	
600		600	
800		800	
1000		1000	

C4 Plant Results:



LAB REPORT: CONTROL OF PHOTOSYNTHESIS IN C3 AND C4 PLANTS.

You are expected to write a lab report following the format of a scientific paper that combines your modeling and experimental results. Your "Introduction" should be between 1-3 paragraphs long and have a clearly written purpose statement. You may choose to focus on the control of photosynthesis in C3 and C4 plants or on implications of plant response in future atmospheres based on the CO₂ response curve. The "Methods" section can describe the general approaches used in one to several paragraphs and refer to the lab handouts for the details of the measurements. Your "Results" should describe the main trends in the data and also include estimates of parameters derived from the photosynthesis measurements (see the lab handout). Use the results from your lab group only--we will not hold you to replicated statistical rigor in this report. Your "Discussion" should focus on comparing the trends evident in the modeling and the lab measurements to better understand differences in C3 and C4 photosynthesis. You may also want to discuss implications. **YOUR DISCUSSION AND INTRODUCTION SHOULD UTILIZE AT LEAST TWO (2) REFERENCES. THESE MUST BE FROM PUBLISHED, PEER-REVIEWED JOURNALS (NO WEB PAGES ALLOWED).**