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Endogenous circadian regulation of carbon dioxide exchange in terrestrial ecosystems


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Abstract

It is often assumed that daytime patterns of ecosystem carbon assimilation are mostly driven by direct physiological responses to exogenous environmental cues. Under limited environmental variability, little variation in carbon assimilation should thus be expected unless endogenous plant controls on carbon assimilation, which regulate photosynthesis in time, are active. We evaluated this assumption with eddy flux data, and we selected periods when net ecosystem exchange (NEE) was decoupled from environmental variability in seven sites from highly contrasting biomes across a 74° latitudinal gradient over a total of 36 site-years. Under relatively constant conditions of light, temperature, and other environmental factors, significant diurnal NEE oscillations were observed at six sites, where daily NEE variation was between 20% and 90% of that under variable environmental conditions. These results are consistent with fluctuations driven by the circadian clock and other endogenous processes. Our results open a promising avenue of research for a more complete understanding of ecosystem fluxes that integrates from cellular to ecosystem processes.

Keywords: biosphere-atmosphere interactions, canopy conductance, circadian clock, ecosystem exchange, gas exchange, global change, photosynthesis, source/sink regulation

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Introduction

One of the major assumptions underlying studies of land-atmosphere exchange is that daily fluctuations in the net ecosystem exchange of CO₂ (NEE) are driven almost exclusively by direct physiological responses to changes in irradiance, temperature, humidity, and other environmental factors (Hollinger et al., 1994; Sellers et al., 1997; Chapin et al., 2002; Hanson et al., 2004). This assumption arose largely because leaf photosynthesis, which represents the major input of carbon to an ecosystem, responds strongly and rapidly to changes in the meteorological environment. However, it is increasingly recognized that diurnal changes in NEE could also result from a variety of endogenous processes (Hennessey & Field, 1991; Wingler et al., 2000; Franks, 2004; Doughty et al., 2006; Resco et al., 2009a; Brodersen et al., 2010), or indirect physiological responses to the environment.

NEE is the difference between gross ecosystem exchange and respiration. Thus, variation in both carbon assimilation and respiration determine fluctuations in
daily NEE. We will focus here on the physiological drivers of carbon assimilation that affect NEE, as discussions on how direct and indirect responses of respiration to environmental variation may affect NEE have been addressed elsewhere (Davidson et al., 2006; Högberg & Read, 2006; Trumbore, 2006; Bahn et al., 2010).

Under the standard physiological convention, where increasing carbon assimilation is represented as more positive NEE, the diurnal pattern of NEE during the growing season often follows a common trend whereby NEE increases during the morning, reaches a maximum around noon, and declines thereafter. A variety of endogenous factors affecting carbon assimilation have been reported to accelerate the afternoon decline in NEE. For instance, reduced carbon assimilation resulting from afternoon stomatal closure is often observed, reflecting the loss of hydraulic conductivity (Franks, 2004; Brodersen et al., 2010). Moreover, stomatal limitations tend to intensify under high light, causing photorespiration to act as a major energy sink in C3 plants, which further contributes to the afternoon photosynthetic reduction (Wingler et al., 2000). The reduction in NEE over the course of an afternoon might also result from the feedback inhibition of photosynthesis due to starch accumulation in the chloroplast (Paul & Foyer, 2001).

The circadian clock has also been hypothesized to influence the daily pattern of NEE (Doughty et al., 2006; Resco et al., 2009a). Under constant light and temperature, leaf carbon assimilation in a variety of species has been reported to follow a diurnal pattern that increases in the morning and decreases after noon (Hennessey & Field, 1991; Webb, 2003; Dodd et al., 2004). This is because the circadian clock acts as a central ‘orchestra’ of plant activity (sensu Harmer et al., 2000; McClung, 2009) and directly controls (amongst other processes) stomatal opening and the transcription of genes underlying Rubisco activity as a function of time of day (Hennessey & Field, 1991; Liu et al., 1996; Dodd et al., 2004; Doughty et al., 2006). The core mechanism of the circadian clock is a ‘central oscillator’ responsible for generating cycles of ca. 24 h period under constant levels of light and temperature over a broad range of temperatures. This oscillator is a molecular mechanism involving a series of highly conserved transcriptional-translational positive and negative feedback loops (McClung, 2009). Unlike the previously cited endogenous mechanisms, which only contribute to the afternoon decline in NEE, the circadian clock at the leaf level mirrors the typical daily trend in carbon assimilation observed in the field (Hennessey & Field, 1991; Dodd et al., 2004; Doughty et al., 2006).

The vast majority of experiments on circadian regulation of leaf gas exchange have been conducted with model species, under low levels of light (photosynthetically active radiation, PAR, <200 μmol m⁻² s⁻¹), and in lab settings. Direct evidence that this molecular clock mechanism is an important driver of leaf photosynthesis in the field is scarce (Williams & Gorton, 1998), and even more scarce are tests on whether its effect may scale up to affect a whole ecosystem. However, preliminary studies suggest that this is likely. Doughty et al. (2006) observed that the uptake of CO₂ in a tropical forest in Pará, Brazil increased almost fivefold (from 3.6 to 16.1 μmol m⁻² s⁻¹ between 0645 h and 0945 h), whereas light, air temperature and soil respiration rates remained relatively constant. Doughty et al. (2006) also measured leaf photosynthesis under constant light and temperature and concluded that the increase in NEE generally coincided with the measured increase in leaf photosynthesis under a constant environment.

Here, we test the assumption that daily NEE fluctuations are driven almost exclusively by direct physiological responses to environmental cues, and that NEE would remain constant over a day given constant environmental conditions. Instead of the logistically challenging approach of enclosing entire ecosystems within a chamber at constant temperature and light levels, we employed data filtering and statistical modeling techniques to remove the potential effects of variation in the external environment on NEE. We applied these techniques to NEE that was measured with the eddy covariance technique together with concurrently measured environmental data from sites in each of seven biomes across a 74° latitudinal gradient: tropical forest (Tapajos), chaparral (Sky Oaks), savanna (Santa Rita Mesquite), hardwood temperate forest (Bartlett), conifer temperate forest (Howland), subalpine conifer forest (Niwot Ridge), and tundra (Barrow; see Table 1). The dataset included half-hourly observations over a total of 36 site-years (Tables 2 and 3).

Our filtering approach extracted a subset of observations during the growing season for which environmental variables (e.g. temperature, humidity, soil water, light) were nearly constant. This filtering defined our data set of observations made under ‘constant environmental conditions’. Because carbon assimilation is co-regulated by leaf biochemistry and stomatal conductance, we also calculated canopy conductance on the filtered dataset by inverting a widely used evapotranspiration model (Monteith & Unsworth, 2008; see Appendix S1 in Supporting Information).

Methods

Eddy covariance data
We selected seven sites from the AmeriFlux network, representative of contrasting climate regions and vegetation types.
<table>
<thead>
<tr>
<th>Site</th>
<th>Vegetation type</th>
<th>Location</th>
<th>References</th>
<th>Data file</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrow</td>
<td>Tundra</td>
<td>Alaska. 71.32° (N); 156.62° (W)</td>
<td>Harazono et al. (2003)</td>
<td>ftp://cdiac.ornl.gov/pub/ameriflux/data/Level2/Sites_ByName/Barrow/with_gaps/ (17/08/2009)uakbarr_1999_L2.csv (5.0 MB); uakbarr_2000_L2.csv (5.0 MB); uakbarr_2001_L2.csv (5.0 MB); uakbarr_2002_L2.csv (5.0 MB)</td>
</tr>
<tr>
<td>Bartlett</td>
<td>Hardwood temperate forest</td>
<td>New Hampshire. 44.06° (N); 71.28° (W)</td>
<td>Jenkins et al. (2007)</td>
<td>ftp://cdiac.ornl.gov/pub/ameriflux/data/Level2/Sites_ByName/Bartlett_Experimental_Forest/with_gaps/ (09/09/2009)AMF_USBar_2004_L2_WG_V002.csv (4.2 MB); AMF_USBar_2005_L2_WG_V002.csv (4.2 MB); AMF_USBar_2006_L2_WG_V002.csv (4.0 MB); AMF_USBar_2007_L2_WG_V002.csv (4.2 MB)</td>
</tr>
<tr>
<td>Howland</td>
<td>Coniferous temperate forest</td>
<td>Maine. 45.20° (N); 68.74° (W)</td>
<td>Hollinger et al. (2004); Savage et al. (2009)</td>
<td>ftp://cdiac.ornl.gov/pub/ameriflux/data/Level2/Sites_ByName/Howland_Forest_Main/with_gaps/ (1/10/2009)AMF_USHo1_2000_WG_V001.csv (4.5 MB); AMF_USHo1_2001_WG_V001.csv (4.5 MB); AMF_USHo1_2002_WG_V001.csv (4.5 MB); AMF_USHo1_2003_WG_V001.csv (4.5 MB); AMF_USHo1_2004_WG_V001.csv (4.5 MB)</td>
</tr>
<tr>
<td>Niwot Ridge</td>
<td>Taiga</td>
<td>Colorado. 40.03° (N); 105.54° (W)</td>
<td>Hu et al. (2010)</td>
<td>ftp://cdiac.ornl.gov/pub/ameriflux/data/Level2/Sites_ByName/Niwot_Ridge/with_gaps/ (17/08/2009)AMF_USNR1_2002_L2_WG_V003.csv (4.3 MB); AMF_USNR1_2003_L2_WG_V003.csv (4.4 MB); AMF_USNR1_2004_L2_WG_V003.csv (4.3 MB); AMF_USNR1_2005_L2_WG_V003.csv (4.4 MB)</td>
</tr>
<tr>
<td>Sky Oaks</td>
<td>Mediterranean chaparral</td>
<td>California. 33.37° (N); 116.62°(W)</td>
<td>Luo et al. (2007)</td>
<td>ftp://cdiac.ornl.gov/pub/ameriflux/data/Level2/Sites_ByName/Sky_Oaks_Old/with_gaps/ (19/08/2009)uscaskyo_1997_L2.csv (4.2 MB); uscaskyo_1998_L2.csv (5.1 MB); uscaskyo_1999_L2.csv (5.1 MB); uscaskyo_2000_L2.csv (5.0 MB); uscaskyo_2001_L2.csv (5.1 MB); uscaskyo_2002_L2.csv (5.0 MB); uscaskyo_2003_L2.csv (5.1 MB); uscaskyo_2004_L2.csv (5.0 MB); uscaskyo_2005_L2.csv (5.0 MB)</td>
</tr>
<tr>
<td>SRM</td>
<td>Savanna</td>
<td>Arizona. 31.90°(N); 110.83°(W)</td>
<td>Scott et al. (2009)</td>
<td>ftp://cdiac.ornl.gov/pub/ameriflux/data/Level2/Sites_ByName/Santa_Rita_Mesquite_Savanna/with_gaps/ (06/07/2009)AMF_USSRM_2004_L2_WG_V003.csv (4.5 MB); AMF_USSRM_2005_L2_WG_V003.csv (4.5 MB); AMF_USSRM_2006_L2_WG_V003.csv (4.5 MB); AMF_USSRM_2007_L2_WG_V003.csv (4.5 MB)</td>
</tr>
<tr>
<td>Tapajos</td>
<td>Tropical forest</td>
<td>Pará. −3.01° (S); 54.97° (W)</td>
<td>Goulden et al. (2004)</td>
<td><a href="http://www.ess.uci.edu/%7Elba/">http://www.ess.uci.edu/%7Elba/</a> (23/11/2009)LBA-ECO_CD04_TNF_KM83_METEOROLOGY_AND_FLUXES_MEASURED.zip (8 MB)</td>
</tr>
</tbody>
</table>
Table 2  Environmental filters applied to daytime data, such that NEE variation may be considered independent of the environment

<table>
<thead>
<tr>
<th>Site</th>
<th>Years (sample size)</th>
<th>PAR (µmol m⁻² s⁻¹)</th>
<th>PAR_{dir}</th>
<th>K_{net} (Wm⁻²)</th>
<th>SWC (%)</th>
<th>T_a (°C)</th>
<th>T_s (°C)</th>
<th>RH (%)</th>
<th>VPD (kPa)</th>
<th>T_l (°C)</th>
<th>u (ms⁻¹)</th>
<th>u' (ms⁻¹)</th>
<th>H (Wm⁻²)</th>
<th>LE (Wm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrow</td>
<td>7-8 1999-2002 &gt;500 (1977)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.001)</td>
<td>NA (0.010)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td></td>
</tr>
<tr>
<td>Bartlett</td>
<td>6-7 2004-2007 &gt;1000 (3529)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td></td>
</tr>
<tr>
<td>Howland</td>
<td>5-9 2000-2004 1000-1600 (740)</td>
<td>&gt;0.36 (0.010)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td>NF (&lt;0.001)</td>
<td></td>
</tr>
<tr>
<td>Niwot Ridge</td>
<td>6-8 2002-2005 1000-1600 (275)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
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<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td></td>
</tr>
<tr>
<td>Sky Oaks</td>
<td>5-6 1997-2006 &gt;1000 (596)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
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<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td></td>
</tr>
<tr>
<td>Santa Rita Mesquite</td>
<td>8-9 2004-2007 &gt;1000 (160)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td></td>
</tr>
<tr>
<td>Tapajos</td>
<td>1-12 2000-2004 &gt;700 (2114)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td>NF (&lt;0.010)</td>
<td></td>
</tr>
</tbody>
</table>

NF indicates that no filter was necessary to apply for the associated variable because NEE and the variable already appeared decoupled (R²<0.04). Numbers in parentheses below each filter range indicate the $R^2$ of a simple regression model between filtered NEE and each variable, except under the column ‘years’, where parentheses indicate the sample size. PAR is photosynthetically active radiation, PAR_{dir} is the fraction of direct to total PAR (and has relative units), K_{net} is net radiation, SWC is soil water content, T_a is air temperature, T_s is soil temperature, RH is relative humidity, VPD is vapor pressure deficit, T_l is leaf temperature, u is wind speed, WD is wind direction, u' is friction velocity, H is sensible heat, and LE is latent heat. No SWC data were available from Barrow or Sky Oaks.
Table 3  Environmental filters applied to nighttime data, such that NEE variation may be considered independent of the environment

<table>
<thead>
<tr>
<th>Site</th>
<th>Months (sample size)</th>
<th>Years (1956–1970)</th>
<th>PAR (μmol m⁻² s⁻¹)</th>
<th>( R_{\text{net}} ) (Wm⁻²)</th>
<th>SWC (%)</th>
<th>( T_s ) (°C)</th>
<th>( T_a ) (°C)</th>
<th>RH (%)</th>
<th>VPD (kPa)</th>
<th>( T_{s} ) (°C)</th>
<th>( u ) (ms⁻¹)</th>
<th>WD (°)</th>
<th>( u^* ) (ms⁻¹)</th>
<th>H (Wm⁻²)</th>
<th>LE (Wm⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bartlett</td>
<td>6-7</td>
<td>2004-2007 (136)</td>
<td>&lt;5 (&lt;0.010)</td>
<td>NF (0.001)</td>
<td>NF (0.010)</td>
<td>&lt;18</td>
<td>50-95</td>
<td>NF</td>
<td>NF (0.010)</td>
<td>&lt;100</td>
<td>&gt;0.275</td>
<td>NF</td>
<td>NF (0.010)</td>
<td>NF (0.010)</td>
<td>NF (0.010)</td>
</tr>
<tr>
<td>Howland</td>
<td>5-9</td>
<td>2000–2004 (422)</td>
<td>&lt;5 (&lt;0.001)</td>
<td>NF (0.010)</td>
<td>NF (0.010)</td>
<td>15-18</td>
<td>10-15</td>
<td>NF</td>
<td>0.01-0.05</td>
<td>NF (0.010)</td>
<td>NF (0.010)</td>
<td>NF</td>
<td>NF (0.010)</td>
<td>NF (0.010)</td>
<td>NF (0.010)</td>
</tr>
<tr>
<td>Niwot Ridge</td>
<td>6-8</td>
<td>2002-2005 (1243)</td>
<td>&lt;5 (&lt;0.001)</td>
<td>NF (0.010)</td>
<td>NF (0.010)</td>
<td>15-10</td>
<td>10-15</td>
<td>NF</td>
<td>NF (0.010)</td>
<td>&lt;0.1</td>
<td>&lt;0.040</td>
<td>NF</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Sky Oaks</td>
<td>5-6</td>
<td>1997–2006 (365)</td>
<td>&lt;5 (&lt;0.010)</td>
<td>NF (0.010)</td>
<td>NA</td>
<td>0–15</td>
<td>360-200</td>
<td>NF</td>
<td>NF (0.010)</td>
<td>&lt;0.15</td>
<td>&lt;0.15</td>
<td>NF</td>
<td>NF (0.010)</td>
<td>&lt;0.040</td>
<td>&lt;0.040</td>
</tr>
<tr>
<td>Santa Rita</td>
<td>8-9</td>
<td>2000–2004 (156)</td>
<td>&lt;5 (&lt;0.010)</td>
<td>NF (0.010)</td>
<td>NF (0.010)</td>
<td>7-14</td>
<td>60-80</td>
<td>NF</td>
<td>NF (0.010)</td>
<td>&gt;0.2–0.8</td>
<td>&gt;0.2-0.8</td>
<td>NF</td>
<td>NF (0.010)</td>
<td>&lt;0.040</td>
<td>&lt;0.040</td>
</tr>
<tr>
<td>Mesquite</td>
<td>1-12</td>
<td>2000–2004 (4598)</td>
<td>&lt;5 (&lt;0.010)</td>
<td>NF (0.010)</td>
<td>NF (0.010)</td>
<td>22-28</td>
<td>60-80</td>
<td>NF</td>
<td>NF (0.010)</td>
<td>&lt;0.2–0.8</td>
<td>&gt;0.2-0.8</td>
<td>NF</td>
<td>NF (0.010)</td>
<td>&lt;0.040</td>
<td>&lt;0.040</td>
</tr>
</tbody>
</table>

NF indicates that no filter was necessary to apply for the associated variable because NEE and the variable already appeared decoupled (\( R^2 < 0.04 \)). Numbers in parentheses below each filter range indicate the \( R^2 \) of a simple regression model between filtered NEE and each variable, except under the column 'years', where parentheses indicate the sample size. PAR is photosynthetically active radiation, \( R_{\text{net}} \) is net radiation, SWC is soil water content, \( T_s \) is air temperature, \( T_a \) is soil temperature, RH is relative humidity, VPD is vapor pressure deficit, \( T_{s} \) is leaf temperature, \( u \) is wind speed, WD is wind direction, \( u^* \) is friction velocity, H is sensible heat, and LE is latent heat. No SWC data were available from Sky Oaks and no nighttime data were available from Barrow due to the short duration of summer nights at high latitude.
Data filtering

We partitioned the effect of the environment on NEE from that of endogenous plant rhythms by extracting a subset of the data when the environmental effect on NEE was negligible. We selected a subset of the data when: (a) there were no seasonal differences in the daily NEE patterns (we selected only the months with highest NEE within the growing season; Fig. 1); (b) the ranges of observed environmental variables — PAR, net radiation, the ratio of direct to total photosynthetically active radiation (Appendix S2), soil water content, air and soil temperature, relative humidity, vapor pressure deficit, wind speed and direction, friction velocity, and latent and sensible heat fluxes—were narrow enough (Tables 2 and 3) that they did not significantly affect NEE ($r^2$ between NEE and each variable was lower than 0.01–0.04), and (c) there was little day-to-day variation in environmental variables and in antecedent conditions such that the environmental conditions over the 2–3 days prior to each NEE observation were similar to the day of measurement. These requirements ensured that photochemical energy supply and environmental factors directly affecting carbon assimilation were effectively constant.

For clarity, we explain the procedure followed in data filtering using the example of the Bartlett site, although the same procedure was followed at each of the seven sites. First, we discarded all daytime and nighttime observations during periods when the friction velocity ($\bar{u}'$) was below a minimum threshold. This threshold was based on previous publications for the site (Table 2: 0.375 m s$^{-1}$ in Bartlett), and was determined to eliminate any statistical relationship between NEE and $\bar{u}'$ ($P > 0.1$). Second, we avoided seasonal effects by selecting only those growing season months with a comparable daily pattern of NEE (June and July; differences across each half-hour bin are smaller than 1.5 μmol m$^{-2}$ s$^{-1}$, Fig. 1). Only these 2 months were used in subsequent analyses. Third, these data were divided into night (PAR $<$ 5 μmol m$^{-2}$ s$^{-1}$) and day. For daytime analyses, we selected NEE values that occurred on the asymptotic (saturating) part of the NEE vs. PAR curve. Variation in PAR within this asymptotic region explained less than 1% of the variation in NEE data (PAR $>$ 1000 μmol m$^{-2}$ s$^{-1}$ in Bartlett). PAR cut-off values for the other sites are given in Table 2. Fourth, we used a simple regression to quantify the correlation between NEE and the diffuse PAR fraction, air temperature ($T_a$), net radiation ($R_{net}$), soil water content (SWC), relative humidity (RH), vapor pressure deficit (VPD), wind speed ($u$), wind direction (WD), friction velocity ($\bar{u}'$), sensible (H) and latent (LE) heat flux. We selected the environmental variable that had the largest effect on NEE (VPD for Bartlett, $r^2 = 0.21$, $p < 0.01$), and defined values within a narrow range of VPD, such that VPD variation accounted for less than 1% of NEE variation (for Bartlett, VPD $=$ 1.5–1.8 kPa, $r^2 < 0.01$; $P = 0.97$). Fifth, we analyzed the correlation of this subset of NEE data with the abovementioned environmental variables after applying the VPD filter, and observed that RH was then the most important variable affecting NEE. Hence, we selected NEE values with RH between 40% and 70%, and NEE variation then became independent of RH ($r^2 = 0.01$; $P = 0.039$). We followed this procedure until we obtained a subset of the NEE data where all of the environmental variables had a negligible ($r^2 < 0.04$) effect on NEE.

The filter also included $u$, WD, and $\bar{u}'$ to avoid the potential influence of changing meteorological conditions, such as daily...
changes in local wind patterns affecting the footprint of the eddy covariance measurement, or micro-to-mesoscale meteorological effects such as convection. The effect of early–morning releases of nighttime-stored CO₂ in tall forest canopies was assumed to be negligible because the filter selected data at least 2.5–3 h after dawn (defined as PAR >5 μmol m⁻² s⁻¹; Table 4).

We also assessed whether: (a) daily NEE was within one standard deviation of the mean NEE for the study period (determined for the aforementioned subset) to ensure that filtered NEE data were representative of the larger NEE dataset; and (b) daily NEE up to 2 days before a particular NEE observation was within one standard deviation of the mean NEE. This assessment was necessary to minimize day-to-day variation and ensure comparable antecedent conditions; our goal was to exclude NEE data from days for which the near-past environmental conditions could have been quite different from the day in question (Resco et al., 2009b; Savage et al., 2009). However, the magnitude of daily variation in NEE under a constant environment after and before applying this filter for antecedent conditions was not significantly different (t-test; P = 0.8).

Finally, we discarded individual half-hour bins with a sample size less than 5, to avoid the effects of a low sample size. Final sample sizes varied across stations, ranging from 160 to 2114 data points per site for daytime and from 136 to 4598 for nighttime data (Tables 2 and 3). On average, there were 104 data points for any given time period and site. Normality of the filtered dataset was tested with a quantile-quantile plot.

Because leaf and air temperature can be temporarily decoupled (Smith, 1978; Helliker & Richter, 2008), we also calculated leaf temperature (Tᵢ; Blanken & Black, 2004):

\[ T_\alpha = T_a + \left( \frac{1}{\rho C_p} \right) \frac{H}{G_a} \]  
(Eqn 1)

where \( T_a \) is air temperature, \( \rho \) and \( C_p \) the density and specific heat of air, respectively, \( H \) the sensible heat flux, and \( G_a \) the aerodynamic conductance (calculation in Appendix S1). We observed that, after filter application, the effect of leaf temperature was also negligible (r² < 0.01, Tables 2 and 3).

### Statistical analyses

If regulation of NEE by endogenous processes is present, variation in the filtered dataset should vary significantly with time. However, incorporating the effects of changes in the environment should not significantly increase the goodness-of-fit of a model based solely on time. This was tested by fitting a linear model that only included time (model 1):

\[ NEE_f = a + b \cos(2\pi/24) + c \sin(2\pi/24) + e \]  
(Eqn 2)

where NEEf indicates filtered NEE, \( t \) indicates time (in hours) and \( a, b, \) and \( c \) indicate fitting parameters. We compared the performance of model 1 to that of a mixed model (sensu Crawley, 2007) that extended Eqn 2 to also include PAR, \( T_a \), and VPD as continuous random terms (model 2). The models were fit using maximum likelihood by assuming that the errors (\( e \)) are normally distributed; ten-thousand Monte Carlo iterations were run to obtain maximum likelihood estimates (MLEs) and approximately 95% confidence intervals. Appendix S3 presents the R code for the analyses. Only VPD, \( T_a \) and PAR were selected in the mixed model, as these are considered the main drivers of daytime ecosystem assimilation (Lasslop et al., 2010).

To avoid the potentially problematic assumptions of normally distributed errors and of the functional forms assumed in the linear models above, we also parameterized the Self-Organizing Linear Output map (SOLO; Hsu et al., 2002), an Artificial Neural Network that has been proposed for use as a benchmark to evaluate the performance of land surface models (Abramowitz, 2005). The relationship between inputs and outputs in SOLO is established in three stages. First, the Self Organized Feature Map (SOFM; Kohonen, 1989) is used to classify input data into different nodes. A linear regression is then performed between input and output data within each node. This results in a piecewise linear regression of the training data. Following the same logic as in the previous analysis, we...

### Table 4 Temporal changes in NEE and canopy conductance \( (G_c) \), the effect of PAR on filtered NEE and time periods selected by the filter

<table>
<thead>
<tr>
<th>Site</th>
<th>DiurnalΔNEE (μmol m⁻² s⁻¹)</th>
<th>Filtered ΔNEE (μmol m⁻² s⁻¹)</th>
<th>Filtered ΔNEE normalized (%)</th>
<th>Filtered ΔGc normalized (%)</th>
<th>Sensitivity to changes in PAR (±95% CI)</th>
<th>Dawn-dusk (h)</th>
<th>Daytime filtering (h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrow</td>
<td>2.16</td>
<td>1.76</td>
<td>89.57</td>
<td>48.06</td>
<td>0.05 (±0.17)</td>
<td>00.00–23.30</td>
<td>07.00–20.30</td>
</tr>
<tr>
<td>Bartlett</td>
<td>6.86</td>
<td>3.56</td>
<td>20.18</td>
<td>25.34</td>
<td>−0.39 (±1.13)</td>
<td>04.00–19.30</td>
<td>09.00–15.30</td>
</tr>
<tr>
<td>Howland</td>
<td>7.41</td>
<td>4.77</td>
<td>32.88</td>
<td>38.41</td>
<td>0.53 (±0.61)</td>
<td>03.30–19.30</td>
<td>07.00–15.30</td>
</tr>
<tr>
<td>Niwot Ridge</td>
<td>4.84</td>
<td>4.51</td>
<td>40.69</td>
<td>50.08</td>
<td>0.29 (±0.59)</td>
<td>04.30–19.00</td>
<td>07.30–16.00</td>
</tr>
<tr>
<td>Sky Oaks</td>
<td>1.55</td>
<td>1.62</td>
<td>24.96</td>
<td>21.80</td>
<td>−0.04 (±0.58)</td>
<td>04.00–20.00</td>
<td>08.00–16.00</td>
</tr>
<tr>
<td>SRM</td>
<td>3.29</td>
<td>3.25</td>
<td>44.77</td>
<td>44.77</td>
<td>0.32 (±1.19)</td>
<td>06.30–19.30</td>
<td>09.30–16.00</td>
</tr>
<tr>
<td>Tapajos</td>
<td>15.66</td>
<td>17.24</td>
<td>84.76</td>
<td>61.64</td>
<td>−0.77 (±0.66)</td>
<td>06.00–18.30</td>
<td>08.30–16.30</td>
</tr>
</tbody>
</table>

ΔNEE (minimum NEE – maximum NEE) from Fig. 2 across the study period before (diurnal) and after (filtered) applying the filter, ratio of filtered ΔNEE and ΔGc to minimum NEE and Gc after filtering (filtered ΔNEE and ΔGc normalized, respectively), sensitivity of endogenous NEE to the changes in PAR that occurred during the filtered dataset, time of dawn and dusk (PAR >5 μmol m⁻² s⁻¹) and the part of the day that resulted after filtering in local time.

compared the performance of two different SOLO parameterizations for each site. The first one included time as the only input (model 3), and the second one included time, PAR, $T_{\nu}$, and VPD (model 4).

These different models were compared with the Akaikes Information Criterion (AIC) and the Bayesian Information Criterion (BIC). Simplifying, both criterions evaluate the maximized value of the likelihood function (related to 'goodness-of-fit') and 'penalize' for increasing model parameters, with BIC putting greater emphasis on penalization. The model with the lowest AIC and BIC is deemed the better model; AIC and BIC are computed as:

$$AIC = -2L(MLE) + 2p$$ (Eqn 3)

$$BIC = -2L(MLE) + \log(n)p$$ (Eqn 4)

where $L(MLE)$ is the likelihood function evaluated at the maximum likelihood estimates, $p$ is the number of parameters and $n$ is the number of observations. Akaikes Information Criterion reduction ($\Delta AIC$) was slightly modified from Burnham & Anderson (2002) and calculated as $AIC_1 - AIC_{\nu}$, where $AIC_1$ indicates AIC values for models incorporating only time (models 1 and 3), and $AIC_{\nu}$ is for models incorporating time and environmental variables (models 2 and 4). $\Delta BIC$ was computed similarly to $\Delta AIC$. It is important to note that we only compared models 1 with 2 and 3 with 4, and no attempt was made for a full comparison of the 4 models. In addition, the root mean square error and mean absolute error were calculated for models 3 and 4. Statistical analyses were implemented in R (R Development Core Team, 2011), using the packages ‘MCMCpack’ for linear regression with Monte Carlo simulations (Martin et al., 2011), ‘lme4’ for mixed models (Bates et al., 2011) and ‘languageR’ (Baayen, 2011) to extract confidence intervals in mixed model estimates.

**Results**

The filter was effective in removing the direct effects of the environment on filtered NEE; the coefficient of determination ($r^2$) between filtered NEE and each environmental variable was always lower than 0.04 (Tables 2 and 3). However, a similar temporal pattern between filtered and nonfiltered NEE emerged at all sites even after decoupling NEE from environmental variation. Indeed, time of day was the only covariate significantly correlated with filtered daytime NEE, and the significance of time persisted across all sites except the chaparral site (Fig. 2a-g). A large portion of the day was left out at all sites as a result of selecting only high PAR values. For instance, data for only 6.5 h, from 09:30 to 16:00 hours, were available at the savanna site (Fig. 2f). However, even in this extreme case, there is a statistically significant and visually apparent decline in both filtered and nonfiltered NEE through time.

Following Burnham & Anderson (2002), $\Delta AIC$ shows that model 1 was more likely than model 2 at Bartlett, Niwot Ridge, and Santa Rita Mesquite; that models 1 and 2 were equally likely at Tapajos; and that model 2 was more likely than model 1 at Barrow, Howland, and Sky Oaks. $\Delta BIC$ indicates that model 1 is more likely than model 2 at all sites except Barrow and Sky Oaks. Thus, we can conclude that the inclusion of PAR, $T_{\nu}$, VPD in model 2 did not significantly improve model performance as compared with considering only time (model 1) at all sites except at the tundra and chaparral sites. That is, the effect of time on filtered NEE precedes the effect of these environmental variables (Fig. 2a-g, S6, Table 5).

However, it could be argued that this statistical modeling approach is arbitrary and not very flexible as, amongst other potential problems, certain assumptions about the distribution of the data and functional relationships are made. Thus, one may argue that a nonparametric approach, such as the SOLO algorithm, is more appropriate. Results from the SOLO algorithm further indicate a nonsignificant effect of environmental variables at nearly all sites. We observed a smaller AIC in the model that was solely dependent on time (model 3) than on the model with time and environmental drivers (model 4) at all sites except the chaparral site (Table 5). The root mean square error and the mean absolute error for both models are very similar, and the increase in AIC observed in model 4 was largely due to increasing the number of parameters. Examination of the 95% CI in Fig. 2 also indicate that Sky Oaks is the only site where no statistical differences across half-hour average values are observed.

A sensitivity analysis reinforced the finding that environmental variation exerted a negligible effect on filtered NEE. It could be argued that, despite the restrictive filtering, PAR could still exert some influence over NEE under constant conditions. However, the effect of changing PAR under constant conditions was rather limited. Following the Bartlett example, we observed that the estimated slope of the relationship between filtered NEE and PAR was $-0.00062$. Mean half-hour PAR at Bartlett varied by 632.2 $\mu$mol m$^{-2}$ s$^{-1}$ (spanned from 1732.3 (at 12:30 hours) to 1100.2 $\mu$mol m$^{-2}$ s$^{-1}$ (at 16:00 hours)) after filtering, a range of 632.2 $\mu$mol m$^{-2}$ s$^{-1}$. The expected change in the filtered NEE to this change in PAR (that is, 632.2 $\times$ 0.00062) was 0.39 $\mu$mol m$^{-2}$ s$^{-1}$, which could not explain the much larger variation in NEE observed under constant conditions (range $=3.56$ $\mu$mol m$^{-2}$ s$^{-1}$; Fig. 2c; Table 4). The sensitivity of NEE to changes in PAR for all sites is given in Table 4, where the 95% CI revealed that no slope was statistically different from zero.

The filter selects for a limited set of NEE values, and this selection is based on visual inspection of the relationship between NEE and each environmental variable.
It could thus be argued that if different thresholds had been selected for the acceptance of data, a different result would have emerged. In our preliminary analyses, we selected different combinations of environmental conditions until the final $r^2$ conditions were met, and the temporal pattern of filtered NEE remained unchanged (data not shown).

There were differences in the pattern of filtered NEE across sites. A morning increase in filtered NEE can be seen at the tundra (Fig. 2a), conifer temperate (Fig. 2c), subalpine conifer (Fig. 2d), and tropical forest (Fig. 2g) sites. An afternoon decline in filtered NEE is apparent at all sites. Filtered NEE is higher than nonfiltered NEE at all sites except the tundra (Fig. 2a).

Fig. 2 Temporal variation in Net Ecosystem Exchange (NEE) of CO$_2$ and soil respiration (SR). Daytime data for (a) Barrow (tundra), (b) Bartlett (hardwood temperate forest), (c) Howland (coniferous temperate forest), (d) Niwot Ridge (subalpine conifer forest), (e) Sky Oaks (chaparral), (f) Santa Rita Mesquite (mesquite savannah), and (g) Tapajos (tropical forest). (h) Nighttime variation in filtered NEE as a function of time since dusk (when PAR < $5 \mu$mol m$^{-2}$ s$^{-1}$). The X and Y axis are scaled differently because the period with constant conditions and flux magnitude, respectively, differed across sites. Error bars represent 95% CI Sample size is given in Tables S2 and S3. ‘Non-filtered NEE’ represents NEE for the same part of the year as filtered NEE.
Table 5 Parameter estimates and model comparison

<table>
<thead>
<tr>
<th>Site</th>
<th>AIC – Model 3</th>
<th>AIC – Model 4</th>
<th>ΔAIC</th>
<th>RMSE – Model 3 (μmol m⁻² s⁻¹)</th>
<th>RMSE – Model 4 (μmol m⁻² s⁻¹)</th>
<th>MAE – Model 3 (μmol m⁻² s⁻¹)</th>
<th>MAE – Model 4 (μmol m⁻² s⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrow</td>
<td>3860.91</td>
<td>3862.66</td>
<td>−1.75</td>
<td>1.37</td>
<td>1.36</td>
<td>1.04</td>
<td>1.05</td>
</tr>
<tr>
<td>Bartlett</td>
<td>1003.03</td>
<td>1026.81</td>
<td>−23.78</td>
<td>4.85</td>
<td>4.84</td>
<td>3.84</td>
<td>3.85</td>
</tr>
<tr>
<td>Howland</td>
<td>3987.85</td>
<td>3991.89</td>
<td>−4.04</td>
<td>3.76</td>
<td>3.71</td>
<td>2.85</td>
<td>2.78</td>
</tr>
<tr>
<td>Niwot Ridge</td>
<td>1225.68</td>
<td>1260.22</td>
<td>−34.54</td>
<td>2.45</td>
<td>2.50</td>
<td>1.93</td>
<td>1.91</td>
</tr>
<tr>
<td>Sky Oaks</td>
<td>2686.18</td>
<td>2628.49</td>
<td>57.69</td>
<td>2.38</td>
<td>2.22</td>
<td>1.92</td>
<td>1.76</td>
</tr>
<tr>
<td>Santa Rita</td>
<td>739.28</td>
<td>779.66</td>
<td>−40.38</td>
<td>2.05</td>
<td>2.15</td>
<td>1.56</td>
<td>1.66</td>
</tr>
<tr>
<td>Tapajos</td>
<td>10914.85</td>
<td>10978.85</td>
<td>−64</td>
<td>10.96</td>
<td>11.11</td>
<td>8.03</td>
<td>8.25</td>
</tr>
</tbody>
</table>

Parameter estimates for model 1 (Eqn 2); comparison of models 1 and 2 and models 3 and 4. Reduction (Δ) Akaike and Bayesian Information Criterions (AIC and BIC) were used to compare the performance of models 1 and 2. ΔAIC, Root Mean Square Error (RMSE) and Mean Absolute Error (MAE) were used to compare the performance of models 3 and 4.

Discussion

**NEE is not exclusively driven by direct physiological responses to environmental cues**

Based on the filtered dataset, we observed significant, rhythmic, daily variation in NEE under nearly constant environmental conditions during the daytime (Fig. 2a–g), but not during nighttime (Fig. 2h) at six of seven sites. This temporal behavior followed a generally similar pattern among sites and had a magnitude comparable to the daily NEE variation within each site (Fig. 2a–g, Table 4). The ratio of NEE variation to the maximum NEE under constant environmental conditions ranged from 20% to 90%, with an average across sites of 48% (Table 4). Despite the large variation in the filtered dataset with time, each environmental variable under the constant environment typically explained less than 1% of NEE variation (Tables 2 and 3). This is in contrast with current conventional wisdom that daily NEE variations result almost exclusively from direct physiological responses to environmental cues.

Net ecosystem exchange is the difference between gross ecosystem-level carbon assimilation and ecosystem respiration, which is often dominated by the soil CO₂ efflux (Janssens et al., 2001). The rhythmic behavior of daytime NEE under constant environmental conditions appears to be caused by changes in gross ecosystem-level assimilation because the filtered soil respiration data exhibited either an invariant or a different temporal pattern (Fig. 2a–g), at least at those sites with available data. Moreover, temporal changes in the rates of foliage and stem respiration would not explain the observed temporal variation in NEE because respiration is a negative contribution to NEE that tends to peak around noon (Hibbard et al., 2005), which would have led to reduced NEE around that time, while we observed the opposite pattern. The presence of daytime temporal variation in NEE (i.e., a significant time effect) under constant environmental conditions, and its absence during nighttime, suggests the potential for a...
strong endogenous control of photosynthesis, which in-
turn affects NEE.

Despite our restrictive filtering procedure, it could
still be argued that other environmental or biological
factors could have produced the temporal variation in
observed NEE. For example, changes in the geometry
of leaf angles and azimuth relative to solar elevation
(Falster & Westoby, 2003) could have contributed to the
observed NEE patterns. This could be particularly trou-
blesome at the tundra site (Barrow) where monocotyle-
dons and dicotyledons show contrasting orientations
and canopy positions (Tieszen, 1978). However, leaf
angles only influence carbon assimilation when radia-
tion is direct; under diffuse radiation, the angular dis-
tribution of light is isotropic and does not change
throughout the day. We repeated the filtering analysis
at Barrow under high diffuse radiation (>70%) and
found that the filtered NEE pattern observed at Barrow
is not the result of the changes in the leaf energy bal-
ance or canopy illumination which would result from
varying leaf angle (data not shown).

Possible mechanisms leading to a diurnal pattern of
filtered NEE

Variation in net carbon assimilation under constant
conditions could be driven by one or more endogenous
mechanisms, including fluctuations in chloroplast car-
bohydrate concentrations, changes in stomatal conduc-
tance, photorespiration, or circadian regulation of gas
exchange. Accurately quantifying the explicit impor-
tance of each of these different mechanisms would
require very detailed experiments under controlled
environments. Nevertheless, some hypotheses may be
drawn from this study.

Fluctuations in carbohydrate concentrations could
affect the daytime pattern of filtered NEE if source/sink
dynamics drive carbon assimilation. If the sink of car-
bohydrates (any part of the plant to which carbohy-
drates are transported) saturates, a feedback inhibition
on the source (leaves) carbon fixation could occur. Con-
versely, a large demand for carbohydrates in sink tis-
ues could lead to greater photosynthesis. Increased
carbohydrate concentrations lead to a feedback inhibi-
tion of Rubisco activity (Paul & Foyer, 2001), and this
feedback could partially explain the afternoon decline
in CO₂ uptake under constant environmental condi-
tions observed at the temperate hardwood (Fig. 2b)
and savanna (Fig. 2d) sites. However, the increasing
rate of CO₂ uptake observed during the morning (from
~7 to 10 local time) at the tundra (Fig. 2a), conifer tem-
perate (Fig. 2c), subalpine coniferous (Fig. 2f), and
tropical forest (Fig. 2g) sites cannot be explained by
carbohydrate accumulation. Moreover, as foliage
carbohydrate concentration is minimal at dawn (Smith
& Stitt, 2007), we should expect maximum assimilation
early in the morning if this were the main process con-
trolling NEE under constant conditions.

Lower CO₂ uptake in the morning and afternoon
under constant environmental conditions could be dri-
ven by reductions in either stomatal conductance or
biochemical capacity (Farquhar & Sharkey, 1982). Daily
changes in stomatal conductance are concurrently dri-
ven by endogenous processes (e.g., the circadian clock,
increasing losses in hydraulic conductivity, morning
stomatal ‘sluggishness’; Dodd et al., 2004; Franks, 2004)
as well as by direct feedback and, potentially, feedfor-
ward loops from direct responses to environmental
changes (Raschke, 1975; Buckley, 2005). Reduced sto-
matal conductance early and late in the day would be
expected to influence photosynthetic carbon uptake
leading to a draw-down of intercellular CO₂ concen-
tration. A decline in intercellular CO₂ driven by stomatal
closure could occur if the diurnal proportional change
in conductance was larger than in NEE. In our filtered
dataset, the changes in NEE could not be solely attrib-
uted to changes in canopy conductance. The diel
change in canopy conductance was either proportion-
ally smaller than the changes in NEE (Fig. 3a, e, f, g;
Table 4) or largely decoupled from the changes in NEE
(Fig. 3b, c, d). For instance, carbon assimilation at the
temperate conifer forest (Fig. 3c) increased between
07:00 hours and 09:00 hours (local time) and decreased
in the afternoon, whereas canopy conductance
decreased between 07:00 hours and 09:00 hours and
remained fairly constant afterward (Fig. 3c). This
implies that the temporal patterns in NEE under con-
stant environmental conditions are not due solely to
variations in stomatal conductance. The absence of
strong stomatal limitations in the afternoon does not
suggest an a priori reason to expect diel changes in the
strength of photorespiration leading to a diurnal CO₂
uptake pattern in the filtered dataset (Wingler et al.,
2000).

We therefore propose that circadian regulation of
biochemical capacity is an important driver of daily
NEE patterns. In particular, circadian regulation is the
most plausible explanation for the morning increase in
CO₂ uptake at the tundra (Fig. 2a), temperate conifer
(Fig. 2c), subalpine coniferous (Fig. 2d), and tropical
forest (Fig. 2g), and is a plausible explanation for at
least part of the afternoon decline in CO₂ uptake under
constant conditions observed at all sites.

We note that the possible endogenous controls on gas
exchange are not mutually exclusive, but probably
co-occur, and may shift in relative importance as the
day advances. For instance, stomatal sluggishness may
be more important in the morning than carbohydrate

feedbacks, which may increase in importance later in the day, whereas the circadian clock effect is likely to remain constant throughout the day.

It is important to note that endogenous regulation will not increase NEE when external conditions are limiting. Instead, endogenous regulation will yield a predictable, time varying 'base-line' carbon uptake capacity that will be further modified by the environmental conditions at any given moment. At the tundra site (Fig. 2a), the filter selected for constant, yet suboptimal conditions for carbon assimilation, which resulted in lower NEE in the filtered dataset as compared with the non-filtered dataset. The higher NEE values of the filtered dataset at the conifer temperate and subalpine forests, chaparral, and savanna sites indicate that the filter selected for constant and close to optimal environmental conditions.

Our hypothesis that the circadian clock affects diel patterns of NEE may sound surprising at first. It has been often argued that “nothing in biology makes sense except under the light of evolution” (Dobzhansky, 1973). Much current research on NEE lies, either implicitly or explicitly, on evolutionary assumptions about the adaptation of organisms to climatic or other conditions.

Fig. 3 Relationship between Net Ecosystem Exchange (NEE) and canopy conductance ($G_c$) for the filtered dataset. (a) Barrow (tundra), (b) Bartlett (hardwood temperate forest), (c) Howland (coniferous temperate forest), (d) Niwot Ridge (subalpine conifer forest), (e) Sky Oaks (chaparral), (f) Santa Rita Mesquite (mesquite savanna), and (g) Tapajos (tropical forest). The X and Y axis are scaled differently because the period with constant conditions and flux magnitude, respectively, differed across sites. Error bars represent 95% CI. Sample size is given in Table S2. ‘Non-filtered NEE’ represents NEE for the same part of the year as filtered NEE.
environmental factors, many of which show high interannual variability and limited predictability (such as rainfall or temperature regimes; Chapin et al., 2002). However, the photoperiod is a highly predictable and constant (across years) environmental variable that exerts a central control on carbon assimilation. All photoperiod responses studied to date are regulated by the circadian clock (Yakir et al., 2007), and circadian regulation of gas exchange has been explicitly linked with evolutionary success (Dodd et al., 2004).

Implications

Perhaps the most important implication in a circadian regulation of NEE is that it opens a new and promising understanding of ecological systems that truly and directly connects molecular mechanisms with land surface processes, in previously unrecognized ways. Another important conceptual implication stems from the fact that circadian rhythms are cell-autonomous systems entrained by environmental cues of light and temperature (Harmer, 2009). This implies that asynchronous circadian regulation, not only within different plant functional types (e.g., canopy trees and below-canopy shrubs), but also within a single organism (e.g., shade vs. sun leaves, photosynthesis vs. phloem loading) and, perhaps, even within a single leaf (when the outer portion is more exposed to different light and temperature regimes than the inner portion) is likely to occur as these different components will be exposed to different oscillations in the light and temperature regimes. However, this cell autonomous process seems to lead to an emergent ecosystem synchrony of gas exchange.

This emergent synchrony in endogenous regulation of NEE could perhaps pave the way to a novel generation of integrated, gene-to-ecosystem NEE models with endogenous processes as the core mechanism, and exogenous responses that would modify this core or base-line behavior. However, we first need to clarify the mechanisms underlying gas exchange regulation by the clock beyond the molecular scale.

Hewitt et al. (2011) incorporated circadian regulation of isoprene emissions as a high order polynomial function of time, which may be justified considering our poor mechanistic understanding of the underlying processes. For carbon assimilation models, we suspect that incorporation of empirical time-vary functions, meant to represent endogenous effects, into current mechanistic models of plant photosynthesis may often lead to only limited improvements to model fit or predictive ability. This was demonstrated by Williams & Gorton (1998), who incorporated sinusoidal temporal variation in electron transport, carboxylation capacity, and stomatal conductance into a mechanistic model, and found only a small (but significant) improvement in the fit of the model to field data. However, we do not believe it is appropriate to represent endogenous processes within a modeling framework by adding an empirical function of time without having previously removed any environmental effects. Any increase in model fit by adding such an empirical function may just be the result of the spurious correlation of time with light, temperature or other environmental cues, or from the inaccurate mathematical representation of how these factors affect leaf biochemistry.

Close synchronization of endogenous controls with the typical daily oscillations of light, temperature, and evaporative demand usually occur in the field (Doughty et al., 2006; Webb, 2003; Yerushalmi & Green, 2009; Fig. 2 a-g). Light and temperature show strong diurnal trends, and their variation is highly correlated with time. Endogenous plant rhythms also show strong diurnal trends that are similarly correlated with time. Empirical and mechanistic models of carbon assimilation already incorporate daily variations of light and temperature and are thus likely to indirectly absorb a large part of the variation in daily carbon assimilation that may be attributed to endogenous plant rhythms. In other words, the tight association between the daily pattern of light and temperature with endogenous rhythms obscures the potential importance of endogenous controls, and creates a situation where strong correlations between NEE and the physical environment may be interpreted as exclusive causation, overlooking the possibility that NEE may be controlled by a combination of endogenous and exogenous factors.

A seemingly logical conclusion would be that endogenous regulation is insignificant as its effect is already captured by our current modeling approaches, albeit indirectly. However, this assumption could reduce the predictive ability of such models, and may result in incorrect interpretations of how different environmental drivers govern NEE. That is, a danger in ignoring endogenous regulation is that current models based on the direct effects of the physical environment on leaf physiology (Hanson et al., 2004) may produce a ‘correct’ result for a partially ‘wrong’ reason, potentially compromising their ability to predict CO₂ fluxes and carbon budgets under future no-analog, novel conditions. Thus, we argue for new research aimed at understanding the effect of different endogenous processes, and particularly the circadian clock, on NEE. In the longer term, this may lead to novel and deeper understanding of ecological systems that integrates from genes to ecosystems.
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References


**Supporting Information**

Additional Supporting Information may be found in the online version of this article:

**Appendix S1.** Estimation of canopy conductance.

**Appendix S2.** Estimation of diffuse and direct radiation.

**Appendix S3.** R code for models 1 and 2.

**Appendix S4.** Supplementary references.

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