

Article

Using Eddy Covariance Sensors to Quantify Carbon Metabolism of Peatlands: A Case Study in Turkey

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Abstract: Net ecosystem exchange (NEE) of carbon dioxide (CO₂) was measured in a cool temperate peatland in northwestern Turkey on a continuous basis using eddy covariance (EC) sensors and multiple (non-)linear regression-M(N)LR-models. Our results showed that hourly NEE varied between -1.26 and 1.06 mg CO₂ m⁻² s⁻¹, with a mean value of 0.11 mg CO₂ m⁻² s⁻¹. Nighttime ecosystem respiration (R_E) was on average measured as 0.23 ± 0.09 mg CO₂ m⁻² s⁻¹. Two best-fit M(N)LR models estimated daytime R_E as 0.64 ± 0.31 and 0.24 ± 0.05 mg CO₂ m⁻² s⁻¹. Total R_E as the sum of nighttime and daytime R_E ranged from 0.47 to 0.87 mg CO₂ m⁻² s⁻¹, thus yielding estimates of gross primary productivity (GPP) at -0.35 ± 0.18 and -0.74 ± 0.43 mg CO₂ m⁻² s⁻¹. Use of EC sensors and M(N)LR models is one of the most direct ways to quantify turbulent CO₂ exchanges among the soil, vegetation and atmosphere within the atmospheric boundary layer, as well as source and sink behaviors of ecosystems.

Keywords: carbon cycle; flux tower; biogeochemical model; diurnal variation

1. Introduction

Though spatially small (5% of the terrestrial biosphere) compared with most other ecosystems [1,2], peatlands play a significant role in carbon (C) and water metabolism of the World. Understanding and quantifying C dynamics of peatlands are crucial to prediction of responses to global climate change and rehabilitation of peatlands under the increasing magnitude and rate of human-induced disturbances. Eddy Covariance (EC) sensors are one of the most direct ways to measure and estimate turbulent carbon dioxide (CO₂), water vapor and energy fluxes exchanged among soil, vegetation, and atmosphere within the atmospheric boundary layer. The use of the EC method and sensors on a long-term and continuous basis across the World has led to the establishment of an integrated global network for standardization of flux tower activities (called FLUXNET) and a network for standardization and development of spectral sensors toward bridging the gap between remote and proximal sensing (called SpecNET).

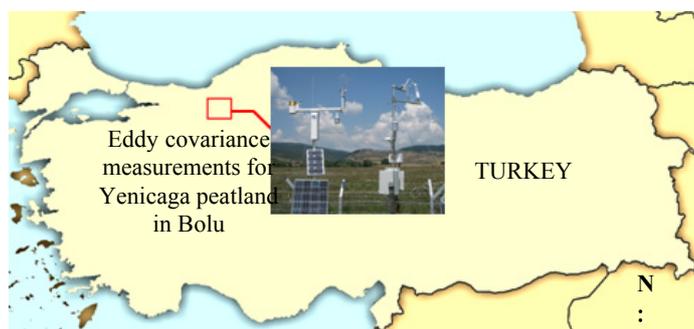
Our study area in Turkey, the Yenicaga peatland area that at one time occupied 240 km², has diminished to less than 30 km² due to drainage, cultivation, afforestation, and peat mining [3,4]. There is a lack of information about C metabolism of peatland ecosystems in Turkey, and this study is the first to comprehensively determine C dynamics and components in one of the remaining major peatlands. The objective of this study was to quantify the rate, magnitude, and timing of CO₂ exchange between the atmosphere and Yenicaga peatland using the EC sensors and multiple (non-)linear regression-M(N)LR-models.

2. Study Site and Methodology

2.1. Description of Study Site

The Yenicaga peatland is located about 38 km east of the city of Bolu (40°47'N, 32°1'E) in the western Black Sea region of Turkey (Figure 1).

Figure 1. Location of the study site “Yenicaga peatland” in northwestern Turkey.



An EC flux tower site was installed about 1 km north of Lake Yenicaga (18 km²) at the elevation of 988 m above seal level on July 12, 2010. The climate in the Yenicaga region is classified as cool temperate, with a mean annual temperature and precipitation of 10.2 °C and 538 mm, respectively [5]. The Yenicaga peatland is reported to contain Devonian and cretaceous limestone, basaltic tuff, lava, and olistolites, with the uppermost layer consisting of tertiary and quaternary formations [5]. The natural vegetation types of the Yenicaga peatland consist of the following dominant communities:

(1) *Phragmites australis* and *Typha domingensis* (41.2 ha); and (2) *Ranunculus lingua*, *Acorus calamus*, *Najas marina*, *Pedicularis palustris*, *Senecio paludosus* (107.8 ha) [6]. The mean vegetation height around the flux tower is about 0.5 m, and the terrain observed around the flux tower exhibits flat and uniform grasslands.

2.2. Eddy Covariance Flux and Ancillary Measurements

Net ecosystem exchange (NEE) rates of carbon dioxide (F_c , $\text{mg m}^{-2} \text{s}^{-1}$) in Yenicaga peatland were estimated using an eddy covariance (EC) system consisting of an open-path $\text{CO}_2/\text{H}_2\text{O}$ gas analyzer (LI-7500, Licor Inc., Lincoln, NB, USA), a 3-D sonic anemometer/thermometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA), a data logger (CR3000, Campbell Scientific Inc.), and a 3-m tower on which EC flux sensors were mounted. The distance between the LI-7500 and CSAT3 sensors was 0.15 m, with CSAT3 oriented towards the prevailing wind direction (an azimuth angle of 30° from true north) and LI-7500 vertically rotated 15° towards the footprint.

Eddy fluxes and associated signals were recorded at 10 Hz, block averaged over one hour (h) and corrected for the effects of fluctuations in air density on $\text{CO}_2/\text{H}_2\text{O}$ fluxes (F_{c_wpl} and LE_{wpl} with WPL correction) through the online flux computation. EC data were collected swapping two 2-GB Compact Flash cards at 14-to-18-day intervals. The net radiation (R_n), downwelling and upwelling longwave (4 to $50 \mu\text{m}$) and shortwave radiation (0.2 to $4 \mu\text{m}$) (R_{l_dn} , R_{l_up} , R_{s_dn} , and R_{s_up} , W m^{-2}) were measured using Kipp & Zonen CNR-4 net radiometers (Kipp & Zonen USA Inc., Bohemia, NY, USA). Air temperature (T_a , $^\circ\text{C}$), and relative humidity (RH, %) were sampled using HMP45C probe (Vaisala, Finland). Precipitation (PPT, mm), evapotranspiration (ET, mm), soil water content (SWC, %), and mean, maximum and minimum soil temperature (ST , ST_{max} , and ST_{min} , $^\circ\text{C}$) were measured on a hourly basis using ET107 weather monitoring station (Campbell Scientific Inc.). Photosynthetically active radiation (PAR) was estimated from net shortwave radiation (R_{s_n}) using a conversion factor of PAR: $R_{s_n} = 0.5$ [7-9]. The values of CO_2 fluxes in unit of $\text{mg m}^{-2} \text{s}^{-1}$ were also converted to unit of $\text{kg C ha}^{-1}\text{day}^{-1}$, based on the following conversion ratios of $\text{mg}:\text{kg} = 10^6$; $\text{s}:\text{day} = 86,400$; $\text{m}^2:\text{ha} = 10,000$; and $\text{CO}_2:\text{C} = 44/12$.

2.3. Data Processing and Analyses

As with the conventional meteorological sign notation, downward and upward fluxes are considered negative ($-$) and positive (\pm), respectively. The first step of data processing involved the removal of erroneous spikes and their associated CO_2 fluxes when latent heat flux (LE_{wpl}) < -100 or $> 800 \text{ W m}^{-2}$; sensible heat flux (H_s) < -150 or $> 500 \text{ W m}^{-2}$; and precipitation events occurred [10]. For both hourly daytime and nighttime CO_2 fluxes, descriptive statistics were given, and best-fit cumulative distribution function (CDF) was selected. Tukey's multiple comparison was performed after one-way analysis of variance (ANOVA) for the entire dataset in order to test significant differences in hourly, nighttime *versus* daytime and monthly means. All the statistical analyses were performed with Minitab 15.1 (Minitab Inc. 2006).

Second, EC data were separated into daytime (R_n and/or $R_{s_dn} > 10 \text{ W m}^{-2}$) and nighttime (R_n and/or $R_{s_dn} \leq 10 \text{ W m}^{-2}$) periods since EC data are more reliable during daytime hours than during nighttime

hours, and nighttime EC data ($F_{c_wpl}^{night}$) can be used to estimate daytime as well as nighttime ecosystem respiration (both plant and soil respiration) ($R_E = F_{c_wpl}^{night}$). Negative night CO₂ flux data were deleted as no gross primary productivity (GPP = 0) occurs during the nighttime. The site-specific threshold value of friction velocity (u^*) was determined as 0.03 m s⁻¹ below which low vertical wind velocity led to underestimation of the nighttime CO₂ fluxes [11]. Likewise, nighttime periods where horizontal wind velocity was less than 1 m s⁻¹ were removed from the dataset. Finally, night fluxes where CO₂ density data had the standard deviation of > 14 mg m⁻³ (0.6 μmole m⁻³) were eliminated from further analyses [12]. Multiple (non-)linear regression models were fitted to the resultant night CO₂ dataset, and best-fit M(N)LR models with and without the inclusion of temporal variables (hour, and month) were chosen using best subsets procedure (low Mallows' C_p , high adjusted R^2 , and low SE). The following soil respiration equations of RothC [13] and CENTURY [14] models were also used to model daytime R_E :

$$f(R_{soil}) = \frac{47.9}{1 + \exp\left(\frac{106}{ST + 18.3}\right)} \text{ for RothC model} \quad (1)$$

$$f(R_{soil}) = 0.56 \pm 0.465 * \arctan(0.097 * (ST - 15.7)) \text{ for CENTURY model} \quad (2)$$

where R_{soil} is soil respiration (mg CO₂ m⁻² s⁻¹), and ST is soil temperature (°C). Net ecosystem exchange (NEE, mg CO₂ m⁻² s⁻¹) can be expressed as follows:

$$NEE = -GPP \pm R_E \quad (3)$$

Hourly GPP values were estimated as the sum of NEE and daytime R_E . Daytime R_E was obtained extrapolating nighttime R_E fluxes to the remaining daytime fluxes, based on M(N)LR models.

3. Results and Discussion

3.1. Diurnal CO₂ Fluxes

Descriptive statistics of despiked and averaged EC data for the period of July 12 to October 17, 2010 indicated that mean hourly CO₂ fluxes above the canopy had a larger temporal variability (CV = 498) than the rest of the measured variables and varied between -1.5 and 1.5 mg m⁻² s⁻¹ (Table 1). During the study period, the study site cumulatively received 92 mm PPT and lost 305 mm water vapor via ET. The mean Bowen ratio of $H_s:LE_{wpl}$ quantifying the evaporative demand of an environment was estimated at 0.37, thus characterizing the Yenicaga peatland as a mesic environment. A logistic CDF with a location of 0.05197 and a scale of 0.1596 appeared to fit our daytime and nighttime F_{c_wpl} data fairly well as follows ($r = 0.99$; $n = 1884$; $P < 0.001$) (Figure 2):

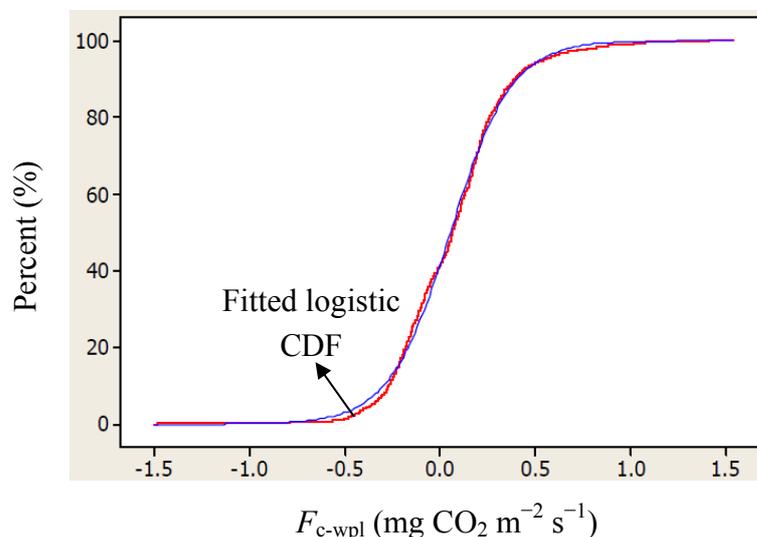
$$CDF_{\text{logistic}} = \frac{1}{1 + e^{-(F_{c_wpl} - \mu)/s}} \quad (4)$$

where μ and s are location and scale parameters of the logistic CDF, respectively. The fitted logistic CDF can be used to estimate percentiles for the CO₂ flux data (Figure 2).

Table 1. Descriptive statistics of eddy covariance and meteorological data collected on an hourly basis in the Yenicaga peatland.

Variable	<i>n</i>	mean	±SD	CV	min	median	max
F_{c_wpl} (mg CO ₂ m ⁻² s ⁻¹)	1,884	0.06	0.30	498	-1.50	0.06	1.53
H_s (W m ⁻²)	1,884	38.40	58.44	152	-78.86	3.01	238.80
LE_{wpl} (W m ⁻²)	1,884	102.69	130.79	127	-92.89	41.40	517.29
u^* (m s ⁻¹)	1,884	0.18	0.12	68	0.01	0.14	0.57
CO ₂ density (mg m ⁻³)	1,884	633.34	118.19	19	243.45	598.57	1,577.23
H ₂ O density (g m ⁻³)	1,884	12.34	4.77	39	-2.62	12.94	47.82
T_a (°C)	1,884	18.15	7.05	39	-0.67	17.95	34.00
RH (%)	1,884	71.54	22.30	31	16.09	76.13	107.80
WD (degree)	1,884	219.91	127.29	58	0.04	265.93	359.89
WS (m s ⁻¹)	1,884	1.73	1.40	81	0.04	1.19	6.14
R_{s_up} (W m ⁻²)	1,884	263.80	309.91	117	-4.91	104.18	981.88
R_{s_dn} (W m ⁻²)	1,884	44.14	48.88	111	-0.19	18.63	153.55
R_{l_up} (W m ⁻²)	1,884	386.85	34.95	9	294.45	386.94	474.95
R_{l_dn} (W m ⁻²)	1,884	413.84	47.55	11	307.63	405.96	531.50
R_n (W m ⁻²)	1,884	192.66	245.44	127	-35.80	68.69	766.03
ET (mm h ⁻¹)	1,680	0.14	0.21	124	0.0	0.02	0.75
PPT (mm h ⁻¹)	1,680	0.04	0.36	825	0.0	0.0	7.8
ST _{min} (°C)	1,680	19.66	3.92	20	8.11	20.03	26.18
ST _{max} (°C)	1,680	19.84	3.96	20	8.19	20.24	27.24
SWC (%)	1,680	75.37	8.73	12	62.98	73.75	89.90

F_{c_wpl} = WPL-corrected CO₂ flux; H_s = sensible heat flux; LE_{wpl} = WPL-corrected latent heat flux; u^* = friction velocity; T_a = air temperature; RH = relative humidity; WD = wind direction; WS = wind speed; R_{s_up} = upwelling shortwave radiation; R_{s_dn} = downwelling shortwave radiation; R_{l_up} = upwelling longwave radiation; R_{l_dn} = downwelling longwave radiation; R_n = net radiation; ET = evapotranspiration; ST_{min} = minimum soil temperature; ST_{max} = maximum soil temperature; SWC = soil water content; CV = coefficient of variation; and SD = standard deviation.

Figure 2. Logistic cumulative distribution function (CDF) fitted to both daytime and nighttime CO₂ fluxes for the Yenicaga peatland: (Location (μ) = 0.05197; scale (s) = 0.1596; $r = 0.99$; $n = 1884$; $P < 0.001$).

Quartic functions (an equation of fourth degree) fitted to both entire and monthly F_{c_wpl} datasets as a function of the explanatory temporal variable (h) provided a meaningful representation of CO₂ fluxes, with a R^2_{adj} value range of 70.9% in July to 31.3% in October (Figures 3 to 7).

Figure 3. A quartic function fitted to the entire F_{c_wpl} dataset in the Yenicaga peatland for the period of July 12 to October 17, 2010: F_{c_wpl} (mg CO₂ m⁻² s⁻¹) = 0.2807 h – 0.0602 h² ± 0.0038 h³ – 7 × 10⁻⁵ h⁴; (R^2_{adj} = 0.5368; SE: 0.2016; n = 1884; P < 0.001).

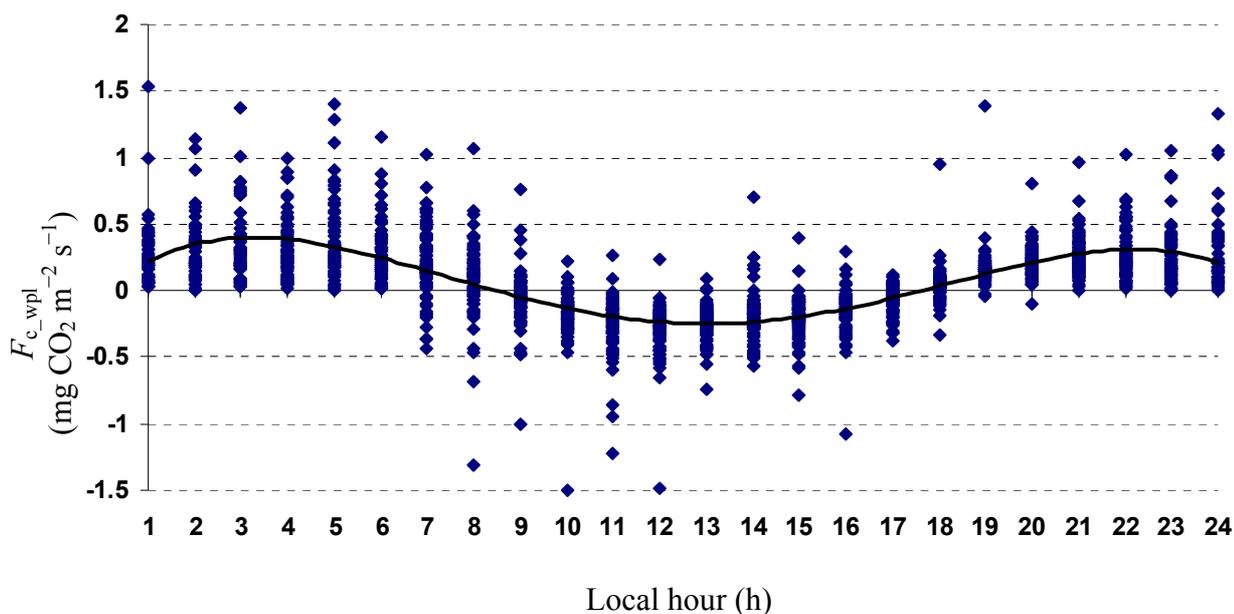


Figure 4. A quartic function fitted to F_{c_wpl} dataset for Yenicaga peatland in July of 2010: F_{c_wpl} (mg CO₂ m⁻² s⁻¹) = 0.3575 h – 0.077 h² ± 0.0049 h³ – 9 × 10⁻⁵ h⁴; (R^2_{adj} = 0.7087; SE = 0.1905; n = 412; P < 0.001).

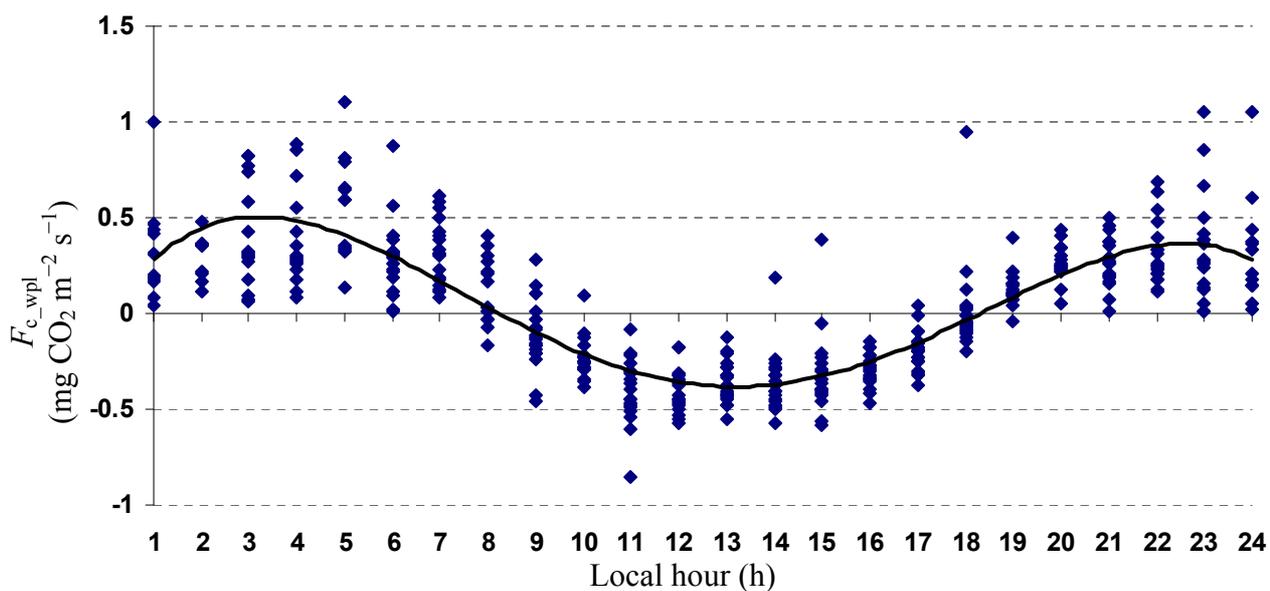


Figure 5. A quartic function fitted to F_{c_wpl} dataset for Yenicaga peatland in August of 2010: F_{c_wpl} ($\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) = $0.3242 \text{ h} - 0.0696 \text{ h}^2 \pm 0.0044 \text{ h}^3 - 9 \times 10^{-5} \text{ h}^4$; ($R^2_{\text{adj}} = 0.5963$; $\text{SE} = 0.1957$; $n = 620$; $P < 0.001$).

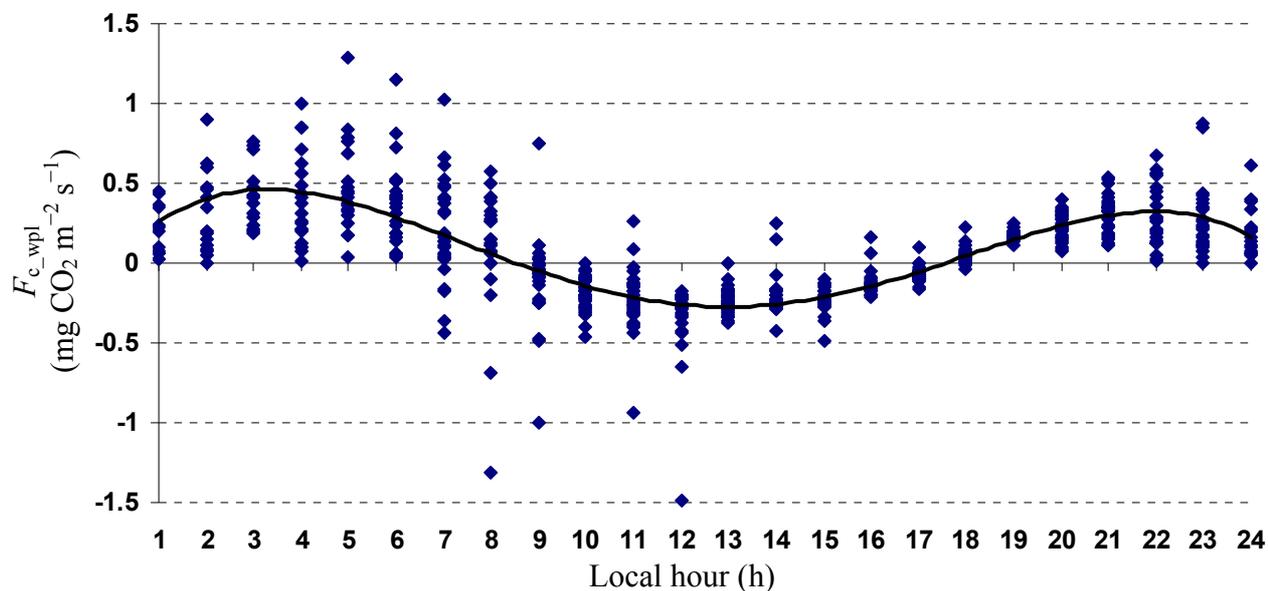


Figure 6. A quartic function fitted to F_{c_wpl} dataset for Yenicaga peatland in September of 2010: F_{c_wpl} ($\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) = $0.2297 \text{ h} - 0.0488 \text{ h}^2 \pm 0.0031 \text{ h}^3 - 6 \times 10^{-5} \text{ h}^4$; ($R^2_{\text{adj}} = 0.4726$; $\text{SE} = 0.1875$; $n = 603$; $P < 0.001$).

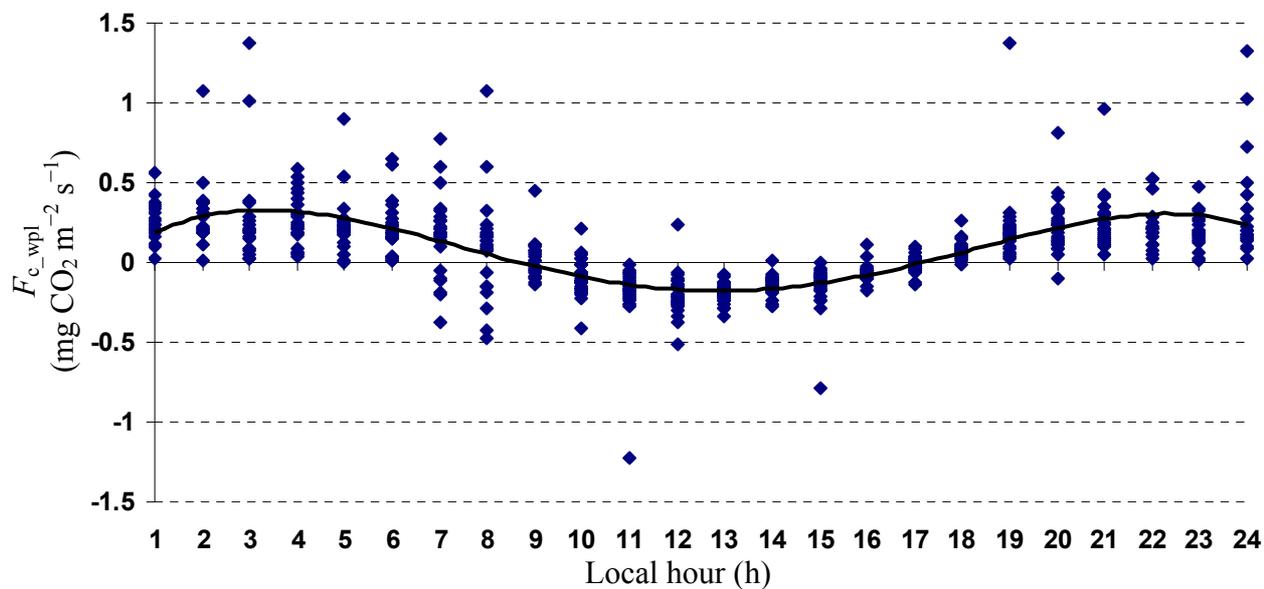
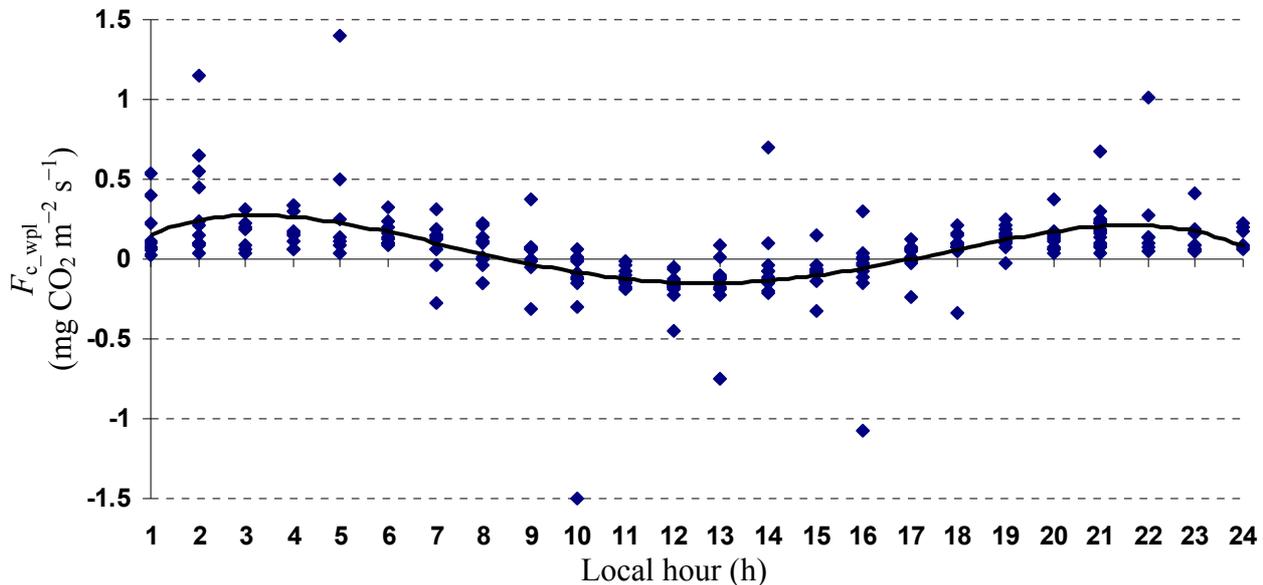


Figure 7. A quartic function fitted to F_{c_wpl} dataset for Yenicaga peatland in October of 2010: F_{c_wpl} ($\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) = $0.1951 \text{ h} - 0.0423 \text{ h}^2 \pm 0.0027 \text{ h}^3 - 5 \times 10^{-5} \text{ h}^4$; ($R^2_{\text{adj}} = 0.3127$; $\text{SE} = 0.2074$; $n = 249$; $P < 0.001$).



3.2. Multitemporal Comparisons of CO_2 Fluxes

The entire dataset of daytime and nighttime CO_2 fluxes ($n = 1,884$) was used for a multiple comparison according to hours, nighttime *versus* daytime, and months, based on Tukey's test following one-way ANOVA (Table 2). A comparison of hourly mean F_{c_wpl} values showed that the Yenicaga peatland acted as a CO_2 sink for the daytime periods between 9:00 AM and 17:00 PM and acted as a CO_2 source for the periods between 18:00 PM and 8:00 AM. On average, the Yenicaga peatland had minimum and maximum CO_2 fluxes ranging from $-0.05 \pm 0.21 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at 9:00 AM to $-0.28 \pm 0.18 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at 12:00 PM as a CO_2 sink and from $0.05 \pm 0.12 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at 18:00 PM to $0.38 \pm 0.29 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ at 5:00 AM as a CO_2 source, respectively (Table 2).

Mean daytime CO_2 flux ($-0.11 \pm 0.22 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) significantly differed from mean nighttime CO_2 flux ($0.26 \pm 0.23 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) ($P < 0.001$). All the monthly mean CO_2 fluxes were positive (upward into the atmosphere) and varied between $0.03 \pm 0.35 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in July and $0.07 \pm 0.25 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in September. However, the monthly mean CO_2 fluxes did not appear to significantly differ from one another (Table 2). The best-fit MNL model was derived from the entire dataset of nighttime and daytime F_{c_wpl} by exploring possible interaction effects among the EC and meteorological variables as follows:

$$\begin{aligned}
 F_{c_wpl} (\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}) = & 0.001394 \text{ month} \pm 0.13776 \text{ h} - 0.029586 \text{ h}^2 \pm 0.0018587 \text{ h}^3 - \\
 & 0.0000358 \text{ h}^4 - 0.05387 \text{ daytime} - 0.003694 H_s \pm 0.00001183 H_s^2 \pm 0.016833 \log(H_s^2) - \\
 & 0.0008682 \text{ LE}_{wpl} - 0.00000059 \text{ LE}^2 \pm 0.038155 \log(\text{LE}^2) - 0.000013 P_a - 0.009471 T_a - \\
 & 0.000879 \text{ RH} \pm 0.00022167 \text{ RH} * T_a - 0.007483 R_{s_dn} \pm 0.0000339 R_{s_dn} * R_{l_up} - \\
 & 0.00000001 \text{ RH} * T_a * R_{s_dn} * R_{l_up} \pm 0.009735 U_z * R_{s_dn} \\
 & (R^2_{\text{adj}} = 62.6\%; \text{SE} = 0.181; n = 1882; P < 0.001)
 \end{aligned} \tag{5}$$

where the variable “daytime” was used as an indicator variable coded as 1 and 0 for daytime and nighttime, respectively, and the sign “*” between the variable notations denotes two-to-four-way interactions.

Table 2. A multiple comparison of mean F_{c_wpl} fluxes ($\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$) in the Yenicaga peatland by different temporal scales ($P < 0.001$).

Local hour	<i>n</i>	mean	SD	Comparison based on 95% confidence intervals
1:00	57	0.254	0.248	(--*-)
2:00	53	0.313	0.242	(--*-)
3:00	55	0.337	0.277	(--*-)
4:00	69	0.320	0.229	(--*-)
5:00	65	0.382	0.296	(--*-)
6:00	72	0.276	0.215	(--*-)
7:00	85	0.209	0.256	(--*-)
8:00	76	0.087	0.295	(--*-)
9:00	82	-0.053	0.210	(--*-)
10:00	90	-0.171	0.187	(--*-)
11:00	89	-0.242	0.203	(--*-)
12:00	91	-0.280	0.187	(--*-)
13:00	91	-0.237	0.122	(--*-)
14:00	91	-0.191	0.168	(--*-)
15:00	89	-0.200	0.156	(--*-)
16:00	88	-0.144	0.158	(--*-)
17:00	90	-0.069	0.101	(--*-)
18:00	91	0.052	0.128	(--*-)
19:00	89	0.171	0.145	(--*-)
20:00	91	0.222	0.117	(--*-)
21:00	85	0.262	0.149	(--*-)
22:00	69	0.275	0.193	(--*-)
23:00	72	0.248	0.212	(--*-)
24:00	54	0.267	0.266	(--*-)
Day vs. night	<i>n</i>	mean	SD	(*)
Daytime	1030	-0.111	0.222	(*)
Nighttime	852	0.266	0.235	(*)
Month	<i>n</i>	mean	SD	(-----*)
July	412	0.039	0.351	(-----*)
August	620	0.054	0.307	(-----*)
September	603	0.077	0.257	(-----*)
October	249	0.064	0.248	(-----*)

3.3. Ecosystem Components of Carbon Metabolism

Nighttime R_E was modeled using (1) best-fit M(N)LR models with/without the forced inclusion of temporal variables (hour and month), and (2) ST-dependent R_{soil} equations [Equations (1) and (2)] of

RothC and CENTURY models with/without the forced addition of SWC. All the R_E models were built with the intercept forced through zero as follows:

$$R_E \text{ (mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}) = 0.0004922 \text{ h} - 0.02111 \text{ month} \pm 0.13747 T_{\text{sonic}} - 0.1496 T_a \pm 0.01119 \\ \text{ST}_{\text{min}} \pm 0.0032329 \text{ SWC} \pm 0.5456 u^* \pm 0.5201 U_z - 0.04903 \text{ WS} - 0.00061 P_a \pm 0.0021203 R_n \\ - 0.0027481 H_s \quad (6)$$

$$(R^2_{\text{adj}} = 73.8\%; \text{ SE} = 0.0473; n = 203; P < 0.001)$$

$$R_E \text{ (mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}) = 0.005383 T_{\text{sonic}} \pm 0.0026921 \text{ SWC} \pm 1.0846 u^* \pm 0.0733 U_z - 0.09595 \\ \text{WS} \pm 0.0009581 H_s - 0.0003665 \text{ RH} \quad (7)$$

$$(R^2_{\text{adj}} = 70.8\%; \text{ SE} = 0.0677; n = 207; P < 0.001)$$

$$R_E \text{ (mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}) = 0.33084 \text{ CENTURY} \quad (8)$$

$$(R^2_{\text{adj}} = 42.0\%; \text{ SE} = 0.0708; n = 207; P < 0.001)$$

$$R_E \text{ (mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}) = 0.085842 \text{ RothC} \quad (9)$$

$$(R^2_{\text{adj}} = 44.3\%; \text{ SE} = 0.0686; n = 207; P < 0.001)$$

$$R_E \text{ (mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}) = 0.071387 \text{ RothC} \pm 0.0005546 \text{ SWC} \quad (10)$$

$$(R^2_{\text{adj}} = 53.0\%; \text{ SE} = 0.0684; n = 207; P < 0.001)$$

$$R_E \text{ (mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}) = 0.28185 \text{ CENTURY} \pm 0.0004839 \text{ SWC} \quad (11)$$

$$(R^2_{\text{adj}} = 53.3\%; \text{ SE} = 0.0708; n = 207; P < 0.001)$$

where T_{sonic} is sonic temperature ($^{\circ}\text{C}$), U_z is vertical wind speed (m s^{-1}), and P_a is air pressure (kPa). Nighttime R_E Equations (6) and (11) were used to estimate daytime R_E values which in turn led to the estimation of $-GPP$ component from Equation (3) as can be seen in Figures 8 and 9.

Figure 8. Estimation of GPP and daytime R_E components for the Yenicaga peatland based on Equation (6) ($n = 1021$ for NEE; and $n = 896$ for GPP and R_E).

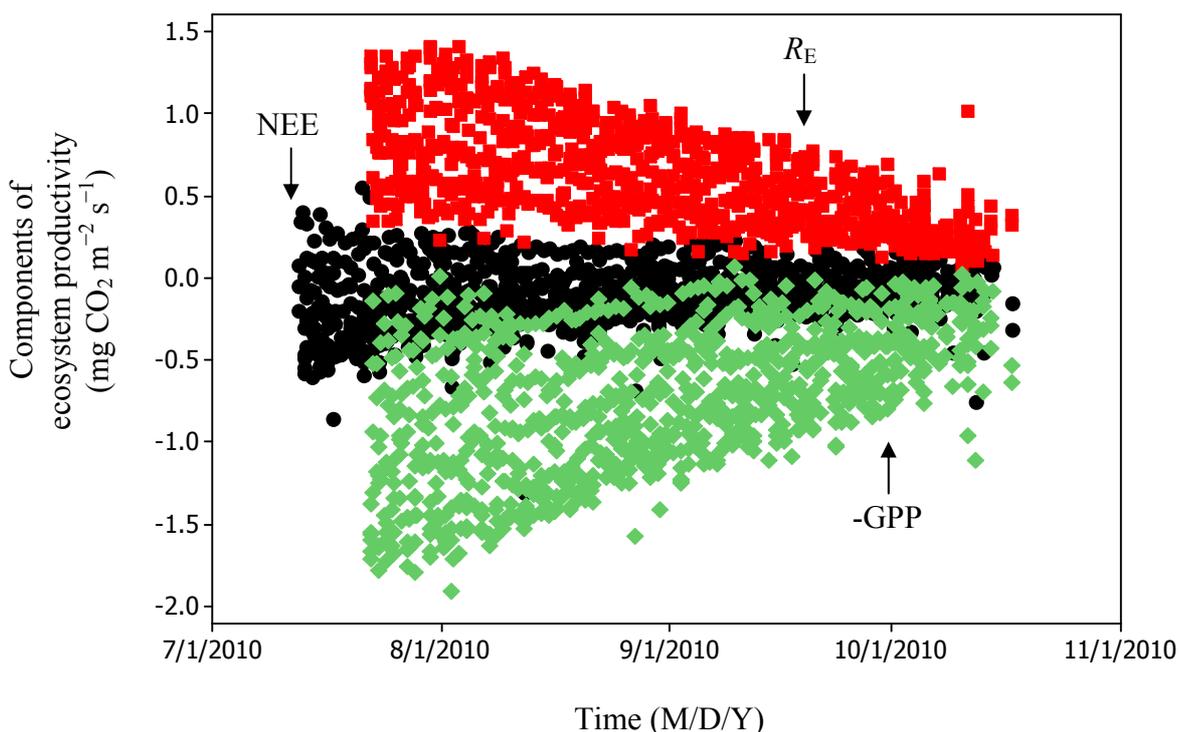
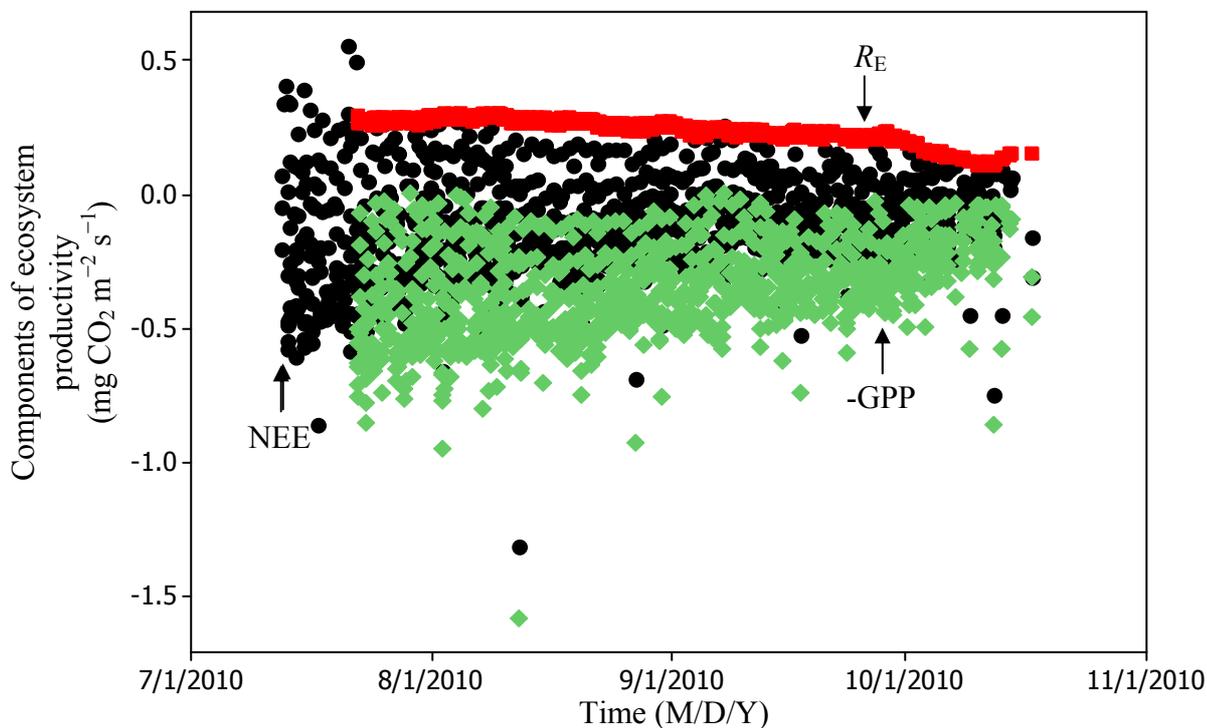


Figure 9. Estimation of GPP and daytime R_E components for the Yenicaga peatland based on Equation (11) ($n = 1021$ for NEE; and $n = 896$ for GPP and R_E).



A comparison of daytime R_E versus ST_{max} resulted in R^2_{adj} values of 39.3% and 99.3% based on Equations (6) and (11), respectively (Figures 10 and 11).

Figure 10. A comparison of ST_{max} versus daytime R_E based on Equation (6) for the Yenicaga peatland ($R^2_{adj} = 39.3\%$; $SE = 0.245$; $n = 896$; $P < 0.001$).

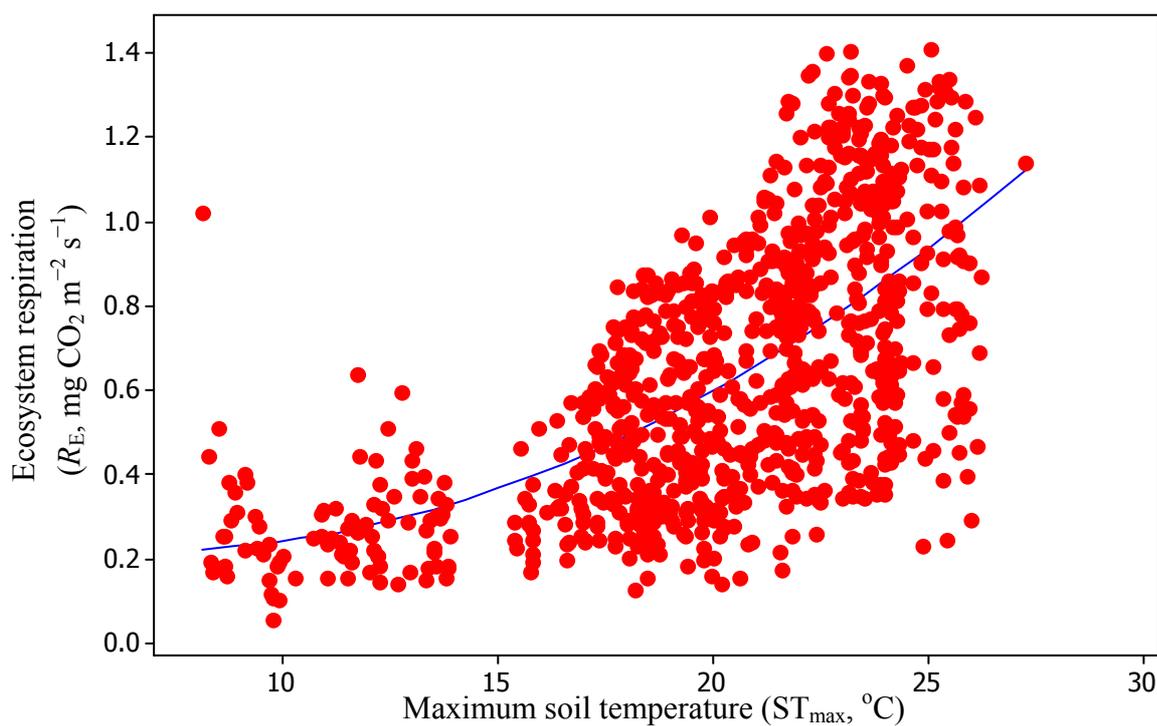
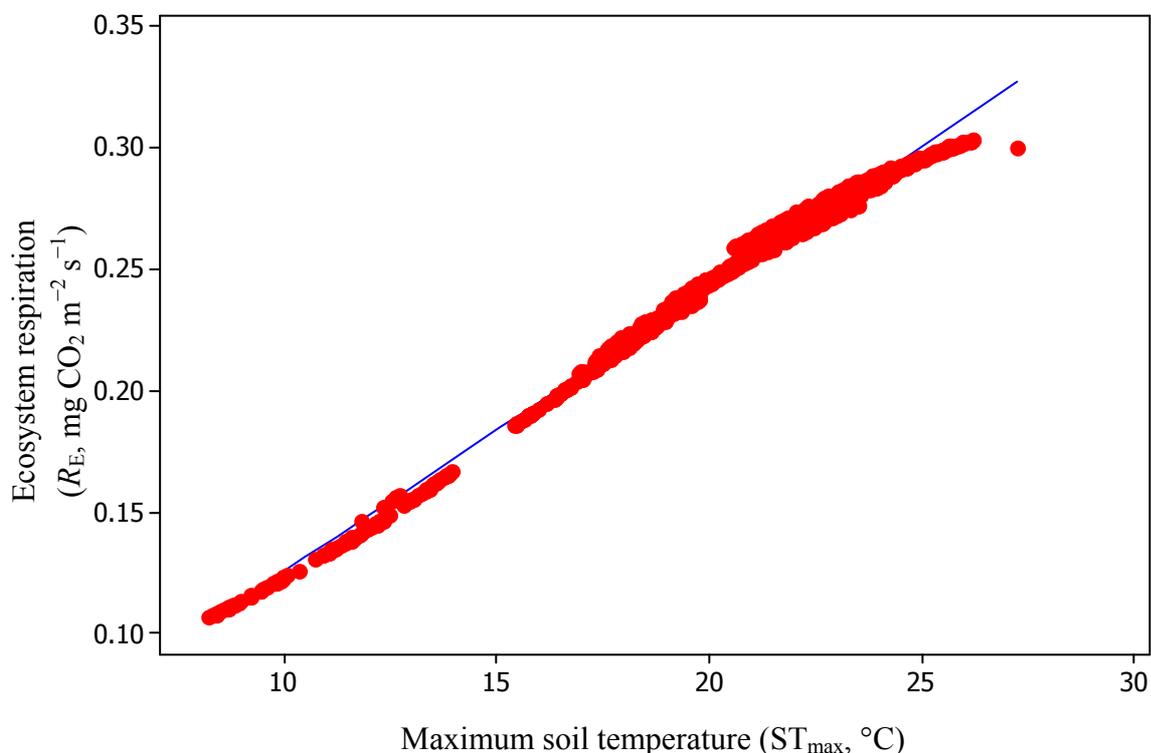


Figure 11. A comparison of ST_{max} versus daytime R_E based on Equation (11) for the Yenicaga peatland ($R^2_{adj} = 99.3\%$; $SE = 0.0039$; $n = 896$; $P < 0.001$).



Soil water content was also determined to play a significant role in controlling daytime R_E from the Yenicaga peatland. As a function of SWC, quadratic regression models elucidated 39.2% and 68.7% of variation in daytime R_E according to Equations (6) and (11), respectively (Figures 12 and 13). A significant relationship between estimated GPP and PAR values was found, yielding R^2_{adj} values of 80.3% and 55% from Equations (6) and (11), respectively (Figures 14 and 15). The rate of NEE in the Yenicaga peatland for the study period was on average estimated at $0.11 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($26.5 \text{ kg C ha}^{-1} \text{ day}^{-1}$) and ranged from $-1.26 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($-297 \text{ kg C ha}^{-1} \text{ day}^{-1}$) to $1.06 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($249 \text{ kg C ha}^{-1} \text{ day}^{-1}$). This case points to the domination of total (positive daytime \pm nighttime fluxes) R_E over GPP (negative flux) throughout most of the study period, especially, towards the end of the period during which GPP decreased at a faster rate than R_E (Figures 8 and 9). During the peak growing season in July, GPP peaked and decreased as the season progressed. Over the study period, GPP was on average $-0.74 \pm 0.43 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($-175 \pm 102 \text{ kg C ha}^{-1} \text{ day}^{-1}$) and $-0.35 \pm 0.18 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($-2 \pm 41 \text{ kg C ha}^{-1} \text{ day}^{-1}$) according to Equations (6) and (11), respectively. On average, nighttime R_E was estimated at $0.23 \pm 0.09 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($53 \pm 22 \text{ kg C ha}^{-1} \text{ day}^{-1}$) based on the EC sensors, while daytime R_E values were $0.64 \pm 0.31 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($150 \pm 74 \text{ kg C ha}^{-1} \text{ day}^{-1}$) and $0.24 \pm 0.05 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ ($57 \pm 11 \text{ kg C ha}^{-1} \text{ day}^{-1}$) based on Equations (6) and (11), respectively.

Figure 12. A comparison of SWC *versus* daytime R_E based on Equation (6) for the Yenicaga peatland ($R^2_{\text{adj}} = 39.2\%$; $SE = 0.245$; $n = 896$; $P < 0.001$).

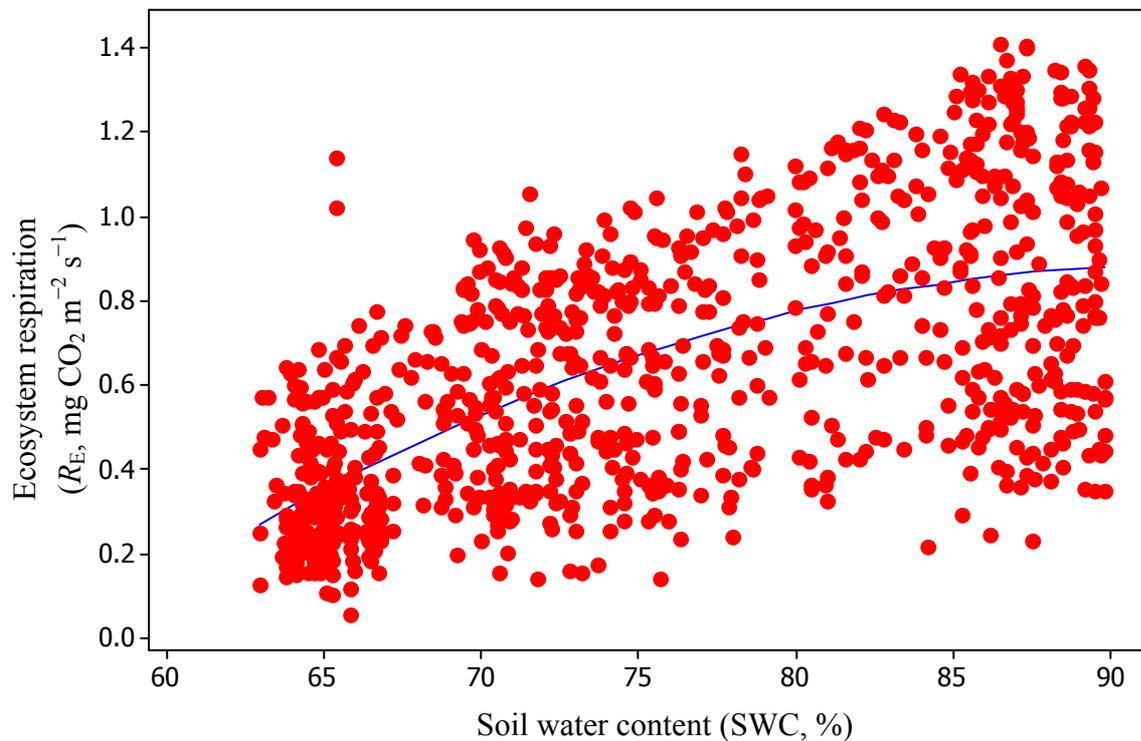


Figure 13. A comparison of SWC *versus* daytime R_E based on Equation (11) for the Yenicaga peatland ($R^2_{\text{adj}} = 68.7\%$; $SE = 0.025$; $n = 896$; $P < 0.001$).

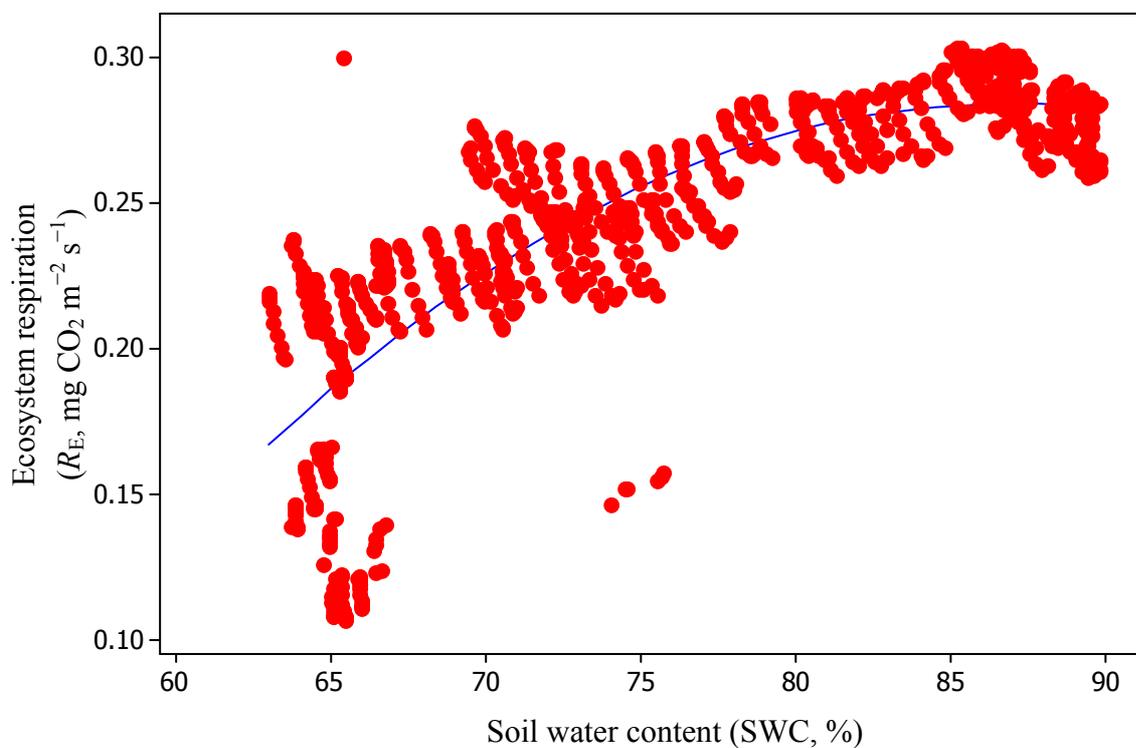


Figure 14. Quantification of relationship between PAR and GPP based on Equation (6) for the Yenicaga peatland ($R^2_{\text{adj}} = 80.3\%$; $\text{SE} = 0.1929$; $n = 896$; $P < 0.001$).

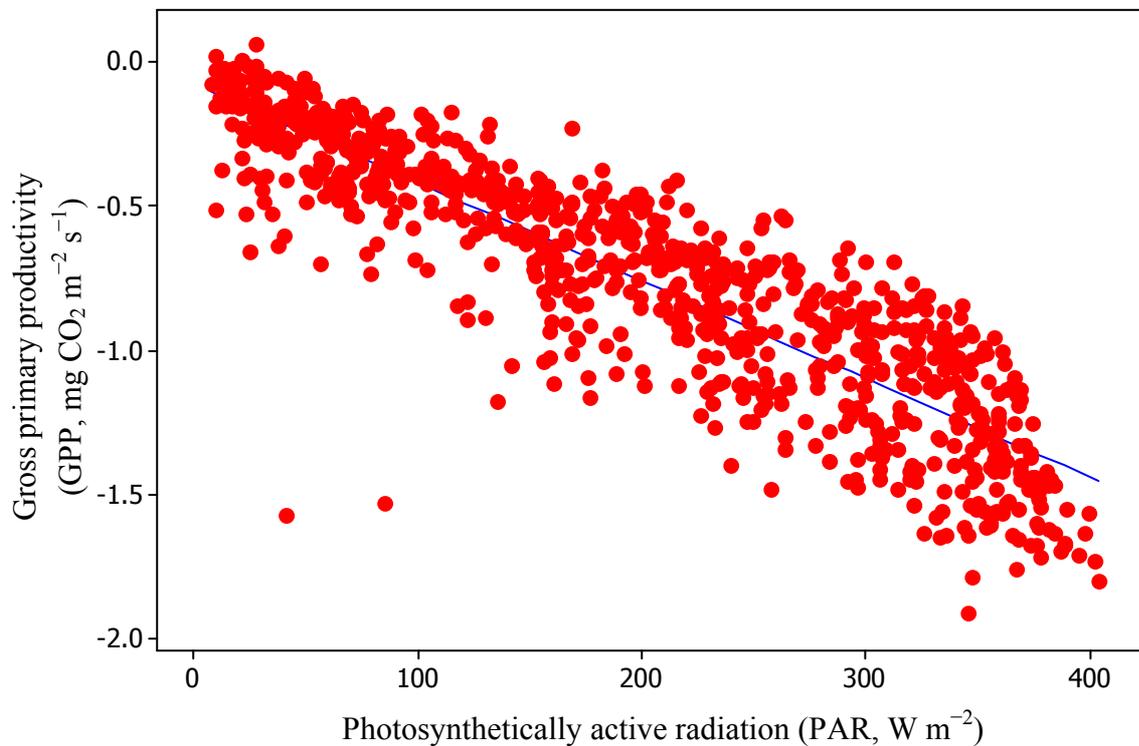
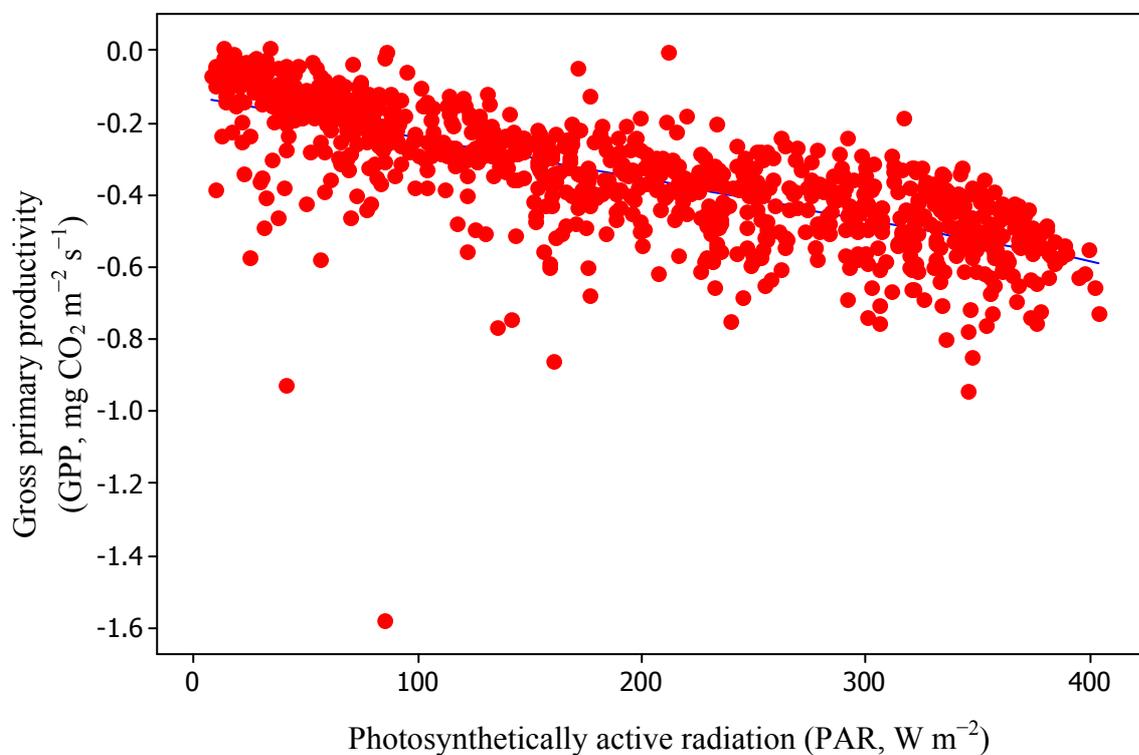


Figure 15. Quantification of relationship between PAR and GPP based on Equation (11) for the Yenicaga peatland ($R^2_{\text{adj}} = 55.0\%$; $\text{SE} = 0.1182$; $n = 896$; $P < 0.001$).



Peatlands (bog hummock, bog hallow, and poor fen) in a cool temperate region of eastern Canada were reported to have NEE range from -0.18 to 0.13 $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$; nighttime R_E range from 0.07 to 0.36 $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$; and GPP range from -0.20 to -0.33 $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ [15,16]. The reported ranges of NEE, R_E and GPP values are in a close agreement with our findings for the Yenicaga peatland [NEE = 0.11 $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ based on the EC data; nighttime $R_E = 0.23$ $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ based on the EC data; daytime $R_E = 0.24$ $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ based on Equation (11); daytime $R_E = 0.64$ $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ based on Equation (6); GPP = -0.35 $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ based on Equation (11); and GPP = -0.74 $\text{mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ based on Equation (6)] , in particular, based on Equation (11). Similarly, EC measurements from 12 wetlands ranging from ombrotrophic and minerotrophic peatlands to wet tundra ecosystems across Europe and North America under temperate-to-arctic climate regimes showed that CO_2 fluxes in July varied considerably between -3 and 1 $\text{g C m}^{-2} \text{ day}^{-1}$ for NEE; 1 and 4 $\text{g C m}^{-2} \text{ day}^{-1}$ for R_E ; and -1 and -6 $\text{g C m}^{-2} \text{ day}^{-1}$ for GPP [17], which were close to our results.

4. Conclusions

Carbon metabolism components of the Yenicaga peatland as measured by EC sensors and quantified by M(N)LR models clearly revealed that diurnal and seasonal variations in exchange rates of CO_2 between the atmosphere and the peatland ecosystem are dependent on the magnitude, rate and timing of GPP and total R_E , which are in turn strongly controlled by the dynamics of soil moisture and temperature, and PAR. Peatlands experiencing drought conditions are reported to be able to act as a CO_2 source. Given the total PPT: ET ratio of 0.3 during the study period, the Yenicaga peatland is considered to undergo a dry season and signals what future rate and amount of changes may be expected in the face of an increase in ET, air temperature and ecosystem disturbances as well as a decrease in PPT. The present study is the first one to quantify CO_2 exchanges for a peatland in Turkey using real-time monitoring by the EC sensors. It is also the first time in Turkey that diurnal source and sink behaviors of a rarely occurring ecosystem like the Yenicaga peatland, which at the same time undergoes severe human-induced pressures such as conversions to rangeland and cropland, and peat mining, were quantitatively assessed using EC sensors. Further research is needed to explore an integration of remote and proximal sensors, and biogeochemical process-based models in improving our understanding and predicting impacts of human-induced disturbances on ecosystem metabolism.

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References

1. Gorham, E. Northern peatlands: role in the carbon balance and probable responses to climatic warming. *Ecol. Appl.* **1991**, *1*, 182-195.
2. Schindler, D.W. The mysterious missing sink. *Nature* **1999**, *398*, 105-106.
3. Cayci, G.; Ataman, Y.; Unver, I.; Munsuz, N. Distribution and horticultural values of the peats in Anatolia. *Acta Hortic.* **1988**, *238*, 189-196.
4. Malone, S.; O'Connell, C. *Ireland's Peatland Conservation Action Plan 2020: Halting the Loss of Peatland Biodiversity*; Irish Peatland Conservation Council: Kildare, UK, 2009.
5. Dengiz, O.; Ozaytekin, H.; Cayci, G.; Baran, A.; Characteristics, genesis and classification of a basin peat soil under negative human impact in Turkey. *Environ. Geol.* **2009**, *56*, 1057-1063.
6. Sumer, N. *Flora of Yeniçağa*. M.Sc. Thesis, Graduate School of Abant İzzet Baysal University, Department of Biology, Bolu, Turkey, 2002.
7. Daughtry, C.S.T.; Gallo, K.P.; Goward, S.N.; Prince, S.D.; Kustas, W.P. Spectral estimates of absorbed radiation and phytomass production in corn and soybean canopies. *Remote Sens. Environ.* **1992**, *39*, 141-152.
8. Running, S.W.; Hunt, E.R. Generalization of a forest ecosystem model. In *Scaling Physiological Processes: Leaf to Globe*; Ehleringer, J.R., Fields, C.B., Eds.; Academic Press: New York, NY, USA, 1993; pp. 141-157.
9. Melillo, J.M.; McGuire, A.D.; Kicklighter, D.W.; Moore, B., III; Vorosmarty, C.J.; Schloss, A.L. Global climate change. *Nature* **1993**, *363*, 234-240.
10. Thomas, M.V.; Malhi, Y.; Fenn, K.M.; Fisher, J.B.; Morecroft, M.D.; Lloyd, C.R.; Taylor, M.E.; McNeil, D.D. Carbon dioxide fluxes over an ancient broadleaved deciduous woodland in southern England. *Biogeosciences* **2010**, *7*, 3765-3814.
11. Arneth, A.; Veenendaal, E.M.; Best, C.; Timmermans, W.; Kolle, O.; Montagnani, L.; Shibistova, O. Water use strategies and ecosystem-atmosphere exchange of CO₂ in two highly seasonal environments. *Biogeosciences* **2006**, *3*, 421-437.
12. Billesbach, D.P.; Fischer, M.L.; Torn, M.S.; Berry, J.A. A portable eddy covariance system for the measurement of ecosystem—atmosphere exchange of CO₂, water vapor, and energy. *J. Atmos. Oceanic. Technol.* **2004**, *21*, 639-650.
13. Coleman, K.; Jenkinson, D.S. *ROTHC-26.3: A Model for the Turnover of Carbon in Soil. Model Description and Windows Users Guide*; Rothamsted Research: Harpenden, UK, 2005; p. 45.
14. Parton, B.; Ojima, D.; Del Grosso, S.; Keough, C. *CENTURY Tutorial. Supplement to CENTURY User's Manual*; Great Plain System. Research Unit Technical Report No. 4 [R]; NREC Pub. Natural Resource Ecology Laboratory, Colorado State University: Fort Collins, CO, USA, 2001.
15. Moore, T.R.; Bubier, J.L.; Frolking, S.E.; Lafleur, P.M.; Roulet, N.T. Plant biomass and production and CO₂ exchange in an ombrotrophic bog. *J. Ecol.* **2002**, *90*, 25-36.
16. Lafleur, P.M.; Roulet, N.T.; Bubier, J.L.; Frolking, S.; Moore, T.R. Interannual variability in the peatland-atmosphere carbon dioxide exchange at an ombrotrophic bog. *Global Biogeochem. Cy.* **2003**, *17*, 1036.

17. Lund, M.; Lafleur, P.M.; Roulet, N.T.; Lindroth, A.; Christensen, T.R.; Aurela, M.; Chojnicki, B.H.; Flanagan, L.B.; Humphreys, E.R.; Laurila, T.; Oechel, W.C.; Olejnik, J.; Rinne, J.; Schubert, P.; Nilsson, M.B. Variability in exchange of CO₂ across 12 northern peatland and tundra sites. *Glob. Change Biol.* **2010**, *16*, 2436-2448.

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