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# Nocturnal evapotranspiration in eddy-covariance records from three co-located ecosystems in the Southeastern U.S.: Implications for annual fluxes

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ABSTRACT

Nocturnal evapotranspiration ($ET_N$) is often assumed to be negligible in terrestrial ecosystems, reflecting the common assumption that plant stomata close at night to prevent water loss from transpiration. However, recent evidence across a wide range of species and climate conditions suggests that significant transpiration occurs at night, frustrating efforts to estimate total annual evapotranspiration (*ET*) from conventional methods such as the eddy-covariance technique. Here, the magnitude and variability of $ET_N$ is explored in multiple years of eddy-covariance measurements from three adjacent ecosystems in the Southeastern U.S.: an old grass field, a planted pine forest, and a late-successional hardwood forest. After removing unreliable data points collected during periods of insufficient turbulence, observed $ET_N$ averaged 8–9% of mean daytime evapotranspiration ($ET_D$). $ET_N$ was driven primarily by wind speed and vapor pressure deficit and, in the two forested ecosystems, a qualitative analysis suggests a significant contribution from nocturnal transpiration. To gapfill missing data, we investigated several methodologies, including process-based multiple non-linear regression, relationships between daytime and nighttime *ET* fluxes, marginal distribution sampling, and multiple imputation. The utility of the gapfilling procedures was assessed by comparing simulated fluxes to reliably measured fluxes using randomly generated gaps in the data records, and by examining annual sums of *ET* from the different gapfilling techniques. The choice of gapfilling methodology had a significant impact on estimates of annual ecosystem water use and, in the most extreme cases, altered the annual estimate of *ET* by over 100 mm year$^{-1}$, or ca. 15%. While no single gapfiling methodology appeared superior for treating data from all three sites, marginal distribution sampling generally performed well, producing flux estimates with a site average bias error of <10%, and a mean absolute error close to the random measurement error of the dataset (12.2 and 9.8 W m$^{-2}$, respectively).

## 1. Introduction

### 1.1. Motivation

Until recently, it had been commonly assumed that plant stomata close at night, preventing water loss through transpiration during non-photosynthetic periods. However, sap-flux measurements are now showing that nocturnal transpiration is widespread among woody plants and shrubs (Burgess et al., 1998; Dawson et al., 2007; Donovan et al., 1999; Fisher et al., 2007; Hogg and Hurdle, 1997; Marks and Lechowicz, 2007; Oren et al., 1999; Snyder et al., 2003; Oishi et al., 2008; Ward et al., 2008). Typically, nocturnal transpiration accounts for 10–30% of the total daily transpiration flux (Fig. 1), although higher rates have been reported in some extreme cases (Snyder et al., 2003). Hence, models and data collection methodologies that do not sufficiently account for nocturnal water loss due to transpiration may systematically underestimate the contribution of total evapotranspiration (*ET*) to ecosystem water budgets.

During the past 15 years, over 250 eddy-covariance towers have been installed across the full range of global biomes to measure ecosystem evapotranspiration and trace gas fluxes (Baldocchi, 2003). The eddy-covariance methodology can directly measure whole ecosystem fluxes of water vapor and is often used to develop estimates of annual *ET* (Schäfer et al., 2002; Alavi et al., 2006; Barr et al., 2007; Burba and Verma, 2005; Gholz and Clark, 2002; Grünwald and Bernhofer, 2007; Kucharik et al., 2006; Stoy et al., 2006a). However, weak turbulence constraints, which most often occur at night, create frequent gaps that may infect well over 50% of eddy-covariance records (Falge et al., 2001).

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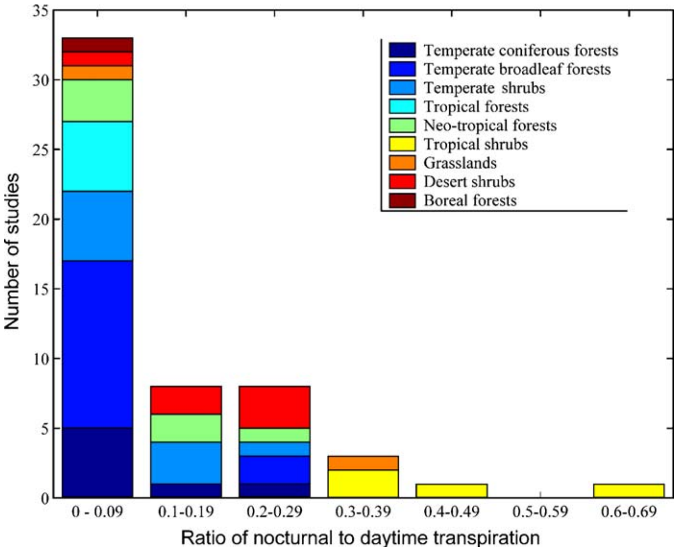

**Fig. 1.** Histrogram describing the occurrence of mean nocturnal transpiration as a fraction of mean daytime transpiration rates from over 50 surveyed species representing both field and greenhouse data. In the case where ranges of percentages were given, the average of the minimum and maximum rates was used. The data are described elsewhere (Barbour and Buckley, 2007; Benyon, 1999; Caird et al., 2007; Cavender-Bares et al., 2007; Daley and Phillips, 2006; Dawson et al., 2007; Donovan et al., 1999; Feild and Holbrook, 2000; Fisher et al., 2007; Kavanagh et al., 2007; Kobayashi et al., 2007; Rawson and Clarke, 1988; Scholz et al., 2007; Snyder et al., 2003; Ward et al., 2008).

Much effort has been dedicated to developing appropriate and standard methods of gapfilling missing eddy-covariance data for the net ecosystem exchange of carbon dioxide (*NEE*) (Falge et al., 2001; Moffat et al., 2007; Reichstein et al., 2005; Stoy et al., 2006b). However, relatively little attention has focused on evaluating and standardizing gapfilling methods for evapotranspiration, and in particular, nocturnal evapotranspiration ($ET_N$). While the two gapfilling problems share some similarities, there are a number of important differences: (1) $ET_N$ is often small and is generated in part by foliage, while nighttime respiration is a significant component of *NEE* and is dominated by soil processes; (2) the meteorological variables impacting $ET_N$ are more numerous and dynamic (e.g., vapor pressure deficit, wind speed, net radiation, air temperature) when compared to respiration processes, which are considered to be governed by a smaller number of variables (i.e. soil temperature and soil moisture) that do not vary appreciably during the night (at least when compared to wind speed and vapor pressure); and (3) many variables that influence $ET_D$ cannot explain variation in $ET_N$ (i.e. assimilation rates, light).

In response to these challenges, a variety of approaches have been developed at individual sites to gapfill for *ET* and $ET_N$, including:

(a) Process-based models such as the Penman–Monteith equation (Anthoni et al., 1999; Stoy et al., 2006a) and the Priestly–Taylor equation (Vourlitis et al., 2002; Wilson and Baldocchi, 2000). These models have the advantage of robustly considering the physiological and some of the physical determinants of daytime *ET*, though it appears that the current suite of models does not appropriately accommodate the potential for large $ET_N$ (Fisher et al., 2007).

(b) Look-up tables and similar methodologies that rely on ensemble averages of acceptable data collected under similar meteorological conditions (Falge et al., 2001; Hirano et al., 2003; Law et al., 2000; McCaughey et al., 2006).

(c) Multiple linear regression of acceptable fluxes on meteorological variables (Berbigier et al., 2001; Greco and Baldocchi, 1996). This approach incorporates process information empirically, though it does not distinguish between meteorological variables that may influence evaporation and transpiration differently.

(d) Setting missing nocturnal *ET* fluxes equal to zero either directly or indirectly through empirical relationships with photosynthetically active radiation (Novick et al., 2004; Wever et al., 2002).

(e) More complex statistical techniques including the Kalman filter (Alavi et al., 2006) and multiple imputation (Hui et al., 2004).

### *1.2. Goals of the analysis*

We investigated the patterns and drivers of $ET_N$ using long-term eddy-covariance records collected over three ecosystems co-located in the Duke Forest near Durham, NC (USA). Because these three sites experience similar climatic and edaphic conditions, but differ in species composition and leaf area dynamics, a cross-site $ET_N$ comparison is used to elucidate, qualitatively, the relative contribution of evaporation and transpiration to $ET_N$. A range of gapfilling methodologies are applied to the datasets from these three sites and then compared on seasonal and annual time scales. We selected five gapfilling methods of varying complexity: (1) a simple filter that sets all missing $ET_N$ data to 0 (hereafter referred to as ZERO), which is treated as a null dataset for comparison; (2) multiple non-linear regression on covariates of observed meteorological variables (PROCESS); (3) a simple linear regression between the relationship of observed daytime and nighttime fluxes (DAYNIGHT); (4) marginal sampling distribution (DIST_SAMP) after Moffat et al. (2007), which is a variant of the look-up table approach; and (5) the multiple imputation technique (MULT_IMP). The primary criterion for evaluating these five methods is their ability to reproduce artificially generated gaps in data records of acceptable $ET_N$ measurements.

In many applications, evapotranspiration data is gapfilled or modeled with the Penman–Monteith equation because the daytime drivers of *ET* are well known and can be well represented by this model (Campbell and Norman, 1998). The drivers of nocturnal *ET*, on the other hand, are not as well understood and models for $ET_N$ may require fundamentally different frameworks. For example, the link between assimilation and transpiration that instructs the Ball–Berry model for stomatal conductance (Collatz et al., 1991) clearly cannot explain the variability in nocturnal transpiration reported in the literature. Similarly, the variation in *ET* explained by radiation, which is a key input to the Penman–Monteith model and its variants, may be much greater during the day when *ET* is a more significant component of the net radiation balance. In fact, the Penman–Monteith model is likely to estimate zero or negative *ET* at night when net radiation is negative and sensible and ground heat fluxes are not largely negative. Until the mechanisms controlling nocturnal *ET* are better elucidated, separate algorithms for daytime and nighttime gapfilling should be considered. For these reasons, we did not include the Penman–Monteith equation in the range of nocturnal gapfilling procedures considered here.

## 2. Materials and methods

### *2.1. Site description*

Eddy-covariance derived *ET* data were collected from three adjacent ecosystems in the Duke Forest in Durham, North Carolina (35°58′41″N, 79°05′39″W, 163 m a.s.l.) between 2002 and 2006.