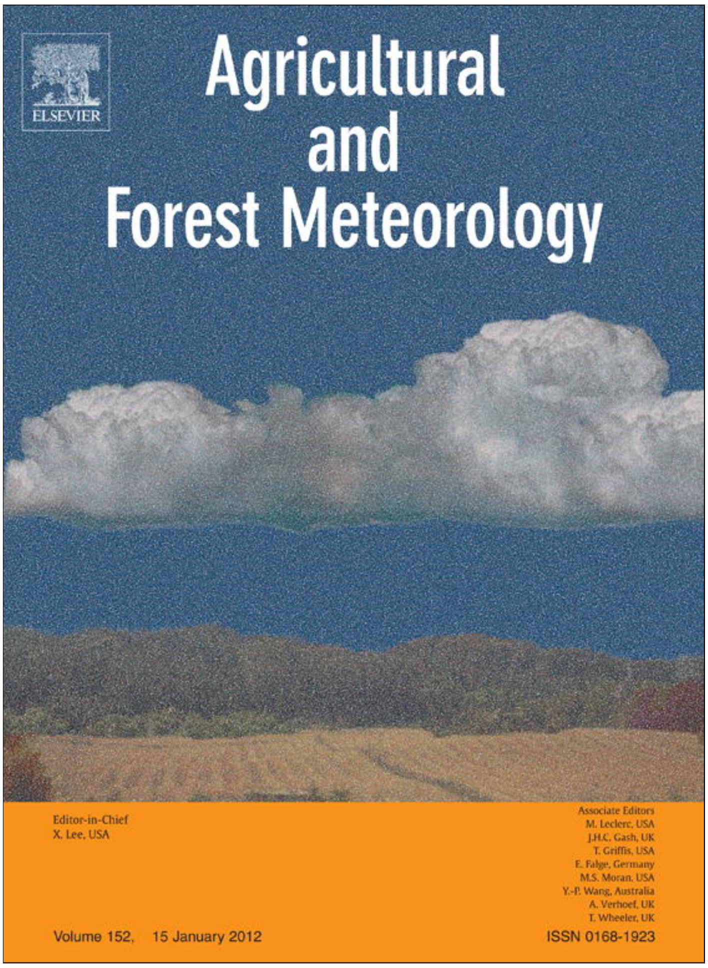

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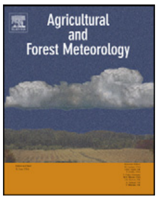
Agricultural and Forest Meteorology 171–172 (2013) 137–152

Contents lists available at SciVerse ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



# A data-driven analysis of energy balance closure across FLUXNET research sites: The role of landscape scale heterogeneity

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## ARTICLE INFO

*Article history:*
Received 7 August 2012
Received in revised form 4 November 2012
Accepted 9 November 2012

*Keywords:*
Eddy covariance
Energy balance closure
Enhanced vegetation index

## ABSTRACT

The energy balance at most surface-atmosphere flux research sites remains unclosed. The mechanisms underlying the discrepancy between measured energy inputs and outputs across the global FLUXNET tower network are still under debate. Recent reviews have identified exchange processes and turbulent motions at large spatial and temporal scales in heterogeneous landscapes as the primary cause of the lack of energy balance closure at some intensively-researched sites, while unmeasured storage terms cannot be ruled out as a dominant contributor to the lack of energy balance closure at many other sites. We analyzed energy balance closure across 173 ecosystems in the FLUXNET database and explored the relationship between energy balance closure and landscape heterogeneity using MODIS products and GLOBEstat elevation data. Energy balance closure per research site ($C_{EB,s}$) averaged 0.84 ± 0.20, with best

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http://dx.doi.org/10.1016/j.agrformet.2012.11.004

FLUXNET
MODIS
Plant functional type

average closures in evergreen broadleaf forests and savannas (0.91–0.94) and worst average closures in crops, deciduous broadleaf forests, mixed forests and wetlands (0.70–0.78). Half-hourly or hourly energy balance closure on a percent basis increased with friction velocity ($u_*$) and was highest on average under near-neutral atmospheric conditions. $C_{EB,s}$ was significantly related to mean precipitation, gross primary productivity and landscape-level enhanced vegetation index (EVI) from MODIS, and the variability in elevation, MODIS plant functional type, and MODIS EVI. A linear model including landscape-level variability in both EVI and elevation, mean precipitation, and an interaction term between EVI variability and precipitation had the lowest Akaike's information criterion value. $C_{EB,s}$ in landscapes with uniform plant functional type approached 0.9 and $C_{EB,s}$ in landscapes with uniform EVI approached 1. These results suggest that landscape-level heterogeneity in vegetation and topography cannot be ignored as a contributor to incomplete energy balance closure at the flux network level, although net radiation measurements, biological energy assimilation, unmeasured storage terms, and the importance of good practice including site selection when making flux measurements should not be discounted. Our results suggest that future research should focus on the quantitative mechanistic relationships between energy balance closure and landscape-scale heterogeneity, and the consequences of mesoscale circulations for surface-atmosphere exchange measurements.

## 1. Introduction

The surface-atmosphere exchanges of energy, momentum, water and trace gases are central components of the Earth system. Our understanding of these processes at the ecosystem level increasingly relies on observations from single or multiple eddy covariance flux measurement towers, regional flux measurement networks (e.g. Aubinet et al., 2000; Li et al., 2005), and the global FLUXNET database (Baldocchi et al., 2001; Papale et al., 2006). Most FLUXNET studies seek to understand processes controlling the biosphere–atmosphere flux of CO$_2$ (e.g. Baldocchi, 2008; Jung et al., 2009; Law et al., 2002; Stoy et al., 2009). Fewer studies to date have investigated global and regional water and energy fluxes apart from their relationship to CO$_2$ flux, with notable exceptions (e.g. Falge et al., 2001; Law et al., 2002; Hollinger et al., 2009; Jung et al., 2011). The relative paucity of eddy covariance energy and water flux studies is disproportional to the importance of these fluxes to the climate system.

Water, carbon and energy flux studies that rely on eddy covariance data are challenged by incomplete energy balance closure at most research sites (Aubinet et al., 2000; Leuning et al., 2012; Wilson et al., 2002). To date, multi-site syntheses have found an average eddy covariance energy balance closure ($C_{EB}$) ranging between 0.75 and 0.87 (Barr et al., 2006; Falge et al., 2001; Hendricks Franssen et al., 2010; Li et al., 2005; Wilson et al., 2002). Near-to-full $C_{EB}$ has been reported at some sites (e.g. Haverd et al., 2007; Heusinkveld et al., 2004; Lindroth et al., 2009; Moderow et al., 2009; Vourlitis and Oechel, 1999), but these studies are in the minority. $C_{EB}$ can be increased by measuring energy storage terms that are often excluded from conventional observations (Heusinkveld et al., 2004; Lindroth et al., 2009; Meyers and Hollinger, 2004), but additional measurements, including advective transport, often prove ineffective for closing the energy balance completely (Aubinet et al., 2010; Etzold et al., 2010; Moderow et al., 2011), in part because of the critical role of sensor accuracy for advection measurements (Dellwik et al., 2010a,b; Leuning et al., 2008). Large surface flux field campaigns have yet to report full energy balance closure (Beyrich et al., 2002; Foken, 1998; Foken et al., 1997; Kanemasu et al., 1992; Koitzsch et al., 1988; Mauder et al., 2006; Panin et al., 1998; Tsvang et al., 1991) (see Table 2 in Foken, 2008), suggesting that a fundamental aspect of surface-atmosphere exchange has yet to be ascertained.

Foken (2008) and Panin and Bernhofer (2008) concluded that buoyancy-driven turbulent circulations resulting from landscape heterogeneity are likely responsible for energy imbalance at the tower measurement level. These studies follow work by Panin et al. (1998) and Mauder et al. (2007b), who identified a relationship between energy balance closure and landscape patterns on a spatial scale on the order of tens of kilometres. In essence, this 'mesoscale hypothesis' suggests that relatively cool and dry air layers aloft are exchanged with relatively warm and moist air layers near the surface, and both the downward motion of cooler air and upward motion of warmer air result in a positive $\overline{w'T'}$ that contributes to a lack of energy balance closure if this flux is unmeasured by the eddy covariance instrumentation (Fig. 1). More experimental evidence of the interaction between surface heterogeneity and mesoscale circulations were obtained from aircraft measurements (Mauder et al., 2007a) and a multi-tower experiment (Mauder et al., 2010), but potential impacts of landscape-level heterogeneity on energy balance closure has not been tested across flux networks to date.

Other results highlight the importance of correctly measuring and interpreting energy storage terms to achieve energy balance closure. A recent study by Leuning et al. (2012) found that 45% of FLUXNET sites approached energy balance closure using daily averages after correctly accounting for lags in heat flux into soils, biomass, and the canopy air space (Gao et al., 2010; Haverd et al., 2007). Accounting for all energy storage terms results in a closed energy balance at select sites (Lindroth et al., 2009).

From these studies, it is clear that a closed energy balance can occur at certain sites, yet the energy balance at hundreds of flux sites worldwide remain unclosed. We adopt a data-driven approach (Gray, 2009; Hunt et al., 2009) and combine eddy covariance and remote sensing databases to test if millions of observations are consistent with the expectations of the mesoscale hypothesis that landscape-level heterogeneity is negatively related to energy balance closure. Our objectives are twofold. First, we characterize $C_{EB}$ at 173 sites in the FLUXNET database as it relates to micrometeorological drivers, considering both half-hourly (or hourly) observations ($C_{EB,i}$) and site-level means ($C_{EB,s}$). We then test the hypothesis that energy balance closure is related to landscape-level heterogeneity using data products from the Moderate-Resolution

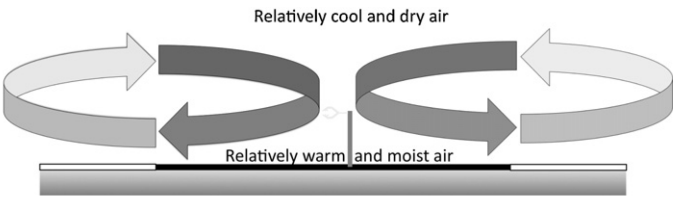

**Fig. 1.** Conceptual description of mesoscale circulations, driven in part by landscape-level heterogeneity, suggested by Foken et al. (2011), Mauder et al. (2010) and others to contribute to lack of energy balance closure at single-tower sites. The anisotropic nature of the mesoscale circulations is on the order of tens of kilometres in the horizontal direction.

Imaging Spectroradiometer (MODIS) and the GLOBEsat elevation data set. We hypothesize that $C_{EB}$ is related to landscape-level heterogeneity following the conclusions of Foken et al. (2011).

## 2. Methods

### 2.1. FLUXNET: instantaneous energy balance closure

Flux and meteorological data from the LaThuile FLUXNET database [www.fluxdata.org, accessed May 31, 2008] and processed according to FLUXNET protocols (Papale et al., 2006; Reichstein et al., 2005) were used here. Energy balance closure on the half-hourly or hourly basis is denoted for the purposes of this analysis as 'instantaneous' ($C_{EB,i}$), and was calculated as:

$$C_{EB,i} = \frac{\lambda E + H}{R_n - G - J} \tag{1}$$

i.e. the fraction of available energy defined as the net radiation ($R_n$) minus soil heat flux ($G$) that is realized as surface-atmosphere turbulent fluxes of latent heat ($\lambda E$) and sensible heat ($H$). Minor storage and metabolic terms ($J$) were set to zero here as they are neither included in the database nor measured at most FLUXNET sites, but their inclusion is important for $C_{EB}$ at many sites (Haverd et al., 2007; Lindroth et al., 2009). $C_{EB,i}$ data for which all measured terms in equation 1 pass the FLUXNET quality control criteria (Papale et al., 2006), and for which friction velocity ($u_*$) measurements were available, are examined here; no gapfilled data products were used.

During periods when energy fluxes are small, $C_{EB,i}$ may degrade although the absolute energy balance residual is only a few W m$^{-2}$, which is of minor concern. For a comprehensive interpretation of the results, we also exploree the absolute energy balance residual, which can be defined as:

$$R_{EB,i} = R_n - G - \lambda E - H - J \tag{2}$$

with $J$ again set to zero.

### 2.2. FLUXNET: energy balance closure per site

For the analysis of energy balance closure per site, we explored the 173 (of 253) sites, where observations of $R_n$, $\lambda E$, $H$, and $G$ were available (Table A1). Two sites with energy balance closure greater than 2 were excluded for quality control concerns. Energy balance closure for each site, $C_{EB,s}$, was defined as:

$$C_{EB,i} = \frac{\sum(\lambda E + H)}{\sum(R_n - G - J)} \tag{3}$$

again assuming that $J$ is negligible. This approach is sometimes called the 'bulk method' (Hendricks Franssen et al., 2010), the energy balance ratio (Wilson et al., 2002), or the relative energy balance closure (Aubinet et al., 2000). Half-hourly data for which $R_n$, $\lambda E$, $H$, and $G$ were measured and passed quality-control criteria, including sufficient $u_*$ to assure turbulent transport for the turbulent flux terms (Reichstein et al., 2005), were converted from W m$^{-2}$ to J m$^{-2}$ per half hour (or hour) and summed for the calculation of $C_{EB,s}$. We note that the apparent lack of energy balance closure need not constitute evidence for erroneous turbulent flux measurements (Aubinet et al., 2000).

Both $C_{EB,s}$ and mean $C_{EB,i}$ may be expected to be somewhat less than unity if energy storage in the aboveground vegetation, in the canopy air space, above the soil heat flux plates, and owing to metabolism (i.e. the terms that contribute to $J$) are not considered. We note that energy storage terms average out on an annual basis under steady-state conditions. Choosing only individual years with excellent data acceptability (>90%) to further minimize the role of canopy and soil heat storage variability does not change mean $C_{EB,s}$ (data not shown). Regardless, one may assume that metabolism and unmeasured storage terms contribute to $C_{EB}$. We test surrogates for metabolism using gross primary productivity (GPP) and we use precipitation (P) as a surrogate for soil moisture, a primary control over soil heat storage, which is seldom reported in the FLUXNET database. For the statistical analyses, we treat each FLUXNET site, not site-year, as independent.

### 2.3. Environmental variables

Energy balance closure can be expected to be a function of $u_*$ and atmospheric stability (Aubinet et al., 2000), both of which vary diurnally in most instances. We explore relationships between $C_{EB,i}$ and $u_*$, the solar zenith angle, and the Obukhov length ($L$) as a primary determinant of atmospheric stability using:

$$L = \frac{-\rho C_p u_*^3 T}{kgH} \tag{4}$$

where $\rho$ is the density of air, $C_p$ is the specific heat capacity of dry air, $k$ is von Kármán's constant, $g$ is gravitational acceleration and $T$ is air temperature in Kelvin.

Daytime periods are defined as those during which the solar zenith angle is less than 90°. To differentiate between morning and afternoon we define 'zenith 2' as the solar zenith angle with periods before solar noon denoted as negative.

### 2.4. Kernel density estimation

Visualizing relationships amongst millions of observations is a formidable challenge. We used two-dimensional kernel density estimates to present the relationships amongst $C_{EB,i}$ and environmental variables. Kernel density estimation is a non-parametric approach for estimating probability density functions from a given dataset. Histograms are the simplest non-parametric density estimator, but suffer from the arbitrary choice of bin size. Kernel density estimators place a smooth kernel (usually a Gaussian window, also chosen here) with a given bandwidth about measured data points, and combine these to create an estimate of the probability distribution of all observations. We used a linear diffusion algorithm following Botev et al. (2010) to choose optimal kernel bandwidths and avoid over- or under-smoothing. Kernel density estimation is used here to improve visual display rather than for the statistical interpretation of the data, and like a probability distribution or density function the sum of all kernel density values equals one.

### 2.5. MODIS: land cover classifications

Following the suggestions of Foken (2008), the landscape characteristics of the 20 × 20 km area surrounding the 173 flux towers were analyzed in relation to $C_{EB,s}$. The 20 km length scale was suggested to be representative of anisotropic atmospheric motions that exhibit statistical stationarity (Mauder et al., 2007a). The MODIS MCD12Q1 PFT (plant functional type) land cover classification product was downloaded for the 20 × 20 km areas surrounding all 173 towers for 2006. As these data are categorical, an appropriate metric for their variability is their information entropy after Shannon (1948):

$$I(X) = -\sum_{i=1}^{N} p(x_i) \ln p(x_i) \tag{5}$$

where $N$ is the number of bins that a pixel can take for each attribute and $p(x_i)$ is the fraction of pixels in each bin $i$ representing each different MODIS PFT classification. The PFT product has 12 classes

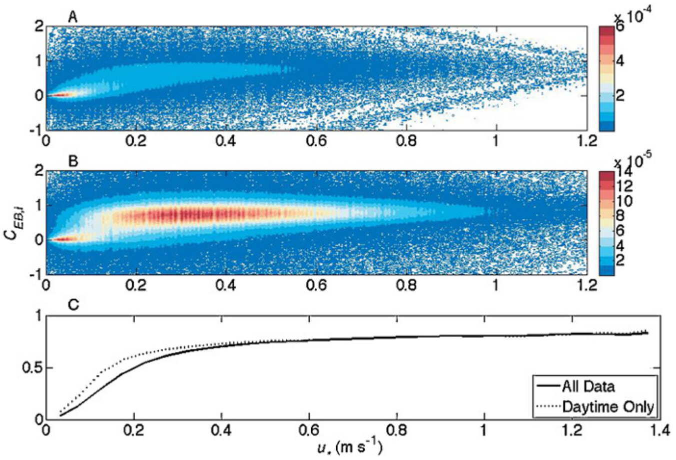

**Fig. 2.** The instantaneous energy balance closure, $C_{EB,i}$ as a function of the friction velocity ($u_*$, m s$^{-1}$) for all observations (A) and daytime periods (B) for which the solar zenith angle was less than 90° plotted as a distribution using a two-dimensional kernel density estimate. The colorbar denotes probabilities. Subplot C is the median $C_{EB,i}$ per $u_*$ bin.

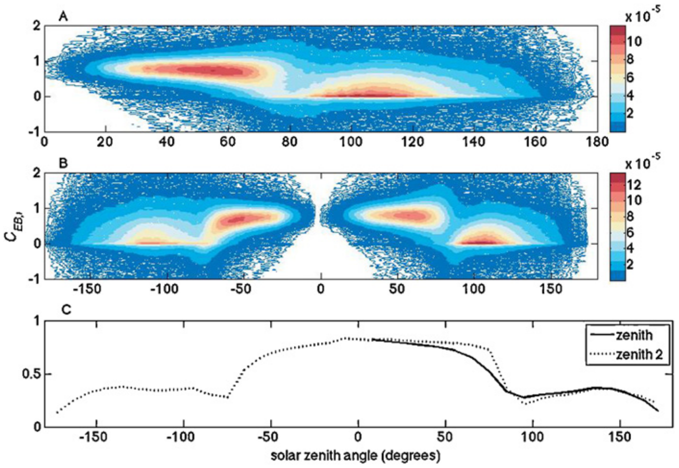

**Fig. 3.** The instantaneous energy balance closure, $C_{EB,i}$ as a function of (A) solar zenith angle and (B) adjusted zenith angle ('Zenith 2') in which all times between midnight and solar noon (i.e. morning) are denoted as negative. The colorbar denotes probabilities following Fig. 2. Subplot C is the median $C_{EB,i}$ per solar zenith angle bin.

(water = 0, evergreen needle leaf forest = 1, evergreen broadleaf forest = 2, etc.), therefore $N = 12$ and the Shannon entropy of a uniform landscape with a single plant functional type is zero. Unfilled and unknown MODIS pixels were excluded from the entropy calculations.

### 2.6. MODIS: enhanced vegetation index (EVI)

We chose the MODIS product with the highest spatial resolution, 250 m in the MOD13Q1 product, for the calculation of EVI in the 20 × 20 km area surrounding the 173 flux towers analyzed here. EVI was chosen over the normalized difference vegetation index (NDVI) because of the saturating NDVI–leaf area index (LAI) relationship in forest canopies (Huete et al., 2002). EVI was chosen over LAI to avoid uncertainties in the MODIS LAI algorithm.

The 16-day resolution of the MOD13Q1 EVI product creates a challenge for quantifying a simple metric of landscape-level variability. A full spatiotemporal analysis of EVI across 173 sites is complicated by quality control issues including the presence of clouds and/or snow. To simplify the comparison between $C_{EB,s}$ and EVI, we obtained 20 × 20 km EVI data for each site for 2005–2007, and chose the scene with the greatest amount of reliable data that had the highest mean EVI. This approach calculated landscape-level variability with high data quality during growing season periods when incident solar radiation was greatest, on average, and when most energy on an absolute basis tends to go missing (see Fig. 4C). The total variance of the EVI observations across the 20 × 20 km region, $\sigma^2(EVI)$, was used as the metric of landscape-level heterogeneity in subsequent analyses. We also investigated the mean EVI, $\mu(EVI)$, at the tower location to explore the effects of canopy density (as a surrogate for heat storage in the canopy) in determining $C_{EB,s}$. Per the recommendations of the MODIS land surface project team, the average of the nine MODIS pixels surrounding and including the flux tower was taken to represent $\mu(EVI)$.

## 3. Results

### 3.1. Instantaneous energy balance closure

The FLUXNET quality control criteria (Papale et al., 2006) were met by nearly 7.7 × 10$^6$ half-hourly (or hourly) data points. $C_{EB,i}$ as a function of $u_*$ is shown in Fig. 2. The peak of the 2D kernel density estimate between $u_*$ and $C_{EB,i}$ lies near the origin (Fig. 2A), but shifts to a space between ca. 0.2 and 0.5 m s$^{-1}$ when only daytime data are considered (Fig. 2B). The median $C_{EB,i}$ per $u_*$ bin increases quickly until a $u_*$ value of about 0.2 m s$^{-1}$ is reached, and continues to increase albeit with a smaller slope at higher $u_*$ values (Fig. 2C) and does not reach unity.

$C_{EB,i}$ is consistently low during nighttime periods with solar zenith angles > 90°, especially during the day/night and night/day transitions (Fig. 3A). $C_{EB,i}$ increases more slowly during the morning than the corresponding decrease in the afternoon (Fig. 3B). Median $C_{EB,i}$ approaches 0.8 under near-neutral conditions and decreases as the atmosphere becomes more stable or unstable (Fig. 4A and B). The energy balance residual ($R_{EB,i}$) is also higher during near-neutral periods when both $C_{EB,i}$ and $u_*$ are highest (Fig. 4C and D). $u_*$ and $H$ enter into the calculation of $L$ and are shown with respect to $L$ in Fig. 4 for reference.

Of the 173 sites explored here, 73 sites show significantly lower $C_{EB,i}$ as a function of time from the beginning to the end of the measurement record, 69 sites have significantly higher $C_{EB,i}$ over time, and 31 sites were unchanged. In other words, energy balance closure declined over the measurement period at over 40% of the sites studied here.

### 3.2. Site-level energy balance closure

The mean (standard deviation) of the energy balance closure, $C_{EB,s}$, for the 173 sites listed in Table A1 is 0.84 ± 0.20 (Table 1). $C_{EB,s}$ ranges from 0.28 to 1.67 after excluding severe outliers that were not analyzed on account of quality control concerns. The slope and intercept of the relationship between $\Sigma(R_n - G)$ and $\Sigma(\lambda E + H)$ for all sites (with 95% confidence intervals in parentheses) are 0.82 (±0.035) and 57 (±261) MJ m$^{-2}$ (Fig. 5). The intercept is not statistically different from zero.

**Table 1**
The mean and standard deviation of the energy balance closure ($C_{EB}$) in the FLUXNET database for different plant functional type groupings.

| | $n$ | $C_{EB}$ |
|---|---|---|
| All | 173 | 0.84 ± 0.20 |
| Forest | 88 | 0.83 ± 0.22 |
| Non-forest | 57 | 0.83 ± 0.19 |
| Other[a] | 28 | 0.87 ± 0.15 |

[a] Savannas, shrublands and wetlands that may or may not be dominated by woody vegetation.

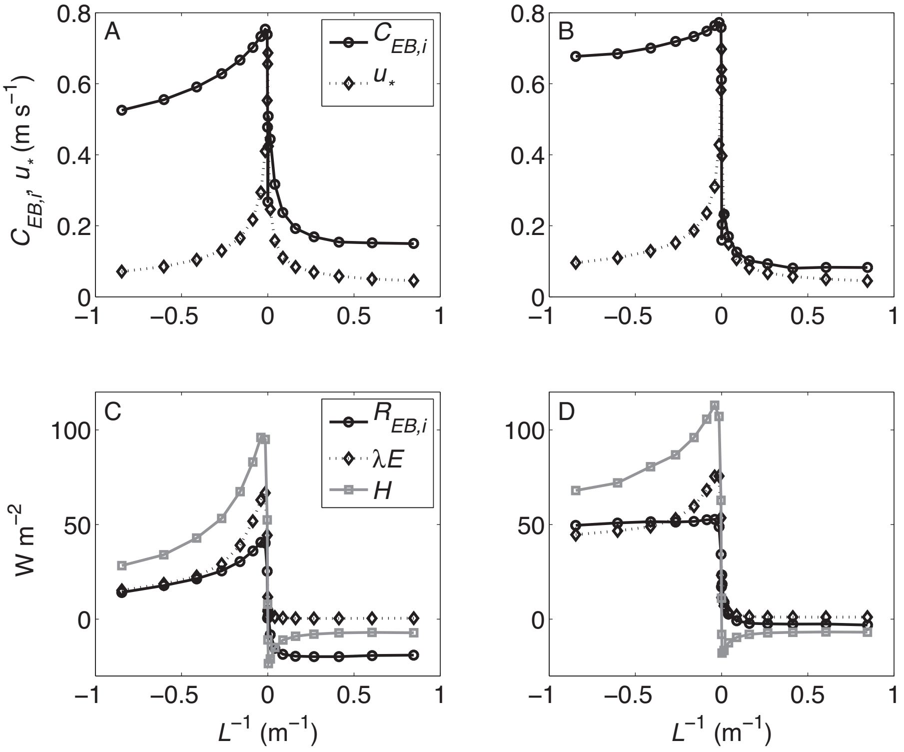

**Fig. 4.** The median instantaneous energy balance closure ($C_{EB,i}$, subplots A and B), friction velocity ($u_*$) and absolute energy balance residual ($R_{EB,i}$, subplots C and D) including sensible heat ($H$) and latent heat flux ($\lambda E$) as a function of the inverse of the Obukhov length $L$ (m). Plots for all data observations are on the left (subplots A and C) and plots for daytime only periods (with solar zenith angle < 90°) are on the right (subplots B and D).

Mean $C_{EB,s}$ for different vegetation types are listed in Table 2. Evergreen broadleaf forests and savannas tend to have the highest values of $C_{EB,s}$, and deciduous broadleaf forests, mixed forests, crops and wetlands the lowest. The $C_{EB,s}$ of forests ($0.83 \pm 0.22$) short-statured vegetation ($0.83 \pm 0.18$), and other vegetation (grouped as savannas and wetlands, $0.87 \pm 0.19$) do not differ as determined by a two-sided $t$-test ($p > 0.05$) and a two-sample Kolmogorov-Smirnov test at the 0.05 probability level. $C_{EB,i}$ is not related to the Bowen ratio (data not shown), but site-level $C_{EB}$ ($C_{EB,s}$) is negatively related to the site-level Bowen ratio ($\Sigma H/\Sigma\lambda E$; $r = -0.16$; $p = 0.04$).

### 3.3. Energy balance closure in relationship to landscape variability

MODIS PFT and EVI for the 20 × 20 km area surrounding the tower in Hainich Forest, Germany are shown as examples in Fig. 6. There is a significant negative relationship ($r = -0.17$; $p = 0.011$) between $C_{EB,s}$ and $I$(PFT) with an intercept at 0.89, suggesting that energy balance closure approaches *ca.* 0.9 in landscapes with uniform vegetation type. $C_{EB,s}$ is significantly related to both $\mu(EVI)$ in the nine pixels surrounding the tower ($r = -0.20$; $p = 0.008$) and $\sigma^2(EVI)$ for the 20 × 20 km area surrounding the tower (Fig. 7, $r = -0.21$; $p = 0.004$) even after excluding obvious outliers [$\sigma^2(EVI) > 0.04$] that may have spuriously influenced this relationship ($r = -0.24$; $p = 0.001$). The intercept is not statistically different than unity.

### 3.4. Models for energy balance closure

$C_{EB,s}$ is significantly related to MODIS PFT and EVI, but also to mean precipitation, GPP, the site-level Bowen ratio, and landscape-level variability in elevation derived from the GLOBEsat elevation dataset ($p < 0.05$ in all cases). We created linear models of the variables that contribute to $C_{EB,s}$, and subjected these to information criterion analyses to identify a minimal model for $C_{EB,s}$. The minimal model identified by the Akaike information criterion

**Table 2**
The mean and standard deviation of energy balance closure ($C_{EB}$), the mean EVI of the pixels surrounding flux towers [$\mu(EVI)$], and the variance of EVI in 20 × 20 km regions surrounding flux towers [$\sigma^2(EVI)$] for different ecosystem types for the 173 sites in the FLUXNET database with measurements of available energy that sum to greater than zero. Three sites had no available ecosystem type information and are excluded from this table but are included in the analysis.

| Vegetation type | Abbrev. | $n$ | $C_{EB}$ | $\mu(EVI)$ | $\sigma^2(EVI)$ |
|---|---|---|---|---|---|
| Crops | CRO | 25 | $0.78 \pm 0.16$ | $0.45 \pm 0.13$ | $0.014 \pm 6.9 \times 10^{-3}$ |
| Shrubs[a] | SHR | 9 | $0.87 \pm 0.15$ | $0.32 \pm 0.16$ | $0.010 \pm 8.4 \times 10^{-3}$ |
| Deciduous Broadleaf Forest | DBF | 20 | $0.70 \pm 0.19$ | $0.47 \pm 0.12$ | $0.014 \pm 7.6 \times 10^{-3}$ |
| Evergreen Broadleaf Forest | EBF | 10 | $0.94 \pm 0.16$ | $0.39 \pm 0.12$ | $0.008 \pm 5.9 \times 10^{-3}$ |
| Evergreen Needleleaf Forest | ENF | 47 | $0.88 \pm 0.23$ | $0.43 \pm 0.11$ | $0.013 \pm 1.2 \times 10^{-2}$ |
| Grasslands | GRA | 32 | $0.86 \pm 0.20$ | $0.42 \pm 0.12$ | $0.010 \pm 5.5 \times 10^{-3}$ |
| Mixed Forest | MF | 10 | $0.79 \pm 0.18$ | $0.47 \pm 0.13$ | $0.011 \pm 4.4 \times 10^{-3}$ |
| Savanna[b] | SAV | 10 | $0.91 \pm 0.14$ | $0.36 \pm 0.11$ | $0.007 \pm 4.6 \times 10^{-3}$ |
| Wetlands | WET | 7 | $0.76 \pm 0.13$ | $0.39 \pm 0.13$ | $0.007 \pm 4.5 \times 10^{-3}$ |

[a] Open and closed shrublands.
[b] Savannas and woody savannas.

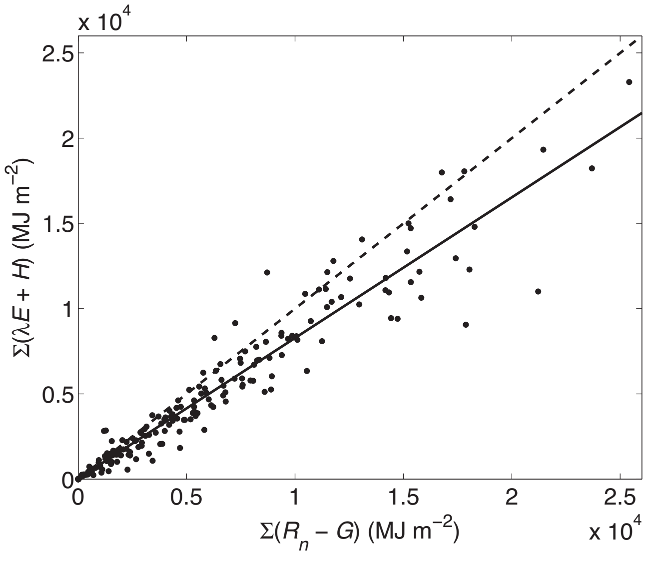

**Fig. 5.** The relationship between the cumulative sum of available energy (net radiation, $R_n$ minus soil heat flux, $G$) and the cumulative sum of surface fluxes of latent heat ($\lambda E$) and sensible heat ($H$) for each of the 173 research sites in the FLUXNET database for which all four variables are measured and sum to a positive value. The slope of the best-fit linear relationship, in black, is 0.82 (±0.035) and the intercept is 57 (±261) MJ m$^{-2}$ for the measurement record of each site. The 1:1 relationship is shown as a black dashed line.

included $\sigma^2(EVI)$, mean precipitation, landscape-level variability in elevation, and an interaction term between $\sigma^2(EVI)$ and mean precipitation. A model with only $\sigma^2(EVI)$ and mean precipitation had the lowest value of the Bayesian information criterion.

## 4. Discussion

### 4.1. Instantaneous energy balance closure

More energy (i.e. $R_{EB,i}$) goes missing during periods with better relative energy balance closure, which tend to occur during daytime (Fig. 4, Hendricks Franssen et al., 2010; Wilson et al., 2002). Research on energy balance closure and surface atmosphere exchange should continue to focus on the challenges presented by both daytime and nighttime conditions. However, as more energy goes missing during daytime periods (when more energy is available), breakthroughs in understanding the energy balance closure problem will likely come with a focus on daytime periods. We also note that mornings tend to have slightly worse $C_{EB,i}$ (Fig. 3) and higher $R_{EB,i}$ (data not shown) when $G$ and the storage terms that contribute to $J$ tend to be positive rather than later in the afternoon when $G$ and $J$ have peaked or are decreasing (Hendricks Franssen et al., 2010; Leuning et al., 2012), demonstrating the importance of accounting for storage terms in the energy balance. Median $C_{EB,i}$ is only *ca.* 0.8 during near-neutral conditions and decreases to nearly 0.7 during highly unstable conditions (Fig. 4; Aubinet et al., 2000; Hendricks Franssen et al., 2010). In other words, periods dominated by the convective production of turbulent kinetic energy, often characterized by larger eddies, have lower energy balance closure on average.

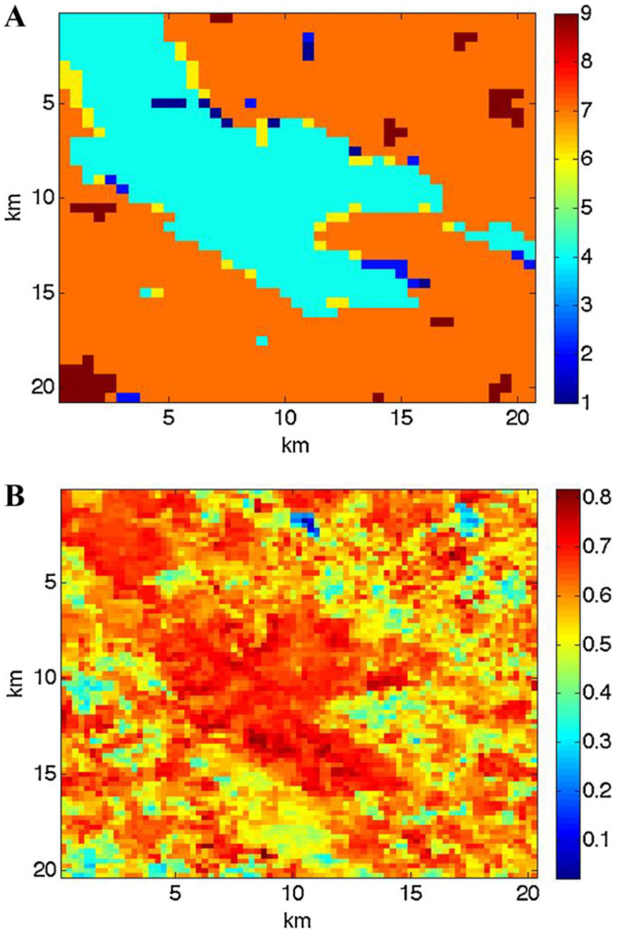

**Fig. 6.** The MODIS MCD12Q1 plant functional type (PFT) for the 20 × 20 km area surrounding the Hainich deciduous broadleaf forest, Germany for 2006 (A) and the MODIS MOD13Q1 enhanced vegetation index (EVI) for the same area, measured on DOY 177, 2005 (B). The eddy covariance tower site is at the center point of both scenes. The legend for subpanel A follows the MODIS PFT convention. The entropy of plant functional type, $I$(PFT), for Fig. 5A is 0.90 and the variance of EVI, $\sigma^2(EVI)$, of Fig. 5B is 8.6 × 10$^{-3}$.

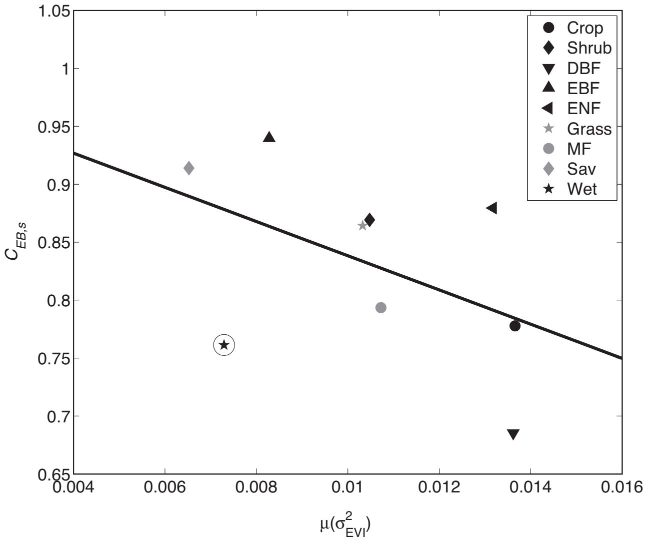

**Fig. 7.** Energy balance closure for FLUXNET eddy covariance research sites ($C_{EB,s}$) as a function of the variance of the MODIS enhanced vegetation index (EVI) for the 20 × 20 km region surrounding each eddy covariance tower and averaged per ecosystem type. The solid line is the best-fit relationship after removing wetland ecosystem types and is defined as $C_{EB,s} = -14.76\mu(\sigma^2_{EVI}) + 0.99$. Excluding wetland sites (circled) results in a squared correlation coefficient of 0.54.

### 4.2. Energy balance closure per FLUXNET site

Mean $C_{EB,s}$ of the 173 FLUXNET sites investigated here (0.84) is of a similar magnitude to many previous multi-site synthesis (0.79, ranging from 0.53 to 0.99 (Wilson et al., 2002); 0.84, ranging from 0.58 to 1 (Li et al., 2005; Yu et al., 2006)) if not slightly worse than other syntheses (0.85–0.89, Barr et al., 2006). $G$ may be underestimated in many instances (Hsieh et al., 2009), suggesting that any system-wide underestimation in energy balance closure would likely occur in ecosystems with more incident radiation upon the soil surface. However, $C_{EB,s}$ tends to be higher in sites with lower $\mu(EVI)$ and there is no difference in $C_{EB,s}$ among forested and non-forested ecosystems. Combined with the observation that $C_{EB,i}$ is slightly lower on average during morning periods when $G$ tends to increase, these results demonstrate that the correct measurement of $G$ is a critical component of energy balance analyses, but by itself will not close the energy balance across many FLUXNET sites (Leuning et al., 2012).

The question remains, why is the energy balance not closed at most tower sites? One might expect forests to have lower or at least significantly different $C_{EB,s}$ than short-statured vegetation, because the role of heat storage in the larger canopy, lower average $G$, and possible advection and/or decoupling of above and below canopy flows in the larger canopy air space (Cava et al., 2008; Lindroth et al., 2009; Meyers and Hollinger, 2004; Moderow et al., 2009; Staebler and Fitzjarrald, 2004). Although these impacts may be important at many individual forest sites, the mean $C_{EB,s}$ in our analysis did not differ among forest and non-forest sites, suggesting that other mechanisms are also at play. The finding that $C_{EB,i}$ is lower during unstable conditions (Fig. 4; Aubinet et al., 2000) hints that mechanisms that drive convection may contribute to the lack of energy balance closure.

### 4.3. Landscape heterogeneity and energy balance closure

The large number of sites in this analysis permits us to perform a cautious interpretation of $C_{EB,s}$ for different vegetation types. If forest and non-forest ecosystems do not differ with respect to $C_{EB,s}$, why should $C_{EB,s}$ for grasslands average 0.86 but $C_{EB,s}$ for crops average 0.78 (Table 2, Fig. 7)? Likewise, why should evergreen broadleaf forests have nearly complete closure on average (0.94) when mean $C_{EB,s}$ for deciduous broadleaf forests is only 0.70? Our dataset shows that there are systematic relationships between vegetation types and landscape heterogeneity, e.g., savanna sites are found in more homogeneous landscapes than deciduous forest sites (Fig. 7). This might either be specific for the biome or an effect of the flux tower site selection. Differences in vegetation types (i.e. short vs. tall vegetation) cannot explain $C_{EB,s}$, but $C_{EB,s}$ varies systematically with landscape-level heterogeneity (Fig. 7). We argue therefore that landscape-level variability plays an important role that is often overlooked in single tower investigations by the flux measurement community.

In contrast, many studies of boundary-layer meteorology and turbulence place emphasis on the role of landscape-level heterogeneity on determining boundary layer dynamics (e.g. Shen and Leclerc, 1995). Some of these findings link strongly to the present analysis. For example, Baidya Roy et al. (2003) compared Regional Atmospheric Modeling System (RAMS) output across domains with different characteristic length scales in the central U.S. (longer than 25 km) and the Amazon (3–5 km). Heterogeneity in $H$ occurred at across a wide range of length scales during boundary layer development, but eddies within the 10–20 km scale range intensified and organized into coherent structures by early afternoon in both cases, which dominated the dynamics of turbulence. Future work should further investigate the role of such organized coherent structures on the measured energy balance closure near the surface.

Foken (2008) reviewed the results of multiple large surface flux campaigns and argued that the problem of eddy covariance energy balance closure is fundamentally a problem of scale: lower frequency motions (Foken et al., 2006; Mauder et al., 2007a; Panin et al., 1998), possibly resulting from surface heterogeneity at the landscape scale (Mauder et al., 2010), explain in part the lack of energy balance closure. Our results agree with these conclusions; landscape-level heterogeneity, here quantified by the $I$(PFT) and $\sigma^2(EVI)$ (Fig. 7) is significantly related to $C_{EB,s}$. Both the Akaike and Bayesian information criteria suggested that $\sigma^2(EVI)$ should not be excluded from models for $C_{EB,s}$. These empirical relationships become more clear with the graphical representation of Table 2 in Fig. 7; grasslands and evergreen broadleaf forests in the FLUXNET database tend to lie in homogeneous areas with low $\sigma^2(EVI)$, and crops and deciduous broadleaf forests tend to lie in heterogeneous areas with high $\sigma^2(EVI)$. Excluding wetlands, $\sigma^2(EVI)$ explains 54% of the variance in $C_{EB,i}$ when averaged by plant functional type.

Leuning et al. (2012) point out that mesoscale circulations are unlikely to fully close the energy balance at many sites if mean vertical wind velocities on the order of 20–40 mm s$^{-1}$ are required for advective flux divergence errors on the order of 50–100 W m$^{-2}$ for vertical temperature differences of 2 K. Mauder et al. (2010) demonstrated that such mean vertical wind velocities are possible in a heterogeneous agricultural landscape. Characteristic values of mean vertical wind velocity across global eddy covariance sites remain uncertain, as do their temporal variability, and the contribution of mesoscale circulations to lack of energy balance closure at different sites remains unclear.

Our analysis does not suggest that landscape-level variability is the only contributing factor to $C_{EB,s}$, in fact many variables investigated here are significantly related to $C_{EB,s}$. The role of water (approximated by $P$), with its large heat capacity, also plays an important role in $C_{EB,s}$ noting the low $C_{EB,s}$ of wetlands (Fig. 7) and the relationship between $C_{EB,s}$ and $P$ in the linear models. This result agrees with Leuning et al. (2012) and others that demonstrate that energy storage terms cannot be excluded as a principal contributor to the lack of energy balance closure. Landscape-level variability in topography is an important factor contributing to lack of closure, as one might anticipate given the challenges of measuring surface-atmosphere flux in topographically diverse terrain. Relationships with latitude and seasonality should also be explored further. The information criteria analyses suggest that landscape-level variability in vegetation and topography and indices of ecosystem water content should not be excluded when interpreting the surface-atmosphere energy balance at the network level. Consistent measurements of soil moisture across the tower network will likely add clarity to the role of energy storage and hydrological advection on energy balance closure. Our findings place observations from FLUXNET in agreement with the major results from large surface-atmosphere exchange observation campaigns (Foken, 2008; Foken et al., 2006; Mauder et al., 2007a; Panin et al., 1998). It is important to note that invoking landscape-level arguments undoubtedly does not take the place of proper practice when measuring surface-atmosphere exchange at a point.

The surface heterogeneity relationships, whereas significant, have substantial scatter as may be expected given the multiple factors that contribute to the lack of closure (Fig. 7). These include sensor separation and high frequency losses (Clement et al., 2009) (especially for latent heat flux measurements with closed-path sensors (Ibrom et al., 2007)), footprint variability in space and time (Oren et al., 2006), unmeasured energy fluxes (i.e. 'minor terms'; Oncley et al., 2007) including canopy heat storage (Lindroth et al., 2009; Moderow et al., 2009) and metabolic terms (Meyers and Hollinger, 2004), instrument biases in radiation measurements (Brotzke and Duchon, 2000), advection (Aubinet et al., 2010; Moderow et al., 2011), the length of the averaging period (Malhi et al., 1998; Sanchez et al., 2010; Voronovich and Kiely, 2007), sonic angle of attack (Cava et al., 2008; Nakai et al., 2006), $G$ measurement accuracy (Hsieh et al., 2009) and open *versus* closed path methodologies (Burba et al., 2008; Teklemariam et al., 2009). Different explanations for lack of energy balance closure are likely to dominate at different sites (Kidston et al., 2010; Moncrieff et al., 1996).

The mechanisms relating surface heterogeneity to $C_{EB,s}$ can only be inferred with the available data. If, in fact, surface heterogeneity contributes to buoyancy-driven turbulent circulations (Foken, 2008), the best strategy for including the flux information contained in these larger atmospheric motions remains to be discovered. Longer averaging periods are frequently cited (Cava et al., 2008; Finnigan et al., 2003; Malhi et al., 1998; Mauder and Foken, 2006), but this comes at the expense of capturing the diurnal variability in flux and may violate the steady state criterion underlying EC measurements. Accounting for turbulent organized structures (Badiya Roy and Avissar, 2002; Kanda et al., 2004; Steinfeld et al., 2007) may improve energy balance closure if simple parameterizations can be found. If larger atmospheric motions dominate $C_{EB,s}$, $CO_2$, water and energy flux estimates should not be simply adjusted for lack of closure (Baldocchi, 2008) because such a correction relies on similarity assumptions that are not supported by low frequency spectra (Foken et al., 2011; Kidston et al., 2010; Mauder et al., 2007a; Ruppert et al., 2006), although we note that many watershed-level analyses demonstrate improved water budget closure when correcting $\lambda E$ for lack of energy balance closure (Barr et al., 2012; Jung et al., 2011; Twine et al., 2000). Our analysis cannot preclude effects due to fetch or forest canopy edges (Detto et al., 2008; Sogachev et al., 2008), which are difficult to ascertain using 250 m or 1 km MODIS products. The connection between the flux footprint and energy balance closure is discussed in Appendix B.

### 4.4. Conclusions

The flux community has made substantial advances in understanding the mechanisms underlying the energy balance closure problem (Foken et al., 2011; Leuning et al., 2012), but additional work needs to be done (Mahrt, 2010). However, assuming conservatively that the terms excluded from equation 1 comprise a couple to a few percentage points apiece, on average, then $C_{EB}$ is on the order of 0.95 or greater for many sites and vegetation types (namely grasslands, evergreen broadleaf forests and savannas) in version 2 of the FLUXNET database. These assumptions lend confidence to eddy covariance-based surface energy balance studies on long-term flux sums although further investigations into the energy balance closure problem are needed.

No surface flux campaign project (e.g. LITFASS-2003) has reported full energy balance closure to date (see Table 2 in Foken, 2008), suggesting that the same will hold for individual towers. The leading hypothesis from comprehensive surface flux investigations is that larger atmospheric motions, potentially driven by surface heterogeneity, are the principal explanation for lack of closure. The present study agrees that landscape-level heterogeneity is an important contributor to lack of energy balance closure from a data-driven perspective (Gray, 2009); $C_{EB,s}$ in globally-distributed flux towers is significantly related to landscape-level heterogeneity in land cover (via PFT) and characteristics (via EVI, Fig. 7). Models for $C_{EB,s}$ across the FLUXNET database cannot exclude $\sigma^2(EVI)$, landscape-level topographic variability, or $P$. The placement of future flux towers should be cognizant of the larger region beyond the immediate flux footprint.

The physical explanations behind the relationship between energy balance closure and landscape heterogeneity should be investigated mechanistically, for example using large eddy simulation or regional atmospheric modeling approaches (Badiya Roy and Avissar, 2002; Kanda et al., 2004; Steinfeld et al., 2007). A greater mechanistic understanding of flux transporting mechanisms and heat storage terms will add value to the water and energy flux observations in the FLUXNET database and, finally, bring closure to the energy balance closure problem.

## Acknowledgments

We would first and foremost like to acknowledge the FLUXNET data providers and the organizers of the FLUXNET database. This work is an outcome of the La Thuile FLUXNET workshop 2007, which would not have been possible without the financial support provided by CarboEurope-IP, FAOGTOS-TCO, iLEAPS, Max Planck Institute for Biogeochemistry, National Science Foundation, University of Tuscia, and the U.S. Department of Energy. The Berkeley Water Center, Lawrence Berkeley National Laboratory, Microsoft Research eScience, Oak Ridge National Laboratory provided databasing and technical support. The AmeriFlux, AfriFlux, AsiaFlux, CarboAfrica, CarboEuropeIP, ChinaFlux, Fluxnet-Canada, the Canadian Carbon Program, KoFlux, LBA, NECC, OzFlux, TCOS-Siberia, and USCCC networks provided data. Tristan Quaife provided the MATLAB code to download and organize MODIS data from the ORNL MODIS web service. Eva Falge contributed to the analyses in the Appendix. PS-O would like to acknowledge CARBORED. PCS acknowledges funding from the Marie Curie European Incoming International Fellowship (project number 237348, TSURF), the National Science Foundation ('*Scaling ecosystem function: Novel Approaches from MaxEnt and Multiresolution*', DBI #1021095), and Montana State University. PCS would like to thank Hans-Peter Schmid and the Karlsruhe Institute of Technology for logistical support, Robert Bemis for creating the MATLAB code that followed the suggestions of Light and Bartlein (2004) for improved use of color in images, and Stefan Metzger, Andrew Richardson and LobsterFest participants, Eva Falge and Pierre Brender for helpful discussions about the manuscript.

## Appendix A.

Table A1 details the FLUXNET sites used in this analysis.

## Appendix B. The relationship between flux footprints and energy balance closure

It must be assumed that both the area surrounding a flux station (classified for example with satellite data) and the footprint climatology of a station have a significant influence on energy balance closure. Unfortunately, footprint information is only available for a few stations, although recent analyses have extended footprint analyses to entire flux networks (e.g. Chen et al., 2011, 2012). Göckede et al. (2008) performed a footprint classification for the European FLUXNET sites (i.e. the CarboEurope-IP sites) to quantify the contribution of the target area to the measured flux according to the footprint climatology. Site evaluations were performed by calculating the percentage of half-hourly measurements exceeding the threshold of 80% flux contribution from the target land cover type. No statistical relationship was found between relative energy balance closure and the percentage of half hourly measurements exceeding the threshold of 80% flux contribution from the target land area for three sites, using both the entire data set and data with a zenith angle $< 50^\circ$ to incorporate only daytime values that may feature secondary circulations (data not shown). Only for four of twenty sites (DK-Sor, BE-Bra, DE-Tha and IT-Ren) were significant differences between the entire observational data set and data with a solar zenith angle $< 50^\circ$ found.

The satellite pictures of the stations DK-Sor, BE-Bra, DE-Tha and IT-Ren (Fig. A1) demonstrate that each tower is in a nearly homogeneous area related to the turbulent eddy covariance flux footprint, but the larger landscape exhibits considerable

**Table A1**
Ecosystem type and geographic information for the 173 FLUXNET sites with available soil heat flux measurements investigated here. Abbreviations follow Table 2. NA means that ecosystem type information was not available; these sites are excluded from the analyses in Table 1 and Fig. 3. References follow information in fluxdata.org when possible.

| Site | Veg. | Latitude | Longitude | Reference |
|---|---|---|---|---|
| ATNeu | GRA | 47.11667 | 11.3175 | Wohlfahrt et al. (2008) |
| AUFog | WET | −12.5425 | 131.307 | Guerschman et al. (2009) |
| AUHow | SAV | −12.4943 | 131.152 | Hutley et al. (2000) |
| AUTum | EBF | −35.6557 | 148.152 | Finnigan and Leuning (2000) |
| AUWac | EBF | −37.429 | 145.187 | Beringer et al. (2006) |
| BEBra | MF | 51.3092 | 4.52056 | de Pury and Ceulemans (1997) |
| BEJal | MF | 50.5639 | 6.07333 | – |
| BELon | CRO | 50.5522 | 4.74494 | Moureaux et al. (2006) |
| BEVie | MF | 50.3055 | 5.99683 | Aubinet et al. (2001) |
| BRBan | EBF | −9.82442 | −50.1591 | Borma et al. (2009) |
| BRMa2 | EBF | −2.6091 | −60.2093 | – |
| BRSa3 | EBF | −3.01803 | −54.9714 | Saleska et al. (2003) |
| BRSp1 | SAV | −21.6195 | −47.6499 | Baker et al. (2004) |
| BWMa1 | SAV | −19.9155 | 23.5605 | Veenendaal et al. (2004) |
| CACa1 | ENF | 49.8672 | −125.334 | Morgenstern et al. (2004) |
| CACa2 | ENF | 49.8705 | −125.291 | Humphreys et al. (2006) |
| CACa3 | ENF | 49.5346 | −124.9 | Jassal et al. (2008) |
| CAGro | MF | 48.2167 | −82.1556 | Pejam et al. (2006) |
| CAMer | WET | 45.4094 | −75.5186 | Lafleur et al. (2003) |
| CAOas | DBF | 53.6289 | −106.198 | Black et al. (1996) |
| CAObs | ENF | 53.9872 | −105.118 | Jarvis et al. (1997) |
| CAOjp | ENF | 53.9163 | −104.692 | Baldocchi et al. (1997) |
| CAQcu | ENF | 49.2671 | −74.0365 | Giasson et al. (2006) |
| CAQfo | ENF | 49.6925 | −74.3421 | Bergeron et al. (2007) |
| CATP1 | ENF | 42.6609 | −80.5595 | Peichl and Arain (2007) |
| CATP2 | ENF | 42.7744 | −80.4588 | Peichl and Arain (2007) |
| CATP3 | ENF | 42.7068 | −80.3483 | Peichl and Arain (2007) |
| CATP4 | ENF | 42.7098 | −80.3574 | Arain and Restrepo-Coupe (2005) |
| CHOe1 | GRA | 47.2856 | 7.73214 | Ammann et al. (2007) |
| CHOe2 | CRO | 47.2863 | 7.73433 | Kutsch et al. (2010) |
| CNBed | EBF | 39.5306 | 116.252 | Liu et al. (2009) |
| CNCha | MF | 42.4025 | 128.096 | Guan et al. (2006) |
| CNDo1 | WET | 31.5167 | 121.961 | Yan et al. (2008) |
| CNDo2 | WET | 31.5847 | 121.903 | Yan et al. (2008) |
| CNDo3 | WET | 31.5169 | 121.972 | Yan et al. (2008) |
| CNDu1 | CRO | 42.0456 | 116.671 | Zhang et al. (2007) |
| CNDu2 | GRA | 42.0467 | 116.284 | Zhang et al. (2007) |
| CNHaM | GRA | 37.37 | 101.18 | Fu et al. (2006) |
| CNKu1 | EBF | 40.5383 | 108.694 | Wilske et al. (2009) |
| CNKu2 | SHR | 40.3808 | 108.549 | Wilske et al. (2009) |
| CNXfs | NA | 44.13417 | 116.3286 | Miao et al. (2009) |
| CNXi1 | GRA | 43.54583 | 116.6778 | Chen et al. (2009) |
| CNXi2 | GRA | 43.5544 | 116.671 | Wang et al. (2008) |
| DEBay | ENF | 50.1419 | 11.8669 | Valentini et al. (2000) |
| DEGeb | CRO | 51.1001 | 10.9143 | Anthoni et al. (2004a) |
| DEGri | GRA | 50.9495 | 13.5125 | Owen et al. (2007) |
| DEHai | DBF | 51.0793 | 10.452 | Knohl et al. (2003) |
| DEHar | ENF | 47.9344 | 7.601 | Bernhofer et al. (1996) |
| DEKli | CRO | 50.8929 | 13.5225 | Owen et al. (2007) |
| DEMeh | GRA | 51.2753 | 10.6555 | Don et al. (2009) |
| DETha | ENF | 50.9636 | 13.5669 | Bernhofer et al. (2003) |
| DEWet | ENF | 50.4535 | 11.4575 | Anthoni et al. (2004b) |
| DKFou | CRO | 56.4842 | 9.58722 | Soegaard et al. (2003) |
| DKLva | GRA | 55.6833 | 12.0833 | Soussana et al. (2007) |
| DKSor | DBF | 55.4869 | 11.6458 | Pilegaard et al. (2001) |
| ESES1 | ENF | 39.346 | −0.31881 | Sanz et al. (2004) |
| ESES2 | CRO | 39.2755 | −0.31522 | – |
| ESLJu | SHR | 36.9282 | −2.75047 | Serrano-Ortiz et al. (2007) |
| ESLMa | SAV | 39.9415 | −5.77336 | – |
| ESVDA | GRA | 42.1522 | 1.4485 | Gilmanov et al. (2007) |
| FIHyy | ENF | 61.8474 | 24.2948 | Suni et al. (2003) |
| FIKaa | WET | 69.1407 | 27.295 | Aurela et al. (2002) |
| FISod | ENF | 67.3619 | 26.6378 | Thum et al. (2007) |
| FRAur | CRO | 43.5494 | 1.10778 | Beziat et al. (2009) |
| FRGri | CRO | 48.844 | 1.95243 | Laville et al. (1999) |
| FRHes | DBF | 48.6742 | 7.06462 | Granier et al. (2000) |
| FRLam | CRO | 43.4933 | 1.23722 | Beziat et al. (2009) |
| FRLBr | ENF | 44.7171 | −0.7693 | Berbigier et al. (2001) |
| FRPue | EBF | 43.7414 | 3.59583 | Rambal et al. (2004) |
| HUBug | GRA | 46.6911 | 19.6013 | Nagy et al. (2005) |
| HUMat | GRA | 47.8469 | 19.726 | Nagy et al. (2005) |
| IECa1 | CRO | 52.8588 | −6.91814 | Black et al. (2006) |
| IEDri | GRA | 51.9867 | −8.75181 | Peichl et al. (2011) |
| ILYat | ENF | 31.345 | 35.0515 | Grunzweig et al. (2003) |

Table A1 (*Continued*)

| Site | Veg. | Latitude | Longitude | Reference |
|---|---|---|---|---|
| ISGun | DBF | 63.8333 | −20.2167 | Falge et al. (2002) |
| ITAmp | GRA | 41.9041 | 13.6052 | Wohlfahrt et al. (2008) |
| ITBCi | CRO | 40.5238 | 14.9574 | Reichstein et al. (2003) |
| ITCas | CRO | 45.06285 | 8.668539 | Skiba et al. (2009) |
| ITCol | DBF | 41.8494 | 13.5881 | Valentini et al. (1996) |
| ITCpz | EBF | 41.7052 | 12.3761 | Tirone et al. (2003) |
| ITLav | ENF | 45.9553 | 11.2812 | Cescatti and Marcolla (2004) |
| ITLec | EBF | 43.3046 | 11.2706 | Maselli et al. (2009) |
| ITLMa | GRA | 45.5813 | 7.15463 | Maselli et al. (2006) |
| ITMal | GRA | 46.1167 | 11.7028 | Flechard et al. (2007) |
| ITMBo | GRA | 46.0156 | 11.0467 | Marcolla et al. (2011) |
| ITNoe | SHR | 40.606 | 8.151 | Reichstein et al. (2002) |
| ITNon | DBF | 44.6898 | 11.0887 | Nardino et al. (2002) |
| ITPT1 | DBF | 45.2009 | 9.06104 | Migliavacca et al. (2009) |
| ITRen | ENF | 46.5878 | 11.4347 | Marcolla et al. (2005) |
| ITRo1 | DBF | 42.4081 | 11.93 | Rey et al. (2002) |
| ITRo2 | DBF | 42.3903 | 11.9209 | Tedeschi et al. (2006) |
| ITSRo | ENF | 43.72786 | 10.28444 | Chiesi et al. (2005) |
| JPMas | CRO | 36.05397 | 140.0269 | Saito et al. (2005) |
| JPTom | MF | 42.7395 | 141.5149 | Hirano et al. (2003) |
| KRHnm | NA | 34.55 | 126.57 | Lee et al. (2003) |
| KRKw1 | MF | 37.7486 | 127.163 | Kim et al. (2006) |
| NLCa1 | GRA | 51.971 | 4.927 | Jacobs et al. (2007) |
| NLLan | CRO | 51.9536 | 4.9029 | Moors et al. (2010) |
| NLLoo | ENF | 52.1679 | 5.74396 | Dolman et al. (2002) |
| NLLut | CRO | 53.3989 | 6.356 | Moors et al. (2010) |
| PLWet | WET | 52.7622 | 16.3094 | Chojnicki et al. (2007) |
| PTMi2 | GRA | 38.4765 | −8.02455 | Pereira et al. (2007) |
| RUChe | WET | 68.6147 | 161.339 | Corradi et al. (2005) |
| RUFyo | ENF | 56.46167 | 32.92389 | Kurbatova et al. (2008) |
| RUZot | ENF | 60.8008 | 89.3508 | Kurbatova et al. (2002) |
| SEAbi | DBF | 68.36239 | 18.79475 | Christensen et al. (2007) |
| SEFaj | WET | 56.2655 | 13.5535 | Lund et al. (2007) |
| SEFla | ENF | 64.1128 | 19.4569 | Valentini et al. (2000) |
| SENor | ENF | 60.0865 | 17.4795 | Lagergren et al. (2008) |
| SESk1 | ENF | 60.125 | 17.9181 | Gioli et al. (2004) |
| SKTat | ENF | 49.1208 | 20.1635 | Matese et al. (2008) |
| UKAMo | WET | 55.7917 | −3.23889 | Hargreaves et al. (2003) |
| UKEBu | GRA | 55.866 | −3.20578 | Famulari et al. (2004) |
| UKESa | CRO | 55.90694 | −2.85861 | Hendricks Franssen et al. (2010) |
| UKGri | ENF | 56.60722 | −3.79806 | Medlyn et al. (2005) |
| UKHam | DBF | 51.15353 | −0.8583 | Wilkinson et al. (2012) |
| UKHer | CRO | 51.7838 | −0.47608 | – |
| USARb | GRA | 35.5497 | −98.0402 | Fischer et al. (2007) |
| USARc | GRA | 35.54649 | −98.04 | Fischer et al. (2007) |
| USARM | CRO | 36.6058 | −97.4888 | Fischer et al. (2007) |
| USAtq | WET | 70.4696 | −157.409 | – |
| USAud | GRA | 31.5907 | −110.51 | – |
| USBkg | GRA | 44.3453 | −96.8362 | Gilmanov et al. (2005) |
| USBlo | ENF | 38.8952 | −120.6328 | Goldstein et al. (2000) |
| USBn1 | ENF | 63.9198 | −145.378 | Liu et al. (2005) |
| USBn2 | DBF | 63.9198 | −145.378 | Liu et al. (2005) |
| USBn3 | SHR | 63.9227 | −145.744 | Liu et al. (2005) |
| USBo1 | CRO | 40.0062 | −88.2904 | Meyers and Hollinger (2004) |
| USBo2 | CRO | 40.009 | −88.29 | Meyers and Hollinger (2004) |
| USBrw | WET | 71.3225 | −156.6259 | Vourlitis and Oechel (1999) |
| USCaV | GRA | 39.0633 | −79.4208 | Owen et al. (2007) |
| USFmf | ENF | 35.1426 | −111.7273 | Dore et al. (2008) |
| USFPe | GRA | 48.3077 | −105.1019 | Gilmanov et al. (2005) |
| USFR2 | SAV | 29.9495 | −97.9962 | Heinsch et al. (2004) |
| USFuf | ENF | 35.089 | −111.762 | Dore et al. (2008) |
| USFwf | GRA | 35.4454 | −111.7718 | Dore et al. (2008) |
| USGoo | GRA | 34.2547 | −89.8735 | Wilson and Meyers (2007) |
| USHo1 | ENF | 45.2041 | −68.7402 | Hollinger et al. (1999) |
| USIB1 | CRO | 41.8593 | −88.2227 | Allison et al. (2005) |
| USIB2 | GRA | 41.8406 | −88.241 | Allison et al. (2005) |
| USIvo | WET | 68.4865 | −155.75 | Epstein et al. (2004) |
| USKS2 | SHR | 28.6086 | −80.6715 | Powell et al. (2006) |
| USLos | DBF | 46.0827 | −89.9792 | Desai et al. (2008) |
| USMe1 | ENF | 44.5794 | −121.5 | Law et al. (2001) |
| USMe2 | ENF | 44.4523 | −121.5574 | Campbell et al. (2004) |
| USMe3 | ENF | 44.3154 | −121.6078 | Vickers et al. (2009) |
| USMe4 | ENF | 44.4992 | −121.6224 | Irvine et al. (2004) |
| USMMS | DBF | 39.3231 | −86.4131 | Schmid et al. (2000) |
| USMOz | DBF | 38.7441 | −92.2 | Gu et al. (2006) |
| USNC1 | SHR | 35.8115 | −76.7115 | Noormets et al. (2010) |
| USNC2 | ENF | 35.8031 | −76.6679 | Domec et al. (2009) |

Table A1 (*Continued*)

| Site | Veg. | Latitude | Longitude | Reference |
|---|---|---|---|---|
| USNe1 | CRO | 41.1651 | −96.4766 | Verma et al. (2005) |
| USNe2 | CRO | 41.1649 | −96.4701 | Verma et al. (2005) |
| USNe3 | CRO | 41.1797 | −96.4397 | Verma et al. (2005) |
| USNR1 | ENF | 40.0329 | −105.546 | Monson et al. (2002) |
| USOho | DBF | 41.5545 | −83.8438 | DeForest et al. (2006) |
| USSO2 | SHR | 33.3739 | −116.6229 | Lipson et al. (2005) |
| USSO3 | SHR | 33.3772 | −116.6227 | Lipson et al. (2005) |
| USSO4 | SHR | 33.3844 | −116.6403 | Lipson et al. (2005) |
| USSP1 | ENF | 29.7381 | −82.2188 | Clark et al. (1999) |
| USSP2 | ENF | 29.7648 | −82.2448 | Clark et al. (1999) |
| USSP3 | ENF | 29.7548 | −82.1633 | Clark et al. (1999) |
| USSRM | SAV | 31.8214 | −110.866 | Scott et al. (2009) |
| USSyv | MF | 46.242 | −89.3477 | Desai et al. (2005) |
| USTon | SAV | 38.4316 | −120.966 | Ma et al. (2007) |
| USVar | GRA | 38.4133 | −120.9507 | Ma et al. (2007) |
| USWBW | DBF | 35.9588 | −84.2874 | Verma et al. (1986) |
| USWCr | DBF | 45.8059 | −90.0799 | Cook et al. (2004) |
| USWi1 | DBF | 46.7305 | −91.2329 | Noormets et al. (2007) |
| USWi2 | ENF | 46.6869 | −91.1528 | Noormets et al. (2007) |
| USWi8 | DBF | 46.7223 | −91.2524 | Noormets et al. (2007) |
| USWkg | GRA | 31.7365 | −109.942 | Scott et al. (2010) |
| USWrc | ENF | 45.8205 | −121.952 | Chen et al. (2002) |

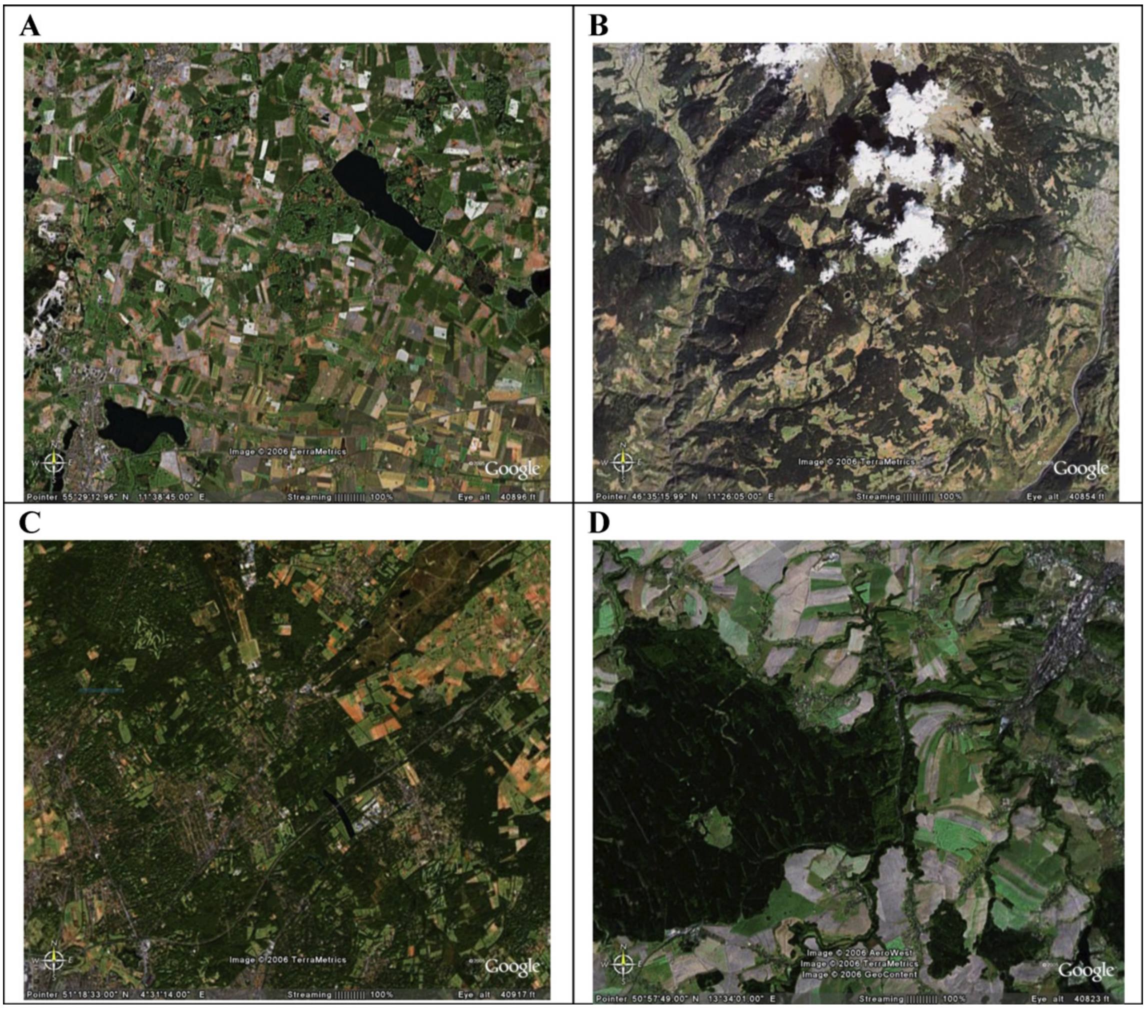

**Fig. A1.** Satellite photographs taken from *ca.* 13,400 m over a small forest in an agricultural landscape (DK-Sor, A), an alpine region (IT-Ren, B), a forest in a suburban area (BE-Bra, C) and a managed forest surrounded mainly by agriculture (DE-Tha). Site information is presented in Table A1. The eddy covariance tower is located in the middle of all images, which are approximately 20 km along the east-west axis.

variability. The surface energy balance is likely affected on a scale of *ca*. 20 km × 20 km, possibly as a result of secondary circulations, during daytime periods. On the other hand, for the station DK-Sor, the energy balance closure is better for daytime data, when the small forest area tends to lie within the flux footprint.

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