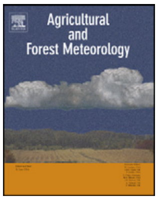
Agricultural and Forest Meteorology 150 (2010) 519–530

Contents lists available at ScienceDirect

Agricultural and Forest Meteorology

journal homepage: www.elsevier.com/locate/agrformet



Management and climate impacts on net CO_2 fluxes and carbon budgets of three grasslands along an elevational gradient in Switzerland

Matthias J. Zeeman [a,*], Rebecca Hiller [a], Anna K. Gilgen [a], Pavel Michna [b], Peter Plüss [a], Nina Buchmann [a], Werner Eugster [a]

[a] Institute of Plant Sciences, ETH Zurich, Universitaetsstrasse 2, CH-8092 Zurich, Switzerland
[b] Institute of Geography, University of Bern, Hallerstrasse 12, CH-3012 Bern, Switzerland

ARTICLE INFO

Article history:
Received 1 December 2008
Received in revised form 14 January 2010
Accepted 15 January 2010

Keywords:
Net ecosystem exchange
Eddy covariance
Mountain agriculture
Swiss Alps

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, and 2000 m elevation) and estimated carbon sequestration for two different but exceptionally warm 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). 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 were 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 25 and 150 g C m^{-2} yr^{-1}).

1. 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 Switzerland, 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 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, while at the same time organic matter is added to soil and biomass, or released via respiration back to the atmosphere. 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, 2008; Hammerle et al., 2007; Ammann et al., 2007; Soussana et al., 2007; Gilmanov et al., 2007; Cernusca et al., 2008; Wohlfahrt 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 the Alps (Boesch, 1951), in

---

* Corresponding author.
E-mail address: matthias.zeeman@alumni.ethz.ch (M.J. Zeeman).

0168-1923/$ – see front matter © 2010 Elsevier B.V. All rights reserved.
doi:10.1016/j.agrformet.2010.01.011

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., unpublished results; 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., unpublished results). 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 only allow to support a smaller number of lifestock 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 temporal 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.

2. 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).

2.1. 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 (*T. 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 rhaeticum*), white clover (*T. repens*) and dandelion (*T. officinale*) as dominant species (Keller, 2006).

2.2. 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).

2.2.1. Chamau and Früebüel

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 center 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 s for air temperature and relative humidity (at 2 m, a shaded, sheltered and ventilated HydroClip S3, Rotronic AG, Basserdorf, Switzerland), photosynthetic photon flux density (PPFD, at 2 m, K&Z PARlite, Kipp & Zonen B.V., Delft, The Netherlands), incoming and outgoing short and longwave radiation (at 2 m, a ventilated CNR1, Kipp & Zonen B.V., Delft, The Netherlands), soil heat flux (at −0.03 m, $n = 2$, model HFP01, Hukseflux B.V., Delft, The 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 min averages (or sums for precipitation) and stored on a field data logger (CR10X-2 M, Campbell Scientific Inc., Logan, USA) and a field computer. A wire fence (about 1 m high) perimeter of 5 m × 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 data 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 minimize disturbance of the wind field and to prevent influences through shading.

2.2.2. Alp Weissenstein

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. Environmetal variables were measured each 10 s for air temperature and relative humidity (at 2 m, a shaded, sheltered HydroClip S3, Rotronic AG, Basserdorf, Switzerland), photosynthetic photon flux density (PPFD, at 1 m, K&Z PARlite, Kipp & Zonen B.V., Delft, The 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, The 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 min averages (or sums for precipitation) and stored on a field data logger (CR10X-2 M, 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 min 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 min means of air temperature (at 2.50 m), incoming shortwave radiation (at 2.50 m, SP Lite, Kipp & Zonen B.V., Delft, The 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 $\approx$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).

2.3. 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 are defined as

$$F_N = \rho_a \overline{w'c'} \tag{1}$$

where the overbar denotes temporal averaging (typically 30 min), 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, which imply the assumption that advection is small and conditions are stationary.

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

$$F_N = F_A + F_R \tag{2}$$

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 respiration–temperature function (Lloyd and Taylor, 1994) to model F_R and a light–response function (Falge et al., 2001b) to model F_A 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)

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

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, and E_0 is a fit parameter for the activation energy. The model is parametrized using only nighttime data for T_{soil} and F_N (as $F_{N,night} = F_{R,night}$). Besides $F_{R,ref}$, T_0 and E_0 can also be included to fit the model, but we use the values as given by Lloyd and Taylor (1994), i.e. $T_0 = 227$ K and $E_0 = 308$ K) and only fit the model to $F_{R,ref}$.

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

$$F_A = \alpha \frac{Q_{PPFD}}{(1 - (Q_{PPFD}/2000)) + Q_{PPFD}(\alpha/F_{A,opt})} \tag{4}$$

where α denotes the ecosystem quantum yield (i.e., the flux of CO_2 per flux of photons, $\mu\text{mol m}^{-2}\text{ s}^{-1} \cdot (\mu\text{mol m}^{-2}\text{ s}^{-1})^{-1}$), Q_{PPFD} denotes the photosynthetic photon flux density ($\mu\text{mol m}^{-2}\text{ s}^{-1}$), and $F_{A,opt}$ represents the assimilation rate at optimal light conditions. The model is parametrized 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 these F_A values also $F_{A,opt}$ is determined for optimal daytime conditions with a clear sky ($Q_{PPFD} > 1200\ \mu\text{mol m}^{-2}\text{ s}^{-1}$) 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 gas of a known concentration. Fluxes of CO_2 and H_2O were calculated for 30 min periods using the *e*th-flux flux analysis tool (Eugster and Senn, 1995; Mauder et al., 2008) and R for statistical analysis and nonlinear least squares fitting functions (R Development Core Team, 2008). We applied a two-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 to correct for timing differences between the EC sensors and the sensor separation, a combined shift of typically in the order of 4 data samples, or 0.2 s. Post-calibration of the flux data consisted of a dampening loss correction (following Eugster and Senn, 1995) and a correction for the effects of density fluctuations (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 ($|F_N| > 50\ \mu\text{mol m}^{-2}\text{ s}^{-1}$), for $\overline{u'w'} < 0\text{ m s}^{-1}$ and for low friction velocity ($u_* < 0.08\text{ m}^2\text{ s}^{-2}$). We further tested stationarity and turbulent conditions following Foken and Wichura (1996). The stationarity test was based on a comparison of the 30 min averages for CO_2 and H_2O fluxes with 5 min 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 for all quality tests were used.

Data coverage of the environmental variables required for the model fits for F_A and F_R was >99% of the time at all sites and therefore provided a good base 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 $\leq$4 values ($\leq$2 h). 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 gap filling 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. Model parameters were fitted for each season, for the harvest intervals (period between harvests) in each season as well as for each day in each harvest interval using data from the three preceding and three following days (i.e. a seven-day time window), which is according to the findings of Falge et al. (2001a). In case a model for a particular day or period could not be fitted or a model fit was not significant ($p < 0.05$) or the fitted parameter value exhibited the wrong sign, a larger per harvest period (or subsequently the seasonal) model fit was used. This way, the prediction of daytime respiration and missing values were preferably made using the smallest time window model estimates, followed by the harvest period intervals and eventually the seasonal values. The aim of this approach was to obtain gap-filled time series for F_R, F_A and F_N which are adapted to rapidly changing conditions during the harvest intervals throughout the season. The model parameter α was determined only for low to moderate light conditions ($10 < Q_{PPFD} < 400\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$) and $F_{A,opt}$ in high light conditions ($Q_{PPFD} > 1200\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$) considering only the 10 days before each harvest. Soil moisture did not add an obvious constraint to F_R and this added 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 of 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)

$$Q_* - Q_G = Q_E + Q_H, \tag{5}$$

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),

$$\Delta S = c_v \frac{\Delta T_{soil}}{\Delta t}(z_d - z_0), \tag{6}$$

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 $1.0 \times 10^3\ \text{kg m}^{-3}$ for Chamau and Früebüel based on laboratory estimates (Roth, 2006). Particle density is taken as $2.65 \times 10^3\ \text{kg m}^{-3}$ (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. For Alp Weissenstein, Hiller et al. (2008) reported 81%. These results are 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. In addition, the advection and its extension layer in relation to the elevation difference from the crest of the mountain is approximately 5% according to Whiteman (2000) and we therefore assume that the low measurement height and the distance from the crest is enough to minimize advection influence.

2.4. Management data

To quantify the harvested biomass and the 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, 2009). The harvest biomass was averaged for five or more replicates of $0.20\ \text{m}^2$ 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, determined using the Kljun et al. (2004) footprint model.

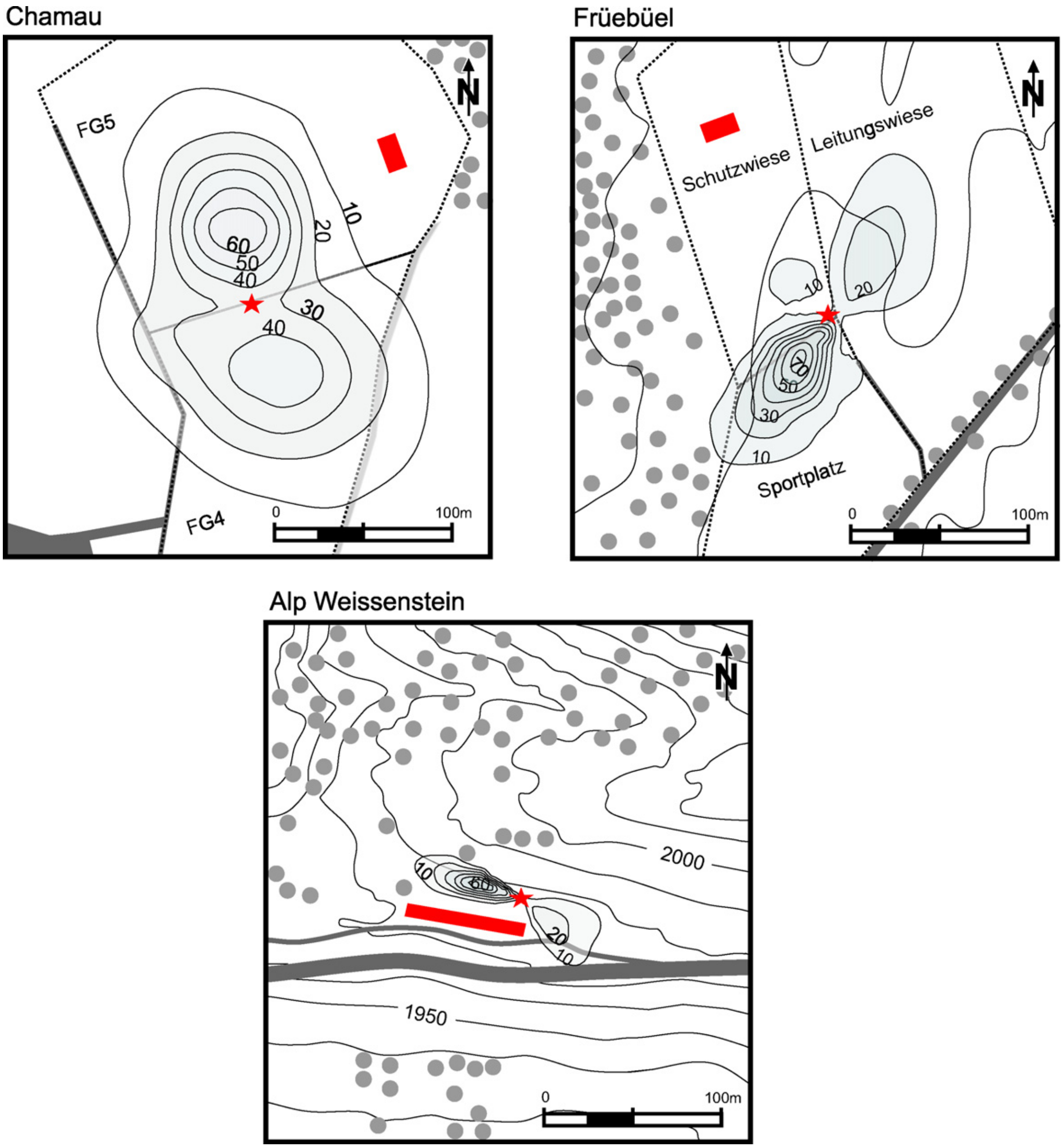
The amount of carbon in the applied manure was calculated based on the average dry weight (DW) and organic carbon content (C_{org}) of samples from Chamau taken in 2007 (liquid manure, DW = 3.85 ± 0.95%, $C_{org} = 461 \pm 21\ \text{g kg}^{-1}$, $n = 8$) and from Früebüel in 2006 (dung, DW = 27.82%, $C_{org} = 451\ \text{g kg}^{-1}$, $n = 1$). The amount of applied manure is derived from the change in level of a known storage volume (liquid manure) or volume of the wagon (solid manure). 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 analyzed in an external, specialized laboratory (LBU, Labor für Boden- und Umweltanalytik, Eric Schweizer AG, Thun, Switzerland). 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.

2.5. 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

$$\frac{\Delta C}{\Delta t} = F_N + F_i + F_o, \tag{7}$$

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). Here we do not include other greenhouse gases than CO_2, such as CH_4, and we assume the loss through the weight gain of grazing livestock to be small. For an accurate comparison of carbon input from manure



Chamau

Früebüel

Alp Weissenstein

Fig. 1. Flux footprint areas of the research sites at Chamau (left), Früebüel (middle) and Alp Weissenstein (right). At Chamau, the EC setup (red 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 northeast 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 (red 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). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

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 and footprint calculations following Kljun et al. (2004).

The uncertainty of the carbon budget can be estimated from the uncertainties of each flux component. The significance of the cumulative sums of fluxes of F_R, F_A and F_N were evaluated using a parametric bootstrapping approach similar to Knohl et al. (2008), in which the estimated model parameters ($F_{R,ref}$ and α, see Eqs. (3) and (4)) were substituted by univariate replacements in Monte Carlo type simulations. These simulations yielded a distribution of annual (or period) cumulative sums ($n = 1000$). This distribution was considered more representative of the uncertainty of F_N and the dependencies between F_R and F_A than the simple addition of the model uncertainties of F_R and F_A. To estimated uncertainty in F_o, we have used the statistics of the biomass sampling and have added an additional 10% uncertainty for using the farmer's estimations of the harvested volumes, which fit very well with the known storage volumes for each season (personal communication, Luginbühl, ETH Chamau). Since manure analysis data were not available for the whole measurement period (detailed analyses were only started in 2007), we have used a 10% uncertainty limit for the liquid manure, which is based on the 2007 dry weight and carbon content measurements and an estimate of 20% uncertainty for the solid manure. We add to this an estimated 5% error margin in the farmer's readings used for the volume applied to each field. Therefore, we assumed the typical uncertainty for F_i to be 15% and 25% for Chamau and Früebüel, respectively. The effects of grazing on the uncertainty of the carbon budgets are however considered small, as the animals were out in the field during the whole period and contribute to a weight gain of 1% of the biomass. The loss due to methane emissions is however larger during grazing, but has been shown to be 3% of a cow's daily carbon intake (Minonzio et al., 1998). Milk production is a large component (≈15%, see Minonzio et al., 1998) but not applicable for most of the grazing periods (e.g., grazing cattle at Früebüel and sheep at Chamau). Literature values were used for the estimations of carbon intake and respiration for the livestock.

3. Results

3.1. Climate conditions

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 effected 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 decline in soil moisture in July 2006 was less pronounced than at Chamau, which can be related to the lower temperatures at this higher elevation in addition to 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 and snow cover data. 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, as also indicated by the snow pack data for for the nearest representative weather stations (Fig. 2).

Table 1
Climate variables for Alp Weissenstein (AWS), Früebüel (FRU) and Chamau (CHA) in 2006 and 2007, consisting of the sum of precipitation (ΣP), 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.

		ΣP (mm)	Mean T_{air} (°C)	Mean $T_{air} > 5$ °C (days per year)
2006	AWS (2000 m)	(609)[a]	2.4	149
	FRU (1000 m)	1651	7.2	231
	CHA (400 m)	1136	9.5	246
2007	AWS (2000 m)	(756)[a]	2.2	142
	FRU (1000 m)	1765	7.7	234
	CHA (400 m)	1232	10.0	265

[a] Only liquid precipitation (during the warm season, April-November).

At Alp Weissenstein, 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 recognized from the precipitation amounts, which were generally lower than those at the sub-alpine site Früebüel, despite its higher elevation.

3.2. Net CO_2 exchange

The 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 little net uptake and a per harvest interval net CO_2 release. As a result, nearly the same annual sum of F_N was estimated for 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, Fig. 3). From 2006 to 2007 the sum of F_R increased for Chamau and decreased for Früebüel with a difference of +132 and $-137\ \mathrm{g\,m^{-2}\,yr^{-1}}$, respectively. Based on the increase in average temperature between the years, an increase is expected for Chamau and Früebüel. We believe the decrease at Früebüel is caused by the difference in snow cover, which showed the largest change at Früebüel. A snow pack has an insulating effect and causes a higher soil temperature, hence a higher F_R. Without a snow cover the soil temperature is allowed to cool below 0 °C, reducing F_R.

In the periods of overlapping data coverage for all three sites, the cumulative carbon uptake at Alp Weissenstein was slightly higher than at Früebüel (Table 2). For 2007, the comparison was made based on modelled F_N for 45 consecutive days during the season (26 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 net CO_2 uptake with elevation (Table 2).

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. 3a). 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. 3b). 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 favorable 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 1–2 times per year, as less manure was available. Although the number of harvests was the same in 2006 and 2007, the duration of the harvest intervals (time between harvests) increased by a factor of

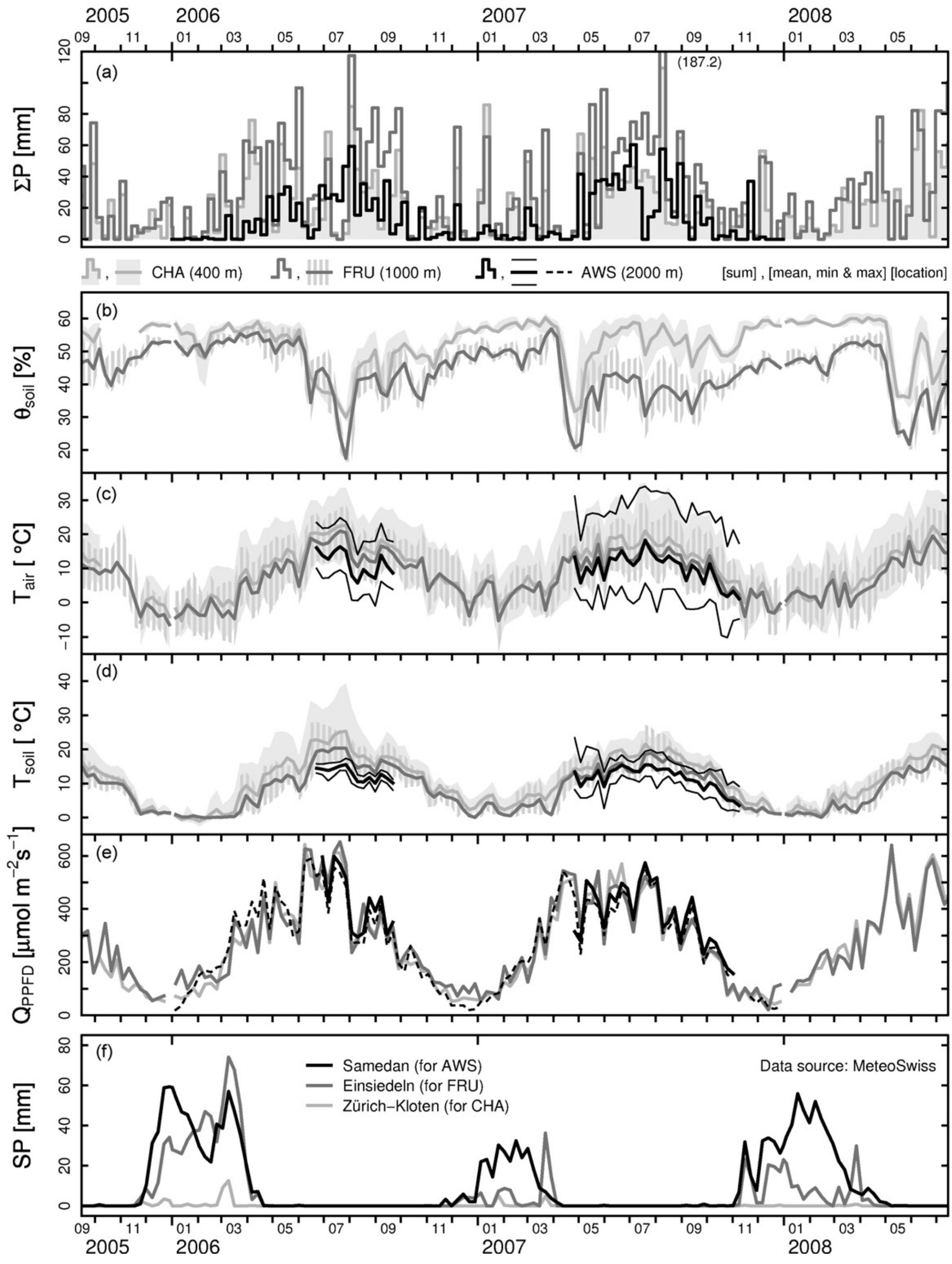


Fig. 2. Summary of the environmental conditions at the three grassland sites Chamau (CHA), Früebüel (FRU) and Alp Weissenstein (AWS) in the period September 2005 to July 2008. The variables shown are (a) the weekly sum of precipitation (ΣP), the two-week averages (b) of soil humidity (θ_{soil}), (c) of air temperature (T_{air}) and (d) of soil temperature (T_{soil}), (e) the two-week averaged daily (24 h) mean PPFD (Q_{PPFD}), and (f) weekly mean snow pack (SP) for the nearest representative weather stations. 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). The snow pack data were retrieved from the digital database of MeteoSwiss and are shown for Zürich–Kloten, Einsiedeln and Samedan, representing Chamau, Früebüel and Alp Weissenstein, respectively.

approximately two. 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)

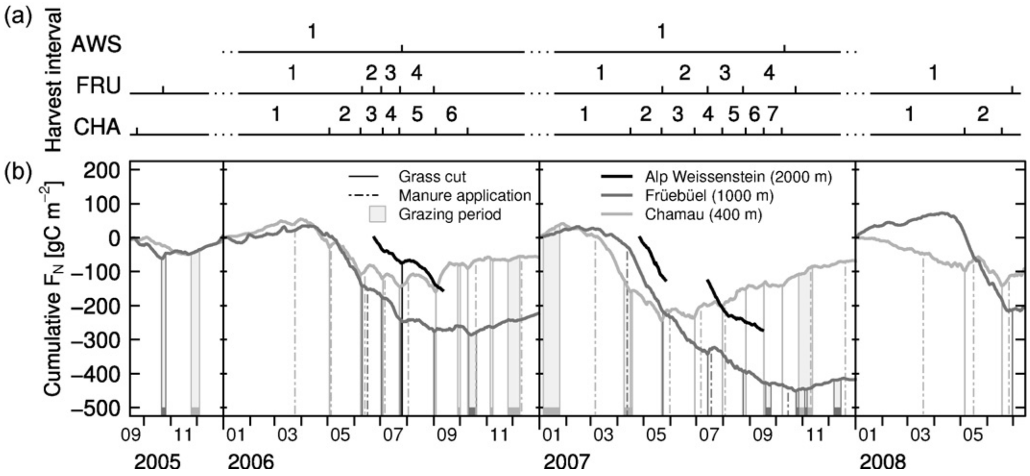


Fig. 3. Seasonal dynamics of the cumulative net ecosystem flux of CO_2 (cumulative F_N) for the three grassland sites in relation to management events in the period September 2005 to July 2008. (a) The timing and duration of harvest intervals change from year to year as the farmer follows the environmental 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.

uptake of CO_2 (Fig. 3), while at Früebüel assimilation typically was equal to or exceeded respiration within days after the harvest (Fig. 4). Although these patterns were variable over the growing season, they did not follow a clear 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 seven days was used. The ratios of F_A over F_R for the later harvest intervals at Chamau 2007 showed a dominant role of F_R (below 100% means a net loss, see Fig. 4), indicating that more carbon is respired than is assimilated during these harvest intervals, for which we assume the large quantity of manure previously applied in the season was the main source. Summarizing, 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.

3.3. Carbon stock

The annual budgets for carbon stock have been calculated from the sums of input and output fluxes (Table 2, Eq. (7)). For Chamau there was a significant increase of carbons stock in 2007 as well as for Früebüel in both 2006 and 2007, resulting in a two-year total of ≈95 g C m^{-2} and ≈290 g C m^{-2} for Chamau and Früebüel, respectively. Chamau was a small but not significant source in 2006.

The fluxes observed in the carbon budget are determined on different time scales and could be better matched than is the case when presented in annual intervals from 1 January to 31 December. This is specifically the case for manure inputs at the end of a year and the respiration fluxes that follow, which also influences the harvest outputs in the next year. Based on the strong implications of management on net CO_2 fluxes, budget calculations need to take into consideration the timing of management

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 (CHA), Früebüel (FRU) and Alp Weissenstein (AWS). Annual sums are given only for Chamau and Früebüel. The 46 day gap in summer 2007 for the F_N of Alp Weissenstein were modelled using a light–response and a temperature-response function that are parametrized using available F_N data, soil temperature and PPFD (see text).

Annual		Flux sums ± SE (g C m^{-2})					
		F_N	F_A	F_R	F_i	F_o	ΔC
2006	FRU (1000 m)	−222 ± 96	−1915 ± 105	1693 ± 20	−108 ± 27	208 ± 10	−122 ± 100
	CHA (400 m)	−59 ± 60	−2576 ± 67	2517 ± 42	−256 ± 36	326 ± 18	11 ± 72
2007	FRU (1000 m)	−417 ± 80	−1973 ± 91	1556 ± 22	−167 ± 27	414 ± 34	−170 ± 91
	CHA (400 m)	−69 ± 49	−2718 ± 56	2649 ± 42	−408 ± 42	372 ± 29	−105 ± 71
Period[a,b]		F_N	F_A	F_R			
2006[a] (n = 79 days)	AWS (2000 m)	−158 ± 24	−501 ± 38	343 ± 8			
	FRU (1000 m)	−117 ± 15	−767 ± 17	650 ± 12			
	CHA (400 m)	−11 ± 22	−983 ± 25	972 ± 26			
2007[b] (n = 139 days)	AWS (2000 m)	−414 ± 138[c]	−1238 ± 168[c]	828 ± 15[c]			
	FRU (1000 m)	−327 ± 29	−1347 ± 32	1020 ± 16			
	CHA (400 m)	31 ± 38	−1548 ± 44	1579 ± 36			

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

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

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

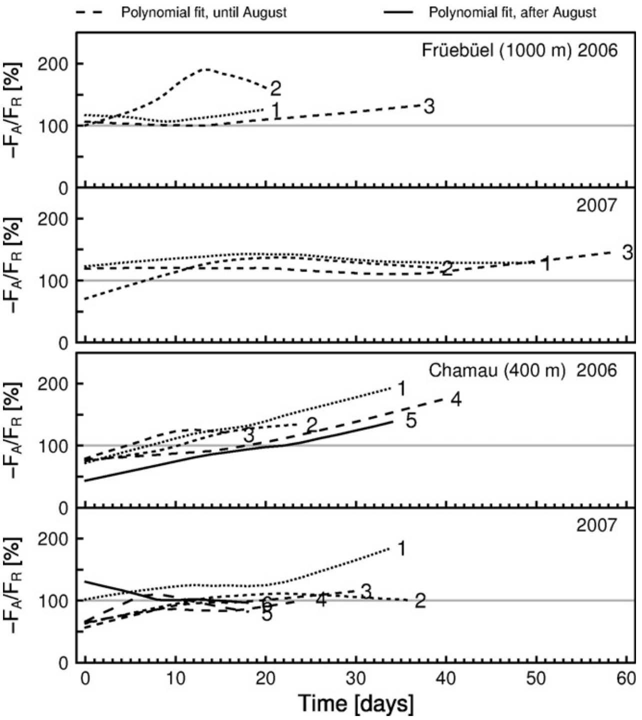


Fig. 4. Ratios between assimilation F_A and respiration F_R over the course of each harvest interval, shown as smoothed polynomial fits for each harvest interval. When the relationship is above 100% (horizontal grey line), the ratio of fluxes indicates net ecosystem uptake of CO_2. For Chamau, the crossing 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.

practices as well as inputs of carbon (F_i; manure inputs) and outputs of carbon (F_o; harvest output) for each management interval separately. Annual management cycle periods can be defined for calculating the carbon budgets, for instance between the last harvest of a previous year and the last harvest of the current year. During the period between the last harvest of 2005 and the last harvest of 2007 (representing the 2006 and 2007 seasons based on such management practice periods) the carbon stocks increased by ≈150 g C m^{-2} and ≈260 g C m^{-2} for Chamau and Früebüel, respectively (Fig. 5). However, while the increase in carbon stock for 2006 was 25 ± 89 g C m^{-2} at Chamau, in 2007 this was 125 ± 90 g C m^{-2}, which is comparable to the 110 ± 102 and 150 ± 92 g C m^{-2} increases for Früebüel in the 2006 and 2007 management periods, respectively. The duration of the management periods in 2006 and 2007 were 382 days and 363 days for Chamau and 313 and 418 days for Früebüel, respectively. Comparing management cycle period values with the annual values showed that the effect of choosing management cycle periods on the calculated carbon budgets are small, despite the considerable differences in length of the periods. However, for Chamau the application of management cycle periods resulted in a calculated carbon budget that represents a small but not significant sink in 2006, as opposed to a small but not significant source for the budget on an annual basis. At Chamau, manure inputs and application intensity were high as application occurred after most harvests and during winter. We assume that these inputs did not respire immediately after application and were not converted into the biomass of the next following harvest, but showed a time-lag within the year and to the next year, which helps explain the seasonal course of the carbon budget (Fig. 5). The increase for Chamau in 2007 was contributed by a much larger manure input (F_i) in 2007, that even exceeds the harvest outputs (F_o) that year. This relates to the opportunity for the farmer to utilize more of the manure reserves than in other years. 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, micro-climate 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 farmers 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.

Combining the information of the carbon budgets and net carbon fluxes for both years, a different pattern emerges for Chamau and Früebüel. While at Chamau both assimilation flux F_A and respiration flux F_R were both higher in 2007 at a similar F_N as in 2006, the increase in manure inputs F_i did not increase the harvest output F_o as much as the carbon stock ΔC. In contrast, at Früebüel a reduction in respiration flux F_R from 2006 to 2007 caused an increase in net uptake F_N, which together with a small increase in F_i caused a larger increase in harvest output F_o than in the carbon stock ΔC. This inter-annual pattern suggest that for Früebüel the variation in harvest output was to large extend defined by environmental conditions, and that at Chamau the variations in ΔC were mainly driven by manure inputs.

4. Discussion

If we compare the conditions between the years 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 in 2007 (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 three and five 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).

Although the use of management cycle introduces a considerable variation in the length of the periods, it allows an improved match of the fluxes that integrate different time scales in the carbon budget of managed grasslands. However, significant differences between managament cycle period and annual carbon budgets could not be shown here. The management cycle approach does therefore not provide a clear improvement for use in inter-annual comparisons of the carbon stock of managed grasslands until uncertainties in the component fluxes can be reduced significantly.

Although the uncertainties of using model fits have been estimated for F_R, F_A and subsequently F_N, there is an additional uncertainty mentioned in literature which is caused by the sampling used for the model fits, which accounts to ≈15% of F_N

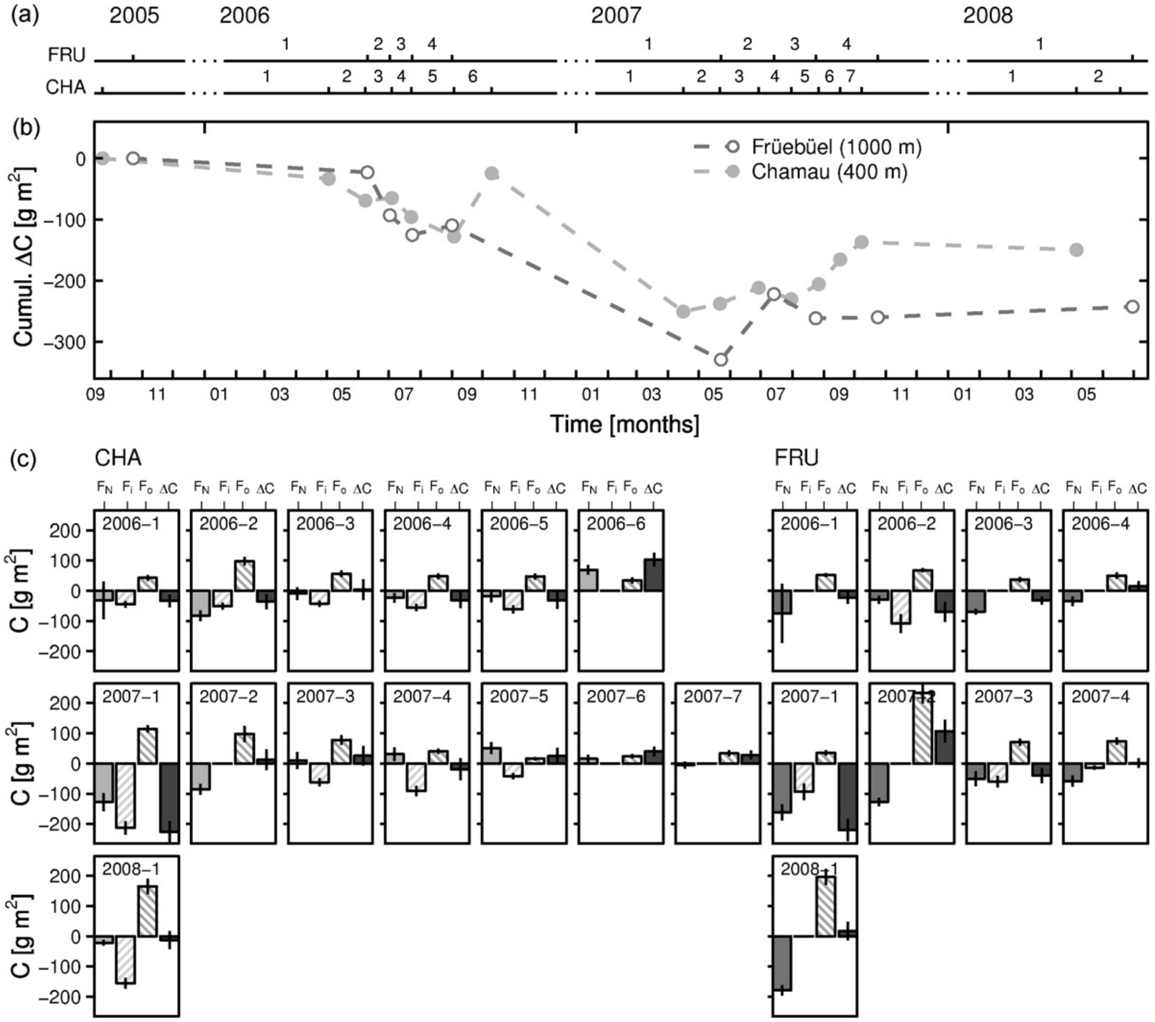


Fig. 5. The net carbon stock change (ΔC) for Chamau (CHA) and Früebüel (FRU) from the last harvest in 2005 until the first harvest in 2008. The timing of each harvest (a) is linked to the cumulative CO_2 flux for each site (b), as calculated from the components of ΔC (c). These components are the net totals of C per harvest interval with their uncertainties (see text) for the net ecosystem exchange (F_N), manure and liming application inputs (F_i) and harvest outputs (F_o), which sum up to a ΔC value per harvest interval.

according to Goulden et al. (1996), and has been shown to exhibit larger variability for nighttime than for daytime values (Oren et al., 2006). This additional uncertainty affects the net CO_2 exchange values as well as the carbon budget estimates but has not been added to the uncertainties such as mentioned in Table 2.

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), harvest losses and grazing 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 7 g C m^{-2} yr^{-1} for the A + B horizon (Kindler, Siemens, Heim, Schmidt, and Zeeman, unpublished 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.

The effects of grazing on the significance of the carbon budgets can be estimated using literature values for the carbon cycle of the animals. Of each kg carbon intake, a milk cow respires 50% to the air (as CO_2 or CH_4), 35% is excreted on the field and 15% goes to milk production for the mature animals (Minonzio et al., 1998; Kinsman et al., 1995; Jungbluth et al., 2001). We assumed these ratios to be similar for cattle and sheep, but instead of milk production we assumed a 15% weight gain. The loss due to methane emissions from the field is larger during grazing due to the presence of the animals, but has been shown to be only ≈3% of a cow's daily carbon intake. An average intake value of 15 kg DW (≅6.7 kg C) for cows and cattle and 2 kg DW (≅0.92 kg C) for sheep was used based on earlier surveys for Switzerland (Minonzio et al., 1998). Based on the number of days of grazing and number of animals in the field, the F_o due to weight gain and milk production is estimated at approximately 20 and 65 g C m^{-2} for Chamau and Früebüel, respectively, for the period of the last harvest of 2005 to the last harvest of 2007. The respiration of the animals is estimated for the same period at 55 and 100 g C m^{-2} for Chamau and Früebüel, respectively. In an ideal case where the grazing animals are spread evenly over the fields at all times, their respiration signal becomes part of the EC measurements for F_N. However, such distribution are not to be expected. However, these values must be interpreted as the potential loss of respiration to the measured F_N by grazing, if none of the respiration by grazing animals was measured by the EC setup. In reality this loss must be a fraction of these values and therefore the losses due to grazing are considered relatively small. 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 ΔC 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 2002–2004. Although the Oensingen grassland is intensively managed, it receives less manure inputs (an average 46 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 2–7 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 2002–2004 (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 favorable 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 1–3% of top soil carbon.

5. 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 Chamau and Früebüel. Both systems were carbon sinks in 2006 (although less clear for Chamau) and 2007, two very different but exceptionally warm years. This provides strong evidence that C stock can and must be regarded in carbon cycle related management in the future, when climatic conditions not only affect carbon dynamics in soils and vegetation but also adaptive management of Swiss grasslands.

Acknowledgments

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, and Alexander Knohl and Nadine Ruehr (both ETH Zurich) for advise on error estimations. We also thank two anonymous reviewers for their constructive critiques and helpful comments. Patrick Flütsch (ETH Zurich) has provided essential technical support for the development and establishment of the sites. The snow pack data were retrieved from the digital database of MeteoSwiss. 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).

References

Ammann, C., Flechard, C.R., Leifeld, J., Neftel, A., Fuhrer, J., 2007. The carbon budget of newly established temperate grassland depends on management intensity. Agriculture Ecosystems & Environment 121 (June (1–2)), 5–20.

Aubinet, M., Grelle, A., Ibrom, A., Rannik, U., Moncrieff, J., Foken, T., Kowalski, A.S., Martin, P.H., Berbigier, P., Bernhofer, C., Clement, R., Elbers, J., Granier, A., Grunwald, T., Morgenstern, K., Pilegaard, K., Rebmann, C., Snijders, W., Valentini, R., Vesala, T., 2000. Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. Advances in Ecological Research 30, 113–175.

Baldocchi, D., Falge, E., Gu, L., Olson, R., Hollinger, D., Running, S., Anthoni, P., Bernhofer, C., Davis, K., Evans, R., Fuentes, J., Goldstein, A., Katul, G., Law, B., Lee, X., Malhi, Y., Meyers, T., Munger, W., Oechel, W., Paw, U., Pilegaard, K., Schmid, H., Valentini, R., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001. Fluxnet: a new tool to study the temporal and spatial variability of ecosystem-scale carbon dioxide, water vapor, and energy flux densities. Bulletin of the American Meteorological Society 82 (11), 2415–2434.

Boesch, H., 1951. Nomadismus, Transhumanz und Alpwirtschaft. Die Alpen 27, 202–207.

Bolliger, J., Hagedorn, F., Leifeld, J., Böhl, J., Zimmermann, S., Soliva, R., Kienast, F., 2008. Effects of land-use change on carbon stocks in Switzerland. Ecosystems 11 (September (6)), 895–907.

Calanca, P., Fuhrer, J., 2005. Swiss Agriculture in a Changing Climate: Grassland Production and its Economic Value. Springer, Netherlands, pp. 341–353.

Cernusca, A., Bahn, M., Berninger, F., Tappeiner, U., Wohlfahrt, G., 2008. Effects of land-use changes on sources, sinks and fluxes of carbon in european mountain grasslands. Ecosystems 11 (December (8)), 1335–1337.

De Vries, D., 1963. Thermal Properties of Soils. North-Holland Publishing Company, Amsterdam, pp. 210–235.

Ehlers, E., Kreutzmann, H., 2000. High Mountain Pastoralism in Northern Pakistan. Franz Steiner Verlag.

Eugster, W., Leuenberger, H., 2007. Alpine Landwirtschaft: 40 Jahre ETH-Forschung am Albulapass. Die Alpen 83 (10), 56–59.

Eugster, W., Senn, W., 1995. A cospectral correction model for measurement of turbulent NO_2 flux. Boundary-Layer Meteorology 74 (June (4)), 321–340.

Eugster, W., Zeeman, M.J., 2006 Jul. Micrometeorological techniques to measure ecosystem-scale greenhouse gas fluxes for model validation and improvement. International Congress Series 1293, 66–75.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, G., Clement, R., Dolman, H., Granier, A., Gross, P., Grunwald, T., Hollinger, D., Jensen, N.O., Katul, G., Keronen, P., Kowalski, A., Lai, C.T., Law, B.E., Meyers, T., Moncrieff, J., Moors, E., Munger, J.W., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001a. Gap filling strategies for long term energy flux data sets. Agricultural and Forest Meteorology 107 (March (1)), 71–77.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grunwald, T., Hollinger, D., Jensen, N.O., Katul, G., Keronen, P., Kowalski, A., Lai, C.T., Law, B.E., Meyers, T., Moncrieff, J., Moors, E., Munger, J.W., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T., Wilson, K., Wofsy, S., 2001b. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology 107 (March (1)), 43–69.

FAO, 1997. Report on the 1990 world census of agriculture. In: FAO statistical development series No. 9. Food and Agriculture Organization of the United Nations.

Foken, T., 2008. The energy balance closure problem: An overview. Ecological Applications 18 (September (6)), 1351–1367.

Foken, T., Wichura, B., 1996. Tools for quality assessment of surface-based flux measurements. Agricultural and Forest Meteorology 78 (January (1–2)), 83–105.

Fuhrer, J., Beniston, M., Fischlin, A., Frei, C., Goyette, S., Jasper, K., Pfister, C., 2006. Climate risks and their impact on agriculture and forests in Switzerland. Climatic Change 79 (November (1)), 79–102.

Gilgen, A.K., Buchmann, N., 2009. Response of temperate grasslands at different altitudes to simulated summer drought differed but scaled with annual precipitation. Biogeosciences Discussions 6 (3), 5217–5250.

Gilmanov, T.G., Soussana, J.E., Aires, L., Allard, V., Ammann, C., Balzarolo, M., Barcza, Z., Bernhofer, C., Campbell, C.L., Cernusca, A., Cescatti, A., Clifton-Brown, J., Dirks, B.O.M., Dore, S., Eugster, W., Fuhrer, J., Gimeno, C., Gruenwald, T., Haszpra, L., Hensen, A., Ibrom, A., Jacobs, A.F.G., Jones, M.B., Lanigan, G., Laurila, T., Lohila, A., Manca, G., Marcolla, B., Nagy, Z., Pilegaard, K., Pinter, K., Pio, C., Raschi, A., Rogiers, N., Sanz, M.J., Stefani, P., Sutton, M., Tuba, Z., Valentini, R., Williams, M.L., Wohlfahrt, G., 2007. Partitioning European grassland net ecosystem CO_2 exchange into gross primary productivity and ecosystem respiration using light response function analysis. Agriculture Ecosystems & Environment 121 (June (1–2)), 93–120.

Goulden, M.L., Munger, J.W., Fan, S.M., Daube, B.C., Wofsy, S.C., 1996. Measurements of carbon sequestration by long-term eddy covariance: methods and a critical evaluation of accuracy. Global Change Biology 2 (June (3)), 169–182.

Graber, W.K., Neininger, B., Furger, M., 1998. CO_2 and water vapour exchange between an alpine ecosystem and the atmosphere. Environmental Modelling and Software 13 (October), 353–360.

Hammerle, A., Haslwanter, A., Schmitt, M., Bahn, M., Tappeiner, U., Cernusca, A., Wohlfahrt, G., 2007. Eddy covariance measurements of carbon dioxide, latent and sensible energy fluxes above a meadow on a mountain slope. Boundary-Layer Meteorology 122 (February (2)), 397–416.

Hiller, R., Zeeman, M., Eugster, W., 2008. Eddy-covariance flux measurements in the complex terrain of an Alpine valley in Switzerland. Boundary-Layer Meteorology 127 (June (3)), 449–467.

Hotz, M.-C., Weibel, F., 2005. Arealstatistik Schweiz: Zahlen-Fakten-Analysen, 1992–1997. Tech. rep., BFS-Bundesamt für Statistik.

IPCC, July 2007. Climate Change 2007: The Physical Science Basis. Contribution of Working Group I Contribution to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Jeangros, B., Thomet, P., 2004. Multifunctionality of grassland systems in Switzerland. In: Lüscher, A., Jeangros, B., Kessler, W., Huguenin, O., Lobsiger, M., Millar, N., Suter, D. (Eds.), Multifunctionality of grassland systems in Switzerland Land Use Systems in Grassland Dominated Regions.

Jungbluth, T., Hartung, E., Brose, G., 2001. Greenhouse gas emissions from animal houses and manure stores. Nutrient Cycling in Agroecosystems 60 (1–3), 133–145.

Kaimal, J.C., Finnigan, J.J., 1994. Atmospheric Boundary Layer Flows: Their Structure and Measurement. Oxford University Press.

Keller, P., December 2006. Vegetationskundliche Untersuchungen und Ertrag der Grünlandflächen im Gebiet der ETH-Forschungsstation Alp Weissenstein GR. Master's thesis. Institute of Geography, University of Zurich.

Kinsman, R., Sauer, F.D., Jackson, H.A., Wolynetz, M.S., 1995. Methane and carbon dioxide emissions from dairy cows in full lactation monitored over a six-month period. Journal of Dairy Science 78 (December (12)), 2760–2766.

Kljun, N., Calanca, P., Rotachhi, M.W., Schmid, H.P., 2004. A simple parameterisation for flux footprint predictions. Boundary-Layer Meteorology 112 (September (3)), 503–523.

Knohl, A., Soe, A.R.B., Kutsch, W.L., Gockede, M., Buchmann, N., 2008. Representative estimates of soil and ecosystem respiration in an old beech forest. Plant and Soil 302 (January (1–2)), 189–202.

Leifeld, J., Bassin, S., Fuhrer, J., 2005. Carbon stocks in Swiss agricultural soils predicted by land-use, soil characteristics, and altitude. Agriculture Ecosystems & Environment 105 (January (1–2)), 255–266.

Lloyd, J., Taylor, J.A., 1994. On the temperature-dependence of soil respiration. Functional Ecology 8 (June (3)), 315–323.

Mauder, M., Foken, T., Clement, R., Elbers, J.A., Eugster, W., Grünwald, T., Heusinkveld, B., Kolle, O., 2008. Quality control of carboeurope flux data—part 2: inter-comparison of eddy-covariance software. Biogeosciences 5 (2), 451–462.

MeteoSwiss (Eds.), 2006. Witterungsbericht - Jahr 2005. Federal Office of Meteorology and Climatology MeteoSwiss.

MeteoSwiss (Eds.), 2007. Witterungsbericht - Jahr 2006. Federal Office of Meteorology and Climatology MeteoSwiss.

MeteoSwiss (Eds.), 2008. Witterungsbericht - Jahr 2007. Federal Office of Meteorology and Climatology MeteoSwiss.

Michna, P., Eugster, W., Hiller, R., Zeeman, M.J., Wanner, H. Topoclimatological characteristics of the Alp Weissenstein research site in the Swiss Alps. Advances in Meteorology, unpublished results.

Minonzio, G., Grub, A., Fuhrer, J., 1998. Methan-Emissionen der schweizerischen Landwirtschaft. Schriftenreihe Umwelt 298, Swiss Federal Office of the Environment (FOEN/BUWAL).

OcCC, 2008. Das Klima ändert - was nun? Der neue UN-Klimabericht (IPCC 2007) und die wichtigsten Ergebnisse aus Sicht der Schweiz. OcCC - Organe consultatif sur les changements climatiques, Bern.

Oke, T.R., 1987. Boundary Layer Climates, 2nd ed. Methuen, London, New York, 435 pp.

Oren, R., Hseih, C.I., Stoy, P., Albertson, J., McCarthy, H.R., Harrell, P., Katul, G.G., 2006. Estimating the uncertainty in annual net ecosystem carbon exchange: spatial variation in turbulent fluxes and sampling errors in eddy-covariance measurements. Global Change Biology 12 (May (5)), 883–896.

Potthoff, K., 2004. Change in mountain summer farming practices: a case study from Stølsheimen, western Norway. Norwegian Journal of Geography 58, 158–170.

R Development Core Team, 2008. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria. , ISBN: 3-900051-07-0, http://www.R-project.org.

Reichstein, M., Rey, A., Freibauer, A., Tenhunen, J., Valentini, R., Banza, J., Casals, P., Cheng, Y.F., Grunzweig, J.M., Irvine, J., Joffre, R., Law, B.E., Loustau, D., Miglietta, F., Oechel, W., Ourcival, J.M., Pereira, J.S., Peressotti, A., Ponti, F., Qi, Y., Rambal, S., Rayment, M., Romanya, J., Rossi, F., Tedeschi, V., Tirone, G., Xu, M., Yakir, D., 2003. Modeling temporal and large-scale spatial variability of soil respiration from soil water availability, temperature and vegetation productivity indices. Global Biogeochemical Cycles 17 (November (4)), 1104.

Rogiers, N., Conen, F., Furger, M., Stöckli, R., Eugster, W., 2008. Impact of past and present land-management on the C-balance of a grassland in the Swiss Alps. Global Change Biology 14, 2613–2625.

Rogiers, N., Eugster, W., Furger, M., Siegwolf, R., 2005. Effect of land management on ecosystem carbon fluxes at a subalpine grassland site in the Swiss Alps. Theoretical and Applied Climatology 80 (April (2–4)), 187–203.

Roth, K., December 2006. Bodenkartierung und GIS-basierte Kohlenstoffinventur von Graslandböden: Untersuchungen an den ETH-Forschungsstationen Chamau und Früebüel (ZG, Schweiz). Master's thesis. Institute of Geography, University of Zurich.

Sautier, S., January 2007. Zusammensetzung und Produktivität der Vegetation im Gebiet der ETHZ-forschungsstation Früebüel (ZG). Master's thesis. Institute of Geography, University of Zurich.

Soussana, J., Allard, V., Pilegaard, K., Ambus, P., Amman, C., Campbell, C., Ceschia, E., Clifton-Brown, J., Czobel, S., Domingues, R., Flechard, C., Fuhrer, J., Hensen, A., Horvath, L., Jones, M., Kasper, G., Martin, C., Nagy, Z., Neftel, A., Raschi, A., Baronti, S., Rees, R., Skiba, U., Stefani, P., Manca, G., Sutton, M., Tuba, Z., Valentini, R., 2007. Full accounting of the greenhouse gas (CO_2, N_2O, CH_4) budget of nine European grassland sites. Agriculture, Ecosystems & Environment 121 (June), 121–134.

van der Molen, M.K., Zeeman, M.J., Lebis, J., Dolman, A.J., 2006. EClog: a handheld eddy covariance logging system. Computers and Electronics in Agriculture 51 (April (1–2)), 110–114.

Vonlanthen, C.M., Buhler, A., Veit, H., Kammer, P.M., Eugster, W., 2006. Alpine plant communities: a statistical assessment of their relation to microclimatological, pedological, geomorphological, and other factors. Physical Geography 27 (March (2)), 137–154.

Webb, E., Pearman, G., Leuning, R., 1980. Correction of flux measurements for density effects due to heat and water vapour transfer. Quarterly Journal Royal Meteorological Society 106 (447), 85–100.

Weiss, R., 1941. Das Alpwesen Graubündens: Wirtschaft, Sachkultur, Recht, Älplerarbeit und Älplerleben. Eugen Rentsch Verlag, Erlenbach-Zürich, 385 pp.

Weiss, R., 1959. Häuser und Landschaften der Schweiz. Eugen Rentsch Verlag, Erlenbach-Zürich, 368 pp.

White, R., 2005. Principles and Practice of Soil Science: The Soil as a Natural Resource, 4th ed. Blackwell Publishing.

Whiteman, C.D., 2000. Mountain Meteorology: Fundamentals and Applications. Oxford University Press, New York, Oxford, 355 pp.

Wilson, K., Goldstein, A., Falge, E., Aubinet, M., Baldocchi, D., Berbigier, P., Bernhofer, C., Ceulemans, R., Dolman, H., Field, C., Grelle, A., Ibrom, A., Law, B.E., Kowalski, A., Meyers, T., Moncrieff, J., Monson, R., Oechel, W., Tenhunen, J., Valentini, R., Verma, S., 2002. Energy balance closure at fluxnet sites. Agricultural and Forest Meteorology 113 (December), 223–243.

Wohlfahrt, G., Anderson-Dunn, M., Bahn, M., Balzarolo, M., Berninger, F., Campbell, C., Carrara, A., Cescatti, A., Christensen, T., Dore, S., Eugster, W., Friborg, T., Furger, M., Gianelle, D., Gimeno, C., Hargreaves, K., Hari, P., Haslwanter, A., Johansson, T., Marcolla, B., Milford, C., Nagy, Z., Nemitz, E., Rogiers, N., Sanz, M., Siegwolf, R., Susiluoto, S., Sutton, M., Tuba, Z., Ugolini, F., Valentini, R., Zorer, R., Cernusca, A., 2008. Biotic, abiotic, and management controls on the net ecosystem CO_2 exchange of european mountain grassland ecosystems. Ecosystems 11 (December (8)), 1338–1351.

Wohlfahrt, G., Anfang, C., Bahn, M., Haslwanter, A., Newesely, C., Schmitt, M., Drosler, M., Pfadenhauer, J., Cernusca, A., 2005. Quantifying nighttime ecosystem respiration of a meadow using eddy covariance, chambers and modelling. Agricultural and Forest Meteorology 128 (February (3–4)), 141–162.