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Interannual variability of grasslands' carbon balance depends on soil type

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Abstract: Interannual variation of carbon fluxes of grasslands on sandy (5 years data) and heavy clay soils (4 years data) have been analysed. The sandy grassland was carbon sink in 3 (2004, 2005, 2006) out of the investigated 5 years. Its annual C-balance is precipitation limited, the relation seems strongly conservative, with r^2 of 0.83. More than half of the net source activity fell to the summer droughts. The heavy clay grassland was net source of carbon in one year (2007) only with no whole year record from 2003, a drought and heat wave year. Dependence of the C-balance on precipitation was somewhat weaker (r^2=0.57) than in the sandy grassland. Length of growing period showed less variation here compared to the sandy grassland. Recovery of sink activity after rains was much slower for the heavy clay grassland than for the sandy grassland. The reason behind is that the amount of water required to reach optimal soil water content for plant functioning is several times larger for the mountain grassland. This fact and the low conductivity of the clay soil for water decrease the heavy clay grassland's recovery potential after droughts. Owing to these soil characteristics, the clay grassland may be more vulnerable to droughts in terms of decreased C-assimilation and (soil) carbon losses under the predicted drier summers even if the annual precipitation sum was higher by 10.7% on average for the mountain compared to the sandy grassland. The annual precipitation sum is close to the threshold, below which the grasslands may turn into source of carbon. While in one hand this can be viewed as an example of ecosystem scale adaptation to available water, drought events also involve loss of soil carbon and a potential positive feedback between source activity and decreasing net primary production, on the other.

Introduction

Carbon balance of ecosystems is under climatic constraints with significant carbon losses occurring during droughts in water limited ecosystems (Nagy et al. 2007, Novick et al. 2004, Pereira et al. 2007, Reichstein et al. 2007). In the contrary, in the case of humid grassland ecosystems the amount of carbon uptake can be less in a wet year than in a year with less precipitation as found by Jaksic et al., 2006. Long term eddy covariance measurements over grasslands have been conducted to characterize the interannual variability of the C-balance of grasslands on three different soil types in Hungary. The first measuring site was established in the north western part of the country near Hegyhátsál (Barcza et al. 2003). The second one is located in the central region of Hungary, in Kiskunság National Park near Bugacpuszta (Nagy et al. 2007), and the third one is in the north eastern region in Mátra Mountains near Szurdokpüspöki. The last two sites are within the scope of this article. While the grasslands were sinks for carbon in the majority of the study years on annual basis, droughts have been shown to turn these ecosystems into net source of carbon (Nagy et al. 2007). While the origin (age) of the lost carbon was not directly identified, the length of the source activity periods suggest this carbon at least partly arose from older soil organic matter (SOM) fractions. This, in addition to the potential possibility of the positive feedback between climate warming and carbon loss from ecosystems on global scale, may drive latent desertification process locally, with productivity decrease associated to loss of SOM. Studying this process is crucial in assessing future impacts of climate change on the potential desertification process through loss of soil carbon and calls the attention to revisit the cost-benefit problem of irrigation.

Materials and methods

Site description and instrumentation

The measurements at Bugacpuszta (46.69°N, 19.60°E, 111.4 m a.s.l.) were started in July, 2002 and are run since then continuously. In this region the soil type is sandy chernozem with sand content of 90%, and the characteristic plant species are *Festuca pseudovina* Hack. ex Wiesb., *Carex stenophylla* Wahlbg. and *Salvia pratensis* L. The mean annual (10 years average, 1995-2004) temperature and sum of precipitation are 10.4°C and 562 mm, respectively.

At the other study site, near Szurdokpüspöki (47.85°N, 19.73°E, 300 m a.s.l.), the experimental tower was set up in June, 2003. The soil type of the meadow is heavy clay, brown forest soil with 46% clay content, and the main components of grass are *Festuca pseudovina* Hack. ex Wiesb., *Arrhenatherum elatius* L., *Poa pratensis* L. and *Plantago lanceolata* L. Mean annual temperature is 10.2°C and the annual sum of precipitation is 622 mm in the region.

Both stations are equipped with a CSAT3 sonic anemometer and a Li-Cor 7500 open path IRGA to measure eddy fluxes of sensible and latent heat and CO_2 and several other sensors to measure micrometeorological variables (including wind speed and wind direction, temperature and relative humidity, precipitation, global radiation, reflected global radiation, net radiation, photosynthetically active photon flux density (PAR), reflected PAR, soil heat flux, soil temperature, soil moisture). The eddy covariance measurements are carried out at 4 m and 3 m above ground level at Bugacpuszta and Szurdokpüspöki, respectively.

Data processing

Eddy covariance measurements

The calculation of momentum, sensible and latent heat and CO_2 fluxes is based on high frequency (10 Hz) measurement of wind speed, temperature, water vapour and CO_2 concentration data. Spike detection and removal are done after Vickers and Mahrt 1997. The values considered as spikes are replaced by linear interpolation. To calculate fluctuations from the raw data series linear detrending is performed. The disturbance effect of sensor heads is influenced by the angle between the wind vector and horizontal plane, the so called angle of attack. To avoid errors caused by this error our database is calibrated after van der Molen et al. (2004). The error caused by the inaccurate levelling of the sonic anemometer is corrected by the planar fit method (Wilczak et al. 2001), but in a modified way. Average vertical wind speed for 5° wind direction bins has been determined, and the calculation of the half hour mean wind speed was performed by taking into consideration this average vertical wind speed (Haszpra et al. 2005). 3D coordinate rotation is then applied according to these corrected mean wind speeds. According to the changes in wind speed perpendicular to the pathways between the sensor heads, the sound has to travel a longer distance. In order to correct this effect the crosswind correction for sensible heat flux is done after Liu et al. (2001). The fluctuation in air density influences the concentrations measured by the open path IRGA, which is not taken into account during the measurements, but has to be done afterwards by the Webb correction (Webb et al. 1980). To take into consideration the damping effect of sensor line averaging, separation distance between scalar and wind sensor and the limited response time of both the anemometer and the Li-Cor 7500 the Moore correction (Moore 1986) was applied. All these calculations and corrections are implemented through a software written in IDL.

Table 1. Annual mean temperature and annual sum of precipitation and NEE at Bugac and at Mátra from 2002 to 2007.

	Bugac			Mátra		
	T	P	NEE	T	P	NEE
	°C	mm	gC m^{-2}	°C	mm	gC m^{-2}
2003	9.8	456	73			
2004	10	728	-186	10.1	635	-35
2005	9.2	587	-113	9.7	704	-68
2006	9.9	524	-81	10.5	650	-133
2007	11.1	461	105	11.6	560	64

These time series are usually not continuous because of technical problems or environmental influence (eg. failure of power supply, dew formation on sensors, rain). Additionally EC systems are unable to measure correctly in case of weak turbulence, furthermore the effect of night time advective fluxes is still in question (Feigenwinter et al. 2008), so flux data associated with low u_* values has to be rejected, which practically increases the amount of missing data. To calculate the daily, monthly and annual sums of NEE these gaps have to be filled and to estimate daytime ecosystem respiration and GPP ecosystem respiration (R_{eco}) has to be modelled. This stage of work is done after Reichstein et al. (2005). The basis of the gap-filling method is to search for values associated with similar meteorological conditions, and then replace the missing values with their average. R_{eco} values are estimated within the above tool according to Lloyd-and-Taylor regression model (Lloyd and Taylor 1994).

Results

Micrometeorological conditions

Results of micrometeorological measurements at annual basis are summarized in Table 1. The annual mean temperature ranges from 9.2°C to 11.1°C at Bugacpuszta and from 9.7°C to 11.6°C at Szurdokpüspöki, 2007 being the hottest year. Mean annual temperature can mask important interannual differences, for example the effect of the heat wave experienced in summer, 2003 was faded by the negative temperature anomalies measured in January and February. The sum of precipitation was less than the 10 years mean in 2002, 2003 and 2007 at Bugacpuszta and in 2003 and 2007 at Szurdokpüspöki. There is about 270 mm difference between the annual precipitation sums considering the driest (2002) and the wettest (2004) years at Bugacpuszta. This difference is smaller (ca. 230 mm) in the case of the mountain site.

The most summer days (daily maximum temperature above 25°C) occurred at Bugac in 2003 and 2007 (120 and 101 days, respectively) and in the other years the number of summer days was about 80 (Table 2.). Number of heat days (daily maximum temperature above 30°C) was highest in 2003 and 2007 (59 and 54 days, respectively), and the highest daily maximum temperatures were recorded (38.4°C and 41.0°C) in these years, too. The situation was very similar at Mátra site, where the most summer days were recorded in

Table 2. Number of summer and heat days and daily maximum temperatures at the Bugac and Mátra sites from 2003 to 2007.

	2003	2004	2005	2006	2007
Bugac					
Number of summer days	120	80	79	84	101
Number of heat days	59	20	18	36	54
Daily maximum temperature	38.4	37.0	35.0	36.5	41.0
Mátra					
Number of summer days	88*	53	49	46	76
Number of heat days	24*	10	6	12	24
Daily maximum temperature	34.4*	33.5	33.1	33.0	37.5

*Since there was no measurement in the first half of the year, daily maximum temperature data were gap-filled from a near meteorological station

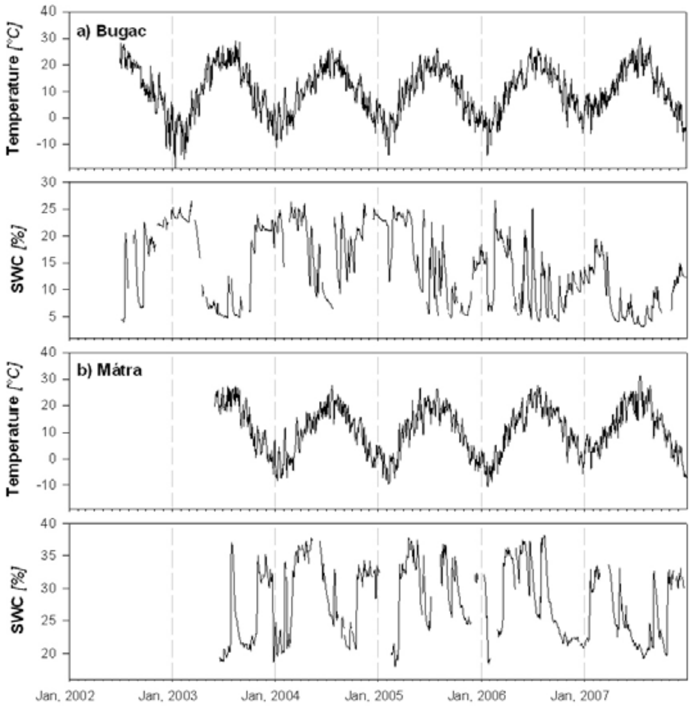

Figure 1. Variation of daily mean temperature and soil water content at Bugac and Mátra from January, 2002 until December, 2007.

2003 and 2007 (88 and 76 days, respectively) and there were 24 heat days in both of these years. Highest daily maximum temperature was recorded in 2007 (37.5°C). Interannual variability in heat patterns may be characterized by the ratio of heat days to summer days. This ratio gives value of 0.5 in heat wave years and about 0.25 in the other years at the sandy grassland, while it is about 0.3 and 0.15 at the mountain grassland (Mátra) site.

High temperatures were associated with lack of precipitation causing severe droughts in 2003 and 2007 at both sites (Fig. 1). In the other years the frequency and amount of precipitation was enough to increase soil water content (SWC) above 10-15% several times during summer at Bugac, and above 25% at Mátra. The range of SWC differs between the two sites, it changed between 5% and 25% (vol) on the sandy soil at Bugac and between 20% and 38% on the heavy clay at Mátra. Characteristics associated to the soil physical structure, (e.g. pF curve, conductivity for water for a sand and a heavy clay soil, respectively) leads to differences in plant available water and evaporation between the two sites. Plant available water is 9.8% (vol) in the heavy clay soil and 18.1% in the sandy soil at field capacities of 44% and 26%, respectively (Hagyó et al. 2006, Table 3). The annual precipitation sum is not differing much between the sites, therefore less water is available for plants growing on the heavy clay soil, than for the ones in the sandy grassland as also shown by the relationship between SWC and daily mean evapotranspiration (Fig. 2). Daily mean evaporation values were averaged for 2 % (vol) SWC bins (Fig. 2) for the whole measurement period for the two sites separately. According to this graph there is about 25% (vol) difference between the optimum domains for evapotranspiration at the two sites, that can be attributed largely to the different soil characteristics. This figure is rather large, considering that the amount of water responsible for this difference in the upper 30 cm of the soil amounts to 75 mm of precipitation.

Variation of annual sum of NEE

The annual sum of NEE varied between -186 gC m^{-2} and 105 gC m^{-2} at Bugac (sand), at the central part of Hungary while it was between –133 gC m^{-2} and 64 gC m^{-2} at the northern part of the country (clay soil, Table 1). These values are

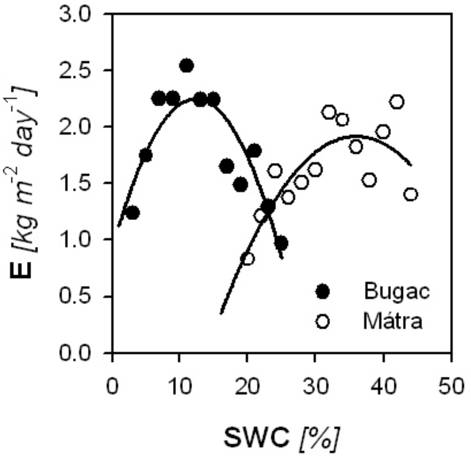

Figure 2. Daily mean evapotranspiration (E) rates between April and September averaged for 2% (vol) SWC bins at the two measuring sites.

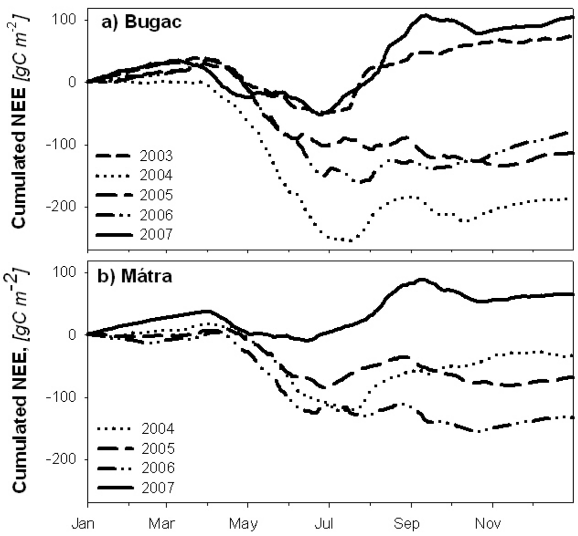

Figure 3. Cumulative sum of NEE at the measuring sites.

within the range for grassland ecosystems as summarized by Novick et al. (2004).

Source and sink periods can be clearly identified on the cumulated NEE curves (Fig. 3). During winter the grasslands were sources of carbon with an exception of the beginning of 2004, when the cumulative curve was flat, showing that respiration and photosynthesis cancelled out on a daily scale. Identification of the start of growing season was based on the slope of cumulative NEE curve against time. A linear curve was fitted using 5 days time windows and the intensive growth period was defined as the period where the successive slopes were continuously negative. The intensive growing period started between 69-109 day of year (DOY) at Bugac and 89-108 DOY at Mátra in the study years. Length of the main growing period (as defined by the above procedure) ranged between 45 (in 2003) and 99 days (in 2004) at the

Table 3. Values of soil water content (%, vol) at wilting point (pF 4.2) and at field capacity (pF 2.3) in the upper 30cm soil layer at the two measurement sites.

	at pF2.3	at pF4.2
Bugac (sand)	25.7	7.6
Mátra (heavy clay)	44.4	34.6

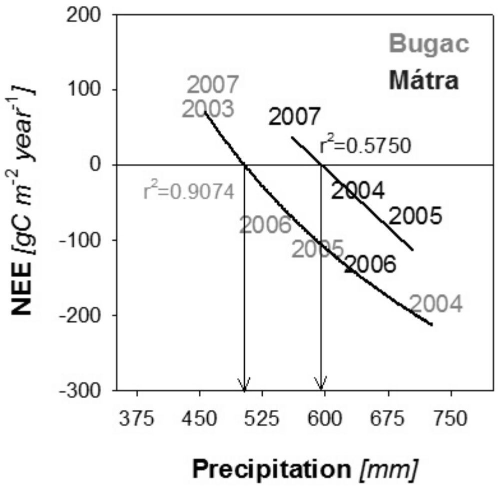

Figure 4. Scatter plot of precipitation (P)and NEE at Bugac and Mátra. A Michaelis-Menten like equation (NEE= - a P/(b + P) + c) was fitted to the sandy grasslands' data (Bugac) and a linear equation (NEE= a P + b) to the data of mountain site (Mátra). (Data points are represented by the middle of the date of year.)

sandy grassland. Main growing periods were slightly shorter at the mountain site ranging from 37 (2007) to 72 days (2006). The carbon uptake during the longest intensive growing period was 251 gC m^{-2} at Bugac and 128 gC m^{-2} at Mátra, while it was 55 gC m^{-2} at Bugac and 38 gC m^{-2} at Mátra, during the shortest periods of intensive growth.

Important feature of the grassland's annual C-cycle is the secondary growing period beginning from late August till end of September. Depending on the micrometeorological conditions this recovery may show remarkable interannual variation. Due to heat wave in 2003 the sandy grassland was source of CO_2 from July until the end of the year. On the contrary there was a strong secondary growing period in 2004 due to the favourable precipitation conditions also in early autumn, when an additional 41 gC m^{-2} was taken up during the period between the beginning of September till the first third of October. The cumulative sum of NEE was already positive at the end of summer in 2007 in both ecosystems, when secondary growth decreased the source activity by 31 gC m^{-2} and 36 gC m^{-2} at Bugac and Mátra, respectively.

Discussion

The relationship between the annual sum of precipitation and NEE was strong with different characteristics at the two sites (Fig. 4). A Michaelis-Menten type equation was fitted to the Bugac (sandy grassland) data, and linear regression was applied in the case of Mátra site as no saturation of the

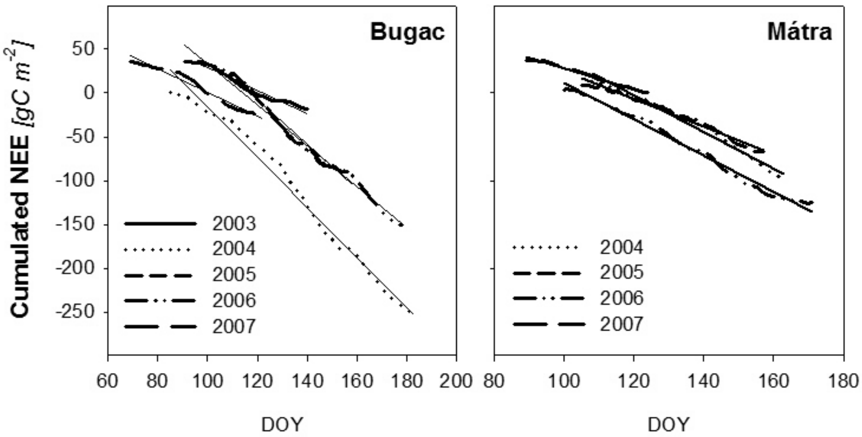

Figure 5. The intensity of carbon uptake in the growing season at Bugac and Mátra

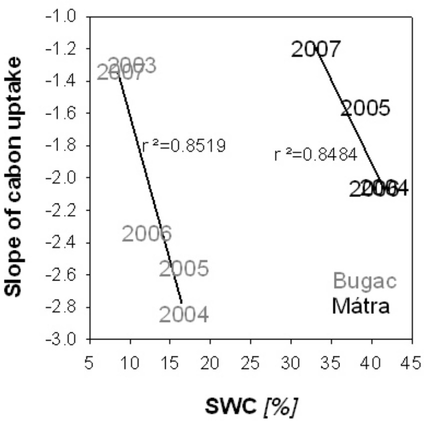

Figure 6. Relationship between soil water content during the main growth period and sink strength (slope of carbon uptake) during the same period at the two grasslands.

curve could be suspected in the latter case. Based on these relationships a threshold can be quantified below which the grassland might act as a net carbon source, which is 503 mm in the case of sandy grassland, and 596 mm in the case of the mountain site. The sink-source precipitation threshold is 10% below the ten year average precipitation sum, while the range of variation was on the order of 50% of the average in the last six years. Further, the NEE response to precipitation is rather steep at the threshold, consequently, the chance of these ecosystems to turn into a source of carbon is high. As carbon sequestration potential of the grasslands is the highest during intensive growth, water supply during this period is critical. Occurrence of net source periods during droughts is common and was responsible for up to 70% of the net source activity during the years studied.

There is an outlier point (Fig. 4, year 2006) at the Mátra site, caused by the spring and summer timing of precipitation in 2006, while much of the precipitation felt during the winter months in 2005 (wettest year in Mátra data series). The intensity of CO_2 uptake during the main growing period is decisive for the whole year's C-balance. One method to characterize this is to look at the slope of the cumulative NEE curve against time in that period. The value of the slope varied in wide range between the years at the two sites (Fig. 5) and showed highly significant correlation with the soil water content (Fig. 6).

Conclusions

Interannual variation of carbon balance is primarily constrained by the annual sum of precipitation at the sandy grassland, while timing of the precipitation events seemed to be also important in the case of the grassland on heavy clay. Depending on the precipitation supply and timing of precipitation and temperature conditions (Urban et al. 2007) the same sandy grassland ecosystem can be a sink with strength of -186 gC $m^{-2}year^{-1}$ or may loose 73 gC $m^{-2}year^{-1}$. Largely different precipitation sums are needed to reach the field capacity on light sand and heavy clay soils. Further, the amount of plant available water is also largely different between the two soils and the annual NEE and the slope of the annual NEE during the intensive growth period is obviously limited by available soil water in both ecosystems. The heavy clay grassland is more dependent on the frequency of precipitation events than the sandy grassland, because in the case of the mountain (heavy clay) grassland the plant available soil water content range is narrow, therefore more frequent replenishment is necessary to maintain favourable soil water conditions. Further, when dried out (upper soil layer) the conductivity dramatically decreases and runoff fraction increases. For the same reason (low conductivity for water) rainstorms are less efficient in improving the water status of the soil than rains of lower intensity. The sandy soil, on the other hand, show wider range of plant available soil water content in absolute terms, has much higher conductivity for water and therefore is better suited for utilizing rainstorm precipitation.

This picture is also verified by the fact, that the sandy grassland's sink activity was generally stronger than that of the grassland on heavy clay soil, in spite the fact that the sandy grassland received less precipitation on annual basis. The main cause of this discrepancy between the grasslands therefore is not the precipitation difference between the sites. Plant available soil water is much less on the heavy clay soil than on the sandy soil, and while the latter is well suited for utilizing rainstorm precipitation, the opposite is true for the heavy clay soil. Since frequency of both droughts and rainstorms are predicted to increase in the region (Christensen et al. 2007) the grassland ecosystem on the heavy clay soil is predicted to be more vulnerable weather induced carbon loss than the sandy grassland.

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