

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 gapfilling 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).

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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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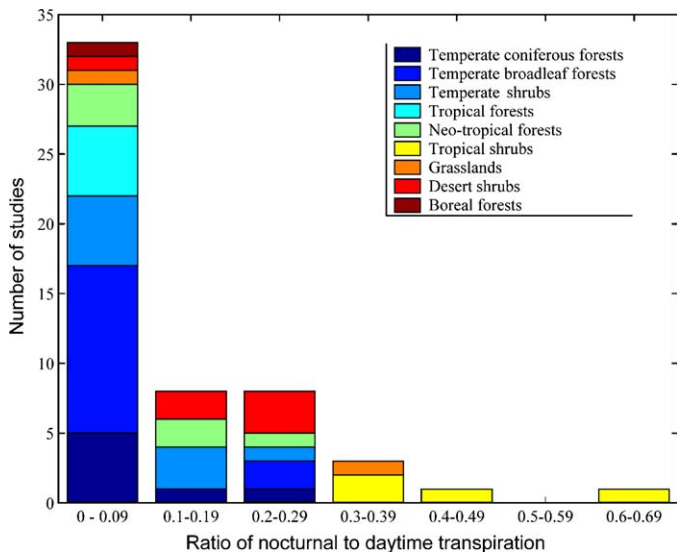


Fig. 1. Histogram describing the occurrence of mean nocturnal transpiration as a fraction of mean daytime transpiration rates from over 50 surveyed species representing both field and greenhouse data. In the case where ranges of percentages were given, the average of the minimum and maximum rates was 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:

- 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).
- 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).

- 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.
- 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).
- 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.

These ecosystems vary in vegetation cover and canopy structure but experience nearly identical climatic and edaphic conditions. They are an old grass field, a loblolly pine plantation, and a deciduous hardwood forest. Detailed characteristics of each of the ecosystems can be found elsewhere (Ellsworth et al., 1995; Novick et al., 2004; Oishi et al., 2008; Palmroth et al., 2005; Stoy et al., 2006a). However, a brief description is provided here for completeness.

The old field was burned in 1979 and is harvested annually during the summer for hay according to local practices. It is dominated by the grass *Festuca arundinacea* Shreb., with contributions from other C3 and C4 grasses and various herbs. The height of the vegetation reaches 1 m during the middle of the growing season, concurrent with a peak in leaf area index (*LAI*) of about $2 \text{ m}^2 \text{ m}^{-2}$. Eddy-covariance instrumentation at this site is positioned 2.8 m aboveground.

The pine plantation was established in 1983 following a clear cut and a burn. *Pinus taeda* L. (loblolly pine) seedlings were planted at 2.0 m by 2.4 m spacing and the stand has not been managed after planting. Canopy height increased from 16 m in 2001 to 19 m in 2006. The canopy is comprised primarily of *P. taeda* with some emergent *Liquidambar styraciflua* L. and a diverse sub-canopy. Eddy-covariance instrumentation is positioned at 20.2 m above ground on a 22 m tower. Peak *LAI* at this site was nearly $6.0 \text{ m}^2 \text{ m}^{-2}$ in 2001, although it was significantly decreased in later years following repeated droughts and a severe ice storm in 2002 (McCarthy et al., 2007).

The hardwood forest is classified as an uneven-aged (90–110-year old) oak (*Quercus*)–hickory (*Carya*) forest with *L. styraciflua* and *Liriodendron tulipifera* L. also contributing to the canopy and a diverse understory (Pataki and Oren, 2003). The forest has not been managed after establishment. Mean canopy height is 25 m, with the upper canopy, broken by many large gaps, reaching over 35 m. Eddy-covariance instrumentation is positioned at 39.8 m on a 42 m tower. Peak *LAI* at this site is $6.3 \text{ m}^2 \text{ m}^{-2}$.

All three ecosystems have little topographic variation and lie on Enon silt loam, a low fertility Hapludalf typical of the Southeastern U.S. Piedmont, with a transition to Iredell gravelly loam toward the hardwood forest (Pataki and Oren, 2003). A clay pan underlies the research sites at ca. 35 cm below ground (Lai et al., 2000; Oren et al., 1998) and imposes similar constraints on root-water access for all three ecosystems. Long-term mean annual temperature and precipitation are 15.5°C and 1146 mm, respectively.

2.2. Evapotranspiration measurements

Latent heat flux (*LE*) was measured using eddy-covariance systems comprised of triaxial sonic anemometers (CSAT3, Campbell Scientific, Logan, UT, USA) and open-path infrared gas analyzers (IRGA, LI-7500, Li-Cor, Lincoln, NE, USA). Measurements of vertical wind velocity and scalar concentrations of water vapor were collected at 10 Hz and flow statistics were processed in real time into half-hour averages using CR23X data loggers (Campbell Scientific) with spurious data filtered as described by Katul et al. (1997). The Webb–Pearman–Leuning correction (Webb et al., 1980) for the effects of air density fluctuations on flux measurements was applied. To ensure that mean streamlines are parallel to the ground surface, horizontal wind speed components were rotated to determine an average horizontal wind speed, and then data for periods during which the inverse tangent of the ratio between average horizontal and vertical windspeed exceeded 15° were filtered after Stoy et al. (2006a). The portion of data points filtered through this procedure is less than 0.1%. Measured latent heat fluxes were converted to *ET* fluxes, in units of mm per half hour, using the temperature-dependent latent heat of vaporization for water vapor.

2.3. Meteorological measurements

A suite of meteorological measurements was also collected at each site. Half-hourly precipitation was measured using a tipping bucket (TI, Texas Instruments, Austin, TX, USA) in the pine plantation. Net radiation (R_n), air temperature (T_a), and relative humidity were sampled every second and averaged for half-hour periods in all three sites. R_n measurements were made with Fritschen-type net radiometers (Q7, REBS, Seattle, WA, USA) through 2003 and with CNR1 net radiometers (Kipp & Zonen, Delft, the Netherlands) thereafter. T_a and relative humidity were measured with HMP35C T_a /RH (Vaisala, Finland) probes positioned at 2 m in the old field and at two-thirds canopy height in the pine plantation and hardwood forest, and then used to calculate vapor pressure deficit (*VPD*). Mean wind speed (u) and friction velocity (u^*) were measured at each site from the velocity components of the sonic anemometer.

2.4. Leaf area index measurements

In the old field, *LAI* was estimated by measuring PAR transmission with a series of 80 quantum sensors (AccuPAR model PAR-80 Ceptometer, Decagon Instruments, Pullman, WA, USA) to calculate gap fractions, which were inverted to calculate *LAI* after Campbell and Norman (1998). In the pine plantation, the contribution to *LAI* from *P. taeda* trees was calculated using needle elongation and litterfall measurements, and *LAI* of understory hardwood species was calculated using degree-day sums and litterfall measurements (McCarthy et al., 2006). In the hardwood forest, *LAI* was determined using *LAI*-2000 (Li-Cor, Lincoln, NE, USA) measurements adjusted by litterfall measurements (Oishi et al., 2008).

2.5. Data pre-processing

LE measurements were subjected to a quality control procedure to remove excessive sensor noise and data collected under very stable conditions. First, spikes in the data record were removed using the algorithm recommended for FLUXNET (Papale et al., 2006). Fluxes were then filtered to remove data collected during stable atmospheric conditions using a u^* filtering method similar to the method described by Reichstein et al. (2005). Briefly, flux data were sorted into T_a and u^* classes, and a threshold u^* for three-month periods was determined as the value for which mean flux exceeded 95% of the mean flux at higher values of u^* . Flux data were then removed if they were collected during periods in which u^* was less than the mean of the three-month threshold series. Finally, *LE* fluxes were rejected if the half-hourly flux magnitude was outside the logical expectation window of -100 to 700 W m^{-2} .

When the measurement of any meteorological variable was unavailable due to equipment failure or other error, a continuous record was obtained by fitting a linear regression between measurements from the sensor of interest and a nearby sensor of the same type.

2.6. Artificial gap generation

After filtering the data, artificial gaps were created in the datasets for the purpose of evaluating the prognostic ability of the gapfilling methods. Actual gaps in nocturnal eddy-covariance records can range in length from one half-hour to well over 50 consecutive nocturnal hours. Due to the scarcity of acceptable nocturnal data and the size of some of the longer gaps in the dataset, artificial gaps cannot be created that fully reproduce the gap statistics derived from the entire record. In this analysis, artificial gaps were created by randomly removing all acceptable nighttime data from roughly 10% of the nights.

Table 1
A comparison of the five gapfilling methods used in this analysis. The reference numbers are for: (1) Reichstein et al. (2005); (2) Stoy et al. (2006a); (3) Moffat et al. (2004); and (4) Hui et al. (2004).

Method	Description	Ref.	Process-based?	Required variables	Time window	Computational cost
ZERO	All missing fluxes replaced with zero	This study		ET_N	N/A	Low
PROCESS	Multiple non-linear regression	1, 2	×	$VPD, t_p, u_{sub}^*, LAI, ET_N$	Monthly	Low
DAYNIGHT	Simple relationships between ET_N and ET_D	This study	×	ET_N	Monthly	Low
DIST_SAMP	Marginal distribution sampling	1, 3		$VPD, t_p, u_{sub}^*, LAI, R_n, ET_N$	Variable – 14 days minimum	High
MULT_IMP	Multiple imputation	4		VPD, t_p, LAI, R_n, ET_N	Entire record	High

Data that remained after the quality control filtering and artificial gap generation procedures (hereafter “acceptable” flux data) were used to evaluate the magnitude of ET_N and its seasonal trends and driving variables. To assess the impact of gapfilling methodology on long-term flux estimates, the data records were then gapfilled as described in the next section.

3. Gapfilling techniques

Five gapfilling techniques for ET_N were selected for evaluation in this analysis. These techniques are summarized in Table 1 and described below. Three of the methods (PROCESS, DAYNIGHT, and MULT_IMP) require model parameters, which were estimated by inverting the acceptable flux data (i.e. the data that remained after quality control filtering and artificial gap creation) using non-linear optimization schemes in Matlab. Nocturnal gaps were then filled with each of the techniques described below. Daytime gaps were filled separately using the Penman–Monteith equation with estimated aerodynamic, boundary layer, and stomatal conductances as described in Stoy et al. (2006a).

3.1. Simple filter (ZERO)

We created a ‘dummy’ gapfilled dataset by replacing all missing nocturnal ET data with zero. This method reflects the common assumptions that (1) plant stomata are closed and no transpiration occurs at night; and (2) no significant nocturnal evaporation occurs, which is an assumption in any model that drives surface conductance to near zero at night.

3.2. Process-based model (PROCESS)

This technique relies on the parameterization of non-linear relationships between ET_N and meteorological variables. To develop the non-linear relationship, we began by noting that canopy transpiration (T) may be represented as (Monteith and Unsworth, 1990):

$$T = a_1 \cdot G_s \cdot VPD \cdot LAI, \quad (1)$$

where a_1 is a constant derived from the latent heat of vaporization, the specific heat capacity of dry air, mean air density, and the psychrometric constant. G_s is the canopy conductance to water vapor per unit leaf area, which is commonly expressed with a Jarvis-type reduction function (Jarvis, 1976) such as:

$$G_s = G_{Sref} f(VPD) f(t_p), \quad (2)$$

where t_p is the time (in days) since a major rain event (defined as greater than 2 mm of rain in a half-hour period)—a generic proxy for soil moisture availability. The functions $f(VPD)$ and $f(t_p)$ adjust a reference conductance rate (G_{Sref}) to reflect meteorological conditions. Here we chose a reduction function for VPD of the form $f(VPD) = 1 + b_1 \log(VPD)$, which describes well the response of G_s to VPD for a wide range of species (Oren et al., 1999). We chose a soil moisture reduction function of the form $f(t_p) = t_p^{-1/2}$, which

describes the soil-regulated drying with time following a wetting event (Campbell and Norman, 1998).

The second component of ET , evaporation (E), may be expressed as a function of VPD (Mihailovic et al., 1995):

$$E = c \cdot VPD \cdot \frac{1}{r_{s,a}} f(t_p), \quad (3)$$

where c is a constant that incorporates a_1 and information about the relative humidity at the soil surface. $r_{s,a}$ is the sum of the surface (r_s) and aerodynamic (r_a) soil resistances; the former may be represented as a function of the inverse of the friction velocity (u^* , Ye and Pielke, 1993) and the latter is largely a function of the inverse of u (Mihailovic et al., 1995). Noting that u^* and u are strongly correlated via a constant soil-surface drag ($C_d = (u^*/u)^2$), we can approximate $1/r_{s,a} \propto u^{*2}$ (Katul et al., 2004). While u^* was measured at the top of the canopy, the bulk of evaporation occurs below the canopy at the soil-atmosphere interface when the canopy is dry. Therefore, we estimated (u_{sub}^*) just above the ground surface using measured vertical leaf area distributions with an analytical second-order closure model (Massman and Weil, 1999). Assuming the same soil moisture reduction function for E as we assumed for T , we have:

$$ET = E + T = VPD \cdot t_p^{-1/2} [(a + b \log(VPD)) LAI + cu_{sub}^{*2}], \quad (4)$$

where the new constants are $a = a_1 G_{Sref}$ and $b = a_1 b_1$.

It should be emphasized here that $t_p^{-1/2}$ has some theoretical justification in the case of E . This time dependence arises during the soil-regulated stage of drying and follows from analytical solutions to Richard’s equation that describes soil moisture redistribution (Black et al., 1969; Gardner, 1959; Gardner, 1962). This analytical solution is based on the so-called Boltzmann-similarity variable ($B = zt_p^{-1/2}$, where z = depth into the soil) applied to Richards’ equation assuming infinite soil wetting, and neglecting gravitational drainage. A linearized variant of this solution ($E_t = D_e t_p^{-1/2}$, where E_t is soil evaporation, and D_e is the effective desorptivity) was shown to predict bare soil evaporation reasonably well over extended periods (Parlange et al., 1992; Parlange et al., 1993).

The parameters of Eq. (4) were determined using a non-linear optimization technique for monthly blocks of data. Average values of the parameters for each month of the year were determined, and combined with Eq. (4) to fill missing nocturnal data.

3.3. Day–night relationships (DAYNIGHT)

Correlation between nocturnal and daytime transpiration rates has been observed in some species (Cavender-Bares et al., 2007) and forms the basis of the DAYNIGHT method, which relies on a simple linear regression model for ET_N as a function of mean daytime ET (ET_D), parameterized for monthly time blocks. For this procedure, we limited our analysis to day–night pairs for which three or more acceptable nocturnal half-hour fluxes were available. For months in which less than three such pairs of data were available, the linear relationship was derived from the

average slope and intercept obtained during the same months in other years.

3.4. Marginal distribution sampling (DIST_SAMP)

Marginal distribution sampling is an enhanced look-up table technique (Falge et al., 2001; Moffat et al., 2007; Reichstein et al., 2005) whereby fluxes collected during similar meteorological conditions are sampled within a dynamic window of time centered on the missing data point, and the missing data is replaced with the mean of the sampled fluxes. In this analysis, we considered data that were collected under conditions within 0.5 kPa for VPD , 50 W m^{-2} for R_n , $0.04 \text{ m}^2 \text{ s}^{-2}$ for u_{sub}^2 , three days for t_p , and $1 \text{ m}^2 \text{ m}^{-2}$ for LAI in a two-week window centered around the missing flux value. These ranges were selected heuristically to maximize the number of sampled fluxes within the two-week time window while insuring similar prevailing meteorological conditions. In the event that less than three data points within this window met the specified criteria, the window size was expanded by two weeks iteratively until an average of three flux rates could be obtained. In cases when three data points meeting the specified criteria were not available in the entire data record, missing data were linearly interpolated.

3.5. Multiple imputation (MULT_IMP)

Multiple imputation is a general technique for replacing missing values in large datasets that has recently been used to gapfill eddy-covariance records (Hui et al., 2004; Moffat et al., 2007). Briefly, the parameters of a multivariate normal distribution of the acceptable ET_N data and meteorological variables of interest (in this case, VPD , t_p , R_n , and LAI) were estimated using maximum likelihood. We did not include u_{sub}^2 in the imputation routine because stable periods are typically characterized by low wind speeds and momentum fluxes, and one of the assumptions of the algorithm is independence between the covariates and the likelihood that data is missing.

Missing data were then sampled from this distribution, and the maximum likelihood estimates of the parameters were again estimated using this new dataset. These two steps were iterated until the distribution parameters converge (i.e. the change in the parameters is smaller than an arbitrary threshold set here to $10e^{-4}$). At this point, a Markov Chain Monte Carlo algorithm was used to simulate each missing flux value independently using the derived distribution parameters and the corresponding observed meteorological data. Six imputed datasets were generated in this way and pooled into the final gapfilled dataset, which includes variance estimates for every gapfilled point.

3.6. Estimation of gapfilling error

The accuracy of the gapfilling techniques was assessed with four performance measures: the coefficient of determination (r^2), the relative root-mean-square error (R_RMSE), the mean absolute error (MAE), and the bias error (BE), where each measure is calculated after Moffat et al. (2007) for each gapfilling technique using observed and simulated data over the artificial gaps. Additionally, frequency distributions of the observed and simulated data are compared to better identify biases in the distributional properties.

For the process-based methods relying on a monthly parameterization scheme (PROCESS and DAYNIGHT), the precision of the gapfilling technique was estimated through a non-parametric bootstrap by randomly selecting monthly parameters from the set of all optimized parameters in the corresponding month. The 95% confidence intervals in the annual and growing season ET

estimates were calculated from a Monte Carlo simulation with 100 realizations. The precision of the multiple imputation and marginal distribution sampling methods was not explicitly assessed because, when applied to datasets as large as these eddy-covariance records, these statistical techniques produce very narrow confidence intervals through both parametric and non-parametric bootstrap assessments.

4. Results

We begin by briefly describing the meteorological and hydrological conditions experienced during the study period and the data availability at each site. The magnitude and direction of observed ET_N fluxes, as well as the dominant meteorological drivers for these fluxes, are then presented. We discuss the parameterization of relationships used in some gapfilling methods. We end by describing the impact of the gapfilling methods on annual ET flux estimates, and assessing the ability of each method to reproduce the artificially generated gaps in the dataset.

4.1. Meteorological and hydrological variability

The study period was marked by one year of severe growing season (April–September) drought in 2002, when growing season precipitation was nearly 200 mm below the study period average. Growing season and annual precipitation were also well below the long-term mean in 2005, though cooler than average temperatures and relatively normal precipitation in the early growing season prevented drought status from becoming as severe as in 2002. The sites experienced an exceptionally wet year in 2003, with annual precipitation exceeding the long-term average by 18%. Accordingly, mean annual temperature was nearly 1°C lower in this year when compared to the entire study period. Growing season precipitation rates were closest to normal in 2004 and 2006. The latter year was one of the hottest on record for the study area, and average annual VPD was approximately 40% higher in 2006 than in 2004.

Precipitation across the three ecosystems is identical, and they do not experience marked inter-site variations in T_a or VPD (Stoy et al., 2006a). Soil moisture tends to be highest in the hardwood forest in the wintertime when leaf area is largely absent and transpiration drops to nearly zero; soil moisture content is similar across sites during the growing season (Palmroth et al., 2005). Within-canopy wind speed and momentum fluxes vary considerably across the sites (Stoy et al., 2006a), with the hardwood forest experiencing the greatest momentum sink for most time periods and greatest within-canopy wind speeds during winter months. Within-canopy wind speeds are comparable across the forested sites during summer months.

4.2. Data availability

Approximately 6.5% of the ET flux data records were lost due to instrument failures from power outages, sensor malfunctions, and downtime during calibration of the gas analyzers (Table 2). The majority of instrument down time occurred during daytime hours when the bulk of maintenance work and calibration was performed. Approximately 9% of data were rejected by the despiking routine in all sites, with an additional 38%, 41%, and 42% of data rejected due to u filtering across the three sites, the majority of which was collected at night. A small percentage of the data (<3%) was rejected for falling outside of the range $-100 \text{ W m}^{-2} < LE < 700 \text{ W m}^{-2}$.

After these filters were applied, 41%, 39% and 45% of the original datasets remained in the old field, pine plantation, and hardwood forest, respectively, although the percentage of nighttime data

Table 2

The percentage of 30-min flux data removed or lost over the entire study period after progressively employing four data filters and the artificial gap generation procedure.

	OF		PP		HW	
	Day	Night	Day	Night	Day	Night
%Lost to power outage	10	7	10	7	3	2
%Lost to despiking	4	14	4	15	4	14
%Lost to u^* filtering	20	55	24	58	27	56
%Lost to thresholding	3	2	1	~0	1	~0
%Lost to artificial gap creation	0	3	0	2	0	3
Total %lost	37	81	40	82	35	75
# Half-hour data points remaining	27479	8400	26102	8060	28116	10870

remaining was much less (18–25%). Artificial gap creation resulted in the exclusion of an additional 2.7%, 1.9%, and 2.8% of data in the old field, pine plantation, and hardwood forest, which represents 12.3%, 9.6%, and 13.9%, respectively, of the acceptable nocturnal data remaining after the data quality filters were employed. The average artificial gap length was approximately eight half-hour periods (or 4 h), ranging up to 12 h.

4.3. Presence and seasonal patterns of measured ET_N

Mean ET_N over the course of the study period was positive for all sites and the distributions of acceptable ET_N data were all positively skewed (Fig. 2, with skewness values of 0.63, 0.74, and 0.46 in the old field, pine plantation, and hardwood forest, respectively). Occasionally, negative ET_N was observed, reflecting condensation or random measurement error. ET_N was typically largest in the pine plantation during both summer and winter months, following trends for ET_D . Average growing season ET_N was similar in the forest sites (ca. 0.02 mm h^{-1}) and considerably lower in the old field (ca. 0.014 mm h^{-1}). During winter months, when the hardwood forest LAI was near zero, ET_N in the old field was somewhat higher than flux rates in the hardwood forest (0.014 and 0.012 mm h^{-1} , respectively). Annually, average acceptable ET_N was 8.0%, 9.1%, and 8.0% of ET_D in the old field, pine plantation, and hardwood forest, respectively. The ratio decreased slightly during the growing season, averaging 5.9%, 7.0%, and 7.3%.

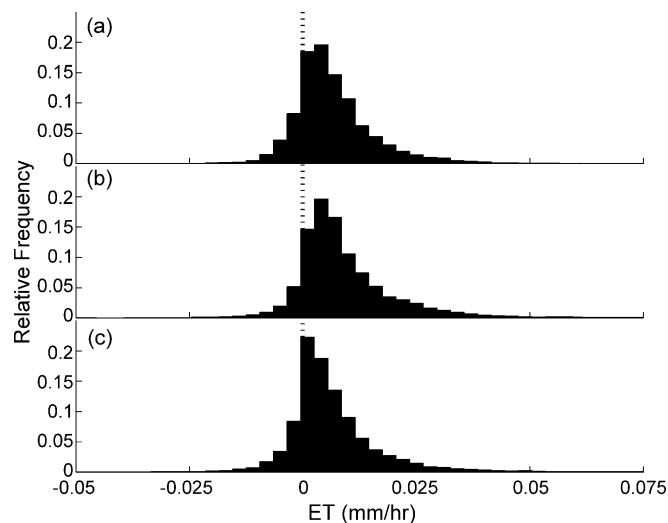


Fig. 2. Histograms of the acceptable nocturnal evapotranspiration (ET) flux data for (a) the old field; (b) pine plantation; and (c) hardwood forest. Dotted lines are drawn at 0 for reference. 'Frequency' represents number of half-hour measurements.

Mean monthly ET_N was calculated for all months for which at least 48 acceptable half-hour nocturnal flux measurements were available (Fig. 3). A strong seasonal pattern in mean monthly ET_N is clearly evident in the hardwood forest, but not in the pine plantation and old field. The hardwood forest experiences large seasonal variations in LAI , with a difference of over $5 \text{ m}^2 \text{ m}^{-2}$ between peak summertime and wintertime LAI . By contrast, LAI in the pine plantation and old field differ by a factor of two or less between summer and wintertime; furthermore, LAI in the old field experiences rapid fluctuations in summer months as the field is mowed and harvested for hay once or twice each growing season.

In the forested ecosystems, mean annual measured ET_N was lowest in 2002, the year of the extreme drought. Mean fluxes in the old field and pine plantation were high in 2003, which was the exceptionally wet year, and high in 2006 in all sites, which was an abnormally warm year with near-normal precipitation.

4.4. Relationship between measured ET_N and meteorological variables

Half-hourly ET_N was strongly and nearly linearly related to half-hourly u_{sub}^{*2} in the old field and pine plantation, but not the hardwood forest (Fig. 4a–c). In the hardwood forest, the largest ET_N occurred when u_{sub}^{*2} was very low, which is characteristic of the growing season (i.e. when high LAI in hardwood forest creates a large momentum sink). At all three sites, ET_N was strongly related to VPD (Fig. 4d–f) and increased sharply during periods of strongly negative R_n (i.e. $R_n < -100 \text{ W m}^{-2}$, Fig. 4g–i), which corresponds to highly negative nocturnal sensible heat fluxes (data not shown). ET_N appeared to decrease strongly with t_p during the first week following a major rain event in the pine plantation and hardwood forest (Fig. 4k–l), although there were no clear trends in ET_N with t_p in any of the three sites over much shorter or much longer time scales.

Monthly parameters for the processed based model of Eq. (4) were successfully determined through optimization routines for 47, 56, and 57 of the 60 months of the study period in the old field, pine plantation, and hardwood forest respectively (Fig. 5). The parameter a , which represents a base nocturnal transpiration rate, was near zero in all three sites (Fig. 5a). The parameter b was typically negative in all three sites ($\bar{b} = -0.012$, -0.0023 , and $-0.014 \text{ mm kPa}^{-2}$ for the old field, pine plantation, and hardwood forest, respectively), which means that the nocturnal stomatal conductance will increase over the base rate a when $VPD < 1 \text{ kPa}$ (and $b \log(VPD) > 0$), which is typical during nighttime. The parameter c was positive in all three sites (Fig. 5c), but highest in the old field and pine plantation, reflecting the relationships with u_{sub}^* shown in Fig. 4.

On average, about nine day–night pairs of mean ET fluxes were used each month in the DAYNIGHT gapfilling parameterization. Correlation between mean ET_N and mean ET_D within each month was typically low, ranging from $r^2 = 0.02$ – 0.35 . No seasonal trend is evident in the correlation between these two variables, and relationships between ET_D and ET_N are similar across sites.

4.5. Gapfilling results

Among the three sites, all five methods estimated the lowest annual flux in 2002, consistent with observed decreases in measured ET_N and ET_D during this extreme drought year (Table 3). Further, all gapfilling methods estimate the largest annual ET in 2006 in all three sites, following observed trends in the measured daytime fluxes in this particularly warm year. The magnitude of estimated annual ET was generally highest in the forested ecosystems regardless of gapfilling.

Due to the paucity of nocturnal ET data, the ZERO gapfilling procedure produced annual and growing season estimates that

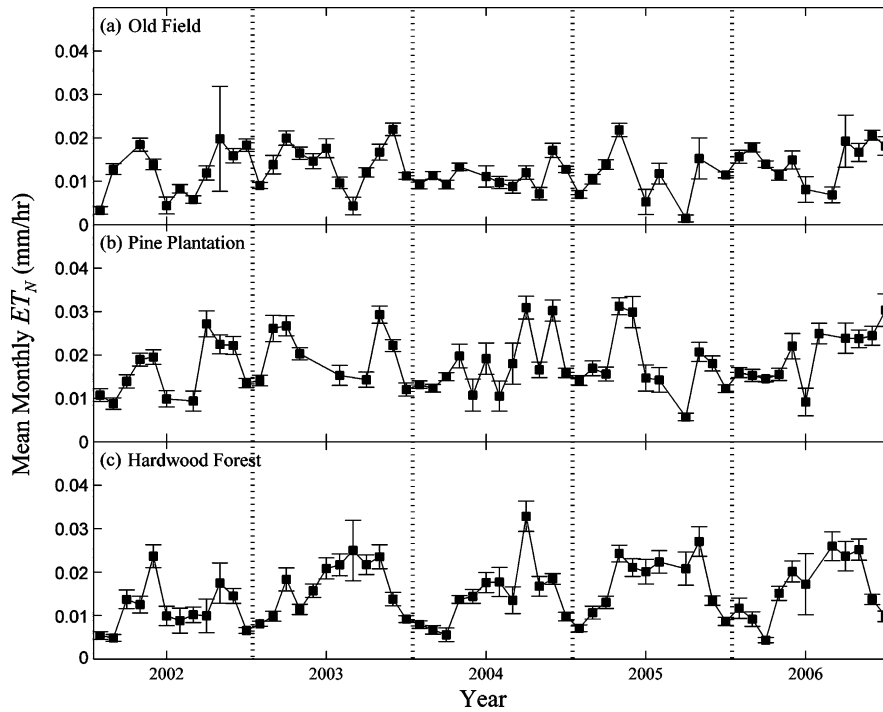


Fig. 3. The seasonal course for mean monthly ET_N at (a) the old field; (b) pine plantation; and (c) hardwood forest. The squares show the mean flux, and the errorbars show the standard error of the mean.

were just marginally higher than the sums of observed ET_D alone. Therefore, most of the variance in the gapfilled estimates from the other four methods can be attributed to the algorithms, which we focus on in this section and the discussion.

In the old field, the various gapfilling methods produced relatively low estimates for the ratio of annual ET_N to ET_D as

compared to the pine plantation, with the exception of PROCESS. On average, the gapfilled estimates of ET_N in the old field represented $\sim 6.9\%$ of the mean annual ET_D . Across most years in the old field, PROCESS and DAYNIGHT produced nocturnal flux estimates that were typically 1.5–2 times as large as the

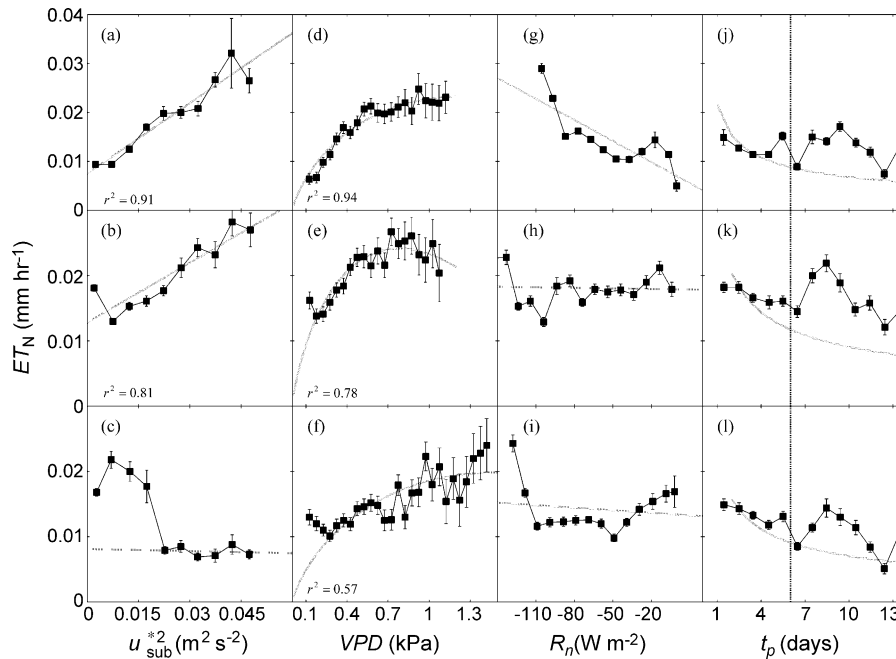


Fig. 4. The relationship between ET_N and four meteorological drivers: (a–c) u_{sub}^2 ; (d–f) VPD; (g–i) R_n ; and (j–l) t_p . The top row is data from the old field (a, d, g and j), the middle row is data from the pine plantation (b, e, h and k), and the bottom row is data from the hardwood forest (c, f, i and l). The circles represent binned averages for discrete classes of the meteorological variables. The error bars show the standard error of the mean for ET_N within each meteorological class. Trendlines are derived from non-linear regression of the binned averages with Eq. (4). In the case of the relationship between ET_N and u_{sub}^2 in the hardwood forest (c), the trendline is derived using averages associated with high u_{sub}^2 only, since lower u_{sub}^2 is associated with greatly different vegetation cover (i.e. much higher LAI). The trendlines associated with t_p reflect data collected only within the first six days of a major rain event, as indicated by the dotted line in j, k, and l, as no relationship between ET_N and t_p is evident over longer times. Correlation is given for some of the significant relationships discussed in the text.

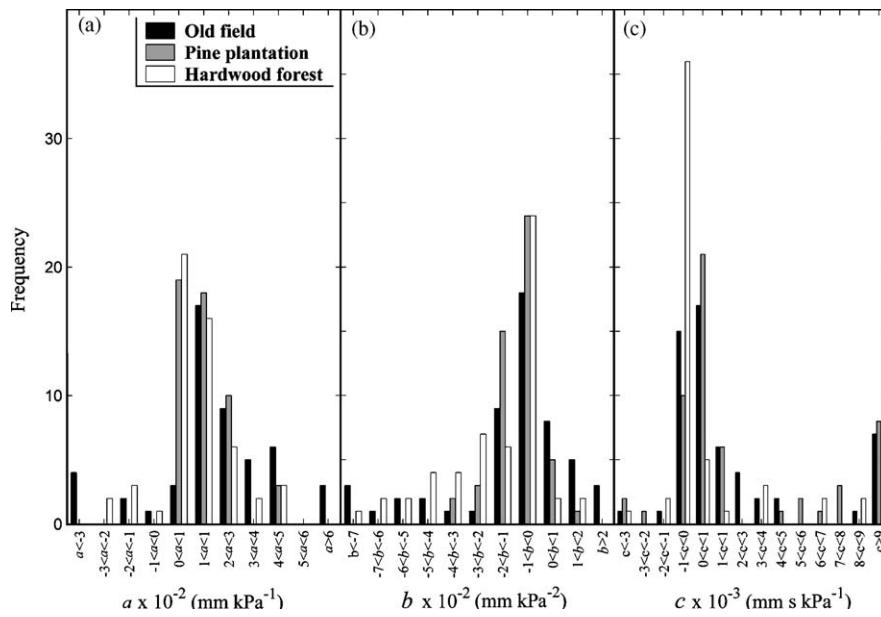


Fig. 5. Histograms of the monthly parameters for the non-linear model of Eq. (4) as derived from an optimization routine.

DIST_SAMP and MULT_IMP estimates, with the exception of 2002, when all gapfilled ET_N estimates were low (i.e. $<40 \text{ mm year}^{-1}$).

In the pine plantation, gapfilled annual ET_N estimates were approximately 60% higher than in the old field and, on average, comprised a larger percentage of ET_D (8.5% vs 6.9% in the pine plantation and old field, respectively). The largest estimate of annual ET_N in the pine stand (113 mm, or 15% of ET_D) was produced by the PROCESS method in 2004, the year with normal temperature and precipitation regimes. In other years, DAYNIGHT generally produced the highest ET_N estimates. Estimates from MULT_IMP method were consistently low for all sites and years.

In the hardwood forest, mean annual ET_D was quite stable, varying by $\sim 90 \text{ mm year}^{-1}$ over the five-year study period. The range in mean annual estimated ET_N was also similar, with no annual estimates from any of the gapfilling techniques exceeding 100 mm year^{-1} . DAYNIGHT produced the highest ET_N estimates and PROCESS produced the lowest estimates each year, with the notable exception of 2006.

The simulated fluxes were compared to those measured during the artificial gap periods via the summary performance measures in Table 4 and the frequency distributions in Fig. 6. The MULT_IMP method was generally associated with the best R_RMSE, though for all methods this quantity is usually within $\sim 20\%$. Estimates of the

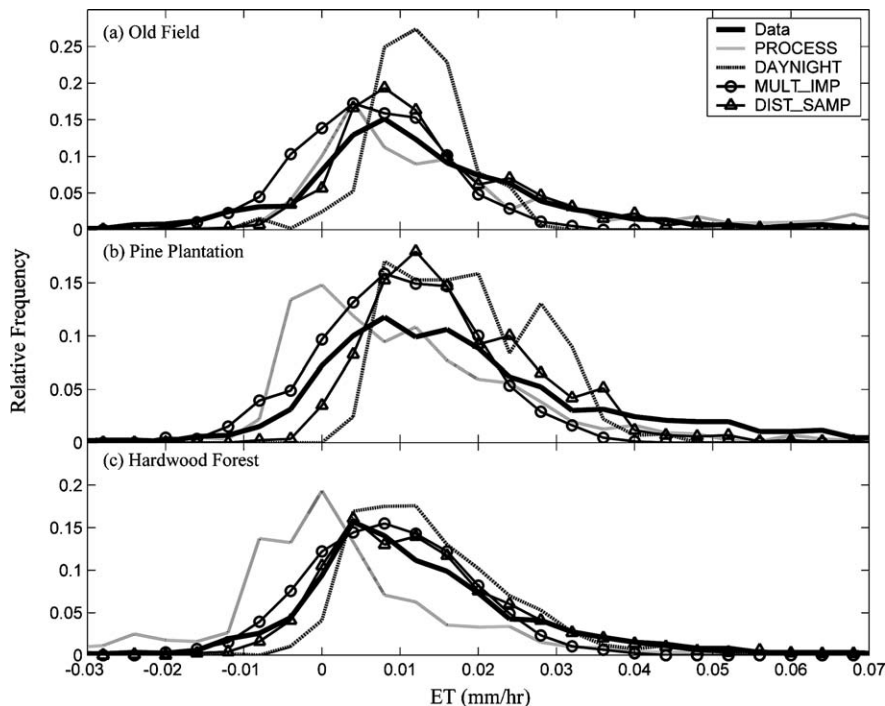


Fig. 6. Relative frequency distributions of the observed acceptable ET_N and four of the gapfilled series for (a) old field; (b) pine plantation; and (c) hardwood forest.

Table 3
 The annual and growing season (GS, April–September) evapotranspiration sums (in mm) for the three sites across the five years of the study period. The “Daytime Flux” is the sum of the Penman–Monteith gapfilled daytime *ET* fluxes. The other quantities represent the sum of the observed and gapfilled daytime and nocturnal fluxes. The numbers in parentheses show the 95% confidence interval for the *ET* estimates as determined by a non-parametric bootstrap analysis for the PROCESS and DAYNIGHT methods. ET_N/ET_D is the ratio of nocturnal to daytime evapotranspiration.

	Old field				Pine plantation				Hardwood forest			
	Annual		GS		Annual		GS		Annual		GS	
	<i>ET</i>	ET_N/ET_D	<i>ET</i>	ET_N/ET_D	<i>ET</i>	ET_N/ET_D	<i>ET</i>	ET_N/ET_D	<i>ET</i>	ET_N/ET_D	<i>ET</i>	ET_N/ET_D
2002												
Daytime Flux	482		338		587		434		600		502	
ZERO	486	0.01	340	0.01	593	0.01	436	0.00	607	0.01	505	0.01
PROCESS	503 (495–676)	0.04	346 (348–360)	0.02	620 (612–731)	0.06	442 (447–566)	0.02	615 (611–661)	0.02	518 (516–564)	0.03
DAYNIGHT	521 (516–532)	0.08	356 (350–360)	0.05	653 (642–666)	0.11	465 (453–470)	0.07	656 (653–672)	0.09	532 (531–542)	0.06
MULT_IMP	510	0.06	350	0.04	627	0.07	451	0.04	638	0.06	520	0.04
DIST_SAMP	517	0.07	350	0.04	642	0.09	453	0.04	635	0.06	517	0.03
2003												
Daytime Flux	680		511		708		542		656		532	
ZERO	687	0.01	514	0.01	715	0.01	544	0.00	667	0.02	536	0.01
PROCESS	728 (690–783)	0.07	537 (529–559)	0.05	754 (732–845)	0.06	584 (553–665)	0.08	675 (668–709)	0.03	554 (543–586)	0.04
DAYNIGHT	732 (723–735)	0.08	532 (528–533)	0.04	775 (763–791)	0.09	569 (559–583)	0.05	731 (713–729)	0.11	568 (559–573)	0.07
MULT_IMP	707	0.04	523	0.02	748	0.06	560	0.03	696	0.06	550	0.03
DIST_SAMP	726	0.07	528	0.03	788	0.11	577	0.06	721	0.10	567	0.07
2004												
Daytime Flux	611		455		775		590		666		531	
ZERO	616	0.01	457	0.00	783	0.01	592	0.00	675	0.01	534	0.01
PROCESS	654 (603–730)	0.07	482 (475–506)	0.06	888 (794–895)	0.15	673 (597–683)	0.14	712 (676–715)	0.07	573 (542–583)	0.08
DAYNIGHT	660 (653–663)	0.08	478 (469–477)	0.05	847 (833–852)	0.09	620 (613–627)	0.05	727 (721–736)	0.09	563 (560–569)	0.06
MULT_IMP	636	0.04	466	0.02	814	0.05	607	0.03	704	0.06	578	0.09
DIST_SAMP	650	0.06	471	0.04	841	0.09	620	0.05	720	0.08	561	0.06
2005												
Daytime Flux	579		463		792		628		645		529	
ZERO	584	0.01	466	0.01	802	0.01	632	0.01	653	0.01	533	0.01
PROCESS	631 (587–670)	0.09	492 (473–491)	0.06	886 (810–928)	0.12	712 (637–740)	0.13	675 (656–693)	0.05	554 (539–577)	0.05
DAYNIGHT	628 (620–640)	0.08	479 (479–485)	0.03	862 (856–875)	0.09	660 (651–668)	0.05	717 (700–721)	0.11	570 (558–569)	0.08
MULT_IMP	606	0.05	475	0.03	832	0.05	644	0.03	682	0.06	547	0.03
DIST_SAMP	614	0.06	476	0.03	858	0.08	659	0.05	703	0.09	563	0.06
2006												
Daytime Flux	734		546		842		627		689		572	
ZERO	736	0.00	547	0.00	850	0.01	629	0.00	693	0.01	573	0.00
PROCESS	866 (776–1017)	0.18	590 (563–589)	0.08	911 (877–1026)	0.08	672 (664–780)	0.07	775 (724–817)	0.11	658 (604–694)	0.15
DAYNIGHT	791 (780–799)	0.08	568 (565–572)	0.04	922 (904–935)	0.10	661 (651–673)	0.05	755 (758–769)	0.10	605 (603–616)	0.06
MULT_IMP	759	0.03	557	0.02	888	0.05	646	0.03	724	0.05	591	0.03
DIST_SAMP	770	0.05	560	0.03	917	0.09	656	0.05	751	0.09	616	0.08

Table 4

Statistical performance measures for four of the gapfilling methods described in Table 1. r^2 is the coefficient of determination, R_RMSE is the relative absolute error, MAE is the mean absolute error, and BE is the bias error. All four measures were calculated after Moffat et al. (2007).

	Old field				Pine plantation				Hardwoodforest			
	PROCESS	DAY_NIGHT	MULT_IMP	DIST_SAMP	PROCESS	DAY_NIGHT	MULT_IMP	DIST_SAMP	PROCESS	DAY_NIGHT	MULT_IMP	DIST_SAMP
r^2	0.04	~0	~0	0.16	0.15	0.11	~0	0.13	0.12	0.08	~0	0.05
R_RMSE	1.42	0.98	0.99	0.95	1.12	0.87	0.93	0.89	1.02	0.94	0.96	1.04
MAE	17.8	11.1	12.4	11.2	16.5	12.9	14.1	13.6	12.4	10.9	11.4	11.7
BE	0.37	-0.20	-0.60	-0.09	-0.23	-0.13	-0.54	-0.14	-0.62	0.10	-0.36	0.06

MAE are generally between 10 and 18 $W\ m^{-2}$. Estimates of the bias error exceed 50% in some cases, and are almost exclusively negative due to a general inability of the gapfilling methods to reproduce the largest observed half-hourly fluxes of ET_N .

Frequency distributions of the observed and gapfilled data within the artificially generated gaps were examined to further assess the biases associated with the various gapfilling methods (Fig. 6). In the old field and hardwood forest, $DIST_SAMP$ reproduced the shape of the frequency distribution of observed ET_N best (Fig. 6a and c). In the pine plantation, $PROCESS$ returned the lowest absolute difference between the measured and modeled distributions (Fig. 6b), followed closely by $DIST_SAMP$ and $MULT_IMP$. Generally, $MULT_IMP$, which assumes a multivariate normal distribution between the ET flux and driving variables, failed to reproduce the observed positive skewness in all three sites. The other methods tend to overestimate the degree of skewness, with the exception of $DIST_SAMP$ and $DAYNIGHT$ when employed for the old field.

$PROCESS$ and $DAYNIGHT$, both relying on monthly parameter estimates, were highly sensitive to these parameters (see Fig. 5) as demonstrated by the wide range of annual and growing season ET estimates produced by the bootstrap algorithm (Table 3). In some cases, the lower range of the 95% confidence intervals were close to or even below the $ZERO$ flux estimates (e.g., the old field in 2004), although in general the bootstrap estimates suggest a strongly positive ET_N .

5. Discussion

The eddy-covariance methodology does not often produce reliable estimates of evapotranspiration due to the frequent suppression of turbulence at night (Falge et al., 2001; Moffat et al., 2007), and even eddy flux measurements collected during near-neutral conditions are often impacted by dynamic flux footprints and sensor noise to the extent that many physiological processes may be obscured (Oren et al., 2006). Nonetheless, in this study, we were able to detect a significant nocturnal evapotranspiration signal from eddy-covariance records at all three study sites (Figs. 2 and 3) that accounted for an average of 8.0%, 9.1%, and 8.0% of the annual daily ET flux in the old field, pine plantation, and hardwood forest respectively. These ratios are at the low end of the range of nocturnal ET flux magnitudes reported in other studies that rely primarily on sap-flux or porometry data (Fig. 1), and we expect that they may be underestimated by 12–20%. This is the underestimation range in nocturnal NEE derived from eddy-covariance (Soegaard et al., 2000; Wilson et al., 2002), which is similar to the underestimation of ET_N in a recent study (Fisher et al., 2007).

We further discuss errors for, and independent checks on, these estimates. We also discuss the contribution of T and E to ET_N , as well as the relationships between these fluxes and meteorological drivers. We then evaluate the accuracy of the gapfilling methodologies employed in this analysis, and conclude by discussing the significance of these findings with respect to ecosystem water budgets and ecophysiological modeling.

5.1. Measured ET_N —sources of error

Eddy-covariance estimates of surface fluxes are not direct measurements of the true scalar ecosystem emission or uptake rate. Rather, these estimates represent observations of the true flux modified by two types of error: random measurement error (δ) and systematic error (ϵ) (Richardson et al., 2006). The former term incorporates all instrument errors, as well as errors due to surface heterogeneity and stochastic noise inherent to turbulent transport. The latter term incorporates persistent biases associated with experimental design and methodology, which may be best assessed via independent flux measurements. The systematic error also reflects the impacts of insufficient turbulent mixing during stable boundary conditions, which may be mitigated via a range of quality control procedures advocated by the eddy-covariance community (Papale et al., 2006; Richardson et al., 2006).

Our data quality filtering scheme resulted in the rejection of a large portion of the data records (ca. 60%, Table 2), which is at the upper limit of data rejection reported from other sites (Moffat et al., 2007). While the proportion of the data rejected by these procedures is similar to that derived from another quality control assessment employed at these sites incorporating an atmospheric stability filter in place of u^* filtering (Stoy et al., 2006a, b; Novick et al., 2004), it is possible that acceptable data instructional to the analysis and gapfilling has been removed while attempting to minimize systematic errors associated with stable boundary conditions.

To address this concern, we calculated the MAE in the nocturnal LE measurements by comparing acceptable flux measurements collected during the same time period on consecutive days under similar environmental conditions (u within $1\ m\ s^{-1}$, D within $0.5\ kPa$, and R_n within $50\ W\ m^{-2}$). Flux error estimated using this daily differencing technique has been previously shown to follow a double-exponential (Laplacian) distribution, for which the scale parameter is δ (Richardson et al., 2006). Our derived estimates of MAE (9.19, 12.20, and $8.26\ W\ m^{-2}$ for the old field, pine plantation and hardwood forest, respectively) are within the range of errors in LE reported for seven other Ameriflux sites (3.4 – $15.6\ W\ m^{-2}$) for $R_n < 100\ W\ m^{-2}$ (Richardson et al., 2006). The same quantities derived from the datasets filtered with a standard u^* threshold of $0.25\ m\ s^{-1}$ in place of the dynamic despiking and thresholding routines were comparable in pine plantation ($11.6\ W\ m^{-2}$), but significantly higher in the old field and hardwood forest (19 and $11.5\ W\ m^{-2}$, respectively). Thus, there was a tradeoff in using the less rigorous quality control procedure: it increased data availability but, in the old field and hardwood forest, it injected additional systematic error into the records.

In all three sites, MAE is directly related to u^* ($r^2 = 0.7, 0.84, 0.62$ in the old field, pine plantation, and hardwood forest, respectively). Because most data collected during stable boundary conditions is associated with low u^* , removing these data points should not result in large increases in the uncertainty of flux estimates. Indeed, the estimated ratio of nocturnal to daytime ET varies by $<10\%$ in all three sites when additional artificial gaps are created in the data records to simulate up to 90% “loss” of the data.

However, we cannot entirely discount the possibility that greater data availability would impact flux estimates, especially considering that much more data is missing during the growing season. Because ET_N is highest during the growing season, the greater portion of missing data during summer months is likely to inject a negative bias in flux estimates. Further, previous work has shown that biases in measured and gapfilled nocturnal eddy-covariance records are expected to be about -12 to -20% (Soegaard et al., 2000; Wilson et al., 2002) due to biases in both δ and ε caused by some combination of the following: mismatches between flux footprints and ecosystem dimensions (Detto et al., 2006; Oren et al., 2006; Schmid, 1997), mismatches between footprints for the net radiometer and the eddy-covariance system (Baldocchi, 2003; Oren et al., 2006), instrument biases (Wilson et al., 2002), the separation of the gas analyzers and sonic anemometers, which acts as a low-pass filter (Oren et al., 2006), and possibly micro-scale advective and drainage flows (Lee and Hu, 2002). Therefore, estimates of the magnitude of ET_N presented in this study should be considered as conservative minima.

5.2. Independent validations

For independent checks of the nocturnal ET estimates, we turn to porometric gas exchange and sap-flux measurements conducted at our study sites. In the pine plantation, leaf-level gas exchange measurements have been collected as part of a separate study and used to parameterize the Ball–Berry model for stomatal conductance (Ball et al., 1987; Collatz et al., 1991), which may be expressed as:

$$G_s = m \frac{A \cdot RH}{C_s} + b' \quad (5)$$

where A is the CO_2 assimilation rate, RH is relative humidity, C_s is the ambient CO_2 concentration, and m and b' are constants. The latter constant, which has been measured as $0.015 \text{ mol m}^{-2} \text{ s}^{-1}$ in the pine plantation (Lai et al., 2000), represents the stomatal conductance during non-photosynthetic periods (i.e. nighttime). Using this baseline stomatal conductance rate with Eq. (1) together with observed VPD and LAI generates estimates for annual ET_N in the pine plantation between 56 and 91 mm year^{-1} over the course of the study period, or between 10% and 18% of ET_D . These estimates are comparable to those produced with the eddy-covariance gapfilling procedures (Table 3).

In the hardwood forest, sap-flow in dominant canopy species was measured using heat dissipation probes as part of a separate study performed concurrent to this investigation (Oishi et al., 2008). The ratio of nocturnal to daytime water flux through the stem determined from sap flow measurements averaged $17 \pm 0.2\%$ during the period of 2002–2005. This is within the range of ratios reported by other studies (see Fig. 1), although it is approximately twice the observed ratio of acceptable ET_N/ET_D from eddy-covariance fluxes. The discrepancy between eddy-covariance estimates of ET_N and sap flux derived estimates of nocturnal T in the hardwood forest may be explained in part by the known systematic underestimation of nocturnal eddy-covariance fluxes (see Section 5.1). Further, a portion of the nocturnal water uptake measured with sap flow probes is used for water recharge in the trees, and would not be sensed by the eddy-covariance instrumentation.

5.3. Determinants of measured ET_N

Measured ET_N was related to VPD in all three sites, consistent with previous studies (Daley and Phillips, 2006; Dawson et al., 2007; Fisher et al., 2007; Kavanagh et al., 2007; Oren et al., 2001b; Ward et al., 2008). It was strongly correlated with u_{sub}^{+2} in the old field and pine plantation, and in the hardwood forest during

periods of low LAI (i.e. higher u_{sub}^{+2}). In all three sites, ET_N did not appear to be strongly driven by t_p except within the first week to 10 days following a rain event. This scale separation may simply reflect the influence of noise on smaller fluxes during dry periods, or suggest the presence of more complex processes such as hydraulic redistribution that alter relationships between ET and t_p (Siqueira et al., 2008). Further, the $t_p^{-1/2}$ relationship holds only during the second-stage of soil evaporation, and does not necessarily reflect the sensitivity of transpiration to soil moisture or the final stages of evaporation.

Significant relationships between nocturnal and daytime transpiration rates were observed for at least some months in all three sites, consistent with previous findings (Cavender-Bares et al., 2007). We also observed greatest nocturnal ET_N rates in the pine plantation (Fig. 3, Table 3), which is dominated by the fast-growing, shade-intolerant *P. taeda*. This result is consistent with previous observations that nocturnal transpiration is highest in species with high extension growth rates and low shade tolerance, and may represent a tendency for these species to trade water for enhanced nocturnal carbon export driven by dark respiration (Marks and Lechowicz, 2007).

5.4. Influence of T and E on ET_N

Partitioning the measured above-canopy ET fluxes into its E and T components is challenging even during daylight hours (Roupsard et al., 2006; Stoy et al., 2006a; Williams et al., 2004), and we will not attempt a formal quantification of the contribution of T and E to ET_N . Instead, we discuss the relative contribution of these fluxes qualitatively.

In the hardwood forest, perhaps the strongest evidence that a significant portion of the observed ET_N is transpiration comes from the seasonal trends in monthly averaged ET_N (Fig. 3). If ET_N in the hardwood forest was dominated by E , then we would expect to see declined rates of ET_N during summer months, when increased leaf area reduced the wind speed and momentum at the canopy floor (i.e. u_{sub}^{+2} is at its lowest), and soil moisture content was substantially lower. Instead, ET_N rates were substantially higher during the growing season (see Fig. 3c), suggesting a significant contribution from T .

No seasonal pattern of monthly ET_N is evident at the pine plantation; however, LAI is high at this site year-round, and data from this site were most often missing during summertime, which are both conditions that may obscure seasonal differences in the flux record. In both forested ecosystems, the response of ET_N to the primary meteorological variables VPD and u_{sub}^{+2} is not as strong as in the old field, suggesting a biological control of ET_N that, with respect to VPD , may reflect reduced stomatal conductance at high VPD (Oren et al., 2001b).

A priori, we expected that nocturnal E would be highest in the old field due to the low degree of canopy cover, which generally increases soil evaporation (Mihailovic et al., 1995). The greater magnitude of ET_N in the pine plantation relative to the old field during all seasons, and in the hardwood forest relative to the old field during the growing season, suggests ET_N includes significant contributions from T in the pine plantation and hardwood forest. And finally, the magnitude of nocturnal sensible and latent heat fluxes is more similar in the old field than in the forests (data not shown), suggesting a greater contribution to ET_N from E in the old field since nighttime evaporation fluxes are typically induced by large downward sensible heat fluxes (Fisher et al., 2007).

5.5. Evaluating gapfilling methods for ET_N

The recent evidence for significant nocturnal transpiration in a wide range of ecosystems (Burgess et al., 1998; Dawson et al.,

2007; Donovan et al., 1999; Fisher et al., 2007; Hogg and Hurdle, 1997; Kim et al., 2008; Marks and Lechowicz, 2007; Oren et al., 1999; Oren et al., 2001b; Snyder et al., 2003; Ward et al., 2008) necessitates the selection of an eddy-covariance gapfilling methodology that can mechanistically reproduce ET_N fluxes. In this study, four such methods were investigated and compared with a simple filter that replaced all missing ET_N fluxes with 0. All four of these methods produced positive nocturnal ET fluxes in most years, averaging 6.9%, 7.5%, and 7.0% of the gapfilled daytime flux in the old field, pine plantation, and hardwood forest, respectively. These ratios are slightly lower than the ratio of observed acceptable nighttime and daytime fluxes (8%, 9%, and 8% in the old field, pine plantation and hardwood forest, respectively). Variation among gapfilling methods within each year in each site was quite large, and in some cases produced estimates of annual fluxes that differed by $>100 \text{ mm year}^{-1}$ (see Table 4).

In all sites, the DAYNIGHT and DIST_SAMP methods consistently ranked highly for at least two of the four performance measures presented in Table 4. The coefficient of determination is quite small for all techniques, which is not surprising given that the magnitude of ET_N at these sites ($.01\text{--}.02 \text{ mm h}^{-1}$ or $9\text{--}13 \text{ W m}^{-2}$) is on the same order of estimates of the random measurement error in ET during low radiation periods ($3.4\text{--}15.6 \text{ W m}^{-2}$) according to Richardson et al. (2006). Therefore, this is not viewed as a reliable performance measure, although we note that, on average, the best correlation between measurements and observations is associated with the DIST_SAMP.

The MAE associated with DAYNIGHT and DIST_SAMP is typically within 2 W m^{-2} of the MAE estimated for the data from the paired-point technique described in Section 5.1, suggesting that the uncertainty associated with these two methods is close to the random error in the data (i.e. δ). Generally, all gapfilled fluxes have a negative bias error, due to the inability of the methods to reproduce extremely large fluxes; however, the bias error associated with DAYNIGHT and DIST_SAMP is within $\sim 20\%$, as compared to errors that may exceed 50% for the other methods.

Among all sites and years, the MULT_IMP flux estimates were consistently low and the DAYNIGHT flux estimates were consistently highest. For MULT_IMP, the apparent underestimation of nocturnal ET flux rates is directly linked to the assumption of multivariate-normality in the joint-distribution between ET and the driving variables, which contradicts the prominent positive skewness observed in the data (Figs. 2 and 6). In DAYNIGHT, all missing nighttime data were replaced with a constant value for each night obtained using relationships developed with the mean of observed nighttime values. Because data were more likely to be observed at high wind speeds (when atmosphere is near-neutral conditions), the measurements used to parameterize these relationships are also high.

In all three sites, the DIST_SAMP was one of the top performing gapfilling estimates considering the relative frequency of the gapfilled and the measured estimates of ET_N within the artificial gaps (Fig. 6). This method is also not susceptible to large variation in annual ET_N driven by sensitivity to model parameter estimation (see Fig. 5), as are both PROCESS and DAYNIGHT.

Based on these assessments, we conclude that the DIST_SAMP method is the best performing gapfilling method examined in this study. However, we caution that all the methods, including the DIST_SAMP, are negatively biased with respect to the observations, which in turn may be negatively biased with respect to the true fluxes due to under-representative sampling during the growing season and well-known measurement and systematic errors associated with nocturnal eddy-covariance measurements as discussed in Section 5.1. Therefore, all gapfilled estimates of ET_N represent conservative minimum annual flux estimates, and more work is necessary to

elucidate the drivers of nocturnal evapotranspiration and to modify gapfilling methods accordingly.

5.6. Broader implications

The evidence for significant nocturnal T challenges the long-held notions that plant stomata close at night and that the primary drivers for ecosystem water use are only important during daylight hours (Oren et al., 2001a). Nocturnal evapotranspiration, which until recently has been largely ignored in ecosystem water budgets, appears to be a non-trivial factor in site water balances (Dawson et al., 2007). This new evidence invalidates many models and gapfilled eddy-covariance ET estimates (Fisher et al., 2007), necessitating a more robust treatment of ET , particularly in light of changing climate conditions. If nocturnal transpiration functions to prevent CO_2 accumulation at night, transpiration might increase as dark respiration increases with rising assimilation rates (Marks and Lechowicz, 2007). Similarly, if nocturnal transpiration enhances nutrient uptake, as was shown in savanna trees (Scholz et al., 2007), ET_N may be of greater importance in nutrient poor sites, and in the future as CO_2 -induced enhancement in growth rates lead to increased nutrient demand (Oren et al., 2001a).

Little is known about the drivers and functions of nocturnal ET , and explicit incorporation into process-based models is needed to set testable hypotheses. Nevertheless, our results show that ET_N is detectable and correlates with driving variables despite the noise and numerous gaps infecting eddy-covariance datasets. The DIST_SAMP method used here was shown as the best for gapfilling eddy-covariance ET . Until better process-based models are available, the large differences in annual ET estimates among these methods compel us to recommend checking gapfilled ET against independent estimates of nocturnal water use (i.e. from sap flux, porometry, or isotope data) or, at the least, performing a frequency distribution analysis similar to those we performed and searching for potential biases in the gapfilled records.

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