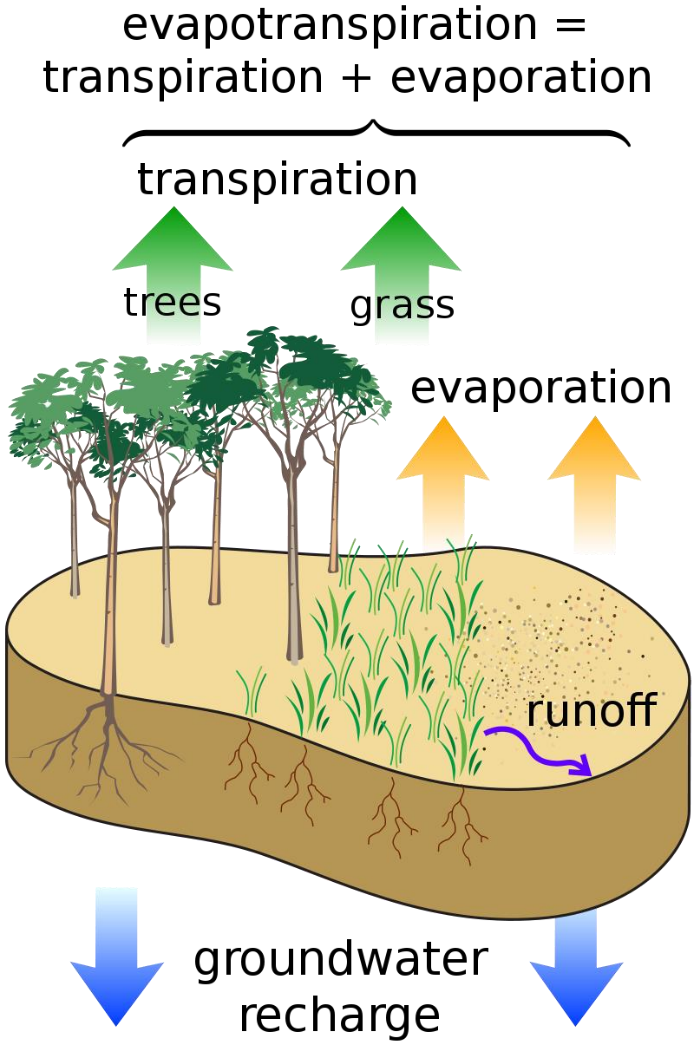
GEO892-001-Biophysical Models and Applications in Ecosystem Analysis

Modeling Evapotranspiration (ET) (Chapter 4)

4.1 Introduction
4.2 Methods for Quantifying ET
4.3 *ET* Models
    4.3.1 PET *models*
        4.3.1.1 Penman–Monteith Model: FAO reference ET Model
        4.3.1.2 Thornthwaite Model
        4.3.1.3 Hamon's PET Model
        4.3.1.4 Blaney–Criddle PET Model
        4.3.1.5 Turc PET Model
        4.3.1.6 Priestley–Taylor Model
        4.3.1.7 Makkink PET Model
    4.3.2 Empirical actual ET models
4.4 Model Demonstrations (Cheyenne Lei)



https://en.wikipedia.org/wiki/Evapotranspiration#/media/File:Surface_water_cycle.svg

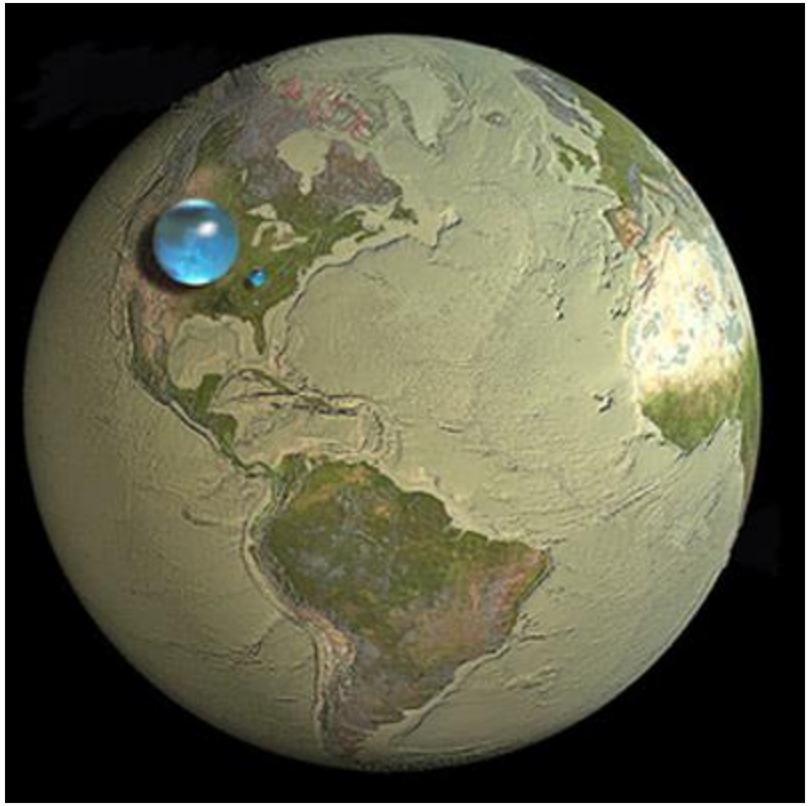
Exercise: Construct PM model using data from the OO (2010)

Alternative: calculating ET based on simple energy balance equation

Water on Earth:

(http://water.usgs.gov/edu/earthhowmuch.html)

About 71% of the Earth's surface is water-covered, and the oceans hold about 96.5% of all Earth's water. But water also exists in the air as water vapor, in rivers and lakes, in icecaps and glaciers, in the ground as soil moisture and in aquifers



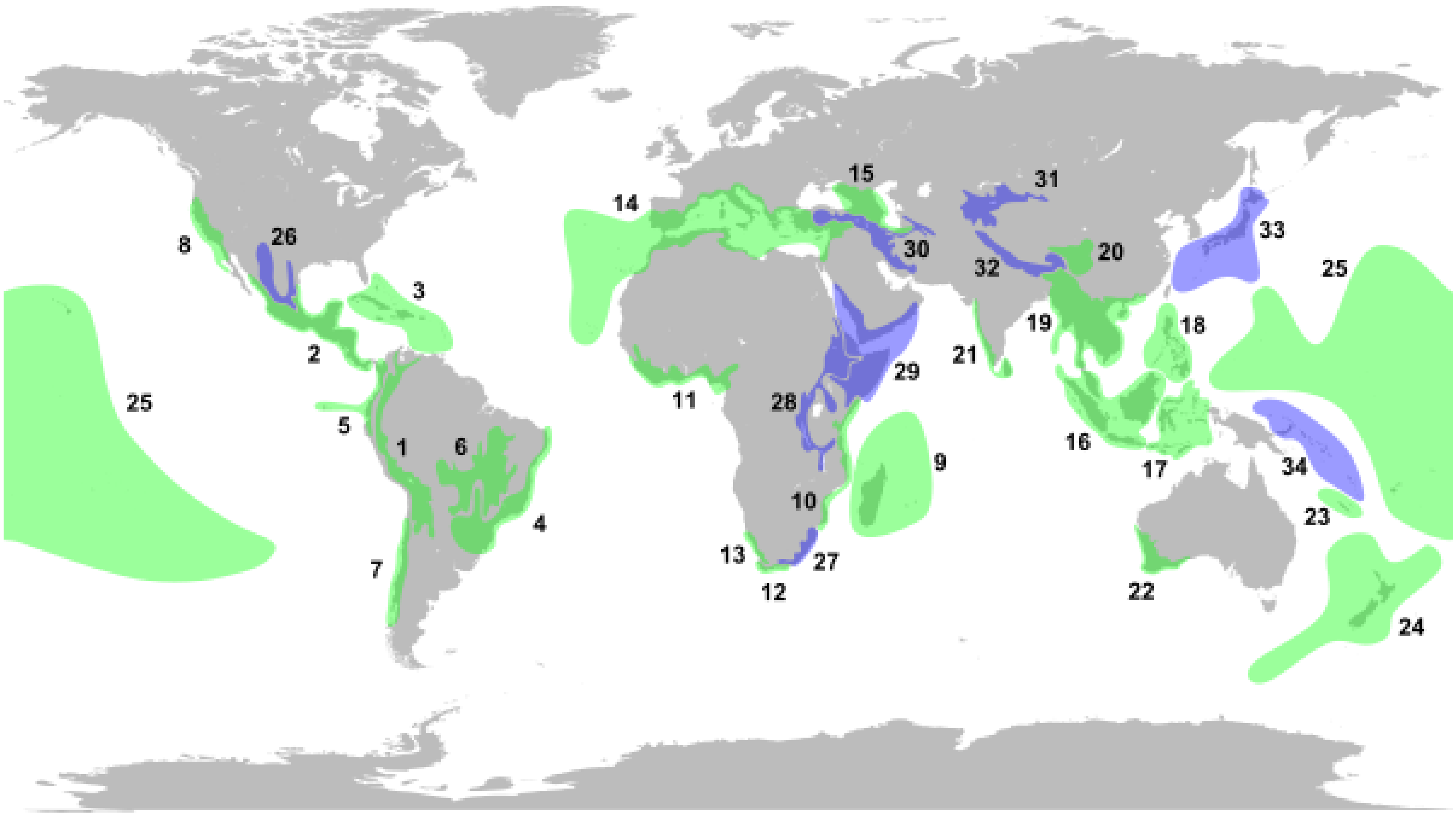
The vast majority of water on the Earth's surface, over 96 percent, is saline water in the oceans. The freshwater resources, such as water falling from the skies and moving into streams, rivers, lakes, and groundwater, provide people with the water they need every day to live. Water sitting on the surface of the Earth is easy to visualize, and your view of the water cycle might be that rainfall fills up the rivers and lakes. But, the unseen water below our feet is critically important to life.

how much water is there on (and in) the Earth?

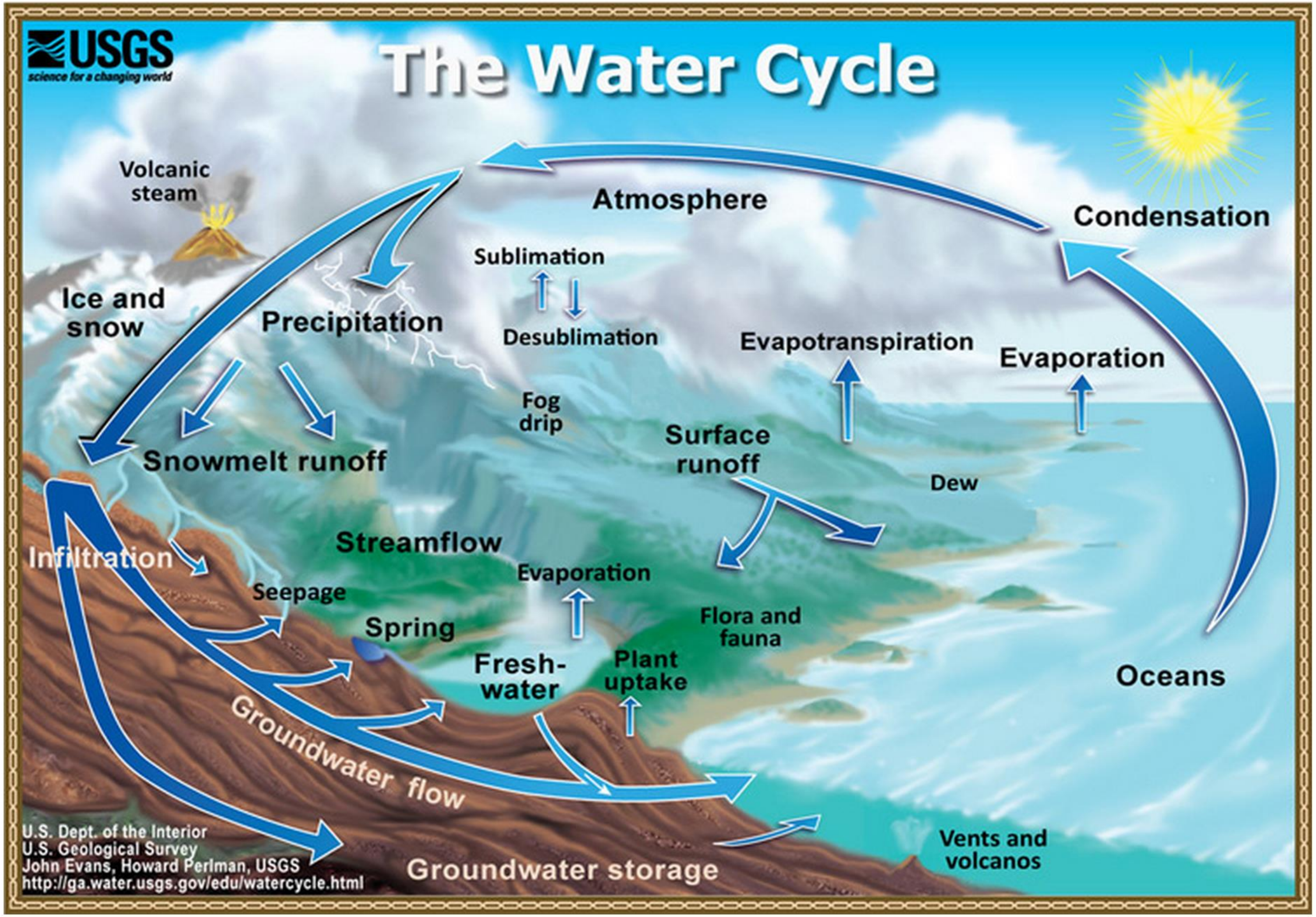
- If all of Earth's water (oceans, icecaps and glaciers, lakes, rivers, groundwater, and water in the atmosphere was put into a sphere, then the diameter of that water ball would be about 860 miles (about 1,385 km), a bit more than the distance between Salt Lake City, Utah to Topeka, Kansas. The volume of all water would be about 332.5 million cubic miles (mi^3), or 1,386 million km^3. A cubic mile of water equals more than 1.1 trillion gallons. 1 km^3= 264 billion gallons.
- About 3,100 mi^3 (12,900 km^3) of water, mostly in the form of water vapor, is in the atmosphere at any one time. If it all fell as precipitation at once, the Earth would be covered with only about 1” of water.
- The 48 contiguous US states receives a total volume of about 4 mi^3 (17.7 km^3) of precipitation each day.
- Each day, 280 mi^3 (1,170 km^3) of water evaporate or transpire into the atmosphere.
- If all of the world's water was poured on the contiguous (lower 48 states) United States, it would cover the land to a depth of about 107 miles (145 km).
- Of the freshwater on Earth, much more is stored in the ground than is available in lakes and rivers. More than 2,000,000 mi^3 (8,400,000 km^3) of freshwater is stored in the Earth, most within one-half mile of the surface. But, if you really want to find freshwater, the most is stored in the 7,000,000 mi^3 (29,200,000 km^3) of water found in glaciers and icecaps, mainly in the polar regions and in Greenland.

Biodiversity Hotspots: a biogeographic region with a significant reservoir of biodiversity that is under threat from humans.

Water is the most important variable determining their locations!



Water Cycle on Earth



Evapotranspiration: ET

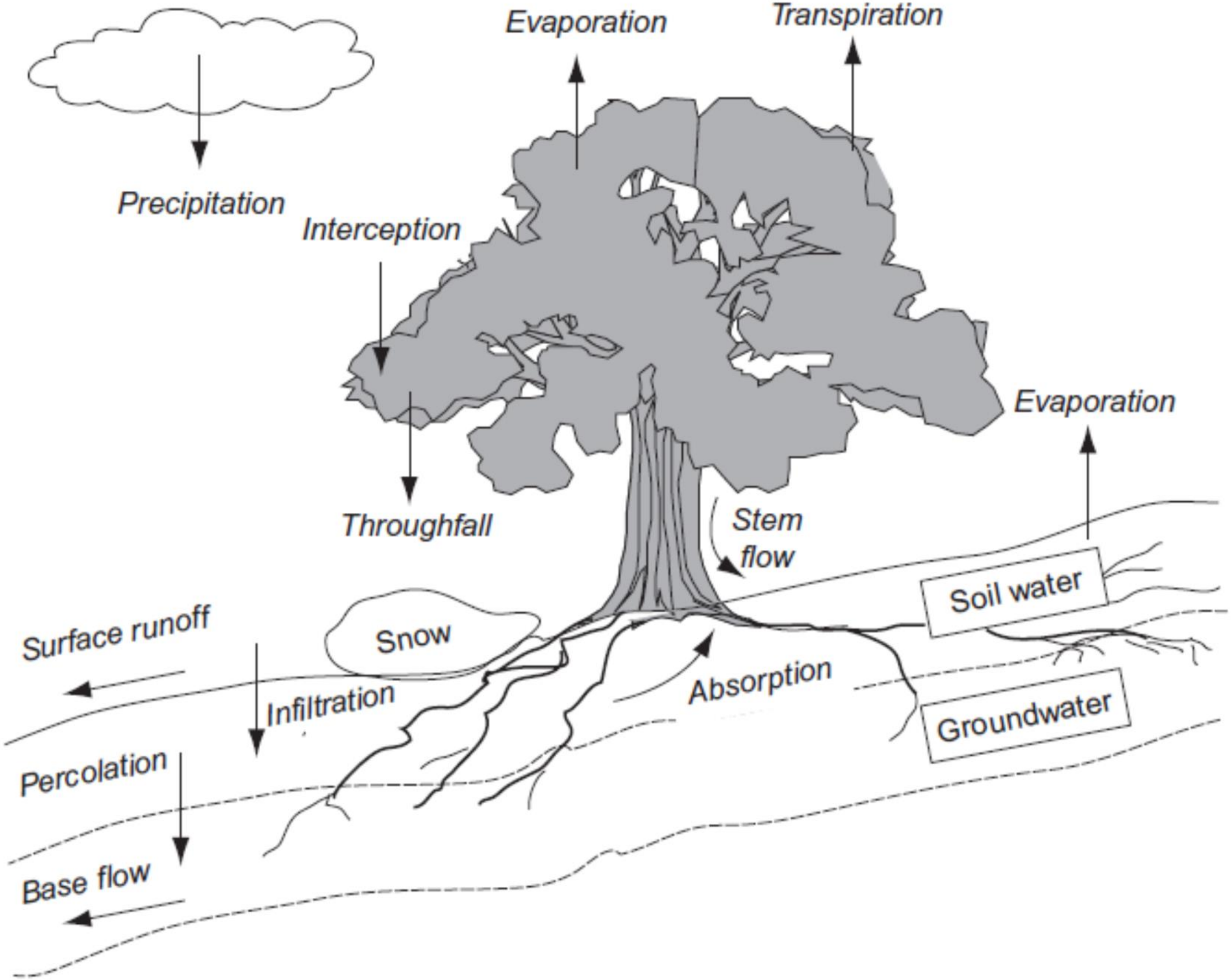
- A large component of the water budget. Worldwide, mean annual ET rates were estimated to be about 600 mm, or 60-70% of precipitation.
- Climate change and land use change directly affect the hydrological cycle and water resources through altering the ET processes.
- The key link between energy, water balances, and climate systems. More than half of the solar radiation absorbed by the land surface.
- An index to represent the available environmental energies and ecosystem productivity (i.e., water use).

$$ET = T + I + E$$

T: plant transpiration
I: canopy interception, and
E: soil (vegetation) surface evaporation

Water Balance of a Terrestrial Ecosystem

- $P=Q+ET+R$
- $ET=E+T$



Terminology

Evapotranspiration (ET, mm): sum of evaporation and plant transpiration from the Earth's land and ocean surface to the atmosphere

Evaporation (E): a process that water changes from liquid gas phase

Transpiration (T, Tr): a process of water movement through a plant and its evaporation from aerial parts, such as **leaves**, stems and flowers

Actual evapotranspiration (AET, ET, ET_a): the quantity of water that is actually removed from a surface due to the processes of evaporation and transpiration.

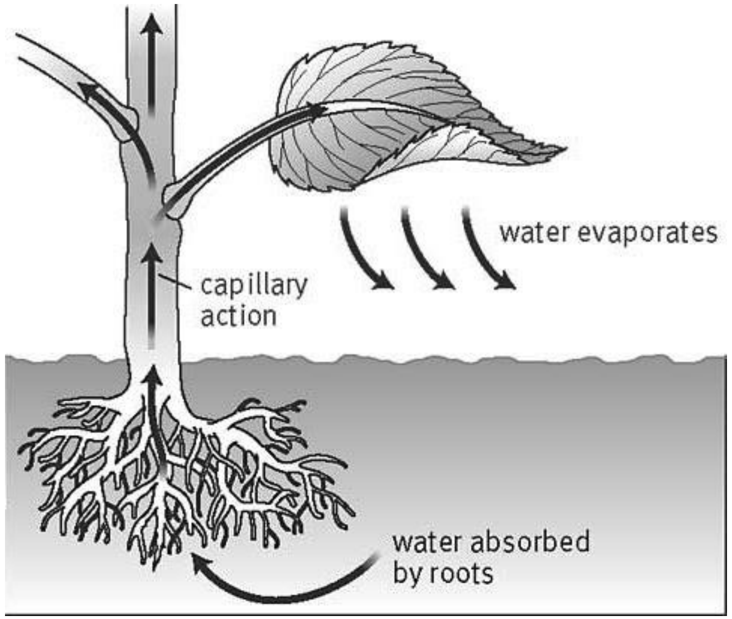
Potential evapotranspiration (PET, ET_o): the ability of the atmosphere to remove water from the surface through the processes of evaporation and transpiration assuming that there is no limitation or control on water supply.

Precipitation (P, mm): any product of the condensation of atmospheric water vapor that falls under gravity from clouds. The main forms of precipitation include drizzle, rain, sleet, snow, ice pellets, graupel and hail.

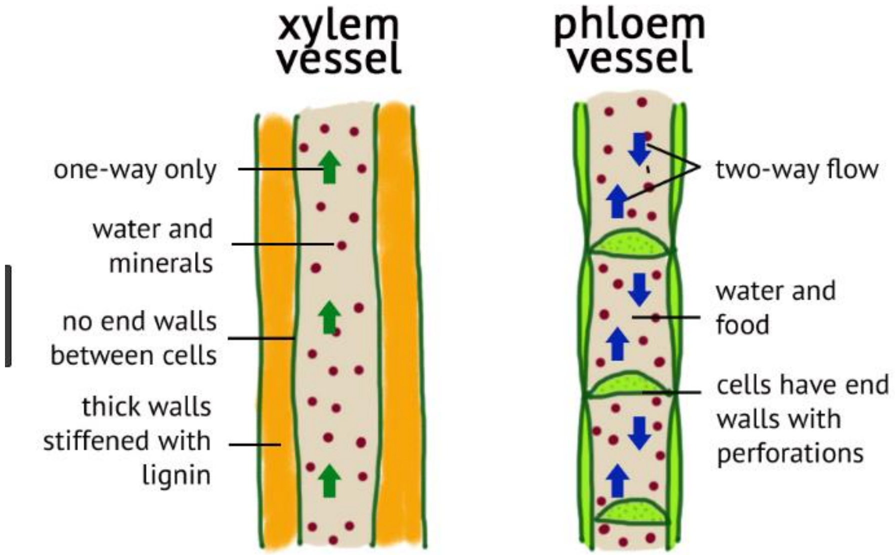
Terminology

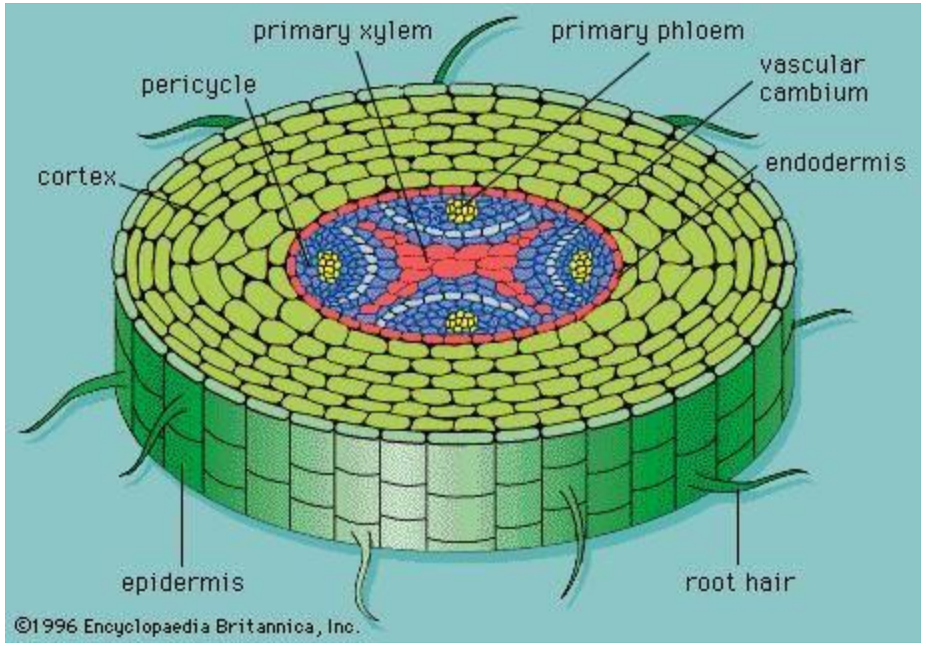
Transpiration (T, T_r): The water is then transported through the Xylem and into the leaf. When the water has been used it is then evaporated by the sun. The water comes out of the Stoma. As more water gets evaporated it sucks more out from the soil from the roots.

- Tr is an evaporation process from the leaf surfaces.



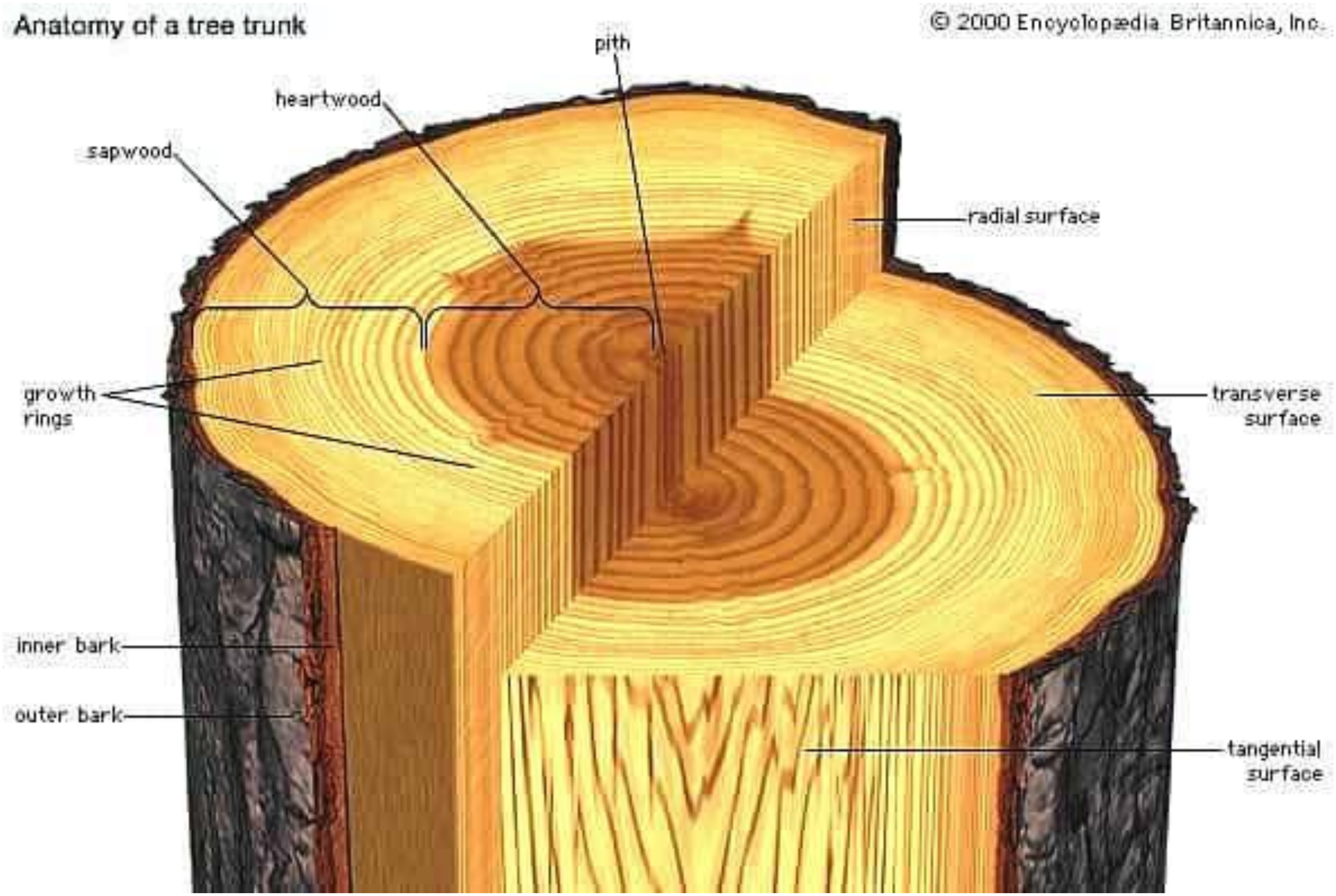
Xylem: plant vascular tissue that conveys water and dissolved minerals from the roots to the rest of the plant. It provides physical support.





Terminology: sapwood

Water is moved up from roots to shoots/leaves via the xylem cells of "sapwood", i.e., transpiration



How do you calculate Tr from?

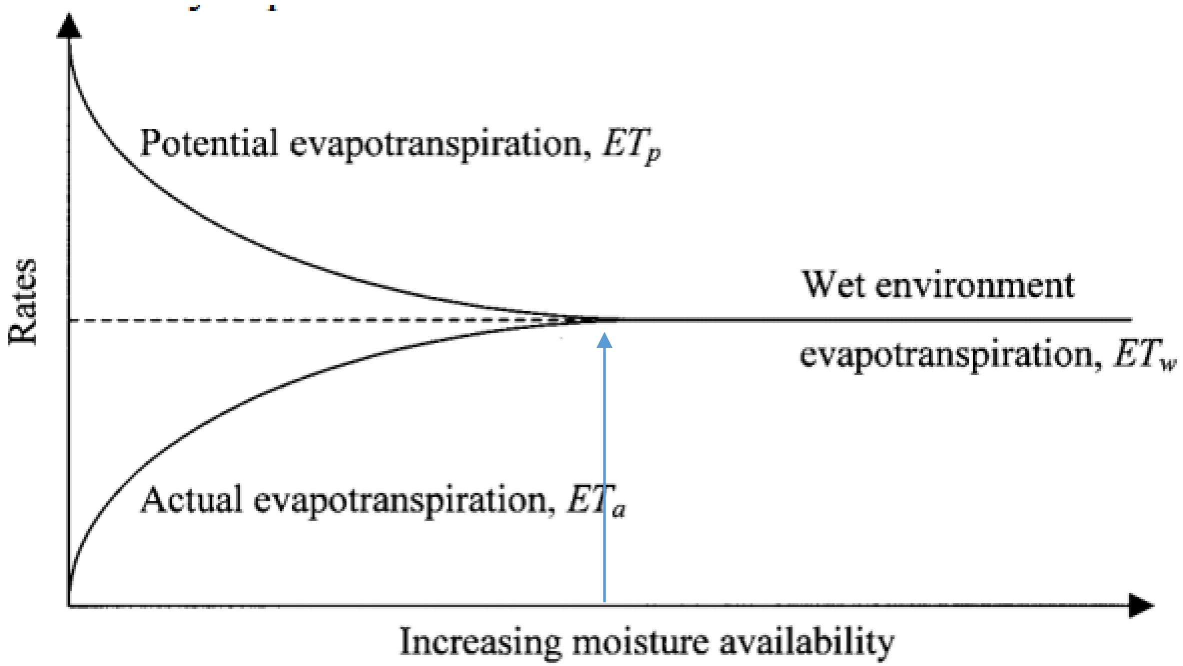
- Sapwood width (mm)
- Stand density (no/ha)
- DBH (cm)
- g_s, e_a

Terminology

Tr:ET (0-1, unitless): portion of ET that is used for transpiration. It is a function vegetation type, climate, LAI, time, stress, soil moisture.

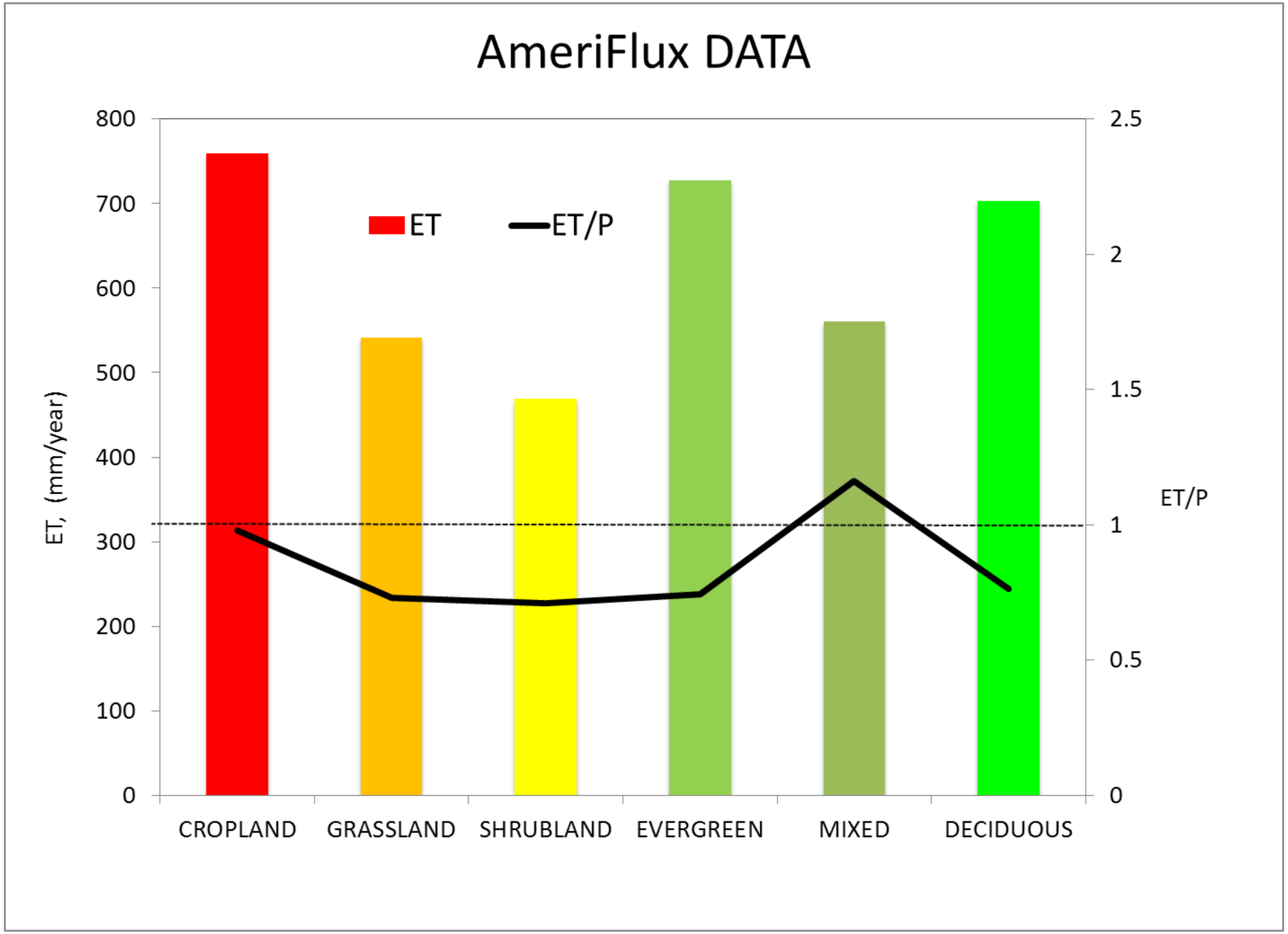
ET:P (0-1, unitless): amount of water used for ET from total P. It indicates major water balance.

PET vs ETa: potential and actual as indicated by their names (i.e., supplies for evaporation)



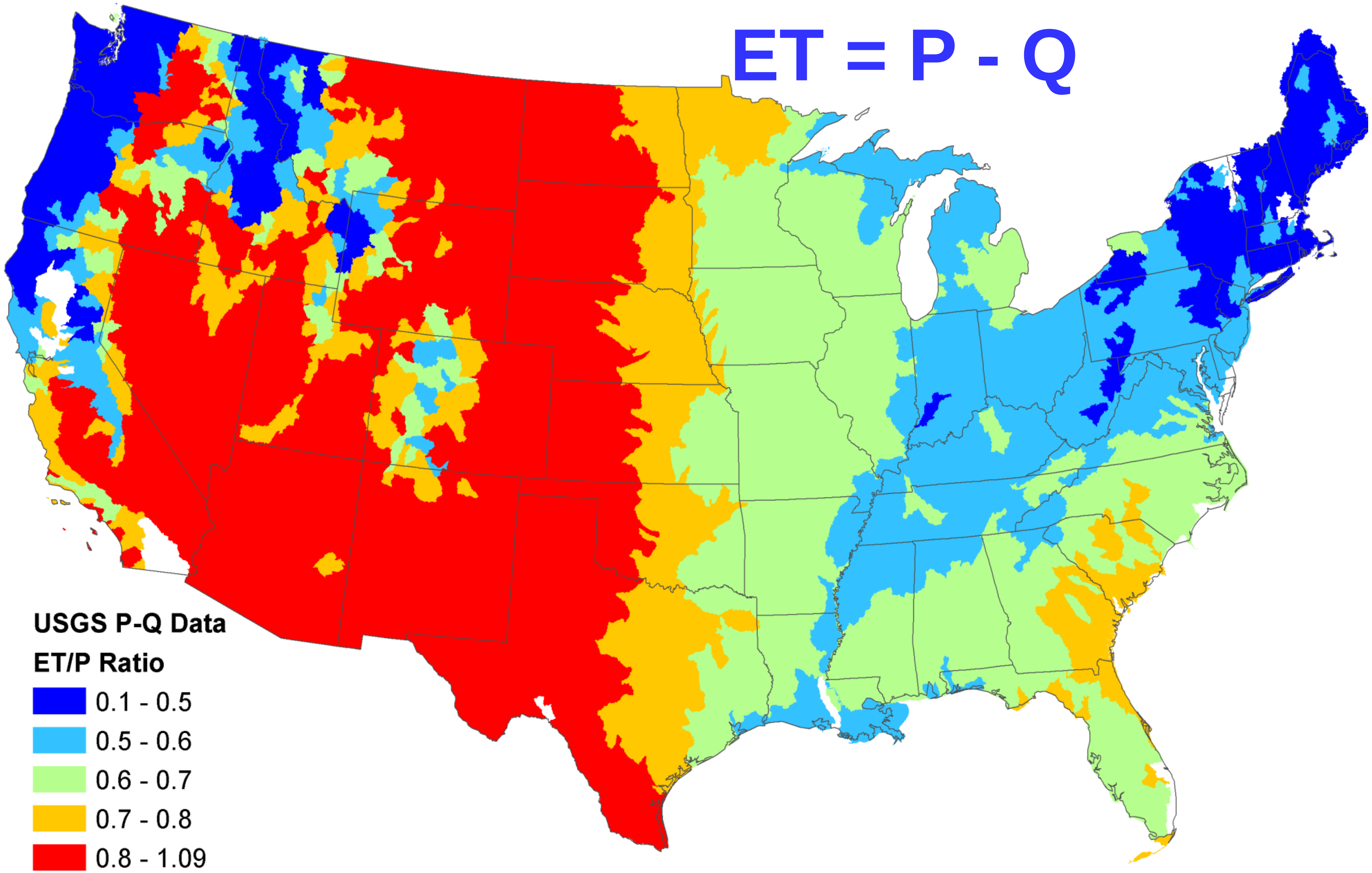
Water Balance

$\Delta S = P - R - ET$



Yuan et al. (2014)

ET/P Ratio Based on USGS Streamflow Data



Ge Sun, SGCP

ET Basics

TABLE A4. Conversion factors

Length	1 m = 100 cm = 1000 mm
Area	$1 m^2 = 10,000 cm^2 = 10^6 mm^2$
Volume	$1 m^3 = 10^6 cm^3 = 10^9 mm^3$
Density	$1 Mg/m^3 = 10^3 kg/m^{-3} = 1 g/cm^{-3}$
Pressure	1 kPa = 10 mb
Heat	1 Joule = 0.2388 cal
Heat flux	1 Watt = 0.8598 kcal/hr
Heat flux density	$1 W/m^2 = 0.8598 kcal m^{-2} hr^{-1}$
	$1 W/m^2 = 1.433 \times 10^{-3} cal cm^{-2} min^{-1}$
	$1 W/m^2 = 2.388 \times 10^{-5} cal cm^{-2} s^{-1}$

What Is Water?

- Water is a chemical compound. Each molecule of water, H_2O or HOH, consists of two atoms of hydrogen bonded to one atom of oxygen.

- Water is the most abundant molecule on the Earth's surface and one of the most important molecules to study in chemistry.

Water Facts

- Mass of water: 18.01528(33) $g.mol^{-1}$
- Density 1000 kg m^{-3} (1 $ton.m^{-3}$, 1 $Mg.m^{-3}$), liquid (4 °C) or 917 kg m^{-3}, solid.
- Melting point: 0°C, 32°F (273.15 K)
- Boiling point: 100°C, 212°F (373.15 K)
- Water has a high heat capacity and vaporization (40.65 $kJ \cdot mol^{-1}$). One consequence of this is that water is not subject to rapid temperature fluctuations. On Earth, this helps to prevent dramatic climate changes.

Source: http://chemistry.about.com/od/waterchemistry/a/water-chemistry.htm?utm_term=water&utm_content=p1-main-3-title&utm_medium=sem-sub&utm_source=msn&utm_campaign=adid-4ab0c3ff-4b77-4c4f-b3a0-5bacfcbaae58-0-ab_msb_ocode-4604&ad=semD&an=msn_s&am=broad&q=water&dqi=&o=4604&l=sem&qsrc=1&askid=4ab0c3ff-4b77-4c4f-b3a0-5bacfcbaae58-0-ab_msb

ET Basics

Specific latent heat (L): the amount of energy in the form of heat (Q) required to completely effect a phase change of a unit of mass (m), usually 1 kg.

The specific latent heat of condensation of water in the temperature range from −25 °C to 40 °C is approximated by the following empirical cubic function:

$$L_{\text{water}}(T) \approx \left(2500.8 - 2.36T + 0.0016T^2 - 0.00006T^3\right)\ \text{J/g}$$

Substance	SLH of fusion (kJ/kg)	Melting point (°C)	SLH of vaporization (kJ/kg)	Boiling point (°C)
Ethyl alcohol	108	−114	855	78.3
Ammonia	332.17	−77.74	1369	−33.34
Carbon dioxide	184	−78	574	−57
Helium			21	−268.93
Hydrogen(2)	58	−259	455	−253
Lead[9]	23.0	327.5	871	1750
Nitrogen	25.7	−210	200	−196
Oxygen	13.9	−219	213	−183
Refrigerant R134a		−101	215.9	−26.6
Refrigerant R152a		−116	326.5	-25
Silicon[10]	1790	1414	12800	3265
Toluene	72.1	−93	351	110.6
Turpentine			293	
Water	334	0	2264.705	100

ET Basics

Precipitation = 1 mm

= 1 g mm^{-2}

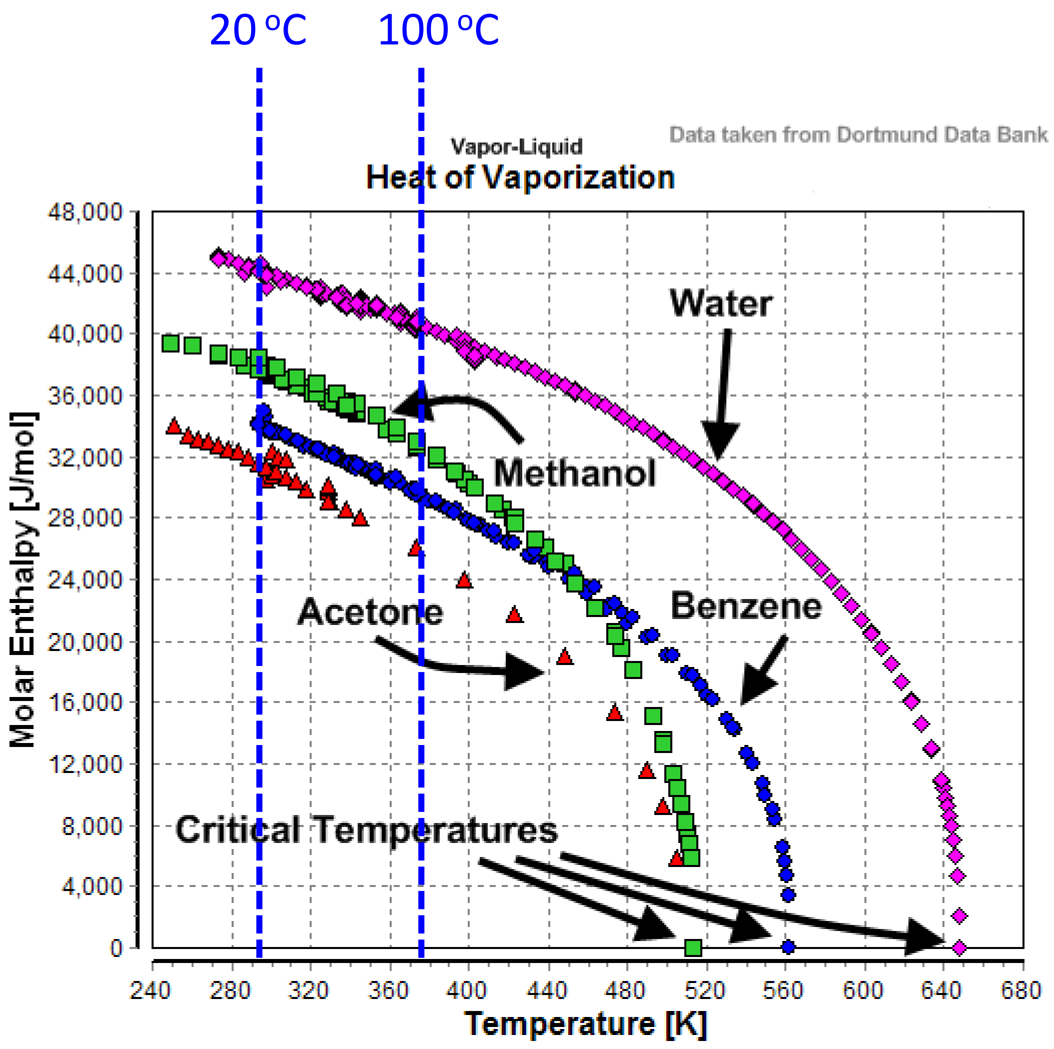
ET = 1 mm

= 1 g mm^{-2}

= 2264.705 J

= 2264.707*0.2388 Cal = 540.8 Cal

- The amount of energy needed to evaporate water is called latent heat of vaporization of water (λ, J mol^{-1}), which varies by temperature and atmospheric pressure.
- At air pressure of 101 kPa, its value is 44.6 kJ mol^{-1} at 10 ^{o}C and 44.1 kJ mol^{-1} at 20 ^{o}C.
- 40.65 kJ mol^{-1} = 2.265 kJ g^{-1} at 100 ^{o}C



Molecular weight of H_2O = 18.01528 g mol^{-1}

ET Measurements

Eddy-Covariance Methods & aerodynamics (Chapter 1)

Bowen Ratio: S:H

Pan Evaporation: by weight or volume

Lysimeter: The amount of water lost by calculating the difference between the weight

Sap flow: Tr is proportion to temperature change, when coupled with chamber measurements (including leaf and branches)

Energy Balance: $\lambda ET = Rn - G - H + delta(S)$

λ is "latent heat of evaporation -- the energy needed to change the phase of water from liquid to gas

Catchment water balance: difference of P from streamflow (*Q*), and groundwater recharge (*D*).

$$ET = P - \Delta S - Q - D$$

Stable isotopic analysis of H and O^{18}

Biophysical model: This class

ET Measurements: Bowen Ratio Method based on the energy balance

R_n = G + H + L

β = H:L = H:λET

Assuming that the transfer coefficients K of heat and water vapor and other scalar entities are equal:

$$H = \rho \cdot c_p \frac{\Delta T}{\Delta z}$$

$$\beta = \frac{\rho \cdot c_p \frac{\Delta T}{\Delta z}}{\rho \cdot \lambda \cdot \frac{\Delta e}{\Delta z}} = \frac{c_p \Delta T}{\lambda \cdot \Delta e}$$

$$= \frac{c_p}{\lambda} \cdot \frac{\Delta T}{\Delta e} = \gamma \cdot \frac{\Delta T}{\Delta e}$$

Temperature difference

Vapor density difference

Ta and Tw

https://www.sciencedirect.com/topics/earth-and-planetary-sciences/bowen-ratio#:~:text=The%20energy%20balance%20Bowen%20ratio%20(BR)%20method%20uses%20simultaneous%20measurements,)%20(Bowen%2C%201926).

$\gamma = \frac{c_p}{\lambda}$ psychrometric constant (mb °C^{-1})

ET Measurements: Bowen Ratio Method based on the energy balance

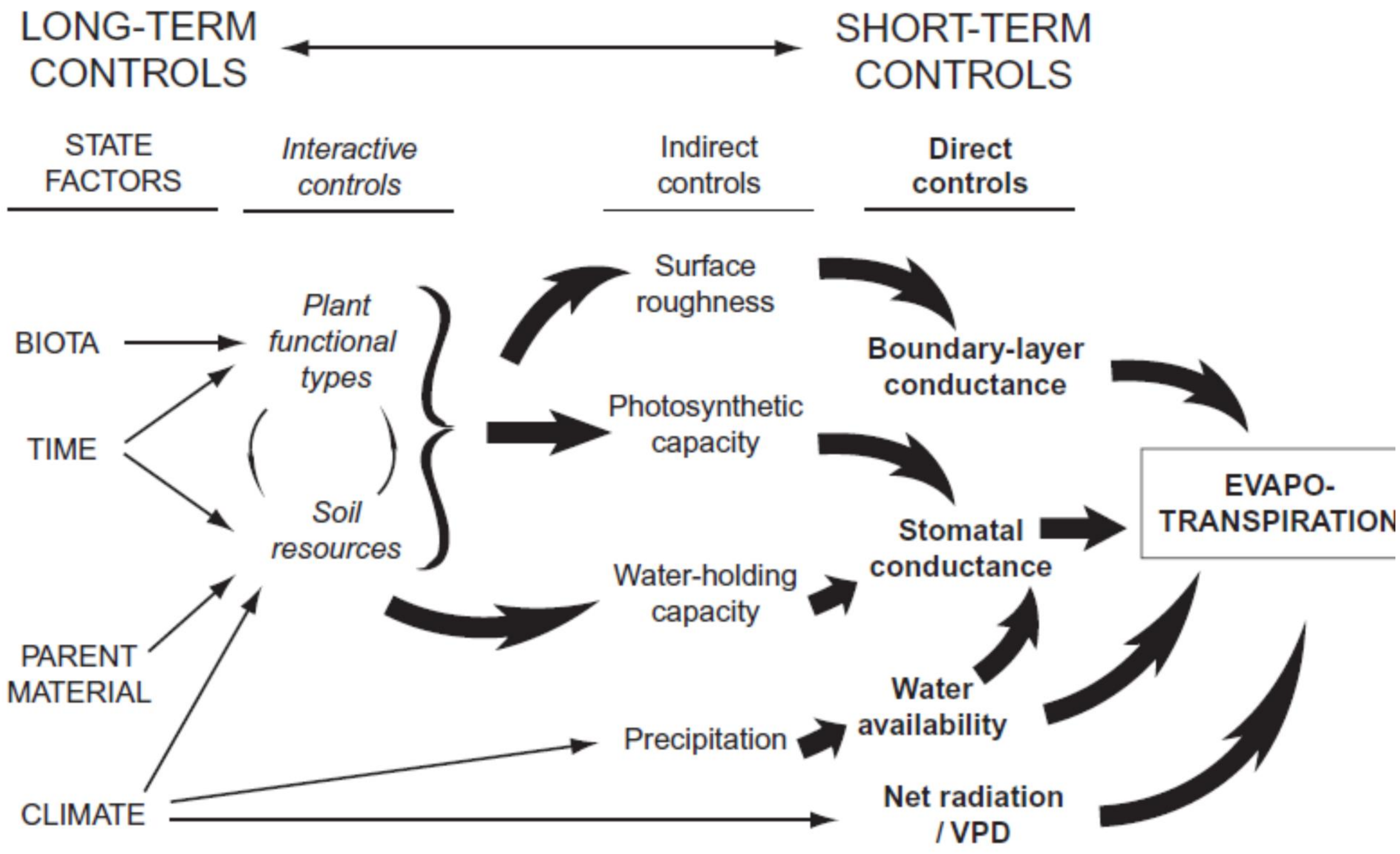
$\gamma = \frac{c_p}{\lambda}$ psychrometer constant (mb °C^{-1}).

Table 1. Variation of psychrometric constant *γ* with temperature, at standard atmospheric pressure.

T (°C)	*λ* (cal gr^{-1})	*γ* (mb °C^{-1})
0	597.3	0.655
5	594.5	0.658
10	591.7	0.661
15	588.9	0.664
20	586.0	0.668
25	583.2	0.671
30	580.4	0.674
35	577.6	0.677
40	574.7	0.681

http://ponce.sdsu.edu/psychrometric_constant.html

Regulations of ET: short- and long-term



Brief History of ET Modeling

- Evaporation – a term used since the mid-1600s (Stanhill 2005)
- PET used since 1937 (Stanhill 2005)
- Thornthwaite (1948), with a unit that is the same as precipitation (*e.g.*, cm):

$$PET = c \cdot T^a$$

where T (°C) is the monthly mean air temperature and c and a are empirical parameters that are hypothesized as a function of heat index (Thornthwaite 1948).

- Penman (1963) objected the use of the term *evapotranspiration* because evaporation already includes transpiration, since the latter is an evaporation process from leaf surface
- *ET* includes three sub-components:

$$ET = T + I + E$$

where T is vegetation transpiration, I is evaporation from canopy interception, and E is evaporation from soil and vegetation surfaces.

Types of the ET Models

- Pan evaporation-based equations
- Temperature-based equations
- Radiation-based equations
- Combination-type equations

There is a broad consensus that

- Performances of most methods have been found to vary from one climate to another
- Combination-type methods are more accurate (e.g. Katul et al. 1992)

Table 4-1. A comparison of major methods for estimating evapotranspiration (ET)

	Methods	Strengths	Weaknesses	Sources
Field measurements	Catchment water balance	Easy to measure; low cost	Only long-term average is reliable	(Sun et al. 2002)
	Sap flow	Allows routine unsupervised measurement accurately at single plant scale	Large-scale measurement errors are determined by the sample size and variability of samples	(Domec et al. 2012); (Ford et al. 2007)
	Eddy covariance	Measures fluxes continuously, offering high temporal resolution data	High cost in instrumentation; gap filling required; energy imbalance problems	(Baldocchi et al. 1988); (Sun et al. 2008b)
	Bowen ratio	Low cost; works for both crops and natural vegetation	Relies on several assumptions; errors associated with low gradients	(Irmak et al. 2014); (Bowen 1926)
Remote sensing	Remote sensing	Spatially continuous; low temporal resolution	Uncertainties due to errors generated by measurement of sparse canopies; data mostly from clear sky conditions	(Kustas & Norman 1996); (Mu et al. 2007); (Justice et al. 1998)
Modeling	Theoretical models (e.g., Penman–Monteith)	Widely used; long accepted; low cost	Requires site-specific parameters; not easy to apply on large scale	(Penman 1948); (Priestley & Taylor 1972); (Allen et al. 1994)
	Empirical (Budyko curves; flux data based)	Easy to understand; long-term mean estimate; easy to apply	May not be applicable to short-term estimates	(Budyko et al. 1962) (Zhang et al. 2004) (Sun et al. 2011a)

Estimating/Modeling ET: There are approximately 50 methods or models available to estimate ET. Some popular ones include

- Penman-Monteith Model (FAO)
- Thornthwaite Model
- Hamon’s PET Model
- Blaney–Criddl Model
- Turc PET Model
- Priestley-Taylor Model
- Makkink Model (1957)
- Hargreaves-Samani Model
- Empirical ET Models

4.3.1.1 Penman–Monteith Model: FAO reference ET Model

$$ET_o = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{Cn}{T+273} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + Cd \cdot u_2)}$$

[4.4]

Where

ET_o = grass reference *ET* (mm)

Δ = slope of the saturation water vapor pressure at air temperature (*T*, kPa $^oC^{-1}$)

$$\Delta = 2503 \frac{e^{\frac{17.27 \cdot T}{T+237.3}}}{(T + 237.3)^2}$$

R_n = net radiation (MJ m^{-2})

G = soil heat flux (MJ m^{-2})

γ = psychrometric constant (kPa $^oC^{-1}$)

e_s = saturation vapor pressure (kPa)

e_a = actual vapor pressure (kPa)

μ_2 = wind speed (m s^{-1}) at 2 m height

Cn = numerator constant that that changes with reference surface and calculation time step (900 ^oC mm s^{-3} Mg^{-1} d^{-1} for 24 h time steps, and 37 ^oC mm s^{-3} Mg^{-1} d^{-1} for hourly time steps)

Cd = denominator constant that changes with reference surface and calculation steps (0.34 s m^{-1} for 24 h time steps, 0.24 s m^{-1} for hourly time steps during daytime, and 0.96 s m^{-1} for hourly nighttime for grass reference surface) (Djaman *et al.*, 2018).

4.3.1.1 Penman–Monteith Model: FAO reference ET *Model*

Available energy

Wind & Pressure regulations

VPD regulations

$$ET_o = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{Cn}{T + 27 \cdot 3} \cdot u_2 \cdot (e_s - e_a)}{\Delta + \gamma \cdot (1 + Cd \cdot \mu_2)}$$

Wind, Pressure, air density regulations

Ta, RH, U, Rn, G

4.3.1.1 Penman–Monteith Model: FAO reference ET *Model*

$$ET_o = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \dfrac{Cn}{T + 27 \cdot 3} \cdot u_2 . (e_s - e_a)}{\Delta + \gamma \cdot (1 + Cd \cdot \mu_2)}$$

This model assumes:

- a stand of 0.12 m canopy height,
- a leaf area index (*LAI*) of 4.8,
- a bulk surface resistance of 70 s m^{-1}, and
- an albedo of 0.23.

FAO ET model and reference ET_o: https://www.youtube.com/watch?v=gtV_RpXsMJI

4.3.1.2 Thornthwaite Model

Temperature-based monthly scale *PET*

$$PET = 1.6 \cdot L_d \cdot \left(\frac{10 \cdot T}{I}\right)^a$$

Solar model

where

PET = monthly PET (cm)

L_d = mean daytime length (h), it is time from sunrise to sunset in multiples of 12 hours

T = monthly mean air temperature (°C)

$a = 6.75x10^{-7} \cdot I^3 - 7.71x10^{-5} \cdot I^2 + 0.01792 \cdot I + 0.49239$

I = annual heat index, which is computed from the monthly heat indices

$$I = \sum_{i=1}^{12} i_j$$

$$i_j = \left(\frac{T_j}{5}\right)^{1.514}$$

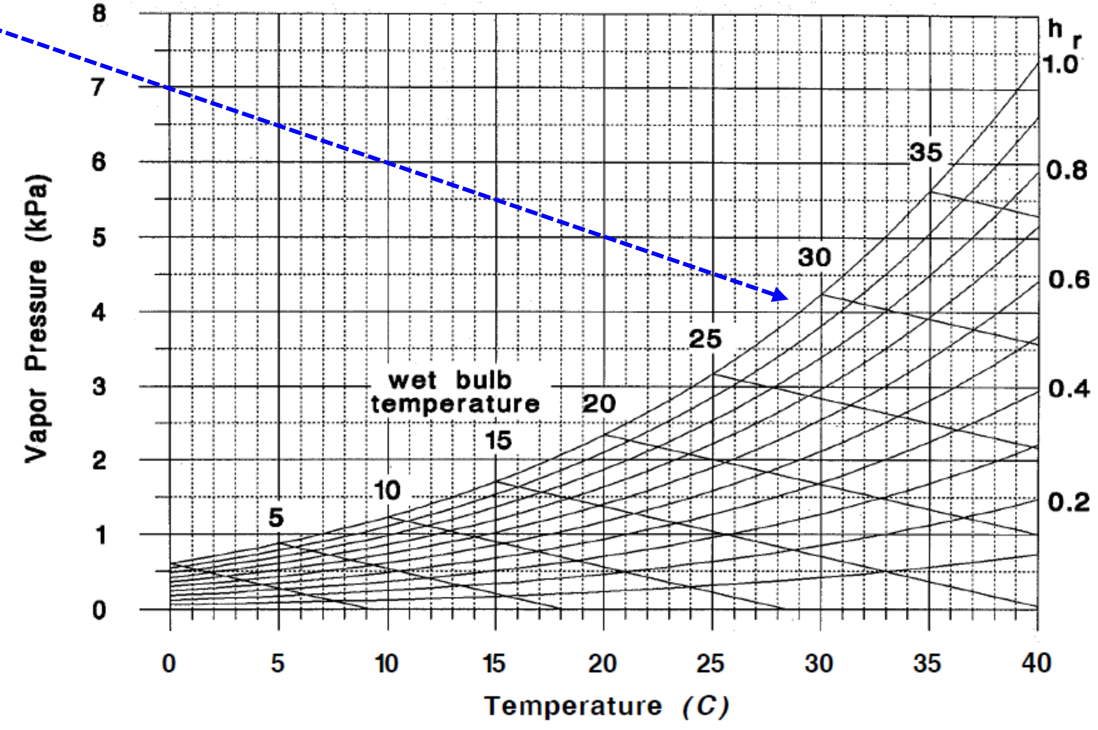
Simple and easy to calculate!

4.3.1.3 Hamon's PET *Model*

- A temperature-based model (Hamon 1963)
- It computes daily *ET* based on air temperature and theoretical daytime length (DAY)

$$PET = 0.1651 \cdot DAY \cdot \frac{216.7 \cdot e_s}{t_a + 273.3}$$

Solar model



4.3.1.4 Blaney–Criddle PET *Model*

Blaney & Criddle (1957) proposed a model for estimating *ET* for the western USA

$$PET = P \cdot (0.46 \cdot T + 8.13)$$

- *T* (°C) is mean temperature, and
- *P* (%) is percentage of total daytime hours for the period used (daily or monthly) out of total daytime hours of the year (365·12 = 4380 h).

$$ET = PET \cdot k$$

- *k* is a monthly consumptive use coefficient, depending on vegetation type, location and season.
- For the growing season (May-October), *k* varies from 0.5 for orange tree to 1.2 for dense vegetation

4.3.1.5 Turc PET *Model*

Turc (1961) simplified earlier versions of a *PET* (mm day^{-1}) equation for 10-day periods under general climatic conditions of Western Europe

When relative humidity (*RH*) is < 50%

$$PET = 0.013\left(\frac{T}{T+15}\right)(R_s + 50)\left(1 + \frac{50 - RH}{70}\right)$$

When *RH* is > 50%

$$PET = 0.013\left(\frac{T}{T+15}\right)(R_s + 50)$$

T = daily mean air temperature (°C)

R_s = daily solar radiation (ly day^{-1}, or $cal cm^{-2}$ d^{-1})

1 cal cm^{-2} d^{-1} = (100/4.1868) (MJ m^{-2} day^{-1})

RH = daily mean relative humidity in percentage (%) .

4.3.1.6 Priestley–Taylor Model

The Priestley–Taylor PET model (Priestley & Taylor 1972) was developed as a substitute to the Penman–Monteith equation to estimate *ET* when there is no soil water stress.

$$\lambda PET = \alpha \frac{\Delta}{\Delta + \gamma}(R_n - G)$$

$$\Delta = 2503 \frac{e^{\frac{17.27 \cdot T}{T+237.3}}}{(T + 237.3)^2}$$

PM Model

$$ET_o = \frac{0.408 \cdot \Delta \cdot (R_n - G) + \gamma \cdot \frac{Cn}{T + 27 \cdot 3} \cdot u_2 . (e_s - e_a)}{\Delta + \gamma \cdot (1 + Cd \cdot \mu_2)}$$

4.3.1.7 Makkink PET *Model*

Makkink (1957) estimated *PET* (mm day^{-1}) over 10-day periods for grassed lands under cool climatic conditions

$$PET = 0.61\left(\frac{\Delta}{\Delta + \gamma}\right)\frac{R_s}{58.5} - 0.12$$

4.3.1.8 Hargreaves–Samani PET *Model*

$$\lambda \cdot PET = 0.0023 \cdot R_a \cdot TD^{0.5} \cdot (T + 17.8)$$

where
PET = daily *PET* (mm day^{-1})
λ = latent heat of vaporization (MJ kg^{-1})
T = daily mean air temperature (°C)
R_a = extraterrestrial solar radiation (MJ m^{-2} day^{-1})
TD = daily difference between the maximum and minimum air temperature (°C)

4.3.2 Empirical actual ET *models*

Sun *et al.* (2011a) developed an empirical model for estimating monthly *ET* as a function of *LAI*, ET_o (mm mo^{-1}), and precipitation (mm mo^{-1}).

$$ET = 11.94 + 4.76 \cdot LAI + ET_o \cdot (0.032 \cdot LAI + 0.0026 \cdot P + 0.15)$$

where ET_o is the FAO 56 reference *ET* (Eq. 4.4) and *P* is monthly precipitation

$$ET = 0.174 \cdot P + 0.502 \cdot PET + 5.31 \cdot LAI + 0.0222 \cdot PET \cdot LAI$$

$$ET = 0.42 + 0.74 \cdot PET - 2.73 \cdot VPD + 0.10 \cdot R_n$$

$$ET = -4.79 + 0.75 \cdot PET + 3.92 \cdot LAI + 0.04 \cdot \mathrm{P}$$

Remote Sensing Modeling

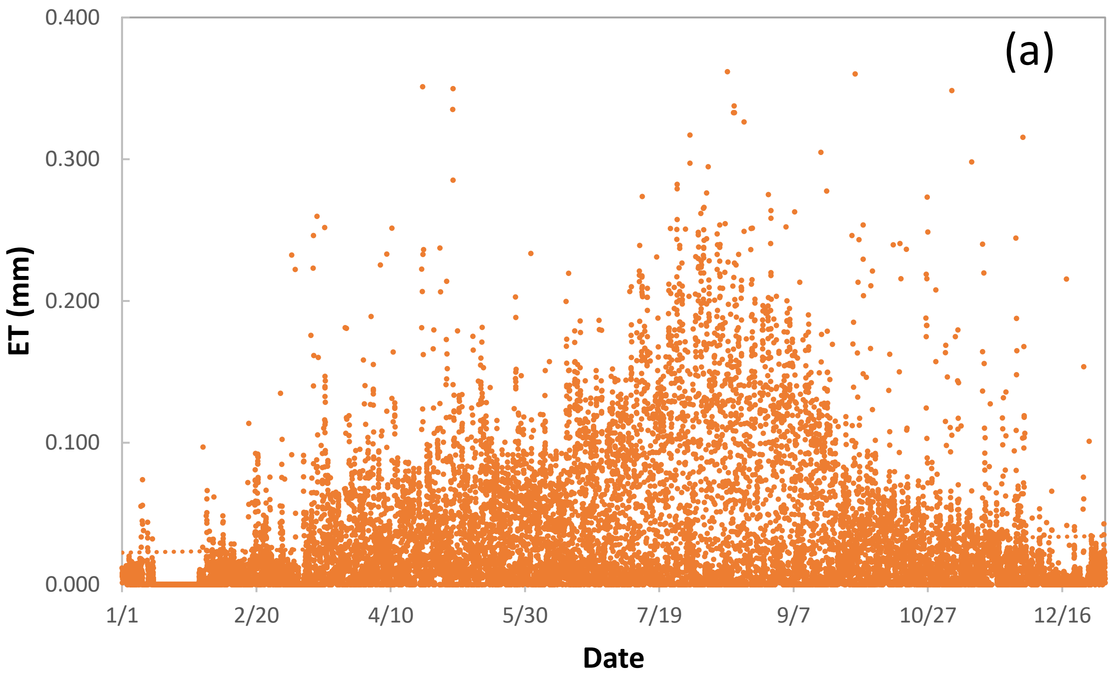
By combining remote sensing and climate data for 299 river basins, Zeng *et al.* (2014) developed an annual *ET* model:

$$ET = 0.4(\pm 0.02) \cdot P + 10.62\ (\pm 0.39) \cdot T + 9.63\ (\pm 2.27) \cdot NDVI + 31.58(\pm 7.89),\ R^2 = 0.85$$

- *ET:* basin-averaged annual evapotranspiration (mm yr^{-1}),
- *P:* annual precipitation (mm yr^{-1})
- *T:* mean annual temperature (^oC)
- *NDVI:* the annual average normalized difference vegetation index

4.4 Model Demonstrations

The one-year demonstration data sets (2016) were collected at one of the seven scale-up sites of the Great Lakes Bioenergy Research Center (GLBRC) at the Kellogg Biological Station (KBS) in southwestern Michigan, USA, with an open-path eddy-covariance flux tower.



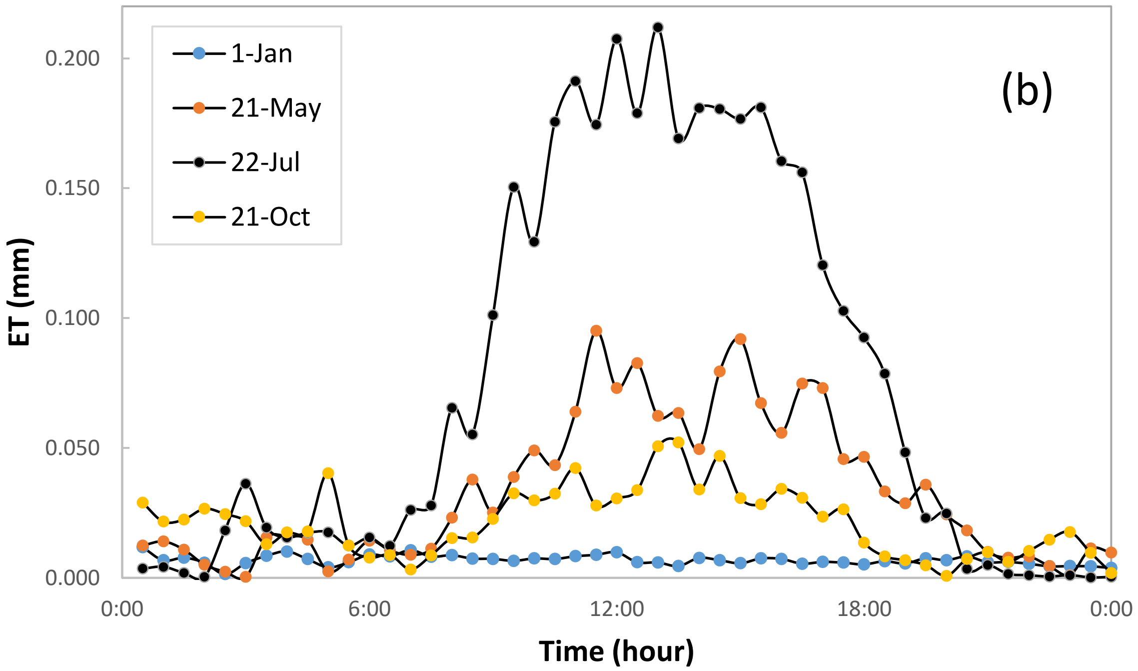


Figure 4-3. Measured *ET* (mm) at daily (a) and monthly (b) scale using the eddy-covariance method at a continuous corn site of the Kellogg Biological Station (KBS) in southwestern Michigan, USA, in 2016. Negative *ET* values from the flux tower were not included in calculations.

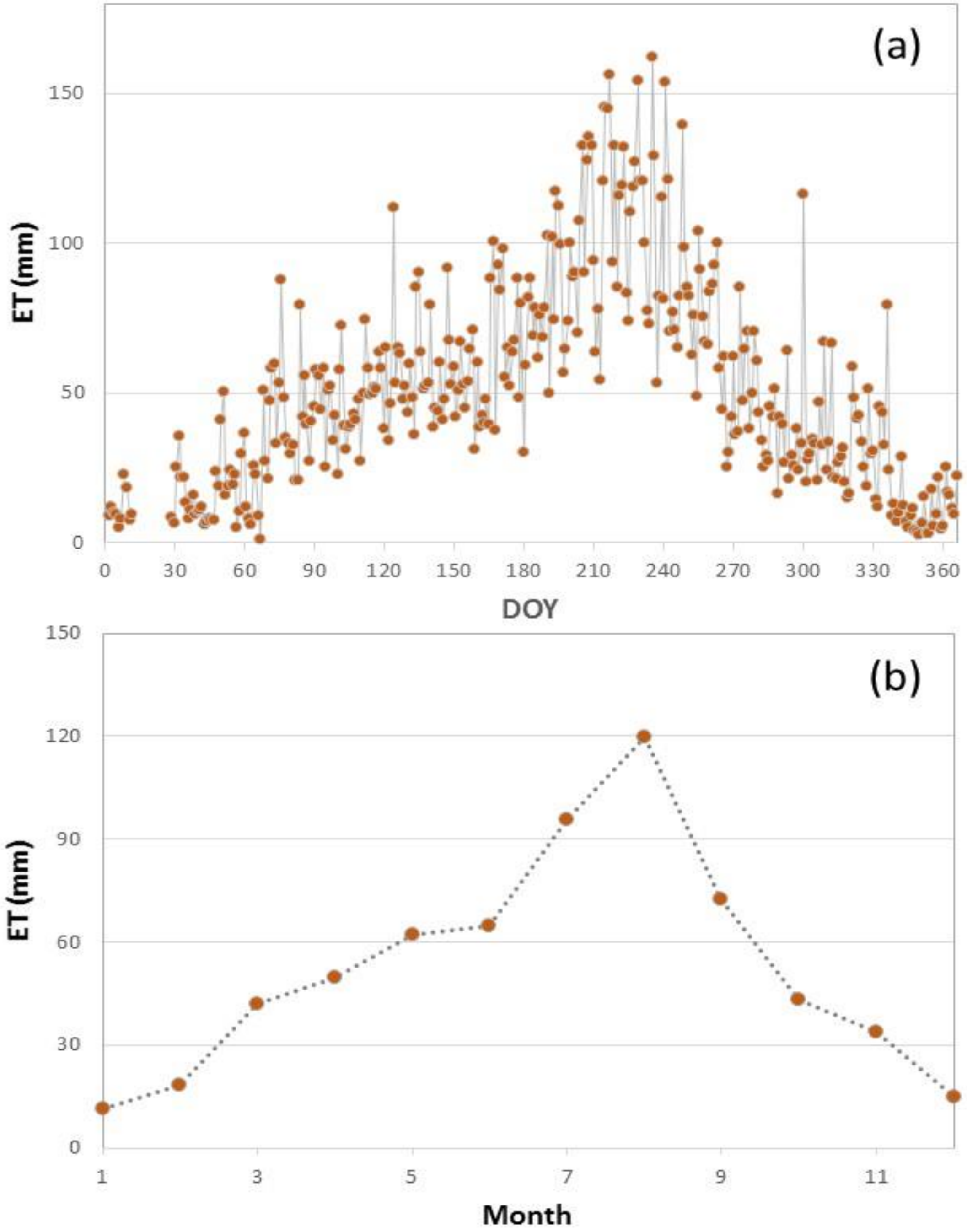


Figure 4-4. Modeled 30-min reference evapotranspiration (*ET_o*) for a continuous corn field at the Kellogg biological Station (KBS) in southwestern Michigan, USA, in 2016.

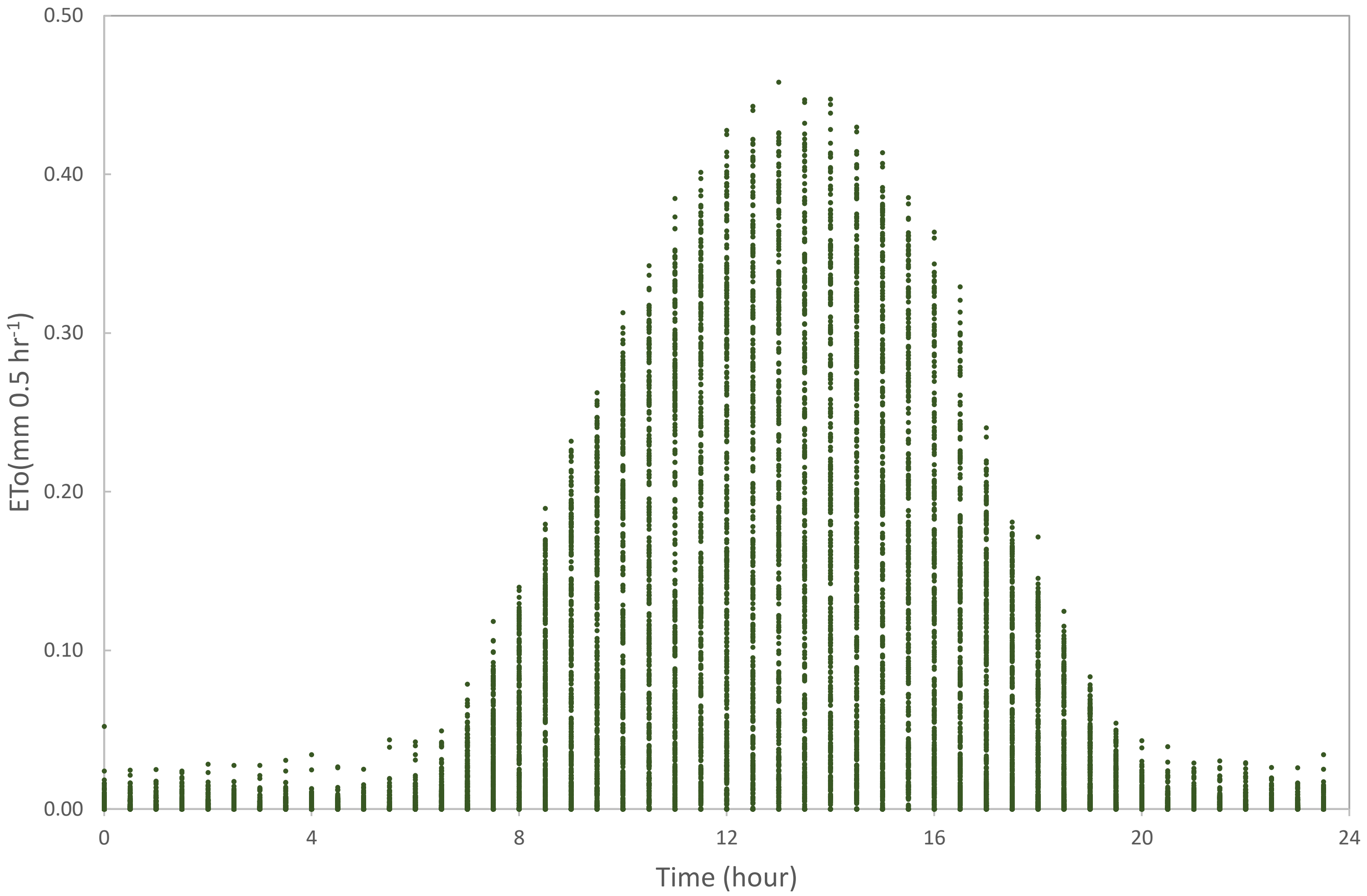


Figure 4-5. Modeled daily reference *ET* (ET_o) and potential evapotranspiration (*PET*) with three biophysical models for a continuous corn field at the Kellogg biological Station (KBS) in southwestern Michigan, USA, in 2016.

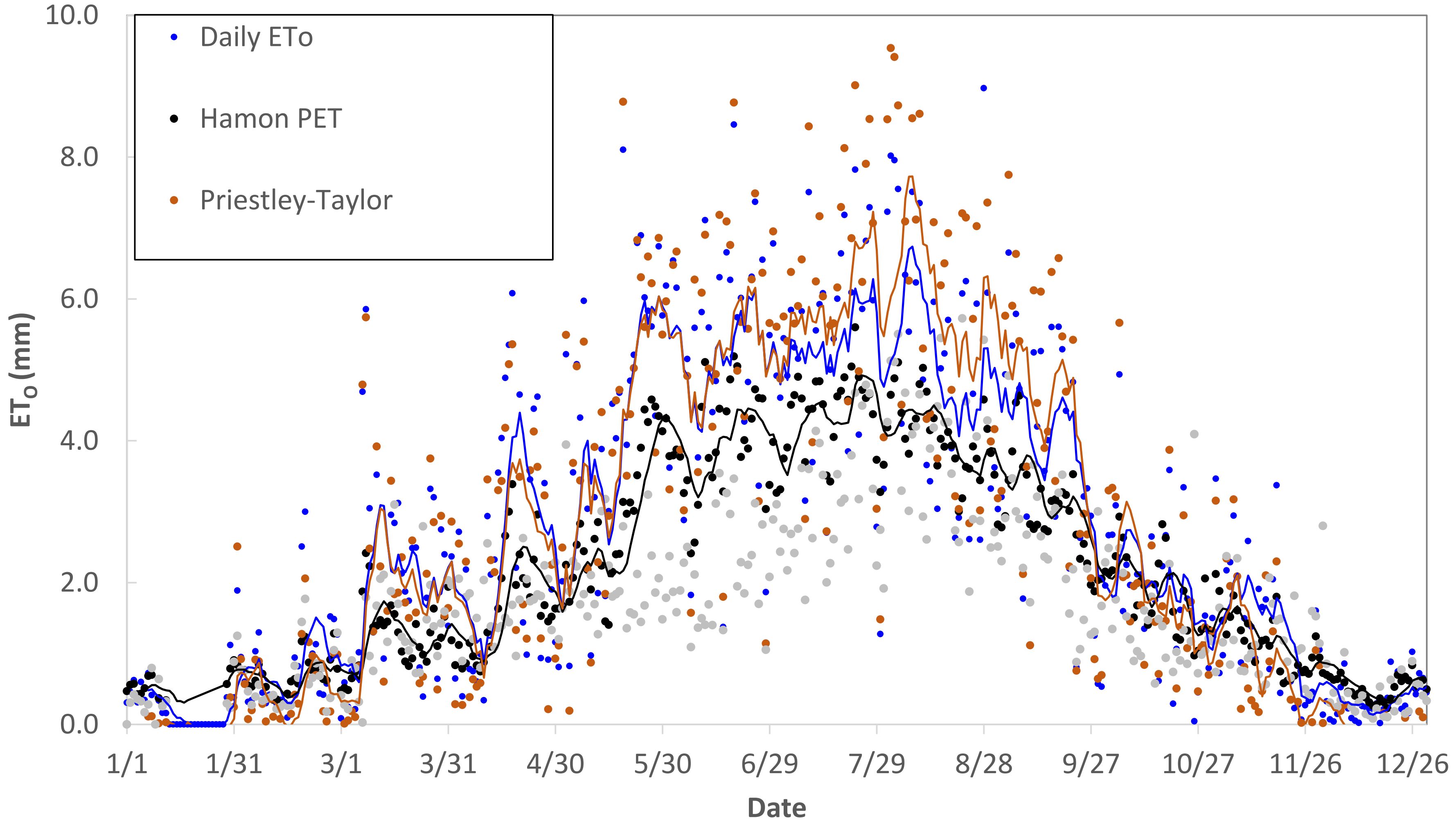


Figure 4-6. Measured and modeled actual monthly evapotranspiration (ET, mm) using two empirical models for the continuous corn site at KBS in southwestern Michigan, USA, in 2016.

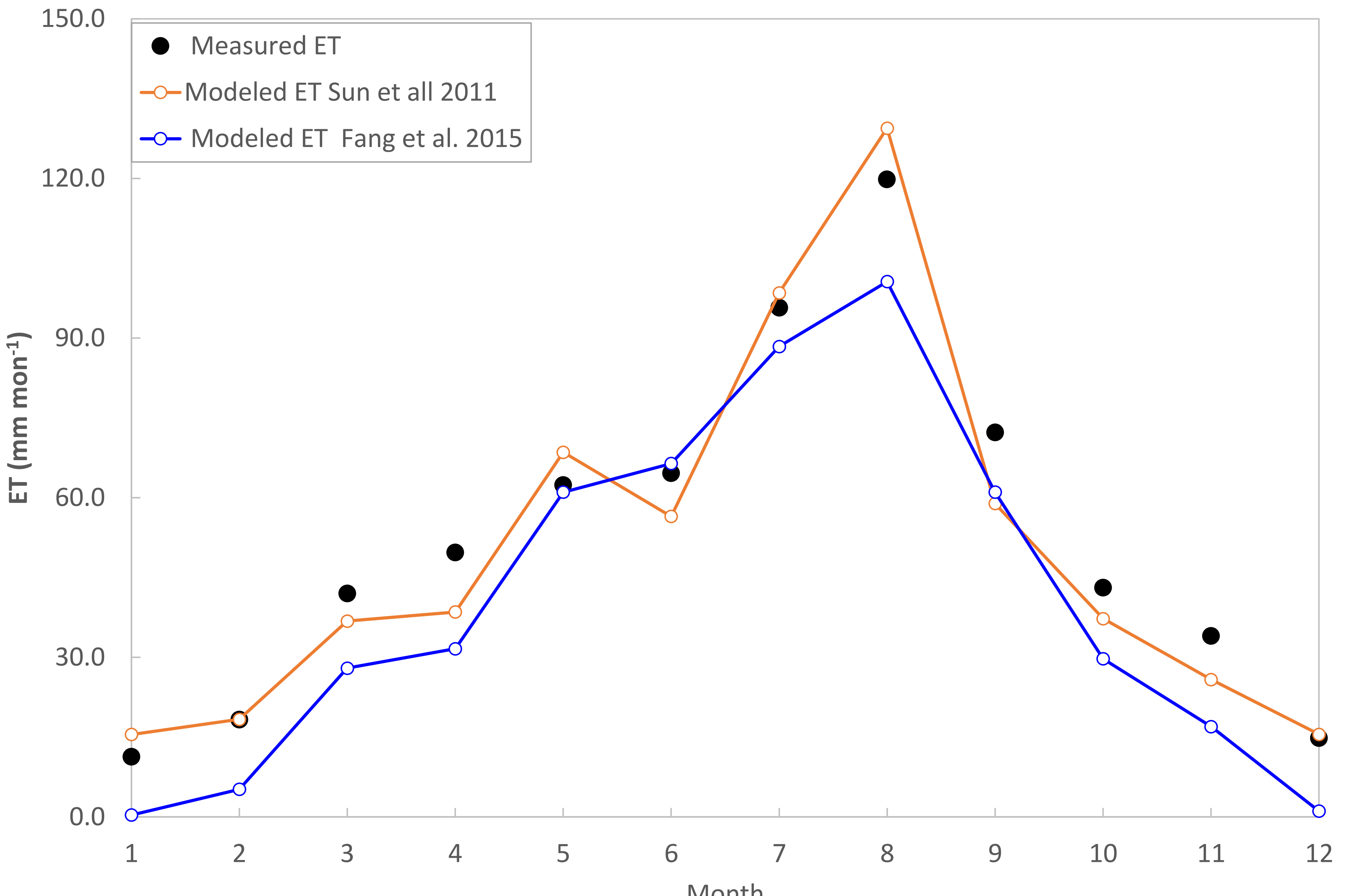


Table 4-3. Type I models by land cover type developed using the three most significant variables. These models are appropriate at a monthly scale. RMSE = Root Mean Square Error, R^2 = Coefficient of Determination, n = number of monthly samples

Land cover type	**Model**	**RMSE (mm mo^{-1})**	**R^2**	**n**
Shrubland	$ET = -4.59+13.02 \cdot LAI+0.10 \cdot Rn+0.11 \cdot P$	11.2	0.85	193
Cropland	$ET = 0.87+0.19 \cdot Rn+13.99 \cdot LAI+0.06 \cdot P$	20.2	0.72	649
Grassland	$ET = -0.87+0.20 \cdot Rn+0.10 \cdot \mathrm{P}+0.24 \cdot SWC$	15.7	0.73	562
Deciduous forest	$ET = -14.22+0.74 \cdot PET+0.1 \cdot Rn$	22.2	0.77	788
Evergreen needleleaf forest	$ET = 13.47+0.10 \cdot Rn+1.35 \cdot Ta$	17.2	0.71	1720
Evergreen broad leaf forest	$ET = 0.01 +0.63 \cdot \mathrm{Ta}+0.46 \cdot SWC +0.14 \cdot Rn$	12.5	0.90	69
Mixed forest	$ET = -8.76+0.95 \cdot PET$	13.1	0.79	259
Savannas	$ET = -8.07+33.46 \cdot LAI+0.07 \cdot Rn$	14.0	0.66	36

Units: ET = mm mo^{-1}; R_n = MJ mo^{-1}; P = mm mo^{-1}; PET = mm mo^{-1} estimated by Hamon's method; VPD = hPa; SWC = soil water content (%)

Table 4-4. Type II models by land cover type developed using three commonly measured biophysical variables. RMSE = Root Mean Square Error, R^2=Coefficient of Determination, n = number of monthly samples

Land cover type	Model	RMSE	R^2	n
Shrubland	ET = -3.11+0.39·*PET*+0.09·P+11.127·*LAI*	12.5	0.80	193
Cropland	ET = -8.15+0.86·*PET*+0.01·P+9.54·*LAI*	20.9	0.70	653
Grassland	ET = -1.36+0.70·*PET*+0.04·P+6.56·*LAI*	16.8	0.66	803
Deciduous forest	ET = -14.82+0.98·*PET*+2.72·*LAI*	23.7	0.74	754
Evergreen needle leaf forest	ET = 0.10+0.64·*PET*+0.04·P+3.53·*LAI*	17.8	0.68	1382
Evergreen broad leaf forest	ET = 7.71+0.74·*PET*+1.85·*LAI*	16.8	0.76	233
Mixed forest	ET = -8.763+0.95·*PET*	13.1	0.79	259
Savannas	ET = -5.66+0.18·*PET*+0.10·P+44.63·*LAI*	11.1	0.68	36

Units: *ET* = mm mo^{-1}; *P* = mm mo^{-1}; *PET* = mm mo^{-1} estimated by Hamon's method; n = sample size

Case Studies

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DOI: 10.1002/hyp.13630

RESEARCH ARTICLE

WILEY

Long-term evapotranspiration rates for rainfed corn versus perennial bioenergy crops in a mesic landscape

Michael Abraha[1,2,3] | Jiquan Chen[1,2,4] | Stephen K. Hamilton[2,3,5,6] | G. Philip Robertson[2,3,7]

TABLE 2 Mean total annual ET rates for all fields and differences between the perennial (restored prairie and switchgrass) and corn fields over 9 years (2010–2018)

		Mean ET_t (mm; 2010–2018)			ET difference			
Season	Land use history	Restored prairie	Switchgrass	Corn	Pr-C (mm)	Pr-C (%)	Sw-C (mm)	Sw-C (%)
Growing season	AGR	411 (7)	396 (8)	409 (9)	1 (11)	0	−13 (12)	−3
Growing season	CRP	428 (8)	446 (8)	408 (9)	20 (12)	5	38 (12)	9
Nongrowing season	AGR	150 (5)	149 (7)	175 (7)	−25 (9)	−14	−26 (10)	−15
Nongrowing season	CRP	153 (6)	151 (6)	172 (8)	−19 (10)	−11	−21 (10)	−12
Annual	AGR	560 (12)	545 (14)	584 (15)	−24 (19)	−4	−39 (20)	−7
Annual	CRP	581 (13)	597 (13)	580 (16)	1 (21)	0	17 (21)	3

Case Studies

Hargreaves, G. H., & Allen, R. G. (2003). History and evaluation of Hargreaves evapotranspiration equation. *Journal of Irrigation and Drainage Engineering*, *129*(1), 53-63.

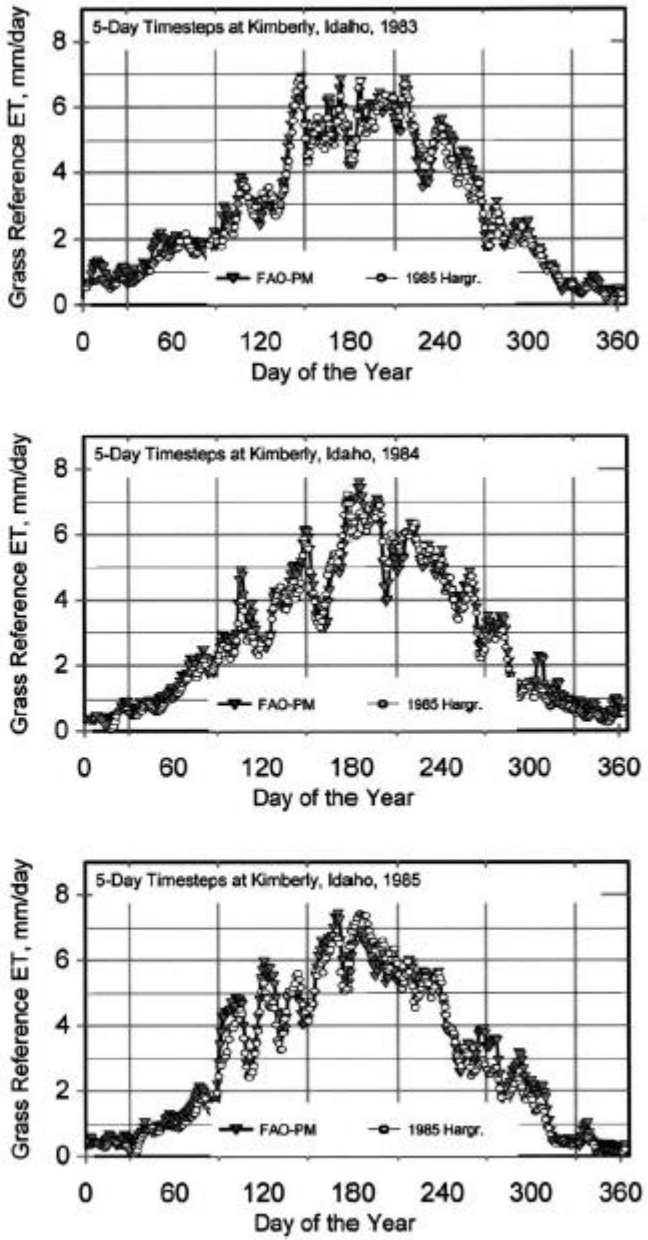


Fig. 3. Comparison of five-day ET_o calculated for three years at Kimberly, Idaho using 1985 Hargreaves method and FAO-Penman-Monteith method

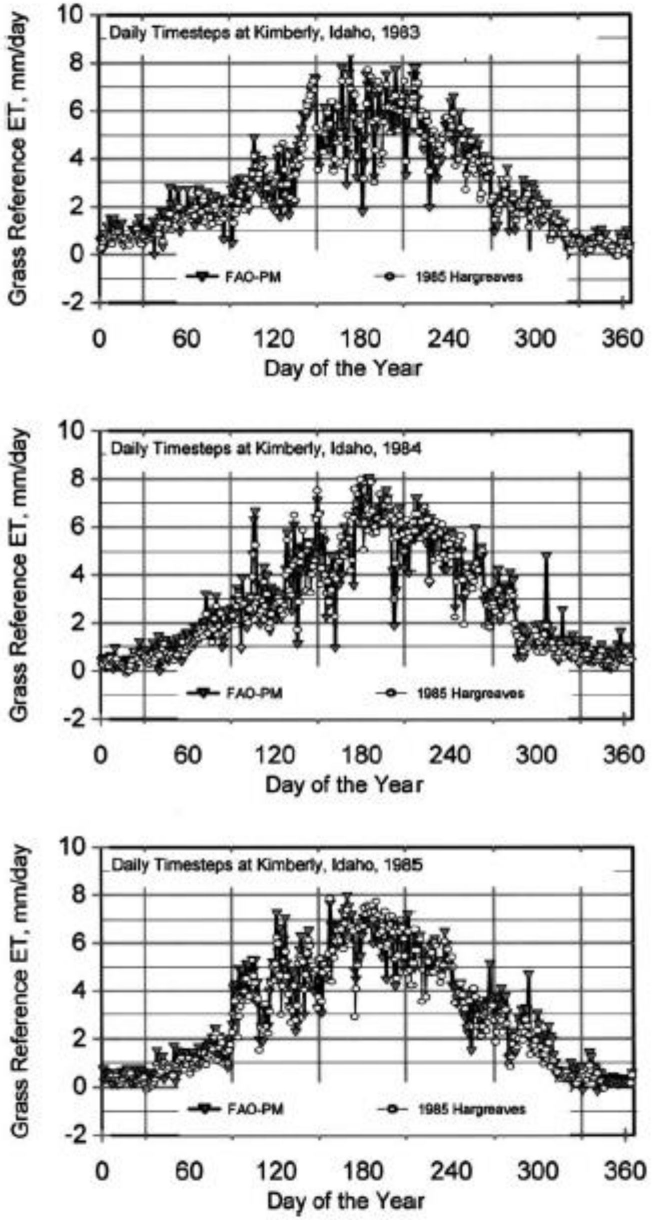


Fig. 2. Comparison of daily ET_o calculated for three years at Ki berly, Idaho using 1985 Hargreaves method and FAO-Penm Monteith method

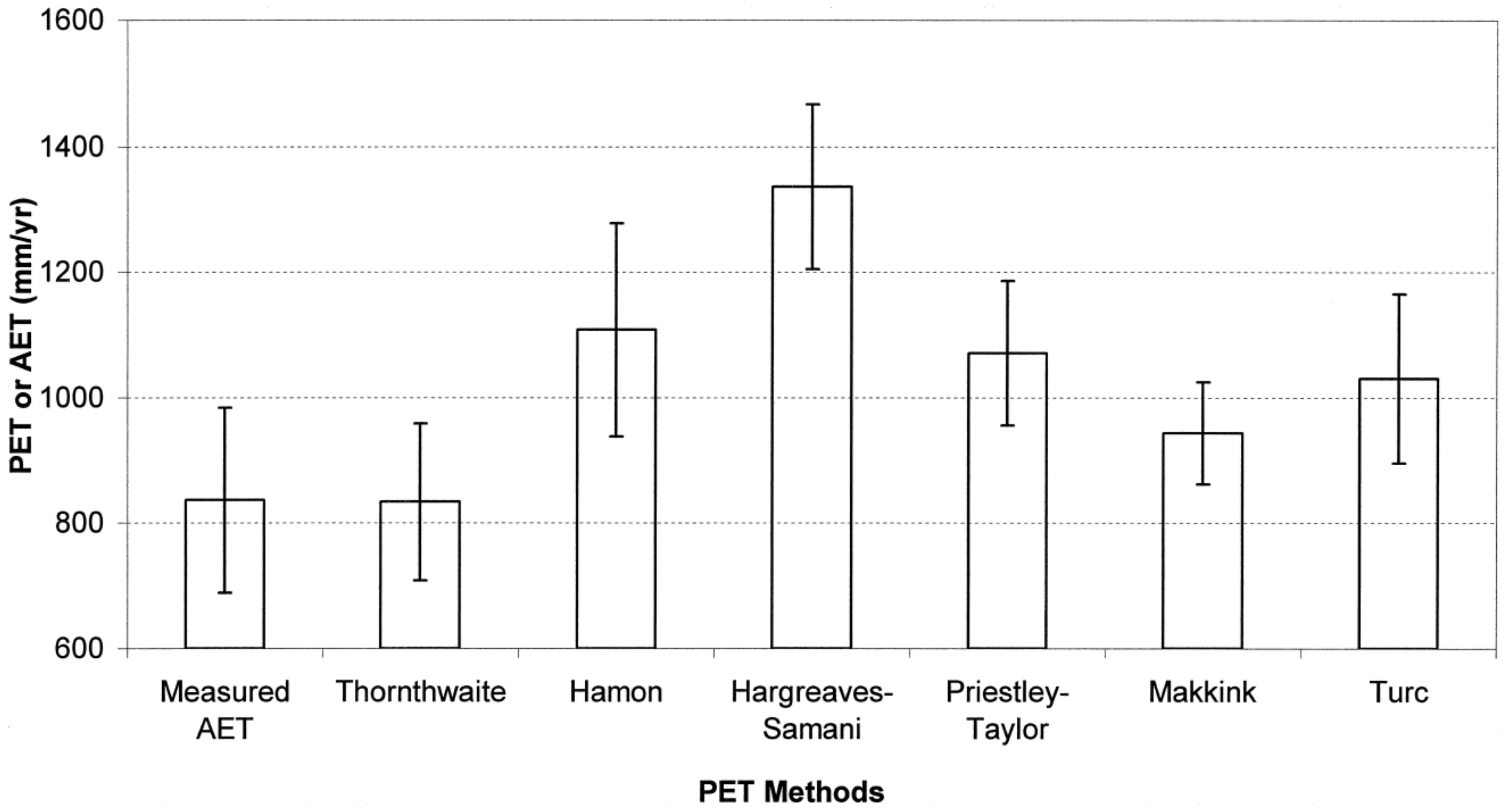
Case Studies

JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
JUNE AMERICAN WATER RESOURCES ASSOCIATION 2005

A COMPARISON OF SIX POTENTIAL EVAPOTRANSPIRATION METHODS FOR REGIONAL USE IN THE SOUTHEASTERN UNITED STATES[1]

Jianbiao Lu, Ge Sun, Steven G. McNulty, and Devendra M. Amatya[2]

A COMPARISON OF SIX POTENTIAL EVAPOTRANSPIRATION METHODS FOR REGIONAL USE IN THE SOU



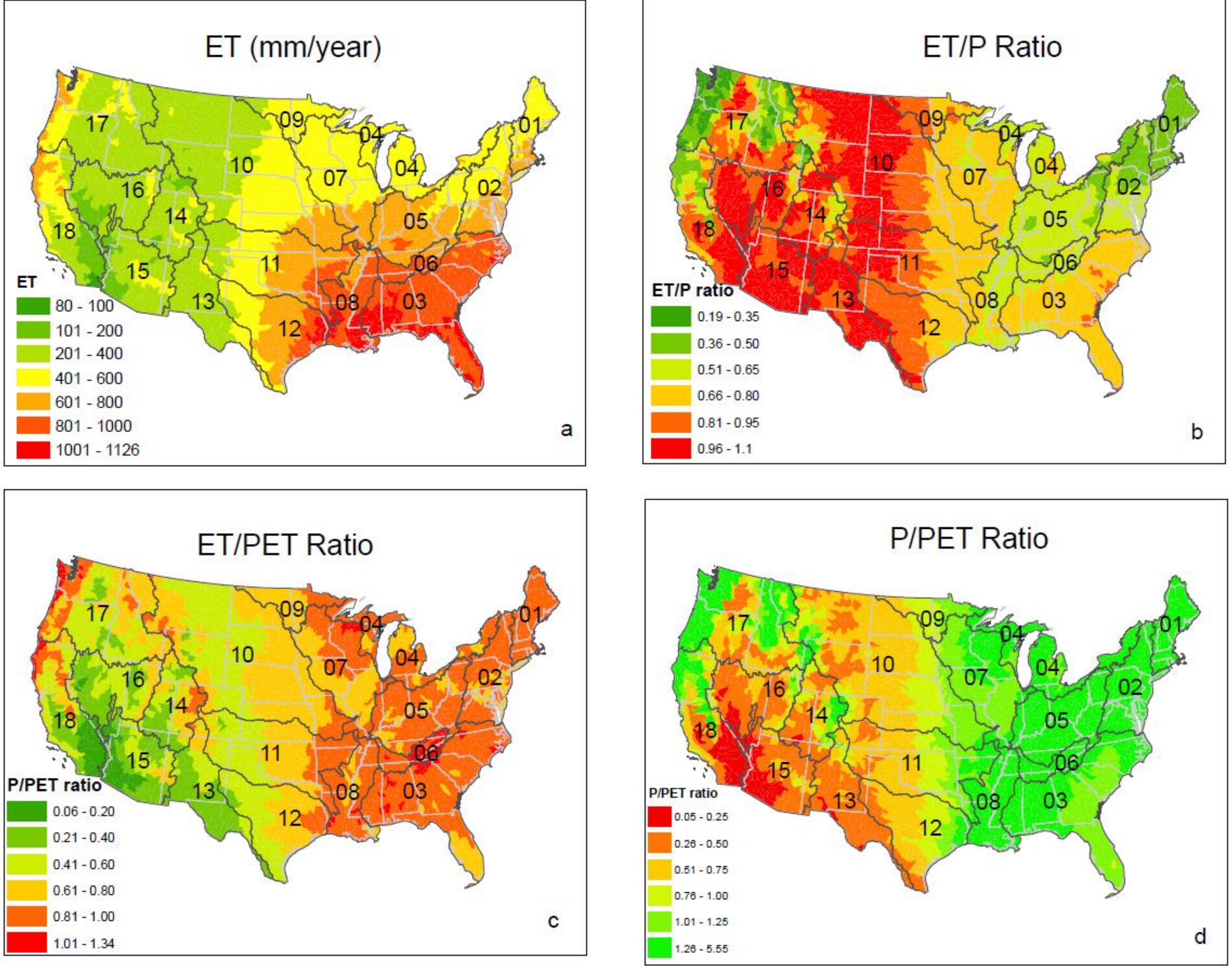
Case Studies

JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 116, G00J05, doi:10.1029/2010JG001573, 2011

Upscaling key ecosystem functions across the conterminous United States by a water-centric ecosystem model

Ge Sun,[1] Peter Caldwell,[1] Asko Noormets,[2] Steven G. McNulty,[1] Erika Cohen,[1] Jennifer Moore Myers,[1] Jean-Christophe Domec,[2,3] Emrys Treasure,[1] Qiaozhen Mu,[4] Jingfeng Xiao,[5] Ranjeet John,[6] and Jiquan Chen[6]

We developed a water-centric monthly scale simulation model (WaSSI-C) by integrating empirical water and carbon flux measurements from the FLUXNET network and an existing water supply and demand accounting model (WaSSI)



Case Studies

JGR Atmospheres

Research Article | Free Access

Satellite Detection of Water Stress Effects on Terrestrial Latent Heat Flux With MODIS Shortwave Infrared Reflectance Data

Yunjun Yao, Shunlin Liang, Bao Cao, Shaomin Liu, Guirui Yu, Kun Jia, Xiaotong Zhang, Yuhu Zhang, Jiquan Chen, Joshua B. Fisher

3.2 Revised PT Algorithm Framework

The terrestrial LE was estimated based on the satellite-based PT algorithm (PT-JPL) framework (Fisher et al., 2008; Priestley & Taylor, 1972) as

$$LE = LE_s + LE_c + LE_i, \quad (5)$$

$$LE_s = \alpha(1 - f_{\mathrm{wet}})f(SM)\frac{\Delta}{\Delta+\gamma}(R_{\mathrm{ns}} - G), \quad (6)$$

$$LE_c = \alpha(1 - f_{\mathrm{wet}})f(g)f(T)f(CM)\frac{\Delta}{\Delta+\gamma}R_{\mathrm{nc}}, \quad (7)$$

and

$$LE_i = \alpha f_{\mathrm{wet}}\frac{\Delta}{\Delta+\gamma}(R_n - G), \quad (8)$$

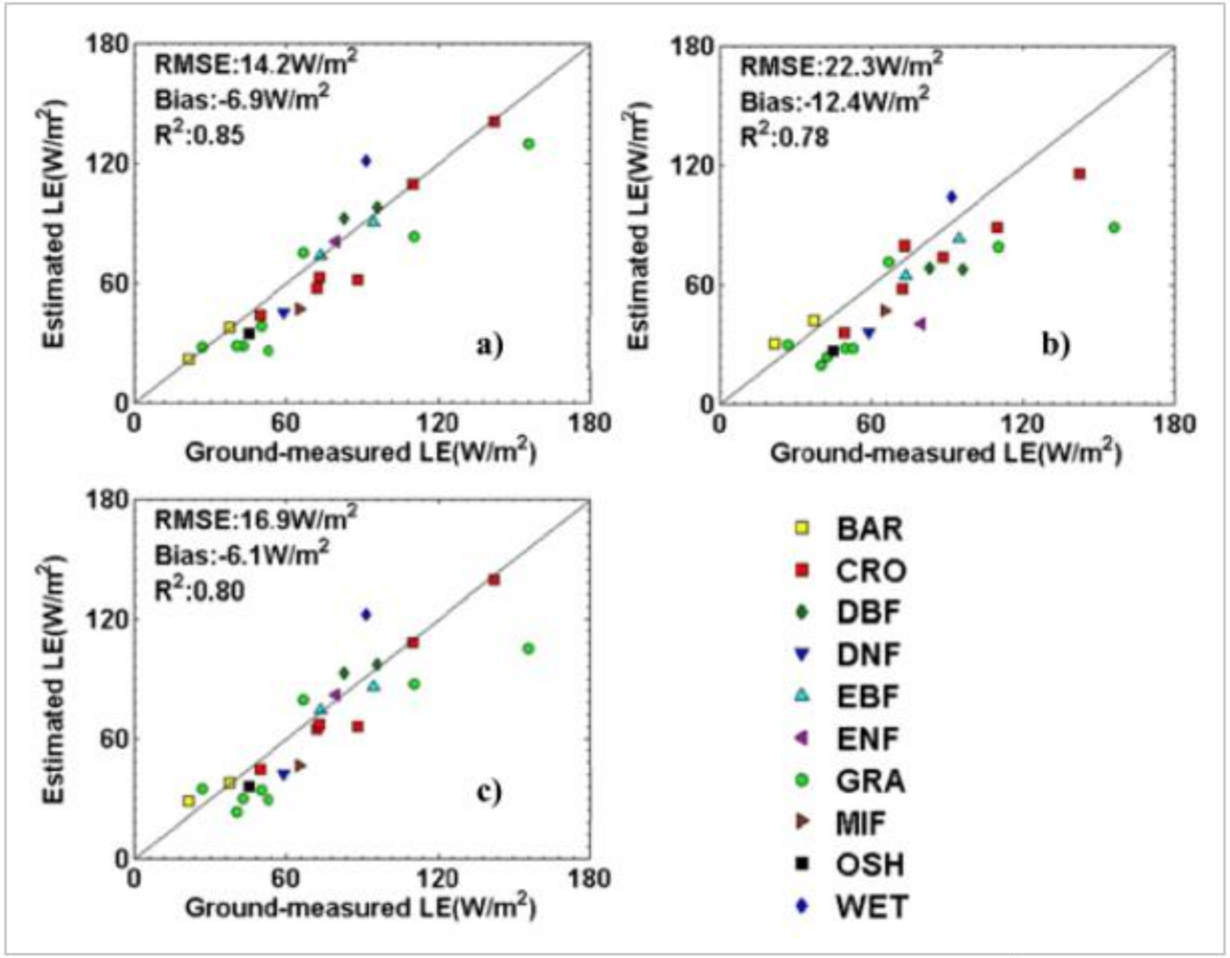


Figure 5 Open in figure viewer | PowerPoint

Comparisons of the estimated (a) LE_swir, (b) LE_sm, and (c) LE_no using tower meteorology and measured site averaged daily LE values for different biomes at 25 sites. LE = latent heat flux; CRO = cropland; GRA = grassland; DBF = deciduous broadleaf forest; EBF = evergreen broadleaf forest; DNF = deciduous needleleaf forest; ENF = evergreen needleleaf forest; MIF = mixed forest; OSH = open shrubland; WET = wetland; BAR = barren lands.

Supplementary Materials

S-1: Field measurements of evapotranspiration (*ET*) and micrometeorological variables at 30 min interval in 2016 in an agricultural site (42°28'36.19" N, -85°26'48.37" W, 294 m a.s.l.) with an eddy-covariance tower of the Kellogg Biological Station, Michigan, USA (ETData.xlsx).

S-2: Spreadsheet modeling of reference *ET* (ET_o), potential evapotranspiration (*PET*), and actual *ET* (Eqs. 4.4, 4.6, 4.12, 4.15, Table 4-4) for a corn field of the Kellogg Biological Station, Michigan, USA (ETmodels.xlsx).

In-class exercises

Using the in-situ measurements of input variables to calculate ET at hourly, daily, and monthly scale

4.3.1.1 Penman–Monteith Model: FAO reference ET Model
4.3.1.2 Thornthwaite Model
4.3.1.3 Hamon's PET Model
4.3.1.4 Blaney–Criddle PET Model
4.3.1.5 Turc PET Model
4.3.1.6 Priestley–Taylor Model
4.3.1.7 Makkink PET Model

Q&A from the Class

In class exercise of ET models

Note: Comments and typos for each chapters are welcome!

List of Symbols

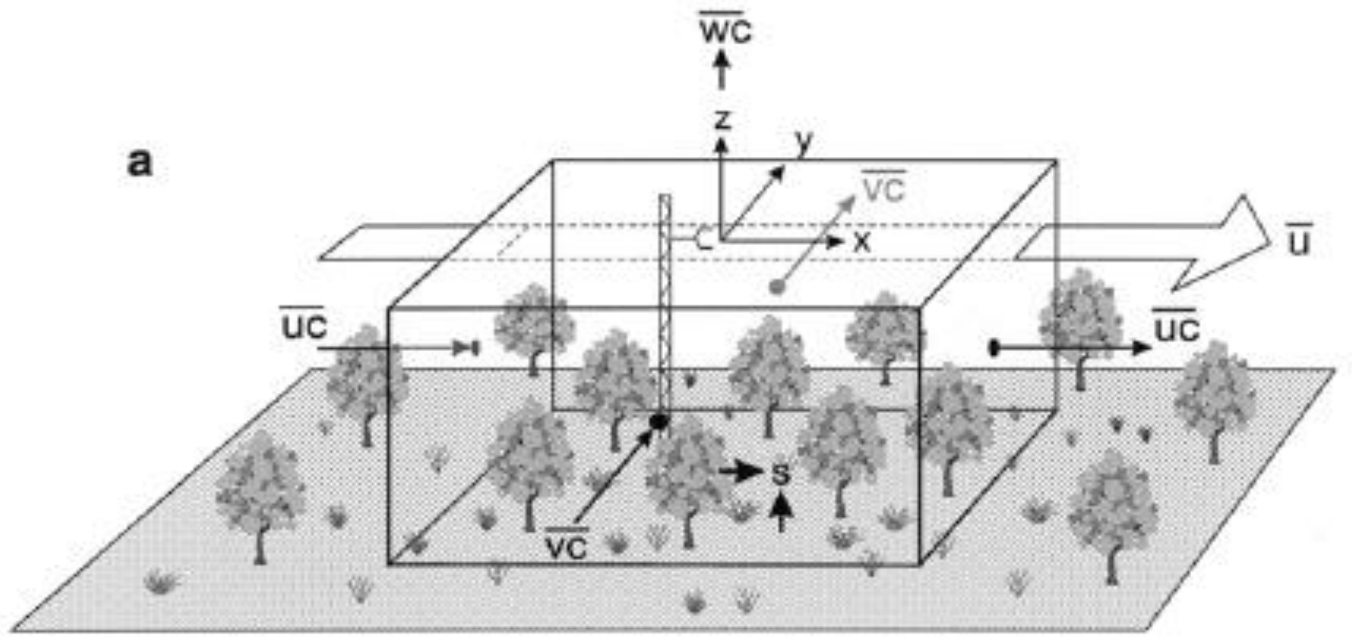
Name	Unit	Full Name
AGB	kg ha^{-1}; g m^{-2}	Aboveground Biomass
ANPP	kg ha^{-1} year^{-1}; g m^{-2} year^{-1}	Aboveground Net Primary Productivity
aPAR	W m^{-2}; mmol m^{-2} s^{-1}	Absorbed Photosynthetic Active Radiation
BGB	kg ha^{-1}; g m^{-2}	Belowground Biomass
BNPP	kg ha^{-1} year^{-1}; g m^{-2} year^{-1}	Belowground Net Primary Productivity
C pool	kg ha^{-1} ; Tg ha^{-1}; Pg ha^{-1}; Gg ha^{-1}	Carbon Pool
DBH	cm	Diameter at breast height (1.37 m)
E	mmol m^{-2} s^{-1}; mm	Evaporation
ER	μmol m^{-2} s^{-1}	Ecosystem Respiration
ET	mmol m^{-2} s^{-1}; mm	Evapotranspiration
EVI		Enhanced Vegetation Index
fPAR	%	Fraction of Photosynthetically-Active Radiation
GPP	μmol m^{-2} s^{-1}	Gross Primary Productivity
HFT	W m^{-2}	Heat Flux Transducer
Hs	W m^{-2}	Sensible Heat Flux
LAI		Leaf Area Index
LE	W m^{-2}	Latent Heat Flux
LSWI		Land Surface Water Index
MBC	mg kg^{-1}	Microbial Biomass Carbon
MBN	mg kg^{-1}	Microbial Biomass Nitrogen
NDVI		Normalized Difference Vegetation Index
NEE	μmol m^{-2} s^{-1}	Net Ecosystem Exchange
NEP	μmol m^{-2} s^{-1}; g m^{-2} year^{-1}	Net Ecosystem Productivity
NH_4^+ -N	mg kg^{-1}	NH_4^+ -N
NO_3^-N	mg kg^{-1}	NO_3^--N
NPP	μmol m^{-2} s^{-1}; g m^{-2} year^{-1}	Net Primary Productivity
NUE	%	Nutrient Use Efficiency
PAR	W m^{-2}; mmol m^{-2} s^{-1}	Photosynthetically Active Radiation
PET	mmol m^{-2} s^{-1}; mm	Potential Evapotranspiration
Q10		Temperature Coefficient
R_a	μmol m^{-2} s^{-1}	Autotrophic Respiration
R_h	μmol m^{-2} s^{-1}	Heterotrophic Respiration
RH	%	Relative Humidity
Rn	W m^{-2}	Net Radiation
R_{ref}	μmol m^{-2} s^{-1}	Respiration at Reference Temperature
SOC	g kg^{-1}	Soil Organic Carbon
SON	g kg^{-1}	Soil Organic Nitrogen
SR	μmol m^{-2} s^{-1}	Soil Respiration
SWC	%	Soil Water Content
Tr	mmol m^{-2} s^{-1}; mm	Transpiration
Ta	° C	Air Temperature
TC	g kg^{-1}	Total Carbon
TN	g kg^{-1}	Total Nitrogen
Ts	° C	Soil Temperature
U*	m s^{-1}	Friction Velocity
VPD	kPa	Vapor Pressure Deficit
VWC	%	Volumetric Water Content
WUE	μmol mmol^{-1}; g m^{-2} mm^{-1}	Water Use Efficiency

Principles of Eddy-Covariance method

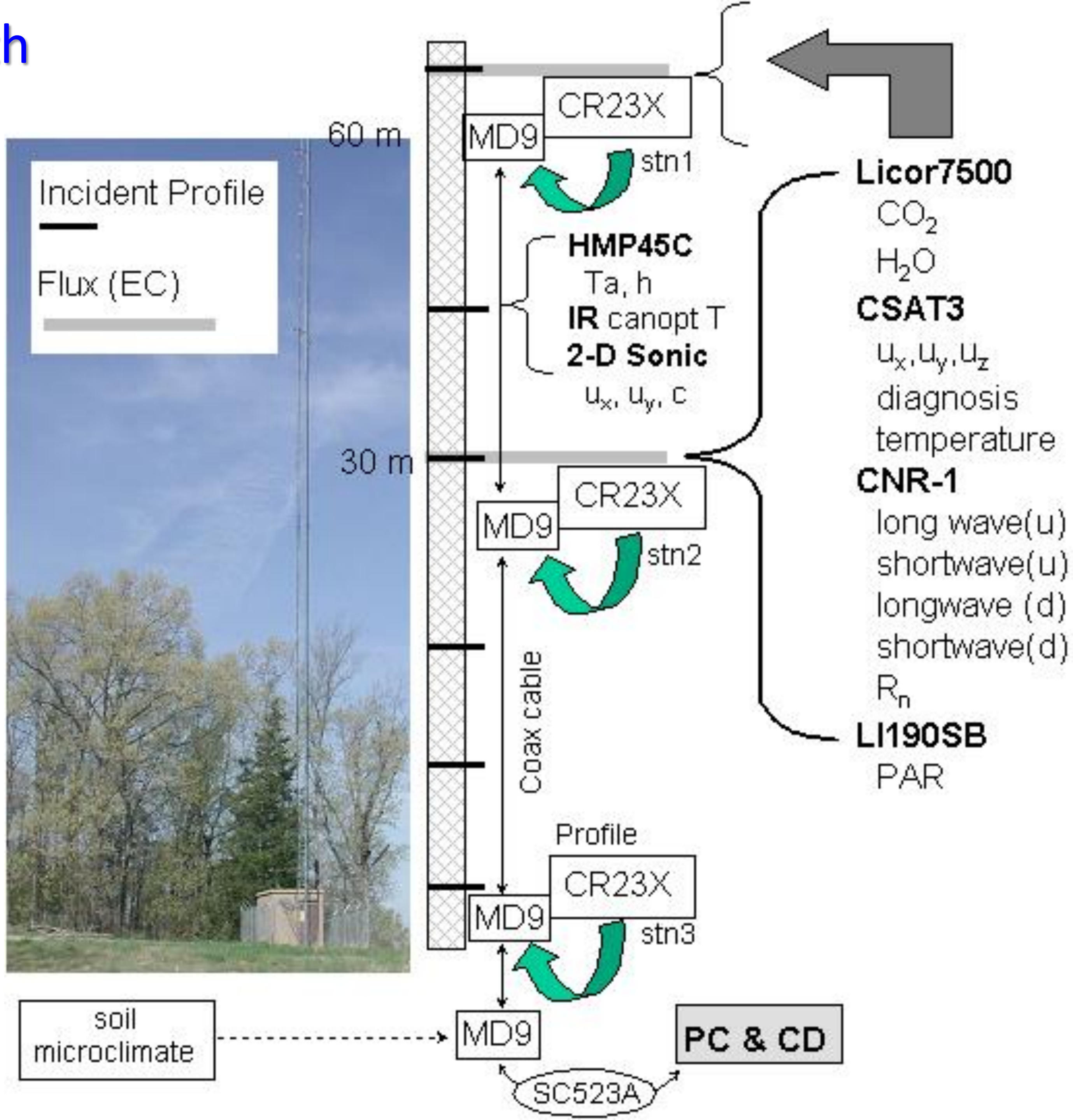
- Wind & Turbulent Transfer
- Wind profile, aerodynamics, eddy-covariance method, Lagrangian method, surface renewal

How we can measure net ecosystem exchange?

NEE of carbon can be monitored using the Eddy Covariance (EC) Technique. EC is based on the covariance between concentration of scalars and vertical wind velocity measurements.



Open Path


Incident Profile
Flux (EC)
60 m
30 m
CR23X
MD9
stn1
HMP45C
Ta, h
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2-D Sonic
u_x, u_y, c
CR23X
MD9
stn2
Coax cable
Profile
CR23X
MD9
stn3
soil microclimate
MD9
SC523A
PC & CD
Licor7500
CO_2
H_2O
CSAT3
u_x,u_y,u_z
diagnosis
temperature
CNR-1
long wave(u)
shortwave(u)
longwave (d)
shortwave(d)
R_n
LI190SB
PAR

Flux Measurements

Eddy-Covariance method, Lagrangian method, Surface renewal analysis

Eddy-covariance has been used for almost half a century, but has become relatively easy to use only in the last decade with the availability of reliable instruments. Because eddy-covariance measurements are sensitive to relatively large areas of ecosystems, can be employed almost continuously, and are non-invasive, they have become one of the preferred choices for estimating carbon and water vapor exchange. It is not surprising that the exchange E_x (units of concentration per second) of any scalar X is assumed to be proportional to the vertical eddy-covariance flux, F_x (units of mass per area per second):

$$E_c \propto F_c = \overline{w'C'}$$

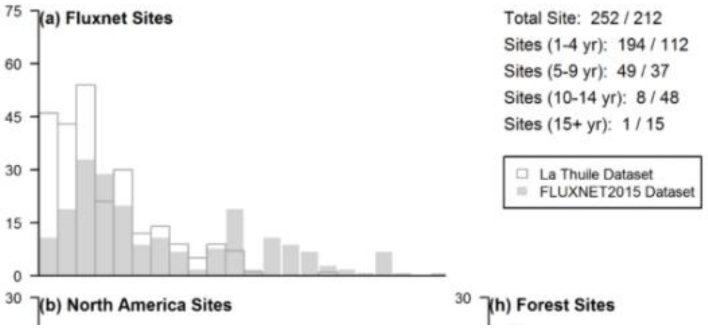
About Data

Welcome to the Data Information page. Here you can find information about the FLUXNET Dataset, such as data availability, data policy, variable explanation, data processing, and most importantly, where to download data.

Briefly, at each tower site, the eddy covariance method is applied to quantify the fluxes of scalars (e.g., CO2, CH4, water vapor) and energy (e.g., sensible, latent heat) between the biosphere and atmosphere. In addition, continuous measurements of ancillary physical variables (e.g., air temperature, precipitation, radiation) are acquired from a large number of sensors at high temporal resolution. The half-hourly or hourly fluxes are calculated and quality-controlled by the local tower teams. The data is then transferred to the Regional Networks and the FLUXNET Data Portal — Fluxdata. In this process, the Regional Network and Fluxdata teams standardize the data format, perform uniform data quality checks, and produce value-added products using highly vetted gap-filling and flux partitioning software developed by the European team and the AmeriFlux team (see data processing). The processed and standardized dataset is then archived and prepared for querying, distributing, and downloading.

Over the past 20 years, there have been several data synthesis activities initiated by the FLUXNET research community (History of Fluxnet). The most recent dataset produced is the **FLUXNET2015 Dataset**, which includes over 1,500 site-years of data from 212 sites. The previous dataset was produced in 2007 (**La Thuile Dataset**), containing over 960 site-years of data from 252 sites. To be involved in upcoming releases please contact your regional network coordination office.

(last updated February, 2017)



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USEFUL LINKS
Blog – What's New
FLUXNET2015 Dataset
La Thuile Dataset
FLUXNET Workshop
Data Change Log
Opportunities
Contact Us

FLUXNET 2015

https://fluxnet.org/data/

Table 1-1. Major variables and their units in the KBS-switchgrass dataset (Switchgrass_metdata2016.xlsx)for September 22, 2016. Variable names match those in the original databases, with some differences from the symbols applied in this chapter.

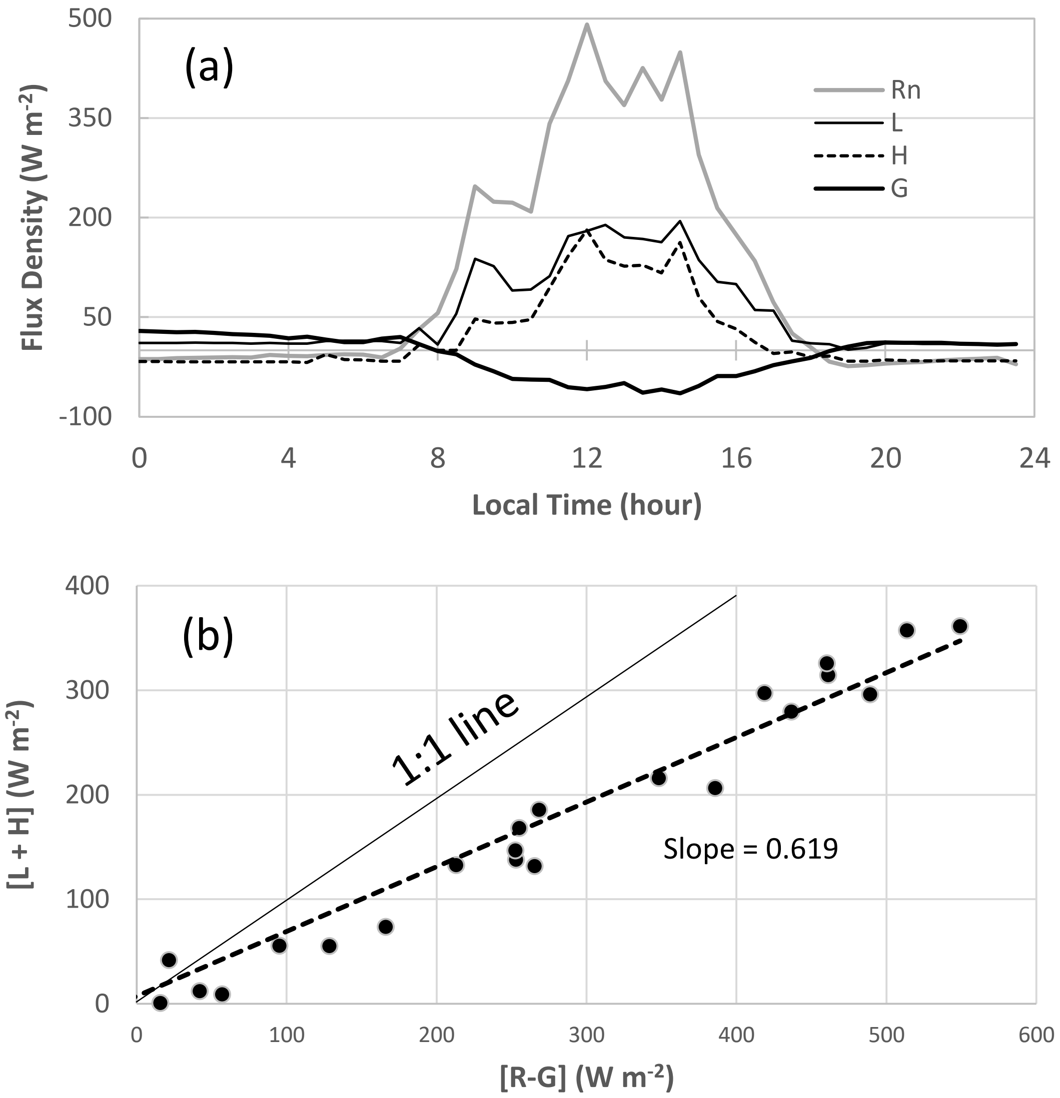
Name in the file	Unit	Description
Fc_wpl	mg m^{-2} s^{-1}	Net ecosystem exchange of CO_2, corrected with WPL method
LE_wpl	W m^{-2}	Latent heat flux density (L)
Hs	W m^{-2}	Sensible heat flux density (H)
tau	kg m^{-1} s^{-2}	Momentum flux (t)
u_star	m s^{-1}	Friction velocity (u*)
rho_a_Avg	kg m^{-3}	Moist air density (r)
press_Avg	kPa	Atmospheric pressure
wnd_dir_compass	degrees	Prevailing wind direction (D)
wnd_spd	m s^{-1}	Average horizontal wind speed (u)
Rad_short_Up_Avg	W m^{-2}	Incoming short-wave radiation
Rad_short_Dn_Avg	W m^{-2}	Outgoing short-wave radiation
Rad_long_Up_Avg	W m^{-2}	Incoming long-wave radiation
Rad_long_Dn_Avg	W m^{-2}	Outgoing long-wave radiation
Rn_short_Avg	W m^{-2}	Average short-wave net radiation
Rn_long_Avg	W m^{-2}	Average long-wave net radiation
Rn_total_Avg	W m^{-2}	Average net radiation (R_n)
t_hmp1_Avg	^oC	Average air temperature (T_a)
rh_hmp1_Avg	fraction	Relative humidity (h)
e_Avg	kPa	Average actual vapor pressure (e_a)
VPD_Avg	kPa	Average vapor pressure deficit (VPD)
par_flxdens_Avg	µmol m^{-2} s^{-1}	Average flux of photosynthetically-active radiation (PAR)
vwc_Avg	%	Average volumetric soil water content of top 30-cm soil
SoilT_Avg (1-3)	^oC	Average soil temperature (T_s) at 2, 5, and 10 cm

1.7 Energy Balance

The energy balance of a terrestrial ecosystem is conventionally described as

$$R_n = H + L + G + \Delta S + \varepsilon$$

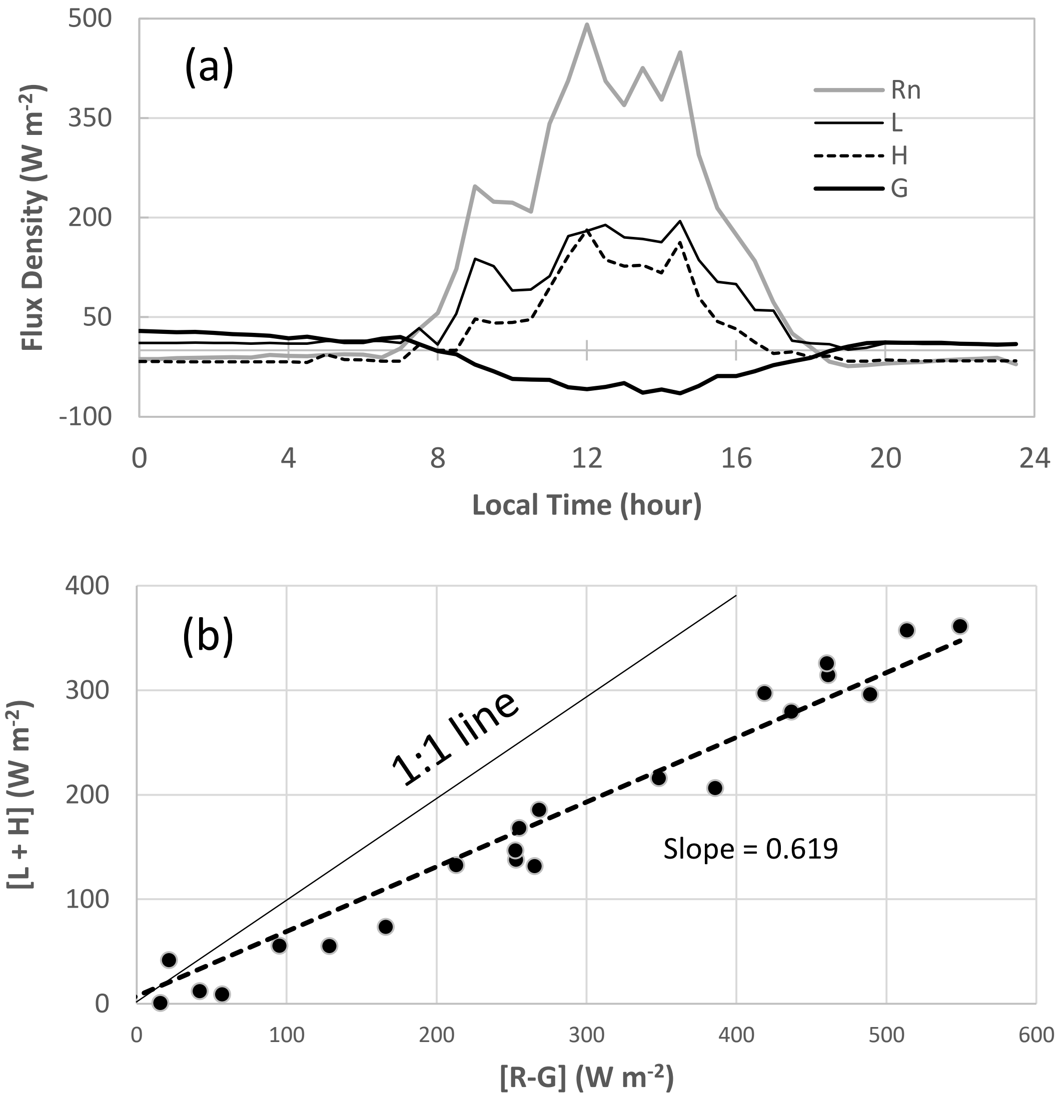
where R_n is net radiation (*i.e.*, incoming – outgoing radiation), H is the sensible heat, L is the latent heat through vaporization (*i.e.*, evapotranspiration, ET), G is the soil heat flux, ΔS is the heat storage over a period of time within the canopy column (air and vegetation), and ε is the energy used for photosynthesis (which is very minor and negligible).



1.7 Energy Balance

$$R_n = \underbrace{H + L}_{\text{Available energy}} + G + \Delta S + \varepsilon$$

Available energy



Bowen Ratio (β): the ratio between *H* and *L*

This ratio was originally proposed as an indirect method to estimate *L* and *H* based on the vertical gradient of temperatures when both *H* and *L* are difficult to measure.

1.7 Energy Balance

Using the Bowen Ratio-Energy Balance Method, *L* can be estimated as

$$L = \frac{R_n - G}{1 + \gamma \cdot \frac{\Delta T}{\Delta e}}$$

where β can be derived expressed as

$$\beta = \gamma \cdot \frac{\Delta T}{\Delta e}$$

- This approach allows us to measure estimate *L* and *H* based on the measurements of dry- and wet-bulb temperatures at two heights for *L* and *H*, avoiding direct measurements of vapor density in the air;
- The Bowen ratio has been widely used to estimate evapotranspiration (ET) prior to the eddy-covariance method.