

Interactions

INVESTIGATION 10

ENERGY DYNAMICS

What factors govern energy capture, allocation, storage, and transfer between producers and consumers in a terrestrial ecosystem?

■ BACKGROUND

Almost all life on this planet is powered, either directly or indirectly, by sunlight. Energy captured from sunlight drives the production of energy-rich organic compounds during the process of photosynthesis. These organic compounds create biomass. Gross productivity is a measure of the total energy captured. The net amount of energy captured and stored by the producers in a system is the system's net productivity. In terrestrial systems, plants play the role of producer. Plants allocate that biomass (energy) to power processes or to be stored. Different plants have different strategies of energy allocation that reflect their role in various ecosystems. For example, annual weedy plants allocate a larger percentage of their annual biomass production to reproductive processes and seeds than do slower-growing perennials. As plants, the producers, are consumed or decomposed, the stored chemical energy powers additional individuals (the consumers) or trophic levels of the biotic community. Biotic systems run on energy much as economic systems run on money. Energy is generally in limited supply in most communities. Energy dynamics in a biotic community is fundamental to understanding ecological interactions.

There are numerous methods and techniques for studying energy dynamics in a biological community. Most are not accessible to the average classrooms, and the complexity of a typical community or ecosystem is so great that often students either are left with oversimplified models of the community or are confused by the overall complexity in the system. An alternate approach is to create a simple model system in the laboratory with a single producer species and a single consumer. The concepts learned by studying this system can then be extended to more complex, natural systems.

Note: This investigation, as written, requires an extended amount of time to conduct (approximately 2–3 weeks) based on the different components, with each building off previous explorations and results.

This laboratory investigation introduces methods for estimating net terrestrial productivity and secondary productivity in a laboratory setting using a model plant species, Wisconsin Fast Plants (*Brassica rapa*) (<http://www.fastplants.org>), and cabbage white butterflies (*Pieris rapae*). Methods for estimating the efficiency of transfer of energy from producer to consumer are also introduced. Together, these model organisms and methods create a rich, accessible research environment that facilitates



student exploration of basic ecological concepts of energy flow, the role of producers, the role of primary consumers, and the complex interactions between organisms.

The first portion of this laboratory investigation, Getting Started, serves as a prelab activity designed to help students establish a context for energy dynamics in living systems. The analogy of accounting or budgeting provides the students with a useful tool to guide their questions and strategies for investigating those questions.

In Procedures, students develop the skills needed to monitor the biomass in growing plants and butterfly larvae. With the prelab work serving as a framework, the practical skill development, along with the insights that are gained growing the plants and butterfly larvae naturally, leads to focused, student-generated questions about the energy dynamics in the system. The skills acquired in Procedures are then put to use in the final part, Designing and Conducting Your Investigation.

In this final part, the students work in teams to investigate their own questions. They present the results of that work in a miniature classroom poster presentation that simulates the poster sessions at meetings of professional societies. How students present their work often depends on class structure; for example, you might prefer that students keep a laboratory notebook.

■ PREPARATION

Materials and Equipment

- Food dehydrator or drying oven
- Electronic balance with 0.001 gram precision (Less precise balances will work if a number of samples are grouped.)
- Digital cameras (or cell phone cameras)
- Fast Plant growth chamber (lights) and growing systems
- Fast Plant seeds (~50–100 seeds)
- Butterfly eggs (~20 eggs)
- Soil mix
- 10-10-10 soluble fertilizer
- Brussels sprouts, broccoli, cabbage
- 10% bleach solution for cleanup of growing systems
- Honey to make honey water nectar substitute for adult butterflies
- Wicking cord for plant growth systems
- Bee sticks (actual honeybee bodies glued to toothpicks for pollinating Fast Plants)

Teachers can purchase a variety of packaged systems for growing plants and rearing butterflies, or they can construct their own. See the Wisconsin Fast Plants website for suggested plant-growing chambers and butterfly-rearing systems. Suggested growing systems are made from recycled one-liter plastic drink bottles. Recycled plastic deli containers work well for making the Brassica Barn or butterfly nursery. Each student team will need a Brassica Barn. Be aware that these instructions for rearing can be considered guidelines. You and your students are encouraged to try different growing systems and to develop your own.



Figures 1 and 2. Plant Growing Systems Made from Plastic Bottles

■ Timing and Length of Lab

Most of the initial student work on these projects can be completed over a two-week period. Only two or three days during that time will require about an hour of classwork. On other days, a small amount of time will be required for maintenance and data collection. Neither you nor your students will have to go to campus on weekends to collect data. However, because of the comprehensive nature of the investigation, you need to allow sufficient time to familiarize yourself with the materials and procedures beforehand to make this exploration a meaningful inquiry-based experience for students.

■ Safety and Housekeeping

- Preapprove all research proposals.
- Students should never place research organisms in extremely stressful situations (e.g., high temperatures).
- The USDA lists cabbage white butterflies (*Pieris rapae*) as a pest species. Therefore, no butterflies or larvae raised in the laboratory should be released to the wild.
- Euthanize the butterflies or larvae by freezing them when your investigation is complete. The plants and soil can simply be discarded.
- Disease outbreaks are common in cultured populations of organisms. Although the diseases associated with the organisms in this investigation are not dangerous to humans, it is important to maintain cleanliness in the laboratory and of your experimental equipment in order to minimize the risk of diseases impacting the study.
- Long-term culturing for plants or butterflies requires cleanliness. Be sure to clean all culturing chambers and wipe them down with dilute Clorox (and then dry the chambers completely) before starting another generation of plants or butterflies. Use new materials if you have any doubts.
- Cultures involve artificial light sources and liquids. Caution should be exercised to keep the two separate.



■ ALIGNMENT TO THE AP BIOLOGY CURRICULUM FRAMEWORK

This investigation will generally be conducted during the study of interactions (big idea 4). It could also be conducted during the study of cellular processes (big idea 2). In addition, some questions uncovered by students during the initial phase of the investigation will connect well with evolution and natural selection (big idea 1). As always, it is important to make connections between big ideas and enduring understandings, regardless of where in the curriculum the lab is taught. The concepts align with the enduring understandings and learning objectives from the AP Biology Curriculum Framework, as indicated below.

■ Enduring Understandings

- 2A1: All living systems require constant input of free energy.
- 2D1: All biological systems from cells and organisms to populations, communities, and ecosystems are affected by complex biotic and abiotic interactions involving exchange of matter and free energy.
- 4A6: Interactions among living systems and with their environment result in the movement of matter and energy.

■ Learning Objectives

- The student is able to explain how biological systems use free energy based on empirical data that all organisms require constant energy input to maintain organization, to grow, and to reproduce (2A1 & SP 6.2).
- The student is able to justify a scientific claim that free energy is required for living systems to maintain organization, to grow, or to reproduce, but that multiple strategies exist in different living systems (2A1 & SP 6.1).
- The student is able to predict how changes in free energy availability affect organisms, populations, and ecosystems (2A1 & SP 6.4).
- The student is able to refine scientific models and questions about the effect of complex biotic and abiotic interactions on all biological systems from cells and organisms to populations, communities, and ecosystems (2D1 & SP 1.3, SP 3.2).
- The student is able to design a plan for collecting data to show that all biological systems are affected by complex biotic and abiotic interactions (2D1 & SP 4.2, SP 7.2).
- The student is able to analyze data to identify possible patterns and relationships between a biotic or an abiotic factor and a biological system (2D1 & SP 5.1).
- The student is able to apply mathematical routines to quantities that describe interactions among living systems and their environment, which result in the movement of matter and energy (4A6 & SP 2.2).
- The student is able to predict the effects of a change of matter or energy availability on communities (4A6 & SP 6.4).

■ Are Students Ready to Complete a Successful Inquiry-Based, Student-Directed Investigation?

This investigation reinforces the following skills:

- Growing and maintaining plants through an entire life cycle, from seed to seed (Wisconsin Fast Plants are recommended.)
- Caring for, providing food for, and maintaining a clean environment to culture butterfly larvae
- Keeping and maintaining accurate records of observations and measurements of cultured organisms in a lab notebook
- Measuring small mass quantities directly or by combining a number of low mass objects and taking an average
- Demonstrating basic accounting or budgeting skills — quantifying inputs and resolving the outputs
- Constructing energy flow diagrams
- Organizing a work-flow timeline for several days (small daily tasks associated with care of organisms)
- Calculating unit conversions in simple equations
- Reporting findings and conclusions in a peer-reviewed environment

If you choose to use lab notebooks to help assess student performance on this lab exercise, make sure that the students are completely informed about your expectations for this product. A well-designed rubric (see Chapter 6) is one important way to communicate your expectations. Likewise, before using a mini-poster presentation format for prelab and summative assessments, make sure students have had practice in producing successful mini-posters.

■ Skills Development

Students will develop the following skills:

- Calculating, recording, and diagramming energy dynamics in a simple model system
- Posing a scientific question regarding energy dynamics, allocation, or capture
- Designing and carrying out an investigation to answer a question regarding energy dynamics, allocation, or capture
- Modeling energy dynamics quantitatively

■ Potential Challenges

Students often don't understand that the fresh weight of a food (for themselves or for other organisms) does not necessarily equal the biomass of that food. Students also should understand that all laboratory research organisms, including those that are considered pests, need to be treated with respect and handled appropriately. Thus, student investigations that create stressful situations for experimental animals (such as exposure of living larvae to high temperatures) should never be allowed.



■ THE INVESTIGATIONS

■ Getting Started: Prelab Assessment

You may assign the following for homework; as a think, pair/group, share activity, in which pairs or small groups of students brainstorm ideas and then share them with other groups; or as a whole-class discussion to assess students' understanding of key concepts pertaining to energy capture and use:

1. The economy of a business or household is somewhat like the energetics of a biological community. A well-run household or business creates a budget based on a careful accounting of money coming in and money going out. Likewise, the energy dynamics of a biological community can be modeled by accounting for the energy coming in and the energy going out through different members of the community. Keeping track of money is relatively straightforward — you count it. You count how much money is coming in and how much is going to various expenses and savings.

How do you keep track of energy in living organisms? It is a challenge. Producers capture light energy and convert it into chemical energy stored in energy-rich molecules. These molecules have mass, so the energy in biological systems can be indirectly measured by mass — biomass. With your lab team, take a moment to brainstorm how you can account for energy use and transfer in a biological system in a manner similar to the way in which people account for money.

2. This investigation requires you to take care of and maintain healthy populations of living organisms — plants and animals. In fact, before you begin this investigation you will need to start both plant and animal cultures. Wisconsin Fast Plants and cabbage white butterflies are both easily raised in the classroom or laboratory. Neither takes up much time or equipment, but they both need to be tended regularly. As a lab team, discuss the care, maintenance, and proper disposal of the organisms you use in this lab. Prepare a schedule and divide up the responsibilities for long-term care and maintenance. (This includes taking care of animal wastes.) Check out online information about care and maintenance of the organisms from teachers like you at <http://fastplants.ning.com/video/2038532:Video:13> and <http://fastplants.ning.com/video/juan-enriquez-wants-to-grow>.
3. This investigation culminates with the students generating and answering authentic research questions. These questions flow naturally from students when they are engaged in authentic inquiry. The more the classroom laboratories rely on inquiry, the greater the skill development of the students. To that end, students' previous experiences solving problems and recording their work reflectively in a laboratory notebook are essential prelab skills.

You will find that the investigation will go more smoothly if students are introduced early to Wisconsin Fast Plants and cabbage white butterfly larvae. Having students start, maintain, and record both plant and butterfly cultures through one life cycle, without using the organisms for experiments, will greatly facilitate successful completion of this investigation. (Figure 3 shows the butterfly life cycle.) The

increased familiarity with the organisms will prompt students to ask questions during the research component. In addition to developing students' familiarity with the organisms, thereby easing completion of the lab, rearing one generation of each culture generates excess offspring of both plants and animals — numbers that are needed to complete this lab.

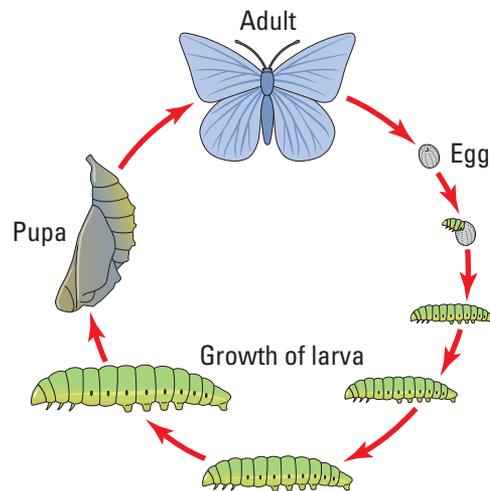


Figure 3. Butterfly Life Cycle

Estimating Net Primary Productivity (NPP) of Fast Plants

Step 1 Students should create a diagram to model energy capture and flow through a plant (see Figure 4). This will help their lab team design the data collection procedure that helps measure energy capture and flow in a plant.

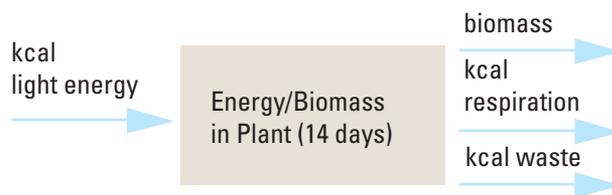


Figure 4. Energy Flow Into and Out of a Plant

Steps 2–3 As a team, students will design their investigation to sample the biomass of an adequate number of plants early in the life cycle and then again later in the life cycle. Remind students that biomass is only the mass of the plant materials, not of the water in the plant. Make sure that the students' procedures account for this. On Day 7 (about one-fifth of the way through a life cycle), students should remove approximately 10 plants from the soil, making sure to get all of the roots. They should carefully wash the soil from the roots while retaining as much of the root system as possible. They gently blot dry and then mass each plant in an aluminum foil weighing boat. (You may want to remind them not to forget to tare each boat.) Students should create a table in their lab notebook to organize the data collected on Fast Plants NPP. They should still have about

30 or 40 plants left in their population that will continue growing. Students should place the 10 plants and aluminum foil weighing boats in a drying oven or dehydrator at about 100°C for 48 hours. Students will describe this procedure in their lab notebook and then check with you for approval and suggestions. Students will record their observations, including the size and overall appearance of the Fast Plants, questions, reflections, and measurements daily in their notebook.

Step 4 Students should determine the dry mass in grams of each plant. This is the individual plant biomass. They should record their answers to the following questions in their lab notebooks (see Table 1):

- What is the mean value for all the dry seven-day-old Fast Plants?
- What percentage of the average mass of a living seven-day-old Fast Plant comes from water?
- What percentage comes from the dry mass (biomass)? (**Note:** You might want to remind students that this percentage will be used later. Students should indicate in their notebooks the range or variation in the data set with appropriate analysis. In particular, they should consider range, standard deviation, and standard error.)

Table 1. Seven-Day-Old Fast Plants

Age	Wet mass/ 10 plants	Dry mass/ 10 plants	Percent biomass	Energy (g biomass x 4.35 kcal)/ 10 plants	Net primary productivity per day per plant
7 day	19.6 grams	4.2 grams	21.4%	18.27 kcal	0.26 kcal/day

Step 5 Students continue caring for and growing the remaining Fast Plants. For the remaining Fast Plants, they should describe the growth over time in their lab notebooks.

Step 6 On day 14, students repeat Steps 2–4 with 14-day-old plants and record their data in their lab notebooks (see Table 2).

Table 2. 14-Day-Old Fast Plants

Age	Wet mass/ 10 plants	Dry mass/ 10 plants	Percent biomass	Energy (g biomass x 4.35 kcal)/ 10 plants	Net primary productivity per day per plant
14 day	38.4 grams	9.3 grams	24.2%	40.46 kcal	0.29 kcal/day

Estimating Energy Flow Between Fast Plants Producers and Cabbage Butterfly Larvae

Step 1 Students create a diagram to model energy capture and flow through a plant, as in Step 1 in the previous procedure.

Step 2 Students mass one large, fresh brussels sprout. They should cut the sprout in half to expose the inner leaves to butterfly larvae and place these sprout halves into the Brassica Barn. (Remind them to remove all other plant materials in the Brassica Barn.) Students mass 8–12 4th instar larvae as a group and then determine the mean mass per individual larva. They should transfer all the larvae into the prepared Brassica Barn with the single brussels sprout cut in half.

Step 3 Students create a table in their lab notebooks to help organize the data collected, including estimates of the energy/biomass flow from plants to butterfly larvae (see Table 3). They collect, dry, and mass the frass (fecal material) produced by the larvae over the next three days. After three days of feeding, they mass the larvae as a group and then determine the mean mass per individual and the mean mass gained per day. Finally, students mass the remaining part of the brussels sprout and determine the amount of brussels sprout biomass consumed by each larva per day.

Table 3. Energy/Biomass Flow from Plants to Butterfly Larvae

Larva age (per 10 larvae)	12 days	15 days	3 days of growth
Wet mass of brussels sprouts	30 g	11 g	19 g consumed
Plant percent biomass (dry/wet)	0.15	0.15	0.15
Plant energy (wet mass x percent biomass x 4.35 kcal)	19.58 kcal	7.2 kcal	12.4 kcal consumed
Plant energy consumed per larvae (plant energy/10)	1.96 kcal	0.72 kcal	1.24 kcal consumed per individual
Wet mass of 10 larvae	0.3 g	1.8 g	1.5 g gained
Wet mass per individual	0.03 g	0.18 g	0.15 g gained
Larvae percent biomass (dry/wet)	0.15	0.15	0.15
Energy production per individual (individual wet mass x percent biomass x 5.5 kcal/g)	0.02 kcal	0.15 kcal	0.12 kcal
Dry mass of the frass from 10 larvae	-----	.5 g	.5 g excreted
Frass mass per individual	-----	0.05 g	0.05 g excreted
Frass energy (waste) (frass mass x 4.76 kcal/g)	-----	.24 kcal	.24 kcal excreted
Respiration estimate (plant energy consumed – frass waste energy production)	-----	-----	0.88 kcal

Note: A large part of the mass of brussels sprouts comes from water. Because larvae obtain a lot of their water from the plants they eat, you cannot feed dry brussels sprouts



to the larvae. However, as you have seen with the Fast Plants, there is a difference between the biomass of a dry brussels sprout and its mass when it is fresh. Ask students to use the percentage of biomass in a living Fast Plant to estimate the amount of biomass in grams available in each fresh brussels sprout.

■ Designing and Conducting Independent Investigations

Designing and Conducting Your Investigation aims to provide an accessible entry point for students as they study the energetics of two model organisms. Together, these two organisms can provide a simple model of ecosystem energetics. This section is fairly explicit about procedure while not providing explicit descriptions of how to record or analyze the data that are collected. Likewise, the students are expected to make observations, to use resources to learn more about the organisms they are studying, and to ask questions while carrying out the procedures. With the tools/skills and questions developed in Procedures, the students are expected (singly or in groups) to carry out their own research or to develop a mathematical model of the energetics of these model organisms in Designing and Conducting Your Investigation.

Just as the students need to build their skills for this laboratory within a scaffold, you should consider that you may need to do the same. Thus, you may consider that you, too, are developing a skill set to help students to investigate their own questions. If you have never worked with these specific organisms, you might want to consider simplifying your first assignments. One suggestion is to limit the students to growing and maintaining these organisms through an entire life cycle while recording daily observations in a laboratory notebook. In this manner, you will learn valuable skills for managing the classroom environment for long-term work and will develop a familiarity with the organisms that is essential as you help students find their own questions. For the first year, you may not feel comfortable dedicating the time beyond becoming familiar with simply growing these organisms. As you develop an understanding for the organisms and how your own students interact with them, you can then proceed to more authentic research.

Help students ask the “right” question in the “right” way. A good question should be focused in such a way that the path to the answer is implicit within the question. The advantage of using live organisms cared for by students is that questions naturally arise. Resist the urge to answer students’ questions; rather, encourage your students to work out answers for themselves. Figure 5, a flow chart/concept map of the investigation, may aid you in helping your students focus on some ideas for research. Also consult the supplemental resources listed at the end of this investigation. There you will find many examples of research that answer ecological questions using these two organisms as models.

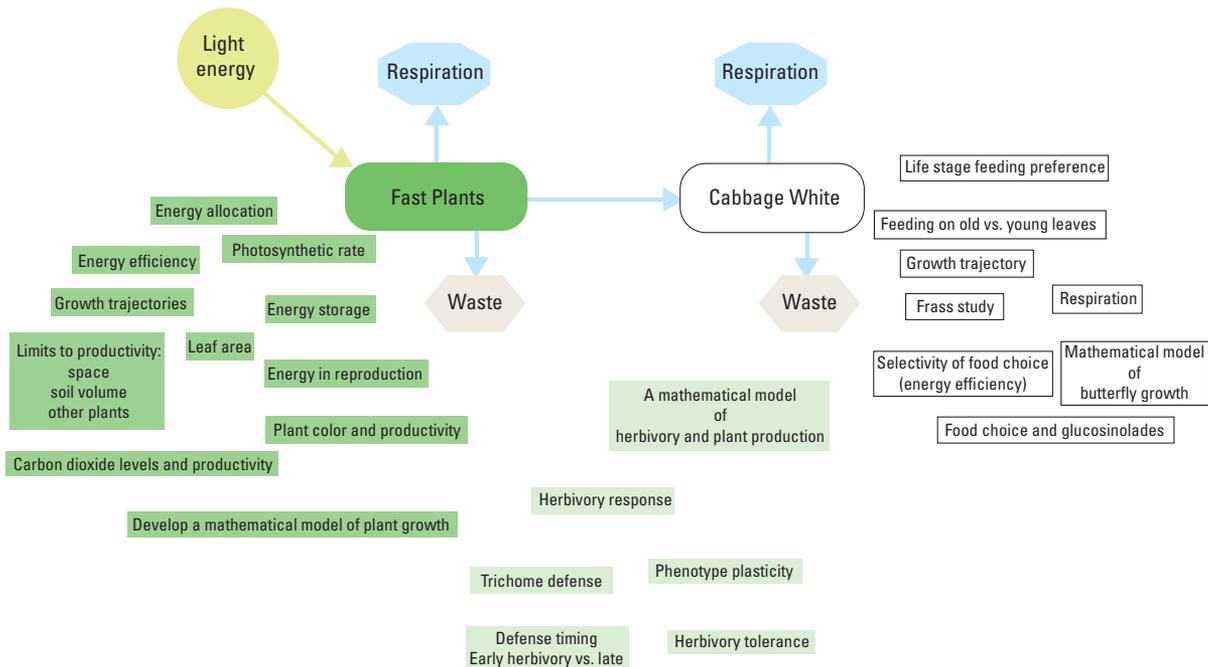


Figure 5. Ideas to Focus Questions

Ultimately, as you develop your own skills for managing and facilitating the research experience, you might decide to modify the investigation in the Student Manual or create your own version. You and your students will naturally arrive at workable procedures for monitoring energy or biomass in plants and animals. The Student Manual is set up only as an example to introduce skills. The ultimate goal is for you and your students to become a research team carrying out an authentic research experience.

The idea of developing mathematical models can be particularly challenging. The values for energy capture and transfer measured in Procedures can serve as a foundation for building a predictive, simple spreadsheet model in the final part of the investigation. The model could focus solely on plant growth or butterfly growth, or it could model the interaction between the two.

Summative Assessment

The scientific community communicates its work to peers, largely relying on three modes of formal communication: peer-reviewed papers published in journals, paper presentations, and poster sessions at professional society meetings. Emulating scientific posters and poster sessions is a particularly effective assessment technique for students' independent work. Posters foster creativity and economy of communication. In particular, the concept of a mini-poster, as described in the blog entry of the National Association of Biology Teachers (<http://www.nabt.org/blog/2010/05/04/mini-posters-authentic-peer-review-in-the-classroom/>), provides a useful, interactive assessment that takes place both during the session presentation and after the poster is reviewed and revised.



During a scientific poster presentation, the authors stand in front of their poster and answer questions from peers about their work. The task of the teacher is to design a situation in the classroom that re-creates the poster session environment.

Generally, it is ideal to split the class into two groups: one group presenting and the other group observing or reviewing the posters. The observers use a simple rubric to summarize their evaluation of the poster under review after asking the presenter a number of questions. With a number of observers reviewing several posters, each presenter receives diverse feedback about his or her work and presentation. This serves as a very effective peer review. Before a final grade for the lab work is assigned, the student is encouraged to revise his or her poster (mini-poster) based on feedback from the observers. The two groups then switch roles for the second half of the presentation time. The effectiveness and efficiency of the process are enhanced by appropriate time management by the teacher or by a student assigned to the task. The NABT blog entry includes information and links to information about contents of a simple rubric.

■ SUPPLEMENTAL RESOURCES

The first five resources provide students and teachers with examples of research that focuses specifically on the concepts and organisms in this laboratory. The hope is that students and teachers will find inspiration for their own work in these references. The final reference (Williams and Hill, 1986) is a paper that introduces the model organism suggested for this laboratory, the Wisconsin Fast Plant.

Agrawal, A. A., S. Y. Strauss, and M. J. Stout. Costs of induced responses and tolerance to herbivory in male and female fitness components of wild radish. *Evolution* 53, no. 4 (August 1999): 1093–1104.

Agren, Jon, and Douglas W. Schemske. The cost of defense against herbivores: an experimental study of trichome production in *brassica rapa*. *The American Naturalist* 141, no. 2 (February 1993): 338–350.

Marshall, Carolyn B., Germán Avila-Sakar, and Edward G. Reekie. Effects of nutrient and CO₂ availability on tolerance to herbivory in *brassica rapa*. *Plant Ecology* 196, no. 1 (May 2008): 1–13.

Orre, G. U. S., S. D. Wratten, M. Jonsson, and R. J. Hale. Effects of an herbivore-induced plant volatile on arthropods from three trophic levels in *brassic*as. *Biological Control* 53, no. 1 (April 2010): 62–67.

<http://dx.doi.org/10.1016/j.biocontrol.2009.10.010>.

Siemens, David H., Shannon H. Garner, Thomas Mitchell-Olds, and Ragan M. Callaway. Cost of defense in the context of plant competition: *brassica rapa* may grow and defend. *Ecology* 83, no. 2 (February 2002): 505–517.

Williams, Paul H., and Curtis B. Hill. Rapid-cycling populations of *brassica*. *Science* 232, no. 4756 (June 1986): 1385–1389.