Science of the Total Environment 554–555 (2016) 192–202

Contents lists available at ScienceDirect

Science of the Total Environment

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

Large interannual variability in net ecosystem carbon dioxide exchange of a disturbed temperate peatland

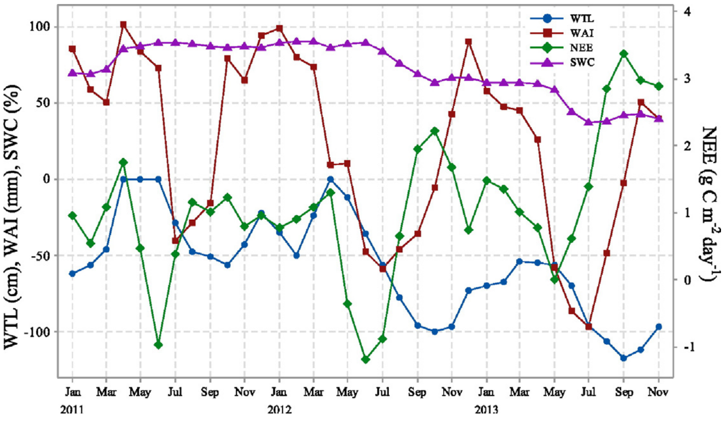
Guler Aslan-Sungur [a,*], Xuhui Lee [b,c], Fatih Evrendilek [d], Nusret Karakaya [d]

[a] Department of Chemical Engineering, Tunceli University, Tunceli 62000, Turkey
[b] Yale-NUIST Center on Atmospheric Environment, Nanjing University of Information, Science and Technology, Nanjing, China
[c] School of Forestry and Environmental Studies, Yale University, New Haven, CT, United States
[d] Department of Environmental Engineering, Abant Izzet Baysal University, Bolu 14280, Turkey

HIGHLIGHTS

- The present study appears to be the first on evaluating long-term interannual variability of NEE in a disturbed temperate peatland.
- Yenicaga peatland was a strong CO_2 source with a large interannual variability with the value of 246, 244 and 663 g C m^{-2} yr^{-1} for 2011, 2012, and 2013 respectively.
- WAI was found to be a better predictor for ER than SWC and WTL.
- T_{air}, ET and VPD were most significant variables strongly correlated with NEE, ER, and GPP.

GRAPHICAL ABSTRACT



WTL: Water table level, WAI: Water availability index, SWC: Soil water content, NEE: Net ecosystem carbon dioxide exchange.

ARTICLE INFO

Article history:
Received 21 September 2015
Received in revised form 17 February 2016
Accepted 21 February 2016
Available online xxxx

Editor: Simon Pollard

Keywords:
Disturbed temperate peatland
Net ecosystem carbon exchange
Water availability
Eddy covariance

ABSTRACT

Peatland ecosystems play an important role in the global carbon (C) cycle as significant C sinks. However, human-induced disturbances can turn these sinks into sources of atmospheric CO_2. Long-term measurements are needed to understand seasonal and interannual variability of net ecosystem CO_2 exchange (NEE) and effects of hydrological conditions and their disturbances on C fluxes. Continuous eddy-covariance measurements of NEE were conducted between August 2010 and April 2014 at Yenicaga temperate peatland (Turkey), which was drained for agricultural usage and for peat mining until 2009. Annual NEE during the three full years of measurement indicated that the peatland acted as a CO_2 source with large interannual variability, at rates of 246, 244 and 663 g C m^{--2} yr^{-1} for 2011, 2012, and 2013 respectively, except for June 2011, and May to July 2012. The emission strengths were comparable to those found for severely disturbed tropical peatlands. The peak CO_2 emissions occurred in the dry summer of 2013 when water table level (WTL) was below a threshold value of −60 cm and soil water content (SCW) below a threshold value of 70% by volume. Water availability index was found to have a stronger explanatory power for variations in monthly ecosystem respiration (ER) than the traditional water status indicators (SCW and WTL). Air temperature, evapotranspiration and vapor pressure deficient were the most significant variables strongly correlated with NEE and its component fluxes of gross primary production and ER.

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* Corresponding author.
E-mail address: guleraslan@tunceli.edu.tr (G. Aslan-Sungur).

http://dx.doi.org/10.1016/j.scitotenv.2016.02.153

1. Introduction

Peatlands are wetland ecosystems under saturated water conditions causing an accumulation of organic matter called peat (Parish et al., 2008). Covering 4.2 million km^2 worldwide or about 3% of the Earth's land surface (Limpens et al., 2008; Dise, 2009; Yu, 2012; McVeigh et al., 2014), peatlands are one of the largest carbon (C) pools. In pristine peatlands, water table is generally close to the surface year-round, causing anaerobic conditions (Holden et al., 2011), slow decomposition rates and gradual accumulation of organic matter (Turetsky et al., 2014). Pristine peatlands have acted as net carbon dioxide (CO_2) sinks for thousands of years (Frolking and Roulet, 2007). However, many peatlands have been disturbed by human activities, such as agricultural usage, drainage for tree planting, and peat extraction (Waddington et al., 2010; Haapalehto et al., 2014). Due to the disturbances, the peatland ecosystems may switch from sinks to sources of atmospheric CO_2. The disturbances of the hydrological regime in the peatland are the main driver of net C loss. Thus, it is important to determine how a peatland continues to be C sink or turns into a C source under what conditions. Long-term and continuous measurements provide first-hand experimental data on CO_2 fluxes, allowing us to understand drivers of interannual variability in C source and sink.

The eddy-covariance (EC) technique allows for direct and long-term observations of the exchange of CO_2, energy and water fluxes between the biosphere and the atmosphere at the ecosystem scale (Baldocchi, 2003). Although the EC technique has been increasingly used across many biome types of the world (Mauder et al., 2013), there have been a few applications of EC at peatland sites (McVeigh et al., 2014). Most peatland EC sites are located in boreal, subarctic and arctic climate zones (Sottocornola and Kiely, 2010), with very few studies reporting longer than two years of interannual variability in CO_2 fluxes (Helfter et al., 2014; McVeigh et al., 2014; Peichl et al., 2014). To the authors' best knowledge, only eleven studies have reported annual net ecosystem CO_2 exchange (NEE) for temperate climate peatlands and of these, only five studies have reported long-term (>2 years) NEE measurements (Table 1). To improve the understanding of peatland C dynamics, long-term measurements and interannual variability analysis should be extended to different climates and peatland types.

The long-term NEE studies conducted for temperate peatlands indicate that interannual variability is mostly attributed to climatic conditions. Hydrometerological changes (Olson et al., 2013), water table variations (McVeigh et al., 2014), drought (Lund et al., 2012), temperature, and growing season length (Helfter et al., 2014) have been found to regulate peatland CO_2 fluxes. Since water is a critical component for peat formation, it is not a surprise that the studies have focused on the relationship between water status, mostly water table level (WTL), and NEE and its components such as ecosystem respiration (ER) and gross primary productivity (GPP). Though no consensus has been reached, discussions on water table variations have been performed to determine whether they affect NEE by controlling primarily GPP (Dimitrov et al., 2011) or ER (Dimitrov et al., 2010). Although WTL is an important measure of peatland water status, uncertainties in its relationship to the C flux components have led to search for other water indicators such as soil water content (SWC) (Parmentier et al., 2009).

Simple statistical models are used to explore environmental drivers of peatland C fluxes. Since NEE varies in space and time due to chemical, biological and physical dynamics of the peatland (Bonneville et al., 2008), it is difficult to establish a generalized relationship between environmental drivers and C fluxes. However, it is helpful to make comparisons of environmental drivers among sites of different characteristics. Previous studies have shown robust linear relationships between ER and air temperature (T_{air}) and between C fluxes and aboveground biomass (Han et al., 2013), and multiple non-linear relationships of C fluxes to T_{air}, soil temperature, vapor pressure deficit (VPD), solar radiation (Zhao et al., 2010), and water depth (Schedlbauer et al., 2012).

So far, the majority of the related studies in the literature have been carried out for intact peatlands. Only a few studies on C fluxes were conducted in disturbed peatlands such as the Sacramento-San Joaquin Delta in California (Knox et al., 2015), Reeuwjik in the Netherlands (Veenendaal et al., 2007), and Waiketo in New Zealand (Nieveen et al., 2005), but with a measurement period of just one year or shorter.

Table 1
A multiple comparison of annual NEE values (g C m^{-2} yr^{-1}) for Yenicaga peatland versus other peatlands in temperate climate regimes.

Site	Location	Climate zone	Status	T_{mean}/PPT_{mean}	NEE	Time period	References
Schechenfilz	Southern Germany	Temperate	Intact	8.6/1127	−62	2012–2013	Hommeltenberg et al. (2014)
Atlantic Blanket Bog	Southwest Ireland	Temperate maritime	Almost intact	10.5/2467	−55.7	2002–2012	McVeigh et al. (2014)
Auchencorth Moss	Scotland, Edinburgh	Temperate	Unknown	8.3/1018	−17.5	2002–2013	Helfter et al. (2014)
Bog Lake Fen	North Minnesota, USA	Temperate	Intact	3.9/210	−38.6	2009	Olson et al. (2013)
				3.5/400	−27.7	2010	
				5.9/450	−39.5	2011	
Mer Bleue	Canada	Cool-temperate	Intact	6.5/871	−104	2006–2007	Strilesky and Humphreys (2012)
Fajemyr	Southern Sweden	Temperate	Intact	6.2/700	21.4	2005	Lund et al. (2007)
					14.3	2006	Lund et al. (2012)
					−29.4	2007	
					23.6	2008	
					−28.9	2009	
Panjin	China	Warm-temperate	Intact	8.6/631	−65	2005–2006	Zhou et al. (2009)
Degero Stormyr	Northern Sweden	Cold-temperate	Intact	1.2/523	−55	2004	Nilsson et al. (2008)
					−48	2005	
Mer Bleue	Southeast Canada	Cool-temperate	Intact	6.5/871	−40.2	1998–2004	Roulet et al. (2007)
Fochtelooer	North Netherland	Temperate	Disturbed	14.9/452	97	1994–1995	Nieveen et al. (1998)
Bog Lake Fen	North Central Minnesota, USA	Temperate	Intact	13.6/553 (May–Oct)	71 g C m^{-2}	May–Oct 1991	Shurpali et al. (1995)
					−32 g C m^{-2}	May–Oct 1992	
Yenicaga Bolu	Northwest Turkey	Cool-temperate	Disturbed	10.2/538	346	2010 (Aug-Dec)	This study
					281	2011	
					265	2012	
					627	2013	
					221	2014 (Jan–April)	

To our best knowledge, there has been no long-term (>2 years) EC study performed for disturbed temperate peatlands. With this motivation, the specific objectives of the present study are to (1) quantify interannual variability in C fluxes (NEE, GPP and ER), (2) explore the relationship between soil water status and interannual variability in C fluxes, and (3) model effects of environmental drivers on C fluxes in a temperate disturbed peatland through multiple linear regression models.

2. Materials and methods

2.1. Site description

Yenicaga peatland (320 ha in 2009, 40°47′24″N, 32°1′44″E) is located at 38 km east of the city of Bolu in the western Black Sea region of Turkey (Fig. 1). The climate is classified as cool temperate, with a mean annual temperature and precipitation of 10.2 °C and 538 mm, respectively (Dengiz et al., 2009). The geology contains Devonian and cretaceous limestone, basaltic tuff, lava, and olistolites, with the uppermost layer consisting of tertiary and quaternary formations (Dengiz et al., 2009). The natural vegetation community consists of the following dominant species: (1) *Phragmites australis* and *Typha domingensis* and (2) *Ranunculus lingua*, *Acoruscalamus*, *Najas marina*, *Pedicularis palustris*, *Senecio paludosus* (Sumer, 2002). There are eight creeks tributaries feeding into Lake Yenicaga, and one creek discharging from the lake classified as an eutrophic lake.

An EC flux tower was installed on 12 July 2010 at about 1 km north of Lake Yenicaga (ca. 5 km^2) at the elevation of 988 m above sea level. The study period was between 1 August 2010 and 30 April 2014. The mean vegetation height around the flux tower was about 0.5 m, and the terrain was flat. Peat meadows consisted of *Ranunculus lingua*, *Acoruscalamus*, *Najas marina*, *Pedicularis palustris*, *Senecio paludosus* species. Yenicaga peat consists of sedge and reed peat whose depth changes up to 12 m, only partially decomposed in the top few meters (GIZ, 2012). The peat around Lake Yenicaga was formed under nutrient rich conditions and is classified as a typical basin peat (Dengiz et al., 2009). The tower was located in the middle of the grazed portion adjacent to an abandoned peat extraction area (GIZ, 2012) and a drainage channel. Additional information about the peatland geology and history can be found in GIZ (2012) and Evrendilek et al. (2011)Water table level is mostly below the peatland surface. However, it may occasionally rise near or above the peatland surface due to the human-induced alteration of the surrounding land drainage.

The Yenicaga peatland has experienced disturbances due to agricultural usage, draining, and peat mining. The disturbance regimes of Yeniçağa peatland were quantified from 1944 to 2009, on the basis of remotely-sensed data and change-detection techniques (Evrendilek et al., 2011). Over this period, the peatland area decreased by 37% mostly because of agricultural usage and afforestation. Drainage of the Yenicaga Lake began in 1965 and continued until the late 1990s (Saygi-Basbug and Demirkalp, 2004). In addition, the Yenicaga peatland was the most important peat extraction site in Turkey; peat extraction in this area continued between 1984 and 2009. Moreover, cows grazing was noticed in some field trips during the growing season, although the frequency of grazing and the question about whether grazing occurred in the EC footprint area cannot be determined at this time.

2.2. EC and micrometeorological measurements

The EC system consisting of an open-path CO_2/H_2O gas analyzer (LI-7500, Licor Inc., Lincoln, NB, USA), and a 3-D sonic anemometer/thermometer (CSAT3, Campbell Scientific Inc., Logan, UT, USA) was mounted at a height of 3 m on a small triangular tower. The distance between the two sensors was 0.15 m, with the anemometer oriented towards the prevailing wind direction (an azimuth angle of 30° from true north). Fetch is >1 km in all the directions. Eddy covariance signals were recorded at 10 Hz by a datalogger (CR3000, Campbell Scientific Inc.), averaged over 1 h and corrected for the effects of fluctuations in air density on CO_2 and H_2O fluxes by the datalogger. The raw EC data were collected by swapping two 2-GB Compact Flash cards at about 15 day intervals. The net radiation (R_n), downwelling and upwelling longwave (wavelength 4–50 μm), and incoming and reflected shortwave radiation (wavelength 0.2–4 μm) were measured with a four-way radiometer (model CNR-4, Kipp & Zonen USA Inc., Bohemia, New York).

Groundwater level was measured monthly using a perforated pipe of 1.5 m in length buried near the EC flux tower. Air temperature (T_{air}, °C), and relative humidity (RH, %) were measured using a HMP45C probe (Vaisala, Finland). Rainfall, evapotranspiration (ET, mm), SWC (%), and soil temperature were measured on an hourly basis using a weather monitoring station (model ET107, Campbell Scientific Inc.).

The ET estimates provided by ET107 on the basis of the Penman-Monteith equation were in a very close agreement with those measured by the EC system. The coefficient of determination (r^2) for the comparison of the ET estimates by the EC versus ET107 was >0.8 with the slope in the range of 1.0–1.1., the ET107 data were used instead for water budget calculations because they were continuous.

2.3. EC data processing

The first preprocessing was done by the datalogger with the application of the WPL correction (Webb and Leuning, 1980). The second step

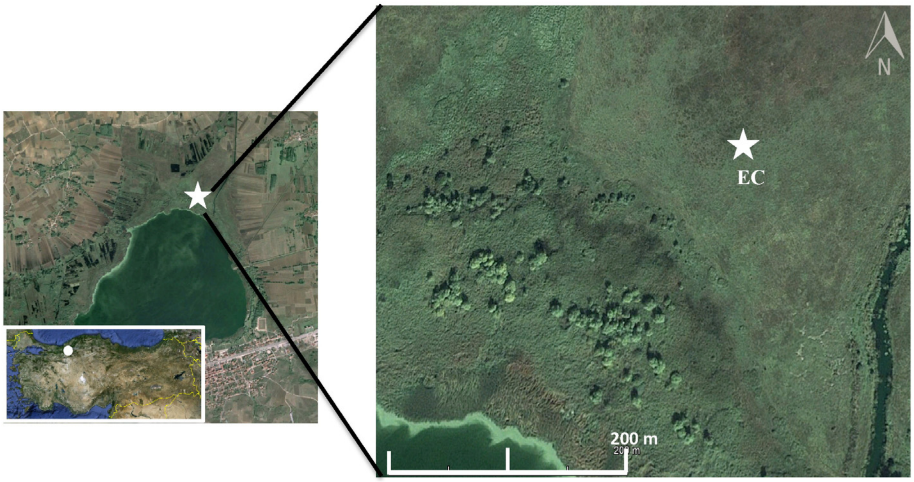

Fig. 1. Location of Yenicaga peatland (circle) in Turkey, with EC tower symbolized by star.

was to apply a filtering procedure to the processed flux data to remove outliers. Threshold values for filtering are site-specific (Moffat et al., 2007; Baldocchi, 2008). Discarded outliers were spikes (Thomas et al., 2011; Liu et al., 2012) and negative nighttime GPP fluxes.

The data spike criteria are defined thus:

$$\left|X_{ij} - X_j\right| \geq 3\sigma_j \rightarrow \text{spike}$$

where $X_{i,j}$ denotes hourly value of quantity X_j at time i, X_j mean value of taken during a selected time window, and σ_j standard deviation of quantity X_j. The time window was three weeks centered at observation i.

Another filtering was applied to nighttime CO_2 flux data. Data were replaced with zero values if the GPP flux was negative, which indicates unrealistic photosynthetic CO_2 uptake at night. If the negative GPP data were retained, the annual GPP and NEE would be about 20 g m^{-2} yr^{-1} greater in magnitude than the values reported below. The flux data were partitioned into daytime and nighttime periods according to a global radiation threshold of 20 Wm^{-2} (Reichstein et al., 2005; Polsenaere et al., 2012; Wilkinson et al., 2012). For this study, no clear correlation was found between the friction velocity and the night CO_2 fluxes (Online Supplementary Fig. S1), and therefore, no friction velocity filtering was performed. The mean (± standard deviation) value of nighttime friction velocity at the site was 0.11 ± 0.08 m s^{-1}.

In this study, the missing values of NEE, H, LE and R_n were substituted with estimates using a marginal distribution sampling method by an online implementation (http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/index.php) of the algorithm by Reichstein et al. (2005). This method is an effective enhancement of look-up tables whereby flux measurements are correlated to meteorological variables of solar radiation, T_{air} and VPD.

2.4. CO_2 flux partitioning

C balance of an ecosystem is presented by the relationship among NEE, GPP, and ER as follows:

$$NEE = GPP + ER. \tag{1}$$

According to the sign convention, negative NEE occurs when the ecosystem becomes a sink taking up CO_2 from the atmosphere, positive NEE occurs when the ecosystem becomes a source releasing CO_2 to the atmosphere, and GPP and ER are always negative and positive, respectively. NEE measurements by EC do not differentiate between photosynthesis- and plant and soil respiration-related CO_2 fluxes. Since the GPP and ER fluxes are important to a better understanding of the mechanisms and are necessary inputs to ecosystem C models, the measured NEE fluxes should be partitioned into ER and GPP. In this study, the nighttime-based model described by Reichstein et al. (2005) was used for the flux partitioning. Reichstein et al. (2005) improved the ecosystem respiration model by Lloyd and Taylor (1994) considering dynamic temperature sensitivity:

$$NEE_{night} = ER_{night} = ER\, e^{E_0\left(\frac{1}{T_{ref}-T_0} - \frac{1}{T-T_0}\right)} \tag{2}$$

where E_0 is an activation energy parameter, R_{ref} is ecosystem respiration at a reference temperature (T_{ref}) (set to 10 °C), T is air or soil temperature (°C), and T_0 is a temperature constant set at −46.02 °C. This is a part of the partitioning tool recommended by CarboEurope (Reichstein et al., 2005) and available at the same website used for gap-filling. The filtered flux data (non-gap-filled) were put into the required format using the R-Studio software program. The online tool resulted in gap-filled hourly NEE and ER estimates, and GPP was then calculated from Eq.(1).

2.5. Water availability index (WAI)

The lack of seasonality in SWC caused a difficulty with discerning how hydrological variations affect short-term NEE changes. Therefore, a water availability index (WAI) was calculated from the water balance equation (Lee et al., 2007) to better describe the hydrological variations.

$$WAI = SWC_0 + \int_0^t (PPT - ET)dt$$

where SWC_0 is the initial soil water content, PPT is the precipitation, and ET is evapotranspiration.

2.6. Statistical analyses

All the statistical analyses were performed using Minitab 17 (Minitab Inc.) over the full year period measurements of 2011, 2012, and 2013 in order to detect interannual variability in peatland C exchanges. Pearson's correlation matrix among the ecosystem C components and the environmental variables was used to screen for the most influential explanatory variables as a function of which the best-fit multiple linear regression models to predict the ecosystem C components were built.

3. Results

3.1. Meteorological conditions

Air temperature during the study period follows a strong seasonal cycle of increases from winter to summer (Fig. 2a). The mean annual T_{air} was 8.0, 8.9, and 8.5 °C for 2011, 2012, and 2013, respectively, below the long-term (1963–2014) mean annual T_{air} of 10.6 °C. The mean growing season (May to September) T_{air} was 15.3 °C, 16.2 °C, and 15.4 °C in 2011, 2012, and 2013, respectively, below the long-term mean growing season T_{air} of 17.5 °C.

Similar to the long-term seasonal precipitation trend, precipitation was lower from July to September than the rest of the year during the study period (Fig. 2b). The annual rainfall was 408.4, 159.8, and 262.6 mm in 2011, 2012, and 2013, respectively, less than the long-term precipitation (547.8 mm). It should be noted that the study measurements only included rainfall and no snowing events. The growing season rainfall in 2012 and 2013 (29.2 and 57.2 mm, respectively) was below the long-term mean (192.9 mm); however, rainfall in the 2011 growing season (193.5 mm) was similar to the long-term mean. From both annual and growing season rainfall data, it is clear that 2011 was the wettest of the three years. There was higher than normal amounts of rainfall in April, May and June 2011 (Fig. 2b), and human-induced alteration of the surrounding land drainage caused flooding in this period. Another flooding event occurred for the same reason in April 2012 even though the growing season rainfall was lower in 2012 than in 2011 and 2013.

3.2. Water availability

Since water is a key component for the formation of the peat, hydrological variables such as WTL and SWC have been explored as major factors driving NEE variability in peatland ecosystems (Sottocornola and Kiely, 2010; Peichl et al., 2014; Lund et al., 2015). The measurements of WTL and SWC (Fig. 3) were reported from January 2011 to December 2013. Soil water content did not show a clear seasonal variation, displaying instead small fluctuations in the following three periods: (period I) between April 2011 and June 2012 (SWC in the 0–55 cm depth > 85%), (period II) between October 2012 and April 2013 (60–70%), and (period III) between July 2013 and December 2013 (<45%). In the transition between the periods, sharp decreases in SWC were accompanied by decreases in WTL. A sharp increase in SWC in April 2011 can be explained by flooding in that month. Moreover, a prolonged

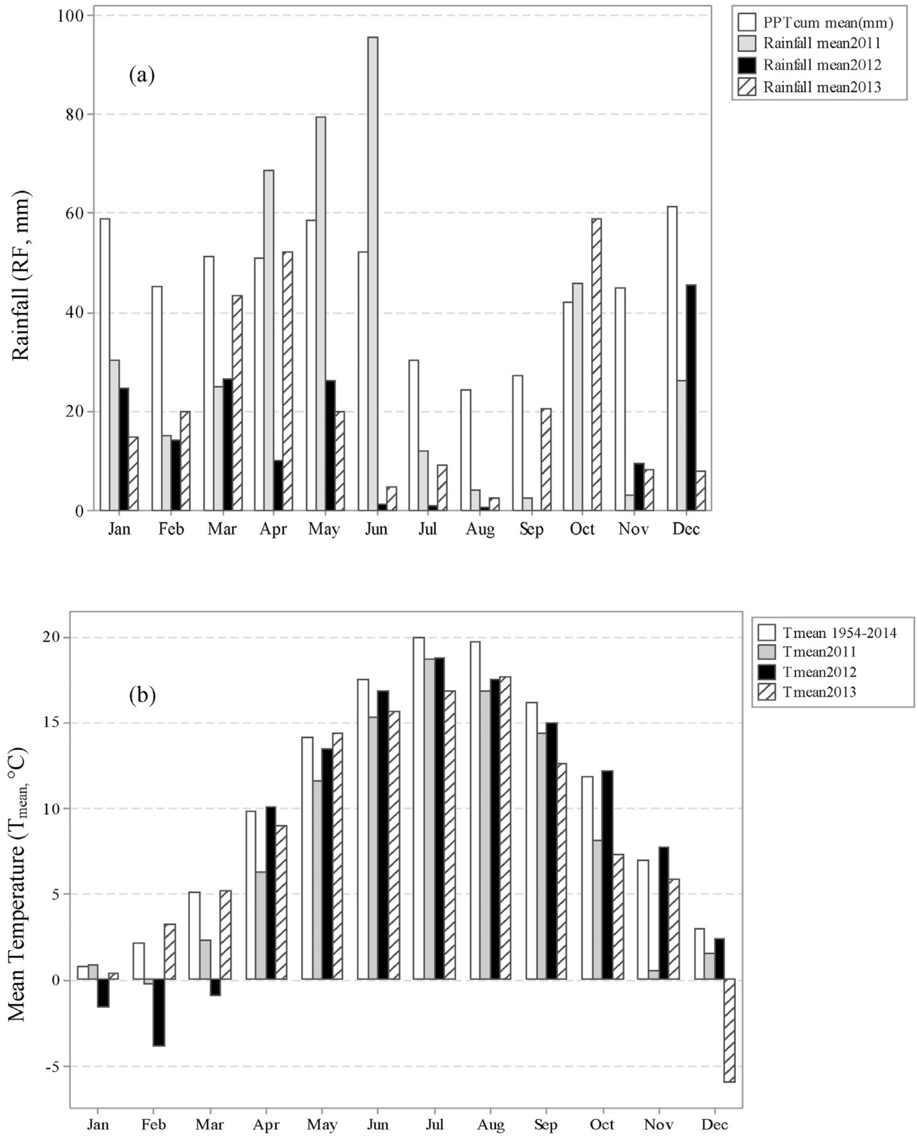

Fig. 2. Monthly (a) cumulative rainfall and (b) air temperature over the 2010–2014 period and mean precipitation and temperature over the 1963–2014 period for the site.

flooding period in April to June 2011 and also flooding in April 2012 resulted in soil water saturation for a long time in period I. Water table level decreased during the summer and reached its lowest level during the fall in each year as it was expected from the low rainfall amount from July to September (Fig. 2b). Water table level was over −55 cm during period I, between −95 cm and −55 cm during period II, and less than −95 cm during period III. The two variables showed virtually no correlation except during the transitional times (June 2012–Oct 2012 and May 2013–July 2013, Fig.3; $r^2 =$ 0.96 and 0.95, respectively).

WAI was generally low during the summer, and the lowest WAI was observed in July in each of the three years. Of the three-year period, the July WAI was lowest in 2013 and highest in 2011. Negative WAI values occurred during the summer time from June to August, mostly notably in 2013, indicating that supply of water via rainfall could keep up with evapotranspiration demand.

3.3. Energy balance closure

Reliability of the EC flux data was assessed calculating the closure of the surface energy budget (Mauder et al., 2013; Morrison et al., 2013; Euskirchen et al., 2014). Theoretically, the ratio of sensible plus latent heat fluxes (H + LE) to available energy (R_n-G) should equal unity. A closer agreement of the ratio of the available energy to the turbulent fluxes means a better quality of EC measurements. In this study, since no soil heat flux was measured, the energy balance assessment was carried out on daily means. On the diurnal time scale, the soil heat flux is much smaller than the other energy balance terms, and hence, can be omitted. The mean daily R_n was compared with H + LE for each year (2010, 2011, 2012, 2013, and 2014, Supplementary Fig. S3, Table 2). Energy balance closure, measured here by the linear regression slope of H + LE against R_n, varied between 0.66 in 2014 and 0.81 in 2012. In addition, the energy balance ratio (EBR) was calculated by dividing the annual total (H + LE) by R_n (Wilson et al., 2002) and varied between 0.54 in 2014 and 0.69 in 2011 (Table 2). The decline in energy balance closure for 2014 could be mainly because of the measurement period (January to April 2014) that consisted of mostly winter months under low wind conditions. Seasonal dependency of energy balance closures has been related to the turbulence intensity (Turnipseed et al., 2002; Sánchez et al., 2010). Other researchers also noted weaker energy balance closure with lower friction velocity in the winter (Blanken et al., 2009; Kim et al., 2014) than in the warm season. In the present study, the winter friction velocity was 0.14 m s^{-1}, slightly lower than the summer mean value of 0.17 m s^{-1}.

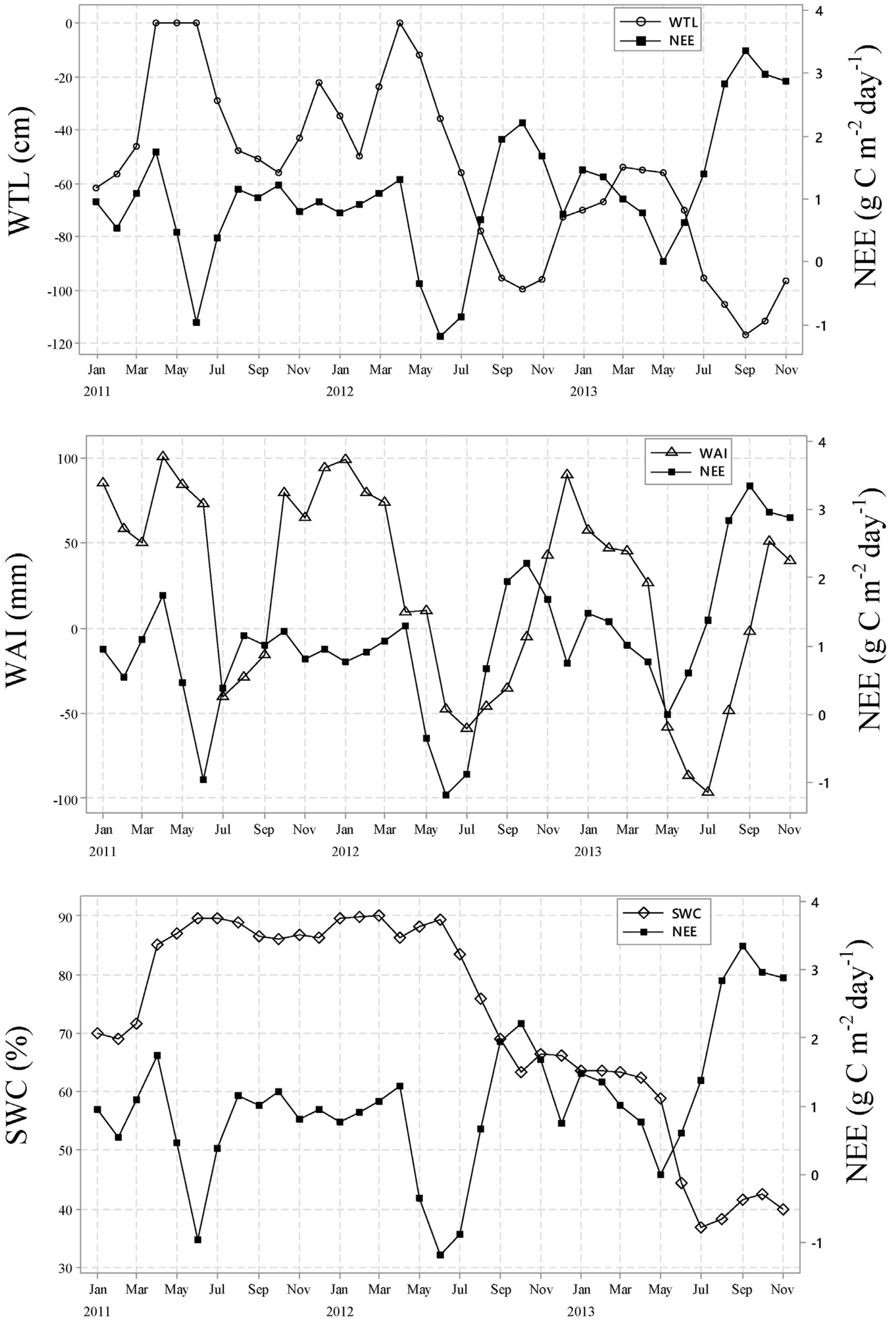

Fig. 3. Monthly mean water table level (WTL), water availability index (WAI), soil water content (SWC) and net ecosystem exchange (NEE).

Although we could not take into account the soil heat flux term in energy balance analysis, our results showed approximately 80% closure for the entire study period (2011, 2012, and 2013), which is consistent with the typical closure of Fluxnet sites (Foken, 2008). Several studies observed a closure rate between 80 and 90% for peatlands (Corradi et al., 2005; Lund et al., 2007; Yurova et al., 2007; Morrison et al., 2013), but one peatland study reported a lower energy closure of 64% (Sottocornola, 2007).

3.4. Seasonal and interannual variability of NEE

At the Yenicaga peatland site, monthly NEE was positive during the winter indicating C release to the atmosphere and occasionally became negative during the summer (Fig. 3). The average midday (10:00–16:00) NEE was mostly negative during the growing season defined for the study site to cover the period of May to September (Online

Table 2
Energy balance ratios (EBR) and linear regression models of daily mean H + LE as a function of R_n for each year.

Response (H + LE)	Coefficients (R_n)	Intercept	r^2	EBR [(H + LE) / R_n]
2010	0.79	−11.1	0.96	0.7
2011	0.79	−15.6	0.93	0.69
2012	0.81	−23.3	0.97	0.65
2013	0.79	−20.1	0.96	0.66
2014	0.66	−14.2	0.93	0.54

Supplementary Fig. S2). The albedo of the Yenicaga peatland achieved maximum values up to 0.9 during the wintertime because of the snow cover (Lohila et al., 2010), and then dramatically dropped to around 0.2 in April (Fig. S2). The albedo was mostly stable around 0.15 during the growing season (Fig. S2). The flooded period in April–May–June 2011 and in April 2012 showed lower albedo (below 0.06). Similarly, Moore et al. (2013) reported lower albedo for a wet peatland site with ponding in the hollows. The average midday NEE values were negative when the albedo values were low due to the vegetation cover between mid-April/early May and the late September (Fig. S2).

The daily NEE data varied between −4.01 and 6.59 g C m^{-2} day^{-1} during the measurement period (Fig. 5). The site was a CO_2 source for most of the months during the study period, and a sink in June 2011and from May to July 2012. The peak CO_2 emissions to the atmosphere occurred in September 2013. The highest CO_2 uptake occurred in June 2012 (Fig. 3). NEE was also high in April 2011 and 2012, the end of the non-growing season (Fig. 3) when the site was flooded. However, no flooding occurred in April 2013, explaining the near zero monthly NEE in that month. Even though flooding seemed to enhance CO_2 source strength in April, the prolonged flooding from April to June 2011 did not show the same consequence. In the months following this long flooding event, CO_2 sink strength was higher in the same months of 2012 and 2013. Consequently, the 2012 growing season NEE was the lowest of the three years (Table 3). The annual NEE was 246, 244, and 663 g C m^{-2} in 2011, 2012 and 2013, respectively, showing a strikingly large interannual variability (Table 3).

3.5. Gross primary production and ecosystem respiration

The daily mean GPP, ER and NEE fluxes from August 2010 to April 2014 are illustrated in Fig. 5. Large negative GPP flux, or high net ecosystem productivity was observed from May to September 2011 (−5.89 to −9.42 g C m^{-2} day^{-1}), 2012 (−9.42 to −10.60 g C m^{-2} day^{-1}) and 2013 (−5.89 to −9.89 g C m^{-2} day^{-1}). Near-zero GPP flux (~0 g C m^{-2} day^{-1}) was obtained during the winter (December to March) 2011, 2012 and 2013. The maximum negative growing season GPP yielding an annual sum of −1014 g C m^{-2} occurred in 2012, while the minimum negative growing season GPP yielding an annual of −715 g C m^{-2} occurred in 2011 (Table 3). ER showed a decreasing trend with time from fall to winter and increased progressively with time through the growing season, mirroring GPP variations (Fig. 5). The cumulative growing season ER was highest in 2013 and lowest in 2011 (Table 3). The annual ER flux was higher than the annual GPP for all the three years causing a positive annual NEE flux (Table 3).

Among the three annual periods, the lowest annual NEE (lowest CO_2 release) in 2012 was associated with the highest annual GPP and an intermediate annual ER. The highest NEE (highest CO_2 release) in 2013 was the result of the lowest GPP during the growing season and the highest ER, which was characterized by the lowest WAI (Table 3). Besides the interannual variability effects of ER and GPP on NEE, there was a stronger correlation between daily NEE and daily GPP ($r = 0.49$ to 0.66) (Table 4) than between daily NEE and daily ER ($r = <0.27$).

3.6. Multiple linear regression analysis

The correlation matrix among the environmental factors (T_{air}, VPD, ET and rainfall) and the C balance components (NEE, ER and GPP) based on daily data for each complete year (2011, 2012 and 2013; Table 4) was used to screen for the most influential predictors to build multiple linear regression models. Correlations between the C components and rainfall were not significant for 2011, 2012 or 2013. Generally NEE did not show good correlations with the environmental variables. GPP and ER had the strongest correlations with T_{air}, VPD and ET for all the years.

ET, T_{air} and VPD were selected as the explanatory variables owing to their high correlations with the C flux components. Results of the best subset regressions are presented in Table 5 for 2011, 2012 and 2013. Significance level (p) of <0.05, and variance inflation factor (VIF) of <6 indicated that the relationship between the predictors (ET, T_{air} and VPD) and the responses (NEE, GPP and ER) were statistically significant and had no multicollinearity issue, respectively. The higher r^2_{adj} values were obtained for GPP and ER (0.63–0.83) than for NEE (0.12–0.47). The strongest and weakest predictive models of NEE, GPP and ER belonged to 2011 and 2013, respectively.

4. Discussion

4.1. Comparison of annual NEE in the literature

The annual NEE data (Table 3) showed that the Yenicaga peatland acted as a strong source of CO_2 with large interannual variability. Its CO_2 source strength was at least two times higher than the peatlands under similar climate regimes (Table 1). These comparable studies show that strong CO_2 uptake during the growing season enabled the peatland to act as a strong CO_2 sink in the absence of extreme weather conditions (Strilesky and Humphreys, 2012). Under the extreme meteorological conditions (e.g. drought, high rainfall, and flooding), the peatland may lose its sink strength (Lund et al., 2012) and even turn into a CO_2 source (Shurpali et al., 1995; Nieveen et al., 1998; Evrendilek, 2015). However, these extreme conditions are not the only explanation for the high source strengths found in the literature (Table 1). Changes in land use can also convert a peatland to a CO_2 source. Drainage (Hooijer et al., 2010; Salm et al., 2011), use of peatland for agriculture (Nieveen et al., 2005; Knox et al., 2015), overgrazing (Hatala et al., 2012; Clay and Worrall, 2013), and peat mining (Basiliko et al., 2007; Salm et al., 2011) appear to have contributed to the source strength of the Yeniçağa peatland. There are a few studies that reported high CO_2 source strength for disturbed peatlands. For example, Hirano et al. (2012) reported interannual variability in NEE between 174 and 499 g C m^{-2} yr^{-1} over four years and stated that peat fires and lowered WTL increased the CO_2 source strength of a tropical disturbed peatland. Similarly, the highest source strength in this study occurred in 2013, a year with the lowest WTL (Fig. 3). Knox et al.

Table 3
Water availability index (WAI, mm) and carbon components (NEE, ER and -GPP, g C m^{-2} period^{-1}) of the peatland ecosystem over the annual and growing season (May to September) periods.

	WAI			NEE			ER			GPP		
	2011	2012	2013	2011	2012	2013	2011	2012	2013	2011	2012	2013
Annual	604.7	210.9	−9.2	246	244	663	1194	1247	1726	−948	−1014	−1090
Growing season	72.1	−177.8	−291.5	62	5	245	777	840	952	−715	−835	−707

Table 4
A matrix of correlation coefficients s (r) among average daily NEE, its components (GPP and ER) and environmental variables for each of the three full year periods (2011, 2012 and 2013).

	Year	NEE	T_{air}	VPD	SWC	ET	RF	GPP
T_{air}	2011	-0.13^{**}						
	2012	-0.22^{*}						
	2013	-0.09^{**}						
VPD	2011	-0.04^{**}	0.77^{*}					
	2012	-0.09^{*}	0.83^{*}					
	2013	-0.08^{**}	0.82^{*}					
SWC	2011	-0.13^{**}	0.61^{*}	0.49^{*}				
	2012	-0.48^{*}	-0.20^{*}	-0.15^{*}				
	2013	-0.31^{*}	-0.04^{**}	-0.06^{**}				
ET	2011	-0.21^{*}	0.85^{*}	0.88^{*}	0.11^{**}			
	2012	-0.39^{*}	0.83^{*}	0.89^{*}	0.04^{*}			
	2013	-0.38^{*}	0.75^{*}	0.63^{*}	0.21^{*}			
RF	2011	0.06^{**}	0.06^{**}	-0.19^{*}	0.07^{*}	-0.12^{*}		
	2012	-0.03^{**}	-0.24^{*}	-0.31^{*}	0.06^{*}	-0.29^{*}		
	2013	0.11^{**}	-0.08^{**}	-0.23^{*}	0.12^{*}	-0.09^{**}		
GPP	2011	-0.49^{*}	0.84^{*}	0.62^{*}	0.59^{*}	0.82^{*}	0.07^{**}	
	2012	-0.66^{*}	0.74^{*}	0.65^{*}	0.24^{*}	0.82^{*}	-0.21^{*}	
	2013	-0.61^{*}	0.69^{*}	0.52^{*}	0.15^{*}	0.77^{*}	0.09^{**}	
ER	2011	-0.03^{**}	0.89^{*}	0.69^{*}	0.61^{*}	0.83^{*}	0.05^{**}	0.89^{*}
	2012	-0.27^{*}	0.83^{*}	0.78^{*}	0.03^{**}	0.83^{*}	-0.28^{*}	0.90^{*}
	2013	-0.13^{**}	0.81^{*}	0.60^{*}	-0.01^{**}	0.73^{*}	0.05^{**}	0.86^{*}

* Significance at 0.05 level.
** Significance at 0.1 level.

(2015) reported an annual NEE of 341 g C m^{-2} yr^{-1} for a peatland drained for agriculture in California. Lohila (2008) found an annual NEE of 210 g C m^{-2} yr^{-1} for a cultivated peatland in southern Finland. NEE measurements were made in two peatlands in Quebec (Canada) where peat extraction lasted for eight years before the start of restoration activities (Strack and Zuback, 2013) showed that the unrestored peatland was a significant CO_2 source with an annual NEE of 344 g C m^{-2} which is similar to NEE estimate of this study. Also, Morrison et al. (2013) reported NEE value of 270 g C m^{-2} from July to October for a drained and intensively cultivated peatland. While pristine peatlands are an important CO_2 sink (e.g. Table 1), this study confirms that human-induced disturbances can turn peatland into a huge CO_2 source.

Our results indicate that the source strength of a disturbed peatland can be substantially enhanced by drought. The source strength observed in the drought year (2013) was 20% higher than even the highest value found in the literature, 499 g C m^{-2} yr^{-1} for tropical peatlands in Indonesia estimated by Hirano et al. (2012). Our study underscores the importance of long-term flux monitoring under different climate types and disturbance regimes.

Table 5
Best-fit multiple linear regression models of daily mean NEE, GPP and ER as a function of ET, T_{air} and VPD for 2011, 2012 and 2013 ($p < 0.05$; VIF < 6; $n = 365$).

Components/year		2011	2012	2013
NEE	Intercept	0.042	0.06	0.09
	ET	−0.55	−1.13	−0.54
	T_{air}	0.0007	−0.0001	0.004
	VPD	0.009	0.017	0.0006
	r^2_{adj}	0.14	0.47	0.22
	S	0.04	0.04	0.05
GPP	Intercept	0.013	0.042	0.09
	ET	1.1	0.61	0.35
	T_{air}	0.007	0.005	0.01
	VPD	−0.01	0.0001	−0.005
	r^2_{adj}	0.80	0.75	0.7
	S	0.04	0.05	0.05
ER	Intercept	0.06	−0.02	0.0002
	ET	0.55	1.74	0.9
	T_{air}	0.008	0.005	0.007
	VPD	−0.006	−0.02	−0.006
	r^2_{adj}	0.83	0.75	0.63
	S	0.03	0.06	0.07

r^2_{adj}: adjusted coefficient of determination; S: standard error.

4.2. Effects of water status on CO_2 exchange

Water status of a peatland plays a critical role in its CO_2 exchange by regulating anoxic conditions of the soil. Water table level and soil water content are the two primary drivers of interannual variability in C fluxes (Sonnentag et al., 2009). The published studies have mostly focused on the response of C fluxes to changes in WTL (Ellis et al., 2009; Mezbahuddin et al., 2014) with little information about SWC (Parmentier et al., 2009). Furthermore, WAI may be a driver of interannual variability in C fluxes since WAI is an integral measure of both the peatland water balance (P-ET) (Roulet et al., 1997) and its SWC.

Soil water content and WTL displayed a strong positive correlation ($r = 0.82$). However, this relationship was driven mostly by the transitional changes between the three stable SWC periods (Fig. 4). The correlation was rather weak ($r = <0.3$) within each of the periods despite large water table variability, in contrast to findings based on undisturbed peatlands (Lapen et al., 2000; Strack et al., 2009) and similar to findings based on disturbed peatlands (Nieveen et al., 2005). Anthropogenic disturbances can critically weaken (Gong et al., 2013) or totally destroy the relationship between the two measures (Strack et al., 2009). Thus, NEE was discussed in relation to each of the two water drivers. NEE showed the maximum CO_2 uptake and release at shallow and deep WTL, respectively, with a linear relationship ($r = -0.64$; $p < 0.05$) (Fig. 3), in close agreement with the finding by Hirano et al. (2012). The seasonal correlation between NEE and WTL was higher from January 2011 to August 2012 than from the rest of 2012 to the end of 2013. Monthly NEE never reached negative values, in other words, the site acted as a CO_2 source from August 2012 to the end of 2013 when WTL was below −60 cm as was similarly reported by Evrendilek (2015) with a non-gap filled data set. This relationship may indicate that the site had a critical WTL of −60 cm, below which the site could not act as a CO_2 sink. Some studies reported similar threshold values (Strack et al., 2009), while others observed different threshold values (Sonnentag et al., 2009; Peichl et al., 2014), thus indicating that the threshold value is highly site specific depending upon peat, vegetation, and drainage history (Mezbahuddin et al., 2014).

Water table threshold for NEE can be explained by a decline in GPP (Dimitrov et al., 2011) and the lack of change in ER (Dimitrov et al., 2010). However, our results suggested that the increase in NEE with low WTL was related to the increase in ER and a small change in GPP. Interannual variability in NEE, ER and GPP (Table 3) revealed that a significant change occurred in ER in 2013 resulting in an almost threefold increase in the annual NEE. As WTL drops below the critical value, desiccation occurs near the surface peat, which may cause a reduction in

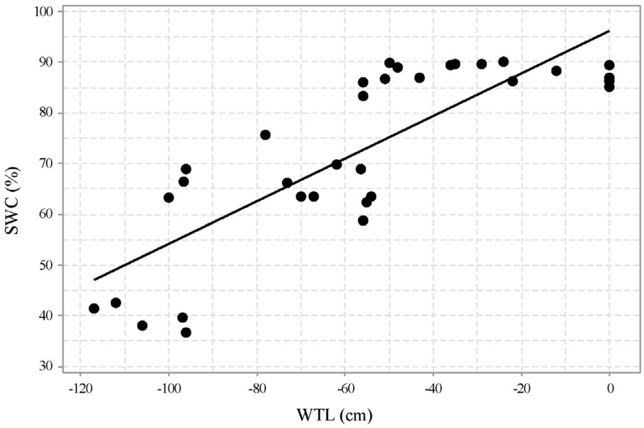

Fig. 4. Monthly mean soil water content (SWC) versus water table level (WTL) during the study period.

soil respiration of the surface peat layer (Dimitrov et al., 2010). Our results suggest that increased soil respiration of the deeper well-aerated peat layer was able to partially or fully offset the reduced soil respiration of the surface layer, as in agreement with the studies by Strack and Waddington (2007); Dimitrov et al. (2010); Marwanto and Agus (2013), and Mezbahuddin et al. (2014).

Past studies demonstrated that soil moisture controlled C fluxes in ecosystems where soil moisture is a limiting factor, as with semi-arid ecosystems (Bell et al., 2008; Scott et al., 2008; Thomas et al., 2009). In peatland ecosystems, soil moisture does not appear to be limiting, at least from the viewpoint of energy exchange. For example, the annual mean Bowen ratio at our site was very low (0.4). For this reason, a few studies focused on the direct response of C fluxes to soil moisture in peatlands. However, soil drying can lead to increased peat decomposition (Waddington et al., 2002), and thus, enhanced soil respiration. At our site, a sharp drop in WTL decreased SWC. Similar to our discussion on WTL, SWC showed a critical value of 70% below which the monthly NEE was always positive (Fig. 3). The highest annual ER, and thus, the highest positive annual NEE in 2013 can be attributed to the presence of SWC below the critical value. Even though WTL showed large fluctuations between 2011 and 2012, the difference in annual ER between 2011 and 2012 was small (4.7%) because there were small variations in SWC. The weak dependence of ER on WTL ($r = -0.13$; $p > 0.5$; Table 6) could be related to the small variations in SWC as pointed by Parmentier et al. (2009). Indeed, several other studies failed to find a significant correlation between ER and WTL (Lafleur et al., 2005; Ellis et al., 2009; Sulman et al., 2009; Lund et al., 2010), whereas some studies reported a strong correlation between ER and WTL (Bubier et al., 2003; McVeigh et al., 2014). Therefore, the relationship between ER and WTL appears to be site-specific.

WAI is another hydrological variable that can help us to understand interannual and seasonal variability in the C flux components. Because SWC was relatively stable during the measurement period, it did not provide sufficient explanatory power for the growing season variations of the C flux components. Water table depth also showed a weak relationship to ER. For these reasons, WAI can be an alternative predictor for the C flux components. WAI at the end of the 2013 growing season (−9.2 mm, Table 3) was the lowest of the three years due to high evapotranspiration, and the lack of rainfall from May to September 2013. The low WAI value in 2013 was associated with the sharp increase in the annual ER and NEE.

Of the three water variables, WAI had the highest explanatory power for monthly mean C flux components (GPP and ER; Table 6). NEE showed a moderate correlation with WTL ($r = -0.64$) and with SWC ($r = -0.62$) but insignificant correlation with WAI ($r = 0.07$, $p > 0.5$). It is worth noting that the highest correlation was found between ER and WAI ($r = -0.83$, $p < 0.05$). In this respect, WAI was a good predictor for ER because it integrated SWC and the water balance (P-ET) variables.

Table 6
A matrix of correlation coefficients (r) among monthly carbon components and hydrological drivers for the 2011–2013 period ($p < 0.05$; $n = 36$).

	WAI	WTL	SWC
NEE	0.07	−0.64	−0.62
GPP	−0.72	0.16	0.07
ER	−0.83	−0.13	−0.23

Part of the interannual variability in the C fluxes was associated with duration and timing of flooding (water logged condition) when WTL was at the surface level. The longest flooding period of ca. 3 months (April to June) occurred in 2011 during which the heaviest rainfall events occurred (Fig. 2a). The site was flooded only for one month (April) in 2012. Our site showed lower NEE in the 2012 growing season than in the 2011 growing season (Table 3). The prolonged flooded inhibited mostly GPP relative to ER (Table 3) resulting in higher CO_2 source strength. However, some studies indicated that ER is inhibited in the flooded peatland sites leading to a net sink of CO_2 (Hatala et al., 2012; Knox et al., 2015).

4.3. Multiple regression models of carbon flux components

A number of environmental factors such as temperature, light, VPD, biomass, and leaf area index (LAI) can regulate the dynamics of NEE, ER and GPP fluxes in peatlands (Han et al., 2013). ET, VPD, and T_{air} were found to be the most important drivers of the daily C fluxes in this study (Table 4). For a peatland in Canada, Bonneville et al. (2008) found that T_{air} is a good predictor for GPP ($r^2 = 0.55$) and for ER ($r^2 = 0.54$) but did not account for much of variation in NEE ($r^2 = 0.39$). Han et al. (2013) reported a significant positive correlation of NEE, GPP, and ER with the aboveground biomass ($r^2 = 0.87$, 0.83, and 0.7, respectively) for a wetland in the Yellow river Delta, China. Zhao et al. (2010) modelled ER, GPP and NEE as a function of T_{air}, T_{soil}, VPD, and PPFD and found higher r^2_{adj} values for GPP ($r^2_{adj} = 0.87$) and ER ($r^2_{adj} = 0.82$) than for NEE ($r^2_{adj} = 0.52$). Similarly, using the predictors of WTL, T_{air}, and VPD led to better predictions of GPP ($r^2_{adj} = 0.65$) and ER ($r^2_{adj} = 0.62$) than of NEE ($r^2_{adj} = 0.26$) for a peatland (Schedlbauer et al., 2012). Our model results (Table 5) indicated that variability in GPP, ER, and NEE were significantly coupled to changes in T_{air}, ET, and VPD. Similar to findings in the literature (Bonneville et al., 2008; Zhao

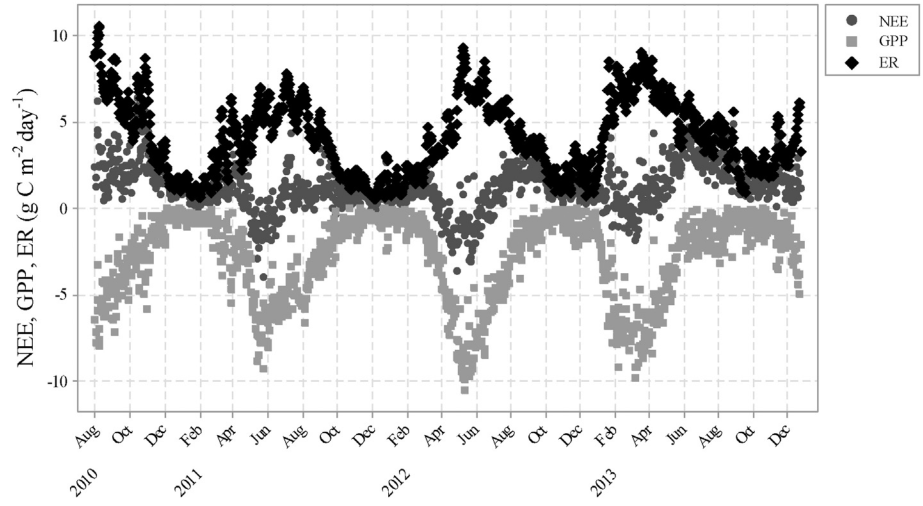

Fig. 5. Daily NEE, GPP and ER fluxes from August 2010 to April 2014.

et al., 2010; Schedlbauer et al., 2012) the multiple regression models had a higher goodness-of-fit for GPP ($r^2_{adj} = 0.80$) and ER ($r^2_{adj} = 0.83$) than for NEE ($r^2_{adj} = 0.47$).

The performance of the models varied among the three years. Their goodness-of-fit for ER and GPP decreased from 2011 to 2013 (Table 5). WAI data indicated an increasing trend in drought from 2011 to 2013 (Table 3), suggesting that as the drought intensity increased, the goodness-of-fit of the models decreased for ER and GPP. The reason for this is may be related to a large decrease in the correlation of ET with ER and GPP in the drought year of 2013 (Table 4). A declined correlation between ER and ET in a dry year was reported for a steppe site (Huang et al., 2010). To compensate for the weakness of the regression models in response to extreme conditions, data on interannual variability provided by long-term studies like ours should help with the search of more robust empirical and mechanistic models.

5. Conclusions

Although several long-term studies have performed in pristine peatland, the present study appears to be the first on evaluating long-term interannual variability of NEE in a disturbed temperate peatland. Our results indicated that Yenicaga peatland was a strong CO_2 source, at a rate of 244, 246 and 663 g C m^{-2} yr^{-1} for 2011, 2012 and 2013 respectively. The large source strength in 2013 was explained by a sharp decrease in WTL. Monthly data indicated that WTL had a threshold value (ca. -60 cm) below which the site was a source of CO_2. Although WTL was a driver for the variation in NEE, SWC was a critical variable to explain changes in source strength of CO_2. The three-fold increase in the annual source strength in 2013 relative to 2011 and 2012 was mainly caused by the increased ER. However, monthly ER did not show any significant relationship to WTL or SWC but displayed a significant negative correlation with WAI ($r = -0.83$). ET, T_{air} and VPD were found to be the most influential environmental drivers of the daily C flux components. The best-fit multiple regression models of GPP, ER, and NEE behaved not well in the 2013 drought year.

Acknowledgements

We would like to thank two anonymous reviewers for their invaluable comments which significantly improved an earlier version of the manuscript. This project (CAYDAG-COST-109Y186) was supported by the Scientific and Technological Research Council of Turkey (TUBITAK). Financial support for the first author provided by TUBITAK under the Grant No. 2219 (International Post-Doctoral Research Fellowship Program) is acknowledged.

Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2016.02.153.

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