

Carbon exchange of grass in Hungary

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ABSTRACT

Continuous measurement of net biosphere–atmosphere carbon exchange was performed in western Hungary over a managed semi-natural grassland field using the eddy covariance technique to estimate Net Ecosystem Exchange (NEE). The paper presents the measuring site and instrumentation, as well as the data processing methods applied. The measurements covered the period March 1999 to December 2000 during which, on an annual time scale, the region acted as a net CO₂ sink, where NEE was -54 g C m^{-2} in 1999 (data for January and February were estimated) and -232 g C m^{-2} in 2000 (negative NEE represents CO₂ uptake by the vegetation). The remarkable inter-annual difference may be the result of the significant climate difference between 1999 and 2000.

1. Introduction

Since it was first proposed at the end of 1980s that there must be a large carbon sink in the northern extra-tropical region (Tans et al., 1989; 1990) several studies have tried to identify the location and nature of that “missing sink.” Inverse models based on the existing measurements and emission data have pointed to the temperate continental biosphere (e.g. Ciais et al., 1995; Fan et al., 1998; Bousquet et al., 1999; Battle et al., 2000; Pacala et al., 2001), but the relative contribution by ecological systems of different types is still uncertain. For clarification of the role of different ecological systems in the carbon budget several long-term carbon flux measuring sites have been established worldwide during the past few years (see e.g. FLUXNET: <http://www-eosdis.ornl.gov/FLUXNET/fluxnet.html>). Currently more than 140 sites are operated in forests, croplands, grasslands, wetlands and tundra environments

(Baldocchi et al., 2001). The first synthesis studies summarizing the current findings have already been published (e.g. Valentini et al., 2000; Baldocchi et al., 2001).

Since forests are expected to sequester a large amount of carbon, that is where most of the monitoring sites are located (Running et al., 1999). Other vegetation types (e.g. crops, grasslands and wetlands) are under-represented. Nevertheless, the role of grasslands may be important in the global carbon cycle because of their large spatial extent (Kim et al., 1992; Suyker and Verma, 2001). The net primary production of grasslands may be rather sensitive to atmospheric CO₂ level (Freedman et al., 1998; Alward et al., 1999; Gitay et al., 2001), and the amount of carbon sequestered may depend on soil type and climate (Hensen et al., 1997; Suyker and Verma, 2001). In spite of this potential importance, long-term (multi-year) monitoring of grassland biosphere–atmosphere exchange of carbon dioxide is surprisingly rare.

According to published year-round net ecosystem exchange (NEE) studies performed over grasslands and rangelands, this vegetation type can be either a source or a sink of carbon (Meyers, 2001; Suyker

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and Verma, 2001). This fact also supports the need for long-term grassland carbon budget studies.

In the present paper the results of a joint Hungarian–Japanese monitoring program are presented in the framework of which the biosphere–atmosphere exchange of carbon dioxide was monitored for two years (1999–2000) over a managed grass field in Hungary.

2. Measuring site and instrumentation

The measurements were carried out in western Hungary (Hegyhátsál, 46°57′N, 16°39′E, 248 m asl) over a managed, species-rich, semi-natural grass field (hay meadow) surrounded by agricultural fields (mostly crops and fodder of annually changing types). The vegetation type belongs to a hardly disturbed *Arrhenatherion* KOCH 1926 alliance. The dominant species are *Arrhenatherum elatius*, *Taraxacum officinale*, *Poa pratensis*, *Agropyron repens*, *Anthoxanthum odoratum*, *Dactylis glomerata*, *Holcus lanatus*, *Briza media* and *Festuca pratensis*. The soil type in the region is ‘Lessivated brown forest soil’ (Alfisol, according to USDA system). These soils have clay migration and moderate acidity as well as the more widespread humification, leaching and clay formation (Stefanovits, 1971). The upper layer is generally 10–20 cm thick, and its organic matter content is 5–8%. Human habitations within 10 km of the tower are only small villages (100–400 inhabitants). The nearest village is Hegyhátsál (170 inhabitants), about 1 km to the north-west. There is no notable industrial activity in this dominantly agricultural region. The long-term average (1961–1990) annual precipitation in the region is around 750 mm, while the average temperature is 8.9 °C.

The NEE of CO₂ was determined using the eddy covariance technique. The monitoring system was based on a LI-COR model LI-6262 closed-path, fast-response infrared gas analyzer (IRGA) and a three-dimensional, fast-response sonic anemometer–thermometer (Kaijo-Denki, model DA-600). The sonic anemometer and the inlet tube of the IRGA were mounted on a mast at 3 m elevation above the grass-covered surface. The inlet tube was mounted at the elevation of the active center of the ultrasonic anemometer, 25 cm away from it horizontally. The IRGA, air sampling pump, a programmable timer and standard gases used for regular calibration of the instrument were located in a ventilated box near the mast to allow a short air inlet tubing but far enough not to disturb

the flow pattern significantly. Raw voltage data provided by the fast response sensors were collected and digitized by means of a TEAC data logger at 5 Hz frequency.

The IRGA was calibrated against two standard gases (traceable to NOAA CMDL primary standards) once a day. Factory calibration (a fifth-order polynomial for CO₂ and a third-order polynomial for H₂O) was applied to convert the raw voltage signals into mole fractions. Dry air mixing ratios of carbon dioxide and water vapor were calculated to avoid the need for the Webb correction (Webb et al., 1980).

Supporting measurements included detection of global solar radiation, radiation balance (net radiation), photosynthetically active photon flux density (PPFD), temperature and relative humidity. Vapor pressure deficit (VPD) was calculated as the difference between saturated and actual vapor pressures at the given temperature, based on the relative humidity and air temperature data.

The measurement site was located in a limited grass field surrounded by agricultural fields. The fetch of the sensors located at 3 m elevation was estimated by means of the Flux Source Area Model (FSAM) of Schmid (1994; 1997) (see the next section for details). In the overwhelming majority of cases the source area was located inside the grass field; thus the fetch could be considered as adequate for the study.

3. Data processing

Based on Ogive tests (Foken and Wichura, 1996) it was found that 30 min. averaging time was appropriate to determine the turbulent fluxes at the height of the measurements. Spectral analysis was performed to check the quality of the measured data. It was found that no extra (e.g. low-frequency) spectral degradation have occurred which could distort the measured fluxes once the usual spectral corrections were performed (see below).

Spikes were removed from the turbulent time series during data processing (data values outside $\pm 5\sigma$ were removed). Instrument noise apparent in the wind speed and sonic temperature data, caused by e.g. rime frost or liquid water, were filtered out.

Three-dimensional wind vector rotation was applied to the sonic anemometer data to ensure that the mean vertical velocity equaled zero. The method was mainly used to account for the shadow effect of the sonic head.

No significant real average vertical wind speed was expected to occur at this low elevation (Lee, 1998).

A linear trend was removed from each half-hourly data point to calculate the fluctuating time series. Lag times caused by the air inlet tube were determined during the data processing using a spectral technique (Barcza, 2001). Raw turbulent fluxes of CO₂ and H₂O were calculated as the covariance between the vertical wind speed and the dry air mixing ratios of CO₂ and H₂O.

Spectral corrections were applied to account for the damping of the signal inside the tube, the sensor line averaging, the limited response time of the anemometer and the IRGA, and the analogue-to-digital conversion (Moore, 1986). The validity of the theoretical spectral correction technique was confirmed using spectral decomposition of the turbulent time series.

Average losses of the eddy covariance system calculated from the theoretical considerations were about 23.1% for CO₂ and 20.4% for H₂O. Since the loss was significant, it was important to account for the flux loss in order to determine correct relationships between NEE and the environmental conditions.

NEE was calculated directly from the loss-corrected carbon dioxide fluxes. It was found that the change of the CO₂ amount stored below the measurement level (3 m) could be ignored, since it did not affect the calculated daily sums, and its amplitude was small.

Source area analysis was performed to elucidate which region was 'seen' by the measuring system. For this purpose the Flux Source Area Model (FSAM) of Schmid (1994, 1997) was used. FSAM is an analytical model that can calculate source area isopleths of different efficiency. The advantage of the method compared to the one-dimensional flux footprint models is that the region of interest can be determined geometrically. The input parameters required (wind direction, Obukhov length, friction velocity and standard deviation of the lateral wind speed fluctuations) were calculated using the data measured by the eddy covariance system. Aerodynamic roughness length as a function of wind direction was determined using the Monin-Obukhov similarity theory for daytime unstable conditions utilizing the average horizontal wind speed. Typical roughness length values ranged between 0.03 and 0.1 m depending on the direction (no time dependency was determined because of the large scatter of data).

The source weight function (or footprint function) is a bell-like surface rising to a maximum with increasing distance from the measurement point then falling off.

The total volume under the source weight function is 100%. The elliptic isopleths of the function surround the most significant source area. Depending on the purpose of the study different isopleths can be chosen arbitrarily to represent the dominant source area. In our case the 50% source areas were calculated giving half of the measured flux for each half hour. It seemed a reasonable value to present the spatial representativeness of the measurements.

Figure 1 shows the frequency distribution of the contribution of different areas to the fluxes measured during summer 1999 (June–August). The figure shows that the night-time source areas were more extended compared to the daytime ones. This can be explained by the formation of low turbulent mixing and strong stability during the nights. The daytime source areas mostly lay inside a 100 m radius around the mast.

It is interesting to note that the daytime and night-time source areas show different pattern not only in size but also in orientation (Fig. 1). It is caused by the fact that the westerly wind, which is rare during daytime, becomes prevailing during the night. This night-time circulation pattern is generated by the Alps west of the monitoring site, although the mountains are relatively far. As the area is fairly homogeneous the different daytime and night-time source areas do not cause any bias in NEE calculated for the grassland.

4. Results

4.1. Daytime NEE

Daytime NEE of carbon dioxide exhibited close coupling with PPFD during the active period of the vegetation (typically from the beginning of March until November). Maximum daytime NEE reached $-1.4 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$ in both 1999 and 2000 (negative NEE represents CO₂ uptake by the vegetation). Ninety-five-percentile values for the period of the highest uptake (March–April) were -1.05 and $-0.92 \text{ mg CO}_2 \text{ m}^{-2} \text{ s}^{-1}$, respectively. Generally, daytime CO₂ uptake reached its maximum value around noon, and decreased as the PPFD declined. PPFD was used to calculate the light response function of NEE using a rectangular hyperbola function (Michaelis-Menten-type function) (Falge et al., 2001).

Figure 2 shows the NEE-PPFD relationship for May 1999 and May 2000. The fitted regression curves are also shown. Data measured during dry conditions (vapor pressure deficit greater than 1.5 kPa) are plotted

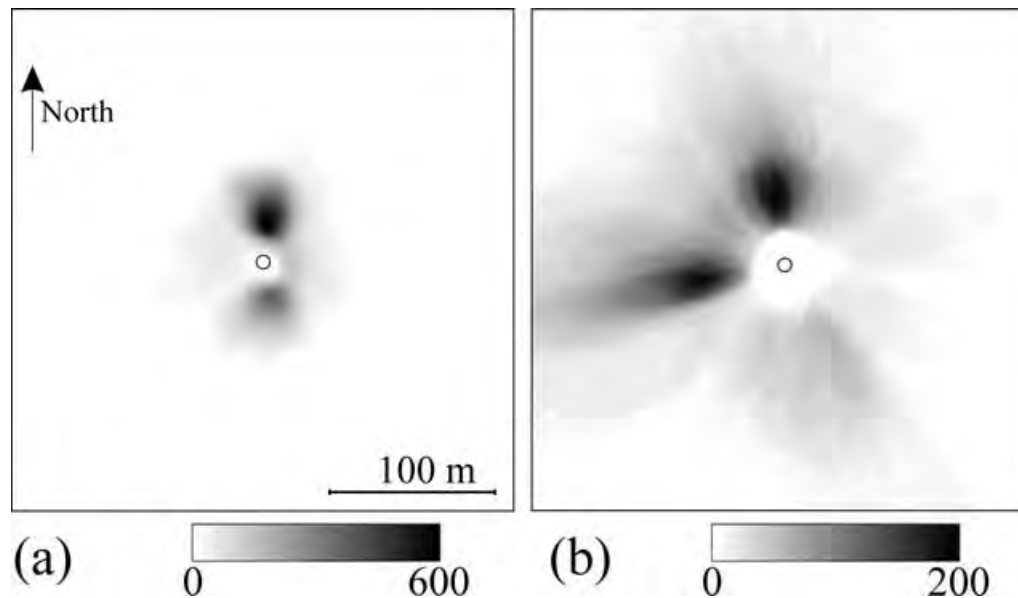


Fig. 1. (a) Frequency distribution of the contribution of the different areas to the measured daytime fluxes during June–August 1999. (b) Same as (a) but during night-time.

with plus signs. As expected, NEE decreased when the available water amount was low, even if the incoming solar radiation was high. Precipitation in May 2000, was below the average, while it was above it in 1999. This resulted in different light response functions for 1999 and 2000.

The last term in the rectangular hyperbola function, which gives the respiration during daytime at zero PPF, is consistent with the measured average night-time respiration values. May 2000 was warmer than May 1999, which caused higher respiration in 2000.

The above results suggest that the respiration was less affected by lower rainfall than was the productivity; however, more data are needed to reinforce the hypothesis.

4.2. Night-time NEE

The temperature dependence of night-time NEE was also determined. Air temperature measured by the Kaijo–Denki anemometer/thermometer at 3 m was used to determine the NEE–temperature relationship. When the individual half-hourly NEE values were plotted against air temperature the scatter of the data was rather high, as was also experienced by other research groups (e.g. Greco and Baldocchi, 1996). Thus, the night-time respiration as a function of temperature

was determined plotting the average night-time NEE against average night-time temperature. An exponential (Q_{10}) function was used for the fit.

Figure 3 shows the data for both years, for months from March to October. Different coefficients were determined for the dormant period (from November to February). The Q_{10} coefficient was 2.36 during the active period (which is rather high because of the large leaf area index) and 1.4 during the dormant period.

One important issue that affects many year-round NEE results worldwide is the unexpected night-time loss of CO_2 fluxes during conditions with low turbulent mixing (Grace et al., 1996; Greco and Baldocchi, 1996; Baldocchi et al., 2000; Paw et al., 2000; Aubinet et al., 2000; Markkanen et al., 2001). It is generally accepted by the above authors that this underestimation has to be corrected, and it is done using the so-called u_* (friction velocity, the measure of shear induced turbulence during night-time) correction. This procedure replaces the low flux values measured during conditions with low u_* with the fluxes that were measured when u_* reached a reasonable threshold value. The phenomenon can also be detected at our site: the night-time NEE systematically decreases during conditions with $u_* < 0.15 \text{ m s}^{-1}$ (which occurred in 50% of the night-time measurement period). Yet there are also arguments that the low night-time fluxes are normal

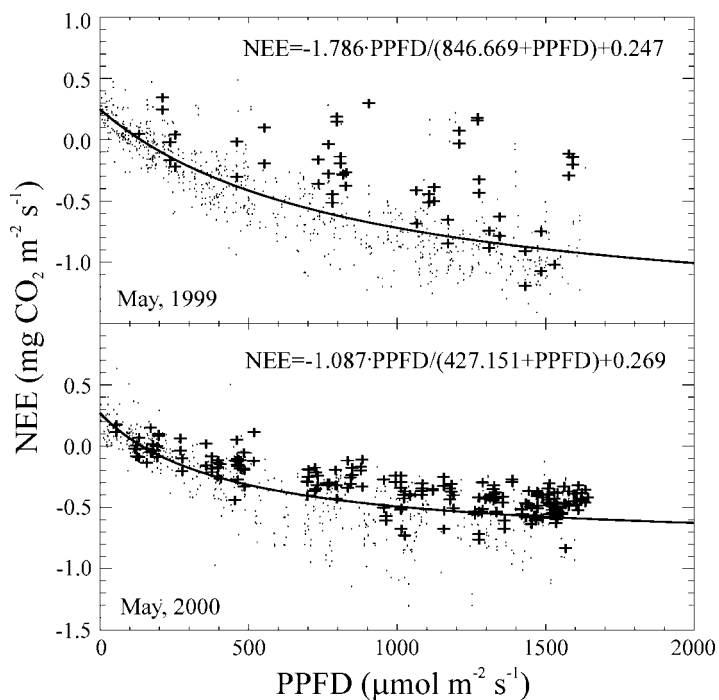


Fig. 2. Daytime NEE plotted against photosynthetically active photon flux density (PPFD) for May 1999 and May 2000. Negative NEE means CO₂ uptake by the ecosystem. Plus signs mark NEE measured at water vapor pressure deficit (VPD) greater than 1.5 kPa, dots mark NEE measured at VPD less than 1.5 kPa. The rectangular hyperbola function that was fitted to all monthly data is given for both months. (1 mg CO₂ m⁻² s⁻¹ = 22.7 μmol m⁻² s⁻¹).

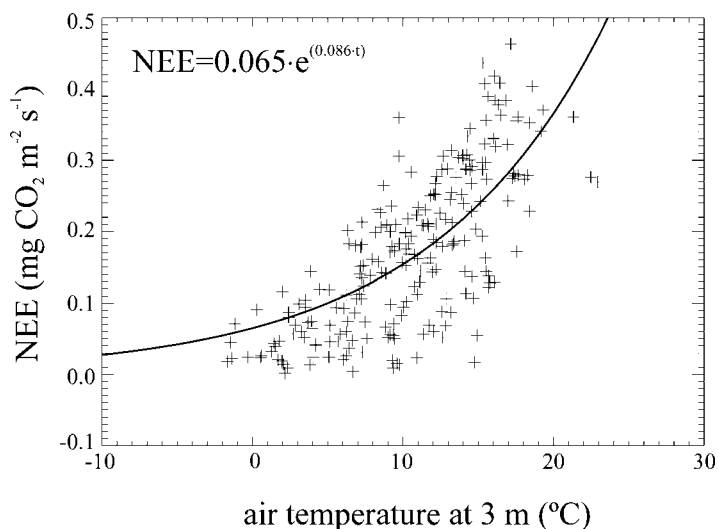


Fig. 3. Average night-time CO₂ efflux as a function of the average night-time air temperature measured at 3 m (t) for the growing period of the grassland. The fitted exponential curve is plotted as a solid line. The analytical form of the curve is also given.

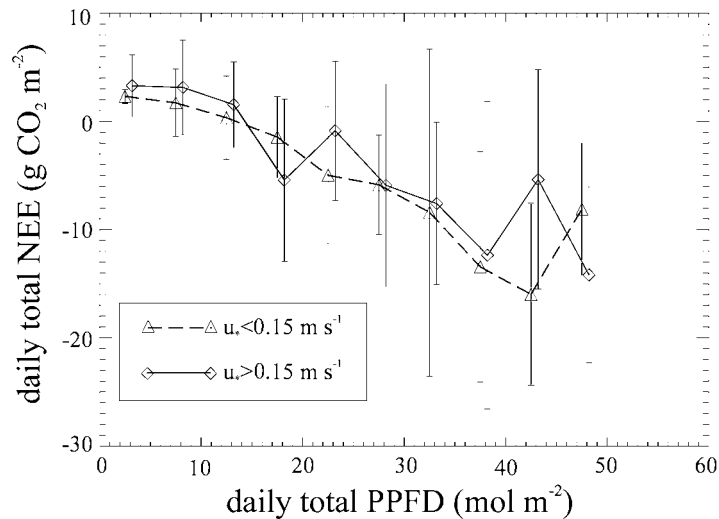


Fig. 4. The response of 24 h total carbon dioxide fluxes to total daily PPFD, averaged for two classes of night-time u_* . Dashed line represents days with calm nights, and solid line shows the average behavior for days with more windy nights. The standard deviation of the block averages is also presented.

phenomena, which are caused by the air trapped in the soil during calm nights (Malhi et al., 1999). Recently Araújo et al. (2002) questioned the validity of the u_* correction. According to this new issue, even if the night-time fluxes seem to be missing with low u_* values, the daily sums can still be correct as the “lost” night-time flux reappears during the day.

Figure 4 shows the corresponding results for our site. The dashed curve represents the days with calm nights (average $u_* < 0.15 \text{ m s}^{-1}$) while the solid one shows NEE for days with more windy nights (average $u_* > 0.15 \text{ m s}^{-1}$). If the fluxes were missing during calm nights, the dashed curve should give significantly more negative values because of the underestimated night-time respiration. However, the figure does not show significant deviation between the two curves. Since there is no clear evidence that the low release occurring during calm nights does cause systematic underestimation of daily NEE, we have not preferred the u_* correction.

4.3. Seasonal cycles of NEE

In order to calculate annual NEE, missing measurement periods were filled using the NEE–PPFD and NEE–temperature functions. In the case of missing environmental data the mean diurnal variance technique was applied, updated on a monthly basis (Falge et al., 2001). Since the measurement started in March

1999, flux data could not be calculated directly for January and February. This large gap was filled with the empirical NEE–temperature function for the dormant period (no NEE–PPFD dependence exists outside the growing season).

The gap-filled daily NEE time series can be seen in Fig. 5 together with the cumulative trend of the daily net CO_2 exchange. The grass field acted as a net sink of CO_2 at annual time scales in both 1999 and 2000, during which the total uptake was 54 and 232 g C m^{-2} , respectively. (If the u_* correction were applied the NEE would be -35 and -182 g C m^{-2} , respectively.) This inter-annual difference may indicate a considerable dependence on climatic conditions.

The year 1999 was somewhat warmer than average, but the amounts of precipitation for both the whole year and the vegetation period (March–October) were close to the multi annual average. By contrast, 2000 was unusually dry and warm (Table 1). This warm and dry year presages the possible future climate of the region.

The NEE–temperature relationship lets us simulate the respiration of the ecosystem, and this makes possible the determination of Gross Primary Production (GPP) as a difference between NEE and total ecosystem respiration. According to the results, total ecosystem respiration was 1546 g C m^{-2} in 1999 and 1621 g C m^{-2} in 2000. The difference can be explained by the higher average temperature in 2000, which

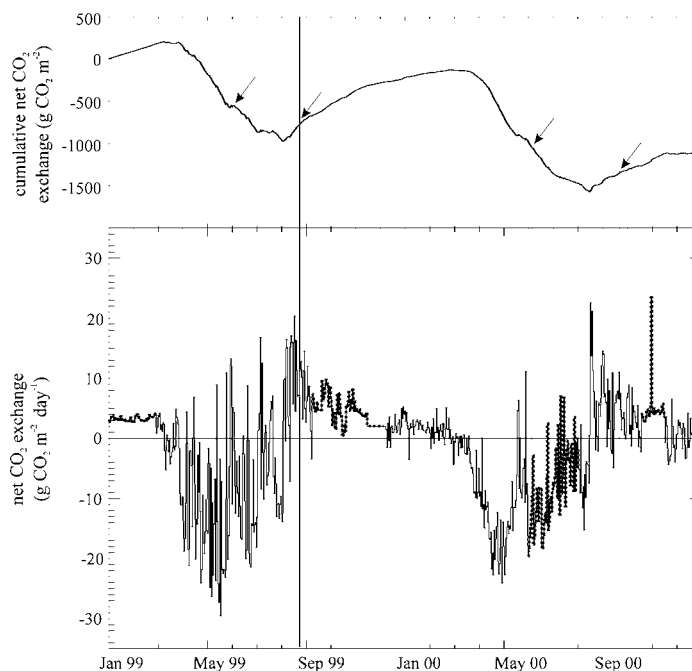


Fig. 5. Gap filled (dotted sections) daily net CO₂ exchange between the biosphere and the atmosphere as a function of time during 1999 and 2000, and the cumulative NEE for the same period. Negative values denote CO₂ uptake by the vegetation. The arrows in the upper plot indicate the times of the mowing.

Table 1. Climate data from a nearby meteorological observatory (Farkasfa, 46°55'N, 16°19'E, 312 m asl), and the carbon uptake observed at Hegyhátsál

| Period | Average temperature (°C) | | Precipitation amount (mm) | | Carbon uptake (g C m ⁻²) |
|-----------|------------------------------------|---------------|------------------------------------|---------------|--------------------------------------|
| | Vegetation period March–October | Whole year | Vegetation period March–October | Whole year | |
| 1961–1990 | 13.2 | 8.9 | 584 | 759 | n.a. |
| 1999 | 14.3 | 9.6 | 582 | 785 | 54 |
| 2000 | 15.1 | 10.9 | 465 | 660 | 232 |

generates higher ecosystem respiration. Year-round GPP was -1600 g C m^{-2} in 1999 and -1853 g C m^{-2} in 2000. These results should be considered as somewhat rough estimates, since the dependency on e.g. soil moisture is not taken into account.

It might be interesting to relate the measured data to the length of the net CO₂ uptake period. The beginning and ending dates can be determined from the cumulative net CO₂ exchange curve in Fig. 5. The uptake period started on 9 March in 1999 and 28 February in 2000. The end of the uptake period was around 2 August in 1999 and 14 August in the following year. Thus,

the active period lasted approximately 3 weeks longer in 2000. Although the amount of available water was less in 2000 (mostly in June), the huge difference in the length of the uptake period contributed to the extra CO₂ uptake in 2000.

Another interesting feature is the negative NEE during November and December 2000. November was 5.3 °C warmer in 2000 (7.5 °C, corresponds to the early April average) than in 1999, while the corresponding value for December was 2.1 °C. Both November and December 2000 were significantly warmer than average. The negative NEE observed during this period

could be related to this unusually warm period, which supported carbon uptake by the grassland normally dormant during this period of the year. This uptake appears as an unusual flat part in the cumulative curve in Fig. 5.

It is important to note that twice a year the grass was cut in both 1999 and 2000, and the mowed grass was taken away. This may affect NEE when making a comparison with results from other sites, since decomposition of part of the organic matter happened elsewhere. Consequently, the local ecosystem CO₂ release became smaller, and the year-round NEE became larger (i.e. more negative). The effect of mowing is clear in Fig. 5 (marked by the arrow). It can be seen that the cumulative net carbon exchange was disturbed for a couple of days, then the normal trend returned. In 2000 the first mowing happened in the beginning of June. Unfortunately, it can not be detected because measurement was suspended during that time due to technical problems. The gap-filling procedure could not reproduce the human intervention. The second mowing happened after the end of the growing season in both years, and thus did not affect the cumulative trend significantly.

Unfortunately, the amount of biomass removed by mowing can not be estimated, thus no information can be provided about the carbon sequestration of the region. Instead, the amount of carbon that was removed from the atmosphere by the grass is measured, keeping in mind that part of the organic matter could return to the atmosphere elsewhere.

Hegyhátsál is also the site of a continuous, long-term regional-scale biosphere-atmosphere CO₂ exchange measurement. Instrumentation is mounted 82 m above the ground on a TV-transmitter tower (Haszpra et al., 2001). The footprint of this measurement is much bigger: it also covers agricultural fields and forest patches in an extended region. According to the measurements the regional-scale NEE in 1999 was -92 g C m^{-2} (unpublished data), which is comparable to the value for the grass field. Unfortunately, for 2000 no regional flux data are available.

5. Summary and conclusions

During the two years of measurements the managed grassland studied acted as a net CO₂ sink, and the uptake was 54 g C m^{-2} in 1999 and 232 g C m^{-2} in 2000. The remarkable inter-annual difference might be the result of the significant difference in temperature and amount of precipitation between 1999 and 2000, which extended the length of the carbon uptake period by 3 weeks in 2000 compared to the previous year. The effect of human intervention (i.e. mowing) is detectable in the variation of the daily NEE results. Realizing the high sensitivity of the grassland to the climate conditions, and the large extension of grasslands in the northern temperate zone, the experiment is expected to be restarted in 2002. For a more sound interpretation of the measurements the monitoring system will be completed by soil temperature and soil water-content sensors.

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