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The carbon budget of newly established temperate grassland depends on management intensity

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Abstract

The carbon exchange of managed temperate grassland, previously converted from arable rotation, was quantified for two levels of management intensities over a period of 3 years. The original field on the Swiss Central Plateau had been separated into two plots of equal size, one plot was subjected to intensive management with nitrogen inputs of 200 kg ha^{-1} year^{-1} and frequent cutting, and the other to extensive management with no fertilization and less frequent cutting. For both plots, net CO_2 exchange (NEE) was monitored by the eddy covariance technique, and the flux data were submitted to extensive quality control and gap filling procedures. Cumulative NEE was combined with values for carbon export through biomass harvests and carbon import through application of liquid manure (intensive field only) to yield the annual net carbon balance of the grassland ecosystems. The intensive management was associated with an average net carbon sequestration of 147 ($\pm$130) g C m^{-2} year^{-1}, whereas the extensive management caused a non-significant net carbon loss of 57 (+130/$-$110) g C m^{-2} year^{-1}. Despite the large uncertainty ranges for the two individual systems, the special design of the paired experiment led to a reduced error of the differential effect, because very similar systematic errors for both parallel fields could be assumed. The mean difference in the carbon budget over the 3-year study period was determined to be significant with a value of 204 ($\pm$110) g C m^{-2} year^{-1}. The difference occurred in spite of similar aboveground productivities and root biomass. Additional measurements of soil respiration under standardized laboratory conditions indicated higher rates of soil organic carbon loss through mineralization under the extensive management. These data suggest that conversion of arable land to managed grassland has a positive effect on the carbon balance during the initial 3 years, but only if the system receives extra nitrogen inputs to avoid carbon losses through increased mineralization of soil organic matter.

Keywords: Carbon sequestration; Temperate grassland; Management intensity; CO_2; NEE; NBP; Fertiliser; Land-use change; Soil organic carbon

1. Introduction

In the wake of the Kyoto Protocol, terrestrial ecosystems have attracted considerable scientific and policy interest because of their potential role as sinks or sources for atmospheric CO_2 (IPCC, 2000). For agricultural ecosystems such as grassland or cropland, suitable management options may sequester carbon by a sustained increase in the soil organic carbon content (SOC) and thus contribute to the committed reduction of greenhouse gas emissions in many countries (Smith, 2004a). Conversion of arable land into permanent grassland is one measure that is believed to have a considerable carbon sequestration potential (IPCC, 2000; Soussana et al., 2004). Under similar site conditions, permanent grasslands typically have higher soil organic carbon (SOC) contents than arable crop rotations, because (i) they receive higher residue inputs, (ii) relatively more carbon is deposited belowground, and (iii) decomposition is slower due to the absence of tillage-induced aeration and due to stronger soil aggregation (Paustian et al., 1997). Calculated over a 50-year period, sequestration rates between 50 and 100 g C m^{-2} year^{-1} have been estimated (IPCC, 2000) corresponding to a total increase of the carbon content of between 2.5 and 5 kg SOC m^{-2}. For temperate

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sites in Switzerland, Leifeld et al. (2003) estimated sequestration potentials of 2.0–2.2 kg SOC m^{-2}.

While positive effects of converting arable land to grassland are generally accepted (e.g. Follett, 2001), the influence of grassland management intensity after conversion is less clear. A review of global data sets revealed that intensively managed and fertilised grasslands had, on average, higher SOC stocks than natural or less intensively managed systems (Conant et al., 2001). Accordingly, Nyborg et al. (1997) found with increasing level of fertilisation larger SOC contents associated with higher productivity for Canadian grasslands. In contrast, no relationship between the intensity of management and SOC stocks was found for Alpine grasslands (Zeller et al., 1997; Bitterlich et al., 1999). Many of the European grasslands are currently cultivated for forage production and reach high productivity in temperate regions with sufficient rain. However, low-input systems are becoming more attractive in areas where the need or profitability of agricultural production declines. This latter trend may counteract efforts to improve the carbon balance of agricultural land, but data from direct comparisons of intensively and extensively managed systems are lacking.

The most direct approach to investigate carbon sequestration effects in soils is through monitoring SOC content over time. However, due to statistical limitations, this method requires a large number of samples and time scales longer than about 5 years (Smith, 2004b), and it yields no information about underlying processes, which would help to understand and interpret differences between ecosystems and management regimes. As an alternative, changes in the carbon balance can be determined from measured carbon imports and exports. This approach is more complex and requires sophisticated measuring systems, but it yields information about processes involved in carbon cycling and their temporal variability. In natural ecosystems, the carbon balance (corresponding to the net biome productivity NBP as described by Schulze et al., 2000) is mostly determined by the net CO_2 exchange with the atmosphere (NEE), and the carbon sequestration can be approximated by integration of the measured NEE over 1 year or more (see e.g. Goulden et al., 1996; Aubinet et al., 2000). For managed agricultural ecosystems, however, harvest biomass export (H_{export}) and carbon import through organic fertilisation (mainly as manure M_{import}) contribute to the carbon budget. Thus, the change in SOC with time (an increase corresponding to a carbon sequestration of the grassland ecosystem) can be expressed as:

$$\frac{\Delta \mathrm{SOC}}{\Delta t} = -\mathrm{NEE} - H_{\mathrm{export}} + M_{\mathrm{import}} \quad (1)$$

It has to be considered that NEE commonly follows the micrometeorological sign convention with positive values indicating an upward net flux of CO_2 and thus a loss of carbon to the atmosphere. Therefore NEE, like H_{export}, occur in Eq. (1) with a negative sign.

The present study was part of the EU project GREENGRASS that aimed at measuring the net global warming potential resulting from the exchange of CO_2, N_2O and CH_4 in managed European grasslands. The aims of our experiment were (i) to investigate the effect of management intensity on the carbon balance after conversion of arable land to grassland, (ii) to test the hypothesis that conversion to a low-input grassland system reduces or even reverses the carbon sequestration effect, and (iii) to establish a full greenhouse gas budget for newly established high- and low-input grassland fields. Here we report results related to the first two aims, while the greenhouse gas budget is treated in Flechard et al. (2005). To address these questions, an arable field on the Swiss Central Plateau was converted to grassland in 2001. The original field was separated into two plots, one subjected to intensive management (i.e. high nitrogen input and frequent cutting), and the other to extensive management (i.e. no fertilization and infrequent cutting). Carbon fluxes were monitored in parallel during a 3-year period starting in spring 2002 in order to obtain the carbon budget of the two grassland systems according to Eq. (1).

2. Methods

2.1. Site description

The experimental site is located on the Central Swiss Plateau near the village of Oensingen in the north-western part of Switzerland (7°44′E, 47°17′N, 450 m a.s.l.). The region is characterised by a relatively small scale pattern of agricultural fields (grassland and arable crops). The climate is temperate with an average annual rainfall of about 1100 mm and a mean annual temperature of 9.5 °C. During wintertime, especially in January and February, a snow cover (mean depth 6 cm) is observed for 27 days per year, on average (see Table 2). Before the experiment, the field was under a ley-arable rotation management (common for the region) with a typical rotation period of 8 years including spring and winter wheat, rape, maize and bi- or tri-annual grass–clover mixture. The nitrogen input depended on the crop type and followed the Swiss standard fertilisation practice (110 kg N ha^{-1} $year^{-1}$ on average). In November 2000 the field was ploughed for the last time. The area was then divided into two equal parts (0.77 ha each) as shown in Fig. 1. They were sown in May 2001 with two different grass–clover mixtures typical for permanent grassland under intensive and extensive management, respectively. The intensively managed field (referred to as intensive field or INT in the following) was sown with a grass–clover mixture of seven species. For the extensively managed field (referred to as extensive field or EXT) a more complex mixture of over 30 grass, clover and herb species was applied. During the measurement period the composition of the vegetation was surveyed by the visual estimation method of Braun-Blanquet (1964) twice each year. It yielded average relative cover values for grass, legume, and herb species of

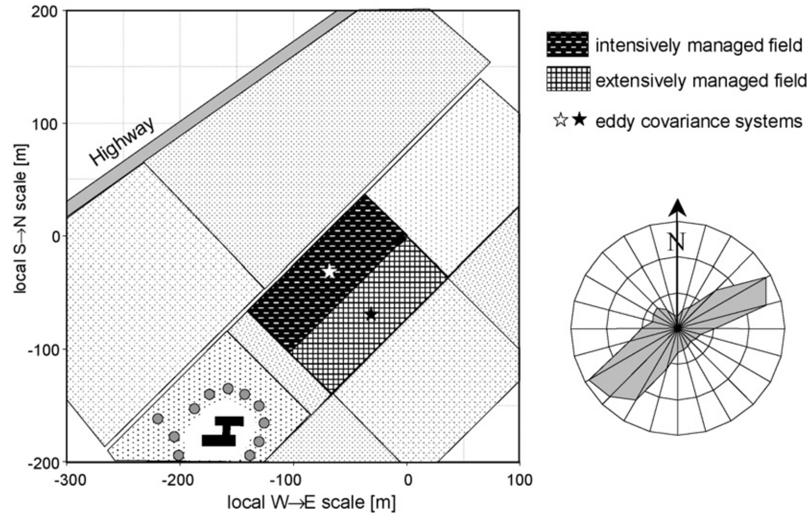

Fig. 1. Map of measurement fields and adjacent agricultural fields, together with mean relative distribution of wind direction at the site. The black structure at the lower edge represents a building surrounded by trees.

91%, 35%, and 7% on the intensive field and 61%, 58%, and 6% on the extensive field, respectively. The intensive field was cut typically four times per year and was fertilized with solid ammonium nitrate or liquid cattle manure at the beginning of each growing cycle (after the previous cut). It received in total about 200 kg nitrogen per ha and year. In contrast, the extensive field received no fertilizer (beside atmospheric deposition) and was cut three times per year, the first time not before 1 June. A detailed list of management activities is given in Table 1.

The soil is classified as Eutri-Stagnic Cambisol (FAO, ISRIC and ISSS, 1998) developed on clayey alluvial deposits. Clay contents between 42% and 44% induce a total pore volume of 55% and a fine pore volume of 32% (permanent wilting point) as measured by means of the soil moisture release curve in the laboratory. Average soil organic carbon contents in the upper 30 cm, which represent the former plough horizon, were 28–29 g kg^{-1} dry soil (without significant gradients with depth) at the beginning of the experiment and were not significantly different between management practices. These organic carbon contents are in the typical range for clayey arable soils in Switzerland (Leifeld et al., 2005). Corresponding soil bulk densities were at around 1.2 g cm^{-3}.

2.2. CO_2 exchange measurements by eddy covariance

The CO_2 and energy fluxes were measured by the eddy covariance (EC) method with nearly identical systems situated in the centre of each field (see Fig. 1). For the dominant wind sectors (SW and NE), the fetch length was between 73 and 78 m; perpendicular to the main field axis (and to the main wind directions) the fetch length was lowest with only 26 m. The EC systems consisted of three-axis sonic anemometers (models R2 and HS, Gill instruments, Lymington, UK) and open-path infrared CO_2/H_2O gas

Table 1
List of fertilisation and harvest events for the 3-year study period for the intensively (INT) and extensively (EXT) managed fields

Year (event no.)	INT fertilisation				INT harvest		EXT harvest	
	Date	Type	Nitrogen (kg N ha^{-1})	M_{import} (g C m^{-2})	Date	H_{export} (g C m^{-2})	Date	H_{export} (g C m^{-2})
2002 (#1)	12 March	NH_4NO_3	34		15 May	135	12 June	187
2002 (#2)	22 April	Manure	69	23	25 June	101	15 August	117
2002 (#3)	01 July	NH_4NO_3	34		15 August	115	27 September	77
2002 (#4)	19 August	Manure	105	36	19 September	79		
2002 (#5)	30 September	NH_4NO_3	30		07 December	31		
2003 (#1)	18 March	Manure	113	45	30 May	174	03 June	136
2003 (#2)	02 June	NH_4NO_3	15		04 August	14	04 August	46
2003 (#3)	18 August	Manure	82	14	13 October	52	13 November	37
2004 (#1)	17 March	Manure	65	15	11 May	183	07 June	186
2004 (#2)	17 May	NH_4NO_3	30		25 June	118	28 August	124
2004 (#3)	01 July	Manure	60	8	28 August	67	03 November	25
2004 (#4)	31 August	NH_4NO_3	30		03 November	34		

M_{import} and H_{export} denote the carbon import as manure and the carbon export by harvest removal, respectively (see Eq. (1)).

Table 2
Weather characterisation of the three measurement years relative to decadal statistical values: data for the measurement site (Oensingen) and the weather network station Wynau (data provided by MeteoSwiss); summer means are averages over 3 months (June–August)

	Wynau				Experimental site (Oensingen)		
	1991–2000	2002	2003	2004	2002	2003	2004
Duration of snow cover (day)	27 ± 12	3	43	46			
Annual mean temperature (°C)	9.2 ± 0.6	9.8	9.7	9.2	9.6	9.6	8.9
Summer mean temperature (°C)	17.7 ± 0.6	17.9	21.3	17.4	17.7	21.4	17.2
Annual rainfall (mm)	1112 ± 195	1290	795	1092	1479	895	1158
Summer rainfall (mm)	341 ± 72	273	226	344	309	193	320

analysers (model LI-7500, Li-Cor, Lincoln, USA). Due to the limited size of the fields, the measurement height of the EC systems was chosen relatively low at 1.2 m above ground. The separation distance between the sonic and the gas analyser was 18 cm aligned perpendicular to the predominant wind directions. The gas analyser was tilted 40° from the vertical towards the north in order to avoid direct sunlight contamination in the optical path and to facilitate the draining of rain water from the lower lens surface. Continuous field operation of the EC systems started in February 2002 on the intensive field and in April 2002 on the extensive field. Flux calculation was done off-line with a self-made program running under PV-Wave (Visual Numerics, San Ramon, USA). First the raw high-resolution time series (20 Hz) were checked for obviously erroneous data points (spikes) that were either outside of a physically plausible range (e.g. 200–1000 ppm for CO_2) or showed a too large difference (>50 ppm for CO_2) to the previous data point. They were replaced by a moving average value. After de-spiking and a two-dimensional wind vector rotation, the cross covariance functions of vertical wind speed and transported quantities was computed by means of Fast Fourier Transform (FFT) for 30 min intervals (cf. Wienhold et al., 1995). The raw fluxes of CO_2 and H_2O were determined as optimum of the covariance function (McMillen, 1988) within a physically limited delay-time range (±0.5 s). Integral corrections were applied to the raw fluxes including the WPL-correction (Webb et al., 1980) for correlated air-density fluctuations and compensation for the damping of high-frequency fluctuations due to sensor path length averaging and separation between sonic and gas analyser. The path averaging effect is of minor importance and was estimated by the commonly applied theoretical parameterisation after Moore (1986). The sensor separation effect was considered to be more crucial due to the low measurement height. It was therefore investigated empirically by comparing the normalised ogives (cumulative cospectra) of trace gas fluxes to the respective ogives of the sensible heat flux (cf. Ammann et al., 2006). For unstable and near-neutral conditions, the empirical damping factors were in good agreement with the parameterisation of Moore (1986), but for stable conditions, they showed a considerably smaller damping. Therefore a polynomial fit (as a function of the stability parameter z/L) to the experimental results of the ogive analysis was used here for correction.

Data loss due to failures in power supply or data acquisition resulted in a basic data coverage of 89% and 94% for the two EC systems, respectively. In order to ensure the quality of the measured fluxes, a careful screening of the data was performed to identify and reject erroneous values or fluxes that were not representative of the investigated field. The quantitative rejection rates and the resulting data coverage of the applied criteria are summarized in Table 3. The most important quality criterion with a rejection rate of about one third was missing stationarity of the half-hourly fluxes (c). Data were rejected if the average flux of the 3-min-subintervals deviated more than 30% from the original flux (Foken and Wichura, 1996; Aubinet et al., 2000). Such cases mainly occurred during the frequent calm nights (ca. 40% with windspeeds below 1 m/s) with breakdown of turbulence. Of similar importance was the footprint criterion (d) that discarded cases with large footprint fractions outside the measurement field. Footprint contributions of the different fields (see Fig. 1) were calculated operationally by the analytical model presented by Kormann and Meixner (2001). Since some simplified and idealised assumptions are made in this and other footprint models, we do not consider the results as very accurate. In addition, the applied analytical model shows a tendency to overestimate footprint size when compared to a more complex Lagrangian model (Kljun et al. (2003)). However, the modelled footprints can be used as semi-quantitative selection criterion. We used a rejection threshold of ≥70% footprint fraction inside the measurement field during daytime. For night-time conditions the threshold was reduced to 50% in order to retain a reasonable amount of data. The nearby highway was also included in the footprint simulation and showed always very low contributions

Table 3
Effect of rejection procedure on data coverage for the intensively (INT) and extensively (EXT) managed fields

Effect/rejection criterion	Individual rejection rate (%)		Data coverage (combined) (%)	
	INT	EXT	INT	EXT
Power/data acquisition failure	11	6	89	94
(a) Erroneous raw data	15	13	76	82
(b) Integral turbulence (σ_w/u^*)	10	14		
(c) Flux stationarity	36	37	49	47
(d) Footprint	35	38	32	30

(<2%). In addition, cases with wind directions directly from the highway (perpendicular to the main field axis and wind directions) were excluded anyway based on the footprint rejection criterion.

The third important quality criterion (a) checked how many erroneous data points outside a physically plausible range and spikes (see previous paragraph) were found in the raw 20 Hz time series. If it contained more than 2% of bad data points, the respective flux was rejected. This criterion mainly identified and rejected periods affected by rain or dew on the optical lenses of the open-path gas analyser leading to large absolute variations of the raw trace gas signals. The remaining criterion (b) was a test for the integral turbulence characteristic σ_w/u^* (ratio of S.D. of vertical wind over friction velocity) after Foken and Wichura (1996) and Aubinet et al. (2000). It mostly coincided with criterion (c). In combination, the strict quality selection procedure resulted in a final coverage of high-quality data of 32% for the intensive and 30% for the extensive field. Since the criteria (b) and (c) predominantly rejected night-time data, the nocturnal data coverage was generally lower (about 22%, 3500 half-hour flux data per year) than the day-time coverage (about 42%, 1900 half-hour flux data per year). The applied physically based criteria removed most of the cases with low friction velocity (u^*), e.g. 80% of cases with $u^* < 0.1$ m/s. We did not apply an empirical u^*-threshold filtering (Gu et al., 2005), because an adequate threshold determination was found to be difficult and an additional filtering was considered as mostly redundant in this case.

2.3. Gap filling procedure

For calculating a total annual CO_2 exchange of the grassland fields, a continuous flux time series and thus a filling of the data gaps due to measurement failures and quality selection was necessary. The applied gap filling procedure is based on the non-linear regression method (Falge et al., 2001) with a partitioning of the measured net CO_2 flux (NEE) into a respiration (R) and assimilation (A) component

$$\mathrm{NEE} = R - A \tag{2}$$

The ecosystem respiration R was parameterised by an exponential function of the soil temperature T_{soil} (at −5 cm) as proposed by Lloyd and Taylor (1994)

$$R(T_{soil}) = R_{10} \exp\left[309\,\mathrm{K}\left(\frac{1}{10\,^\circ\mathrm{C} - T_0} - \frac{1}{T_{soil} - T_0}\right)\right] \tag{3}$$

The coefficient parameter R_{10} denotes the respiration rate at the reference temperature 10 °C (or 283 K) and T_0 determines the growth characteristic of the exponential function. The assimilation A (generally positive sign) was parameterised by a common hyperbolic Michaelis–Menten type function (Falge et al., 2001) of the photosynthetically active radiation Q_{PAR}:

$$A(Q_{PAR}) = \frac{\alpha Q_{PAR}}{1 - Q_{PAR}/2000\,\mu\mathrm{E\,m^{-2}s^{-1}} + \alpha Q_{PAR}/A_{2000}} \tag{4}$$

A_{2000} denotes the assimilation under normalised (optimum) light conditions $Q_{PAR} = 2000\ \mu\mathrm{E\ m^{-2}\ s^{-1}}$ (E = Einstein = mol photons) and α is the light-use efficiency under low-light conditions. We used the parameter A_{2000} rather than the asymptotic saturation value of the hyperbolic function, because it was frequently observed for grassland canopies that the assimilation does not really saturate within the measured Q_{PAR} range, especially during periods with high productivity (e.g. Suyker and Verma, 2001; Xu and Baldocchi, 2004). In such cases the fitted saturation assimilation would correspond to unrealistically high Q_{PAR} levels.

In contrast to Falge et al. (2001) and other authors who applied the gap filling method mainly for forest sites and used monthly to seasonal time windows for the parameter fitting, the managed grassland fields studied here can show very rapid changes in the CO_2 exchange characteristics (within one or few days) for example when the grass was cut, which happened several times per year. In order to account for such fast changes, we applied a moving time window of only 5 days width for the fit of the main functional parameters R_{10} and A_{2000} in Eqs. (3) and (4). The parameter T_0 of function (3) and the parameter ratio α/A_{2000} in (4) were found to have a much lower temporal variability than R_{10} and A_{2000}. They were thus considered to be constant with time and were determined by an overall least-squares fit to the data of the entire measurement period (see Fig. 2). Resulting values for T_0 were 228 and 233 K for the intensive and extensive field, respectively. The values are close to the universal value of 227.13 K proposed by Lloyd and Taylor (1994). The overall fit of the assimilation function was limited to data with canopy heights above 20 cm representing near-optimum growing conditions. Obtained values for α/A_{2000} were 0.0019 and 0.0020 $\mu\mathrm{E^{-1}\ m^2\ s^1}$ for the intensive and extensive field, respectively. The numbers imply a very similar shape of the light response curves for both fields, although the maximum light-use efficiency of the extensive field is somewhat lower.

The detailed steps of the gap filling procedure are illustrated in Fig. 3. The measured flux dataset was divided into night-time and day-time cases according to Q_{PAR} (above or below 10 $\mu\mathrm{E\ m^{-2}\ s^{-1}}$). The night-time data directly represented system respiration R and were used to fit the parameters of Eq. (3). The day-time assimilation was derived by subtracting the measured NEE from the parameterised respiration. The gap filling was actually performed on the time series of the two functional parameters R_{10} and A_{2000} using the 5-day moving average filter. The few larger gaps (>3 days) were linearly interpolated between available values. The resulting

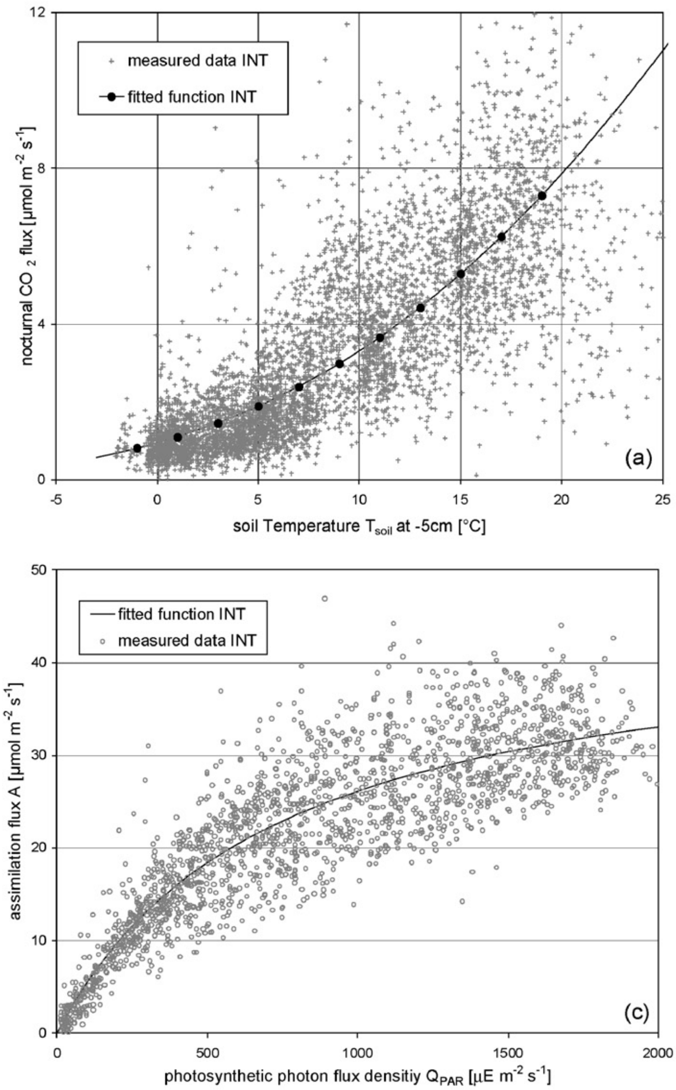

Fig. 2. Overall fit of parameterisation functions for respiration and assimilation (Eqs. (3) and (4)) to measured 3-year dataset of intensive and extensive field for the determination of T_0 and the ratio α/A_{2000}: (a and b) dependence of night-time respiration on soil temperature; (c and d) dependence of day-time assimilation on photosynthetic active radiation for cases with canopy height $\geq$20 cm.

complete time series $R_{10}(t)$ and $A_{2000}(t)$ were then used to calculate the missing CO_2 fluxes and to produce a continuous gap-filled time series.

2.4. Error estimation for annual NEE

The gap-filled time series of the CO_2 flux were cumulated to obtain annual NEE values. The uncertainty of a long-term NEE is mainly a result of systematic errors of the individual half-hourly flux measurements because the relative effect of random errors gets small for a sum over several thousand data points. Systematic errors, in contrast, represent unknown deviations from the true value that is persistent in sign (and size) during a longer period and/or certain environmental conditions. Averaging or summing up over longer time periods does not reduce their relative effect. We largely follow the concept of Goulden et al. (1996) for estimating the systematic errors of the annual NEE. They proposed three different error classes: (1) uniform systematic errors, (2) selective systematic errors that occur selectively under certain environmental conditions and (3) sampling uncertainties due to data gaps. Errors of the first group have a uniform effect for all environmental conditions and their relative effect is directly propagated to the annual NEE. For the present study we estimated a uniform error of $\leq$5% for the calibration slope of the CO_2 analyser. Selective systematic errors of EC flux measurements occur separately for day-time and night-time conditions because of the generally different (stability dependent) turbulence regimes that cause systematic differences in the high- and low-frequency loss, footprint distribution and stationarity. They generally have asymmetric characteristics, which is partly due to the higher probability for a underestimation than for an overestimation of EC fluxes (e.g. Twine et al., 2000; Ham

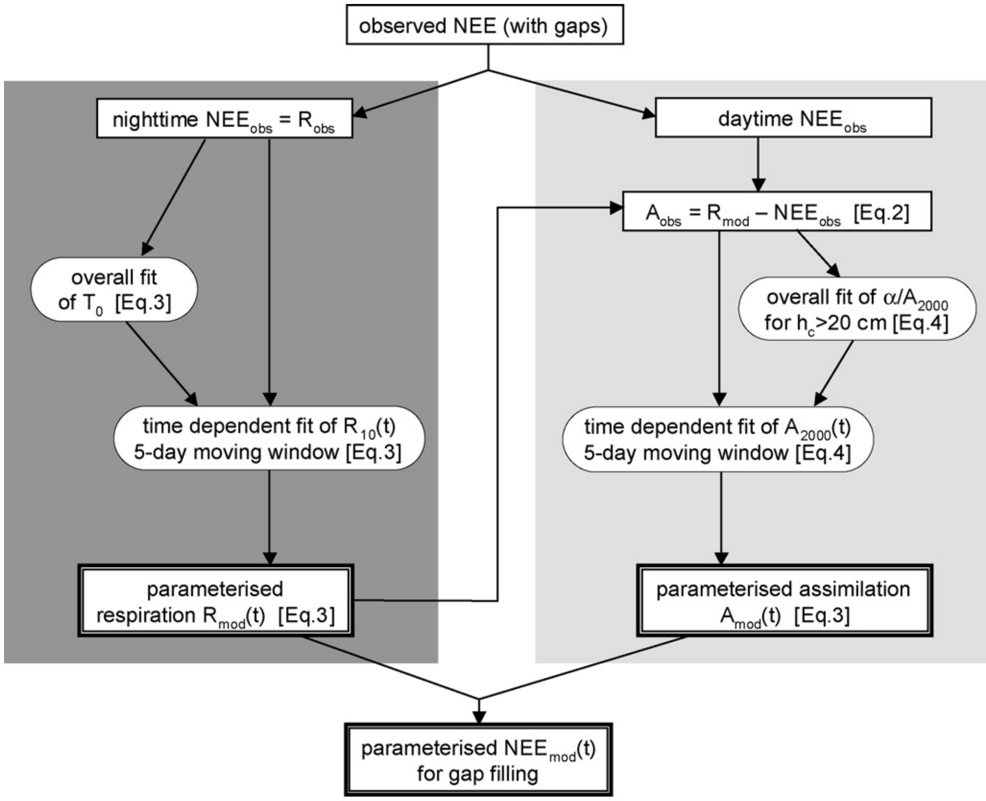

Fig. 3. Schematic overview of applied gap filling procedure for the CO_2 flux time series. Rectangles with thin frames represent observed time series (with gaps), rectangles with bold frames represent parameterised (modelled) time series for gap filling.

and Heilman, 2003) and because they often represent the difference between the actually applied processing or correction procedure and a possible alternative. For the nocturnal NEE, we estimated a one-sided systematic uncertainty of +10% due to limited fetch (the surrounding arable fields tend to have lower respiration) and +7% due to the difference in the empirical and theoretical high-frequency correction (see above). For day-time NEE, Twine et al. (2000) propose a correction according to the non-closure of the surface energy budget including EC measurement of sensible and latent heat fluxes. We did not apply this correction here but considered the observed gap in the energy budget (−9% on average) as a selective day-time error. For the sampling uncertainty (gap filling) we did not perform a specific error analysis but adopted the relative error of ±15% for NEE obtained similarly by Goulden et al. (1996) and Oren et al. (2006) as a rough estimate. In lack of an established statistical method for the combination of systematic errors, each side of the error range was propagated separately according to Gaussian error propagation rules. Since average day-time and night-time fluxes have opposite signs, the resulting relative error of the annual NEE (see Table 4) became significantly larger but less asymmetric.

Table 4
Components of annual CO_2 and carbon budget for the years 2002, 2003 and 2004 for the intensively (INT) and extensively (EXT) managed fields: assimilation (A) and ecosystem respiration (R, also as fraction of A) estimated by the gap filling procedure described in Section 2.3, net ecosystem exchange (NEE), harvest export (H_{export}), manure import (M_{import}), and the resulting ecosystem carbon budget (sequestration, $\Delta SOC/\Delta t$) according to Eq. (1)[a]

Year	Field	A	R	(R/A) (%)	NEE	H_{export}	M_{import}	$\Delta SOC/\Delta t$
2002	INT	2159	1490	(69)	−669 [+130/−140][b]	462 [±69]	59 [±24]	266 [+150/−160]
	EXT	1714	1362	(79)	−352 [+120/−110]	380 [±58]	0	−28 [+130/−120]
2003	INT	1773	1558	(88)	−215 [+100/−90]	241 [±36]	59 [±24]	33 [+120/−100]
	EXT	1750	1678	(96)	−71 [+120/−80]	219 [±32]	0	−148 [+120/−90]
2004	INT	2056	1539	(75)	−517 [+130/−120]	401 [±40]	22 [±9]	138 [+130/−130]
	EXT	2075	1736	(84)	−339 [+130/−110]	335 [±34]	0	4 [+130/−120]

[a] All values have units of g C m^{-2} $year^{-1}$.
[b] Asymmetric uncertainty ranges in square brackets represent estimated systematic errors of the budget components (rounded to significant digits).

2.5. Biomass and carbon content analysis

Harvest yield (H_{cut}) was determined immediately after each cut by weighing and dry matter analysis of cut biomass for five sub-plots (1.2 m × 6 m) per field. Depending on weather and soil conditions the cut grass was usually dried on the field for 1–3 days to produce silage or hay bales. It is well known that the machine processing and drying of grass in the field can lead to significant dry matter loss of the harvest (e.g. Stilmant et al., 2004) due to crumbling of the dry leaf parts (especially for legumes and herbs), respiration loss, and incomplete machine collection. Starting in October 2003, we also determined the effective exported biomass (H_{export}) of the entire fields by weighing the bales on the transport trailers (uncertainty: ±10%) together with a second dry matter analysis. In order to approximate H_{export} also for the previous period, for which only H_{cut} was available, a simple linear relationship $H_{export} = \gamma H_{cut} - \delta$ was used. The parameter δ representing mainly the collection residues was set to 0.9 g C m^{-2} for all cases, while for the factor γ individual values for fresh grass (1.0), half-dried silage (INT: 0.91, EXT: 0.85), and dried hay (INT: 0.83, EXT: 0.70) were used. This procedure resulted in an integrated annual loss of 22% for the intensive field and 29% for the extensive field. Due to the high uncertainty of the application of the loss calculation to the years 2002 and 2003, the error of the respective biomass export increased to ±15%.

Root biomass was measured in May 2004 in both fields. Soil cores (n = 10 per field, diameter 7 cm) were gouged to 1 m depth, and each soil column was partitioned into five increments (0–5, 5–10, 10–30, 30–70, and 70–100 cm). Root biomass of each sample was extracted from soil suspensions in a root washing machine and defined as the floating material on water. Carbon and nitrogen content was determined for dried samples of harvested biomass, root biomass, soil, and liquid manure by dry combustion (CHN Na2000, ThermoQuest) at INRA, France.

2.6. Supporting measurements

An automated weather station was used to monitor the common meteorological parameters at the site. Air temperature and humidity used as a reference for the eddy covariance data were measured by a combined sensor Rotronic MP100A (Rotronic, Bassersdorf, Switzerland) at 2 m above ground. Soil temperature profiles were measured on both fields using high-quality thermistor probes in 2/5/10/30/50 cm depth. Volumetric soil water content was monitored by ThetaProbe ML2 sensors (Delta-T Devices, Cambridge, UK) using the frequency domain reflectometry (FDR) technique at 5/10/30/50 cm depth. Photosynthetically active radiation (Q_{PAR}) was measured by a LI-190SA quantum sensor (Li-Cor, Lincoln, USA). The development of the grass canopies was observed by measurements of canopy height every 2–3 weeks at 9 points on each field. Canopy height was determined manually by measuring the centre height of a light-weight plate (ca. 50 g) of 0.25 m^2 dropped onto the canopy. Less frequent, leaf area index (LAI) was measured by a non-destructive method using the optical LAI-2000 instrument (Li-Cor, Lincoln, USA).

In order to investigate possible differences of SOC decomposition (mineralization) of the two experimental fields, heterotrophic soil respiration was analysed under standardised laboratory conditions by incubation of soil cores. Measurements were carried out at 25 °C on intact soil cores (100 cm^{-3}) taken at the beginning of May 2002, 2003, and 2004 from 5 to 10 and 25 to 30 cm depth (n = 6). Samples were adjusted to a water potential of 60 hPa before incubation and allowed to equilibrate for 1 week before measurement. Headspace CO_2 accumulation was recorded in an automatic static incubation chamber (Barometric Process Separation BaPS, UMS, Munich, Germany). CO_2 concentrations were corrected for solution and dissociation in the soil water, to calculate the effective production. Oxygen concentrations were not allowed to drop below 19% to avoid limitation in aerobic microbial activity.

3. Results

3.1. Weather conditions and vegetation development

In order to describe the local climate at the measurement site and the specific characteristics of the 3 years 2002–2004, mean temperature and rainfall for the whole year and the summer month (June/July/August) for the measurement location are compared in Table 2 to respective values and the 10-year statistics of the long-term weather station Wynau at a distance of about 5 km southward (weather station network ANETZ, MeteoSwiss). The Wynau station is situated about 30 m lower than our site (422 m a.s.l.) and thus shows slightly higher mean temperatures. The annual rainfall is about 10% lower on average. However, the year-to-year variability of both stations is very similar. By comparing the annual Wynau values to the respective 10-year means, it turns out that 2004 was very close to the long-term average. 2002 was overall a relatively wet year apart from the summer month that showed a slight rain deficit. The annual mean temperature was also somewhat increased and the duration of snow cover was extremely short. The year 2003 showed an exceptionally strong summer heat wave all over central Europe (Schär et al., 2004). It is clearly reflected in the mean summer temperature being 3.5 °C (about 6 S.D.) above the decadal mean. In addition, rainfall was considerably reduced compared to the long-term average.

The vegetation development of grassland is influenced mainly by the temperature (especially in late winter and spring) and by the soil moisture available to the plants. The seasonal course of air temperature over the entire period is

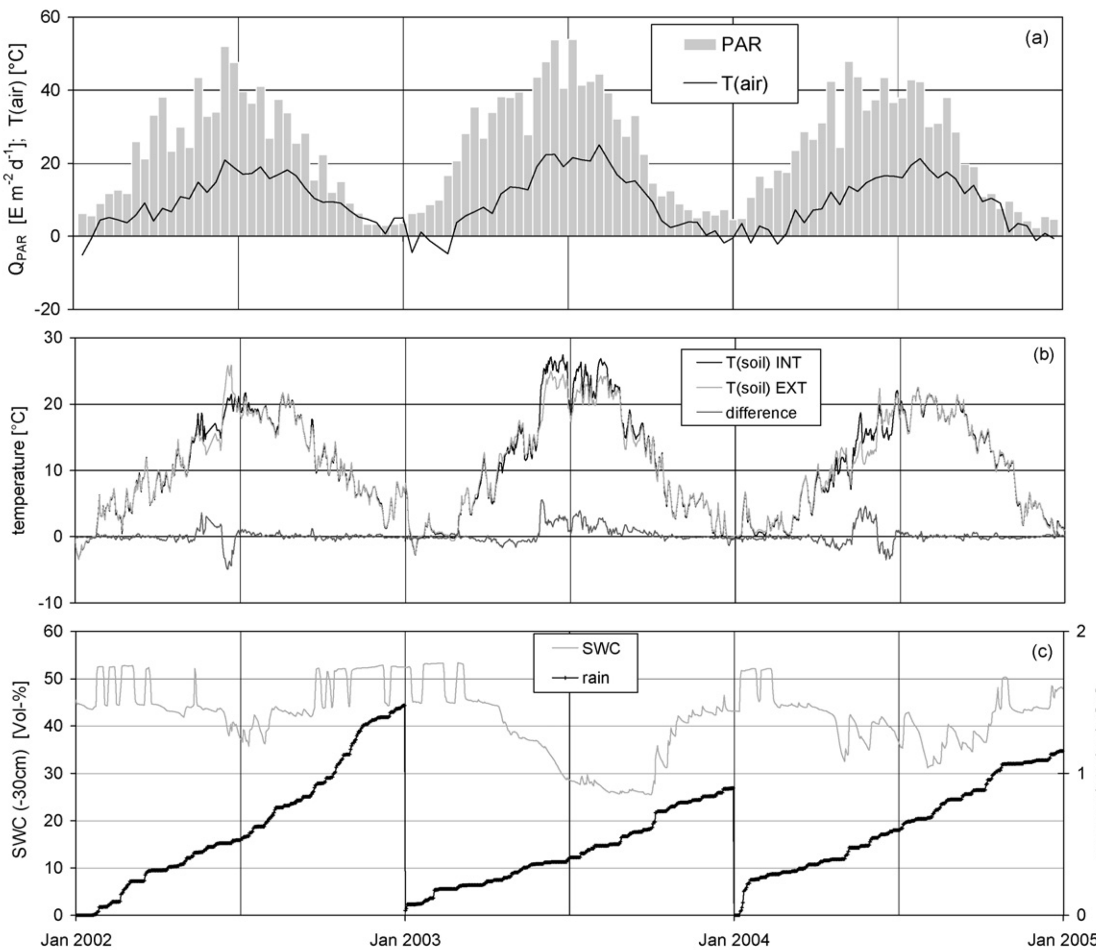

Fig. 4. Temporal course of meteorological and soil conditions over the 3-year measurement period: (a) 10-day averaged values of daily integrated Q_{PAR} and air temperature at 2 m height, (b) daily averages of soil temperatures at −5 cm depth for both fields and the respective difference, (c) accumulated rainfall and daily average volumetric soil water content (SWC) at −30 cm depth (average value of two sensors on each field, no significant difference between the fields was found). The permanent wilting point of the soil was determined at 32% SWC.

plotted in Fig. 4a. It shows exceptionally high daily mean temperatures above 5 °C already at the end of January 2002 favouring an early vegetation development. For the other years, such conditions (apart from short term peaks) are only reached in March. The volumetric soil water content (SWC) displayed in Fig. 4c reflects the differences in seasonal rainfall (see also Table 2) and may be compared to the permanent wilting point that was determined as 32% water content for the site (see Section 2.1). The SWC at −30 cm depth, which is generally reached by the deep roots of the plants, is always above the critical value in 2002 and 2004. Yet in summer 2003 the SWC stayed permanently below 30% from May till August causing a significant drought effect on the vegetation. Consequently canopy growth (Fig. 5a) was strongly reduced for the second and the beginning of the third growth period on both fields in comparison to the other years. The cutting times (see also Table 1) varied somewhat between the years, because they need fair weather periods and drivable soil conditions. Due to the very light plate used for measuring the canopy height, it is not proportional to the LAI development but mainly reflects the height of the fastest growing species in the canopy. Maximum LAI values were ≤7 for the first growth and ≤5.5 for the following re-growth periods. The root biomass survey in summer 2004 yielded similar results of 230 ± 40 and 210 ± 30 g C m^{-2} for the intensive and extensive field, respectively.

3.2. Temporal variation of CO_2 exchange

Fig. 5 gives an overview of the CO_2 exchange characteristics of the two grassland fields for the entire measurement period. Panel (d) shows the seasonal course of the ecosystem respiration and assimilation as resulting from the gap filling procedure (Section 2.3). They follow primarily the temporal variation of their main driving variables, the soil temperature (Fig. 4b) and the photosynthetically active radiation Q_{PAR} (Fig. 4a), respectively. The time series of the parameters R_{10} and A_{2000} in Fig. 5b and c contains the remaining variability of the respiration and assimilation not explained by the main driving variables.

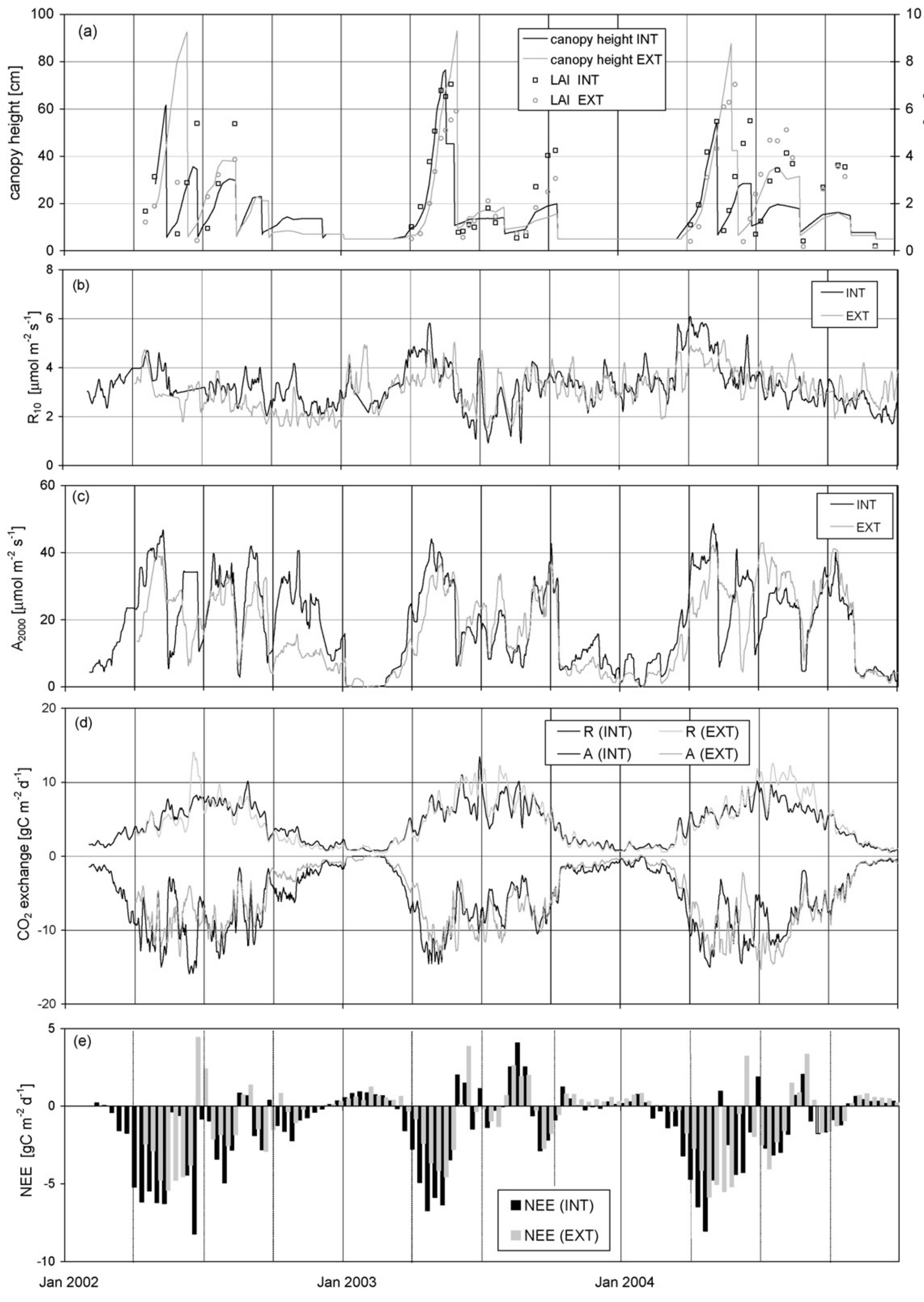

Fig. 5. Temporal course of canopy development and CO_2 exchange over the 3-year measurement period for both fields: (a) canopy height and available LAI measurements, (b) 5-day moving average of normalised assimilation rate A_{2000}, (c) 5-day moving average of normalised respiration rate R_{10}, (d) daily average respiration and assimilation flux, the latter plotted as negative values for practical reasons, (e) 10-day averaged NEE.

Highest R_{10} values occurred generally during the first growing phase (March to May). The lower extreme was observed during the 2003 summer drought, when respiration was most likely limited by the low soil moisture content. The time series of the light-normalised assimilation A_{2000} shows fast changes that are mainly related to cutting events, consecutive re-growth, and the reduced activity at low temperatures (cold season).

A direct comparison of the CO_2 exchange of both fields is somewhat complicated by the different cutting dates. However, the assimilation time series (Fig. 5c and d) clearly indicates that the vegetation development generally started earlier and/or faster on the intensive field which therefore exhibited a larger net CO_2 uptake (negative NEE) in Fig. 5e. In 2002, a significantly higher assimilation of the intensive field was also observed throughout the autumn. In contrast, during the 2003 summer drought period, the extensive field exhibits a larger assimilation (productivity) than the intensive field besides a general reduction effect. The system respiration (Fig. 5d) of the extensive field shows a positive trend over the 3 years (see also Table 4). In the first year it is mostly lower, whereas in 2003 and 2004 it is similar or higher than the respiration of the intensive field.

By summation of the NEE time series in Fig. 5e over the entire year, the cumulative NEE curves as plotted in Fig. 6 are obtained. In this figure, the three measurement years are compared separately for the intensive and extensive management. On the intensive field, EC data were available beginning in February 2002, whereas on the extensive field, EC measurements started only on 3 April 2002. In order to obtain a full annual budget for 2002, the NEE of the lacking periods was estimated from comparison with the winter/spring data of the two other years. For the month of January, the intensive field shows a very similar cumulative NEE in the years 2003 and 2004 (see Fig. 6). Thus their average value of +17 g C m^{-2} for 1 February was used as starting point in 2002. In order to reconstruct the lacking period for the extensive field, the close similarity of the first 4 months 2002 and 2004 observed for the intensive field was assumed to also apply for the extensive system. Therefore the start of the EXT curve in spring 2002 was adjusted to the respective values of 2004. To account for the uncertainty of this procedure, an additional absolute error of ±25 and ±50 g C m^{-2} $year^{-1}$ (for the intensive and extensive field, respectively) was attributed to the annual NEE of 2002.

Throughout summer and autumn, the curves for 2002 and 2004 in Fig. 6 are relatively similar for each field, although the cumulative NEE is generally much lower on the extensive field. The year 2003 exhibits a significantly longer positive NEE phase in spring for both management systems compared to the other 2 years. This is not caused by an enhanced respiration during that period but by a suppressed assimilation till the beginning of March (see Fig. 5d). After the first cut in 2003, assimilation was strongly reduced due to the drought phase (see above) and the course of the NEE curves are again clearly different compared to the other 2 years in that they show no net uptake of CO_2 till September.

3.3. Annual carbon budgets

Annual carbon budgets corresponding to the carbon sequestration of an ecosystem were calculated for the two grassland fields according to Eq. (1). The cumulated NEE for each year and management system is represented by the endpoints of the curves in Fig. 6. The corresponding values are listed in Table 4 together with the respective values of harvest export, manure import and the total carbon budget as resulting from Eq. (1). The error range of the carbon budget is largely determined by the errors of NEE. Fig. 7a shows the carbon budget components averaged over all 3 years. In this way the weather-induced variability of the annual values is reduced. However, as mentioned above, averaging over multiple years does not reduce the systematic errors. The intensive field exhibits a mean annual carbon sequestration of 147 (±130) g C m^{-2} $year^{-1}$ that is significant in relation to the estimated systematic errors, whereas the extensive field shows a carbon loss (negative sequestration) of −57 (+110/−130) g C m^{-2} $year^{-1}$ that is, however, not significantly different from zero. The significance of the budget

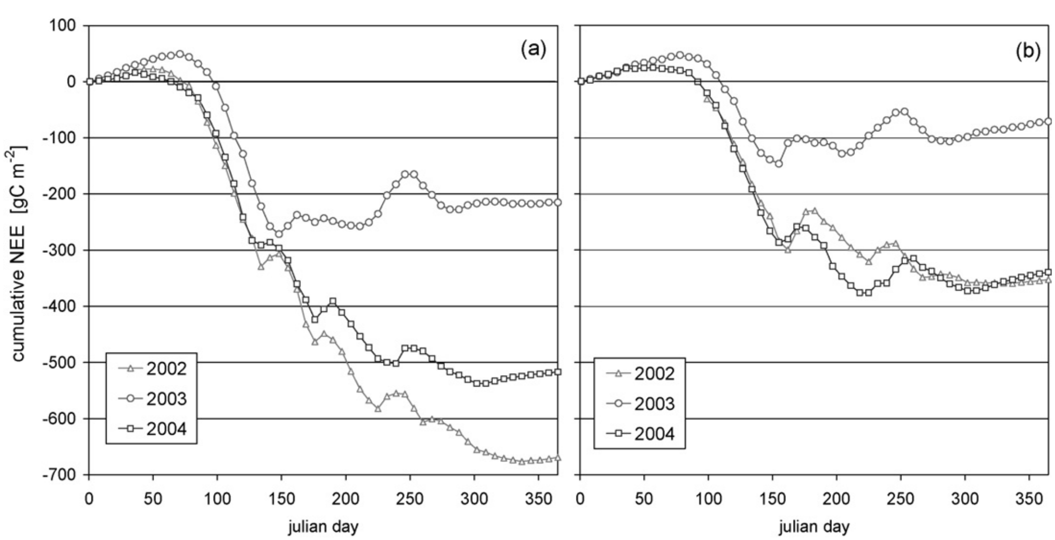

Fig. 6. Cumulative NEE for the three study years for (a) intensively and (b) extensively managed grassland field. The curves for 2002 start only in February (intensive) and April (extensive). Their starting value was estimated by comparison with the other 2 years (details see text).

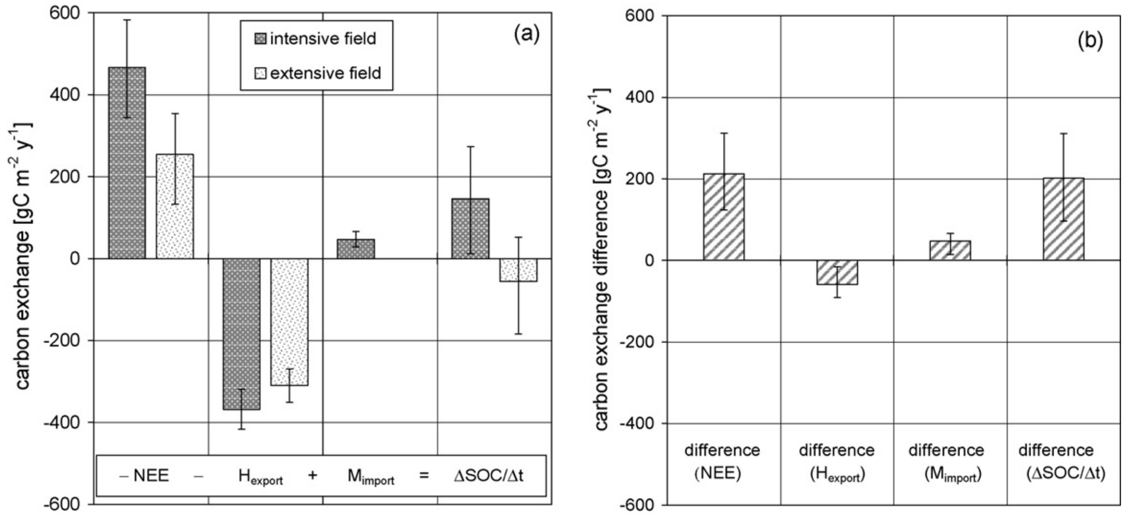

Fig. 7. Average carbon budget for the whole 3-year period, (a) budget components for extensive and intensive field with individual uncertainty range, (b) difference between corresponding components of the two fields with differential uncertainty range (see text).

results is improved, if not the absolute values but the difference between the two management systems is considered (see Fig. 7b). The average difference in the carbon budget between the intensive and extensive management system was determined to 204 ($\pm$110) g C m^{-2} year^{-1}, almost equal to the average difference in NEE. Most of the selective systematic errors of the CO_2 flux measurement (Section 2.4) are supposed to be equal or at least similar for the EC systems on both fields. Thus for the differential effect only the independent (potentially different) systematic errors had to be considered. Since in the main wind directions, potential footprint disturbance was similar for both fields, the respective systematic error was reduced from -10% to $\pm3\%$. The methodological uncertainty of the high-frequency corrections had no effect on the NEE difference since the data treatment was identical for both fields. The imbalance in the day-time energy budget was found to be similar for both fields and therefore the respective systematic error was reduced from -9% to $\pm2\%$.

3.4. Laboratory analysis of soil respiration

Rates of CO_2 production per unit organic carbon measured in the laboratory incubation experiments under standardized conditions (Section 2.6) differed significantly between the two experimental fields, soil depths, and sampling dates (Fig. 8). Production rates were much higher under extensive than under intensive management in each

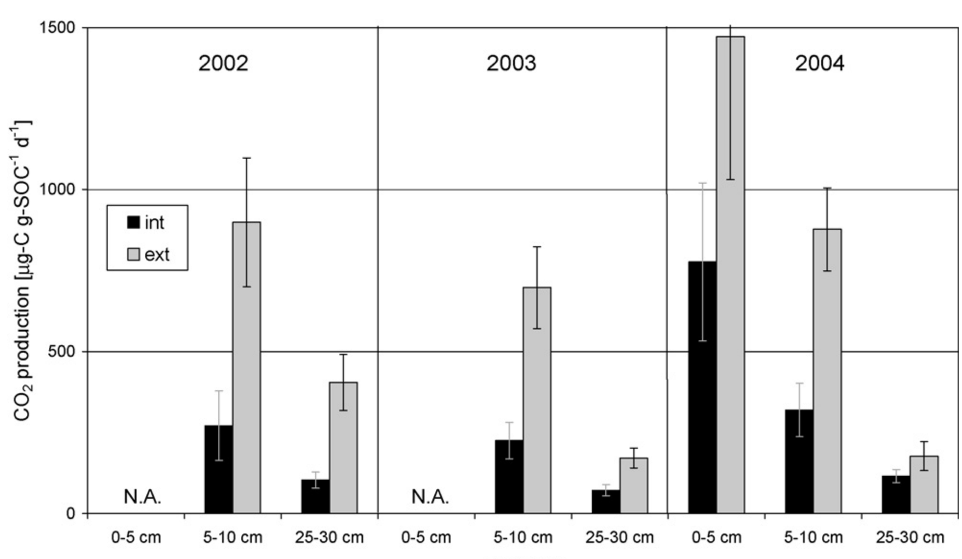

Fig. 8. CO_2 production (heterotrophic respiration) at 25 °C of incubated soil cores taken from the intensive and extensive field. Error bars represent the 5% uncertainty range of the displayed mean values ($n = 6$).

year, and decreased with soil depth in both fields. Data of 2004 for three different depth layers indicate that the largest part of heterotrophic soil respiration originates from the uppermost 10 cm layer. A conversion of the summed production rates of this layer to area related units yields heterotrophic CO_2 emission fluxes of 1.8 and 3.1 μmol m^{-2} s^{-1} for the intensive and extensive field, respectively. Although a direct comparison of laboratory incubation results and field measurements is generally difficult, these values are in a plausible range when compared to the average total ecosystem respiration flux of about 11 μmol m^{-2} s^{-1} observed in the field for soil temperatures of 25 °C (see Fig. 2).

4. Discussion

4.1. Inter-annual variation of carbon budgets

The carbon exchange of two recently established permanent grassland fields under contrasting management intensity was measured over 3 years in a paired experiment. It represents, to our knowledge, the longest continuous field scale carbon budget study of managed temperate grassland published so far. Due to the limitations of the field size and nocturnal wind speed described in Section 2.2, it was crucial to perform a strict quality selection of the flux data that led to a considerable reduction of the data coverage (Table 3). Low data coverage of less than 50% is also reported by Novick et al. (2004) for a temperate grassland site, which has similar problems of limited fetch and frequent night-time stable conditions. In order to obtain annual NEE results, we used a gap filling procedure that was specifically adapted to the particular characteristics of managed grassland with rapid changes in vegetation and soil conditions. The fast temporal adjustment ability of the applied gap filling method is documented in Fig. 5. The time series of the normalised assimilation and respiration capture well the fast changes related to cutting events, consecutive re-growth, and rain events during the 2003 drought periods and thus prevent systematic errors due to non-adequate gap filling in these phases.

On average over all 3 years, the intensive field showed a net sequestration of carbon of 147 ($\pm$130) g C m^{-2} year^{-1}, the extensive field a non-significant net carbon loss (negative sequestration) of -57 (+130/$-$110) g C m^{-2} year^{-1} (see Fig. 7a). The carbon budgets of the individual years (Table 4) exhibit considerable variability and are therefore less indicative concerning the longer-term carbon sequestration effect. Yet, they can be useful to study the influence of seasonal weather conditions and corresponding management variations on the carbon budget. Regardless of statistical limitations, the annual sequestration shows a correlation to the respective harvest export from the field. Largest sequestration occurs together with highest productivity of the grassland vegetation. This observation is in agreement with the general hypothesis that carbon sequestration potential increases with net primary production of the ecosystem (Nyborg et al., 1997; Conant et al., 2001).

The summer 2003 provided a natural drought experiment with strongly reduced rainfall and extremely high average temperatures (see Table 2). When comparing the summer months of 2003 and 2004 (the latter being the wettest and coolest summer of the 3 years), the respiration is almost equal for both years (INT and EXT), whereas the 2003 assimilation is reduced considerably (Fig. 5c and d) leading to a continuously positive NEE during the drought period (Fig. 5e) and strongly reduced harvest yield (Table 1 and Fig. 5a). This effect is observed similarly for the whole years in Table 4. As a consequence, the carbon budgets of both fields in 2003 were shifted towards a net loss (more negative ΔSOC/Δt). As displayed in Fig. 5d, the extensive field showed a somewhat higher assimilation (productivity) in summer 2003 that may indicate a lower susceptibility of the extensive plant community to the low soil water content. The observed drought effects are of special interest for future scenarios, because according to Novick et al. (2004) the hydrological cycle may be the key driver of grassland carbon dynamics. Schär et al. (2004) showed that the temperature and rain characteristics of the summer 2003 in Central Europe are found in future climate simulations for 2070–2100 as average conditions.

The strong decrease in assimilation observed during summer 2003 is in agreement with results reported by Ciais et al. (2005) for various European sites. However, they also report a reduction of the respiration at most sites in comparison to their reference year 2002. The fact that we did not observe a reduction of respiration at our site may have the following reasons: First, Ciais et al. (2005) considered mostly forest ecosystems that usually keep a relatively high LAI throughout the summer. Thus the soil is mostly shaded and soil temperatures do not get very high like they did in our cut grassland (see Fig. 4b). Obviously, the clear reduction effect on respiration due to low soil moisture as indicated by the R_{10} time series in Fig. 5b has been compensated by the much higher soil temperatures. Furthermore, the partitioning of day-time fluxes into assimilation and respiration resulting from the gap filling procedure (Section 2.3) is based on simplified assumptions and is thus less reliable than the gap-filled net flux (NEE). Especially during hot periods, the extrapolation of nocturnal respiration fluxes to day-time conditions might be problematic. Nevertheless, due to its consistent calculation, the partitioning can be useful to interpret differences between individual seasons, years, and management systems.

It is noticeable that 2002 shows the largest annual assimilation for the intensive field, but the lowest for the extensive field (Table 4). The values of the other 2 years are relatively similar to each other. This difference seems extraordinary, also because the high assimilation of the intensive field goes together with the lowest annual respiration value resulting in very high sequestration rate. A possible explanation is that it includes effects of unequal development stages of the vegetation or build-up effects of the root and stubble biomass pool, that had not been fully established in the short vegetation period of the previous year due to the relatively late sowing date in May 2001.

4.2. Difference between intensive and extensive management

The realisation of an optimized paired experiment with two differing management regimes on the field scale necessitated the bisection of the original homogeneously used field and thus contributed to EC measurement problems like the limited fetch. On the other hand, the experimental design allowed determining the differential effect between the two management systems with a considerably reduced uncertainty (compared to the carbon budget of a single field) because of very similar systematic errors for both parallel fields. The mean difference (intensive–extensive management) in the carbon budget over the 3 year study period was determined to be significant with a value of 204 ($\pm$110) g C m^{-2} $year^{-1}$. Despite the year-to-year variability discussed above, a roughly similar difference between 134 and 294 g C m^{-2} $year^{-1}$ was consistently found for all three individual years. Considering that grasslands do not experience sustained carbon accumulation in the aboveground biomass and that similar living root biomass was found for both fields, the observed carbon budget difference represents a difference in the change of the SOC pool. The effect is the result of either a larger input into the intensive SOC pool or a larger decomposition rate of the extensive SOC pool. For the clarification of the effect, the results of the laboratory incubation experiments are very helpful. The observed heterotrophic CO_2 production is largely determined by the easily available, ''active'' SOC pool, which is considered to account for only a few percent of the total SOC (Paul et al., 1999). For the Oensingen site, the size of the active SOC pool has been estimated at around 5% of the total SOC by means of long-term incubations (Leifeld and Fuhrer, 2005). Several studies have shown that this pool typically decreases with depth (e.g., Paul et al., 1997; Bol et al., 1999), which is also confirmed for the Oensingen sites by the incubation measurements. In principle, different pool sizes of the active SOC may contribute to the systematic difference in heterotrophic CO_2 production as found between the two fields (Fig. 8). Given the almost identical site conditions and the similar yield of the two fields and the fact that liquid manure as an additional C source was spread only on the intensive field, a larger active C pool in the extensive field seems unlikely. However, management, in particular fertilisation, may control heterotrophic activity in soil in yet another way. Levels of available nutrients between fields were different as induced by no fertilisation of N, P, K on the extensive field vs. nutrient application at the recommended level on the intensive one. A nutrient limitation with a concomitant large supply of energy (carbon) may substantially raise the decomposition of the native SOC pool ('priming', see Fontaine et al., 2004) and in general stimulate the microbial activity for an increased nutrient mobilisation (Fenchel et al., 1998). Such a mobilisation induces a faster decomposition of the soil organic matter. This mechanism implies an increased heterotrophic release of CO_2 in the extensive field and, in the long-term, a decrease in SOC of the extensive relative to the intensive field.

This findings support the observed difference in the carbon budgets of the two grassland fields. They are also consistent with the results of the annual NEE partitioning into respiration and assimilation listed in Table 4. The ratio *R*/*A* is always higher for the extensive field, which may be explained by a higher heterotrophic respiration (independent of the assimilation). Another strong indication of enforced SOC decomposition for the extensive field results from N-budget considerations as given by Flechard et al. (2005). Summarizing, it is argued that the total N export by harvest of more than 200 kg N ha^{-1} $year^{-1}$ from the extensive field clearly exceeds the estimated N import by atmospheric deposition (20–30 kg N ha^{-1}) and N-fixation. According to Boller and Nösberger (1987) the dominant legume species white and red clover are able to fix about 3 kg N per 100 kg legume yield (dry matter). With an average total dry matter yield of 7030 kg ha^{-1} $year^{-1}$ for the extensive field containing less than 50% legume species (estimated from the relative leaf cover fractions as given in Section 2.1) this results in a contribution of $\leq$100 kg N ha^{-1} $year^{-1}$ from symbiotic fixation. It is thus concluded that a net decrease in the soil N pool (via enhanced mineralization of SOC) is likely to contribute to the closure of the N-budget.

5. Conclusions

Based on the findings of this study, and considering that the carbon stock of the previous arable field was not as depleted as in other studies because of the applied ley-cropping system, the conversion from arable rotation to managed grassland can be regarded as a measure for carbon sequestration only if intensive management (fertilizer application) is maintained. Similar above- and below-ground productivity, together with laboratory respiration experiments and nitrogen budget considerations, indicate that the observed difference in the ecosystem carbon budget is most likely attributable to a faster decomposition of SOC under the extensive management stimulated by a deficit of available nutrients in the unfertilised soil.

The most pronounced effect in the year-to-year variation was caused by the extreme 2003 summer heat-wave involving a significant drought period between June and August. It led to a strongly reduced productivity but an unchanged or even increased system respiration and thus to a net loss of carbon in that period. These observations are of relevance for future climate scenarios predicting hotter and drier summers in Central Europe.

The duration and overall effect of carbon sequestration due to the conversion of arable rotation to permanent grassland as well as the detailed effect of different fertiliser levels cannot be quantified from the available 3-year dataset for the two contrasting management regimes. Beside longer-term observations it needs equilibration and sensitivity studies with appropriate ecosystem models to assess these questions.

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