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P1.12 EVAPOTRANSPIRATION RATES AT THE MORGAN MONROE STATE FOREST AMERIFLUX SITE:
A COMPARISON OF RESULTS FROM EDDY COVARIANCE TURBULENT FLUX MEASUREMENTS
AND SAP FLOW TECHNIQUES

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1 INTRODUCTION

Comprehensive land surface schemes have been used in regional and global climate models to improve the simulation of exchange processes between the earth's surface and the atmosphere. Assessing the performance of these improved models with respect to the evaporative fluxes at the surface has, however, been hampered by the lack of adequate observational data sets. In this paper, daily, and annual fluxes of evapotranspiration (ET) and transpiration (T) at an AmeriFlux site in the Morgan-Monroe State Forest (MMSF), Indiana, USA, are presented for the growing season of 1998. Turbulent flux measurements of ET are obtained using an eddy covariance system at 46 m (1.8 times the canopy height) and at 2 m. These are compared with rates of T determined from measurements of sapflow using the Granier technique.

2 METHOD

2.1 Site Description

Morgan Monroe State Forest (MMSF) in South Central Indiana (39° 19' N 86° 25' W, 275 m a.s.l.), is an extensive managed forest with a total area of 95.3 km². Ridges and ravines, with a relative relief of less than 60 m, dominate the local topography. Overall elevation drops 90 m in 4 km. The area is primarily covered by a secondary successional broadleaf forest (in the maple-beech to oak-hickory transition zone), with a wide variety of tree species present (Von Kley *et al.*, 1994). The total number of species from a survey of all trees with a diameter at breast height of ≥ 7 cm in 50 large plots (150 m² each) was 29 (Table 1). Nearly 75% of the total is made up of sugar maple (*Acer saccharum*), tulip poplar (*Liriodendron tulipifera*), sassafras (*Sassafras albidum*), white oak (*Quercus alba*), and black oak (*Quercus nigra*) based on the basal areas (Ehman *et al.*, 1999). The mean canopy height of the forest is approximately 25-27 m. The study site is located so that the minimum fetch of essentially uninterrupted forest exceeds 4 km in any direction, and reaches up to 8 km in the principal wind direction (westerly - southwesterly).

2.2 Observations

Micro-meteorological instruments are mounted both on a 46 m tower (at 46, 34 and 2 m) and at a series of

below-canopy sites in the expected footprint of the tower. At each level on the tower, measurements of 3-d turbulent velocity fluctuations and eddy-covariance fluxes of momentum, sensible heat, water vapor, and CO₂ are collected. At the two levels above-canopy (46 m and 34 m), the azimuth orientation of the sonic anemometers is 230°. The fluxes of momentum and heat are evaluated directly from the 3-d sonic anemometers (C-SAT, Campbell Scientific Inc. (CSI), Logan, UT, 10 Hz sampling rate). The water vapor and CO₂ concentrations are measured by pumping sample air from the three sonic anemometer levels to individual closed-path infra-red gas analyzers (IRGAs, Li-6262 Li-Cor, Lincoln, NE) inside the shelter at the base of the tower. Eddy covariance fluxes are then obtained during post-processing, by shifting the scalar and vertical velocity time series to maximize the cross-correlation. Schmid *et al.* (1999) provide details of data processing and other measurements conducted at the site.

Individual tree sapflow probes were installed on 9 canopy trees in the vicinity of the eddy covariance tower (2 tulip (yellow)-poplar, 2 white oak, 1 ash, 1 elm, 1 sassafras and 1 sugar maple). Measurements of sap velocity are made using thermal dissipation probes (Dynamax, Inc., Houston, TX) that consist of two probes of 1.1 mm diameter, each of which are inserted 3 cm into the sapwood of the tree bole (Granier 1987). Mean sapflow velocity for the tree (m s⁻¹) was calculated using the empirical calibration of Granier (1987). Sapflow velocity data were collected every minute and hourly mean values stored on a data logger (CR10X, Campbell Scientific, Inc., Logan, UT) from day 98/90 through 98/335 which encompasses the entire leaf out period for this location.

Stand transpiration was calculated from sapflow measurements and knowledge of the stand species composition. Hourly sapflow velocity measurements for indicator trees were adjusted to account for radial gradients in sap velocity (SV_x) and then normalized to their sapwood cross sectional area (SA_x) to obtain sapflow rates in kg water dm⁻² h⁻¹ for each of the key tree species (x) on each plot:

$$Tx = SV_x / SA_x \quad (1)$$

Subsequently, for each hour the sapwood specific rates (Tx) for a species are multiplied by the total sapwood cross sectional area of that species within a given plot area (? SA_x) to yield the species' contribution to stand transpiration (StandTx):

$$\text{StandTx} = Tx * ? SA_x \quad (2)$$

A simple sum of the ground area based transpiration from each species completes the calculation of total stand transpiration (StandT).

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$$\text{StandT} = \sum x * [\text{StandTx}] \quad (3)$$

The hourly stand transpiration values can then be summed to yield daily transpiration.

Observations of the Vegetation Area Index (bole and leaf area) (VAI) were taken periodically over the entire vegetative season along three transects (ten locations each) in the northwestern, western and southwestern direction using a Li-2000 (Licor Lincoln, NE) sensor, with full sky reference measured at the top of the tower. Ecological measurements of the forest are performed by a partner project (Ehman *et al.*, 1999).

Table 1: Species composition, basal area, and sapwood area for the trees surveyed in the stand around the sapflow site (0.16 ha) and for 50 plots around the tower (Ehman *et al.* 1999)

Sapflow site composition				Ehman <i>et al.</i> 50 plots	
Species	Basal Area m ² ha ⁻¹ (%)	Sapwood area m ² ha ⁻¹		Basal Area %	
Elm	7.86	30.5	1.05	Sugar maple	27.09
Oak	5.94	23.1	1.26	Tulip poplar	19.17
Tulip poplar	4.27	16.6	3.07	Sassafras	9.45
Walnut	1.66	6.4	-	White oak	8.99
Locust	1.49	5.8	-	Black oak	8.54
Ash	1.23	4.8	0.94	White ash	5.33
Dogwood	1.09	4.2	0.13	American elm	3.52
Cherry	1.03	4.0	0.10	Red oak	2.46
Sassafras	0.64	2.5	-	Hackberry	1.72
Maple	0.38	1.5	0.50	American beech	1.58
Unknown	0.17	0.7	0.92	Slippery elm	1.56
				Black gum	1.53
				17 other species	9.05
TOTAL	25.76	100	7.97		100.00

3 RESULTS

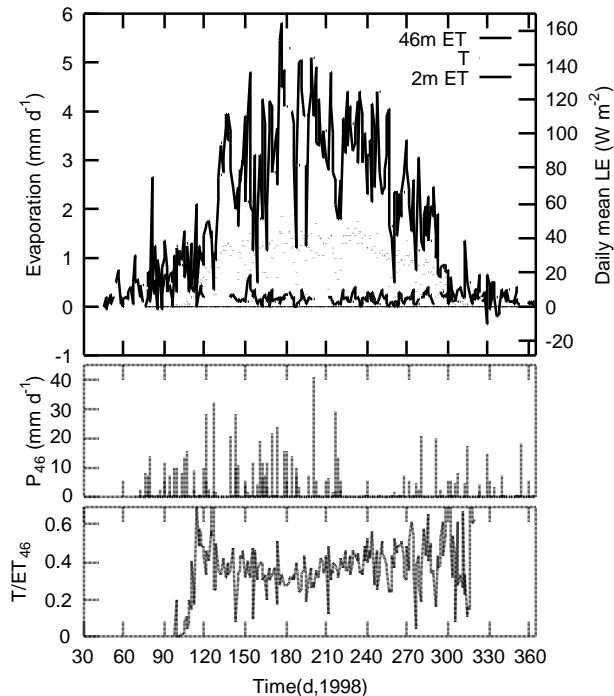
3.1 State of the Forest

The leaf-off bole area index was determined at about 1.3 ± 0.16 on November 13 (98/317), after leaf fall. Because the winter of 1997/98 was unusually mild in this region (mostly attributed to the strong El Nino event during that period), the onset of budding was visually observed to be about two weeks earlier than usual (Randolph, *personal communication*). However, the data show that this period was complete by May 22 (98/142), after which VAI remains approximately constant at 4.7 ± 0.5 until 98/217 (the beginning of August). In August and the first half of September, leaf senescence decreased the VAI to 4.48 ± 0.4 , and after that date (98/259) the foliage began to fall.

3.2 Eddy covariance results

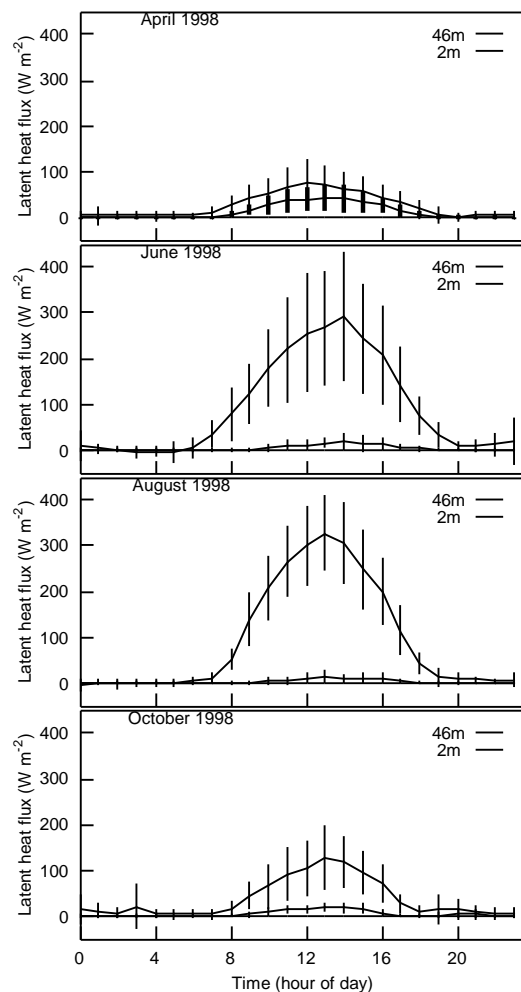
Figure 1 shows the daily variability of ET as measured by eddy covariance at 46 m and 2 m respectively, and average T determined from the sapflow measurements. In Figure 2, the ensemble monthly mean (and ± 1 standard deviation) diurnal patterns for the eddy covariance data are shown for four months (April, June, August and October). Fuller details on the 46 m fluxes, their controls, and relations to other surface energy balance fluxes are presented in Schmid *et al.* (1999).

Figure 1: Top panel - Daily mean evapotranspiration (mm d⁻¹) (latent heat flux - W m⁻²) measured by eddy covariance at 46m and 2 m respectively and T measured by sap flow. Middle panel - daily precipitation measured at 46 m. Lower panel - ratio of T:ET_{46m}.



ET rises rapidly in late April, driven by transpiration from the emerging forest foliage. In April, average ET in the middle of the day was 78 W m^{-2} , with high day-to-day variability (coefficient of variation (standard deviation/mean) (CV) 68%). Close to the forest floor (2 m instrument height), ET was 54% of the 46 m value with similar relative day-to-day variability (CV = 62%). The maximum individual hourly values observed at 2 m were greater than the average hourly 46 m data. By the end of May leaf development was complete. In June, the average hourly maximum (at 1400) ET rose to 293 W m^{-2} , while the relative variability dropped (CV = 48%). In contrast, for the same period near the forest floor, the 2 m data indicate that ET rates dropped (22 W m^{-2} , half the April value) and became more variable (CV 87%). By August, at 46 m the average hourly maximum daily values were 327 W m^{-2} , with a further decrease in relative variability (CV = 25%). During the period of leaf fall, October, ET drops rapidly and sensible heat flux once again becomes more significant to the diurnal course of energy partitioning (see data in Schmid *et al.*, 1999). In October, peak average hourly ET values from 46 m are 130 W m^{-2} , although individual hourly values range up to 300 W m^{-2} . At this time, relative variability increases again (CV = 54%). Between mid-May and mid-September, about 85% of the daytime available energy is consumed by evaporation, in contrast to only around 20-30 % during the leaf-off period (Schmid *et al.*, 1999).

Figure 2: Mean and ± 1 standard deviation of the hourly latent heat flux for four months in 1998 observed using eddy covariance techniques at 46 m and 2 m.



On a diurnal basis, before full leaf-on (April - Figure 2), ET peaks close to noon. By June, full leaf-on, the daily peak is later in the day. June 1998 was characterized by frequent precipitation and cloud cover, so that both radiation loading and water stress during mid-day was reduced. By late summer (August) when water was more limited, the daily peak ET was earlier again, indicating the degree of physiological control that the forest exerts on energy partitioning. As soon as radiative energy is available in sufficient quantity in the morning, it is funneled primarily into transpiration, and photosynthesis. In mid-day, when radiation loading is high, temporary loss of turgor in the stomatal guard cells causes closure of the stoma, and limits transpiration and CO₂ uptake.

3.3 Transpiration results

Transpiration (T) estimated from sapflow velocity observations follow the seasonal patterns of leaf area dynamics for this stand similar to the latent heat flux shown in Figure 2. Transpiration was initiated around 98/105 and reached seasonal maxima by 98/140.

Maximum hourly rates of T during mid-day ranged from 0.14 to 0.16 mm h⁻¹, and daily stand transpiration on days having high radiation inputs topped out near 1.5 mm d⁻¹. Daily T remained near 1.5 mm d⁻¹ through 98/250 at which time stand water use began to drop off with reductions in day length and senescence of the forest canopy.

Although tulip-poplar, elm, and maple species exhibited the highest sapflow velocities (data not shown), stand transpiration for the sapflow measurement plot was dominated by tulip-poplar and ash species because of the combined effect of sapflow velocity and sapwood basal area (Table 1) on stand T.

3.4 Comparison of ET and T

When the 46 m ET values are compared with those for T obvious differences in the magnitudes of the fluxes are evident (Figure 1, Table 2). However, in terms of day-to-day variability, the two fluxes, ET₄₆ and T, clearly are responding to the same local/ meso-scale environmental forcing (see the similarity in trends through time).

At the beginning of the growing season T represents less than 10% of the ET₄₆ data, rising up to a peak of just over 50% at the end of April (Figure 1). From then to the middle of July the ratio drops towards 30%, before rising back to 40% in August and September.

Comparative differences between eddy covariance estimates of ET and sapflow T have been previously documented (Saugier *et al.* 1997, Wullschlegel *et al.* 1999). The magnitude to which ET exceeds T is dependent on the contribution of interception losses, soil evaporation and transpiration to total ET. Wullschlegel *et al.* (1999) observed that sapflow estimates of T for a temperate deciduous forest in eastern Tennessee were 43 to 53% of annual ET as determined by eddy covariance methods. Studies in a boreal pine forest by Saugier *et al.* (1997) showed somewhat closer agreement between T and ET throughout much of the year, although considerable discrepancies were observed during periods of precipitation as would be expected when canopy interception contributes to a substantial fraction of daily ET.

The difference in the species composition of the sapflow plots with the overall composition of the forest is indicated in Table 1. However, the exact distribution of species in the 46-m flux footprint has not as yet been determined. The individual trees studied by sapflow clearly are much more strongly influenced by very localized (small-scale) environmental conditions. The sapflow trees are located right on the crests of the ridges in this area of rolling topography, whereas the tower observations record a more integrated response of the upwind topographic variability. Landsat scenes (G. Greene, personal communication) show that ridges in this region commonly exhibit more signs of water stress than ravines in mid to late summer.

Table 2: Preliminary estimates of cumulative ET, T and P at the MMSF site 1998.

Period	ET (mm)		T	Precip. (mm)		
	Eddy covar.	46 m	Sapflow (mm)	46 m	2 m	
Year	98/76- 99/75	560	69	-	879	582
Growing season	98/98-320	503	46	191	619	384
Full Leaf	98/142-259	364	18	135	355	202

Despite considerable (but unknown) uncertainties associated with precipitation measurements on top of a 46 m tower and below canopy, such measurements serve to elucidate the differences in ET_{46} and sapflow T, at least in part. The precipitation received at the top of the canopy during the full leaf period in 1998 was only slightly less than the ET_{46} (98%). Of the precipitation received at 46 m only 57% was recorded at the surface. Thus during the growing season, evaporation of intercepted water clearly is a significant component of the above canopy measurements of ET and a partial explanation for the ET_{46} and T differences. For the full growing season the above canopy precipitation was > 20% larger than the ET_{46} and the P_2/P_{46} was 62%. As expected there was a smaller loss of intercepted water in the absence of leaf cover. On an annual basis the P_{46} exceeded the ET_{46} by 57%. This is probably an underestimate because of an under-catch of frozen precipitation. In view of the uncertainties, it is encouraging to see that the sum of $T + ET_2 + \Delta P$ for the growing season amounts to 94% of ET_{46} (where $\Delta P = P_{46} - P_2$), and is thus on the same order of magnitude as the total measured ET.

4 CONCLUSIONS

ET is a significant flux for mid-latitude deciduous forests. Between mid-May and mid-September, about 85% of the daytime available energy is consumed by evaporation, in contrast to only around 20-30 % during the leaf-off period. In 1998 the cumulative total for the growing season exceeds 500 mm. On an annual basis the total is 560 mm, which represents more than 60% of the above canopy precipitation at the site.

The below canopy (2 m) latent heat flux, as observed by the eddy covariance technique, shows a decrease in size and increase in variability following leaf-out. During leaf-off the mean fluxes at the two levels (46 m and 2 m) coincide within ± 1 standard deviation throughout the day.

Stand-level estimates of T derived from sapflow instrumentation during the full leaf period in 1998 were 37% of the above-canopy ET. This is a much smaller fraction than initially would be anticipated, but it should be remembered that comparative studies such as those reported here are not yet widespread. Part of the discrepancy can be attributed to evaporation of intercepted rainfall from canopy leaf, branch and litter surfaces, but other scaling issues may also contribute. Appropriate scaling of tree sap flow velocities to stand transpiration requires (1) accurate measurements of sap flow velocities, (2) the choice of representative trees and

saplings, and (3) good allometric relationships from which the sapwood area of each tree species can be estimated. We continue to look for sources of error in each of these steps. Technical issues that surround the proper use of sapflow probes (Clearwater *et al.* 1999) still need to be addressed, as do uncertainties related to functional sapwood area, radial gradients in sap velocity, variation in sap velocity around the circumference of a tree, and the contribution of stored water to transpiration in trees of different species. Many of these topics have not yet been fully resolved and will, in the future, be the focus of comparative studies that seek to examine the magnitude and environmental controls of T and ET in forest canopies.

A second year of growing season data will become available soon which will allow additional comparison of data. Further attention also is to be directed to the magnitude of the stomatal resistances measured independently on individual trees relative to back-calculated local-scale values.

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