Ecological Restoration Institute

***Fact Sheet**: Field Considerations for Measuring Evapotranspiration with the Eddy Covariance Method*

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Field Considerations for Measuring Evapotranspiration with the Eddy Covariance Method

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Introduction

In semi-arid ponderosa pine forests of the southwestern US, up to 90% of the annual water budget is returned to the atmosphere through evapotranspiration (ET). Accurate measurements of this component of the water budget are, therefore, critical to assess hydrological responses to planned forest restoration. The eddy covariance (EC) method is an atmospheric measurement technique that yields accurate ET measurements. The EC method calculates vertical turbulent fluxes within an atmospheric boundary layer over natural ecosystems and agricultural systems to determine gas exchange rates (e.g., water vapor concentration, carbon dioxide (CO_2) concentration) (Burba 2013). Both natural and human-mediated processes affect forest gas exchange. Recent studies of both wildfire and forest restoration treatments in stands of ponderosa pine show a reduction of ET compared to an undisturbed forest site (Dore et al. 2010). Application of EC to investigate CO_2 and water fluxes in ponderosa pine forest improves understanding of CO_2 and water flux exchange patterns. This fact sheet describes installation of an EC system, including flux tower placement requirements and maintenance of scientific instruments.

Flux Tower Placement Requirements

It is important to establish goals for EC measurement because the purpose of the experiment will affect the selection of instruments mounted on the tower. Project goals should be established prior to tower location selection and maintenance plan development (Burba 2013). The tower itself needs to sustain the severe environmental and climatological hardships (Munger et al. 2012).

1) **Location:** The tower must be located at a place where it optimally represents the area of interest, where the area is large enough to provide a sufficient footprint, and where the topography is flat and uniform (Burba 2013; Munger et al. 2012). Usually the tower is installed in the center of the study site (Burba 2013). The recommended uniform upwind fetch is approximately 100 times the instrument height. (In the case of ponderosa pine forest of northern Arizona, this would be about 600 to 900 feet) The tower should be located where a dominant direction or strength of wind flow increases the chance of reliable measurements. Maximizing the useful footprint from all representative wind directions is recommended.

   Power availability and accessibility should also be considered. Forests are usually situated in remote locations; therefore solar power systems would be installed for operating EC systems. Major elements for solar power system include solar panels, deep cycle batteries, charge controllers, wires, and cables. Among those required elements, numbers and orientation of solar panels are determined based on the required power demand of the EC systems and geographic location of field (Li-Cor Biosciences, 2010). Solar power equipment should be situated on the downwind side of the tower relative to the prevailing winds.

2) **Installation**: When installed, the tower structure should not impact the micrometeorological area of interest. If installed in a windy area, the tower should be firmly secured on the ground, for example, by using guy wires. These wires should be regularly checked to ensure no trees or branches have fallen on them. Appropriate grounding must be installed to avoid or minimize damage by lightning. A shelter house is recommended to store necessary power and datalogging equipment nearby the tower. As with the solar power installation, the datalogging shelter should be located downwind of the tower in the prevailing wind direction at a distance of three times the shelter height (Munger et al. 2012).

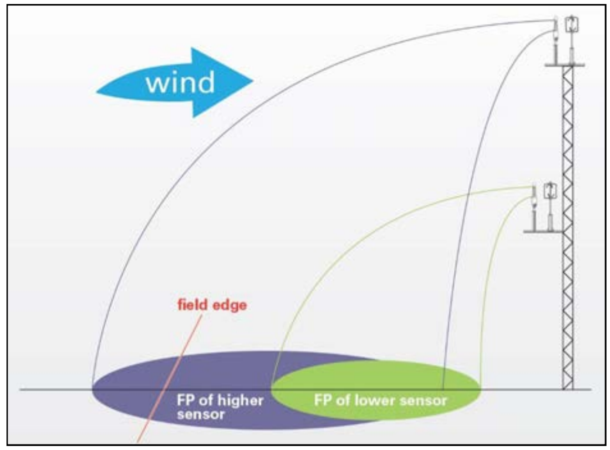

Figure 1. Diagram for footprint (FP) coverage of higher and lower sensors; If sensor is located too high, FP would go beyond the field edge (Burba 2013).

3) **Height**: The tower needs to be tall enough to measure fluxes of plant canopy gasses in the well-mixed surface layer (a zone having nearly constant mean meteorological variables due to the intensive vertical mixing). The tower height should not be too low because measurements could be affected by the canopy roughness layer (a layer of air where air flow is affected by roughness elements such a tree tops). If the tower is too high, this could cause the footprint to stretch beyond the area of interest (Munger et al. 2012) (Figure 1). Numerous models have evaluated footprint contribution. One of the simplest models calculates footprint contribution using analytical solutions of diffusion equation as a function of a distance from the station (Burba 2013); this model explains relationships among the distance from the station, measurement height, and footprint stretch.

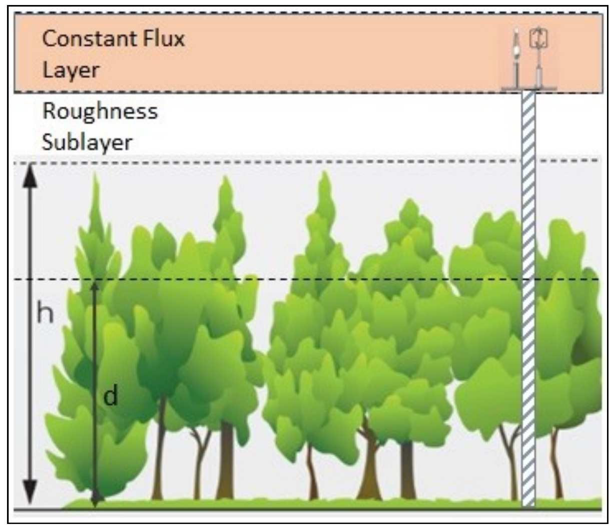

Figure 2. Diagram for recommended tower placement height for tall forested canopy; h: canopy height, d: zero plane displacement height or measurement base (modified from Burba 2013).

For most canopies (such as cropland, grassland, shrubland) the recommended capturing tower height is 1.5–2 times the canopy height (h_c) above the soil surface, usually 1.5h_c for tall canopies (>2–3 m) and 2h_c for short canopies (<2–3 m) (Figure 2). For especially tall canopies such as forests, the zero plane displacement height (d) (a.k.a. measurement base), is used in place of the ground surface for calculating instrument height. The zero plane displacement height is the height above ground where the wind speed would go to zero due to obstacles (i.e., tree canopies) when a logarithmic wind profile is maintained. In forests, this height (d) is estimated between 0.6 and 0.8 times h_c (usually 2/3 of h_c). Instruments are set at d+1.5 (h_c–d) (personal communication with G. Burba). For 60–90-foot high ponderosa pine in northern Arizona, the measurement base (d) would be 40 to 60 feet about the ground surface). The instrument height should then be somewhere in the range of 70–105 feet above the ground surface, depending on the height of the canopy.

4) **Base**: The tower should be wide enough to provide a secure and safe platform , but should not be too wide to affect measurement of interest. To minimize the uncertainty of tower impacts on EC measurement, tower base area should be no greater than 4 m^2 (roughly 6.5 feet by 6.5 feet). For forested sites, tower base area can be increased, if the average projected area of one tree crown is larger than six times the tower projected area (24 m^2) (Munger et al. 2012).

5) **Structure**: The tower must have safe access if personnel needs to climb the tower for maintenance. Otherwise, instruments should be able to be lowered by rope or cable. Tower structure must have minimum sway and vibration due to the wind or snow weight. Guy wires can help minimize the vibration (Burba 2013). More detailed structure limitations include that tower movement should be less than 1.0 mm per 1 m in height and tower should not oscillate more than 20 Hz (oscillations per second) (Munger et al. 2012).

6) **Other factors that affect flux measurements**: There are some other environmental factors that affect flux measurements. The tower should be strong enough for wind speed up to 40m s^{-1}, temperature range -50^{o}C and 50^{o}C, rain 0–6.35 m $year^{-1}$, and snow 5.1 m $year^{-1}$ (Munger et al. 2012). Also, surface roughness and thermal stability affect flux measurement (Burba 2013).

With or Without Eddy Covariance Method

For water-limited semi-arid forests, accurate evapotranspiration (ET) estimates are critical for closing the water balance, since as much as 90% of precipitation received in Southwest forested watersheds returns to the atmosphere through ET. The availability of water for additional groundwater recharge or surface water discharge hinges on the amount and timing of precipitation as well as changes in ET due to forest restoration treatments. Quantifying forest ET is central to making long term water supply projections.

In the **4FRI Paired Watershed Study** researchers hope to use six eddy covariance (EC) towers situated in half of twelve paired watersheds. These EC systems would measure ET in a variety of forest conditions ranging from control watersheds with no forest thinning to watersheds with high-intensity forest thinning (near pre-settlement basal area). The EC systems would generate accurate measurements of evapotranspiration. These measurements would then be compared with soil moisture and tree sapflux data in the six EC-instrumented watersheds to generate a model to estimate ET based on soil moisture and sapflux. The generated model would be used to estimate ET in the six watersheds lacking EC but where soil moisture and sapflux would be measured.

There are three foreseeable alternatives to installing six EC systems. **First**, the number of EC systems could be reduced to two EC towers located in the most extreme conditions – control and high-intensity treatment – with regression analysis providing estimates of intermediate conditions. This approach is problematic and not recommended due to lack of data for intermediate treatments. **A second alternative**, that would not require new EC installations, is to create the soil moisture and sapflux-based model based on historic EC data from the region. The drawback of this approach is that there would be no way to verify the new ET estimates and calibrate the model without at least some present-day eddy covariance measurements. **A third alternative** is to predict ET from micrometeorological models, based on microclimate and stand data. Models such as Penman-Monteith, McNaughton-Black, and Shuttleworth-Wallace could be used. For ponderosa pine forest in northern Arizona, these models have been demonstrated to predict ET within +/-14% of actual ET measured by EC. A combination of alternatives is also possible.

With the eddy covariance method, the best measurements of evapotranspiration changes are possible to inform the most useful water balance models. Without EC, we can still generate ET estimates but those estimates would be based on old data, assumptions, and less complete measurements of water and energy flux, which could generate considerable error and confound the ability to predict forest thinning impacts on water resources.

Guidelines on Installation and Maintenance of Major Instruments for the Flux Tower

If meteorological instruments are mounted together on a horizontal bar, all instruments (except the radiometer) must be spaced at least twice the face-width of the tower (Munger 2012). Each instrument should be placed at a representative location. Instruments that may be mounted on the tower include the following (Figure 3) except for soil heat flux plates, which are buried underground:

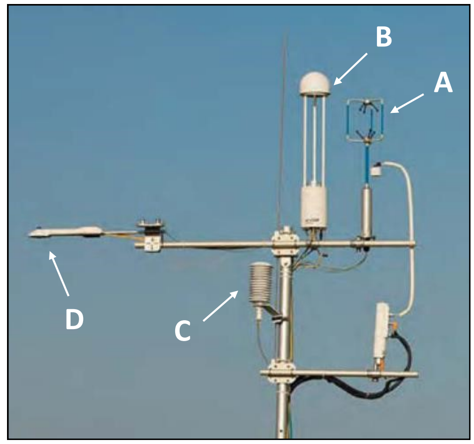

Figure 3. Eddy covariance systems with major instruments including A) 3-D sonic anemometer, B) open path CH_4 analyzer, C) Humidity sensor with radiation shield, and D) Net radiometer (modified from Burba 2013).

1) **Three-dimensional sonic anemometer:** The 3-D sonic anemometer measures wind speed in three dimensions and is mounted on the windward side, not on the tower side (lateral side) or leeward side (Munger et al. 2012). If the anemometer must be located on a bar right above the tower, it should be placed at least five times the tower diameter above the tower. Whether the anemometer is installed on a flat or angled ground, the anemometer head should be parallel to land surface. Removing water droplets on the surface of transducers enables continuous measurements of wind speed. Wicks can be attached at the tips of transducers to prevent water droplets from accumulating. However, wicks should be removed during the wintertime.
2) **Open-path CO_2 and H_2O gas analyzer:** Moisture can prevent the EC system from measuring accurate flux by driving CO_2 signal strength to zero. Dew may be avoided by coating the surface of the measurement window with wax. Also, rain droplets or snowflakes can be in the path of flux measurement and affect the reading, thus these should be minimized. Tilting the sensor head to 10-15^o from the vertical line would help prevent water droplets or snow from accumulating on the surface of the optical measurement window. The open-path gas analyzer is not sensitive to dust and pollen as long as the particles are small. But, if salt deposits exist, removal of salt deposits is required. For maintenance, internal chemicals consisting of Ascarite II (a carbon dioxide absorbent) and magnesium perchlorate (a desiccant) need to be recharged yearly. These chemicals keep the detectors free of H_2O and CO_2. Open-path gas analyzer is recommended as apposed to the close-path one because open-path gas analyzer does not use intake tube to prevent rain or snow from entering the sampling cell and pump to pull air that causes pressure drop in the analyzer. Also, the pump in the close-path analyzer requires high power consumption; therefore operating the close-path gas analyzer is a big challenge in remote locations such as forests (Burba 2013).
3) **Air temperature and relative humidity sensor:** The relative humidity sensor needs to be kept inside a radiation shield when it is used outside. The ground surface below the sensor needs to be natural earth or covered by short grasses for at least 9 m diameter. The sensor requires good thermal radiation protection and satisfactory ventilation. The sensor must be placed away from any nearby obstruction; it should be a distance of at least four times the obstruction's height and also at least 30 m from any paved areas. A radiation shield and the black screen at the tip of the sensor need to be checked for debris and contaminants. If installed nearby the ocean or bodies of salt water, a salt layer on sensor, filter, and radiation shield needs to be removed for an accurate measurement.
4) **Net radiometer:** The net radiometer consists of a pyranometer (measuring incoming and reflected solar radiation) and a pyrgeometer (measuring far infrared radiation from the sky and from the soil surface). No shadow should be cast on the net radiometer during the measurement. The net radiometer needs recalibration every two years. An indoor test using a lamp as a light source can be done. However, an outdoor test with more than 45 degrees of solar elevation above horizon is preferred.
5) **Soil heat flux plate:** At least two sensors are recommended for spatial averaging. A small shovel is used to slice the soil vertically and measure the depth of the soil profile from the ground for the desired heat flux plate location. The soil is cut horizontally in the soil profile with a small knife to bury the plate into the horizontal cut. The plate should be in a maximum contact with the soil for good measurements. Cover the hole with the soil after installation of plates and check monthly for rodent damage.

References

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