Environmental Sensors Lab

The study of plant ecophysiology is concerned with how plant function is shaped by or responds to the environment. Before we can look at plant response to environmental variables, we first need to describe, measure and characterize them. This is done using a wide array of environmental sensors as well as descriptions to the soils, settings, and plant neighborhoods. Today's lab will introduce you to some of the environmental sensors used to characterize plant microclimates. We will get a chance to use the sensors next week in lab.

Today's goals:

1) To take a look at some of the instruments that are used for taking microclimatic data.
2) To discuss examples of ongoing physiological ecology research projects and how they have incorporated the use of environmental sensors.
3) To think about real research scenarios and make decisions about what are the relevant environmental variables to measure, which instruments to use, where to position them and how often to take measurements.

Overview of an instrument

Instruments generally consist of four parts:

1) **sensor-transducer:**
    - the sensor couples the instrument to the environmental phenomenon of interest
    - the transducer converts the signal from the sensor into a form such as voltage or current that varies in some predictable fashion as the phenomenon changes
2) **signal conditioner:** modifies the signal from the sensor-transducer so that it is easily recordable
3) **output:** makes the signal observable though a readout device such as a meter, gauge or a pen on chart paper
4) **power section:** provides energy to the rest of the device; can be thermal energy, a spring, a battery

Deciding which instruments to use

It is important and can be challenging to decide what instruments to use. The decisions are usually dependent on the research questions you are asking. Before we look at the individual instruments we are going to discuss in more general terms why you would choose one type of sensor over another or one brand of sensor over another.

First some definitions:

accuracy - the amount a measured value or quantity differs from its true value. Expressed as either a percentage (%) of the reading.

precision - the repeatability of a measurement or the degree to which successive measurements of a constant input signal give the same output signal. A measurement with a systematic error may be precise yet not very accurate.

noise - any change in an output signal that is unrelated to changes in the measured input signal. Noise is commonly expressed as the squared root of the sum of the squared deviation from the mean signal (or the root mean square = RMS):

$$\text{RMS} = \Sigma\,[(x_i - x)^2]^{-1/2}$$

Noise becomes especially important to quantify when it becomes a significant part of the output signal; what is termed the signal-to-noise ratio (SNR) = signal/noise.

stability - the amount of change or drift in some null point signal over time.
sensitivity - the smallest change in an input signal that will give a quantifiable change in the output signal.
resolution - the smallest scale from an output signal that is readable.

Factors related to instrument performance:

1. Are the accuracy, precision, level of noise, stability, sensitivity, and resolution of the instrument acceptable for the data you need to collect?
2. the cost of equipment
3. availability of equipment
4. range of your instrument
5. response time – How quickly your sensor can respond to a change in the microclimate?
6. memory – How much data can the instrument store?
7. power requirements – Are you going to need a battery for remote work?
8. Is your instrument sturdy enough for field work?

Other factors related to your research question:

1. which aspects of the microclimate you need to quantify
    a) What information would you want if you are interested in how seasonal light patterns affect plant growth? What information would you want if you are interested in how your plant grows in different soil environments?
    b) ***Note:*** *In most cases, it is best to have a complete set of microclimatic data in order to make sure that you do not ascribe a pattern to the wrong microclimatic variable.*
2. the number of measurements you need to make, how frequently you make these measurements, and for how long you need to make these measurements
    a) What information would you want if you are interested in how photosynthetic rates respond to sun flecks?
    b) What information would you want if you are interested in longer-term processes such as how different daily light levels influence plant phenology
3. the spatial scale at which you must take measurements – that is whether you are characterizing the microclimate at the leaf level, the plant level, or canopy or stand level
4. how you should set up the sensors – Do you want the sensors at ground or canopy level? At what orientation do you want the sensors?

Even given careful consideration, there are compromises: The environment within plant communities is spatially heterogeneous (both vertically and horizontally) and it can therefore difficult to sample the microclimate accurately. For example, it has been estimated that 50-400 sensors may be required in a forest understory to obtain a satisfactory idea of the average solar radiation value.

And remember: All instruments need to be regularly calibrated.

Introduction to some instruments

There are many different instruments available for taking different sorts of microclimatic data. I am going to show you some of the ones that we have in lab.

Instruments for measuring temperature

1) max/min thermometer

What it tells you: Max/min thermometers allow you to both know what the current temperature is, as well as the max or minimum that has occurred over a given time period.
How they work: The temperature is sensed by the bulb. As the bulb heats up, the liquid expands causing it

to rise within the capillary. To obtain a temperature reading, you simply read the scale etched on the glass. To determine max and min temperatures during a period of time, there is one continuous band of mercury that is in a curve in these thermometers. As the temperature rises, it pushes a small magnet upward on the right-hand scale (scale for reading maximum temperature) As the temperature decreases, it pushes a magnet upward on the left hand scale, which is the scale for the minimum temperature. The magnet remain in place until you reset the thermometer, allowing you to read the maximum and minimum temperature.

Advantages:
- cheap, easy to use, quite precise
- give you a rough idea of the maximum and minimum temperatures experienced by plants

Disadvantages:
- thermometers are slow to respond to changes in temperature
- need to have manual readouts
- also need to be reset

2) infra-red thermometer

What it tells you: This thermometer measures the infrared radiation (long wave radiation) emitted by a body. (Note: all objects above 0 Kelvin emit radiation)

How to use it: You simply point the thermometer at an object and it tells you its temperature.

How it works: The thermometer measures the amount of longwave radiation being emitted by the body. It is like a light sensor (which we'll discuss shortly) that senses over the 700-1100 nm range. The intensity of the signal is then converted back to a surface temperature using the Stefan-Boltzmann law of radiation emission.

Advantages:
- useful for taking remote measurements (e.g. a leaf in the canopy that you cannot reach) because you do not need to touch the surface in order to obtain a temperature reading

Disadvantages:
- they are usually only accurate to 0.5° C
- not practical for making large continuous measurements, because they have manual readouts

1) hand-held thermocouple meter

What it tells you: Measures temperature

How to use it: Place the soddered end of the wire on any object of interest.

How it works: A thermocouple simply consists of two wires (one copper and one constantan, a mixture or tin and nickel) which are soldered together at the ends of the wire to form a junction. If two dissimilar metals are connected to each other at both their ends, a current will flow in this circuit when the two junctions are at different temperatures. The magnitude of the electrical current depends on the absolute temperature difference between the thermocouple junctions, as well as on the types of metal in the wires. The instrument to which the thermocouple is hooked up then translates the current (actually the voltage) into a temperature using a formula based on the types of metals used in the wires. (For this to work, the reference temperature of the end of the wires inside the box needs to be known.)

Advantages:
- inexpensive
- easy to make
- come in various sizes, so you can use them to measure anything from leaves and other thin objects to air or soil
- they can be various lengths, so the distance between the sensor and the readout devise can be variable and long without affecting the signal
- respond relatively fast to changes in temperature
- you can arrange thermocouples in a series and use them to estimate average temperatures can be

hooked to data loggers

Disadvantages:

- thermocouples that have copper in them may take up or give off excess heat because copper has a high thermal conductivity (it is better to use lead because its thermal properties make it less apt to take on or give off excess heat)

Instruments for measuring precipitation and fog inputs

1) Calibrated rain gauge (manual)

What it tells you: The amount of precipitation to fall

How it works: The gauge has an opening of known area. The precipitation that falls onto this surface is funneled into a graduated cylinder. The numbering on the side of the graduated cylinder is adjusted for the opening size.

Advantages:

- simple, easy to use

Disadvantages:

- you need to empty it manually

2) Tipping-bucket (automated) rainfall collector

What it tells you: The amount of precipitation to fall

How it works: The collector has two small "buckets" of known volume on either side of a fulcrum (looks like a mini see-saw) and when one bucket fills up it tips the see-saw and sends an electronic signal to the data logger. Then the second bucket begins to fill, etc.

Advantages:

- simple, easy to use
- can be attached to a data logger, so the exact time of each bucket recording is noted

3) Fog collector

What it tells you: The amount of for moisture input

How it works: It is an automated rainfall collector above which is rigged a piece of netting on which fog moisture condenses.

Advantages:

- simple, easy to use
- can be attached to a data logger, so the exact time of each bucket recording is noted

Disadvantages:

- you need lots of sensors to measure heterogeneity
- you need a heavy fog, because only fog drip, not for drops on the mesh are recorded

Instruments for sensing humidity

1) Wet and dry bulb sling psychrometer

What it tells you: Humidity is the amount of water vapor in the air. Absolute humidity is the percent of water vapor in the air and is independent of temperature. Relative humidity is on a scale of 0-100%. 100% corresponds to the dew point, or the point at which water in the air begins condensing into droplets. Relative humidity is temperature dependent. If you know the temperature you can use a table to convert between absolute and relative humidity.

How to use it: Sling psychrometers consists of two identical thermometers: one dry bulb and one wet bulb. To use the sling psychrometer, you saturate the wicking covering one of the bulbs with water at room temperature. The other bulb remains dry. You then whirl the instrument for 15-20 seconds holding it away from the body. You then read the wet-bulb thermometer; repeat until 2 or more of the wet bulb readings agreed and then use the table (find wet temp and dry temp) to calculate relative humidity .

How it works: When you swing the instrument, some of the water evaporates into the atmosphere, cooling the thermometer's bulb. The amount of water that evaporates (which correlates with the extent of cooling) depends on how dry or wet the atmosphere is. If the atmosphere is very dry (low relative humidity), then the bulb will evaporate a lot of water. This will result in a cooler wet bulb and the temperature difference between the wet and dry bulbs will be high. If the atmosphere is wet, then less water will evaporate and there will be little difference between the temperature of the dry and wet bulbs. To determine the relative humidity, you simply record the wet and dry bulb temperatures and use a table which correlates these temperatures with the relative humidity.

Advantages:

- cheap
- easy to use
- fairly accurate if used properly
- good for making spot measurements

Disadvantages:

- not very accurate at high relative humidities
- if you swing it unevenly, the evaporation off of the wet bulb is uneven, and this can cause inaccuracies in the temperature readings
- not appropriate for making continuous measurements

2) hand-held relative humidity and temperature probe

What it tells you: humidity and temperature

How it works: The temperature probe is simply a thermocouple. The humidity probe works somewhat like a thermocouple. There are two wires which at their junction are embedded in a plate of material that will take up or release water vapor. The instrument sends current through the material. As the material takes up or gives off water it changes the electrical resistance of the material which affects the rate at which the current moves through material and in turn by the wire leaving the material. The instrument measures the speed at which the current moves through the circuit and converts this rate into relative humidity. As moisture increase, resistance decreases. (Note, the thermometer is needed to determine the relative humidity. No thermometer is needed to record absolute humidity.)

Advantages:

- allows for instantaneous spot readings
- some models can be hooked to a data logger

Disadvantages:

- instantaneous data has more errors than long term averages

Instruments for measuring soil moisture

1) Tensiometer -

What it measures and how it works: measures soil suction or matric potential developed as water is pulled out of a ceramic cup into soil by matric forces. The ceramic cup is sealed to a water-filled tube. The vacuum developed as a result of the water being pulled out of the tube is measured using either a diaphragm-based or mercury manometer. In either case, the vacuum obtained is assumed to be equal to the matric water potential in the soil.

Advantages:

- allows for direct readout of soil water matric potential
- inexpensive
- can be automated for continuous readout

Disadvantages:

- requires a soil moisture characteristic curve (SMCC) to relate matric potential to soil water content
- may lose function if soil is drier than –0.20 MPa
- samples small volume of soil
- measures only matric potential, not soil water potential

- sensitive to air bubbles forming in column

2) Psycrometer

What it measures and how it works: measures total soil water potential (i.e. matric plus osmotic potential). Thermocouple psycrometers are encased in a ceramic bulb which allows for equilibration between soil solution and the atmosphere inside the bulb. At equilibrium, the relative humidity inside the bulb is equal to that of the soil atmosphere. Since both matric and solute forces contribute to the equilibrium relative humidity, the device measures total soil water potential (omitting any gravitational or overburden pressures).

Advantages:
- measures total water potential
- useful over wide range of soil water potentials, especially in very dry soil
- can be automated for continuous monitoring

Disadvantages:
- samples very small fraction of total soil volume
- relatively sensitive to soil temperature gradients
- requires SMCC to convert value to soil water content
- may be inactivated by salinity
- units are fairly expensive

3) TDR/FDR

What it measures and how it works: measures the dielectric constant of soil materials that varies directly with soil water content (an empirical relationship has been determined between these two variables). TDR probes are coaxial cables oriented vertically or horizontally. A voltage pulse is applied from one cable and it is recorded when it reaches the other cable. The length of time or frequency it takes for the signal to travel this known distance is proportional to the dielectric constant. The TDR is most desirable for water-balance studies in the field.

Advantages:
- measures water content
- samples large soil volume
- insensitive to soil texture, density, temperature and salinity
- has the ability to measure soil water salinity as well as water content
- relatively stable over time

Disadvantages:
- requires high initial investment
- insertion of probes may be difficult
- may sample excessively large soil volume
- some inconsistent results near surface

Instruments for measuring wind

1) Handheld anemometer

What it tells you: wind speed

How it works: Hold the opening into the wind and read off the scale.

Advantages:

- allows for instantaneous spot readings
- easy to use and cheep

Disadvantages:

- because it is instantaneous it doesn't record gusts

2) Cup-counter anemometer

What it tells you: wind speed

How it works: This is the classical instrument for measuring wind. it consists of a set of cups, usually three, which are connected by arms to a middle spindle. These cups rotate as a linear function of wind speed, so that wind speed can be determined by simply counting the number of rotations. The cup-counter anemometer can be hooked up to a data logger.

Advantages:

- because it records values on a long term basis it records gusts

Instruments for measuring light

The measurement of solar radiation in plant physiological ecology is important because it is used in energy balance determinations and in studies of plant photosynthesis. All electromagnetic energy (radiation) has WAVE and PARTICLE properties. Although it travels as a wave it is made up of discrete packets of electromagnetic energy (radiation) called photons. A quantum is the amount of energy contained in a photon. The shorter the wavelength, the greater the energy contained in a photon. Therefore, the amount of energy contained in a certain number of photons does not correlate between different wavelengths.

The two units you commonly see in reference to light measurements, Watts (W) and moles, reflect the duality of electromagnetic radiation. Watts (or Joules$\cdot$sec^{-1}) are a measure of energy or heat arriving on a surface per unit time. For instance, energy striking any surface from ALL directions can be called either irradiance or radiant flux density (flux density for short) and is measured in units of W per square meter of surface (W$\cdot$m^{-2}). Watts are calculated by integrating the energy contained in all photons of all wavelengths being measured. The second pair of units often used in photobiology are the Einstein (= 6.02×10^{23} photons = one mol of photons) or the mole (both expressed at µE or µmol). These units only tell you the number of energy packets arriving. In general, Watts are used to express energy over a broad range of wavelengths (such as all radiation from the sun) while moles are used for a narrow range over which the energy per photon is nearly constant. Also, photosynthetic rate is more closely linked to the number of photons than to the energy per photon

Some terminology:

1. Photon flux: net number of photons per unit area *(moles m^{-2})*
2. PAR (photosynthetically active radiation): radiation in the 400-700nm waveband, which plants use for photosynthesis
3. Photon flux density (PFD) is the number of photons per unit area per unit time (sec.) *(moles m^{-2} sec^{-1})*
4. PPFD (photosynthetic photon flux density): the number of photons in the 400-700nm wavebands that are incident per unit time on a unit surface *(moles m^{-2} sec^{-1})*
5. Radiant flux density (irradiance): radiant energy incident on a surface from all directions *(W m^{-2})*
6. PI (Photosynthetic irradiance): the radiant energy (400-700nm) incident on a unit surface *(W m^{-2})*
7. Global radiation: solar radiation received on a horizontal surface; composed of direct + diffuse (scattered radiation)
8. Reflected solar radiation: component of global radiation that is reflected from the earth's surface
9. Total radiation: global radiation and longwave (infrared) radiation (mostly emitted by the atmosphere)
10. Net radiation: incoming solar radiation minus emitted longwave radiation

There are many different instruments for measuring light and these instruments differ in the type of radiation that they measure. Some measure radiation of all wavelengths, whereas others only measure the radiation in the 400 to 700nm wavelength range that plants can use for photosynthesis. In addition, some instruments only measure direct radiation, others measure both direct and diffuse radiation. Still others measure net radiation instead of just shortwave radiation. Some measure energy (Watts), while others measure the number of photons (moles) You are more interested in PAR if you are measuring photosynthetic rates and in all wavelengths if you are creating an energy balance.

Sensors

Two types of sensors are made, thermoelectric and photoelectric.

Thermoelectric sensors are most commonly used in measurements of solar and long wave radiation and respond quite equally to irradiance over a wide range of wavebands. These sensors use temperature transducers attached at two points: one to a black surface and the other to a white surface or the sensor housing which is shielded from radiation. The difference in temperature (ΔT) between these surfaces is then a function of the radiant flux density absorbed by the sensor on the black surface. These types of sensors are covered with glass dome or bulb housings to minimize convective energy losses, thus keeping convective and conductive energy exchange between the two surfaces very similar. These are usually the sensors used to do complete energy balances. However, they are becoming less used as photoelectric sensors become better.

Photoelectric sensors use voltage (rather than temperature) differences across two dissimilar metals sensors to measure irradiance. Silicon (Si; 400-1,165nm) and gallium arsenide phosphide (GaAsP; 370-690nm) cells are the best sensors of this type and use a photovoltaic effect to generate a voltage. That is, when radiation (light) hits the surface of the sensors it sends an electrical signal to the instrument. These sensors are inexpensive and waveband-specific (300-1,200 nm). Often specific filters can be used over these filters to restrict the wavebands they "see". The Silicon sensors also eliminate errors associated with the sun being at different angles away from the sensor surface. Above the sensor is a filter which bends light, so that regardless of the entry angle it hits the sensor at a right angle. This is called cosine corrected. GaAsP sensors do not have this filter and therefore record a lower light reading.

Instruments

In physiological plant ecology we can use three types of solar radiation instruments: pyranometers, pyrheliometers and pyrradiometers (or net radiometers). These can employ either type of sensor. We also use a fourth instrument called a quantum sensor for measuring PAR. For each of these, if the instrument contains alternating black and white sensors it is a thermelectric sensor and if it uses metal sensors is a photoelectric sensor.

1) pyranometer

What it tells you: direct and diffuse solar radiation

How it works: One type uses thermoelectric sensors with alternating black and white surfaces. The Eppley Black and White Pyranometer 15-junction pyranometer is the most accurate instrument of this type made. It is very sensitive, is enclosed in a glass half-sphere, has a waveband response of 300-2,700 nm and an output range of 5-11 $\mu V\ W^{-1} m^{-2}$. A less expensive pyranometer uses a silicon photoelectric cell, is linear in response to ± 1%, is durable and cosine corrected. The photoelectric sensors sense a narrower range of wavelengths, but this rarely matters.

Advantages:

- very sensitive

Disadvantages:

- expensive (thermoelectric sensors)

- doesn't just measure PAR (both)
- not for use under canopies, for artificial light sources, or for measuring reflected radiation (photoelectric sensors)

2) pyrheliometer (Eppley 3-band Pyrheliometer)

What it tells you: measures net direct-beam solar radiation

How it works: uses 50 thermopile (several thermocouples joined in a series) junctions on the back and white bands, is enclosed in a "light bulb" type of enclosure, and has a waveband response of 340-2,500 nm with an output voltage of 7-15 $\mu V\ W^{-1} m^{-2}$

Advantages:

- very accurate

Disadvantages:

- only measures direct-beam radiation
- they measure a wider band than just PAR, so some of the measured radiation is not useful for plants

3) net pyrradiometers (net radiometers)

What it tells you: measures the difference between solar (direct + diffuse) radiation and longwave thermal radiation emitted by the atmosphere, the earth's surface, vegetation, etc.

How it works: Employs thermoelectric sensors to detect the difference in temperature of concentric black and white surfaces. The are called NET radiometers because they measure both solar and reflected radiation simultaneously from two flat sensors facing in opposite directions and insulated from one another and measure the difference between incoming and outgoing total radiation. They are often composed of two half spheres; one with a transparent polyethylene cover with a black surface under it, one non-transparent. This measures the difference between incoming and outgoing total solar radiation. A total radiometer, in contrast, gives you the individual values for incoming and outgoing radiation and therefore is necessary for creating an energy balance.

Advantages:

- allows you to construct a complete energy balance because they give you information on both the radiation that is coming in as well as the radiation that is leaving a site (total radiometer)

Disadvantages:

- they measure a wider band than just PAR, so some of the measured radiation is not useful for plants

4) Quantum radiometers (sensors)

What it tells you: The number of photons in the range of PAR falling at a location

How it works: They use heat-absorbing filters that also block any radiation < 400nm and > 710nm. They usually use photoelectric sensors that are covered by a diffuser to ensure that radiation received from any direction is corrected for its deviation from the Sun's zenith (cosine corrected). Quantum sensors use either silicon (Si; 400-1,165nm) or gallium arsenide phosphide (GaAsP; 370-690nm) photocells.

Advantages:

- this sensor is good for taking spot checks of the amount of PAR in μmol falling at a locations
- measures both direct and diffuse light
- inexpensive
- can be attached directly to a leaf surface
- quick response time
- measures the biologically relevant portion of radiation
- cosine corrected
- If hooked up to a data logger, it can take continuous measurements. If it is only a hand-held meter, it can only take spot checks.

Disadvantages:

- gives spot readings (doesn't give you a true idea of the light environment of a place)

- some types cannot be cosine corrected and hence need to be placed perpendicular to the incoming radiation

- We will discuss other types of sensors which can be used to monitor or measure things such as [CO_2] the actual water vapor concentration in air, atmospheric pollutants, other types of radiation (e.g., UV), etc. in labs later in the semester

Introduction to data loggers: Campbell CR10

As we've gone through the different microclimatological instruments we've talked about which ones need data to be recorded manually and which ones have sensors that can be hooked up to data loggers. Data loggers are simply electronic data collection systems that can be programmed to collect and store data. Most of the data loggers we have seen have been very simple and dedicated to a specific environmental sensor. However, there are also widely used data loggers to which can be hooked a variety of different sensors, depending on what data is needed. You programs them, leave them at a site, and the loggers will collect and store data on their own. You can then return and retrieve that information. These data loggers are widely used in plant ecophysiology studies. One of the most widely used data loggers is the Campbell CR10.

The CR10 has 3 components:
1. keyboard, for entering programs
2. battery (power supply)
3. main body to which you attach sensors and which stores data

The types of sensors that can be hooked up to a CR10 include:
- thermocouples
- quantum sensor (PAR 400-700nm)
- relative humidity sensors
- anemometer
- electronic water
- soil probe for measuring temperature and soil moisture

When programming the data logger, you need to tell it:
- which kinds of sensors it has hooked up to it, and how many of them
- where each of the sensors is hooked up
- how frequently to collect data, and how often to average the data
- where to store the data that the sensors collect

Lab exercise:

First we will give you a brief presentation of three ongoing projects currently being carried out by researchers at UC Berkeley:

1- Alpine Project
Main question: How do different substrate types affect plant distributions and their physiological strategies.

2- Amazonian/savanna Project

Question: What is the effect of drought on belowground ecosystem and plant-level processes in an Amazonian rainforest and a neotropical savanna?

3- Redwood Project
Question: Does physiology vary in relation to the vertical humidity/light gradients present in coastal redwood crowns?

We will then present you with some hypothetical research scenarios. In groups, you will have to choose the most appropriate environmental sensors to fully monitor all relevant environmental variables and justify your choices. Keep in mind this question: *What do you need to know about the environment in order to understand the physiology of the plants that inhabit it?*
After approximately 45 minutes of discussion, each group will present your decisions and justifications to the rest of class.

Study scenarios:

1- You want to study tree performance along an environmental gradient. More specifically, you want to compare the carbon and water relations of trees growing in low versus high elevation sites.

2- You are interested in understanding the influence of deforestation on forest tree performance. You will compare the physiology of trees in a site that has undergone selective logging with trees in another site that is intact.

3- In the chaparral you want to compare the physiology of two plants with contrasting leaf phenologies (one evergreen and one deciduous) and examine the patterns of leaf drop over the course of two growing seasons.