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Recommended Documentation of Evapotranspiration Measurements and Associated Weather Data and a Review of Requirements for Accuracy

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Abstract. *More and more evapotranspiration models, evapotranspiration crop coefficients and associated measurements of evapotranspiration (ET) are reported in the literature. These measurements base from a range of measurement systems including lysimeters, eddy covariance, Bowen ratio, water balance (gravimetric, neutron meter, other soil water sensing), sap flow, scintillometry and even satellite-based remote sensing and direct modeling. All of these measurement techniques require substantial experimental care and can be prone to substantial biases in reported results. Reporting of data containing measurement biases causes substantial confusion and impedence in the advancement of ET models and in the establishment of irrigation water requirements, and can translate into millions of dollars of economic losses caused by misinformed water management.*

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Journal reviewers and readers would benefit from more complete documentation of field procedures, assumptions, instrumentation, data filtering, and site review in order to discern the likely accuracy and representativeness of the report data and ET parameters, including crop coefficients. Documentation should include a description of the vegetation, its aerodynamic fetch, water management and background soil moisture, types of equipment and calibration checks, photographs of the measured vegetation / equipment combinations, and independent assessments of measured ET using models or other means. Documentation and assessment should include all weather equipment and parameters, including the vegetation and water management environment of the weather station.

Suggestions are given for documentation within the primary ET measuring systems including recommended independent testing and filtering. Lists of common biases endemic to the measuring systems are reviewed and upper limits for crop coefficients are proposed.

Keywords. Evapotranspiration, measurement, documentation, quality control, quality assessment, eddy covariance, Bowen ratio, lysimeters, sap flow, soil water balance.

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Introduction

Evapotranspiration (ET) is often modeled using weather data and algorithms that describe surface energy and aerodynamic characteristics of the vegetation. Similarly, ET is often measured using systems that employ similar principles or techniques. In common agricultural systems, where plant density, height, vigor and water availability are generally uniform, the application of these algorithms and measurement of ET are relatively straightforward, although they are not without substantial challenges. In the case of nonagricultural systems such as forests, desert and riparian, however, the heterogeneous nature of vegetation, terrain, soils and water availability make surface energy and aerodynamic processes highly variable and thus poorly defined. This is especially true, for example, for riparian systems such as cottonwood, tamarisk and Russian olive that can have widely varying vegetation density, tree height, stand extent and water availability. Therefore, most information and estimates of water consumption by forest and riparian systems come from in-place measurements and have a strong empirical flavor. Much ET data and ET models or model calibrations reported in the literature for even 'well-behaved' agricultural systems may have serious bias caused by biases in the ET measurement systems and/or in associated weather data.

Measurements of ET include a variety of methods ranging from soil water sampling to lysimeters to eddy covariance to scintillometry. Inherent to all of these methods, however, is the reality that an improperly designed experiment or measurement can lead to highly erroneous water use estimates. Many of the erroneously high estimates violate the law of conservation of energy that governs the conversion of liquid water to vapor during the transpiration and evaporation process. In other words, the environmental energy provided by solar radiation and heat energy advected to the vegetation is insufficient to explain the measurement.

Because of the wide range of complexities in making ET and associated weather measurements and the abundance of opportunities for biases to enter ET and weather data sets, users of ET literature should have sufficient information reported in articles on ET to assess the likelihood for opportunities of bias or error to enter reported data as well as sufficient information to examine or recreate the reported data using some type of ET model. This is often not the case, however, and many past and current journal articles do not contain sufficient information to enable readers to gauge accuracies and representativeness of information. This paper lays out some recommendations for the type and nature of useful documentation and description of information that should accompany ET findings reported in ET-related articles. ET measuring systems including water balance, lysimeters, Bowen ratio, eddy covariance, scintillometry, sap flow and remote sensing are described. In addition, some common errors, biases and shortcomings of common ET measuring systems are discussed to provide support for why the various information is needed.

ET Measurement

The following sections describe primary methods for measuring or deriving ET from extensive vegetation systems, and advantages and disadvantages of the methods and recommendations for best operation. The descriptions and lists of advantages and disadvantages should be used as a guide when evaluating reported data. A table near the end of this section gives estimated ranges of errors in ET derived from the various measurements. Ranges are given for expert and novice users. A second table lists the recommended metadata that should be recorded and reported in future studies of ET

Accuracy of described measurement systems can be good, but in many cases, knowledge of the underlying physics of turbulence and heat and radiation transfer that govern the measurement is essential to avoid subtle biases from degrading data. Systems are sometimes deployed by individuals who do not have sufficient background or experience, and, as a result, substantial measurement biases or extrapolations occur. Deployment of equilibrium boundary layer systems (eddy covariance, Bowen ratio and scintillometers) must adhere to fetch requirements and minimum equipment heights to produce representative and valid data. Energy balance methods such as Bowen ratio and scintillometry must incorporate representative measurements of net radiation and soil heat flux density, which generally requires multiple locations for these sensors, expecially when in spatially nonuniform systems such as riparian, forest, and other nonagricultural systems. Learned "corrections" must be made to eddy covariance and scintillometry measurements.

Lysimeters and soil water balance methods are older methods that can potentially provide dependable estimates, but only if fundamental requirements concerning representativeness of vegetation and environmental conditions.

The following sections briefly describe ET measuring systems and various issues and requirements associated with each to obtain integrity data.

ET using Change in Soil Water

Determining ET by measuring the change in soil water over a period of time has been used for nearly a century (Johns 1988). Up until the early 1960s, the primary measurement was by soil sampling and gravimetric analyses to determine the soil water content. Beginning in the 1960s, the neutron soil water probe largely replaced the gravimetric procedure except for evaluating soil water content in the surface 0 to 0.2, or 0 to 0.3-m layer and for calibrating the neutron probe. Since the 1980's, new types of electromagnetic devices based on dielectric and capacitance have been used to measure soil water content with sometimes mixed results.

A major potential source of error in ET determined by the soil water balance method is uncertainty in drainage from the zone sampled or the upward movement of water from a lower saturated zone into the zone sampled. These errors are difficult to detect, but they can be minimized with proper precautions. The soil is usually sampled 2 to 4 days after major precipitation event or irrigation and again 7 to 15 days later or just before the next major precipitation event or irrigation. The average rate of ET in mm d^{-1} between sampling dates is calculated as the change in total soil water plus effective rainfall minus any known drainage that may have occurred. However, the period immediately following the wetting event can potentially have higher ET rates relative to climatic demand caused by evaporation from wet soil and canopy. Therefore, the measured ET during the 'dry' interval may understate true ET. This can sometimes by corrected by simulating ET during and immediately following wetting events using an ET process model having an evaporation component, where basic vegetation parameters are calibrated using ET from the dry period.

Neutron probes and some electromagnetic devices use access tubes that are left in place and the water content at the same site is measured periodically. A major problem encountered is damage to plants around the access tube by technicians making the readings. Neutron probes measure water content in a sphere of soil with a radius of 0.5 m or less around the sensor, hence even minor damage to the plant community around the probe port will affect readings. Data obtained from sites with damaged plants will cause ET to be understated due to reduced transpiration from damaged or reduced leaf surface and due to reduced infiltration from compacted soil.

Time domain reflectometry (TDR), time domain transmission (TDT) and capacitance-based sensors and probes have become common for measuring soil water content directly or indirectly. Advantages of these electronic sensors are in-situ measurements with nearly continuous recording. Disadvantages and challenges include the relatively small volume of soil sampled (on the order of 1 cm extent from the sensor as compared to 0.1 to 0.5 m for neutron probes) and the possibility of a need to calibrate sensors for soil type. The small volume of soil sampled makes the influence of gaps and lack of contact between sensor and soil problematic (Evett and Steiner 1995).

Determining reliable ET rates by soil sampling is challenging for natural vegetation, especially trees, due to inherent spatial variability in soil water extraction relative to the small area sampled by the measurement technique. Therefore, these methods require adequate precautions such as: 1) using 6 or more sampling sites representative of general field conditions. Kamgar et al. (1993) described the number of neutron probe sites needed relative to plot size; 2) selecting sites where the depth to the water table is much greater than the root zone depth; 3) using only those sampling periods where rainfall is light since values for periods of high rainfall are questionable because runoff may occur and drainage may be excessive; 4) waiting at least 2 days after a moderate precipitation event (or normal irrigation) before taking the first sample, and longer if heavy rainfall or irrigation is involved and when the ET rate is small, but with correction for the surface evaporation occurring during and following the wetting event, and 5) using the active root zone depth for ET computations. Detailed discussions of the problems encountered in determining ET by soil sampling have been given by Robins et al. (1954), Jensen (1967), Jensen and Wright (1978) and Hignett and Evett (2002). General problems of soil sampling were discussed by Taylor (1955), Staple and Lehane (1962), Pratt et al. (1976) and Evett and Steiner (1995).

Typical Problems associated with estimating ET by root zone water balance using gravimetric, neutron scattering, capacitance, time domain reflectometry, or water potential measurement of soil water can involve inaccuracies caused by:

1) Spatial and vertical variability of bulk density and water holding characteristics of the soil so that measurements do not represent the area;

2) Possible deep percolation losses or gains by capillary rise;

3) The possible need for calibration of sensors for soil type;

4) For some vegetation types, perhaps the most serious problem with gravimetric, neutron-scattering, and electromagnetic methods is difficulty in obtaining samples or taking readings (or installing access tubes or sensors) without significantly altering the plant cover at the sampling site. ET from trampled plants is drastically reduced as compared to ET by plants in a pristine condition.

5) A related serious problem is the altering of density, aeration and infiltration characteristics of the surface soil. If water intake and/or aeration at and near the sampling site is quite different from general field areas, then plant growth is very likely to be affected. This may reduce soil water extraction, leading to estimated ET unrepresentative of actual field ET.

6) Differential spatial wetting of soil due to spatial variation in precipitation (or irrigation) additions, for example undertree, beneath the drip line, or between trees

7) Differential spatial extraction of soil water due to spatial variation in root systems, for example with trees.

Mass Balance

For large, integrated areas of land and water, the water balance technique, also referred to as the inflow-outflow or mass balance method has been used. Examples of ET by water balance are applications to large areas such as valleys in which the inflow and outflow are determined from stream flow and precipitation measurements, and where the basin is confined to eliminate other significant sources of inflow or outflow such as groundwater underflow (Lowry and Johnson 1942). Such studies generally provide only gross seasonal estimates of the average water evaporated and transpired from cropped and noncropped areas within a project. The results represent ET from a combination of vegetation types and are generally applicable only to climatic, vegetation and water availability conditions similar to those existing in the study area. An evaluation of large-scale models of an experimental catchment (watershed) and a river basin in Australia indicated satisfactory agreement in monthly values between the computed and measured ET (Dunin and Aston 1984). Wilson et al. (2001) found good agreement between ET derived from an inflow-outflow analysis of a 98 ha forested watershed and eddy covariance methods in Tennessee.

Lysimetry

Lysimeters have been used extensively to provide baseline information for development, calibration, and validation of ET methods (Makkink, 1957; Jensen, 1974; Doorenbos and Pruit, 1977; Wright, 1981, 1982; Allen et al., 1989; Jensen et al., 1990). Unfortunately, lysimeter measurements of ET are extremely sensitive to environmental factors, many of which are often poorly understood or have been ignored in practice. Lysimeter measurements are point measurements, representing measurements of ET from areas generally ranging from 0.05 to 40 m^2. However, a common usage of lysimeter measurements is to characterize ET from large areas. Because of this extrapolation of data from small to large areas, it is paramount that vegetative and environmental conditions of lysimeter systems closely duplicate one-dimensional evapotranspiration from the larger areas.

Insufficient description and documentation of environmental conditions and management of lysimeter data reported in the literature have led to uncertainty and confusion as to the quality and representativeness of reported data sets. Consequently, many poor and non-representative data sets of lysimeter ET reported in the literature have been used in important ET studies (Jensen, 1974), leading to inaccurate and misleading conclusions and with significant economic consequences. High resolution of precision lysimeter systems can give scientists and data users false senses of security concerning the quality and value of collected data. Values of 0.02 to 0.55 mm are commonly cited as “resolutions” and “precisions” of weighing lysimeter systems (Aboukhaled et al., 1982; Lourence and Moore, 1991; Howell et al., 1991), although, if improperly managed from an environmental context, measured ET can differ from actual ET from a one-dimensional extensive system of vegetation by as much as 50 to 100 percent. Machine and system precision never substitute for nor negate the need for environmental representativeness.

Lysimeters can be grouped into three categories: 1) nonweighing, constant water-table type that provide reliable data for weekly or longer time periods in areas where a high water table normally exists and where the water table level is maintained essentially at the same level inside as outside the lysimeter; 2) nonweighing, percolation type, in which changes in water stored in the soil are determined by sampling or neutron methods and the rainfall and percolate are measured (often used in areas of high precipitation); and 3) weighing types, in which changes in soil water are determined either by weighing the entire unit with a mechanical scale, counter-balanced scale and load cell, directly suspended by load cells, or by supporting the

lysimeter hydraulically. Weighing lysimeters, if well managed, will provide the most accurate data for short time periods. ET can be determined accurately over periods as short as 30 minutes with a mechanical scale, load cell system, or a floating lysimeter. Hydraulically weighed lysimeters generally are not accurate for periods less than 24 hours due to thermal and pressure effects. A detailed summary of the use of lysimeters for ET can be found in publications by Harrold (1966), Aboukhaled et al. (1982), Howell et al. (1985), Marek et al. (1988), and Pruitt and Lourence (1985). The proceedings of an international symposium on lysimetry organized by ASCE (Allen et al. 1991b) provides many examples of poor lysimeter systems along with guidelines for the operation of lysimeters to assure high quality data for ET and related environmental purposes.

Weighing lysimeters are isolated blocks of soil or tanks filled with soil suspended on a weighing mechanism in which vegetation is grown under natural conditions. The amount of water lost by evaporation and transpiration is based on the change in weight of the lysimeter. This method provides a direct measurement of ET and is frequently used to study climatic effects on ET and to evaluate estimating procedures. However, lysimeter data may not be representative of natural or field conditions. Soil conditions inside the lysimeters must be essentially the same as those outside to insure that the vegetation density, water availability, vigor and thus ET are the same. The lysimeter must be surrounded by the same vegetation that is growing in the lysimeter to insure one-dimensionality of the measurement (Allen et al. 1991a). The lysimeter should be located within an open area of the same vegetation type, density and height. Studies of advection at edges of fields suggest that the lysimeter should be located at least 100 m from the edge of the field or particular stand of vegetation.

Lysimeters surrounded by sidewalks or gravel will not provide reliable data, nor will lysimeters planted to a tall vegetation if surrounded by shorter vegetation, or planted to short vegetation and surrounded by a taller vegetation. Differences in growth and maturity between the lysimeter plants and surrounding plants and resulting ET measured in the lysimeter relative to ET measured in the surrounding area can be significant (Pruitt and Lourence 1985). Some high crop coefficients (equivalent to ET_oF, defined as the ratio of ET to reference ET_o) reported in the literature may have been the result of such differences in plant growth between the lysimeter and the surrounding field or vegetation stand.

Some of the very seriously-flawed lysimeter results have been produced by a so-called "bloom effect" on small lysimeters where the area of exposed plant canopy has exceeded the assumed effective area of the lysimeter. Tanner (1967) provided an excellent discussion on lysimeters, and was probably one of the earliest to recognize how serious this problem can be. Coverage of this and other aspects of lysimetry was detailed by King et al. (1956), Pruitt and Lourence (1985), Meyer and Mateos (1990) and by Allen et al. (1991b). Examples are frequent in the literature of so-called crop or pan coefficients ranging from 1.5 to 1.8 or even higher. H.L. Penman's early comment may be a bit unrealistic (crop evaporation should never exceed evaporation from an open water surface); however any reported ET that is greater than 1.1 or so times ET for the tall (alfalfa) reference of ASCE-EWRI (2005) or that is greater than 1.4 or so times ET for the short (clipped grass) reference of ASCE-EWRI (2005) and FAO-56 for weekly or longer-periods, should lead to a strong suspicion that the ET determinations (whether by lysimetry or meteorological techniques) are in error, or that they represent conditions other than continuous expanses of vegetative surfaces. The same cautionary statement could be applied in the case of findings of crop coefficients that are greater than 1.1 for use with alfalfa reference ET or greater than 1.3 to 1.4 for use with grass reference ET. These limits are due to energy availability constraints for evaporation and adherence to the law of conservation of energy. ET rates that exceed available radiation energy (R_n) less conducted sensible heat to the ground (G), i.e., R_n-G, must extract the additional energy from the atmosphere via downward

(negative) sensible heat (H) through the equilibrium boundary layer. Because increasingly negative H creates increasingly density-caused buoyant stability, it becomes increasingly difficult to transport the H to the surface to support the conversion to ET, especially without strong mechanical mixing brought about by high wind speed. As a result there is an upper limit on ET caused by the transport and equilibrium forces that is relatively well represented by the tall (alfalfa) reference.

Allen et al. (1991a) described the more common environmental problems that beset lysimeter measurements and that cause lysimeter measurements of ET to deviate from one-dimensional ET measurements characteristic of extensive natural and agricultural environments. Effects of these environmental violations are significant and often invalidate lysimeter measurements for engineering or scientific use. Common environmental problems include two-dimensionality of lysimeter boundaries, vegetation height and density differences, variation within immediate and local fetch around the lysimeter and weather station, thermal conditions of the lysimeter soil block, bulk density and lysimeter depth effects on root development, and effects of the moisture profile or water table within the lysimeter on evaporation and moisture extraction. Allen and Fisher (1990) listed nine recommendations to help preserve the environmental integrity of a lysimeter installation.

When calculating ET in units of depth, the change in lysimeter mass must be divided by the effective evaporating and transpiring area of the lysimeter. This area is often larger than the physical area of the lysimeter due to vegetation extending outside the lysimeter or due to micro advection of energy, via convection or thermal radiation, from immediately outside the inner lysimeter tank to inside. Incorrect estimation of the evaporating area of a lysimeter is probably the most common error made in computing lysimeter evapotranspiration. For example, if a lysimeter is constructed 1 m square, inside, and has a 10 cm total boundary thickness (including bother inner and outer tanks, if present), the average vegetative and evaporating area can be approximated as 1.1 m x 1.1 m. The 1.1 m length is the average dimension of the inner and outer parts of the lysimeter, and is a reasonable approximation, if vegetation from both inside and outside the lysimeter reach across the lysimeter rim and meet midway between outer and inner tanks. The ratio of vegetative area to inside area in this example is $1.1^2/1.0^2$ or 1.21. In other words, lysimeter measurements of ET, if based on the inner dimension of the lysimeter, only, which is a common error, would be overstated by 21 percent. This type of adjustment is often needed for all types of lysimeters, including weighing and water-table types. The bias in reported ET is further exacerbated if the vegetation outside is not identical to that inside the lysimeter and if the outside vegetation does not grow right to the lysimeter edge. Otherwise, a 'bloom' condition can occur, where if the vegetation inside the lysimeter is taller, it will absorb even more solar radiation and be subject to increased turbulent penetration of air, and the effective area of ET is even larger.

The occurrence of dissimilar or missing vegetation directly outside the lysimeter is all too common in practice. In these situations, determination of the true, equivalent area of transpiring vegetation may be complicated by mismatched "leaning" of inside and outside vegetation across lysimeter borders. Outside vegetation leaning into the lysimeter "robs" evaporative energy from the inside vegetation, whereas, inside vegetation leaning outside the lysimeter increases evaporative energy via solar radiation interception and water extraction by the lysimeter system increases. Height and vegetation density differences between the lysimeter and outside vegetation can severely affect lysimeter measurements. One such effect is commonly referred to as the "clothesline" effect, where, due to the taller nature of lysimeter vegetation or increased leaf area, both aerodynamic and radiative transfer to the lysimeter canopy are increased, resulting in increased ET from the lysimeter area. Increased vegetation height within a lysimeter can result from dissimilar fertilization practices, thermal characteristics of the lysimeter

tank, differences in soil moisture regimes inside and outside the lysimeter, or due to reduced plant growth outside the lysimeter caused by foot or vehicle traffic, soil compaction, moisture availability or plant density. Taller vegetation receives evaporative energy not only in the vertical, one-dimensional plane, but also receives side loading of radiation and substantial increases in turbulent exchange of vapor and heat. This side loading significantly alters lysimeter measurements from the one-dimensional case and eliminates them from consideration for agricultural representation. The smaller he lysimeter area, the more pronounced the effect.

One disadvantage of lysimeter systems is that the soil profiles are commonly more shallow than surrounding agricultural soil profiles. As a result, drainage and soil moisture profiles may differ. Often soil profiles of lysimeters may be more moist than surrounding soils. These profiles may effect the total availability of water to plant roots and subsequently the ET process. They may also affect root development, where a water table has been established both inside and outside of the lysimeter, but at different elevations. Presence of a shallow water table or excess moisture in a lysimeter used for soil evaporation studies may also affect results.

Riparian phreatophytes such as tamarisk present a special problem in lysimeter studies. Under normal conditions they are rooted into an aquifer which might be several meters deep, and transpiration can be limited by soil properties such as hydraulic conductivity. In shallow lysimeters they may be exposed to permissive conditions that elevate ET well above normal field values. These problems are likely responsible for early estimates of tamarisk ET in the range of 3-4 m/yr based on lysimetry.

Black et al. (1968) and Dugas and Bland (1991) cautioned against negative impacts of thermal conduction of heat along metal lysimeter container walls that significantly warms the lysimeter soil, especially over long time periods in arid environments. This unnatural heat source can cause drying of the soil profile under bare soil conditions that exceeds that under natural conditions. It can also promote earlier and more extensive root growth and respiration within the lysimeter tank. Black et al. (1968) recommended insulation of the lysimeters. This is especially important for desert environments.

Bowen Ratio Energy Balance (BREB)

The Bowen Ratio Energy Balance (BREB) method is a practical and relatively reliable micro-meteorological method. Use of the BREB concept (Bowen, 1926) enables solving the energy balance equation by measuring simple gradients of air temperature and vapor pressure in the near surface layer above the evaporating surface. The method works best when soil water is not limiting ET. As water becomes less readily available, the Bowen ratio (BR) increases, and the relative error in ET increases (Angus and Watts 1984). Todd et al. (1998) and Devitt et al. (1998) reviewed ET studies based on BREB. Ohmura (1982) and Payero et al. (2003) described relative errors associated with the BREB method as well as techniques for data quality analysis. Important advantages of the BREB method are the ability to measure ET even from non-potential surfaces, the elimination of wind or turbulent transfer coefficients, and absence of surface measurements. The disadvantages are sophistication and fragility of sensors and data logging equipment, the numerical instability of eq. 1 during periods of β near -1, and the heavy reliance of the ET estimate on the accuracy and representativeness of the R_n and G measurements. The requirement for adequate upwind fetch to establish an equilibrium boundary layer where temperature and vapor gradients are constant in horizontal space places substantial and important limits on the method. Details on BREB computations can be found in chapter 4 of the ASCE Hydrology Handbook (Allen et al. 1996).

The BREB equation for application to vegetation is:

$$\lambda E = \frac{R_n - G}{1+\beta} \tag{1}$$

where λE is ET expressed in terms of energy, R_n is net radiation, G is soil heat flux density and β is the Bowen ratio. Given equivalent transport coefficients, β can be expressed in a finite difference form as:

$$\beta = \frac{H}{\lambda E} = \gamma \frac{[T_2 - T_1 + \Gamma(z_2 - z_1)]}{e_2 - e_1} \tag{2}$$

where H is sensible heat flux density, T_2 and e_2 are air temperature and vapor pressure at height z_2 and T_1 and e_1 are air temperature and vapor pressure at height z_1. γ is the pyschrometric constant and Γ is the adiabatic lapse rate, generally taken as 0.01^{o}C m^{-1} for nonsaturated air. Generally the z_1 height should be at least 0.3 m above the crop canopy for a smooth, dense canopy, and should be placed further above the canopy for tall, sparse crops where microscale turbulence among individual plants and differences between source locations for heat and evaporation can disturb exponentially shaped temperature and vapor profiles. Generally, the z_2 height is 1 to 2 m above z_1.

Generally, λE is computed each 20 to 30 minutes and summed over a daylight or 24-hour period to provide daily estimates of ET. Problems with naturally aspirated (exposed) thermocouples include contamination by dust and spider webs that increases radiation loading and thermal bias between T_1 and T_2. Other types of errors associated with BREB measurements are described by Sinclair et al. (1975).

The net radiation measurement in the BREB calculation (and other energy balance closure systems) should be made from an elevation high enough to measure an average representative surface condition similar to that upwind of the measurements. Because of the direct role that R_n plays in the λE measurement, multiple R_n sensors are recommended for improved spatial sampling and quality control. In heterogenous vegetation cover having vegetation type variation on the scale of tens of meters, multiple net radiation systems should always be employed. Idso and Crooley (1971, 1972) and Idso et al. (1974) provided guidance on net radiometer positioning and error analysis. Baldocchi et al. (2000) described a traversing net radiometer system for obtaining a spatially averaged R_n over forest. Anthoni et al. (2000) used ray tracing and rendering software to simulate impacts of differential surface temperature and reflectance in a juniper forest on spatially averaged hemispherical net radiation. Similar challenges exist over agricultural row crops, including orchards and vineyards where soil surface and canopy temperatures can deviate by 30 K so that the total hemispherical R_n measurement can be substantially impacted by sensor positioning. A 30 K difference in surface temperature can cause as much as 100 W m^{-2} difference in emitted long-wave radiation, and thus, 100 W m^{-2} difference in the measured R_n. The user must be aware that the R_n sensor 'sees' in a 360° field of view both horizontally and vertically. Therefore, it will 'see' and be impacted by temperature and reflectance of objects within its view. A R_n sensor will not 'magically' provide accurate and representative R_n measurements simply because it is new and plugged into a datalogger. It must be placed in a proper representative environment.

Soil heat flux density is generally measured at 0.08 to 0.15 m below the surface using soil heat flux plates (Campbell Scientific 2003; Ham 2001). The 0.08- to 0.15-m depth range is recommended to insure that the soil flux density is measured below the zone of soil water vaporization (Ham 2001) and to reduce the influence of vertical conduction of heat near the soil heat flux plate. Sensible heat absorption and release above soil heat flux plates is estimated by measuring soil temperature change above the plate at multiple depths and at multiple locations. Generally, two or more installations of soil heat flux systems are made per BREB site to reduce effects of spatial heterogeneity and to improve representation for the area. The corrected soil heat flux density, G, is computed by combining the heat flux measured by the heat flux system. In some cases, soil heat flux plates have been placed at more shallow depths, for example at 1 cm by Baldocchi et al. (2000) and 2 cm by Anthoni et al. (2000) under forest. The shallow placement depths reduce the uncertainty and errors associated with correcting for soil temperature change above the plate. However, the shallow placement may introduce much larger error associated with differences in thermal conductivity of the plate and soil, which can cause the heat flux to diverge around the plate or converge through the plate. An even larger problem is caused by the impedence of movement of soil water around the plate during infiltration, which becomes more pronounced as the plate is placed closer to the surface.

Because G is quite sensitive to heating of the surface, which in turn is governed by surface wetness and surface shading, soil heat flux stations are needed in both sunlit and shaded portions of the soil. Further, stations should be located in both wet and dry environments, for example, under a canopy and in the open. In wild, heterogeneous systems having a range of vegetation types, further sampling may be needed. In forest and riparian situations, the number of soil heat flux sites needed to provide sufficient sampling of G may exceed 20.

Whether or not correction is needed for air stability conditions in the use of the Bowen ratio-energy balance measurements is open to question. Most of the evidence suggests that correction for stability is not needed, due to nearly equal impact on both λE and H, so that the usual assumption of the near-equality of transfer coefficients for heat and water vapor throughout a wide range of stability conditions is realistic (Cellier and Brunet 1992). However, the major source elevations for λE and H in the canopy should be similar for the transfer coefficients for the two processes to be nearly the same (Tanner 1967).

The Bowen ratio method is recognized as one of the most accurate ET measurement methods if R_n, G, and the gradients of temperature and humidity can be accurately measured, are spatially representative, and β is small. For tree crops and forest canopies, accurate measurement of the gradients at a height far enough above the canopy to avoid effects of individual trees is difficult due to the very small gradients involved. Nevertheless, the Bowen ratio method has served and continues to serve as one of the major methods employed for forest research (McNaughton and Black 1973; Thom et al. 1975; McIlroy and Dunin 1982; Denmead and Bradley 1985; Fritschen and Simpson 1985; Dunin et al. 1985, 1991). Accuracies of well-designed and operated BREB systems have been estimated to be approximately 10% (Sinclair et al. 1975; Seguin et al. 1982). A disadvantage is the need to measure R_n and G, which can be problematic under some conditions such as with sparse or heterogeneous vegetation, and over water surfaces.

Requirements of the Bowen Ratio method are:

- uniform fetch of sufficient distance to establish an equilibrium boundary layer (EBL) deeper than the z_2 height (this is often violated)
- sufficient elevation above canopy to reduce roughness sublayer impacts

- representative measurement of R_n and G
- heterogeneous or sparse systems common to riparian vegetation generally require multiple net radiometers and soil heat flux stations

Advantages of Bowen Ratio systems are:

- nondestructive, direct sampling of the turbulent boundary layer
- no aerodynamic data are required
- simple measurement of T and vapor pressure e at two heights
- can measure ET over both potential and non-potential surfaces
- fluxes are averaged over medium sized area
- automated

Disadvantages of Bowen Ratio systems are:

- accuracy of ET excels and fails with representativeness and accuracy of R_n and G
- assumes that transfer coefficients for H and LE are equal (therefore sources for heat and vapor are similar)
- numerically unstable when H is near zero (however, this is usually a minor problem)
- measurements of T and e must be unbiased because ΔT and Δe can be small.
- requires large fetch
- narrow riparian systems may cause the Bowen ratio system to sample ET from areas upwind of trees (for example, pasture, desert or agriculture)

Recommendations for deployment of net radiometers

- mount over representative vegetation away from any obstructions including
- away from towers
- away from above or below other instruments including bright, white sonic anemometers
- away from above or below dark, hot solar panels
- Deploy a minimum of three R_n sensors in separate locations when over complex or sparse canopies
- mount to view the true proportion of sunlit vegetation, shaded vegetation, sunlit soil and shaded soil
- multiple towers for R_n may be needed.
- Deploy a minimum of six soil heat flux measurement systems under the same conditions
- Use some independent means for testing R_n measurements (remote sensing based R_n estimate, infrared thermometers, modeling with standardized solar radiation-based algorithms, etc.)

Eddy Covariance

Eddy covariance (EC) systems are becoming relatively widely used in ET measurement because of ease of set up, reduced costs for sensors, and the ability to co-measure *H*, *λE* and CO_2 fluxes, depending on the equipment configuration. EC applications require high frequency sampling of the surface boundary layer using the statistical relationship (Swinbank 1951):

$$\lambda E = \rho_a \overline{w'q'} = \frac{0.622}{P}\rho_a \overline{w'e'} \tag{3}$$

Where ρ_a is air density, P is atmospheric pressure, q' is the instantaneous deviation of specific humidity from mean specific humidity (q), e' is the instantaneous deviation of vapor pressure from mean vapor pressure (e), and w' is the instantaneous deviation of vertical wind velocity from mean vertical wind velocity (w). The overbar indicates means of the products of the instantaneous deviations over 15 to 30 minute averaging periods. The concept of eddy covariance (also referred to as eddy correlation) draws on the statistical covariance (correlation) between vertical fluxes of vapor or sensible heat within upward and downward legs of turbulent eddies. This requires high speed measurement of *T*, *w*, and *e* or *q*, usually at frequencies of 5 to 20 Hz (5 to 20 times per second) using quick response sensors. Ten Hz is common. Early examples of eddy instrumentation were described by Tanner (1988) and Tanner et al. (1993). Since then, many advances in instrumentation have been made and this method is now widely used as described by Wilson et al. (2002), Baldocchi (2003) and Shaw and Snyder (2003).

Residual *λE* can also be computed from the energy balance equation as $\lambda E = R_n - G - H$, where sensible heat flux density is measured by eddy covariance as:

$$H = \rho c_p \overline{w'T'} \tag{4}$$

where c_p is specific heat of moist air, and T' is the instantaneous deviation of air temperature from mean temperature (T).

The vertical component of wind, *w*, is generally measured using a sonic anemometer and *T* is measured using ultra fine wire thermocouples or using sonically determined temperature corrected for humidity effects. Specific humidity is measured using quick response hygrometers such as Lyman-alpha, Krypton or other open path hygrometers or using closed path gas analyzers (Buck 1976; Campbell and Tanner 1985; Tanner 1988). All measurements must be made at nearly the same point in order to measure characteristics of the same eddy. For open path hygrometers, corrections must be made to *λE* measurements to correct for temperature and humidity effects on air density of up and down portions of eddies (Webb et al. 1980). Other corrections are required for instrument separation, frequency response, coordinate rotation and to account for the type of hygrometer (Baldocchi et al. 1988; Tanner et al. 1993; Moncrieff et al. 1996; Villalobos 1997; Twine et al. 2000; Aubinet et al. 2000, Paw U 2000; Massman 2000; Sakai et al. 2001; Rannik 2001; Massman 2001; Wilson et al. 2002). Coordinate rotations include those by Tanner and Thurtell (1969), Kaimal and Finnigan, (1994), and Wilczak et al., (2001). Sonic temperature correction is done following Munger and Loescher (2004), air moisture correction following Sun et al. (1995), impacts of density terms following Webb et al., (1980), and correction for pathlength averaging, sensor separation and high frequency spectral losses following Moore (1986). Paw U et al. (2000) introduced corrections for advective effects and converging or diverging flow lines. A variety of software programs for correction of EC data have been produced, including ECPack from Wageningen University, TK2 software of the

University of Bayreuth (Mauder and Foken, 2004), EddySoft developed at the Max-Planck-Institute for Biogeochemistry in Jena (Kolle and Rebmann, 2007), EdiRE software from the University of Edinburgh, and APAK by Oregon State University (Vickers and Mahrt, 1997, 2003). These software packages include a mixture of the corrections listed. In addition to these correction 'issues' are issues related to flux divergence in the equilibrium boundary layer, nonuniform vegetation or moisture conditions in the source area (i.e., footprint), nonrepresentative sensing of R_n and G, and improper averaging times.

Much literature has appeared during the past fifteen years documenting energy balance 'closure error' for eddy covariance (EC) data that indicate undermeasurement of latent heat flux (LE) and sensible heat flux (H) by those systems to be as much as 30% (Twine et al. 2000, Wilson et al. 2002, Foken 2007) even after extensive 'correction'. Wilson et al. (2002) found an average of 20% closure error at 22 *Fluxnet* sites over mostly forest, but including tundra, rangeland and agriculture.

Computing λE as a residual of the energy balance by measuring H so that $\lambda E = R_n - G - H$ has the advantage of eliminating the requirement for the quick response hygrometer, which can be expensive, can require frequent maintenance, and can create high frequency fallout caused by sensor separation from the sonic anemometer. The disadvantage of estimating λE as a residual is the need to measure R_n and G accurately, which can be problematic under some conditions such as with sparse or heterogeneous vegetation, and over water surfaces. The energy balance residual equation can be used in an energy balance closure check on eq. 3. Allen and Tasumi (2005) combined H determined from eddy covariance with Bowen ratio from a BREB system to determine λE from open water without the need to measure or estimate G of water.

In general, the eddy correlation method requires personnel who are well-trained in electronics, turbulent theory, and biophysics. Instrumentation is relatively fragile and expensive. Lack of energy balance closure is common with eddy covariance measurements, where the sum of measured $\lambda E + H$ does not equal measured $R_n - G$ (Baldocchi et al. 1988; Twine et al. 2000; Wilson et al. 2002). Possible reasons for the lack of closure are storage of heat in canopies, horizontal advection, energy used by photosynthesis, change in storage of heat in the developing boundary later below the instrumentation (causing flux divergence), and frequency response. Additional detail on the eddy correlation method can be found in articles by Dyer (1961), Businger et al. (1967), McBean (1972), Brutsaert (1982), and Weaver et al. (1986), Twine et al. (2000), Wilson et al. (2002), Shaw and Snyder (2003) and Baldocchi (2003).

Eddy covariance has disadvantages similar to other boundary layer sampling techniques, including complex instrumentation and fetch requirements. The sonic anemometer must be set parallel to the surface so that no component of wind speed parallel to the surface biases measurements. If not set parallel to the surface, coordinate rotation must be applied.

Requirements of the eddy covariance method are:

- uniform fetch of sufficient distance to establish an equilibrium boundary layer (EBL) deeper than the instrument height (this is often violated)
- sufficient elevation above canopy to reduce roughness sublayer impacts
- various "corrections"

Advantages of the eddy covariance method are:

- nondestructive, continuous direct sampling of the turbulent boundary layer

- can measure ET over both potential and non-potential surfaces
- fluxes are averaged over medium sized (50 to 200 m) paths
- automated

Disadvantages of the eddy covariance method are:

- a number of “corrections” are needed – these are not well sorted out
- may miss transport by very small and very large eddies
- energy balance closure error (R_n-G=LE+H) can be 10-30%
- requires substantial fetch, generally 50 to 100 times the height of the instrument above the zero plane displacement height
- narrow riparian systems may cause the EC (or Bowen ratio) system to sample ET from areas upwind of the riparian area (for example, pasture, desert or agriculture that is beyond the riparian system)
- requires consistent, near horizontal flowlines
- change in vertical direction of flowlines during an averaging period causes large errors (portions of the streamline cam be misinterpreted as w' (relative to mean vertical wind speed) so that $w'T'$ or $w'q'$ are grossly overstated)
- this occurs when
- sensors are too close to roughness elements such as tree limbs
- ‘surface’ of vegetation is irregular, for example, a convex shaped riparian system where the shape and vertical components of streamlines change with respect to wind direction
- problems in eddy formation if sensors are too close to the surface or too close to individual roughness elements
- can be biased by dissimilar upwind vegetation if fetch is too small
- difficult to know impacts of wind direction changes on any change in vertical components of flow lines
- should not be used for understory measurements
- vertical components of streamlines can easily change with wind direction as wind direction changes
- mounting of net radiometer is difficult for representative sampling
- mounting arm and other nearby equipment, including the hygrometer, can impede and distort flowlines and eddy shapes for some wind directions
- Tower or scaffolding may bend and distort flowlines
- Instrumentation is relatively fragile and expensive
- the method requires personnel who are well-trained in electronics, turbulent theory, and biophysics

Fetch Requirements

It has generally been suggested that upwind fetch for boundary layer instrumentation be on the order of 100 m for each m of z_2 above the top of the zero plane displacement height of the surface (Brutsaert 1982) to insure establishment of an internal equilibrium boundary layer that is representative of the surface energy exchange being measured. This means that there should be 100 m of upwind distance of the vegetation for every meter above the ground up to the uppermost temperature and/or humidity sensor. Monteith and Unsworth (1990) recommended that a fetch of 50 to 1 is often adequate for micrometeorological measurement of sensible and latent heat flux. Brutsaert (1982) has provided theoretical considerations of boundary layer development that can be used to estimate minimum fetch requirements as a function of surface roughness (or vegetation height). Table 1 from Allen et al. (1996) shows estimates from Brutsaert's equation in terms of minimum required fetch for a variety of vegetation types. Brutsaert's equation assumes near-neutral stability of the equilibrium boundary layer. Generally, as H and instability of the EBL increase, the required fetch length decreases.

TABLE 1. Minimum Recommended Upwind Fetch Distances, m, for Various Types of Surface Cover (from Allen et al. 1996).

Height and Type of Surface Cover	Height of the eddy covariance or upper bowen ratio measurement above the ground			
	z = 1 m	z = 2 m	z = 3 m	z = 12 m
Water (d = 0, z_{om} = 0.0001 m)	180	400	630	3,000
0.12 m Grass	80	190	300	1,500
0.5 m Alfalfa	45	130	220	1,200
1.5 m Cattails	--	60	140	950
10 m Dense Trees	--	--	--	320

The values for minimum fetch in table 1 follow the 100:1 rule for a relatively wide range of vegetation and equipment heights. As an example of application, for a Bowen ratio installation with the z_2 height at 2 m above the ground surface having 0.1 m tall vegetation, the recommended minimum fetch requirement under neutral conditions is approximately 190 m. For 10 m tall trees, even with the upper Bowen arm as close as 2 m above the tree height, a minimum of 320 m of upwind fetch (i.e., of the same type and height of trees) is recommended. The fetch requirement, which increases as vegetation height increases, makes it difficult to use the BREB, eddy covariance and other boundary layer sampling systems to measure λE from narrow or isolated stands of vegetation.

Additional guidelines on fetch requirements for BREB measurement were given by Heilman et al. (1989) and a number of publications describe a variety of models for estimating footprints for both scalar and flux measurement. The 'footprint' of a flux or scalar measurement represents the upwind surface area that is statistically responsible for the conditioning of the measurement (Hsieh et al. 2000). Schmid (2002) presented a good review of various models, their mechanics and limitations. An expression for estimating the fraction of λE sensed at a specific instrument height that is generated from a specific distance of upwind fetch was presented by Gash (1986), Schuepp et al. (1990), and Shuttleworth (1992) and repeated by Allen et al. (1996). Horst and

Weil (1992), Hsieh et al. (1997), Leclerc et al. (1997), Schmid (2002) and Hsieh et al. (2000) applied Lagrangian stochastic and large eddy simulation (LES) strategies along with Gaussian or non-Gaussian diffusion assumptions to estimate three-dimensional distribution of point source or line source fluxes. These complex models were applied under various stability conditions to demonstrate sensitivities of flux and scalar measurements under various footprint conditions and discontinuities in fetch at various distances from the sensors.

Remote Sensing-Energy Balance

New techniques using satellite imagery have been developed since about 1990 to estimate E and ET from large areas using energy balance (Bastiaanssen et al. 1998a,b, 2005; Kustas and Norman, 1999; Kustas et al. 2003; Moran 2000). The emerging technology of energy balance by satellite shows substantial promise for coverage of large areas and a wide range of vegetation types and water availability. The approach has been used to quantify and illustrate population variance in ET from the same vegetation type and to refine ET_oF (fraction of reference ET_o, equivalent to the crop coefficient) curves (Tasumi et al. 2005a; Anderson et al. 1997, 2005; Kustas et al. 2003; Kustas and Norman, 1999; Li et al. 2005; Norman et al. 1995, 2000, 2003; Allen et al. 2007a,b, Tasumi and Allen 2007). Remotely sensed energy balance techniques are useful for identifying areas experiencing water stress and corresponding reductions in ET. However, users of this information must bear in mind that satellite-based ET data are simply retrievals, or best estimates, of an aerodynamic and radiative process as viewed from space.

The more 'operational' satellite-based energy balance models such as SEBAL (Bastiaanssen et al. 1998a,b, 2005) and METRIC (Allen et al. 2007a,b) employ an internal calibration technique referred to as CIMEC ('calibration using inverse modeling at extreme conditions') (Allen et al., 2008). The CIMEC technique involves the calibration of the energy balance process, in the form of sensible heat flux, H, by specifying ET and thus the energy balance equation at two extreme conditions (dry and wet) in the satellite image. These values for ET are known to the model operator based on estimates of available energy and surface conditions at the two endpoints. The purpose of the CIMEC calibration is to imbed all biases in R_n, G and other intermediate components that are endemic to satellite-based calculations into the estimate and calibration of H. These biases are in turn removed when ET is computed for the millions of pixels as $ET = R_n – G – H$, where H is function of surface temperature.

SEBAL, METRIC and similar models are 'working', operational models whose objective is to produce consistent and dependable maps of ET over areas of about 20,000 km^2 (the size of a Landsat scene). The sensible heat flux estimates, H, because they tend to contain artifacts of biases in estimates for R_n and G that are entrained during calibration, are not considered to be absolutely accurate. However, the model objective, which is the production of spatial estimates for ET, is enhanced by the bias-entraining calibration. Ordinarily, surface energy balance models that do not apply endpoint calibration will be much more impacted by the various biases that can plague satellite-based component estimation.

Advantages of satellite-based energy balance models

- the energy balance yields actual ET
- the process covers large areas, with improved sampling and integration over diverse areas
- they are generally more economic than point measurements
- products can have high spatial resolution (30 m for satellite, 2 to 5 m for aerial)
- they are valuable for determining spatial variation in ET for riparian systems

Disadvantages of satellite-based energy balance models

- temporal coverage if satekkute unages is only periodicm for example, every 16 days for a Landsat satellite
    - evaporation from precipitation events may be missed, or may bias seasonal estimates
- aerial data collection can be expensive
- satellite pixels over narrow riparian systems may overlay a broad mixture of vegetation and surface temperature regimes so that the ET signal is difficult to interpret
- uncertainty in aerodynamics (need to use 'inversion' techniques to calibrate)
    - most remote-sensing energy balance processes assume 1-D aerodynamics
    - this may not hold true for narrow, tall riparian systems
        - aerodynamic exchanges in riparian systems may be three-dimensional
        - therefore, flowlines are poorly behaved
        - Klaassen et al. (2002) found that horizontal penetration of heat into the leading edge of a forest canopy increased available energy by 15% over first 400 m of canopy
        - Klaassen and Sogachev (2006) suggested that flux measurements over riparian systems should be corrected for impacts of horizontal variations in turbulence downwind of the edge.
        - This impacts nearly all measurement systems that use aerodynamics or energy balance (EC, scintillometry, remote sensing based EB), even sap flow due to change in transpiration with distance into riparian system
- satellites view a pixel from a fixed angle
    - Landsat is always nearly nadir (directly overhead)
    - MODIS has a large scan angle, therefore, its view angle varies from -55 to +55 degrees
    - the satellite (and aerial) measurement of reflectance is 'bidirectional' whereas - the reflectance needed in energy balances (for R_n) is directional-hemispherical
    - bidirectional reflectance may be lower than directional-hemispherical reflectance for tall canopies containing shadows, especially at lower sun angles and for nadir looking satellites
    - potential bias in albedo and surface temperature for tall canopies may cause overstatement of ET by 5 to 10% *(this is unclear and needs investigation)*
- potential biases in retrieved albedo and surface temperature (T_s) (thus the need for CIMEC calibration)

Satellite-based ET using Vegetation Indices

Satellite-based or ground-based energy balance methods can be used to calibrate more simple methods that utilize general vegetation indices (VI) to estimate crop coefficients (i.e, ET_oF) (Tasumi et al. 2005a, Tasumi and Allen 2007). This is possible because of the generally close correspondence between vegetation amount and transpiration, where, as vegetation cover increases, leaf area increases, and transpiration increases (reviewed in Glenn et al., 2007). Challenges with VI based methods are estimating evaporation from bare soil following precipitation events and estimating reduced ET associated with soil-water shortage.

A common VI is the Normalized Difference Vegetation Index (NDVI) that is estimated from two shortwave bands measured by many satellites: the red (~0.6–0.7 μm) and the near infrared band (~0.7–1.3 μm). A linear relationship between the NDVI and the crop coefficient K_c was introduced by Heilman et al. (1982) and theoretically established by Choudhury (1994). The resulting equation is:

$$K_c = ET_oF = 1.25\,NDVI + 0.2 \tag{5}$$

Tasumi et al. (2005b) and Tasumi and Allen (2007) found a similar relationship. Generally, NDVI values from different satellites show close correlation (Calera-Belmonte et al. 2005). However, some differences occur due to differences in band widths. Atmospheric correction of the image can also have an impact.

Advantages of VI-based ET_oF are:

- Quick analyses can be made by mid-level technicians
- Large areas can be covered
- Relationships can be calibrated using satellite-based energy balance
- Spatial resolution can be high, especially if aerial imagery is used

Disadvantages of VI-based ET_oF are:

- Relationships may vary with type of vegetation
    - stomatal control (and thus ET_oF vs. VI relationships) can vary among types of vegetation. Therefore, single ET_oF vs. NDVI or ET vs. greenness indices can vary
    - trees, when short of water can exhibit much more stomatal control than agricultural crops
- Relationships tend to overestimate ET under conditions of acute water shortage
- Quality estimates of reference ET_o are required that in turn require quality weather data
- VI's may not identify or quantify multi-storied canopies and their effects on total ET, especially for more dense vegetation.

Nagler et al. (2008) found a reasonable correspondence between saltcedar ET estimated by sap flow sensors and satellite estimates based on a VI at the Cibola National Wildlife Refuge on the lower Colorado River. However, at any given measurement station, ground measurements showed high variability of ET due in part to differences in stomatal conductance due to stress effects, which were not captured in the remote sensing estimates.

Scintillometers

A Scintillometer is an optical device that measures small fluctuations of the refractive index of air caused by temperature, humidity, and pressure induced variations in density. A system for measurement of sensible heat flux consists of an optical transmitter and a receiver at the ends of an atmospheric propagation path. The receiver detects and evaluates the intensity fluctuations of the transmitted signal, called scintillations.

The magnitude of the fluctuations in the refractive index is usually measured in terms of the structure parameter C_n^2, which is the spectral amplitude of refractive index fluctuations in the inertial subrange of turbulence. Scintillometers measure sensible heat flux, H, by relating the structure parameter to a temperature structure parameter and the so-called Monin-Obokhuv stability parameters. Detailed descriptions are available from Meijninger et al. (2000), Meijninger et al. (2002), Hartogensis et al. (2003) and de Bruin (2008).

The distinct advantage of scintillometry is the abilty to derive sensible heat flux that is integrated over a long transect, up to several km in length. This integration is especially useful for measuring H over complex natural vegetation where spatial variation can have scales of 100's of m. Scintillometer measurements do require assumptions related to Monin-Obukhov stability functions, estimation of mean shear stress (or friction velocity) and other empirical corrections related to frequency spectrum. To obtain ET, measurement of R_n and G are needed, which can be problematic and biased with heterogeneous and sparse vegetation systems, as discussed in the Bowen Ratio section. Insufficient representativeness of R_n and G measurement over a transect can greatly reduce the value of the scintillometer-based integration of H. Other requirements of scinillometer-based derivation of H is the need for accurate measurement or estimation of friction velocity, u^*, which may require the deployment of sonic anenometers along the transect and uniform enough terrain along the transect so that all assumptions in Monin-Obukhov similarity theory governing 'shape' and distribution of turbulent structures are valid.

Advantages of scintillometers include:

- Integration of sensible heat flux over large distances
- Relatively simple operation and maintenance
- Apparent good consistency in application (Kleissl et al., 2008)

Disadvantages of scintillometers include:

- Measurement of H only
- ET is estimated ET by residual, requiring spatial representativeness of the R_n and G measurements, and where biases in R_n and G transfer into the ET estimate
- Require a variety of corrections (de Bruin, 2008)
- Need measure of friction velocity if below the free convective layer.
- Expensive

Sap Flow via Heat Pulse Velocity

The earliest sap flow methods used simple relationships based on measuring the onset of an induced heat pulse at one or more points in the stem of a plant downstream from the heat induction site. These methods were followed by compensation techniques in which heat flow in both upstream and downstream directions is detected to allow for conduction, as well as advection of heat from one point to another. In more recent methods, stem anatomy is modeled to scale sap velocity derived from heat pulse velocity and to develop sap flux methods derived from a thermal heat balance. Swanson (1994) suggested that no one set of theory and instrumentation is applicable to all sizes or species of trees. Smith and Allen (1996) reviewed sap flow and heat pulse methods and recommended applications and expected error. Green et al., (2003) suggested that heat pulse methods can provide accurate measurements of sap flow in plant stems provided a reliable, independent calibration procedure is used to relate the measured heat pulse velocity to the actual sap flow. They also discussed problems related to disruption of the sap stream and alteration of thermal homogeneity of the sapwood in the vicinity of probes. A two-dimensional model of heat and water flow was used to derive appropriate correction factors to account for the influence of both probe thermal properties and flow

blockage. Measurements in the trunk of willow (*Salix alba* L.) and poplar (*Populus deltoides* W. Bartram ex Marsh) found two types of heat pulse measurements to be within 5 to 10% of the actual transpiration on a daily basis. The compensation method measured flows accurately to as low as 2 cm/h. The T-max method had difficulty resolving flows slower than about 10 cm/h.

Two heat-balance methods are commonly used today. The first is the heat-dissipation method, using Granier sensors. A heating wire is inserted into the conducting portion of a plant stem, and thermocouples measure the temperature difference of the conducting stream at the heating wire and 10 cm above the heating wire. The difference in temperature between the two sensors is a measure of how rapidly water is moving in the stem, thereby dissipating heat. This method has been widely applied to trees, as the sensors can be inserted into tree trunks to provide estimates of whole-plant transpiration. However, the Granier method requires a detailed knowledge of tree anatomy, especially the actual conducting area in the stem. This is because heat dissipation depends on the volume of water moving through the stem as well as its velocity. While Granier sensors provide accurate information when calibrated through control studies, they have not yet been successfully applied to tamarisk (Dr. Ed Glenn, 2009, pers. commun.).

The second method is the tissue-heat-balance method. In this method, a small (0.5 – 2.0 cm) branch is wrapped with a heating wire that introduces a constant source of low-grade heat into the stem. Thermocouples at the point of heating and 1 cm above and below the heat source measure heat loss due to diffusion through the stem and convection (transpiration), and a thermopile in the insulation surrounding the heating wire is used to estimate radial heat loss. A heat balance equation is used to determine the transpiration flow from the convective heat loss. This is a more direct method to estimate transpiration since (ideally) the whole branch is uniformly heated, but it also has problems in implemention. For example, readings taken between 2-4 am are frequently used to determine heat losses under zero-flow conditions. However, tamarisk and other riparian plants can have substantial rates of night-time transpiration, leading to inaccurate estimates of transpiration (Nagler et al., 2008). Zero-flow conditions can be determined at the end of the experiment by cutting and sealing branches and continuing to measure temperatures. This limitation applies to Granier sensors as well.

Sap flow methods require scaling from branches or whole plants to stands of plants to provide wide area estimates of ET. Granier sensor studies typically use a stem census method for scaling, in which the cross sectional area of gauged trunks are related to the density and cross sectional area of trees in the area of interest. Stem census methods can be very difficult to apply to natural stands of plants, especially when the plants present a myriad of branches of different sizes, as in the case of tamarisk (Dr. Ed Glenn, 2009, pers. commun.). Tissue-heat-balance methods require a further scaling step, to scale from branches to whole plants then to stands of plants. Leaves on gauged branches can be harvested and measured, and scaling can then be accomplished by measuring LAI in plant stands of interest. However, optical methods for estimating LAI must be calibrated by leaf-harvesting, because many plant stands violate the geometric assumptions built into the optical measurement devises. This step is often omitted in published studies (Dr. Ed Glenn, 2009, pers. commun.). Scaling ET from individual limbs to full plants and from full plants to large areas is uncertain due to differences among tree structure, radiation interception per tree, and water availability. Shaded limbs will tend to have lower rates of transpiration than sunlit limbs and limbs lower in a canopy will tend to have less aerodynamic exchange of energy and vapor. Besides scaling of transpiration from specific species of trees, additional uncertainty in areal ET is caused by stands of multiple species, presence of understory vegetation, and evaporation from bare soil. Mackay et al. (2002) used a two-source evaporation model with sap flow data to produce total ET.

Grime et al. (1995) examined the importance of measuring changes in stem temperature and heat storage in the stem heat balance for *Guiera senegalensis* shrubs in the Sahel, Niger. Measurement of the heat balance in zero flow conditions provided determination of the gauge radial conductance and the stem segment heat capacity, both of which are required for accurate sap flow measurement with good dynamic resolution in low flow conditions. Under high sap flow conditions the change in heat storage constitutes only a small component of the balance, and can be neglected, especially for small stems.

Steinberg et al. (1990) described a commercial sap flow system that provided daily transpiration measurements within 5% of directly weighed ET. Shackel et al. (1992), on the other hand, found substantial departure between lysimeter measurements of ET from a peach tree and a heat balance technique for measuring sap flow. Lundblad et al. (2001) used a tissue heat-balance method and the heat-dissipation method in Scots pine and Norway spruce. The latter system measured up to 50% lower sapflow than the tissue heat-balance system under high sap flow rates. They found that natural temperature gradients can cause large errors in measurements made by the heat-dissipation method. Kjelgaard et al. (1997) reported differences between variable heat input and constant heat input systems and improved accuracy when readings were integrated over 24-hour periods. Ewers and Oren (2000) found sap flow velocity in xylem 20 to 40 mm from the cambium to be 50 and 40% of sap flow velocity in the outer 20-mm band of xylem in slow- and fast-growing trees, respectively. Wilson et al. (2001) used commercially-available thermal dissipation probes operated on the constant power principle (Granier, 1987) in a forested Tennessee water shed, where four red maple, four loblolly pine, two chestnut oak, two white oak, one red oak and two yellow-poplar were instrumented. Water use by common understory saplings (one red maple, one dogwood and one beech) was also measured. They found total seasonal ET estimated by the sap flow method to be 50% of that determined by both eddy covariance and inflow-outflow watershed balance.

Nadezhdina et al. (2002) studied sap flow in dominant coniferous (Pinus sylvestris L.) and broadleaf (Populus canescens L.) and in understory species (Prunus serotina Ehrh. and Rhododendron ponticum L.) using heat field deformation (HFD). They identified large systematic errors during flow integration and scaling from single-point measurements to whole trees errors of –90 to 300%. These occurred when it was assumed that sap flow was uniform

over the sapwood depth. They recommended that the radial sap flow pattern be determined using sensors with multiple measuring points along a stem radius followed by single-point measurements with sensors placed at a predetermined depth. Other significant errors occurred in the scaling procedure even when the sap flow radial pattern was known. These included errors associated with uncertainties in the positioning of sensors beneath the cambium (up to 15% per 1 mm error in estimated xylem depth), and differences in environmental conditions when the radial profile applied for integration was determined over the short term (up to 47% error). High temporal variation in the point-to-area correction factor along the xylem radius used for flow integration was also problematic.

It seems clear that large uncertainties can exist with determining accurate transpiration measurements with various sap flow methods and determining quantitative ET estimates.

Advantages of sap flow are:

- Direct measure of transpiration
- show behavior of individual species
- Coupled with micrometeorological systems (i.e., eddy covariance, etc.), can help separate T of understory or evaporation from total ET

Disdvantages of sap flow are:

- Probe spacings and stem geometry are the most significant source of error
- Varying wound responses to probe implantation may cause heat ratios to vary over time
- Implanted sensor techniques cause mechanical damage and interrupt flow by occlusion or blocking of the plant's vascular tissues.
- Area of conductive tissue must be estimated accurately
- To obtain estimate of ET:
    - T of individual branches of plant(s) must be scaled up, which introduces uncertainty due to variation in exposure to solar radiation and aerodynamic turbulence
    - Evaporation from soil and any understory vegetation must be estimated or measured (uncertain)
    - Tree(s) need to be representative of the area
    - Relationships and calibrations may change with soil moisture, LAI, age, disease

Table 2 gives estimated ranges of errors in ET expected from the various measurement systems described. Ranges are given for expert and novice users. These estimates are based on experience of the writer and reviews of literature associated with the descriptions above. These ranges can be used to provide guidance on interpretation of study results and to guide method selection.

Table 2. Error (one standard deviation) expected for various types of ET measurement systems

Method	Typical error, %	Error for an experienced Expert, trained and steeped in the physics of the process, %	Error for novice or person working outside the specialty area, %	Typical error caused by physical and equipment malfunction, %
Lysimeter	5-15	3	20-40	5-40
Soil water balance	10-30	10	20-70	10-40
Bowen ratio	10-20	10	20-50	5-40
Eddy Covariance	15-40	10-15	30-50	10-40
Remote Sensing energy balance	10-20	5-15	30-40	10-30
Remote Sensing using vegetation indices	15-40	10-30	20-40	10-20
Sap Flow	15-40	10-20	40-200	20-100
Scintillometers	10-35	10-15	20-50	5-30

Recommended Documentation

Often, papers and reports on ET measurements do not provide sufficient documentation on instrumentation used, experimental procedures, quality control to data, nor description of the vegetation to provide the reader or reviewer with a means to assess integrity or representativeness of the data. Table 3 lists metadata that are recommended to be recorded

and reported for future studies of ET to provide both reviewers and users of the data with means to scrutinize the integrity of the data as well as means to place reported results in environmental and physiological contexts. This list also summarizes the type of information that should for the basis of questions asked by potential users of the data prior to their usage.

In addition to documentation on ET measurements and associated weather data that may be used in later models, ET documentation should fully describe the nature of the vegetation measured, including type, variety, density, age, health, water availability, timing of development and senescence, height, fraction of ground cover or leaf area index, type of irrigation, if practiced, and other features useful to users of the data or derived crop coefficients or other ET parameters. In the case of crop coefficients, the documentation should describe whether the reported crop coefficient(s) represent potential (i.e, well-watered) conditions and whether they are intended to represent the basal (mostly dry soil surface) or average crop coefficient application (Allen et al., 1998).

Table 3. Recommended Check list on Required and Desired Information to be Reported for ET measurement systems and with Water Consumption Data, Crop Coefficients or Calibrations of Resistance-based ET methods for Publication.

Required	**Desired**
All Systems *Vegetation:* • Vegetation variety(s) • Dates for greenup or planting • Dates for full cover or effective cover or maximum cover • Dates for flowering • Dates for senescence or harvest • Location of measurement system relative to the field, system or expanse of vegetation measured • Plant density • Plant spacing along row (if ag.) • Spacing between plant rows • Measured or estimated vegetation height vs. time • Measured or estimated fraction of ground cover vs. time • Size of field (stand) containing the measurement system • Location of measurement system relative to the field (stand) of vegetation measured • Size of general agricultural area (or other vegetation system) surrounding the measurement field *If a tree crop or forest, additional information*	• LAI vs. time • Crop yield • Photograph(s) of crop and of the ET measurement system • Relative adequacy of soil water in fields (or vegetation systems) surrounding the field (vegetation system) measured (i.e., nonstressed?) • Fitting of measured ET data to a Penman-Monteith equation and indication of required surface resistances for the fit (including statistics) • Error analysis on measurement system • Calibration of a Penman-Monteith or other method to ET data (directly) with: a. error comparison to a K_c based method b. Report values of surface resistances required to fit the PM method and comparison with literature values c. Method to estimate

include: • Age of trees • Year of planting • Crown diameter • Tree spacing along row and between rows • Ground cover: a. type b. height c. density d. soil moisture management e. tillage • Description of uniformity of trees • Dates for: a. leaf out b. leaf fall *Supporting Meteorological Data:* • Description of supporting meteorological data for calculating ET, including solar radiation, net radiation, soil heat flux, air temperature, surface temperature, soil temperature, vapor pressure • Location(s) of meteorological system/sensors • Dryness or wetness of the Met. system environment • Degree and type of QA/QC applied, including calibration adjustment and gap filling. • Reference ET method type (if used) and citation • Description of weather data source (and url) *Soil and Irrigation Description* • Soil type • Irrigation type • Irrigation frequency and duration • Irrigation application depth per irrigation and total • Method for measuring irrigation input (depth) • Fraction of surface wetted by irrigation • Whether incidental or intentional moisture stress was practiced • Relative adequacy of soil water in the field containing the crop measured (i.e., nonstressed?) • Description of treatment of rain events (measurement of rain, inclusion of the rainy day) • Method for soil water measurement • Drainage management • Tillage system type	roughness height and values in model. *If a tree crop or forest, additional information include:* • Photos of : a. individual trees b. community of trees

Relative ET Information • If K_c is reported, provide basal and averaged K_c's based on the standardized reference ET (a second K_c basis is optional) • If K_c is reported, whether it represents potential (well-watered) conditions, or whether it may reflect some type of environmental stresses • Type of filtering or moving average used on the ET and/or K_c data • Comparison of derived K_c to literature values and comments on: a. if grass-reference based, the proximity of K_c for nearly full cover conditions to the expected range of 1.1 - 1.3 b. if alfalfa-reference based, the proximity of K_c for nearly full cover conditions to the expected range of 0.95 - 1.0 c. exceedingly strong justification of values exceeding the above ranges (alarms should sound if values exceed this range), especially if K_c values are to represent agricultural settings • If grass-reference based, co-reporting of midseason K_c values based on the standard FAO climate of RH_{min} = 45% and wind speed at 2 m height = 2 m s^{-1}. • Average daily minimum relative humidity and average wind speed during the four growth stages	
Eddy Covariance • Types of corrections to the flux measurements and specific software used • Type of coordinate rotation employed • Averaging period • Fetch length in predominate wind directions and direction thresholds for data filtering • Measurement of R_n and G for energy balance (EB) closure assessment • Description of a) closure error amount and b) method of closure • Brands and maintenance procedures for R_n and G sensors, sonic anemometer, and hygrometer, including purchase and last rebuild dates	• Description of multiple R_n and G sensors, especially when the fraction of ground cover is less than 0.8 or when mean vegetation height is > 2 m. • Footprint analysis • Indication of adequacy of soil water supply to support transpiration • Description of soil water content monitoring in the vegetation root zone • Soil type, field capacity, wilting

• Description on numbers of and placement of R_n and G sensors relative to plants • Height of R_n , sonic anemometer and hygrometer relative to a) ground, b) mean vegetation height, c) maximum vegetation height (or limb) • For G, method for measuring soil water content and soil temperature • For vegetation, a description of: a. distribution of height b. fraction of ground cover by vegetation c. LAI (measured or estimated) • Anemometer and Hygrometer instrument separation distances and orientation (a photo is desired) • Description of vegetation type, extent and soil water status upwind of the vegetation being monitored.	point (and how these values were determined) • Estimated rooting depth • Summary of QC analysis on R_n measurements using measured R_s and estimated or measured albedo and net long-wave radiation (if there is no R_s measured, use calculated R_{so} on clear days) • Collocation with a Bowen Ratio system to confirm values for ratios of H/LE and to provide independent 'looks' at LE from EC and BR methods as well as aerodynamic estimates of H and LE based on $T_1 – T_2$ and $e_1 – e_2$. • Ages of all sensors and loggers and information on annual maintenance and storage
Bowen Ratio • Brands and maintenance procedures for vapor and temperature sensors, R_n and G sensors, including purchase and last rebuild dates • Description on numbers of and placement of R_n and G sensors relative to plants • Separation of the T and e sensors and placement relative to a) ground and b) vegetation • Timing of exchange of sensors, if applicable • If sensors are not exchanged, indication of reduction system for bias reduction between T and e measurements at the two elevations • For vegetation, a description of: a. distribution of height b. fraction of ground cover by vegetation c. LAI (measured or estimated) • Fetch length in predominate wind directions and direction thresholds • Description of vegetation type, extent and soil water status upwind of the vegetation being monitored.	• Description of multiple R_n and G sensors, especially when the fraction of ground cover is less than 0.8 or when mean vegetation height is > 2 m. • Footprint analysis • Indication of adequacy of soil water supply to support transpiration • Description of soil water content monitoring in the vegetation root zone • Soil type, field capacity, wilting point (and how these values were determined) • Estimated rooting depth • Summary of QC analysis on R_n measurements using measured R_s and estimated or measured albedo and net long-wave radiation (if there is no R_s measured, use calculated R_{so} on clear days) • Collocation with an eddy covariance system to confirm

	values for ratios of H/LE and to provide independent 'looks' at LE from EC and BR methods as well as to provide wind speed or friction velocity, u*, estimates for aerodynamic estimation of H and LE based on $T_1 - T_2$ and $e_1 - e_2$.
Lysimeter • Dimensions: a. inner tank b. outer tank • Tank material and thickness • Gap between inner and outer tank • Photos of lysimeter w/o vegetation • Photos of lysimeter w/ vegetation including immediate area outside • Photo of landscape surrounding the lysimeter • How the representative effective areas of the lysimeter are calculated for evaporation and transpiration determination • Scale type and specifications • No. scans of load cell(s) per reporting period • Method of lysimeter soil construction (monolithic vs. reconstructed) • Comments and notes on any differences between lysimeter vegetation and that of surrounding field or expanse (vegetation amount, fraction of ground cover, height, LAI, soil water availability) • Plant density of field or expanse and inside lysimeter • Fraction of soil visible inside and outside lysimeter • Drainage process for lysimeter • Soil layering inside and outside of the lysimeter • If lysimeter area is not an integer multiplier of average area per plant, including space between plant rows (if applicable), describe how evaporation from nonsampled areas is estimated • Description of supporting vegetation data including height (vs. time), LAI	• Two or more lysimeters with the same vegetation and water treatments with error analysis between/among them • Salinity measurements of lysimeter drainage water • Confirmation of adequacy of soil water supply to support transpiration • Soil water content monitoring in the vegetation root zone • Soil type, field capacity, wilting point (and how these values were determined) • Estimated rooting depth •
Soil Water Differencing • Maximum depth of measurement • No. of locations measured • Locations of measurement sites	

• No. of depths and intervals • ime intervals for measurements • Comments on monitoring locations vs. areas wetted by irrigation, shadows cast by trees, etc. • Special treatment of surface layer • Estimation procedure for drainage and upward flow, including evidence that fluxes were small or negligible • Treatment of rainfall and irrigation events in the water balance	

Quality Assessment and Quality Control

Quality assessment (QA) and quality control (QC) (correction) of any measured data is essential to data integrity. Rigorous procedures should be part of any measurement system. Often QA includes graphical and/or statistical analyses. Comparison of data against independent measurements or models is also advised. For example, plotting measured ET against ET simulated by a model, such as the Penman-Monteith equation calibrated to the data, can identify periods of data that do not conform to expected behavior and give cause for closure scrutiny. In other cases, independent measurements or estimates can be compared, for example, comparing ET derived by eddy covariance with ET derived by Bowen ratio or ET derived via scintillometry to evaluate consistency in measurements. ET and H from eddy covariance or Bowen ratio can also be compared against ET and H derived from aerodynamic methods using the vapor pressure gradient or temperature gradient data from the Bowen ratio system combined with a measurement of wind speed and an estimate of surface roughness, or, if combined with eddy covariance system, using friction velocity. Combined operation of Bowen ratio and eddy covariance systems is strongly encouraged due to the opportunities for independent assessments of data integrity.

If net radiation (R_n) is measured, values should be compared with R_n estimated from standard equations that are based on solar radiation, R_s, for example those presented in FAO-56 (Allen et al. 1998) and elsewhere, as a means of integrity assessment. One should not expect measured R_n to exactly agree with estimated R_n, especially if albedo or surface temperature is substantially different than that from the well-watered reference surface. However, significant variation between the two should be cause for a closer investigation of the measured data. Some net radiometers do not accurately measure the long wave component of net radiation. Other measurement related factors that can shift the relationship between measured and estimated R_n include scratched or dirty radiometer domes, an off-level sensor, condensation of moisture inside domes of the R_n sensor, nonrepresentative vegetation underneath the sensor, an obstructed view of the sky, and obstruction by the mounting tower or other sensors or solar panels.

Weather Data

Quality assessment and control (correction) of weather/meteorological data are essential to calculation of accurate and representative reference ET and to avoid biases in data. Weather/meteorological data should be quality assessed (QA) and quality controlled (QC) before use in any ET equation, including standardized reference ET_o equations, to ensure that data are of good quality and are representative of well-watered conditions. This is especially important with electronically collected data, since human oversight and maintenance may be limited. When measurements are determined to be faulty, they can frequently be adjusted or corrected using justifiable and defensible procedures, such as simple visual (graphics-based) methods by ASCE-EWRI (2005) that can be used to screen and correct large amounts of data. The user may elect to replace perceived faulty data with estimates (ASCE-EWRI 2005).

In the case of calculating reference ET_{ref}, it is best that the weather/meteorological measurements be taken over a relatively well-watered and vegetated surface, for example, from an agricultural environment. This is encouraged because the standardized Penman and Penman-Monteith equations are calibrated to 'expect' the weather data to be from such an environment. The ET from a well-watered environment tends to condition the near surface boundary layer, reducing air temperature as much as 5°C and increasing humidity, as compared to conditions experienced in an arid environment. Use of 'arid' weather data will tend to cause the reference ET estimate to be overstated.

The primary variables are typically solar radiation, air temperature, wind speed and humidity. Because modern AWS stations are electronic and frequently are in remote locations, data are impacted by measurement biases caused by sensor malfunction, sensor aging, sensor miscalibration, sensor alignment, sensor cleanliness, datalogger programming, and sensor environment. When data are used to calculate ET, the AWS should measure air temperature, humidity and wind speed within the dynamic equilibrium boundary layer (EBL) overlying the ground surface in either the same environment as the ET measurement (if reporting ambient conditions) and/or in a 'reference weather environment'. Properties of the boundary layer characterize the energy balance at the surface and are generally implicit to assumptions and conditions used in developing the particular ET equation used, for example, the Penman-Monteith equation (ASCE-EWRI 2005). In the case of calculating 'reference' ET, where the reference ET represents the rate of ET from an extensive surface of well-watered vegetation having full-ground cover, the weather measurements should be made in a setting that includes enough well-watered vegetation within about 1 km in the upwind direction to condition the EBL to create congruency with the reference ET equation. As studies in southern Idaho by Burman et al. (1975) and modern blending height / profile theory models (Chen and Dudhia 2008) have shown how the lower level of the atmosphere (i.e., EBL) changes when going from desert to a patchwork of irrigated and non-irrigated fields. Humidity, temperature and wind speed variables change when entering an irrigated field surrounded by dry or poorly irrigated fields. It is important, when making calculations of reference ET, that weather measurements are accurate and that the weather measurements reflect the environment that is defined by the reference surface.

Failure of a weather station site to meet the definition of a reference condition described above does not preclude the use of the data for estimating ET_o. However, data from such a station should be examined carefully before use, and may, in some cases, require adjustment to make the data more representative of reference conditions. Allen et al., (1998) and ASCE-EWRI (2005), appendices D and E, provide guidance for assessing whether temperature and humidity data from a weather station located in an arid or semiarid climate exhibit 'reference-like' characteristics.

Fetch Requirements for Weather Stations

Allen (2006) applied results from Horst and Weil (1992) and Hsieh et al. (2000) to various fetch lengths of clipped grass and dry soil to demonstrate the impact that fetch at various distances has on air temperature and humidity measurements at weather stations. The impact increases more-or-less log-arithmetically with distance upwind and then decreases after some distance even further upwind. Results indicate that the 100:1 fetch distance:measurement height rule-of-thumb appear to apply to unstable conditions (positive Bowen ratio) for measurement of temperature and humidity at weather stations, but may underestimate the fetch requirement for neutral and stable conditions.

CONCLUSIONS

Accuracy of ET measurement requires well calibrated, well-maintained systems, and, in most cases, a good knowledge of underlying physics of turbulence and heat and radiation transfer that govern the measurement to reduce the impacts of oversight of important biasing factors. Typically, substantial measurement biases or incorrect data extrapolations occur in ET data sets, many of which may not be filtered prior to refereed publication. Deployment of equilibrium boundary layer systems (eddy covariance, Bowen ratio and scintillometers) must adhere to fetch requirements and minimum equipment heights. Energy balance methods such as Bowen ratio and scintillometry must obtain accurate and representative measurements of net radiation and soil heat flux density to produce information on ET. For most vegetation systems, this requires multiple instrument locations within the measurement area to compensate for spatial nonuniformity of vegetation. Learned “corrections” must be made to eddy covariance and scintillometry measurements. All systems must be combined with rigorous quality assessment and quality control procedures.

Cautions are provided that may suggest the types of measurement and data reviews needed to produce accurate and defensible ET data. Recommendations are provided on the types of documentation that should accompany data sets when published and that should be referenced in journal publications. This documentation helps to insure careful and quality data measurement and handling by the data collectors and it provides insights to readers of articles or users of data as to data representativeness, context and quality. These recommendations may be useful for consideration by editors of journals publishing ET information during review of submitted manuscripts.

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