Chapter 3
Meteorological Measurements

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Abstract Environmental measurements are useful for detecting climatic trends, understanding how the environment influences biological processes, and as input to ecosystem models. Landscape-scale monitoring requires a suite of environmental measures for all of these purposes, including air and soil temperature, humidity, wind speed, precipitation and soil moisture, and different aspects of solar radiation. This chapter discusses sensor characteristics, including accuracy and precision, and also provides an overview of electronic data loggers, power systems, towers, and lightning protection. A list of sensors suitable for installation at landscape-scale monitoring sites and manufacturers is included.

Keywords Environmental monitoring, data logger, temperature, humidity, radiation, soil moisture, towers

3.1 Introduction

Meteorological and environmental measurements are needed at landscape-scale monitoring sites for trend detection, developing relationships between biological and climatological variables, and providing inputs to models of ecosystem biogeochemistry, land-surface exchange, or other modeling studies. Here we describe key variables to be monitored, suggest sensor accuracies and precisions, specify site requirements, and provide information about manufacturers of environmental sensors and systems. Mention of specific companies should not be construed as an endorsement by the US Forest Service. Any installation or maintenance of equipment on meteorological towers should be carried out only by qualified personnel, as should installation of such towers. In all cases appropriate safety equipment must be utilized.

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Meteorological variables to be monitored at landscape-scale sites include air temperature, relative humidity, wind speed, wind direction, barometric pressure, precipitation, and direct and diffuse photosynthetically active radiation (Table 3.1). In addition, soil temperature and moisture should be quantified at several depths. If resources permit, the following additional important variables should be monitored; reflected photosynthetically active radiation, canopy wetness, and albedo. Pearcy et al. (1989) discussed general principles for making environmental measurements and describe various sensors and methods in detail. The AmeriFlux web page has additional useful information and measurement guidelines (http://public.ornl.gov/ameriflux/). See also the documentation describing international meteorological station guidelines (WMO, 1996) and the US Climate Reference Network (US Department of Commerce, 2003).

In modern meteorological stations of the type discussed here, environmental data are recorded by sensors connected to electronic data loggers. Data loggers process and store sensor data, typically generating and storing additional information such as means, maxima, standard deviations, wind vectors, etc. More advanced data loggers may be used to initiate events based on time or specific conditions such as rainfall or water level. Data loggers suited for meteorological stations are typically self-contained and capable of operating under extreme conditions. They utilize non-volatile memory so that results are not lost even if batteries fail. Data loggers typically have various communication functions so that data may be moved from the logger to a computer using direct connection, modem, or wireless capabilities. Power may come from replaceable batteries or solar panels and rechargeable batteries. Data loggers come in a range of sizes and capabilities, and are often rated by the number of sensor channels they may read. Data logger

Table 3.1 Environmental parameters to measure at landscape-scale monitoring sites with desired accuracy and precision specifications

Parameter	Accuracy	Precision	Estimated cost each ($)
I. Core parameters			
Air temperature	±0.2°C	±0.05°C	100
Relative humidity	±3%	±1%	150
Precipitation	±0.2 mm	1	500
Wind direction	5%	2°	600
Wind speed	0.5 m s^{-1}	0.2 m s^{-1}	600
Barometric pressure	±1.5 mbar	0.2 mbar	500
Solar radiation	5%	5 W	750
Total PFD	5%	2 µmol	250
Diffuse PFD	5%	2 µmol	3,000
Soil temperature	±0.2°C	±0.05°C	200 (minimum of 2)
Soil moisture	3%	0.1%	300 (minimum of 2)
II. Additional parameters			
Canopy wetness	5%	1%	100
Reflected PFD	5%	2 µmol	250
Below canopy PFD	5%	2 µmol	250
Albedo (long and short wave)	10%	1 W	5000
Data logger	0.1%	12 bit	1500

Table 3.2 Manufacturers of data loggers, environmental sensors, and tower supplies. There are several web-based resources with more comprehensive lists of instrument manufacturers. See for example http://www.meteo-technology.com/index.htm

Company	Equipment and sensors
Campbell Scientific	Data loggers, most sensors
Delta-T Devices	Data loggers, direct and diffuse radiation
Onset	Data loggers, sensors
Vaisala	Most sensors
Met-One	Temperature, humidity, wind, ventilated shields
R.M. Young	Temperature, humidity, wind
The Eppley Laboratory	Radiation sensors
Kipp and Zonen	Radiation sensors
LiCor	PFD sensors
Rohn	Towers
Nello	Towers
Isotruss	Towers
AN Wireless	Towers
Foresight Products	Earth anchors for guy wires
Northern Arizona Wind and Sun	Solar panels, deep cycle batteries, charge controllers
The Alternative Energy Store	Solar panels, deep cycle batteries, charge controllers
Mr Solar	Solar panels, deep cycle batteries, charge controllers

manufacturers are listed in Table 3.2. For the sensor configuration suggested here, data loggers with 12 or more channels are necessary. For meteorological data, sensors need be sampled no more than once every few seconds. We recommend that individual readings from most sensors (except precipitation) be averaged over a 30-min time period for final use and that the data logger also be configured to record the standard deviation of the half-hourly readings. Precipitation data should be summed over the 30-min time interval.

3.2 Sensor Selection

Sensors are quantified via their accuracy, precision, and stability (Table 3.1). Accuracy refers to how close the reading from a sensor may come to the "true" value while precision indicates the smallest change that may be accurately recorded. The output from a sensor may degrade or "drift" over time or the sensor may respond in part to an environmental factor other than that to which it was designed to respond (typically temperature affects the response of most sensors). The stability of a sensor is a quantification of the potential for the sensor output to vary with time or other (non-measured) factor. Generally, sensor accuracy, precision, and stability all increase with price. Because long-term stability and high accuracy are not requirements of overriding concern for landscape-scale monitoring, standard meteorological sensors available from any of the manufacturers listed in Table 3.2, as long as they meet the accuracy and precision guidelines in Table 3.1, are suitable. Table 3.3 lists examples of sensors that are suitable for landscape-scale monitoring.

Table 3.3 A prototype installation for a forest landscape-scale monitoring site. Note that sensors from other manufacturers meeting the specifications in Table 3.1 are suitable

Sensor	Manufacturer and model	Location
I. Basic installation		
Air temperature and RH	Vaisala model HMP45C	5 m above canopy
Precipitation	Texas Electronics model TR-525	Above canopy
	or Vaisala model QMR102	In clearing
Wind direction and speed	Met One model 014A/024A or RM Young model 05103	On boom, 5 m above canopy
Barometric pressure	Vaisala model PTB210	With data logger
Total and diffuse PFD	Delta-T model BF3	Tower top (avoid shading)
Solar radiation[a]	Hukseflux model LP02 or Kipp and Zonen CMP3	Tower top (avoid shading)
Soil temperature	Campbell model 107	5 and 50 cm depth
Soil moisture	Campbell model CS616	5 and 50 cm depth
Data logger	Campbell model CR1000	In enclosure accessible from ground
II. Additional sensors		
Canopy wetness	Campbell model 237	Mid canopy
Reflected PFD	LiCor model LI190SB or Kipp and Zonen model PAR lite	Requires up and down facing above-canopy sensors on 2 m boom towards equator
Below canopy PFD	Kipp and Zonen model PAR lite or LiCor model LI190SB	
Albedo[a] (4 component)	Hukseflux model nr01 or Kipp and Zonen CNR1	On 2 m boom towards equator
Data logger	Campbell model CR3000	In enclosure accessible from ground

[a]Solar radiation sensor not needed when albedo measured

Because all sensors degrade in time and with exposure to the weather, it is important to calibrate or replace sensors on a regular basis following the manufacturer's recommendations. The easiest way to do this is to substitute a spare instrument and send the old one in for calibration at the prescribed interval. Purchasing spare sensors for this purpose should be part of every meteorological equipment budget. Calibration procedures and standards employed should be documented, as should the calibration results of each sensor.

3.2.1 Temperature and Humidity

Biological and physical climate processes are generally sensitive to temperature, and it is a required input to virtually all land surface and biogeochemistry-based models. Temperature sensors rely on different principles but as long as they meet the desired requirements of accuracy and precision (Table 3.1) the particular principle employed is of no importance. Air temperature sensors, however, are susceptible to heating by direct solar radiation, causing errors in the measurement. The recommended solution is to locate the sensor in a ventilated shield where the ventilation is accomplished by a fan. For remote systems, a 12-V DC fan may be powered directly off a small (~5 W) solar panel for this purpose (see later section on power systems). Temperature sensors installed into the soil should be electrically insulated to prevent the development of "ground loops", spurious currents that affect sensor readings. Use of differential inputs and good grounding practices will also help eliminate ground loops (usually data logger manuals have specific information about these topics).

Humidity combined with temperature is an important determinant of evaporation rate. Plant physiological processes such as stomatal conductance are also sensitive to humidity. Generally the simplest way to measure humidity is to use a combination temperature and humidity sensor. For accurate readings these sensors should always be used with a ventilated shield.

3.2.2 Precipitation

Precipitation data are used in conjunction with other data in many models to calculate water balance and drought parameters. "Tipping bucket" type rain gauges are best suited for long-term unattended monitoring. In these gauges water is collected by an integrated funnel and channeled to a small mechanism that "tips" and sends a pulse to the data logger for each increment of rain (such as each 0.2 mm). However, several problems must be recognized with these sorts of remote systems. First, in many climates, low temperatures cause winter precipitation to fall as snow or sleet and simple tipping bucket type rain gauges will fail to detect these events, instead falsely recording precipitation when temperatures rise sufficiently for trapped precipitation to melt. Other alternatives (heated or antifreeze-type weighing gauges) are generally more expensive and difficult to service. A heated gauge also usually requires AC line power although gauges that use propane for heating are available. However, newer load cell based weighing gauges that do not require heating (e.g. Vaisala model VRG101) show promise. A second problem with tower rain gauge installation is wind shielding. It is always recommended that a wind shield be installed around the orifice of a rain gauge to reduce errors associated with wind-driven precipitation but this is generally impossible in a tower-mounted configuration. For these reasons precipitation data from tipping bucket type rain gauges, especially in the winter, must be considered less reliable than ordinary meteorological service data.

3.2.3 Radiation

Solar radiation provides the energy for photosynthesis and drives the climate system through its evaporation of water and heating of the air. Solar radiation is a critical input for virtually all models of biogeochemistry or land surface fluxes. Solar radiation consists of both incident and reflected components and the incident radiation may be further divided into direct (emanating from the solar disk) or diffuse (scattered from the sky and clouds) radiation. Another way to divide solar radiation is by wavelength, typically consisting of shortwave (typically 0.285–2.8 μm in wavelength) and longwave infrared radiation (2.8– ~ 50 μm wavelength). Shortwave radiation consists of UV (0.285–0.4 μm), photosynthetically active radiation (0.4–0.7 μm), and near infrared radiation (0.7–2.8 μm). Net radiometers measure the difference between the incident and reflected short- and long wave radiation. The most useful type measures all four components (incident and reflected short- and longwave radiation) individually allowing calculation of the surface albedo, but these instruments are expensive (~$5,000). Such data are very useful for energy balance studies, and quantify solar and longwave energy fluxes in units of watts (W) m^{-2}.

Photosynthesis is most directly related to the quantity of photons intercepted. This measure of solar radiation is termed photosynthetically active photon flux density (PFD), and is measured in micromole photons per square meters per second between 0.4 and 0.7 μm. Diffuse radiation is used more efficiently by canopies than direct radiation, so the separation of total PFD into direct and diffuse components is valuable. Another useful measure is to record data from PFD sensors installed below as well as above a canopy thus allowing the fraction of incident radiation absorbed by the canopy to be estimated. Because of spatial heterogeneity in plant canopies it is usually desirable to employ many below-canopy sensors when these data are desired.

3.2.4 Wind Speed and Direction

These data are generally used in land surface models and for climatological studies. Wind speed and direction have been traditionally measured by rotating cup and vane systems but require threshold speeds to be exceeded before they provide reliable readings. They are also susceptible to environmental damage from hail and ice. New stationary wind speed and direction probes that measure the transit time of ultrasonic sound pulses are available, and these are generally more reliable, and cost competitive, with older designs.

3.2.5 Soil Moisture

Plant physiological processes and microbial activity are sensitive to the effects of too much or too little soil moisture. This can be a difficult and somewhat expensive measurement, as soil moisture should be measured at several depths. We recommend at least near surface (5 or 10 cm) and mid-profile (50 cm) depths, and duplication of sensors in several profiles is desirable. Many soil moisture probes include integral temperature sensors. Older style systems based on electrical conductivity (e.g. gypsum blocks) should not be used because of calibration problems. Newer sensors rely on different principles such as the soil dielectric constant that is more directly related to total soil water content.

3.3 Power Systems

The power requirements for data loggers and meteorological sensors are generally modest. Most loggers will operate for many months on one set of replaceable batteries. However, solar panels and rechargeable batteries provide greater reliability and flexibility. If higher current devices are in use such as fans for ventilated shields or heaters for radiometers or rain gauges, the best practice is to install a second solar power system that is independent of the data logger. In this way a power shortage resulting from a series of overcast days will only affect the high current devices.

For a simple logger setup, a small solar panel (5–10 W) connected to a small (6–12 Ah capacity) rechargeable battery should provide a reliable supply. Many loggers such as those from Campbell Scientific have optional rechargeable batteries and charge controllers built in. We recommend an additional 5-W solar panel be connected to a 12 V DC fan in the ventilated temperature shield. No battery is necessary for this installation because the problem of solar heating of the temperature sensor only occurs when the sun is out.

For greater current demands more solar panel and battery capacity are necessary, with the specific capacities depending upon climate and desired reliability. For modest demands (0.5 A at 12 V) with good reliability (5 cloudy days operation) in the northern US, a system consisting of 80 W of solar panels, 15 A charge controller, and 120 Ah of deep cycle storage batteries would be adequate. Pulse type solar controllers may cause interference with data loggers so complete separation of the logger and high power charging systems (including separate grounds) is necessary.

To optimize power when it is least available (midwinter) panels need to be inclined steeply. The general rule is latitude plus 23.5°.

3.4 Lightning Protection

In many parts of the United States lightning can be an important hazard to field meteorological sites. The data loggers available from the manufacturers listed in Table 3.2 generally include built-in lightning protection (from spark gaps or other devices) that works well *if* the datalogger and tower are grounded properly (follow manufacturer's directions). One should always avoid running wires along the ground for long distances (e.g. >30 m) because high voltages may be induced into such lines even in the absence of nearby lightning strikes. Additional protection of sensor and data lines using gas discharge tubes, tranzorbs, and/or lightning fuses is always recommended.

3.5 Sensor Installation

The World Meteorological Organization (WMO 1996) provides guidance for the installation of meteorological sensors at conventional climatological sites. The recommended sensor height (1.5 m above the ground except higher at sites which typically experience significant snow) is consistent with the recommended height for sensors in the US Climate Research Network, the Automated Surface Observing System (ASOS), Automated Weather Observing System (AWOS), and US Cooperative Observing Network (COOP). If the landscape monitoring site is dominated by short-stature vegetation or a mostly open canopy (projected canopy coverage is less than one-third of the ground area) then the 1.5 m sensor height should be used for temperature, humidity, precipitation, and wind speed data. For open sites that experience significant snow cover, sensors are to be installed at a height of 0.6 m above the surface of the average maximum snow depth or 1.5 m above the surface of the ground (no snow), whichever is higher. Radiation sensors should be mounted at the top of the sensor support structure or on a boom that extends toward the equator to avoid shadows on the sensors.

There are no standard guidelines for sensor installation at sites with partial or complete plant canopy coverage. We recommend in this instance that meteorological sensors be located 5 m above the average canopy height, which may require the installation of a meteorological mast or tower.

3.6 Meteorological Towers

Towers suitable for micrometeorological investigation are available from several manufacturers (Table 3.2). These are generally modular in design so that each section attaches to the one below. Towers are rated by their wind and ice load capabilities and because of the unpredictable nature of a forest environment (branch or tree fall upon a tower or guy wire), we recommend purchasing towers with the highest available wind load rating (typically 120 mph). Towers must be installed by qualified personnel and according to the manufacturer's instructions. Requirements for grounding should be strictly followed. Towers should never be erected near overhead electrical lines. Towers should only be climbed by trained personnel utilizing appropriate, OSHA-approved, safety equipment. Tower construction and safety courses are available from e.g. ComTrain, LLC.

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