Management, not climate, controls net CO_2 fluxes and carbon budgets of three grasslands along an elevational gradient in Switzerland

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Abstract

In Switzerland, the traditional three-stage grassland farming system consists of grazed or cut grasslands along a gradient from lowland to alpine elevations. We measured carbon dioxide (CO_2) fluxes at three grassland sites (400, 1000, 2000 m elevation) and estimated carbon sequestration for two years (2006 and 2007). Grasslands at higher elevations (>1000 m), managed at lower intensities, exhibited a larger net CO_2 uptake compared to intensively managed grasslands at lower elevations (400 m). Nevertheless, net CO_2 uptake rates during optimal growth were very similar for all three sites. Taking into account harvest outputs as well as manure inputs, we calculated the carbon stocks and their changes for grasslands at 400 m and 1000 m during two years. Similar to the cumulative net ecosystem CO_2 fluxes, the seasonal course of carbon stock changes was strongly driven by management intensity, in particular by timing and amount of manure applications. Despite differences in environmental and management conditions with elevation, both grassland sites were carbon sinks during 2006 and 2007 (between 60 and 150 g C m^{-2} a^{-1}).

Key words: net ecosystem exchange, eddy covariance, mountain agriculture, Swiss Alps

Introduction

Global observations and climate model predictions describe a changing climate with rising temperatures and changes in the hydrological cycle (IPCC 2007). For Europe, these changes are expected to be largest in the Alpine region, with an increase of weather extremes, such as droughts and floods (OcCC 2008). For Swit-

source: https://doi.org/10.7892/boris.5454 | downloaded: 4.3.2021

zerland, in the central Alps, the predicted changes in climate raise questions (a) on the reliability of fodder production with current agricultural practices, and (b) whether continued sustainable management can be achieved in agronomic (Calanca and Fuhrer 2005; Fuhrer *et al.* 2006) as well as environmental terms. Closely linked to climate is the carbon cycle, with carbon dioxide (CO_2) as its largest atmospheric fraction. Atmospheric CO_2 is fixed by the biosphere via photosynthesis, released via respiration back to the atmosphere, while at the same time organic matter is added to the soil. The carbon stocks in grassland biomass and particularly in grassland soils are significant (≈11% of total C stock for Switzerland, Bolliger *et al.* 2008), and any changes of the environmental conditions can potentially change their role in the carbon cycle, i.e. carbon sink or source.

Grasslands in Switzerland occupy about 20-30% of the land surface (depending on classification, FAO 1997; Jeangros and Thomet 2004; Hotz and Weibel 2005; Leifeld *et al.* 2005), and cover a large range in elevations in the Swiss Alps (Boesch 1951; Jeangros and Thomet 2004). The assessment of carbon stocks in these grasslands has received attention recently (Leifeld *et al.* 2005; Bolliger *et al.* 2008), but the topographic complexity introduces a large heterogeneity in the response of grasslands to climate and land use change for which the necessary process understanding is still lacking. Process studies on the exchange of CO_2 of alpine grassland ecosystems with the atmosphere are limited (Graber *et al.* 1998; Rogiers *et al.* 2005; Hammerle *et al.* 2007; Ammann *et al.* 2007; Soussana *et al.* 2007; Gilmanov *et al.* 2007; Cernusca *et al.* 2008) and have not yet been integrated over an elevational range that follows the traditional three-stage grassland farming system ("Alpage" in French or "Alpwirtschaft" in German, combined mountain agriculture; see Boesch 1951; Ehlers and Kreutzmann 2000) applied in the Alps. In contrast to nomadism and transhumance, this is a form of agricultural economy where the pastures, meadows, and croplands at various elevations are strongly connected in an economic unit of a farmer or group of farmers (Boesch 1951; Weiss 1959). Alpine pastoralism is another term found in the scientific literature (Potthoff 2004). The terminology is not very strict, and in reality there is a large diversity of such production systems, for instance in the Alps (Boesch 1951), in Norway (Potthoff 2004) and in other mountainous parts of Europe, including the Caucasus (Weiss 1941). In Switzerland, the animals are kept at the lowest elevation in the valleys in winter time, and the cattle is fed mostly with hay and grains that are kept in the main farm buildings (Michna *et al.* in review; Boesch 1951). Where possible, the area around the farm houses is also used as winter pasture. When the growing season starts, the fodder stocks from the previous year typically come to an end and the cattle are driven up to the second level of pastures and meadows, the so-called Maiensäss elevational belt. When the snow has disappeared from the higher areas, the cattle are moved to the Alpine pastures where they stay during the short summer (roughly three months in Switzerland, Michna *et al.* in review). The key distinction from nomadism and transhumance is the relevance of the Alpine summer pastures in the overall agronomic production system as an important fodder base of the farm (Weiss 1959; Boesch 1951). Without the seasonal movement of cattle from the farms in the valley bottom up the mountains, the local climate would not allow to support the livestock in such Alpine areas (Weiss 1959, p. 218).

Our goals were thus (a) to quantify and compare the response of grassland ecosystem CO_2 exchange to the change in environmental conditions with elevation; (b) to investigate the influence of weather changes, in particular weather extremes, on the grassland ecosystem CO_2 exchange; and (c) to quantify the change in carbon balance of these grasslands in relation to the Swiss farming practice. In order to achieve these goals, we investigated the net ecosystem exchange of CO_2 of three managed agricultural grasslands along an elevational gradient from pre-alpine farmlands to alpine pastures in Switzerland.

Methodology

To address these goals, three research locations have been identified covering the traditional three-stage grassland farming system of Swiss managed grasslands (400–2500 m).

Field sites

At ETH Zurich, the traditional Alpine farming system is represented by three agricultural research stations: Chamau (CHA, 400 m a.s.l.) represents the valley bottom winter location, Früebüel (FRU, 1000 m a.s.l.) the Maiensäss belt and Alp Weissenstein (AWS, 1950–2400 m a.s.l.) represents the alpine level (Eugster and Zeeman 2006; Eugster and Leuenberger 2007; Hiller *et al.* 2008). These locations lie on a geographic transect from central Switzerland to the Swiss canton Grisons (Graubünden in German) in the south-east of Switzerland and follow an elevational gradient. Chamau (8°24'38' E, 47°12'37'' N) is located in a pre-Alpine broad river valley of the Reuss river, Früebüel (8°32'16'' E, 47°6'57'' N) is situated on an undulating plateau of the Zugerberg, a sub-Alpine mountain east of lake Zug, and the site at Alp Weissenstein (9°47'25'' E, 46°34'59'' N) is situated on a south slope of an Alpine dry valley in the Albula mountain range, close to the Albula pass. The research stations have been assigned by the Swiss government for research, and have been under ETH management since 1954, 1989 and 1967 for Chamau, Früebüel and Alp Weissenstein, respectively. The dominant vegetation for Chamau is a mixture of Italian ryegrass (*Lolium multiflorum*) and white clover (*Trifolium repens*), predominantly used for fodder production and occasional winter grazing by sheep. At Früebüel, the species mixture consists of ryegrass (*Lolium* sp.), meadow foxtail (*Alopecurus pratensis*), cocksfoot grass (*Dactylis glomerata*), dandelion (*Taraxacum officinale*), buttercup (*Ranunculus* sp.) and white clover (*Trifolium repens*), which cover up to 90% of the surface (Sautier 2007). The alpine pastures of the Alp Weissenstein site are classified as *Deschampsio cespitosae-Poetum alpinae* community with red fescue (*Festuca rubra*), Alpine cat's tail (*Phleum rhaéticum*), white clover (*Trifolium repens*) and dandelion (*Taraxacum officinale*) as dominant species (Keller 2006).

Instrumentation

At each of these sites, a micrometeorological tower has been set up with the purpose of measuring environmental variables and carbon dioxide fluxes by applying the Eddy Covariance (EC) method (Kaimal and Finnigan 1994; Aubinet *et al.* 2000; Baldocchi *et al.* 2001). The setups at Chamau and Früebüel have been established in early summer 2005 using the same instrumentation at both sites. The EC measurement setup consisted of a three dimensional sonic anemometer (model Solent R3, Gill Instruments, UK) and an open path Infrared Gas Analyzer (IRGA, Li-7500, Li-Cor, Lincoln, NB, USA). The EC sensor separation was 0.25 m, and the IRGA was tilted to the north to prevent incidence of direct solar light. The centre of the sonic anemometer axis was at 2.41 m and 2.55 m for Chamau and Früebüel, respectively. The 20 Hz time resolution data were stored on a field PC for post-calibration and later analysis. Measurements of environmental variables have been made each 10 seconds for air temperature and relative humidity (at 2 m, a shaded, sheltered and ventilated HydroClip S3, Rotronic AG, Bassersdorf, Switzerland), photosynthetic photon flux density (PPFD, at 2 m, PAR LITE, Kipp & Zonen B.V., Delft, Netherlands), incoming and outgoing short and longwave radiation (at 2 m, a ventilated CNR1, Kipp & Zonen B.V., Delft, Netherlands), soil heat flux (at -0.03 m, n=2, model HFP01, Hukseflux B.V., Delft, Netherlands), soil temperature (installed horizontally at -0.01, -0.02, -0.04, -0.07, -0.10, -0.15, -0.25, -0.40 and -0.95 m, TB107, Markasub AG, Olten, Switzerland), soil humidity (installed horizontally at -0.05, -0.15, -0.25, -0.40 and -0.75 m, ML2x, Delta-T Devices Ltd., Cambridge, United Kingdom) and sum of precipitation (Type 10116, Toss GmbH, Potsdam, Germany). These environmental variables were processed into 30 minute averages (or sums for precipitation) and stored on a field logger (CR10X-2M, Campbell Scientific Inc., Logan, USA) and a field computer. A wire fence (about 1 m high) perimeter of 5 × 5 m was placed around the instrumentation to prevent access to grazing livestock. A ventilated metal cabinet (about 1.3 m high) gave shelter to field logger, field computer and communication controllers for the EC system, access to mains power supply and the internet. The cabinet was located orthogonal to the main wind direction and to the north side of the fence to minimise disturbance of the wind field and to prevent influences through shading.

The EC setup at Alp Weissenstein has been run on campaign base (Hiller *et al.* 2008) as the site becomes inaccessible in winter due to snow and avalanches. The EC instrumentation at Alp Weissenstein consisted of a three dimensional sonic anemometer (model Solent R2, Gill Instruments, UK) and an open path IRGA (Li-7500, Li-Cor, Lincoln, NB, USA). The EC data was stored using a portable digital assistant (PDA, a handheld computer), a similar system as described by van der Molen *et al.* (2006). The environmental conditions have been measured at Alp Weissenstein with two different sets of instruments in 2006 and 2007. In 2006, the instruments were installed between 23 June and 21 September. Environmental variables were measured each 10 seconds for air temperature and relative humidity (at 2 m, a shaded, sheltered HydroClip S3, Rotronic AG, Bassersdorf, Switzerland), photosynthetic photon flux density (at 1 m, PAR LITE, Kipp & Zonen B.V., Delft, Netherlands), incoming and outgoing short and longwave radiation (at 1 m, heated in morning hours with high relative humidity to evaporate dew, CNR1, Kipp & Zonen B.V., Delft, Netherlands), soil heat flux (at -0.02 m, n=3, model CN3, Middleton Solar, Melbourne, Australia,), soil temperature (at -0.05 m, TBMS1G, Campbell Scientific Inc., Loughborough, UK) and sum of precipitation (TE225-LC, Texas Electronics, Dallas, TX, USA). These environmental variables were processed into 10 minute averages (or sums for precipitation) and stored on a field logger (CR10X-2M, Campbell Scientific Inc., Logan, UT, USA). In 2007, the setup was installed between 25 April and 6 November, and measurements of environmental variables were made each 30 minutes for air temperature and relative humidity (TRH-100, Pace Scientific Inc., Mooresville, NC, USA), soil temperature (0.05 m, PT940, Pace Scientific Inc., Mooresville, NC, USA) and PPFD using a solar cell (as described by Vonlanthen *et al.* 2006). An alternative meteorological measurement setup, installed at about 980 m distance east and at approximately 45 m higher elevation, was operational during the whole 2006 and 2007 seasons. This additional setup provided alternative 30 minute means of air temperature (at 2.50 m), incoming shortwave radiation (at 2.50 m, SP Lite, Kipp & Zonen B.V., Delft, Netherlands), soil temperature (at -0.05 m, TB107, Markasub AG, Olten, Switzerland) and sums of precipitation (not heated LC, Texas Electronics, Dallas, USA), which were used for comparison and post-calibration. The PPFD measurements for Alp Weissenstein in 2007 are post-calibrated based on a regression of PPFD data with pyranometer measurements from the setup ≈980 m east of the EC setup. The regression between the PPFD and the pyranometer measurements of 2006 is used as a conversion factor of 1.95 to PPFD. No correction was made to compensate for the difference in measurement height above the surface between 2006 and 2007 at Alp Weissenstein (e.g. for air temperature).

Flux calculations and corrections

The EC method combines high time resolution wind vector and scalar (e.g. a concentration) measurements to calculate period averaged turbulent fluxes and has a proven robustness for intercomparisons across climate zones and biomes (Baldocchi *et al.* 2001). The net CO_2 flux (F_N) calculation by EC is defined as

$$F_N = \rho_a \overline{w'c'} \qquad \text{(Eq. 1)}$$

where the overbar denotes temporal averaging (typically 30 minutes), the primes denote the variation from the mean, and ρ_a, w and c denote the air density, the vertical wind speed and the CO_2 concentration, respectively. In the derivation through Reynold's Decomposition the assumption is made that the mean vertical flow and density changes are negligibly small.

The net CO_2 flux can also be expressed as the sum of the assimilation flux (F_A) and total ecosystem respiration (F_R) and becomes

$$F_N=F_A+F_R. \qquad \text{(Eq. 2)}$$

On a diurnal scale, nighttime F_R can be estimated from F_N measurements by EC, while F_R occurs together with F_A during the day. Here we use a light-response function (Falge *et al.* 2001) to model F_A and a respiration-temperature function (Lloyd and Taylor 1994) to model F_R for the different harvest intervals over a season (Ammann *et al.* 2007).

The respiration-temperature model for F_R is defined as (Eq. 11 in Lloyd and Taylor 1994)

$$F_R = F_{R,ref} \cdot \exp\left[E_0 \cdot \frac{1}{T_{ref} - T_0} - \frac{1}{T_{soil} - T_0}\right] \qquad \text{(Eq. 3)}$$

where $F_{R,ref}$ is the respiration at a reference temperature T_{ref} (T_{ref}=283.15 K), T_{soil} is the soil temperature in K (typically at 5 cm depth), T_0 is a temperature between T_{soil} and 0 K (e.g. T_0=227 K), and E_0 is a fit parameter for the activation energy (i.e. 308 K). The model is parametrised using only nighttime data for T_{soil} and F_N (as $F_{N,night}$=$F_{R,night}$). Besides $F_{R,ref}$ and T_0, E_0 can also be included in the optimization of the model.

The light-response model for daytime assimilation is defined as (Eq. A.9 in Falge *et al.* 2001)

$$F_A = \alpha \cdot \frac{Q_{PPFD}}{\left(1 - \frac{Q_{PPFD}}{2000}\right) + Q_{PPFD}\left(\frac{\alpha}{F_{A,opt}}\right)} \qquad \text{(Eq. 4)}$$

where α denotes the ecosystem quantum yield (i.e. the flux of CO_2 per flux of photons, µmol m^{-2} s^{-1} · (µmol m^{-2} s^{-1})$^{-1}$), Q_{PPFD} denotes the photosynthetic photon flux density (µmol m^{-2} s^{-1}), and $F_{A,opt}$ represents the assimilation rate at optimal light conditions. The model is parametrised for α by determining F_A from Eq. 2 using measurements of F_N and model estimates for F_R in daytime conditions using Eq. 3. From this F_A also $F_{A,opt}$ is determined for optimal daytime conditions with a clear sky (Q_{PPFD}>1200 µmol m^{-2} s^{-1}) and a well developed canopy (i.e. the days just before a harvest).

Post-calibration of the IRGA CO_2 and H_2O concentrations was performed based on periodic measurements of standards. Fluxes of CO_2 and H_2O were calculated for 30 minute periods using the *eth-flux* flux analysis tool (Eugster and Senn 1995; Mauder *et al.* 2008) and R for statistical analysis (R Development Core Team 2008). We applied a 2-dimensional coordinate rotation for the wind vector for each averaging period, for a rotation into the mean stream line and an alignment of the vertical to yield $\overline{w} = 0$. The time series for the sonic anemometer and IRGA were shifted for each calculated mean to correct for timing differences between the EC sensors and the sensor separation. Post-calibration of the flux data consisted of a dampening loss correction (following Eugster and Senn 1995) and a correction for the effects of water vapour transfer (Webb *et al.* 1980).

The resulting CO_2 flux data was screened for conditions with high window dirtiness of the IRGA sensor (>70%), for out of range flux values ($|F_N|$>50 µmol m^{-2} s^{-1}), for $\overline{u'w'}$<0 m s^{-1} and for low friction velocity (u_*<0.08 m^2 s^{-2}). We further tested stationarity and turbulent conditions following Foken and Wichura (1996). The stationarity test was based on a comparison of the 30 minute averages for CO_2 and H_2O fluxes with 5 minute averages of the fluxes for the same period. The turbulent conditions were tested by comparing a theoretic value for flux similarity (using Obhukov length) with empirical values. The flux similarity was calculated as dimensionless number from the square root of vertical wind speed variance (σ_w) and the friction velocity (u_*) as $\sigma_w u_*^{-1}$. For both the stationarity and similarity test, the data were kept if <30% (high quality) or 30–100% (good quality) deviation is encountered from the respective references. For the assessment of F_A (Eq. 4) and F_R (Eq. 3), only data flagged as high and good quality were used.

Data coverage of the environmental variables required for the gapfilling procedure was required, at all sites (>99% of the time covered) and therefore provided a good base for the models used for F_A, F_R and the gapfill procedure for F_N. The missing values for the soil temperature and PPFD were gapfilled in two steps. We applied a linear interpolation for gaps ≤4 values (≤2 hours). Then we applied a gapfilling through diurnal (per time of day) averaging within a four day moving time window for each time of day. Data coverage of the CO_2 exchange data after omission of bad data is 57%, 59% and 41% for Chamau, Früebüel and Alp Weissenstein, respectively. The lower data coverage at Alp Weissenstein can be explained by the use of a less refined data rejection procedure for these data, due to the absence of digital status information of the open path IRGA for post processing. On the other hand, most of the rejection for Chamau and Früebüel was related to low turbulence conditions, specifically with low u_*.

The gapfilling procedure for missing values of the net CO_2 flux is based on application of the temperature-respiration (Eq. 3) and light-response (Eq. 4) functions. Missing data were gapfilled in three time steps, from parametrisation in a four day moving window to a periodic parametrisation to a parametrisation based on seasonal values. To achieve this, first the model parameters for $F_{R,ref}$ were determined for a whole period (typically seasonal) and per harvest interval. These parameter values were used as initial values for a four day moving window model parametrisation for $F_{R,ref}$ and subsequent prediction of missing values for F_N, nighttime F_R and daytime F_R. If no suitable model could be determined from the four day moving time window, the harvest interval parameter values were used, and if necessary, followed by seasonal predictions. Second, the F_R data were combined with the available F_N data to calculate F_A, α in low to moderate light conditions ($10<Q_{PPFD}<400$ µmol m^{-2} s^{-1}) and

$F_{A,opt}$ in high light conditions (Q_{PPFD}>1200 µmol m^{-2} s^{-1}), considering only the last eight days before the grass cut for each harvest interval. Again, model parametrisation was based on a four day moving time window to predict F_A values, and – where required – harvest interval or season parameters were used for the light-response function. The approach resulted in a gapfilled time series for F_N, a partly measured and partly modelled time series for F_R and a modelled time series of for F_A, which were adapted to rapidly changing conditions during the harvest intervals throughout the season. Soil moisture did not add an obvious constraint to F_N and this adding support to use of a temperature-respiration model that did not include soil moisture as an explicit variable, in contrast to Reichstein *et al.* (2003). This was in line with the findings by Wohlfahrt *et al.* (2005) for respiration fluxes of an Austrian alpine meadow.

The closure of the energy budget was used as a quality measure of the EC measurements, based on the comparison (see e.g. Aubinet *et al.* 2000; Foken 2008)

$$Q_* - Q_G = Q_E + Q_H \quad \text{(Eq. 5)}$$

in which net radiation influx (Q_*) minus soil heat flux (Q_G) are related to the components latent heat flux (Q_E) and sensible heat flux (Q_H). Soil heat flux was corrected for the storage of heat above the sensor using an adaption of the method suggested by Oke (1987),

$$\Delta S = c_v \cdot \frac{\Delta T_{soil}}{\Delta t} \cdot (z_d - z_0) \quad \text{(Eq. 6)}$$

where T_{soil} is the average soil temperature above the soil heat flux sensor (n=3), t is time, z_d is the sensor depth, z_0 is the surface (z_0=0). Here, the volumetric heat capacity c_v is estimated following De Vries (1963), using the volumetric soil moisture at 0.05 m depth and the fraction of bulk density over particle density as mineral fraction. Bulk density values at the field sites are 1.0·10^{-3} kg m^{-3} for Chamau and Früebüel based on laboratory estimates (Roth 2006). Particle density is taken as 2.65·10^{-3} kg m^{-3} (White 2005), resulting in an estimate for mineral fraction of 37%. The energy budget closure calculated for the whole measurement period for Chamau and Früebüel were 81% and 78%, respectively. These results were comparable with other eddy covariance measurement sites on less complex terrain (e.g. Wilson *et al.* 2002). The applicability of the eddy covariance method at the complex terrain of the alpine sites was facilitated by a strongly developed valley wind system, as has been shown by Hiller *et al.* (2008) for Alp Weissenstein.

Management data

To quantities the volume of harvested biomass and applied manure, the official farm management “LBL Feldbuch” data were used. The carbon content of harvested biomass was determined for each harvest using sample plots at the same study area near the EC setups (Gilgen and Buchmann 2008). The harvest biomass was averaged for five or more replicates of 0.20 m^2 sample plots and was considered representative for the respective reference field, which is FG5 at Chamau and Schutzwiese at Früebüel (Fig. 1). In addition, slight differences between the fields in the footprint area needed to be taken into account for the determination of the carbon amounts per unit area (g C m^{-2}). Therefore, a scaling factor was determined combining amounts of carbon per biomass and the reported volume of the harvest for the reference fields, or in case of the second harvest interval of Früebüel 2007, a scaling factor per grazing cow was calculated. From these scaling factors, the field sizes and the harvest volumes (or cattle numbers) reported by the farmer, the carbon content per harvest (in g C m^{-2}) was determined for the other fields in the EC footprint.

The amount of carbon in the applied manure was calculated based on the average dry weight (DW) and organic carbon content (C_{org}) of samples from Chamau taken in 2007 (liquid manure, DW=3.85 ± 0.95%, C_{org}=461 ± 21 g kg^{-1}, n=8) and from Früebüel in 2006 (dung, DW=27.82%, C_{org}=451 g kg^{-1}, n=1). The method for sampling of the liquid manure and solid manure differed. Liquid manure was sampled directly from the supply tube running into the field, just before application of the manure. This was possible by using an automated system that briefly diverted the manure flow to a 10 l container in regular intervals during the application process. From the collected manure in the container, a well mixed sub-sample was taken. By using this sampling procedure a representative sample was assured for the manure applied to each separate management field (Fig. 1), which would not have been possible by taking samples from the manure storage depot. The solid manure was sampled from the supply just before application. Both liquid and solid manure samples were analysed in an external, specialised laboratory. At Chamau, predominantly liquid manure was applied, except for one occasion on 6 March 2007. At Früebüel, one of the fields received lime mixed with soil on 15 October 2007, for which the organic carbon content was considered as carbon input.

Carbon budget

The carbon balance not only contains turbulent flux components, but also management inputs and outputs. The change in the carbon balance of a site due to turbulent exchange and management can thus be written as

$$\Delta C/\Delta t = F_N + F_i + F_o \qquad \text{(Eq. 7)}$$

where F_i represents the carbon inputs through management (i.e. application of manure, fertilizer or lime), and F_o represents the carbon outputs through harvest (i.e. grass biomass, and biomass increase of grazing livestock). For an accurate comparison of carbon input from manure and carbon output through harvested biomass to F_N, the values were weighted by percentage of time each field in the footprint contributed to the F_N measurements. This percentage was determined from the wind direction data of the EC setup.

Results and discussion

The three sites differed strongly in their overall climatic conditions as well as in the seasonal course of climatic parameters. With increasing elevation, the average temperature decreased and the growing season became shorter (Table 1). The period 2005–2008 included two exceptionally warm years, namely 2006 and 2007, but also exceptionally cold and mild winters, 2005–2006 and 2006–2007, respectively. The cold winter of 2005–2006 was followed by a record warm July 2006. The warm winter 2006–2007 was followed by an early spring and summer in 2007, and with frequent precipitation in summer and autumn, 2007 became a record warm year (MeteoSwiss 2006, 2007, 2008).

At Chamau, this weather pattern resulted in high levels of available light (PPFD) and dry soil conditions in July 2006, which also dramatically affected mean soil temperature and the amplitude of soil temperature until a cool period with precipitation came in August 2006 (Fig. 2). The temperatures in winter 2006–2007 were on average well above freezing for both air and soil. In April 2007, soil conditions were again dry but contrary to July 2006, temperatures did not rise as high. The pre-alpine region is known for fog conditions, which created a difference in available light (PPFD) compared to higher elevations, but predominantly in the months outside the growing season (Fig. 2e).

At Früebüel, the conditions in July 2006 resulted in a temperature rise and steep decline in soil moisture, but these were moderated by elevation and higher amounts of precipitation in the month before. Soil moisture recovered in the months thereafter with higher levels of precipitation compared to the other sites (Fig. 2). The air and soil temperatures during the 2006–2007 winter at Früebüel are distinctly different from the other winters, which is especially clear from the course of soil temperatures. The course of the soil temperature in the 2006–2007 winter is also a clear indication that a snow cover was only present intermittently and for short periods.

At Alp Weissenstein, soil temperatures were influenced by snow cover and increased rapidly after snow melt. Nevertheless, snow cover influenced growing season length. Due to the elevation, warm periods such as in July 2006 did not cause high temperatures in air and soil, but cool periods such as in August 2006 brought critically cold conditions during the growing season, with temperatures close to freezing and snowfall. The orographic locality in a dry alpine valley can be recognised from the precipitation amounts, which were generally lower than those at the subalpine site Früebüel, despite its higher elevation.

If we compare the conditions between the year 2006 and 2007 for all three sites, the difference in mean annual temperature changed the most for Chamau. At Chamau, the number of days with average temperature above 5 °C increased by 19 days to 264 days (Table 1), which is high compared to the reported average of a grassland site at comparable elevation and latitude (244 days for Oensingen, Switzerland, 450 m a.s.l. according to the GREENGRASS synthesis Soussana *et al.* 2007). At Früebüel and Alp Weissenstein, this increase was only 3 and 5 days, while for instance at Früebüel the increase in average air temperature was the same (0.5 °C, Table 1) as for Chamau. For all three sites, there was ≈100 mm more precipitation recorded in 2007 compared to 2006 (Table 1).

This pronounced difference between 2006 and 2007 can also be seen in the net CO_2 exchange of our sites (Fig. 3). The start of the growing season differed between the two years: the turning point when daily uptake of CO_2 exceeded daily release started about 65 and 15 days earlier in 2007 compared to 2006 for Chamau and Früebüel, respectively. At Chamau, this early start in 2007 already in July was followed by a period with continuous net CO_2 release. This resulted in nearly the same annual sum of F_N in 2007 compared to 2006 (Table 2). For Früebüel, the shape of the seasonal pattern in cumulative carbon exchange for 2006 were comparable to 2007, but due to the early start of the growing season resulted in a larger sum of annual CO_2 uptake (Table 2).

In the periods of overlapping data coverage for all three sites, the cumulative carbon uptake was higher at Alp Weissenstein and similar to that of Früebüel (Table 2).

For 2007, the comparison was made based on modelled F_N for 45 consecutive days during the season (6 April to 15 September 2007). The sums of F_N were nevertheless in the same order of magnitude as in 2006 for which a shorter, but continuous dataset was available for Alp Weissenstein. Taken altogether, we observed that with increasing elevation the relative decrease in F_R was stronger than the relative increase in F_A, hence the sum of F_N showed an increased CO_2 uptake with elevation (Table 2).

In mid-season (July and August), the daily cumulative fluxes were similar on all three sites after the initial recovery following harvest and manure application, as can be seen from the slope of the curves for cumulative flux at the end of each harvest interval (Fig. 5). This is supported by the cumulative sums of fluxes for overlapping measurement periods in summer of the years 2006 and 2007, but contradicting to the annual sums of net CO_2 fluxes (Table 2). This indicates that management intensity has a strong effect on F_R and therefore also on the cumulative F_N, especially when integrated over longer periods (e.g. several harvest intervals).

The three sites are located along an elevational gradient where not only climatic but also management factors differ substantially. While Chamau is harvested 6-7 times, Früebüel is harvested 2-4 times, and Alp Weissenstein is harvested 1-2 times. For all three sites, the management decisions and thus the timing of harvest, manure application or grazing, is clearly influenced by climate, e.g. by the early season start of the growing season and its length, as can be seen in the occurrences of management over the course of both years (Fig. 4a). At Chamau, manure is applied throughout the season, typically within days after harvest and whenever possible during winter to ascertain that the manure stock does not reach the farm's storage limits (Fig. 4b). In the winter of 2006–2007, more grazing was required to manage the farmland at Chamau, as harvest was not feasible due to the wet soil conditions (Hans Leuenberger, ETH Chamau, pers. comm.), while high temperatures were favourable for growth. The intensity of manure application during the 2006–2007 winter was also higher than in the 2005–2006 and 2007–2008 winters. For Früebüel, the intensity of the manure application was much lower, typically only 1 to 2 times per year, as less manure was available. Although the number of harvests was the same for 2006 and 2007, the difference in duration of the harvest intervals was increased by a factor of about 2 from 2006 to 2007. At Alp Weissenstein, no manure was added, and only one harvest was made as late in the season as possible. For 2006, the occurrence of a cold period with snow fall required a harvest in late July, while in 2007 this harvest was delayed until October.

At each event of grass cut and subsequent manure application, the balance in cumulative (and thus diurnal) F_N shifted towards CO_2 release. This is clearly seen for example at Chamau, where it takes up to two weeks for the ecosystem to recover, thus before the net cumulative loss changed back to a net cumulative (and diurnal) uptake of CO_2 (Fig. 4), while at Früebüel assimilation typically was equal to or exceeded respiration within days after the harvest (Fig. 6). Although these patterns were variable over the growing season, they did not follow a temporal trend. However, the expected increase of respiration due to manure inputs is not visible in the ratios of F_A over F_R after application. Manure application is often made when light rain is forecasted, hence coincides with conditions where EC data are poor and thus need to be discarded. We therefore suspect that the gap filling for the period of manure application introduced a smoothing that masked the short term response of F_R to manure input, even if a small moving window of four days was used. Summarising, management strongly influenced the annual balance of net CO_2 fluxes. Particularly the intensity of manure application is highly relevant as observed most clearly at the intensively managed lowland site Chamau.

Based on those strong implications of management on net CO_2 fluxes, budget calculations need to take into consideration the timing of management practices as well as inputs of carbon (F_i; manure inputs) and outputs of carbon (F_o; harvest output) for each management interval separately (Eq. 7). During the period of 2006–2007 carbon stocks increased by ≈220 g C m^{-2} and ≈120 g C m^{-2} for Chamau and Früebüel, respectively (Fig. 7). However, while the increase in carbon stock for 2006 was ≈60 g C m^{-2} for Chamau and Früebüel, the increase in 2007 was 150 g C m^{-2} and 60 g C m^{-2} for Chamau and Früebüel, respectively. At Chamau, manure inputs and application intensity were high as application occurred after most harvests and during winter. These inputs did not respire immediately and were not converted into the biomass of the next following harvest, but showed a timelag within the year and to the next year. For Chamau the differences in management between the fields adjacent to the measurement setup were minimal and the carbon fluxes should therefore be a good representation. At Früebüel, management within the EC footprint was very heterogeneous, but at the same time, this site represents typical conditions in mountain grassland ecosystems, where management practices are generally adapted to small-scale variations in topography, microclimate and soil fertility conditions. Less manure was applied due to the dominance of pastoral grazing, and manure was applied in solid form for which it was more difficult to obtain representative estimates of C contents compared to liquid manure. In addition, the fields border a natural reserve, for which by recent legislation a perimeter of land was required (a so called «Ökologische Ausgleichsfläche», a zone assigned to an agri-environmental scheme of reduced management intensity) where no management was allowed until July (2006) or until mid July (2007). The values are however the best available estimates. If we examine the information on carbon fluxes, changes in carbon stock, the management patterns and weather changes, we see that farmer's management strongly adapts to any changed weather situation. By doing so, management strongly influences the resulting patterns in the carbon flux and stock. This is inherent to the timing of management and practice of the farmer, who will prefer to harvest in good weather and apply manure when rainy weather is expected.

While the harvest output flux (F_o) is well constrained by measurements, additional output fluxes such as DOC loss, non-CO_2 greenhouse gas fluxes (e.g. VOC, CH_4) and harvest losses are not. However, DOC and non-CO_2 greenhouse gas losses are expected to be small (Rogiers *et al.* 2008). The loss through leaching of dissolved organic carbon (DOC) between October 2006 and May 2008 was estimated for Früebüel to be about 5 g m^{-2} a^{-1} for the A+B horizon (Kindler, Siemens, Heim, Schmidt and Zeeman, unpubl. data). Similarly, bias due to harvest loss seems negligible as well. The amount of biomass per unit area sampled by us might differ from the amount of biomass per unit area harvested by the farmer, due to the lack of harvest losses in the biomass samples taken manually. Thus, the difference in harvest methodology might introduce inaccuracies in the overall carbon balance, but the carbon of the decomposing harvest is already accounted for with our measurements of net ecosystem CO_2 flux. Furthermore, since harvest loss is controlled by the efficiency of farm machinery and this machinery was not changed or modified during our measurement period, we can assume harvest loss to be similar for each harvest. Thus, we conclude that the carbon stock changes estimated for the two sites are based on the best information available.

This conclusion is supported by the fact that our results for F_N and C compare well with other recent studies of managed grasslands in Switzerland. At the CarboEurope site Oensingen (OEN-1), an intensively managed grassland at 450 m a.s.l. in northern Switzerland, Ammann *et al.* (2007) found a net sequestration of 147 ± 130 g C m^{-2} for the years 2002 to 2004. Although the Oensingen grassland is intensively managed, it receives less manure inputs (about 21 and 59 g C m^{-2} during 2002–2004) than the Chamau site (319 and 417 g C m^{-2} in 2006 and 2007) at comparable elevation (Ammann *et al.* 2007), i.e. only about 15% of the amount applied at Chamau. The higher manure input at Chamau also explains the differences in annual sums of F_N, which are in the range of -215 to -669 g C m^{-2} for Oensingen (Ammann *et al.* 2007), about a factor of 2 to 7 larger compared to Chamau (Table 2).

Comparing an extensively managed grassland at Rigi Seebodenalp (1025 m a.s.l., approximately 7 km south-east of Früebüel) points at the importance of soil carbon. The Rigi Seebodenalp site showed a significant carbon loss during the years 2002 to 2004 (Rogiers *et al.* 2005, 2008), much in contrast to the carbon uptake at Früebüel in 2006 and 2007. This difference is not primarily a result of the summer 2003 heat wave, but mainly explained by the difference in soil properties between the two sites. Rigi Seebodenalp is located on a rich organic soil of a former lake bottom (Rogiers *et al.* 2008) with large CO_2 flux driven by peat decay (Leifeld *et al.* 2005), while Früebüel is located on a mineral soil (Roth 2006).

Finally the question arises, where does the carbon go? In grassland ecosystems, any carbon sequestration can only occur in the soil compartment. The soil organic carbon (SOC) stocks at Chamau and Früebüel are 55.5–69.4 t C ha^{-1} (n=2) and 39.4–60.4 t C ha^{-1} (n=2), respectively (Roth 2006). This is within the range determined for favourable grassland sites (50.7 ± 12.2 t C ha^{-1}) in Switzerland, as shown in an earlier national survey by Leifeld *et al.* (2005, n=544) for soil depth 0–0.20 m. The SOC stocks in the top soil (0–0.10 m) within the footprint area of Chamau and Früebüel have been determined as 32.9 ± 2.2 t C ha^{-1} (n=41) and 38.9 ± 5.7 t C ha^{-1} (n=44), respectively (Roth 2006). When we assume that most of the estimated carbon sequestration of the grassland ecosystems must be found in the soil, in particular in the Ah horizon, then the annual increase in carbon stocks for Chamau and Früebüel are on the order of 1–2% of top soil carbon.

Conclusions

Based on our measurements of F_N and our estimates of carbon sequestration of three grasslands within the traditional three-stage grassland farming system in Switzerland, we conclude that management practices strongly influence the carbon fluxes and the carbon budgets of these grasslands, with strong interactions with climatic conditions triggering management decisions. Carbon stock changes were similar for Früebüel and Chamau in 2006, but higher for Chamau in 2007, while both systems clearly were carbon sinks during 2006 and 2007, two very different but warm years. This provides also strong evidence that C stock can and must be managed adequately in the future, when climatic conditions not only affect carbon dynamics in soils and vegetation but also adaptive management of Swiss grasslands.

Acknowledgements

We would like to acknowledge Hans Leuenberger's key role in the establishment of the measurement site infrastructure and would like to thank him and Hans-Rudolf Wettstein for their support and guidance at the ETH Research stations. The authors would further like to thank Peter Luginbühl (ETH Chamau), Fritz Grunder and Pascal Notdurft (both ETH Früebüel), Saro Keith and Peter Frieden (both ETH Alp Weissenstein), Christof Ammann (Agroscope ART), Jürg Fuhrer (Agroscope ART), Ottmar Joos (Uni Zurich), Constant Signarbieux (Uni Bern), Pietro Panzacchi (Uni Bologna), Robert Finger (ETH Zurich), Irene Lehner (ETH Zurich), Johannes Fritsche (Uni Basel), Kristina Roth (Uni Zurich) and Sibylle Sautier (Uni Zurich) for fruitful discussions and assistance. We thank Natascha Kljun (ETH Zurich) for making the Fortran source code of her footprint model available to us. Patrick Flütsch (ETH Zurich) has provided essential technical support for the development and establishment of the sites. This work has been supported by the Swiss National Science Foundation (SNF), grant 200021-105949 (WE, MJZ) and by NCCR Climate, Project Plant/Soil (NB, AKG).

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Table 1: Climate variables for Alp Weissenstein, Chamau and Früebüel in 2006 and 2007, consisting of the sum of precipitation (P), mean annual air temperature (T_{air}) and days with average temperature above 5 °C as indicator for growing season length. For Alp Weissenstein, the rain gauge was not heated, causing an underestimation of the annual sum of precipitation for the period with snowfall.

		$\sum P$ [mm]	Mean T_{air} [°C]	Mean T_{air} > 5 °C [days per year]
2006	Alp Weissenstein (2000 m)	609[1]	2.4	149
	Früebüel (1000 m)	1649	7.2	231
	Chamau (400 m)	1136	9.5	246
2007	Alp Weissenstein (2000 m)	756[a]	2.2	142
	Früebüel (1000 m)	1764	7.7	234
	Chamau (400 m)	1232	10	265

[1] Only liquid precipitation (during the warm season, April–November).

Table 2: Cumulative sums of net ecosystem exchange (F_N), the modelled components of ecosystem assimilation (F_A) and ecosystem respiration (F_R), application of manure or liming (F_i) and harvest output (F_o) for Chamau, Früebüel and Alp Weissenstein. Annual sums are given only for Chamau and Früebüel. The 46 day gap in summer 2007 for the F_N of Alp Weissenstein were been modelled using a light-response and a temperature-response function that are parametrised using available F_N data, soil temperature and PPFD (see text).

		Flux sums [g C m^{-2}]				
Annual		F_N	F_A	F_R	F_i	F_o
2006	Früebüel (1000 m)	-165	-1756	1591	-108	208
	Chamau (400 m)	-81	-2304	2222	-256	326
2007	Früebüel (1000 m)	-300	-1796	1496	-167	414
	Chamau (400 m)	-94	-2566	2472	-408	372
Period[2][3]		F_N	F_A	F_R		
2006[a] (*n*=79 days)	Alp Weissenstein (2000 m)	-134	-500	366		
	Früebüel (1000 m)	-134	-750	616		
	Chamau (400 m)	-51	-874	823		
2007[b] (*n*=139 days)	Alp Weissenstein (2000 m)	-488[4]	-1171[c]	679[c]		
	Früebüel (1000 m)	-314	-1292	977		
	Chamau (400 m)	-9	-1470	1461		

[2] Only time period 2006-06-24 to 2006-09-11.

[3] Only time period 2007-04-26 to 2007-09-15.

[4] Modelled values for time period 2007-05-29 to 2007-07-14.

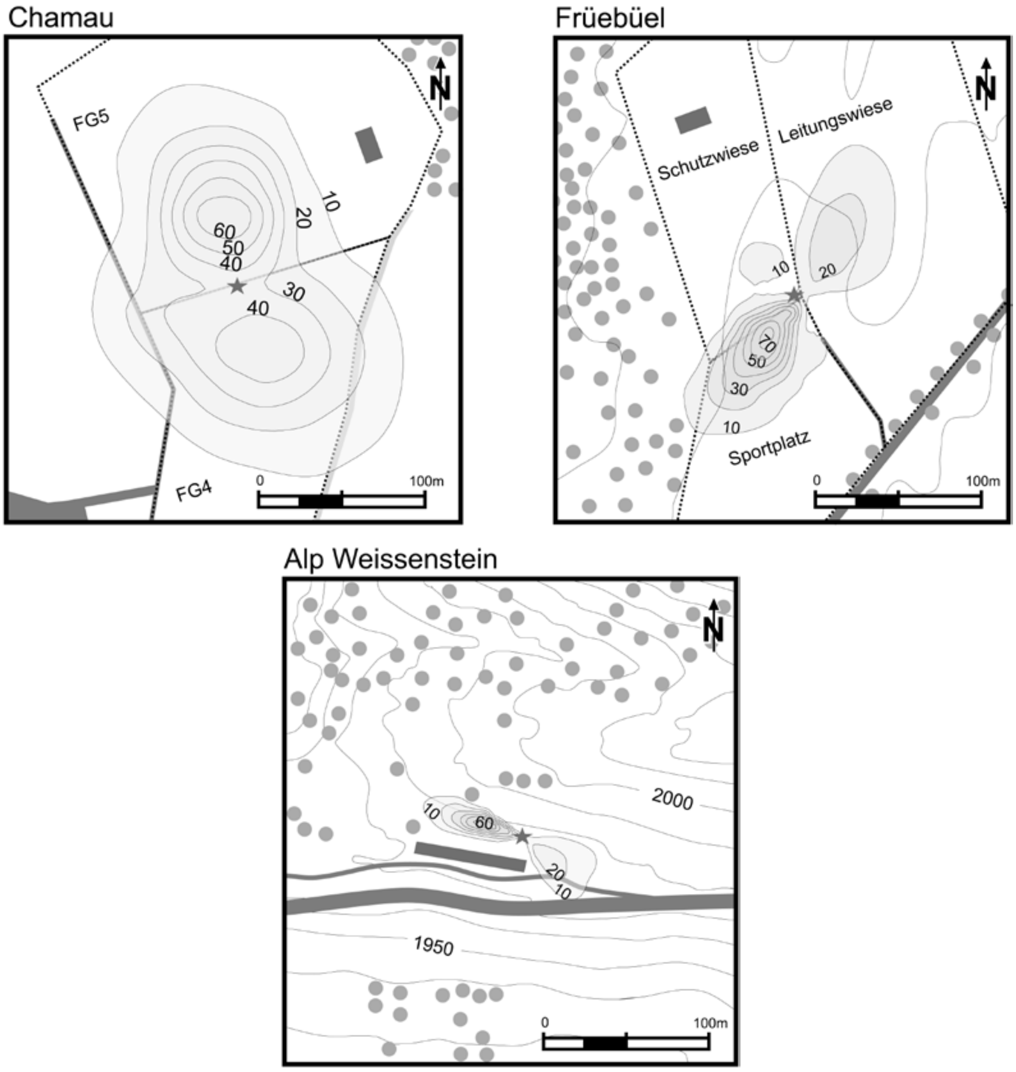

Figure 1: Flux footprint areas of the research sites at Chamau (top left), Früebüel (top right) and Alp Weissenstein (bottom). At Chamau, the EC setup (star) is located about 150 m north-northeast of the farm buildings complex, and the grass pastures are bordered to the east by forested area. The Früebüel EC setup is located about 200 m north east of the farm complex, and the managed pastures are bordered by forested peatlands to the west. The Alp Weissenstein EC setup is located about 500 m west of the Crap Alv farm complex, just north of the road to the Albula pass. The maps further show the location of the biomass sample plots (rectangle), the managed pastures adjacent to the setup (outlined with dashed lines) with their respective names, the contours of percentage influence for the calculated footprint (light gray areas, calculated with the Kljun *et al.* (2004) footprint model), roads and buildings (dark gray), trees (gray circles) and elevation (black lines). For Chamau, a small drainage canal with reed and bushes is marked east of the setup (light gray).

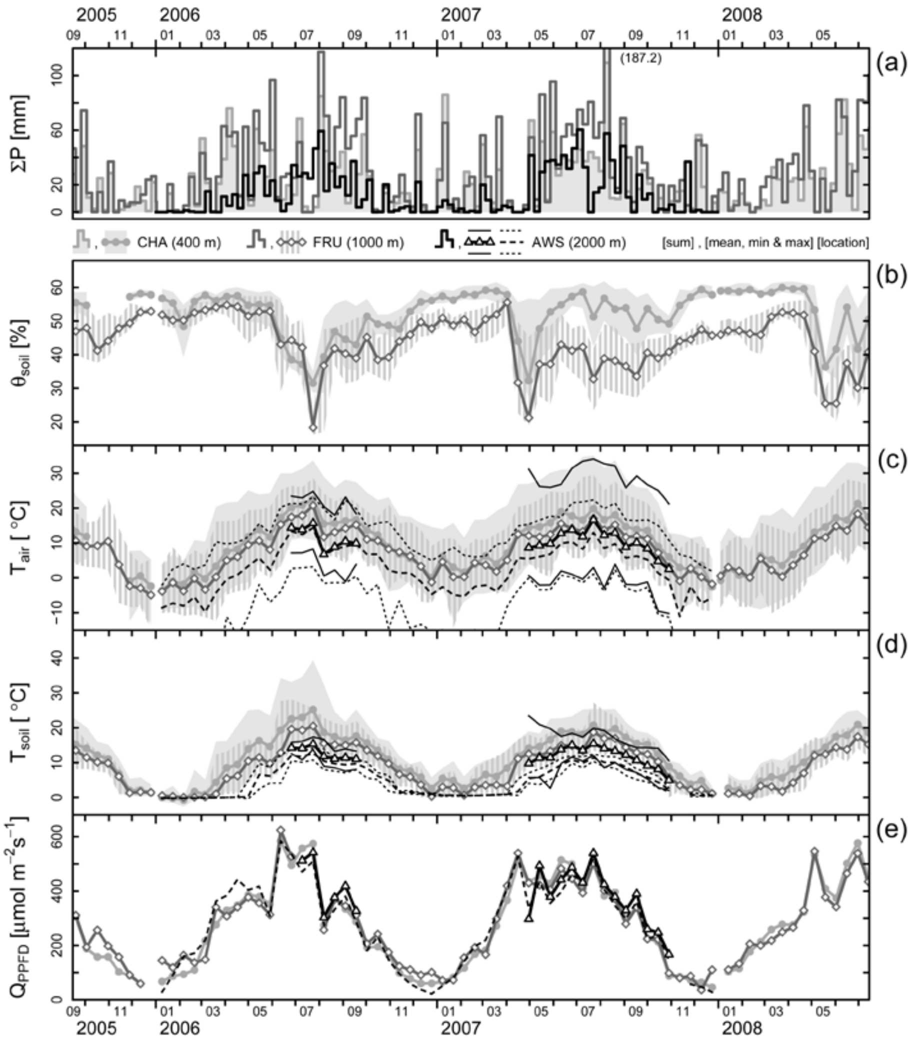

Figure 2: Summary of the environmental conditions at the three grassland sites Chamau (CHA), Früebüel (FRU) and Alp Weissenstein (AWS) in the period September 2005 to July 2008. The variables shown are (a) the weekly sum of precipitation ($\sum P$), the two week averages (b) of soil humidity (θ_{soil}), (c) of air temperature (T_{air}) and (d) of soil temperature (T_{soil}), and (e) the two week averaged daily (24 hour) mean PPFD (Q_{PPFD}). For Alp Weissenstein, seasonal air temperature and PPFD measurements are given for a measurement location about 980 m east of the EC setup, at approximately 45 m higher elevation (dashed lines).

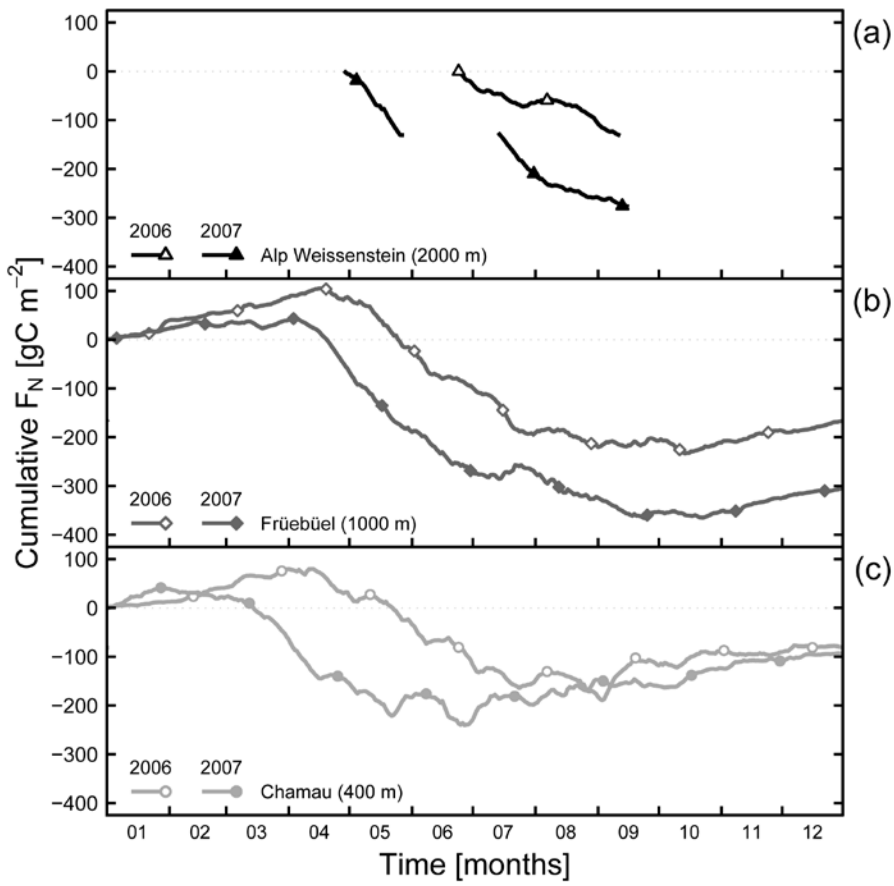

Figure 3: Comparison of the seasonal dynamics in cumulative turbulent flux of CO_2 for the three grassland sites (a) Alp Weissenstein, (b) Früebüel and (c) Chamau for 2006 and 2007. Each season starts with a positive flux (net respiration) and proceeds with a negative flux when assimilation exceeds respiration, until the ecosystem respiration exceeds assimilation again, close to the end of the growing season. The rate of net ecosystem exchange fluctuates throughout the season as a result of changes in environmental conditions and management events (e.g. grass cuts, application of manure, grazing) and hence also differs from one season to the next. The growing season in 2007 started earlier than in 2006.

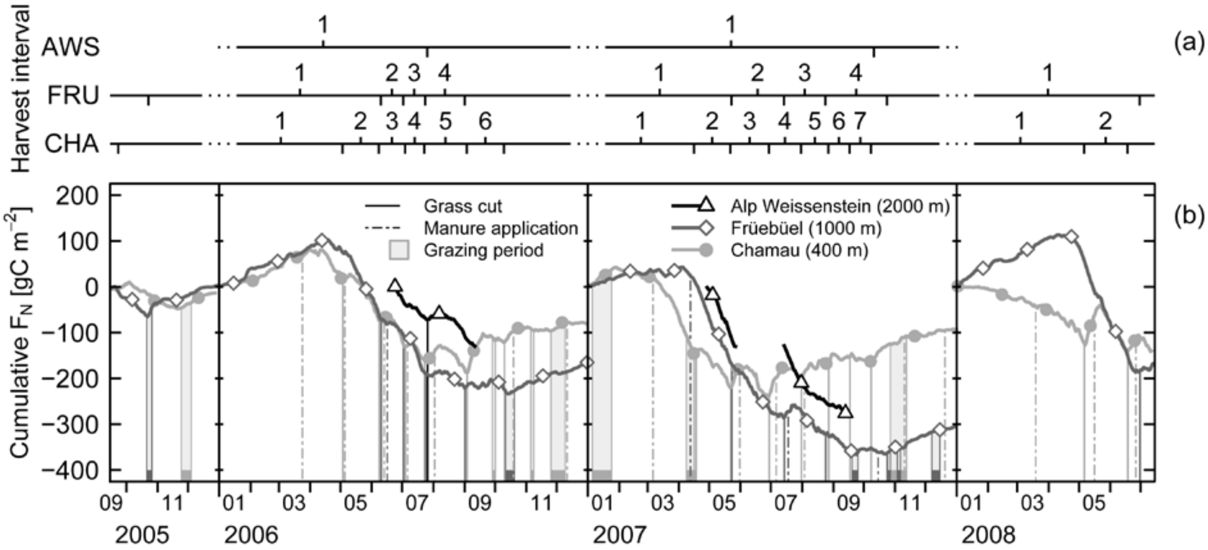

Figure 4: Seasonal dynamics of the cumulative net ecosystem flux of CO_2 (cumulative F_N) for the three grassland sites in relation to management events in the period September 2005 to July 2008. (a) The timing and duration of harvest intervals change from year to year as the farmer follows the environmental conditions and regrowth cycles, and adapts the intensity of management accordingly. These management events can be correlated with fluctuations in (b) the seasonal course of the cumulative F_N. Occurrences of manure application during the growing season are in general within days after the grass cut. Grazing by cattle or sheep took place in autumn and winter, and especially at Chamau 2006–2007 was used as a means to regulate regrowth during the warm winter.

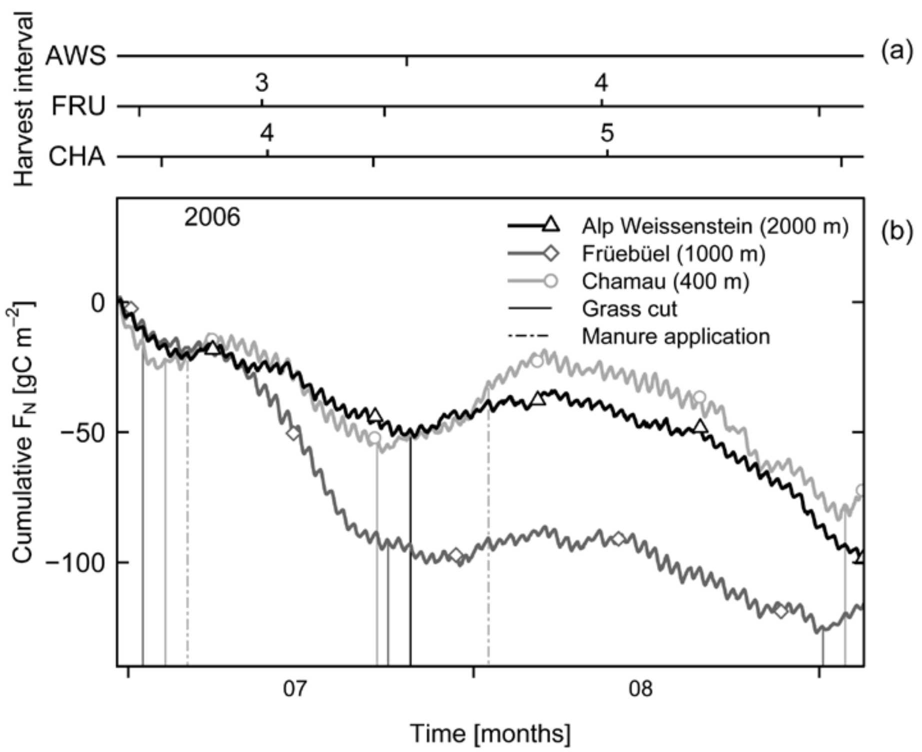

Figure 5: Seasonal dynamics of the cumulative net ecosystem flux of CO_2 (cumulative F_N) for the three grassland sites in relation to management events in July and August 2006. (a) The harvest intervals are given as reference to Fig. 4. (b) In mid season, the net diurnal cumulative change at all three elevations are similar, as indicated by the slope of the curves. The timing of harvest is similar among the sites, as well as the timing of manure application soon after harvest. See text for details.

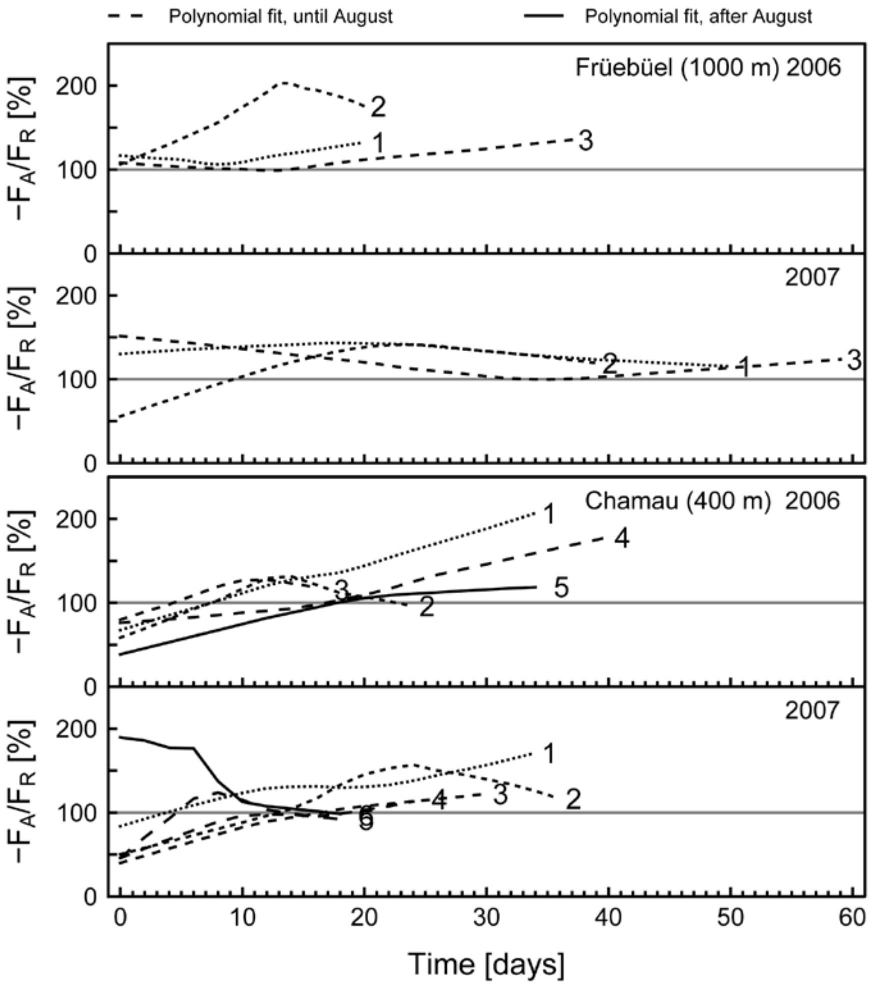

Figure 6: Ratios between assimilation F_A and respiration F_R over the course of each harvest interval, shown as smoothed polynomial fits for each harvest interval. When the relationship is above 100% (horizontal line), the ratio of fluxes indicates net ecosystem uptake of CO_2. For Chamau, the crossing of that threshold is visible for all harvest intervals, except for the last period of 2007. For Früebüel, the smoothed interpolations go below the 100% threshold only in the 2nd harvest of 2007. Note that the harvest intervals of 2007 in Früebüel were exceptionally long.

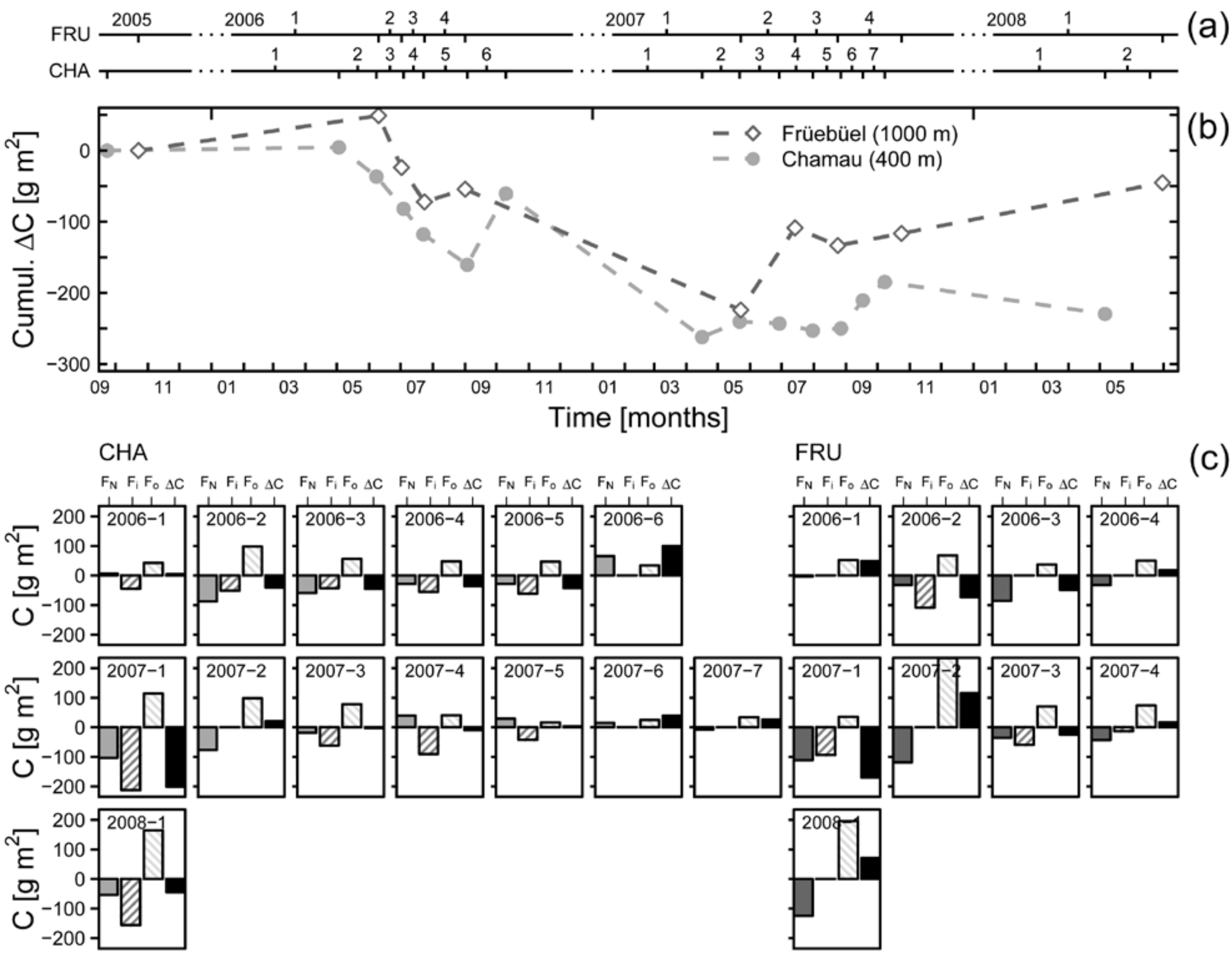

Figure 7: The net carbon stock change (Δ*C*) for Chamau (CHA) and Früebüel (FRU) from the last harvest in 2005 until the first harvest in 2008. The timing of each harvest (a) is linked to the cumulative CO_2 flux for each site (b), as calculated from the components of *C* (c). These components are the net totals of *C* per harvest interval for the net ecosystem exchange (F_N), manure and liming application inputs (F_i) and harvest outputs (F_o), which sum up to a *C* value per harvest interval.