ONLINE HOW-TO-DO-IT

Building Twilight "Light Sensors"

To Study the Effects of Light Pollution on Fireflies

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Lighthouses and illuminated skyscrapers attract migrating birds, thousands of which crash into them and die. Night active insects accumulate around lights on bridges, sometimes piling knee-deep under them. Street lights disorient sea turtle hatchlings en route to the sea as well as females seeking egg-laying sites. And fireflies, their mating signals drowned in showers of photons from a variety of human sources, disappear from the landscape. These are just a few examples of some of the effects of "light pollution." Light pollution is currently defined as unnecessary artificial light from manmade sources such as illuminated billboards, factories, residential porch lights, and street lights, negatively affecting nocturnal organisms. Stray light not only wastes energy but creates problems for astronomical observations, can interfere with natural cycles and rhythms as well as the growth and development of animals and plants, and even affect human health (Mizon, 2002; Rich & Longcore, 2006).

Though light pollution is detrimental to many people and organisms around the world, it usually receives much less attention than other forms of pollution, and is rarely recognized as a problem. Fortunately, many international organizations, conservationists, and biologists are becoming aware of some of the potential effects light pollution can have on living systems. Nocturnal animals known to be adversely affected by stray artificial night-lighting include mammals, birds, reptiles, amphibians, fish, and arthropods. This last group includes perhaps one of the most admired and charismatic nocturnal insects, the firefly (Rich & Longcore, 2006).

Fireflies are beetles that can produce and emit their own light through a chemical reaction called bioluminescence. This chemistry combines the enzyme luciferase and a substrate called luciferin, along with ATP (adenosine triphosphate) and oxygen. The ON and OFF of a firefly's flash is ultimately controlled through the availability of oxygen at the source of the chemical reaction, i.e., the firefly light organ (Trimmer et al., 2001). The flash patterns of adult fireflies are species specific and are used for sexual communication; that is, as mating signals for males and females of the same species to recognize and locate each other. Most North American fireflies producing flash patterns in flight are males; females generally perch on grass or other vegetation below the male activity space and do not flash until they see an appropriate male flash pattern, which they then answer in their species specific manner (McDermott, 1917; Lloyd, 1966; Branham & Greenfield, 1996). A brief flash dialog follows the initial flash exchange. When a male is able to locate and reach a perched female, the male mounts the female and they mate.

In addition to emitting specific light signals, each species has a characteristic nightly window of activity. For some species, this begins at early twilight, even before sunset in deeply-shaded sites. Some twilight species use ambient light levels as cues to begin flash activity. In sites with intrusive artificial light, such as from the above-mentioned sources, flash communication may be disrupted. Increasing levels of intrusive light into an increasing number of natural areas has caused many firefly researchers to consider light pollution as a contributor to declining firefly populations worldwide (Branham, 1998; Lloyd, 2006; Scagell, 2004; Spence, 1997; Tyrrell, 2003). We address the lack of experimental evidence documenting the actual impact of light pollution on fireflies in the study we describe while presenting a relatively simple way for students to experience and gather useful data in this developing area of ecology.

Studying the effects of light pollution on firefly behavior can help students form a better understanding of biodiversity and an appreciation of the need for its conservation. In this article, we explain how to construct simple and inexpensive electronic light sensors to measure ambient light intensity in

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an area along a 27 meter transect. With such a homemade instrument, students can learn the basics of building an electrical circuit as well as conducting field experiments designed to demonstrate the effects of artificial light on firefly behavior.

Constructing Light Sensors

Materials (for nine sensors, for a 27 m transect)

- several packages of assorted photocells (available at RadioShack®)
- 4-conductor, 26-gauge stranded flat modular line cord with color-coded wires (two rolls of 30 m line cord) (available at www.outpost.com, Item no. 1544831)
- plastic electrical tape
- nine ping pong balls
- PVC pipe, 3/4" diameter (nine pieces, ~25 cm long)
- soldering irons and solder
- wire stripper/cutters
- epoxy for plastic
- silicone
- 6" nails (nine total) with heads removed
- permanent marker
- small zip-ties
- ohmmeter (e.g., voltohmmeter)

Construction Procedure

1. Each pack of photocells contains a combination of various types and sizes. Select nine plus "identical" loop photocells (the most effective for measuring low intensity light) by counting the number of yellow loops on the photocell surfaces and measuring their resistance (ohms) with an ohmmeter. Select the nine photocells that produce the closest values under the same light condition.
2. Make a hole the same size as a photocell through the label on all nine ping pong balls. Position the hole through the text (ink lettering on each ball) to free the rest of the ball of any markings that might interfere with the even diffusion of light to the photocells. Epoxy the photocells into the holes in the balls; avoid getting epoxy on the sensor surface of the photocell.
3. Cut the 4-conductor, 26-gauge stranded flat modular line cord (hereafter referred to as "cable") into three pieces of 27.30, 18.30, and 9.30 m long, and set these aside for later use.
4. Remove the covering (sheathing) from the remaining cable to expose the four colored wires within, and cut these into 18 pieces, each 30 cm long. Strip ~2 cm from both ends of each of the 30 cm colored wire pieces with a wire stripper.
5. Insert two of these into two small holes drilled 5 cm from one end of each of the nine pieces of PVC pipe, pushing the wires into the holes and through the pipes until they are exposed at the other end. It is not necessary to color code these 30 cm wire pieces because the photocells are not polarized.
6. Solder each end of the two colored wires inside the PVC pipe to a different wire of the photocells previously epoxyed into the balls and cover each of these connections with electrical tape (Figure 1).
7. Epoxy each ball onto the end of its PVC pipe with the photocells centered over the PVC opening. After the epoxy has cured, measure the resistance of the

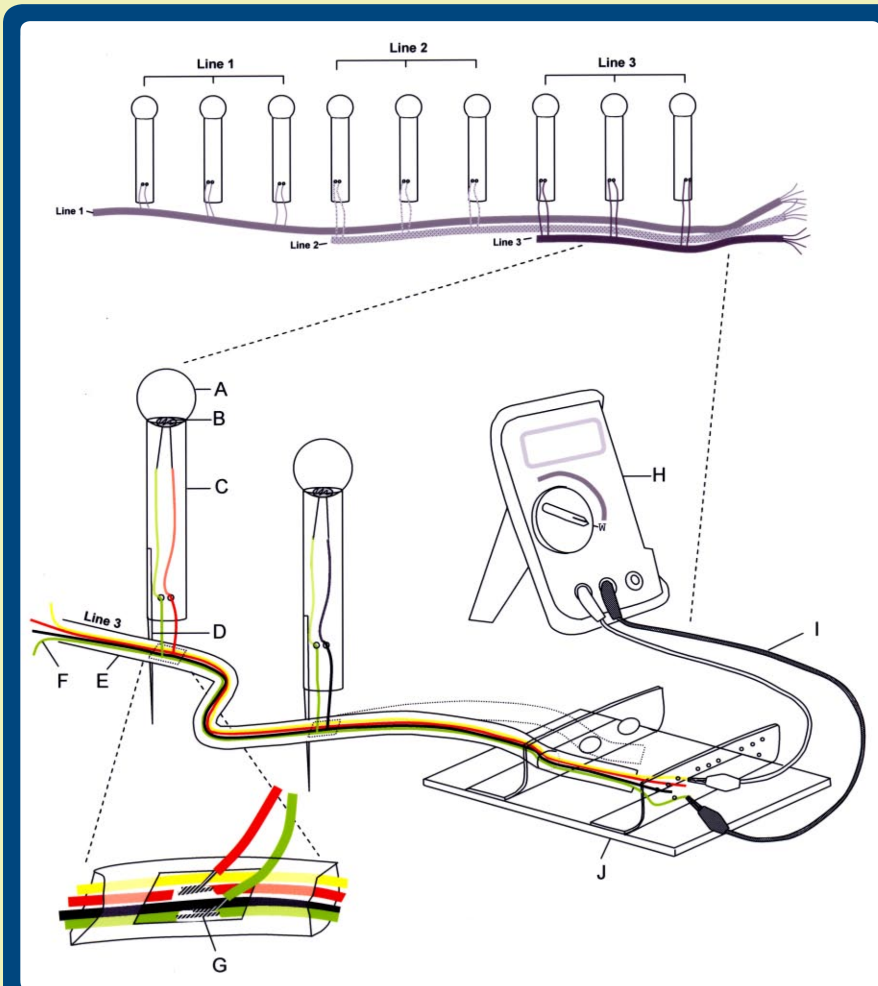


Figure 1. The design and setup of a nine light sensor transect built from three sections of 4-conductor cord: A. ping-pong ball, B. photocell, C. PVC-pipe section, D. large nail with head removed, E. 4-conductor, 26 gauge cord, F. coded, colored internal wire, G. soldered connection between 4-conductor cord and a removed section of colored internal wire, H. voltmeter, I. voltmeter leads, J. Plexiglas (or cardboard) plate to organize and separate the ends of the internal wires for measurements taken via voltmeter.

photocells again from the wires protruding at the ends of the PVC to verify electrical connections.

Connecting the Light Sensors

When connecting the light sensors to the wires in the three cables, assign one wire (for example, green) as the common (ground) line and use the others (black, yellow, and red) to individualize the three light sensors of each set. The different lengths of cables will eventually be zip-tied together into one long, composite cable. Thus, with the connections described, the resistance of each sensor can be read from the terminal end of the composite cable (Figure 1).

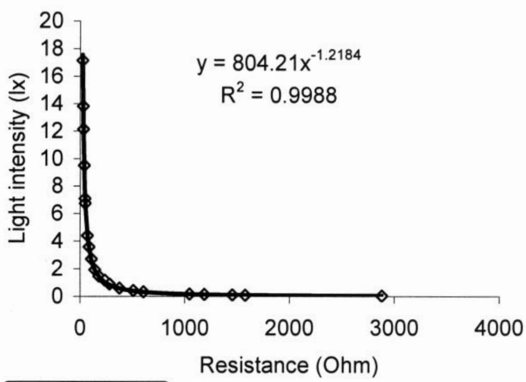
8. Mark the three cables with permanent marker at 3 m intervals to indicate positions for the light sensors. The described connections are made for the sensors of all three cables, but note that the three sensors of each cable are connected (beginning) at different distances from the monitoring position (the position where the ohmmeter will be used to measure the amount of "resistance" from each photocell (level of electrical resistance = level of light) (Figure 1).
9. To connect a light sensor to the wires in each cable, remove a 1" long section of the protective sheathing, exposing the colored wires within. Use the soldering iron to melt ("strip") the colored insulation from two of the inner colored wires until ~2 cm of copper wire is exposed (the green wire for the common line, and a different color (red, black, or yellow) for each of the three photocells in each set (Figure 1).
10. Solder the two colored wires connected to the light sensors to the exposed copper wires in the cable. It is easier to solder these small wires when they are separated from the other wires by a small piece of paper.
11. With the ohmmeter, check that the light sensor is still functional. Carefully mark the color of the wire used on each light sensor's PVC post; remember, it will be used at the measuring terminal (ohmmeter) to identify the source (transect position) of light-level data.
12. Patch the hole in the cable sheathing with silicone, allow it to harden, and wrap the section with electrical tape. After sensors have been connected to all three cables, carefully arrange the three cables as shown in Figure 1, and fasten them together with plastic zip-ties.
13. Epoxy a nail inside each PVC pipe to serve as a post that can be pushed into the ground to position each sensor along the transect.
14. Arrange and affix the ends of the colored wires through a piece of Plexiglas, cardboard, or wood. Be sure to separate each common (green) wire from the other three colored wires in its set in a way that makes each wire easy to identify and access while working in low-light conditions (Figure 1). To take measurements from each individual sensor with the ohmmeter, connect the ends of the coded sensor wires via alligator clips to the meter and read the resistance on the meter.

Calibrating Detectors

At this point, you have constructed a simple instrument with which to measure light intensity at 3 m intervals along 27 m of transect. Though the individual light sensors change their resistance in response to changing light conditions, the sensitivity of each individual sensor is different and must be calibrated. Also, because the standard unit used to quantify light intensity is the lux, the light measured by each ball-unit must be calibrated and converted. Your homemade equipment can be standardized for measurements in "lux" by using a commercial photographic light meter.

Place each light sensor in a dark room with an adjustable light source. Measure the ambient light using both the handmade light sensor and the commercial light sensor at each level of light (from darkness to brightness) and record (Figure 2). Enter the data into a Microsoft Office Excel© spreadsheet and create a curve with a trend line and equation. The nine sensors will each have different equations.

Resistance	Light
23.09	17.14
27.68	13.80
30.76	12.12
37.47	9.51
47.00	7.10
49.80	6.75
70.20	4.40
84.50	3.57
106.90	2.71
141.50	1.93
179.80	1.46
235.00	1.16
282.10	0.89
375.00	0.61
509.00	0.43
603.00	0.34
1046.00	0.17
1185.00	0.16
1455.00	0.11
1576.00	0.10
2880.00	0.04



Equation

$$Y = 804.21\, X^{-1.2184}$$

X = Values from light censors
Y = Calculated light intensity in field

Figure 2. Using a Microsoft Office Excel© spreadsheet to calibrate each sensor across a range of light intensities for use in converting measurements of resistance (ohms) to units of light intensity (lux). To calibrate each sensor and to convert measurement of resistance to intensity, resistance data (x-axis) is plotted against light intensity recorded with a light meter in Excel© to generate an equation that can be used (for that sensor only) to convert ohms to lux.

To get the light intensity value (in lux), input the resistance value from a specific light sensor reading in ohms into the specific equation for that light sensor. The Excel program makes it easy to add and copy data into the function (equation) in cells. The correct calibration requires that the values entered into the equation be of the same unit; because many meters change readout units (e.g., ohms, megaohms) automatically, you must make certain that all measures of resistance are in the same unit (i.e., the decimal points are in the correct position).

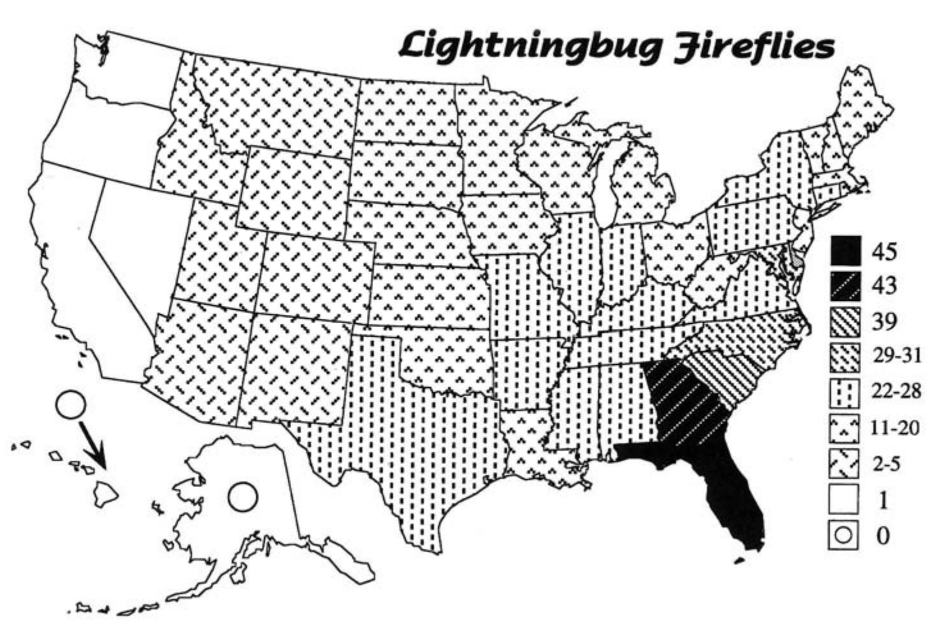


Figure 3. The distribution of firefly species across the United States that produce "flashed signals." The numbers in the figure legend indicate number of flashing species known to occur in each state.

Using Light Sensors in Field Experiments

There are approximately 2,000 described species of fireflies worldwide and more than 180 are known to occur in North America (Lloyd, 2002, 2003), where they are distributed from coast to coast. While some fireflies only glow and others use pheromones for sexual communication, there are at least 130 flashing species and these are almost exclusively restricted to the eastern United States (Figure 3). While flashing species can be found from spring through early fall, the highest numbers of fireflies generally occur in early summer.

The firefly *Photinus collustrans* has been more thoroughly studied than most firefly species, and information has been collected on its behavior, habitat, seasonal abundance, and natural history (Lloyd, 1966, 2000; Adams, 1981; Wing, 1984, 1988, 1989). This species is distributed over areas of low grass in Florida and southern Georgia. Because this species inhabits open grassland habitats, its signaling behavior is easier to quantify than that of species found in woodlands flying over shrubs and trees. *Photinus collustrans* has a signal system (males fly/flash; females perch/answer) similar to that of *Photinus pyralis,* another more widespread flashing species found across much of the eastern U.S. (Lloyd, 1966). Our experience studying light pollution in *P. collustrans* can serve as a model system for studying the effects of light pollution in *P. pyralis* and other species employing the same type of signal system.

This species simple flash/answer mating system is well-suited for field study. It occurs in open grassy-areas—open fields and residential/rural yards—suitable for setting out a transect of light sensors and an artificial light source. Open areas are also generally free from shadow-casting features such as trees and bushes, which make the analysis of intrusive light more difficult. Because males fly near the ground, observations of both population density and behavior are simplified. In addition, it is not difficult to experiment with the effect of intrusive light on the signaling behavior through the use of artificial females.

This field experiment can be divided into two nights, one for the "dark experiment" (without light source) and the other for the "lighted experiment" (with a light source), to compare and determine the effect of artificial lighting on the same population in the same habitat. To provide useful sample sizes, there should be at least 20 active male fireflies present each evening. Before dark, arrange the sensors in a straight line through the middle of the study site (Figure 4). The source of light pollution can be a bare 60-watt incandescent bulb attached to a tripod approximately 3 m off the ground, simulating a porch light. Positioning this artificial light source at the end of the light sensor transect (at the measurement site) facilitates reading and recording the resistance from each sensor.

Experiment 1: Are Fireflies Deterred by the Presence of Artificial Light?

To determine what levels of artificial light, if any, deter male fireflies, students will count the number of flashing males that fly across each section between light sensors per minute (i.e., a section = the 3 m distance between sensors) during the activity period. Students also record the light level across the study area, or the transect of sensors. Students should randomly record one measurement for each of the nine light sensors within one 15-second round, before starting a new count. The length of this experiment is never longer than the active period of the species being studied, but experiments can be shortened if necessary. For example, *P. collustrans* is active for an unusually short time, approximately 18 minutes, so experiments will need to be done over multiple nights to acquire enough data for this species.

Students usually find that trends in data are easier to discover and understand when the data are shown graphically. Collected data can be analyzed by creating a graph of section number (x) versus average light intensity (y) and then including the average number of flashes in each section (z). In our study, we found that the presence of artificial light negatively affects male behavior as compared with the absence of artificial light (i.e., a dark night as a control).

Figure 4. How the nine-light sensor transect is set up at the study site. (Photograph taken at a position near the Plexiglas plate end of the transect.)

Experiment 2: Do Males Have More Difficulty Finding Females in Regions of Artificial Light?

A light bulb placed in the study site not only allows experimentation with the influence of intrusive light on male search, it also provides an opportunity to experiment with the interference of such "noise" on the courtship signaling between the sexes. This can be done simultaneously with the first experiment. To determine whether males have difficulty locating female lights in the presence of artificial light, the best experimental decoys are small light-emitting diodes (LEDs). LEDs require little voltage, are small, and are simple to use. The ideal experiment would be for the decoys to flash properly-timed answers to passing males. Students could flash such responses with a push-button control from a short distance away, where they would not interfere with male flight. Flash-timing should be fixed:

- for *P. collustrans*—a half-second flash immediately after a passing male flashes
- for *P. pyralis*—a half-second flash delayed two to three seconds after a passing male flashes.

One student with three buttons could perhaps keep track of each section of a transect.

There is a better but not so dramatic method. To avoid introducing student behavior, variability, and error into the test, instead of using flashed answers to passing males, use decoys that simply glow. This simulates the glowing that sometimes occurs in mate-ready females. Passing males seeing such glows often fly closer and flash their pattern. Vary decoy glow intensity with a small variable resistor placed in series with the LED and battery. First adjust LED intensity to a desired level by eye, and then equalize the decoys and quantify the intensity by connecting an ammeter in series with the LED.

Figure 5. Photo showing the 60 cm x 60 cm box constructed around an artificial female positioned between two light sensors. The small point-source of light appearing in the middle of the four bamboo stakes is the artificial female.

Place a calibrated decoy in three sections of the transect. To score male ability to detect decoys against illuminated backgrounds, note male flight behavior. There may be different levels of response by males, with some merely swerving slightly in flight to others closely approaching and hovering. An unobtrusive ring of slender bamboo gardening sticks around the decoy provides a hemisphere of space centered on the decoy and is useful when quantifying male response level (Figure 5). The number of attracted males, response level, and time of occurrence can be recorded. Comparison of data from the three sections indicates the impact of intrusive light on firefly sexual communication. Our data with *P. collustrans* indicate that artificial females in areas containing high levels of artificial light do not attract males at the frequency that they do in low artificial light conditions.

Conclusion

Today, environmental pollution, decreasing biodiversity, and conservation are increasingly important global issues (Gayford, 2000; Linklater, 2004). Science education strives to help students see how these issues are interrelated, how extensive the problems are, and what role they themselves play in the "big picture." If this introduction to conservation issues and the biodiversity crisis is successful, students gain a perspective into why these problems happen, and what they can do to help conserve biodiversity at a level as small and as visible as the fireflies in their backyard. Teachers can begin by providing examples of how animal behavior is affected by light pollution (see Rich & Longcore, 2006 and the Web sites provided) as well as asking students to contribute their ideas. Students then learn the basics of electronics by building simple, inexpensive equipment with which to test their hypotheses about how animal behavior is affected by light pollution in particular, or how behavior is affected by light in general. As a conclusion to the experiments, the class can discuss what to do to reduce light pollution, such as:

- Limit the use of external lights at night, and use dimmer rather than brighter lights.
- Use fixtures that direct the light downward where it is unlikely to illuminate large areas of the environment.
- Use low-pressure sodium light sources instead of broad-spectrum bulbs outdoors when possible.

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Web site Resources

http://www.darksky.org/. This site has many links to sources of background information as well as information on the effects of and solutions to light pollution. This is a very good source of pictures.

Light Effects on Wildlife References. From Ecological Consequences of Artificial Night Lighting Conference. February 23-24, 2002. http://fwie.fw.vt.edu/jlw/light.htm. This site summarizes research on the effects of light on wildlife.

Tolea, A. (2000). Light comes from lighting. Light Pollution and us all. http://www.pha.jhu.edu/~atolea/second/page1.html. This site provides a brief background of light pollution and solutions with clear pictures of good and bad fixtures.

http://iris.biosci.ohio-state.edu/projects/FFiles/index.html. This site provides a general introduction into firefly biology, behavioral ecology and natural history. The information provided covers both adult and larval fireflies.

References

Adams, G. (1981). Search paths of fireflies in two dimensions. *Florida Entomologist, 64*(1), 66-73.

Branham, M.A. & Greenfield, M.D. (1996). Flashing males win mate success. *Nature, 381*, 745-746.

Branham, M.A. (1998). The Firefly Files. Available online at: http://iris.biosci.ohiostate.edu/projects/FFiles/frfun.html

Gayford, C. (2000). Biodiversity education: A teacher's perspective. *Environmental Education Research, 6*(4), 347-361.

Linklater, W.L. (2004). Wanted for conservation research: Behavioral ecologists with a broader perspective. *Bioscience, 54*(4), 352-360.

Lloyd, J.E. (1966). Studies on the flash communication system in *Photinus* fireflies. *Miscellaneous Publications Museum of Zoology, University of Michigan,* (130), 1-95.

Lloyd, J.E. (2000). On research and entomological education IV: Quantifying mate search in a perfect insect – seeking true facts and insight. *Florida Entomologist, 83*(3), 211-228.

Lloyd, J.E. (2002). Lampyridae. In R.H. Arnett, Jr., M.C. Thomas, P.E. Skelly & J.H. Frank (Editors), *American Beetles, Vol.* 2 (pp. 187-196). NY: CRC Press.

Lloyd, J.E. (2003). On research and entomological education VI: Firefly species and lists, old and now. *Florida Entomologist, 86*(2), 99-113.

Lloyd, J.E. (2006). Stray light, fireflies, and fireflyers. In C. Rich & T. Longcore (Editors), *Ecological Consequences of Artificial Night Lighting* (pp. 345-364). Washington, DC: Island Press.

McDermott, F.A. (1917). Observations on the light emission of American Lampyridae. The photogenic function as a mating adaptation. Fifth Paper. *Canadian Entomologist, 49*, 53-61.

Mizon, B. (2002). *Light Pollution: Responses and Remedies.* Singapore: Springer-Verlag London.

Rich, C. & Longcore, T. (2006). *Ecological Consequences of Artificial Night Lighting.* Washington, DC: Island Press.

Scagell, R. (2004). *The UK Glow worm Survey Home Page.* Available online at: http://website.lineone.net/~galaxypix/

Spence, C. (1997). *Get Back To Nature To Chase Fireflies.* Available online at: http://website.lineone.net/~galaxypix/lloyd .html

Trimmer, B.A., Aprille, J.R., Dudzinski, D.M., Lagace, C.J., Lewis, S.M., Michel, T., Qazi, S. & Zayas, R.M. (2001). Nitric oxide and the control of firefly flashing. *Science, 292*(5526), 2486-2488.

Tyrrell, M. (2003). Fireflies light up state: Nature's tiny light show is a few weeks late after rainy spring. *The News Journal.* Available online at: http://www.delawareonline.com/newsjournal/local/2003/07/18fireflieslightu.html

Wing, S.R. (1984). Female monogamy and male competition in *Photinus collustrans* (Coleoptera: Lampyridae). *Psyche, 91*(1-2), 153-160.

Wing, S.R. (1988). Cost of mating for female insects: Risk of predation in *Photinus collustrans* (Coleoptera: Lampyridae). *The American Naturalist, 131*(1), 139-142.

Wing, S.R. (1989). Energetic costs of mating in a flightless female firefly, *Photinus collustrans* (Coleoptera: Lampyridae). *Journal of Insect Behavior,* 2(6), 841-847.

Appendix. Using twilight "light sensors" to study the effects of light pollution on fireflies, *Photinus collustrans*.
Time: twilight time in August, 2006
Location: a front yard of a house opposite Newnan's Lake, Gainesville, FL
Camera: Canon SLR 300D, 15 sec shutter speed, F/4.5, 15 sec exposure time, ISO 100
Photograph technique: each shot of firefly flashes was combined in the same picture and adjusted the color via Adobe® Photoshop® CS
Photographed by: Anchana Thancharoen (e-mail: koybio@yahoo.com)