INQUIRY & INVESTIGATION

Investigating Heat Exchange in Ecosystems with Bottle Biology

M. MEGAN WOLLER-SKAR, HEATHER SNYDER, CHRIS DOBSON

Abstract

Logistics often limit the number of field-based labs that include different types of ecosystems. Moreover, few lab classes allow students the opportunity to measure ecosystem-level changes. This article describes an activity appropriate for high school biology or introductory collegiate biology courses, where bottle biology can provide an opportunity for students to measure differences in temperature and humidity that result with different types of vegetation. This approach allows students to develop an understanding of how ecosystems transfer energy and cycle water, as well as the implications of land use change, such as timber harvest or grassland restoration, on regional climate.

Key Words: *latent heat; sensible heat; Earth energy budget; bottle biology; ecosystem ecology; land use change.*

○ Introduction

The *Next Generation Science Standards* (NGSS Lead States, 2013) call for moving students away from memorization and toward an understanding of core disciplinary ideas and science and engineering practices. One popular way to stimulate critical thinking, that often accompanies foundational understanding, is to supplement auditory learning (often presented through lectures) with active learning by way of field-based labs or experiments. Unfortunately, the logistics of travel often limit both the number of locations and the number of different types of ecosystems that can be included in field labs. To facilitate student understanding in the absence of accessible field sites, physical models can demonstrate ecosystem processes and how these processes change from one ecosystem type to another. Our activity addresses high school NGSS standards for life and earth sciences (HS-LS2 Ecosytems: Interactions, Energy, and Dynamics; and HS-ESS2 Earth's Systems) (NGSS Lead States, 2013). In addition to life and earth science disciplinary core ideas, various science and engineering practices (developing and using models; and using mathematics and computational thinking) and crosscutting concepts (energy and matter; and systems and system models) are addressed.

One commonly utilized physical model for ecosystems is a terrarium made with a plastic 2L bottle. The transformation of recycled soda bottles into miniature ecosystems was made popular, in part, by Paul Williams from the University of Wisconsin (www.bottlebiology.org). Ultimately *Bottle Biology*, a book by Mrill and Kelley (1993), outlined several experiments using these model ecosystems. In this activity, we used bottle biology to allow students to measure how different types of ecosystems transfer energy and cycle water.

○ Background

The Earth's energy budget is determined by both heat gain and loss. The Earth and its atmosphere receive shortwave radiation from the sun; some of this energy is reflected back into space, some is absorbed in the atmosphere, and some is transmitted to Earth's surface. Radiation absorbed by the Earth can then be released by processes including latent and sensible fluxes. Latent heat is the energy absorbed or released when a substance changes phase, for example, when a liquid freezes or evaporates, whereas sensible heat is the energy transferred by conduction and convection from warm surfaces to the overlying air. Both latent and sensible heat fluxes contribute to regional climate variation, in part, because they tend to vary with vegetation type. In general, areas with vegetation that support high rates of photosynthesis and evapotranspiration, and thus high latent heat flux, tend to have lower surface temperature and higher humidity. Although energy absorbed for photosynthesis includes

The Earth's energy budget is determined by both heat gain and loss.

The American Biology Teacher, Vol. 80, No 1, pages. 42–46, ISSN 0002-7685, electronic ISSN 1938-4211. DOI: https://doi.org/10.1525/abt.2018.80.1.42.

primarily red and blue light, as opposed to thermal energy, the energy lost with evaporation decreases temperature. Foley et al. (2003) demonstrated how conversion of tropical forest to pasture influenced this energy transfer and water cycling. The complex vegetation of tropical forests allowed energy to be absorbed for photosynthesis and heat to be reduced through transpiration, or latent heat (Foley et al., 2003). Moreover, high precipitation rates in the tropics provided forests with sufficient water to fuel photosynthesis; along with heat, some of this water was cycled back into the atmosphere with evapotranspiration, resulting in high humidity and the formation of cloud forests (Foley et al., 2003). As complex tropical forests were removed, the energy absorbed at the surface declined, decreasing latent heat and ultimately causing the surface to warm (Foley et al., 2003). Pasture not only supported less photosynthesis, its potential to cycle water was reduced. In other words, areas with vegetation that supported low rates of evapotranspiration often had higher surface temperature, lower humidity, and higher rates of sensible heat loss (Chapin et al., 2011). Because latent heat is related to transpiration, high humidity is correlated with high latent heat flux. Likewise sensible heat flux, the transfer of energy from the surface to overlying air, can be approximated with measurements of air temperature. Although these relationships exist, note that measurements of temperature provide only a snapshot or approximation, and not actual movements of energy over time.

Understanding latent and sensible heat exchange is integral to understanding the impact of land use change, such as clearing forests, on regional climate and water cycling. This lesson is most appropriate for students in high school biology, as well as for students taking introductory biology courses at the collegiate level. Prior to running this experiment, students should be familiar with the global energy budget, including latent and sensible heat. In addition, students should be presented with a demonstration on how to create and manipulate data in spreadsheet software, such as entering data, calculating a statistical mean and standard error (measure of central tendency that is corrected based on sample size), creating bar graphs, and adding standard error bars to graphs.

$$\text{standard error} = \text{standard deviation} / \text{square root of sample size}$$

○ Procedure

The purpose of this activity is to demonstrate the effect of vegetation on latent and sensible heat exchange using terraria that contain lush green plants, typical of temperate ecosystems, and arid plants. Similar to the tropical forests mentioned above, temperate ecosystems are characterized by high rates of primary production and evapotranspiration (Rosenzweig, 1968). Primary production is often a function of precipitation (Sala et al., 1988), with biomes such as temperate deciduous forests containing both high precipitation and high primary production, whereas more arid biomes such as the desert have low annual precipitation and rates of primary production. In both instances, the plants are adapted to the precipitation regimes and regulate water usage accordingly.

The specific objectives for this activity include:

1. Students will create model ecosystems in 2L bottles that contain either a temperate or arid plant.
2. Students will collect temperature and relative humidity from terraria once a week for one month.
3. Students will compile data and graph mean temperature and relative humidity from terraria with standard error bars.
4. Students will interpret results from terraria in the context of latent and sensible heat exchange and the overall energy budget.
5. Students will compare their terraria findings to temperature and humidity data collected from an off-site location with two types of vegetation, forested and open field (cleared forest).

This activity was designed using the 5E lesson planning format to support scientific inquiry (Bybee et al., 2006). Creation of terraria requires approximately 50 minutes, data collection each week thereafter requires approximately 15 minutes, graphing data requires approximately 2 hours, and interpretation requires approximately 50 minutes. The final portion of the exercise includes graphing and interpreting data from an off-site location, which requires an additional 50 minutes. Note that it is possible to add a control condition to this experiment, in which terraria are constructed without plants, to demonstrate to students how transpiration is involved in this experiment.

○ Materials & Resources Needed

Per every two students:

- clear 2L plastic soda bottle (label removed)
- razor blade
- plant: Half of student groups need a temperate plant and half need an arid one; we used *Coleus* for temperate and succulents for arid, but other plants that are large and small are appropriate too.
- rocks for drainage: 1–2 cm diameter, available at craft stores; cover the bottom of the bottle 3 cm thick, or ~2,800 cm^3
- potting soil: 3 cm thick from top of the rocks, ~2,800 cm^3
- beakers with 100 mL of water
- lamp (65 watt, 120 V bulb) and lamp stand: place terraria a minimum of 5 cm from bulb
- packing tape

○ Part 1: Using Terraria to Demonstrate the Effect of Vegetation on Latent and Sensible Heat

Over a one-month period, students build terraria in groups of two, collect data, produce figures, and interpret results to compare the two model systems.

Engage

We begin by introducing students to the Earth's energy budget, or how the Earth exchanges energy with the atmosphere. We ask students what happens to incoming solar radiation once it hits the atmosphere, and ultimately what happens after a portion of that radiation is absorbed by the Earth. Most students are aware that incoming radiation might be reflected, transmitted, or absorbed, and simply require an introduction to the terminology. After these are covered, the discussion falls off considerably. As a result, we ask students what would happen to the Earth if it absorbed more solar radiation day after day, at which point they eagerly respond that it would become hotter and hotter with time. How might the Earth cool, or release some of that heat, we ask. We remind students of how the process of evaporation requires energy, and almost instantly they remember that water evaporates from the surface of the Earth, and thus results in cooling. Similarly, we describe how conduction, or direct contact between two objects can result in heat transfer. Students remember how heat is transferred from objects such as humans to furniture, for example. But what about a solid and gas, as in the surface of the Earth and the overlying atmosphere, we ask.

As students make these connections between evaporation and conduction, we add another layer of information: What if we change the ecosystem? How do these two processes of energy exchange vary between a tropical forest and a desert? Where would you expect the highest evaporation, or surface warming? Students tend to have lots of ideas at this point, bringing up everything from the existence of surface water and soil/vegetation color to evapotranspiration. There are some major differences between and amongst biomes, but what about changes in vegetation at one location? How might that influence energy exchange? We begin making a list on the board, with input from students, comparing evapotranspiration and energy exchange via conduction in an area with complex vegetation (typical of a forest), and a cleared area (typical of an open field). Although most students have learned about evaporative cooling and conduction prior to this exercise, the phrases "latent heat" and "sensible heat" are often new. At this time, we summarize the energy budget for the Earth, with an emphasis on evaporative cooling and conduction, and present latent and sensible heat exchange.

Explore

During a 50-minute period, students are presented with all the necessary materials listed above and tasked with building terraria in groups of two. Students start by cutting off the bottom of a clear plastic 2L bottle using a razor blade, 110 mm from the bottom of the bottle. Note that asking students to use razor blades can present a safety issue; if concerns exist, bottles can be prepared in this manor prior to the exercise. Students add 30 cm of rocks approximately 1-2 cm in diameter, then 30 cm of potting soil on top. Half of the students plant "temperate vegetation" sized to fill the top portion of the bottle without actually touching it. The other half of the students plant "arid vegetation"; these plants were succulents and considerably smaller in size. As students plant vegetation, we remind them that everything going into the terraria is the same, besides the two types of vegetation. Before students place the top portion of the terrarium in place using packing tape, they add 100 mL of water at the base of the plant. Next, students make three cuts near the top of the bottle (again, if safety is a concern, these cuts can be made prior to the activity) to create a flap that could accommodate a handheld temperature and humidity meter. (We use a Kestrel 3000 pocket weather meter, available at Amazon.com for $150; if other options exist for measuring temperature and humidity in an object this size, they are appropriate). This opening is covered with packing tape to minimize water escape (Figure 1). Finally, students record baseline data of temperature and humidity, and place terraria under lights, taking care to not place them less than 5 cm from bulbs.

After the terraria are constructed, we remind the students that we will be collecting temperature and relative humidity from the terraria for the next month, and ask what trends they expect, if any, in the data. Students groups are then asked to write down specific hypotheses based on temperature and humidity, as well as latent and sensible heat for terraria with temperate vegetation, as well as for arid vegetation.

Moving forward, student groups are charged with collecting both temperature and relative humidity at the beginning of every class period using the Kestrel 3000. The Kestrel is inserted into the terrarium through the flap toward the top of the bottle. Students from both groups record their data in a shared online spreadsheet. Throughout data collection, students are asked to review the results from both groups. This provides an opportunity for students to consider variation among terraria with similar vegetation.

Explain

At the end of the sampling period, students will have measured each terrarium five times. In the our class (6 temperate terraria, 6 arid terraria), this provided 30 measures of temperature and 30 measures of relative humidity, for a total of 60 values, per ecosystem type, or 120 values total. Using the class data, each student graphed mean temperature and mean relative humidity and associated standard errors per vegetation type (Figure 2) for the terraria.

A series of questions were assigned in conjunction with the graph assignment, which challenged the students to interpret their results and draw conclusions. Working with their partners, students were asked to summarize the findings by interpreting figures, then decide if their hypothesis was supported by the data. Next, students were asked to share some of their interpretations with the entire class. These ranged from statements like, "Temperature was hotter in my (arid plant) terrarium" and "You could see all the water on the inside of the terrarium (temperate plant), so it makes sense that humidity would be high" to "It's a good thing we put all our temperate plants together because ours had weird numbers." Their statements allow for a discussion of temperature with vegetation change and sensible heat flux, humidity with vegetation change and latent heat flux, as well as experimental design, including how more terraria in the exercise could help address variation in both temperate and arid vegetation.

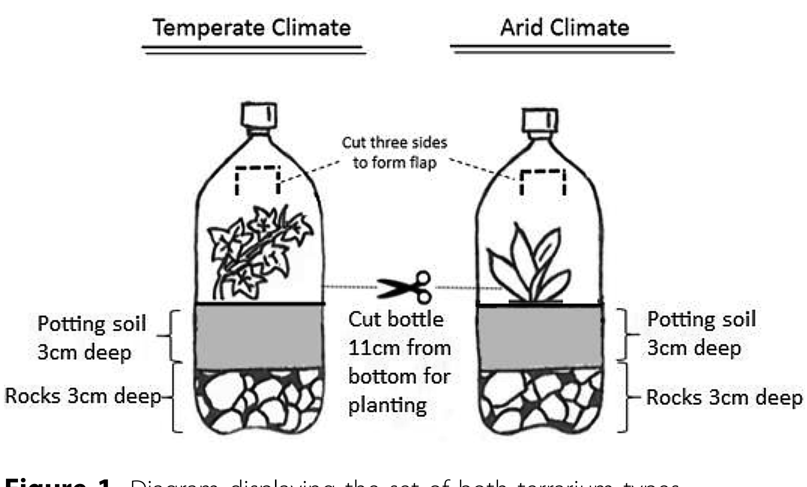

Figure 1. Diagram displaying the set of both terrarium types.

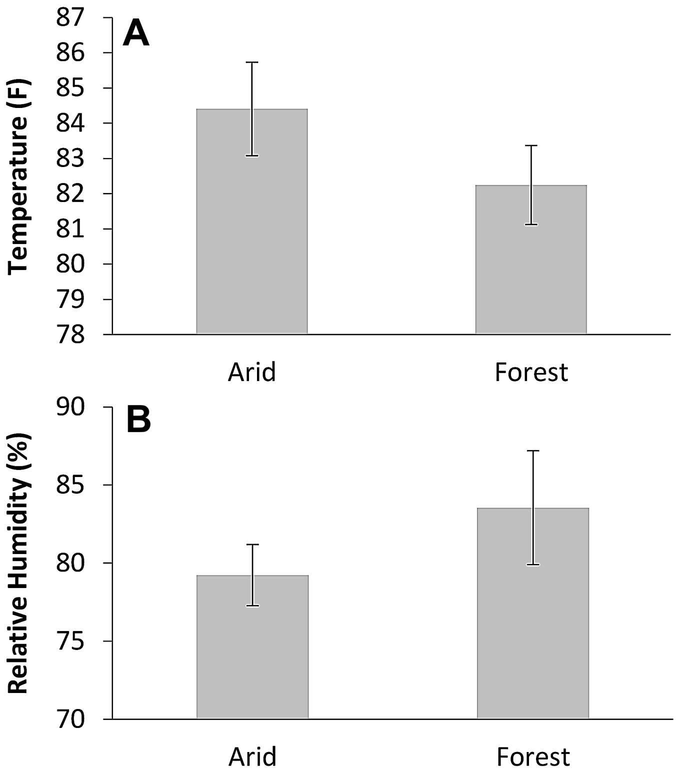

Figure 2. Mean temperature **(A)** and relative humidity **(B)** collected from terraria containing either arid or temperate vegetation. Bars indicate standard error.

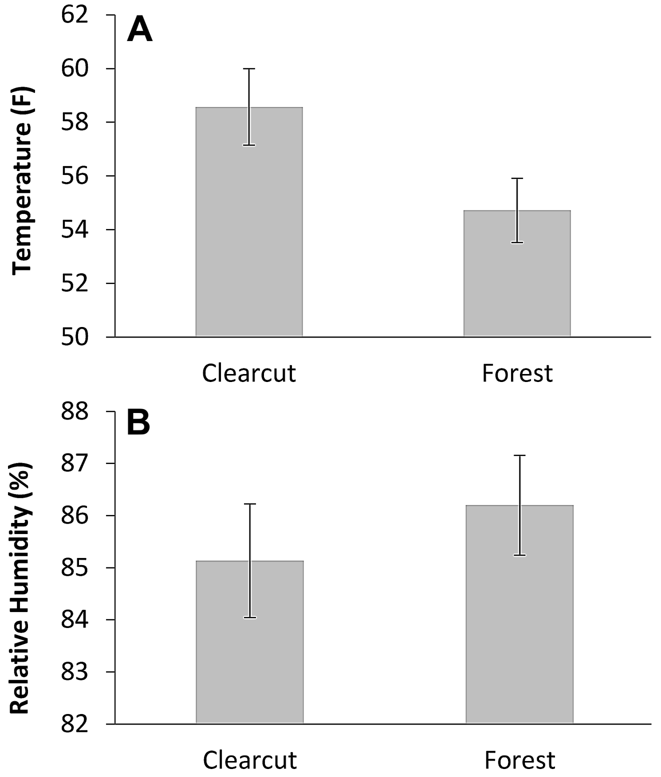

Figure 3. Mean temperature **(A)** and relative humidity **(B)** collected from a clear-cut forest plot and adjacent intact deciduous forest at the Howard Christensen Nature Area (Kent Co., MI). Bars indicate standard error.

○ Part II: Real Life Application

To begin, we ask students if they were surprised that their terraria cycled energy and water differently based on plant type. Their responses are typically mixed, and include thoughts such as, "I was surprised that it didn't take very much time for the two to have different temperatures" or "It does seem weird that it only takes one plant, that we can see it in a bottle." At this time, we ask students if they think they'd see similar results in a natural system. We then share with them temperature and humidity data collected at the Howard Christensen Nature Center (HCNC, Kent Co., MI). Specifically, we present data collected from adjacent habitat patches (with data loggers located approximately 80 meters apart), one in an area that is forested, and one in an area where the forest was cleared. If such data are not available, students can collect additional data using the same handheld instruments at nearby sites with variable vegetation type. This can include areas such as a forest and a parking lot, or an open field.

Elaborate

We asked students to formulate hypotheses related to potential differences in temperature and humidity at the two areas in HCNC. Students were then asked to graph mean values of temperature and relative humidity with standard error from these areas (Figure 3).

Evaluate

After students complete their two graphs for HCNC, we ask them to interpret the figures and address their original hypotheses. We ask them questions such as: Where was temperature/humidity greater? Were the standard error bars similar in both areas? And finally, Should they accept or reject their hypotheses? At this time, we ask students to review their terraria figures and compare them to those generated using data collected at the HCNC. Results from both the terraria and natural environments are very similar, with humidity/latent heat higher with more complex vegetation, and temperature/sensible heat higher with less complex vegetation. Finally, we talk with the class about the possible implications of land use change on regional climate. For example, we ask them to think about latent and sensible heat exchange in a tropical forest and a tropical forest cleared for agriculture, in a grassland and one cleared for development, or in a field and one replanted with trees.

Students individually submit four graphs (two for terraria and two for HCNC) along with a worksheet with questions asking them to formulate hypotheses, summarize results, interpret graphs, and determine if hypotheses were supported or should be rejected. Worksheet questions also link measurements of humidity and temperature to latent and sensible heat exchange. Along with submitted materials, class discussions allow us to determine student understanding of the impact of vegetation on latent and sensible heat exchange.

○ Conclusion

Energy exchange between the Earth and atmosphere influence every biome on Earth. Trying to explain how this exchange happens and why it varies can be challenging. Despite the imperative nature of these concepts, students often struggle with applying energy flux to resource management. This lab allows students to make side-by-side comparisons with changing vegetation types. After conducting this activity, student understanding of latent and sensible heat fluxes improved considerably. This is evident based on the ability of students to hypothesize how clearing a forest might influence temperature and humidity, using the terms "latent heat" and "sensible heat," at the Howard Christensen Nature Center. In addition, student performance and clarity on essay exams that ask them to explain the Earth's energy budget in different ecosystems have improved following this exercise.

We have conducted this experiment three times with 24 students and 12 terraria each time (for a total of 84 students and 36 terraria). Our results were always very similar to those presented herein. Note that the differences between vegetation types is rather small (mean temperature variation of approximately 2°F, mean relative humidity of approximately 4%). As a result, it is very important that 2L bottles be the same color and placed equidistant from light sources that are the same strength. It is also very important that each terrarium port, used for temperature and relative humidity data collection, be completely covered with packing tape to decrease the loss of water.

○ Acknowledgments

We thank Mel Northup, Grand Valley State University, for sharing data collected from the Howard Christensen Nature Center. We also thank Diane Laughlin, Grand Valley State University, for help with the original terrarium design.

References

Bybee, R. W., Taylor, J. A., Gardner, A., Van Scotter, P., Carlson Powell, J., Westbrook, A., & Landes, N. (2006). *The BSCS 5E Instructional Model: Origins and Effectiveness*. Colorado Springs, CO: BSCS.

Chapin III, F. S., Matson, P. A., & Vitousek, P. M. (2011). *Principles of Terrestrial Ecosystem Ecology*. New York: Springer Science and Business Media.

Foley, J. A., Costa, J. H., Delire, C., Ramankutty, N., & Snyder, P. (2003). Green Surprise? How terrestrial ecosystems could affect Earth's climate. *Frontiers in Ecology and the Environment*, *1*(1), 38–44.

Mrill, I., & Kelley, A. (1993). *Bottle Biology: An Idea Book for Exploring the World Through Plastic Bottles and Other Recyclable Materials*. Dubuque, IA: Kendall/ Hunt Publishing Company.

NGSS Lead States. 2013. *Next Generation Science Standards: For states, by states*. Washington, DC: National Academies Press. www.nextgenscience.org/next-generation-science-standards

Rosenzweig, M. L. (1968). Net primary productivity of terrestrial environments: Predictions from climatological data. *American Naturalist*, *102*, 67–84.

Sala, O. E., Parton, W. J., Joyce, L. A., & Laurenroth, W. K. (1988). Primary production of the central grassland regions of the United States. *Ecology*, *69*, 40–45.

M. MEGAN WOLLER-SKAR (correspondence author; wollerm@gvsu.edu) and CHRIS DOBSON are at the Department of Biology, Grand Valley State University, 1 Campus Drive, Allendale, Michigan 49401, USA. HEATHER SNYDER is in the Department of Biology, Washburn University, 1700 SW College Avenue, Topeka, Kansas 66621, USA.