The carbon budget of semi-arid grassland in a wet and a dry year in Hungary

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Abstract

Data on net ecosystem exchange (NEE) dynamics and carbon balance of a dry, extensively managed sandy grassland, as measured in Hungary in the years 2003 and 2004 are reported. The grassland was a weak source of carbon in 2003 (80 g C m^{-2}), owing to the exceptionally hot and dry conditions while it was a strong sink in 2004 (-188 g C m^{-2}), when the amount of precipitation was considerably exceeding the 10 years average. Gross primary production (GPP) values in 2003 and 2004 were 584 and 1112 g C m^{-2}, respectively, while ecosystem respiration (R_{eco}) values were 663 and 924 g C m^{-2} for these 2 years. GPP declined more than R_{eco} due to drought and heat wave effects in 2003 than in 2004. The ratio between net sink and net source days were 0.55 and 1.11 for 2003 and 2004, respectively. The average of daily NEE sums during source periods did not differ between the 2 years (0.796 and 0.777 g C m^{-2} day^{-1}), while for the sink periods the average of daily NEE sums were strongly different (-0.836 and -1.677 g C m^{-2} day^{-1}, for 2003 and 2004). The main difference between the years was found in late winter source activity associated with low temperatures (2003), the degree of summer drought and the absence (2003) or presence (2004) of autumn regrowth. As sink activity potentially may occur in the period April–June, the amount of winter–early spring precipitation proved to be decisive to the carbon balance of the grassland and was much less in 2003 than in 2004. Significant source activity was found during droughts in each year contributing up to 50% to the total source activity. While in the favourable periods the assimilation and respiration components were correlated, significant ecosystem respiration not coupled to current photosynthesis was responsible for large part of the source activity of the grassland. Good correlations were found between satellite derived normalized difference vegetation index (NDVI) and broadband NDVI (NDVI$_b$) values in both years. The relation between GPP and the NDVI$_b$ index was significantly different between the main growth periods (April–June) of the 2 years, while it was statistically not significant during the autumn regrowth period (2004).
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1. Introduction

Grasslands are important for global carbon balance both for their large area and significant sink or source capacities (Suyker and Verma, 2001; Novick et al., 2004; Xu and Baldocchi, 2004; Hunt et al., 2004), depending on the climatic factors. While in water limited situations most of the daily carbon exchange activity is linked to the wet periods (Xu and Baldocchi, 2004; Hastings et al., 2005), significant source activity may occur during droughts (Ciais et al., 2005; Li et al., 2005). In grasslands much of variation in net ecosystem exchange (NEE) is constrained by amount of precipitation (Flanagan et al., 2002). Responses of the ecosystem carbon exchange to climatic factors may change according to the phenological stage (Yuste et al., 2004), with

presumably large effect also on the relation between remotely sensed phenology and the ecosystem carbon exchange activity. Relation between satellite derived NDVI and carbon exchange activity of the vegetation have been studied extensively and good correlation between NDVI and GPP were reported (Gilmanov et al., 2005). The relation proved to be robust also when considering interannual variation (Wylie et al., 2003). An alternative to satellite derived NDVI, is based on ground measurements (Huemmrich et al., 1999; Wang et al., 2004) and provides the possibility of measuring broadband NDVI locally. Large scatter and steep increase of the GPP–NDVI relationship implies the possibility that the relation between these variables may be obscured by relation between vegetation phenology and NDVI (Reed et al., 1994; Moody and Johnson, 2001). Whether the observed GPP–NDVI relations may hold equally for stressed and not stressed vegetation is important when predicting vegetation carbon exchange from the measured NDVI values. Main objectives of the study were to characterize interannual differences in terms of net ecosystem exchange and to investigate the relationship between GPP and NDVI in climatically different years.

2. Materials and methods

2.1. Site description and instrumentation

The measuring site is situated at Bugacpuszta (46°41′30″ N, 19°36′06″ E, 111.4 m a.s.l.) in the Hungarian Plains. The climate of the region is temperate continental, and the soil is a Chernozem-type sandy soil. The vegetation is semi-arid sandy grassland dominated by *Festuca pseudovina* Hack. ex Wiesb., *Carex stenophylla* Wahlbg. and *Salvia pratensis* L. The grassland is part of the Kiskunság National Park and has been under extensive management for the last 20 years. Herd of the ancient variety grey cattle was grazing the grassland at an average grazing pressure of 0.56 animal ha^{-1} in

favourable periods. Electric fence was applied to exclude grazing from an area of 200 m × 200 m. The tower was situated at the border between the grazed and non-grazed area. The footprint of the eddy fluxes was distributed between the grazed and non-grazed halves in the study period.

Micrometeorological and eddy covariance measurements were carried out to quantify the carbon balance of the grassland. The eddy covariance measuring system consists of a Li-Cor 7500 Open Path CO_2/H_2O Infrared Gas Analyzer and a Gill Solent R2 anemometer/thermometer. Additional meteorological measurements of wind speed and wind direction, temperature and relative humidity, precipitation, global radiation, reflected global radiation, net radiation, photosynthetically active photon flux density (PPFD), reflected photosynthetically active photon flux density, soil temperature and soil moisture are measured (Table 1).

2.2. Data processing

The eddy covariance data was processed by software written in IDL. To avoid errors caused by the large angle of attack (of wind relative to the horizontal) our database has been calibrated after van der Molen et al. (2004). An important step of the covariance computation is the spike detection and removal, which is performed by a method calculating the average and standard deviation of the data in moving windows (Vickers and Mahrt, 1997). The values considered as spikes are replaced by linear interpolation. Linear detrending was performed on the raw data. To correct for the systematic error due to the inaccurate levelling of the sonic anemometer the planar fit method (Lee, 1998; Wilczak et al., 2001) was applied, but in a modified form. Average vertical wind speed for every 5° wide wind direction bins has been determined (Haszpra et al., 2005), and the calculation of the half hour mean wind speed was performed by taking into consideration this average vertical wind speed. Two-

Table 1
Measured meteorological parameters and sensors used at the Bugac site

Parameter	Sensor	Measuring height
Wind speed and wind direction	Young wind monitor Model 05103-5	3 m
Wind speed	Vaisala WAA151	1 m
Air temperature and relative humidity	Vaisala HMP35AC	1 m
Air temperature	105T Thermocouple probe	0.05 m
Soil temperature	105T Thermocouple probe	−0.05 m, −0.30 m
Precipitation	ARG 100 Tipping Bucket Rain gauges	Ground level
Global radiation, reflected global radiation	Schenk Pyranometer	2 m
Net radiation	Q7 Net Radiometer	2 m
Photosynthetically active photon flux density, reflected photosynthetically active photon flux density	SKP215 Quantum Sensor	2 m
Soil heat flux	HFP01 Heat Flux Plate	−0.05 m, −0.30 m
Soil moisture	CS615 Water Content Reflectometer	−0.05 m, −0.30 m
CO_2 and water vapour concentration, atmospheric pressure (10 Hz)	Li-Cor 7500 Open Path CO_2/H_2O Infrared Gas Analyzer	4 m
Wind speed, wind direction, temperature (21 Hz)	Gill Solent R2 anemometer/thermometer	4 m

dimensional coordinate rotation was then applied to these corrected mean wind speeds. The crosswind correction for sensible heat flux was done after Liu et al. (2001). The effect of density fluctuations on the fluxes is corrected by the method described by Webb et al. (1980). To take into account the damping effect of the sensor line averaging and the limited response time of the anemometer and the Li-Cor 7500 the Moore correction (Moore, 1986) was applied.

To decide whether the u^* correction is necessary, the relation between the night time average of the ecosystem respiration and the estimation of respiration from light response curves was investigated (Xu and Baldocchi, 2004). Because of the poor correlation between these data, the u^* correction (u^* threshold: 0.1 m s^{-1}) was performed in present analysis after Reichstein et al. (2005).

To estimate the daytime ecosystem respiration and calculate the daily, monthly and annual sums of NEE and GPP, a gap-filling and flux-partitioning procedure was applied after Reichstein et al. (2005).

Satellite-based 250 m spatial resolution TERRA MODIS NDVI values have been extracted for the tower site pixel with data time interval of 16 days. The maximum NDVI value composite (MVC) approach minimizes the effect of cloud cover and variability in atmospheric optical depth (Huete et al., 2002). Although the MVC procedure eliminates most cloudy pixels, some MVC products contain residual cloud contamination that could adversely affect our analysis.

Broadband NDVI (NDVI$_b$) values have been calculated with conversion factors of 0.2195 for incoming PAR and 0.2072 for reflected PAR (Ross and Sulev, 2000; Wang et al., 2004) applying the equations below:

$$NDVI_b = \frac{\rho_{OIR} - \rho_{PAR}}{\rho_{OIR} + \rho_{PAR}} \tag{1}$$

where

$$\rho_{OIR} = \frac{G_{refl} - PAR_{refl}}{G_{in} - PAR_{in}} \tag{2}$$

and

$$\rho_{PAR} = \frac{PAR_{refl}}{PAR_{in}} \tag{3}$$

where ρ_{PAR} refers to ratio of reflected PAR (PAR$_{refl}$) to that of incoming PAR (PAR$_{in}$), ρ_{OIR} refers to reflected ratio of

reflected infrared radiation as calculated from incoming and reflected global radiation (G_{in} and G_{refl}, respectively) and PAR data. Daily average values of global and PAR radiation measured near the tower were used in the above calculations. These broadband NDVI values have been compared to the satellite-based NDVI values of 16 days time interval. In case of a data gap (due to rain, ice, or local sensor failure) the data of the previous or the following day was used to fill the gap (broadband NDVI, five cases in 2004 and four cases in 2003). One of the satellite-based NDVI values (mid January, 2004) was rejected due to cloudy conditions and was replaced by the interpolated value of 1st January and 2nd February (1st and 33rd day's values, respectively).

To investigate the differences between the 2 years, lagged correlations between the years' daily NEE (sum), soil water and VPD average data have been calculated to detect possible shifts of seasonal trends between the years.

3. Results

3.1. Meteorological conditions

3.1.1. Annual and monthly sums

In the last 10 years in the region of the Bugac site the annual average temperature and sum of precipitation were 10.4 °C and 562 mm, respectively. In 2003 the total amount of precipitation (381 mm) was less than the 10 years average, while in 2004 (739 mm) it was considerably more. Annual temperature averages were below the long-term average in both years (9.8 and 10 °C for 2003 and 2004, respectively). Considering the vegetation period only, 2003 was warmer and 2004 was cooler than the 10 years average, the differences were 0.3 and −0.7 °C respectively.

In 2003 there was more precipitation than the long-term average in 2 months (Fig. 1a), but these were February and October. In 2004 the monthly sum of precipitation was above the 10 years average in seven cases. In the first 4 months of 2003 the mean temperatures were less than the average (Fig. 1b), while in the following 4 months the mean temperatures were higher than the average by 0.5–2 °C. In 2004, the monthly average temperatures were below the 10 years mean in 7 cases, in the other months the positive anomaly was small. In 2003 there was a drought period during spring, while in 2004 there was 65 mm more
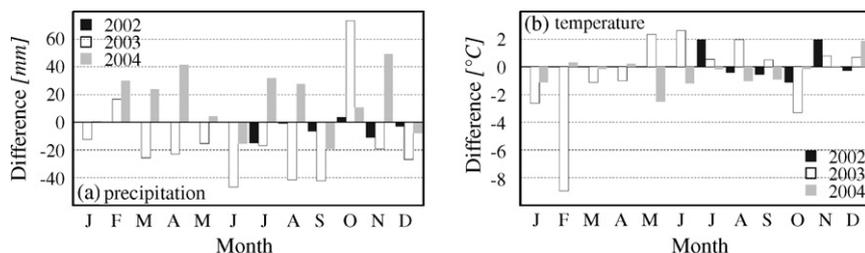

Fig. 1. Deviation of monthly sums of precipitation (a) and monthly mean of temperatures (b) from the 10 years average in July 2002–December 2004 period at the Bugac site.
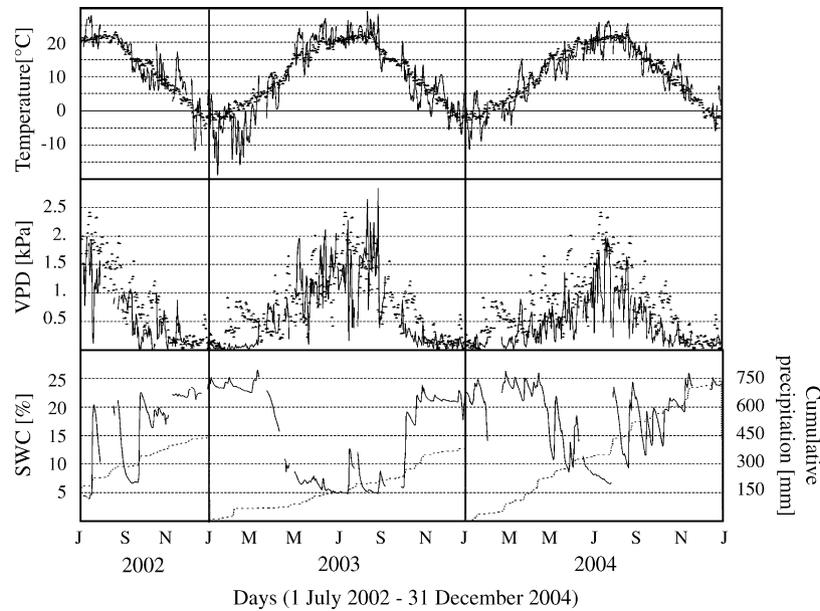
Fig. 2. Daily averages (solid lines) and 10-year averages (dots) of temperature and vapour pressure deficit (VPD) data and daily average of volumetric soil water content (SWC, solid line) and cumulative sum of precipitation (dotted line) in July 2002–December 2004 period at the Bugac site.

precipitation in the same period. The other main difference between the weather conditions of these 2 years was the heat stress occurring in May–June 2003, while in 2004 the late spring–early summer period was cooler.

3.1.2. Seasonal variation of meteorological conditions

In the study period both winters were cooler than the average of the last 10 years. Comparing the 2 years, late winter temperatures were lower in 2003 than in 2004. In 2003 the warming came quickly at the beginning of May and until September the daily mean temperatures were consistently 3–4 °C higher than the 10 years average (Fig. 2). The length of the warm period was longer than usual. In the same period in 2004 the daily mean temperatures were slightly below the average. The daily maximum temperatures were exceeding 30 °C in 48 occasions in 2003, while in 2004 it happened for 16 times,

only (data not shown). In 2003 there were 116 days with precipitation while in 2004 there were 165 rainy days. According to the temperature and precipitation conditions the daily mean vapour pressure deficit (VPD) reached its highest values in 2003. In particular in May, in June and in August, it was higher than the 10 years mean. In 2004, the daily mean VPD was slightly below the 10 years mean, and was considerably lower comparing to 2003. The level of the soil water content at the beginning of the both years was the same at the 15 cm depth, but the soil started to dry out 1 month earlier in 2003 than in 2004. In the first year, until the middle of July, low precipitation occurred, while in the second year significant amount of precipitation has fallen several times during the vegetation period and the soil water content was higher than in the previous year. Summing up, 2003 was a hot and dry year, while 2004 was a wet and not too warm year.

Table 2
Monthly and yearly totals of gross primary production (GPP), ecosystem respiration (R_{eco}) and net ecosystem exchange (NEE) at the Bugac site (in g C m^{-2})

	2002			2003			2004		
	GPP	R_{eco}	NEE	GPP	R_{eco}	NEE	GPP	R_{eco}	NEE
January				4	21	16	7	9	1
February				−3	11	14	12	11	−1
March				33	40	6	42	36	−7
April				94	52	−41	153	92	−61
May				145	117	−28	229	117	−112
June				79	64	−15	207	134	−73
July	32	86	54	65	138	73	45	78	33
August	184	166	−18	27	50	23	97	130	33
September	115	75	−40	65	75	10	173	144	−29
October	73	78	4	35	50	15	87	95	8
November	31	45	15	29	31	1	36	49	13
December	3	21	19	11	16	5	24	29	5
Yearly sum				584	663	80	1112	924	−188

3.2. Carbon exchange

3.2.1. Monthly and annual sums

The investigated grassland acted as a weak source (80 g C m^{-2} year^{-1}) of carbon in 2003, while in 2004 it was a sink (-188 g C m^{-2} year^{-1}). The main part of the sink activity was limited to the period from April to June in both years (Table 2), but in 2004 there was a secondary growing period in September, resulting negative monthly sum. A regrowth period with a considerable sink activity was observable in 2002 as well, but it started earlier, in August, due to precipitation in the middle of August. Annual GPP in 2004 was twice as high as in 2003, while annual R_{eco} in 2004 was 1.4 times the R_{eco} in 2003. In July the grassland acted as a source, in all the 3 years of the measurements. In 2004 the monthly sums were negative already from February.

3.2.2. Seasonal variations of daily NEE

The daily sums of NEE from 1 July 2002 until 31 December 2004 are presented in Fig. 3. At the beginning of the measurements the respiratory processes were dominating, up to the middle of August when the vegetation turned to net sink on daily basis, 10 days after rain events. From the beginning of November the grassland was net source of carbon. In 2003, significant net source activity was detected in January and February on a daily basis. Net sink activity started at the end of March and lasted until the end of June. Afterwards, until end of August the grassland was net source of carbon, with daily carbon release rates of 4 g C m^{-2} day^{-1}. From the middle of September, carbon exchange rate of the ecosystem was ± 1 g C m^{-2} day^{-1}. The vegetation started to take up carbon from the middle of March in 2004, and until the middle of July it acted as a net sink for carbon. The intensive sink period was followed by a summer source period, which was a bit longer but less intensive than the one in the previous year. Autumn regrowth period (net sink activity on daily basis) in 2004 lasted for 45 days. From the middle of October until the end of the year 2004, the grassland was source of carbon. Rain events during the main growing period were followed by positive daily sums of NEE in both years for 1–3 days (Xu et al., 2004). Differences between the annual courses of daily NEE in 2003 and 2004 have been observed in respect of: (a) late winter (January–February) source activity in 2003, not
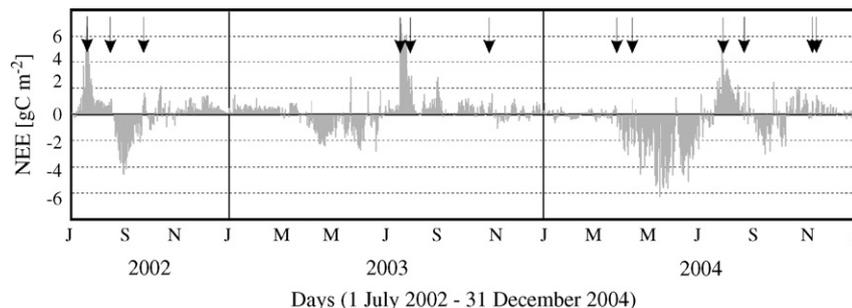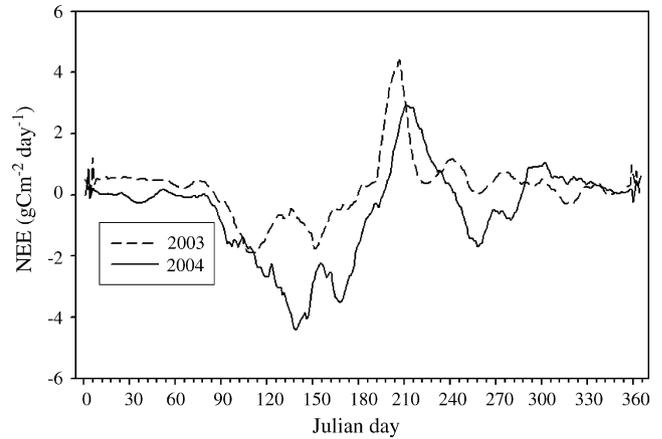

Fig. 4. Smoothed time series of daily sums of NEE values during 2003 and 2004.

observed in 2004 (Fig. 3), (b) larger sink activity during the main growing season in 2004 than in 2003 and (c) lack of autumn sink activity (recovery) in 2003 and presence of it in 2004. These differences are shown more clearly by data smoothed with the boxcar average method of 15 days width (Fig. 4). While much of the variation at the daily scale has disappeared due to smoothing, the seasonal trends and the above-described differences became clear. Series of lagged cross correlations between the 2003 and 2004 NEE time series showed maxima at 8 days positive lag for the raw data (i.e. drought occurred later in 2004 than in 2003). While the maximum of lagged cross correlations using the smoothed data set was found at similar (8–9 days) positive lag, the correlation coefficient was higher (0.779) than that found for the raw data (Table 3). Lagged cross correlations between the 2 years' SWC and VPD data showed maxima at similar lags (Table 3) again. Lagged cross correlation between the 2 years' broadband NDVI values showed a maximum at 0 day lag.

3.2.3. NDVI and GPP

Broadband NDVI time series reached higher values both in the main growing season and in the autumn in 2004 than in 2003 (Fig. 5). Wintertime data were generally more noisy than data from the vegetation period. Onset of the vegetation period and start of the senescence due to drought has been showed by NDVI$_b$ values in both years. Values around 0.5

Fig. 3. Daily sums of net ecosystem exchange in July 2002–December 2004 period at the Bugac site.

Table 3
Maximum of lagged correlations at the applied lags (days) between the 2
years' data for NEE, VPD and SWC data[a]

Variable	Maximum of lagged correlations	Correlation maxima at lag (days)
NEE	0.602	8
SWC	0.745	11
VPD	0.671	9
$NDVI_b$	0.779	0

[a] Positive lags mean that events followed later in 2004 than in 2003.

were indicating the start of the vegetation period. The noise
was smaller during intensive growth, than during regrowth
(2004) or during senescence in the summer of 2003 when the
grass was burnt out. NDVI values were higher in the period
when the grass was burnt out, than during wintertime,
although no green biomass could be seen in any of these
periods.

Time series of satellite-derived (pixel size:
250 m × 250 m) NDVI values shows good correlation with
generally higher values of broadband NDVI (Fig. 6a and b).
While start and intensity of growth were indicated in
accordance by the two methods, $NDVI_b$ values declined less
due to summer senescence than the satellite derived NDVI
values in 2004, while the summer decline was similar for the
two indices in 2003. Correlation between the two NDVI
indices might have been biased by more factors. One of them
is the scale of spatial heterogeneity of the grassland, not
addressed in this study. Vegetation phenology of the patch
measured by local sensors may also differ from that of the
MODIS pixel average. Higher values by the broadband
sensors may arise from possibly lower gap fraction
measured by the ground sensors than by the satellite
spectrometer. Correlation between broadband and satellite-
derived NDVI data was better if not including data from
drought stressed or autumn regrowth periods, when
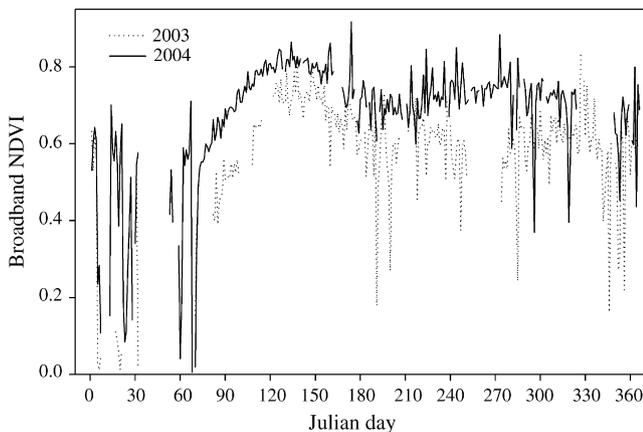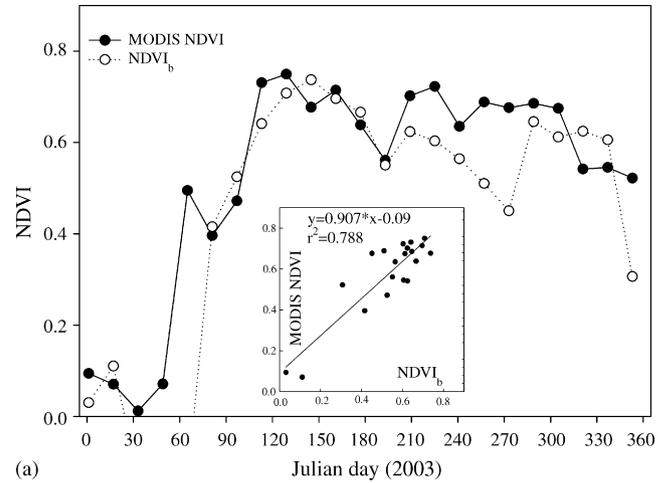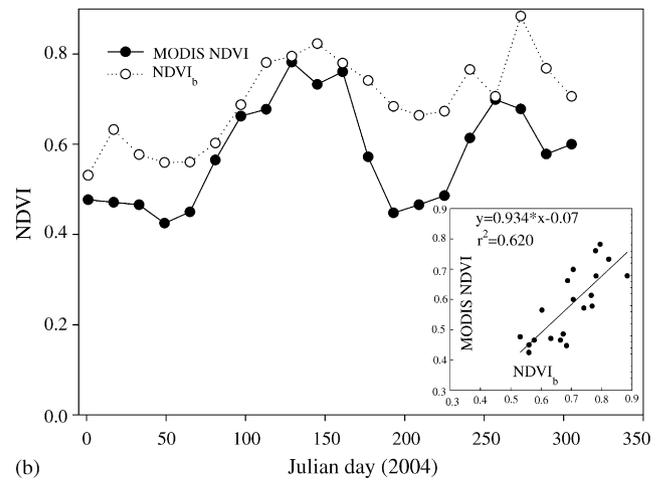vegetation was less active than during intensive growth
(Wang et al., 2004).

Fig. 5. Annual course of broadband NDVI time series. Data are daily
averages.

Fig. 6. Relationship between satellite-based and broadband NDVI values
for 2003 (a, RMSE 0.087) and for 2004 (b, RMSE 0.07).

Three main periods of intensive growth and autumn
regrowth were separated based on the time course of the
cumulative sum (Fig. 7). The first is when the cumulative
sum is increasing in 2003. The main growing season lasted
from 21st March until 23rd June. The second separated
period is the main growing season in 2004, that lasted form
1st March to 17th July. The third investigated period is the
autumn regrowth period in 2004, lasting from 28th August
until 8th October. The relation between the NDVI and GPP
values was investigated in these three periods (Fig. 8).
Strong dependence of GPP on NDVI was found in the main
vegetation period in the favourable year of 2004 (Fig. 8b).
However, in water stressed (2003) (Fig. 8a), or in autumn
regrowth (2004) periods the relation was much weaker
(Fig. 8c).

4. Discussion

Mean annual temperatures in 2003 and 2004 were below
the 10 years average in the region, in spite of the summer of
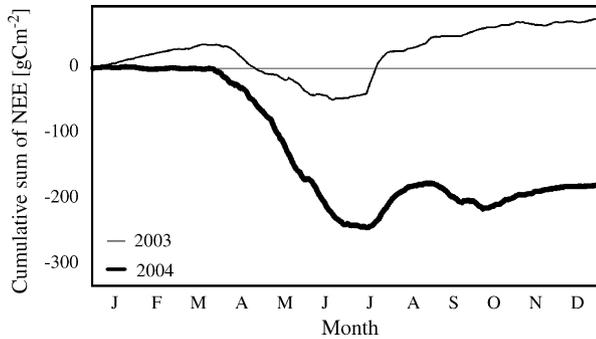
Fig. 7. Cumulative sums of NEE during 2003 and 2004 at the Bugac site.

Fig. 9. Relative contribution of daily NEE sums to the whole year net sink and net source activities respectively during 2003 and 2004.

2003 is remembered as a heat wave. While in 2004, the negative anomaly was caused by consistently lower monthly mean temperatures than the long-term average, in 2003 the region experienced cooler winter and warmer summer temperatures than usually. Lack of precipitation from March to end of September was another important weather feature in 2003, while there was above average supply of precipitation in 2004. Summer drought caused senescence of vegetation in both years in the same period. The duration and magnitude of drought and not the timing of it was different between the years. The heat wave and lack of precipitation caused much larger VPD and earlier depletion of soil water reserves in 2003 than in 2004.

The grassland was a weak source of carbon in 2003 ($80 \, \text{g C m}^{-2}$) owing to the exceptionally hot and dry conditions and a sink in 2004 ($-188 \, \text{g C m}^{-2}$), when the amount of precipitation was considerably exceeding the 10 years average. The GPP values in 2003 and 2004 were 584 and $1112 \, \text{g C m}^{-2}$, respectively, while R_{eco} values were 663 and $924 \, \text{g C m}^{-2}$ for these 2 years. Comparing the 2 years, GPP declined more than R_{eco} due to drought and heat wave effects in 2003 than in 2004. Relative contributions to the whole year sums of net source and net sink activities (daily sums) followed generally similar time courses in 2003 and 2004 (Fig. 9). The relative contribution of the main growing seasons to the total net sink activity were almost the same in each year, while relative contribution to the source activity was larger by the summer respiration peak in 2004 than in 2003. Relative contribution to net source activity reached 70% by the end of July in 2003, while in 2004 the same ratio was reached only in mid of October. These results are in
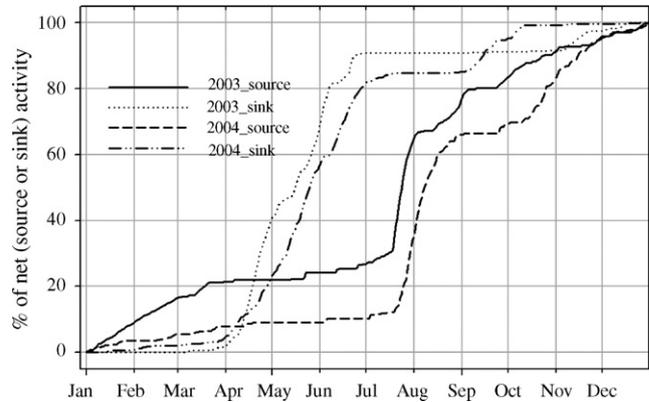
accord with the findings, that while most of the daily carbon exchange activity is linked to the wet periods (Xu and Baldocchi, 2004; Hastings et al., 2005), significant source activity may occur during dry periods (Ciais et al., 2005; Haszpra et al., 2005; Li et al., 2005).

Further difference between the time courses of net source activity is caused by the higher source activity during the first months of the year in 2003 than in 2004. This was probably related to lower winter temperatures in 2003 than in 2004 and therefore the later start of the sink activity, while respiration was not suppressed totally by wintertime freezes. The grassland showed an autumn recovery in 2004, while autumn recovery was absent in 2003, as it is also shown by the relative sink contributions. In 2004, the grassland was net sink for 192 days, while in 2003 the total of net sink days was 129. The ratio between net sink and net source days were 0.55 and 1.11 for 2003 and 2004, respectively. Interestingly, the average carbon exchange rates during source periods did not differ between the 2 years (0.796 and 0.777 g C m^{-2} day^{-1}), while for the sink periods daily NEE rates were strongly different (-0.836 and $-1.677 \, \text{g C m}^{-2}$ day^{-1}, for 2003 and 2004, respectively).

Striking feature of the annual NEE dynamics is that the temporal activity pattern of the vegetation was similar between the years while there was a great difference between the NEE-balance of the years. In other words, the differences between the 2 years' weather was related to magnitudes rather than timing of unfavourable effects (heat and
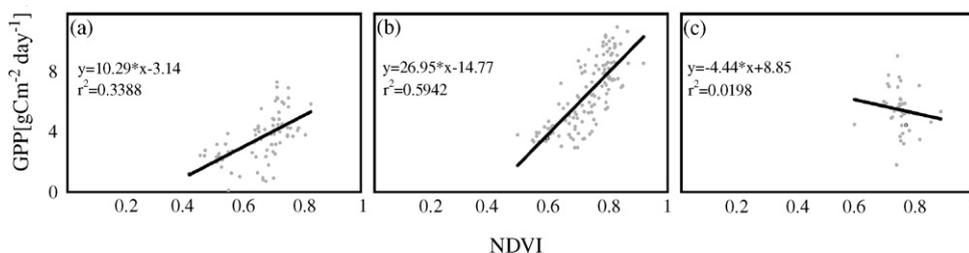

Fig. 8. Relationships between the daily broadband NDVI and GPP estimates in different vegetation periods during 2003 and 2004 during early growth (a, $P < 0.0001$), intensive growth (b, $P < 0.0001$) and during senescence (c, $P = 0.3868$).

drought). Another significant point is that relative contribution of net source activity caused by drought was similar (around 50%) in both years, but the amount of carbon lost during net source days was larger in 2003 (187 g C m^{-2}) than in 2004 (134 g C m^{-2}). Lagged cross correlations between the 2 years time series data showed maximum at positive lags (i.e. the 2004 time series was shifted to the right relative to the 2003 time series) for SWC, VPD and NEE data, showing later occurrence of drought in 2004 than in 2003 and suggesting the decisive role of SWC and VPD on NEE.

GPP was 1.9 times larger in 2004 than in 2003, while R_{eco} was less suppressed by the drought wave in 2003 (the ratio $R_{eco}2004:R_{eco}2003$ was 1.4), so drought was more effective in reducing CO_2 uptake by the vegetation than in reducing ecosystem respiration. This highlights the importance of a respiration component, probably of heterotrophic origin (Xu and Baldocchi, 2004; Xu et al., 2004), unrelated to current day photosynthesis and/or more resistant to drought than photosynthesis. Broadband NDVI showed good correlation to satellite derived NDVI in 2004, and a less strong relation in 2003, where the regression was constrained by two low wintertime values with most of the other points in the higher range. The direct comparison of the two indices are biased by more factors and among them is, that broadband and satellite-derived NDVI values are calculated for different wavelength ranges (Wang et al., 2004). Therefore it is not possible to get conclusions on the scale of heterogeneity of the vegetation as measured locally and from the satellite. Broadband NDVI showed good correlation to GPP during intensive growth in 2004, but this relation was significantly different with a less steep slope during senescence caused by drought (main growing period, 2003) and diminished for the autumn regrowth (2004) period. The same picture was found for the relation between GPP and daily mean absorbed PAR values. As a result the same relation could not be applied between GPP and NDVI$_b$ in climatically different years.

5. Conclusions

The source or sink characteristic of the semi-arid sandy grassland in the Great Hungarian Plain showed strong sensitivity on the weather patterns of the region. During the 2003 heat and drought wave the area acted as a source (80 g C m^{-2}), and the maximum daily uptake was -2.8 g C m^{-2}, whereas in 2004 when there was sufficient amount of precipitation and the temperatures were mainly below the 10 years mean, the grassland's annual sum of carbon exchange was -188 g C m^{-2} with maximum daily uptake rate of -6.3 g C m^{-2}. In comparison, Xu and Baldocchi (2004) reported maximum daily uptake rate of -4.8 g C m^{-2} day^{-1} for a dry Mediterranean grassland. In spite of the large difference in annual sums, dynamics of net source and net sink activities were similar in the 2 years, largely due to the strong source activity during the summer

drought of similar relative magnitude in each year. Drought stress suppressed total ecosystem respiration less than ecosystem carbon uptake. While the relation between the broadband and satellite-based NDVI values proved to be strong, the relationship between GPP and NDVI$_b$ were different between the drought stressed and unstressed periods. Further, the correlation between these variables diminished during autumn recovery period.

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