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Energy balance closure at FLUXNET sites

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Abstract

A comprehensive evaluation of energy balance closure is performed across 22 sites and 50 site-years in FLUXNET, a network of eddy covariance sites measuring long-term carbon and energy fluxes in contrasting ecosystems and climates. Energy balance closure was evaluated by statistical regression of turbulent energy fluxes (sensible and latent heat (LE)) against available energy (net radiation, less the energy stored) and by solving for the energy balance ratio, the ratio of turbulent energy fluxes to available energy. These methods indicate a general lack of closure at most sites, with a mean imbalance in the order of 20%. The imbalance was prevalent in all measured vegetation types and in climates ranging from Mediterranean to temperate and arctic. There were no clear differences between sites using open and closed path infrared gas analyzers. At a majority of sites closure improved with turbulent intensity (friction velocity), but lack of total closure was still prevalent under most conditions. The imbalance was greatest during nocturnal periods. The results suggest that estimates of the scalar turbulent fluxes of sensible and LE are underestimated and/or that available energy is overestimated. The implications on interpreting long-term CO_2 fluxes at FLUXNET sites depends on whether the imbalance results primarily from general errors associated

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overlook biases in the half-hourly data, such as the tendency to overestimate positive fluxes during the day and underestimate negative fluxes at night (Blanken et al., 1998; Mahrt, 1998).

3. Results

3.1. Overall energy balance closure

Regression coefficients of LE + H against $R_n - G - S$, using OLSs on all the half-hour data for each of the 50 site-years, are shown in Table 2. The slope was less than 1 for all site-years, ranging from 0.53 to 0.99, with a mean of 0.79 ± 0.01. The intercept ranged from −32.9 to 36.9 W m^{-2}, with a mean of 3.7±2.0 W m^{-2}. There were more positive (31) than negative intercepts (19). The mean coefficient of determination (r^2) was 0.86, ranging from 0.64 to 0.96.

Using the RMA approach, which accounted for random errors in available energy, increased the mean slope to 0.83 ± 0.01. The increase in slope ranged from 2 to 10% for 43 of the 50 site-years (not shown). The remaining seven site-years increased by more than 10%, with one site increasing by 25%. The sites with the largest increase in slope using the RMA approach had the lowest correlation (r^2 values less than 0.80). The mean intercept using the RMA method was slightly less than using the OLS method (−1.4 ± 1.8 W m^{-2}).

A second method to account for random errors in the independent variable was the MMs approach. The MM approach requires a quantitative estimate of the random error in the measurement of the independent variable ($R_n - G - S$). Setting hypothetical estimates of the random error in $R_n - G - S$ of 10, 20, 40 and 50% resulted in mean slopes of 0.78, 0.82, 0.99 and 1.17, respectively. Random errors of greater than 20% in available energy would be required for substantial improvements in energy balance closure. The mean intercept of the site-years decreased as the random error increased: 2.7 W m^{-2} (for a 10% random error), −0.4 W m^{-2} (20%), −16.3 W m^{-2} (40%) and −33.5 W m^{-2} (50%).

The bias in the energy imbalance is still evident at most sites when it is evaluated as the annual ratio of total annual turbulent heat flux to available energy (i.e. annual value of EBR, Table 2). The mean EBR for

Table 2
Ordinary linear regression (OLR) coefficients for energy balance closure for all site-years[a]

n	Intercept	Slope	r^2	EBR
5129	3.5	0.55	0.80	0.56
3771	7.1	0.58	0.87	0.70
3324	16.8	0.60	0.64	0.77
3495	20.9	0.62	0.74	[b]
6197	29.7	0.64	0.74	0.82
6144	−10.1	0.65	0.83	1.00
8738	−0.8	0.68	0.85	0.68
14418	−0.7	0.69	0.85	1.20
11459	2.5	0.70	0.84	0.72
10227	6.0	0.70	0.83	0.74
9267	−12.3	0.71	0.87	1.03
7952	−18.3	0.72	0.86	0.59
9621	−6.9	0.72	0.86	0.66
3918	12.7	0.73	0.92	0.84
10712	−32.9	0.73	0.80	0.39
11267	7.7	0.74	0.88	0.82
12727	36.9	0.74	0.76	1.00
13834	11.3	0.75	0.84	0.86
14468	9.6	0.75	0.85	0.88
11561	8.4	0.75	0.86	0.83
9649	31.1	0.75	0.89	1.16
12016	3.1	0.75	0.88	0.78
9005	16.6	0.76	0.92	0.88
11789	−6.0	0.77	0.83	0.76
11058	−16.2	0.78	0.81	0.53
4032	2.6	0.78	0.87	0.81
4039	−5.4	0.79	0.85	0.62
4181	4.5	0.80	0.88	0.87
6848	−8.7	0.82	0.83	0.69
3846	16.3	0.83	0.92	0.93
4370	5.0	0.83	0.89	0.79
4896	7.4	0.84	0.96	0.93
14760	6.4	0.85	0.92	0.97
4150	4.1	0.85	0.85	0.92
12751	−1.2	0.85	0.90	0.84
5193	−12.5	0.85	0.95	0.73
15638	−5.3	0.85	0.87	0.69
2594	−2.1	0.85	0.94	0.83
13891	2.6	0.86	0.90	0.89
14198	−7.7	0.86	0.91	1.00
6357	28.6	0.87	0.86	1.09
3850	3.6	0.89	0.90	0.93
3864	6.6	0.89	0.87	0.34
14324	8.9	0.90	0.91	1.69
7993	−18.7	0.90	0.89	0.79
12064	31.5	0.91	0.91	1.17
14545	−15.2	0.92	0.92	0.77
13655	7.1	0.95	0.91	0.89
4670	−23.8	0.97	0.90	0.71
1883	32.6	0.99	0.79	[b]

[a] 'EBR' refers to the annual ratio of $(H + \mathrm{LE})/(R_n - G - S)$; n is the number of half-hours.

[b] A spurious EBR ratio because the summed available energy was close to zero.

all the site-years was 0.84, ranging from 0.34 to 1.69. The ratio of total turbulent heat flux to total available energy across all 50 site-years was similar, 0.82.

3.2. Role of canopy and ground heat storage

Twenty-six site-years with tall vegetation (height > 8 m) reported an estimate of canopy heat storage (S). Including S in the regressions for these sites increased the slope of the OLS regression by an average of 7%, which is why forested sites were required to report S in this study. The mean intercept decreased from 2.1 to $-0.8\,\mathrm{W\,m^{-2}}$. Soil heat flux (G) increased the average OLS slope for grasslands, agricultural and chaparral sites by about 20%. Soil heat flux had much less impact at the forested sites, where the average OLS slope increased by only 3%.

3.3. Vegetation type, vegetation height and IRGA type

Fig. 1 shows the slope of the OLS regression against vegetation height, differentiating between sites using open and closed path IRGAs. There were no obvious differences in the slope for sites using the open and closed path designs. There was also no obvious effect of vegetation height on the OLS slope.

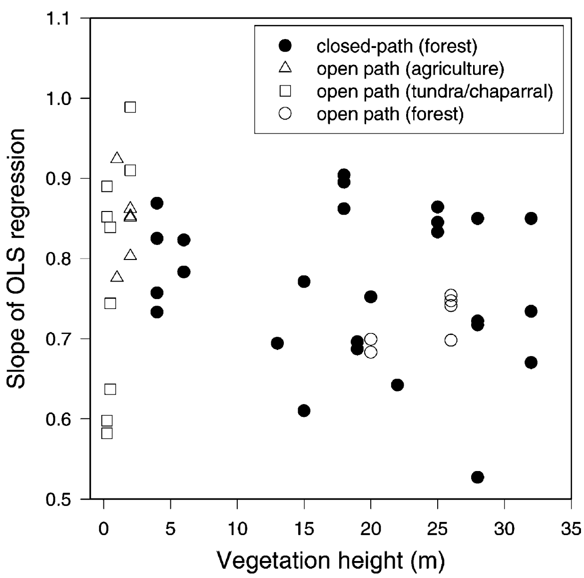

Fig. 1. The slope of the OLS regression against vegetation height for sites using closed (closed symbols) and open (open symbols) path IRGAs. Symbol shapes represent different vegetation types.

3.4. Diurnal variation in closure

The OLS regression statistics during periods of positive net radiation (not shown) were similar to the statistics using all the data that are shown in Table 2. The mean slope was 0.80 ± 0.02, ranging from 0.56 to 0.97. The mean intercept was $-0.3 \pm 3.0\,\mathrm{W\,m^{-2}}$ and r^2 was 0.81. The 'site-year' mean annual EBR during 'daytime' periods was 0.80, and EBR was equal to or greater than 1 at only two site-years. The ratio of total daytime turbulent heat flux to total daytime available energy for all 50 site-years was similar, 0.79.

The mean OLS slope during nighttime periods (net radiation less than zero) was only 0.35 ± 0.03, ranging from -0.04 to 0.69. The mean intercept was $-5.5 \pm 1.4\,\mathrm{W\,m^{-2}}$ and the correlation was typically weak (mean $r^2 = 0.11$). In some cases, the 'site-year' annual nocturnal EBR was negative or was much less or much greater than 1. The ratio of total turbulent flux to the total available energy summed over all the sites was 0.54 during the night, which is less than during the day. The magnitude of the imbalance at night was strongly dependent on turbulent mixing, as shown in the following section.

Data from all the site-years were combined to compute the diurnal course of the EBR. For each of the 24 h the half-hourly $\mathrm{LE} + H$ and $R_n - G - S$ were summed over entire site-years using the entire data set. The ratio between these two sums (Eq. (1)) was the hourly EBR. Fig. 2 shows the diurnal course of the EBR, along with the mean magnitudes of $\mathrm{LE} + H$ and $R_n - G - S$. During morning and evening transition periods, when the mean value of $R_n - G - S$ was close to zero, the EBR is not especially meaningful. Between these two transition periods there was a general increase in the EBR from the morning to afternoon. This pattern of a greater EBR in the afternoon relative to the morning was observed in both the warm and cold seasons and was typical for most of the individual site-years (not shown).

3.5. Effect of turbulent mixing

The effect of turbulent mixing was evaluated between and within sites by analyzing closure with respect to friction velocity. The slope of the OLS regression was not a function of the mean annual friction velocity across all the site-years (not shown).