Supplemental Documents

Quantifying Topographic and Vegetation Effects on the Transfer of Energy and Mass to the Critical Zone

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Supplemental Documents

A.1 Methods for calculation evapotranspiration

A.1.1 Hamon's Equation for EEMT$_{TRAD}$

For EEMT$_{TRAD}$ a monthly PET_H value for each pixel was calculated as:

$$PET_H = \frac{2.1H^2 e_s}{(T_i + 273.2)}, \qquad (\text{m s}^{-1}) \qquad (8)$$

where H is daylight hours for a given month and latitude, T_i is the mean locally modified temperature, and e_s [kPa] is saturated vapor pressure calculated as the mean of the local minimum and maximum saturated vapor pressure (Allen et al., 1998): $e_s = \frac{e_{s(T_{max})} + e_{s(T_{min})}}{2}$, where e_s is the saturated vapor pressure at T_{max} and T_{min} calculated as: $e_s = 0.6108 exp\left(\frac{12.27T}{T+237.3}\right)$, where T is T_{max} or T_{min} (ºC).

A.1.2 Penman-Monteith Equation for EEMT$_{TOPO}$

Potential evaporation from a pan was used in calculating EEMT$_{TOPO}$ using the Penman-Montieth equation (Shuttleworth, 1993):

$$ET = \frac{\Delta(\mathrm{R}_n - G) + \rho_a c_p \left(\frac{e_s - e_a}{r_a}\right)}{\lambda\left(\Delta + \gamma\left(1 + \frac{r_s}{r_a}\right)\right)} \qquad (\text{m s}^{-1}) \qquad (1)$$

modified for calculating potential evapotranspiration from a pan surface such that the surface resistance term (r_s) in the denominator is assumed equal to zero, simplifying Eq. 1 to:

$$PET_{pm} = \frac{\Delta(\mathrm{R}_n - G) + \rho_a c_p \left(\frac{e_s - e_a}{r_a}\right)}{\lambda(\Delta + \gamma)}. \qquad (\text{m s}^{-1}) \qquad (2)$$

The first term in the numerator is the radiation balance with net solar radiation (R_n) and ground heat flux (G). Net radiation was calculated as: $R_n = S_{topo}(1 - \alpha) + L_n$, where total shortwave radiation (S) [MJ m^{-2} month^{-1}] was calculated from the DEM as described above, albedo, α, over the study area was extracted from the MODIS MCD43A3 data product, net longwave radiation was calculated based on air temperature following Allen et al. (1998), and ground heat flux was assumed negligible and set equal to zero. The R_n was set equal to zero for any portions of the landscape with negative values prior to calculating PET_{pm}, *i.e.*, north-facing slopes where outgoing longwave radiation exceeded incoming shortwave in winter months. The second term in the numerator is the ventilation term that includes vapor pressure deficit [kPa], and aerodynamic resistance (r_a) [s m^{-1}] that can be equated as a generalized inverse function of wind speed for neutral conditions as (Thom and Oliver, 1977): $r_a = \frac{[ln(z_m/z_o)]^2}{\kappa^2 U_z}$, with the specific formulation for potential evaporation from an open water body stated as (Shuttleworth, 1993):

$$r_a = \frac{4.72[ln(z_m/z_o)]^2}{1+0.536U_z}, \quad (\text{s m}^{-1}) \qquad (3)$$

where z_m [m] is the height of meteorological measurements at 2 m, z_o [m] is the aerodynamic roughness of an open water surface set equal to 0.00137 m following Thom and Oliver (1977), and U_z [m s^{-1}] is wind speed. Vapor pressure (e_a) [kPa] was determined from relative humidity estimated at each pixel using the monthly elevation relationships derived from local weather station data and the mean saturated vapor pressure calculated based on temperature as above.
The remaining terms in Eq. 9 include the slope of the saturated vapor pressure-temperature relationship (Δ) calculated using mean air temperature: $\Delta = 0.04145e^{0.06088T}$; the psychrometric constant (γ) determined as: $\gamma = \frac{c_p P}{\varepsilon\lambda}$, where c_p is specific heat of moist air at constant pressure [1.013 x 10^{-3} MJ kg^{-1} ºC^{-1}], ε is the ratio of molar mass of water to that of dry air [0.622], P [kPa] is atmospheric pressure at elevation z [m] with local lapse rate η [ºC m^{-1}] determined as: $P = 101.3\left(\frac{293-\eta z}{293}\right)^{5.26}$; mean air density ρ_a [kg m^{-3}], and λ the latent heat of evaporation of water [2.45 MJ kg^{-1}] (Shuttleworth, 1993).

A.1.3 Penman-Monteith Equation for EEMT$_{\text{TOPO-VEG}}$

The approach to calculating EEMT$_{\text{TOPO-VEG}}$ employed the Penman-Montieth approach presented in Eq. 1 that includes the surface resistance term in the denominator and a canopy derived estimate of aerodynamic resistance to provide an estimate of actual evapotranspiration

(AET_{pm}). The aerodynamic resistance term, r_a, here was calculated by expanding the numerator to include canopy height effects on aerodynamic roughness (Shuttleworth, 1993):

$$r_a = \frac{ln\left(\frac{z_m - d}{z_{om}}\right) ln\left(\frac{z_h - d}{z_{oh}}\right)}{\kappa^2 U_z}, \qquad (\mathrm{s\ m^{-1}}) \qquad (3)$$

where z_m [m] is the height of the wind measurement at 2 m above the surface, d [m] is the zero-plane displacement equal to 2/3h, where h [m] is canopy height derived from the LiDAR data, z_{om} [m] is the roughness length governing momentum transfer equal to 0.123h, z_h is the height of humidity measurement and set equal to z_m, z_{oh} [m] is the roughness length governing transfer of heat and vapor set equal to z_{om}, U_z [m s^{-1}] is wind speed, and κ is von Karman's constant [0.41].

Supplemental Figures

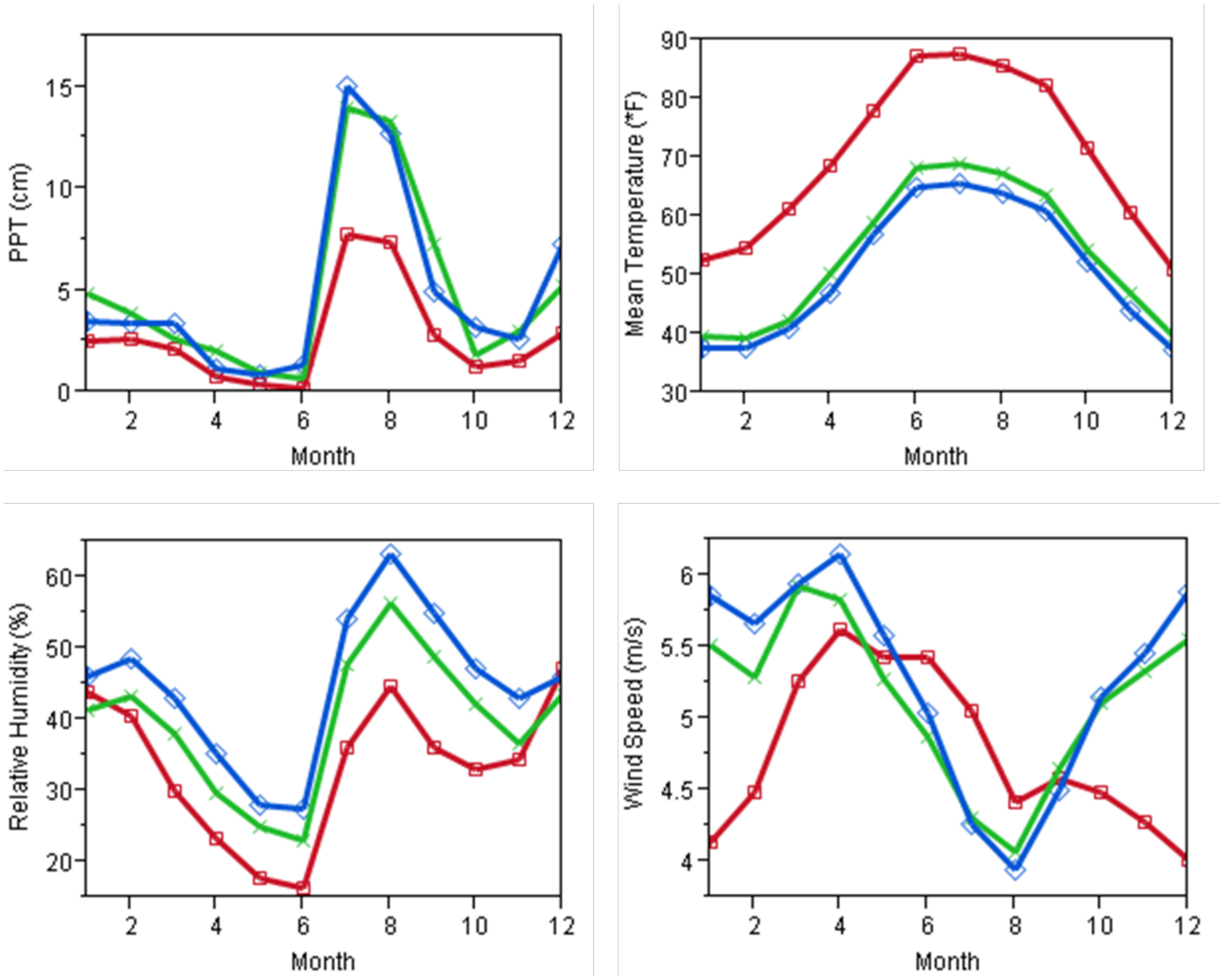

Fig. S1. Climate parameters from RAWS weather stations used to model local microclimate variability. The red sites are the low elevation Saguaro Station data at an elevation of 945 m a.s.l., the green sites are from the Soller Station at an elevation of 2,377 m a.s.l., and the blue sites are from the Rincon Station at an elevation of 2,512 m a.s.l.

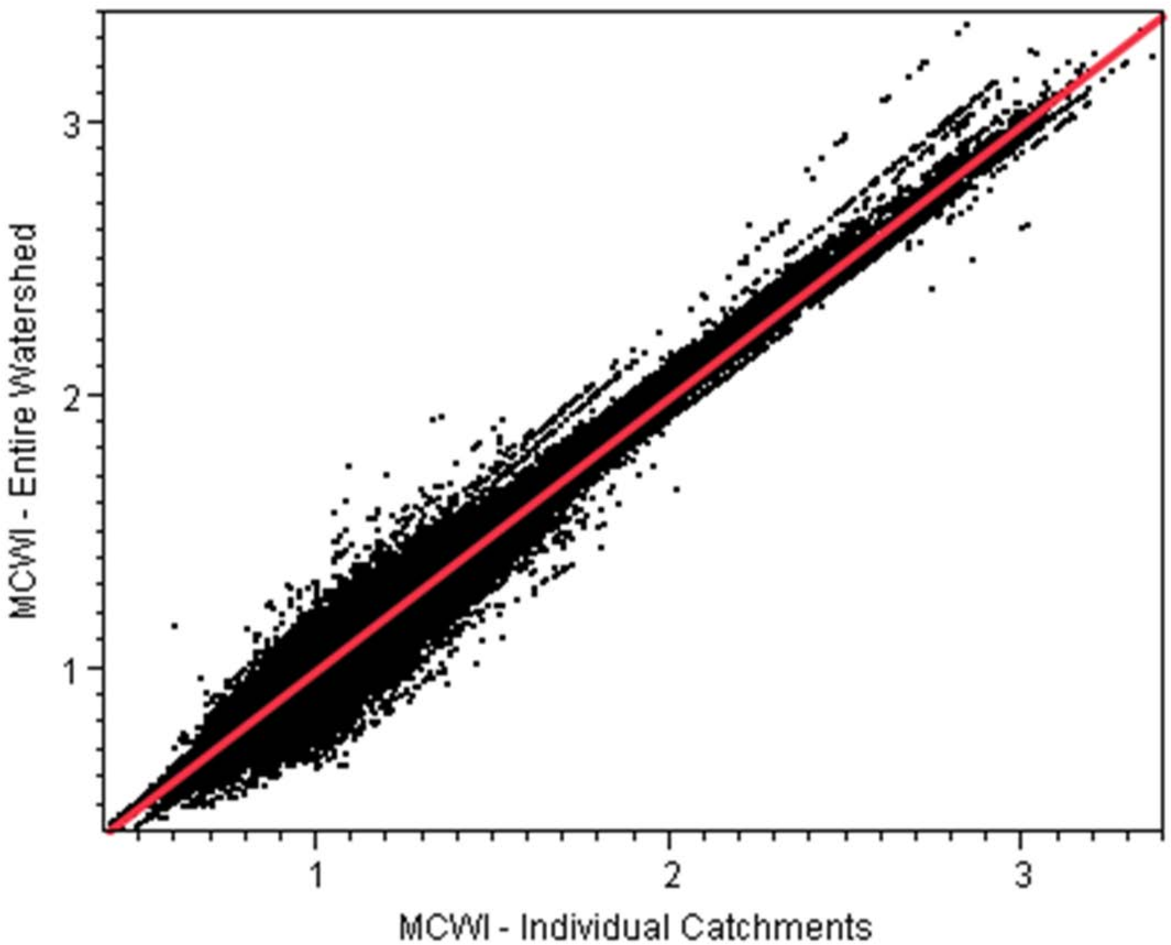

Fig. S2. Values calculated for the mass conservative wetness index (MCWI) using average wetness index for the entire Sabino Watershed versus MCWI calculated using average wetness index values for individual catchments within the Sabino Watershed. Red line indicates the 1:1 relationship.

Supplemental Tables

Table S1. Correlation matrix of environmental parameters and components of EEMT

	Elevation	Northness	Canopy Height	NPP_{TRAD}	NPP_{TOPO}	$NPP_{TOPO\text{-}VEG}$	$Peff_{TRAD}$	$Peff_{TOPO}$	$Peff_{TOPO\text{-}VEG}$	$EEMT_{TRAD}$	$EEMT_{TOPO}$	$EEMT_{TOPO\text{-}VEG}$	$EEMT_{TOPO\text{-}VEG}/EEMT_{TOPO}$
Elevation	1.00	-0.02	0.51	0.89	0.87	0.54	0.98	0.85	0.62	0.99	0.85	0.60	0.06
Northness	-0.02	1.00	0.11	-0.05	0.49	0.10	-0.01	0.37	0.40	-0.01	0.46	0.28	-0.04
Canopy Height	0.51	0.11	1.00	0.37	0.50	0.99	0.54	0.53	0.83	0.54	0.51	0.93	0.78
NPP_{TRAD}	0.89	-0.05	0.37	1.00	0.75	0.39	0.83	0.75	0.45	0.84	0.75	0.43	-0.08
NPP_{TOPO}	0.87	0.49	0.50	0.75	1.00	0.53	0.86	0.93	0.75	0.86	0.97	0.66	0.05
$NPP_{TOPO\text{-}VEG}$	0.54	0.10	0.99	0.39	0.53	1.00	0.57	0.55	0.84	0.57	0.53	0.94	0.78
$Peff_{TRAD}$	0.98	-0.01	0.54	0.83	0.86	0.57	1.00	0.83	0.65	1.00	0.83	0.62	0.14
$Peff_{TOPO}$	0.85	0.37	0.53	0.75	0.93	0.55	0.83	1.00	0.80	0.83	0.94	0.71	0.15
$Peff_{TOPO\text{-}VEG}$	0.62	0.40	0.83	0.45	0.75	0.84	0.65	0.80	1.00	0.64	0.75	0.97	0.62
$EEMT_{TRAD}$	0.99	-0.01	0.54	0.84	0.86	0.57	1.00	0.83	0.64	1.00	0.84	0.62	0.13
$EEMT_{TOPO}$	0.85	0.46	0.51	0.75	0.97	0.53	0.83	0.94	0.75	0.84	1.00	0.68	0.05
$EEMT_{TOPO\text{-}VEG}$	0.60	0.28	0.93	0.43	0.66	0.94	0.62	0.71	0.97	0.62	0.68	1.00	0.73
$EEMT_{TOPO\text{-}VEG}/EEMT_{TOPO}$	0.06	-0.04	0.78	-0.08	0.05	0.78	0.14	0.15	0.62	0.13	0.05	0.73	1.00

Table S2. Multiple linear regression analysis of EEMT values relative to environmental controls

	Variable	Coefficient	Model Sums of Squares	Fraction of Model Sums of Squares	RMSE (MJ m^{-2} yr^{-1})	R_a^2
$EEMT_{TRAD}$	Elevation (m)	0.022	114,159,424	1.00	1.82	0.97
	Intercept	-21.14	--	--		
$EEMT_{TOPO}$	Elevation (m)	0.011	28,391,394	0.74	0.95	0.98
	Northness	9.341	8,654,674	0.23		
	MWCI	4.523	1,228,813	0.03		
	Intercept	-7.48	--	--		
$EEMT_{TOPO-VEG}$	Elevation (m)	0.003	1,732,168	0.04	2.28	0.93
	Northness	5.312	105,761	0.00		
	MWCI	1.333	2,746,674	0.07		
	Canopy Height (m)	2.138	34,832,263	0.88		
	Intercept	0.309	--	--		