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Environmental Systems Science

How do differences in management reflect on the carbon fluxes of a Swiss grassland?

Bachelor Thesis

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Abstract

In times of climate change, a fundamental understanding of carbon dynamics in plant and soil is of great importance. This study examined the short and long-term effects of management events cut, grazing and organic fertilizer application on the carbon dynamics of a high altitude Swiss grassland between 2006 – 2013. The CO_2 flux was measured with the Eddy covariance method and assigned to a particular parcel according to the prevalent wind direction. The parcels differed in management intensity and in soil properties. Generally, cut and grazing led to a significant increase of CO_2 flux whereas the application of organic fertilizer results in a decrease. These findings only apply to a short time period after the events. They slightly affect the temporal course of the CO_2 flux but did not lead to major distinction. The decomposition of peat in a formerly heavily waterlogged parcel turned out to be much more influential on the CO_2 flux than the management differences, even 35 years after the beginning of drainage.

Contents

Abbreviations

DOY	Day of the year
DRP	Digital repeat photography
EC	Eddy covariance
GI	Greenness index
GPP	Gross primary production
m.a.s.l.	meters above sea level
NEE	Net ecosystem exchange
NEP	Net ecosystem productivity
PAR	Photosynthetically active radiation
PPFD	Photon flux density
SOC	Soil organic carbon
SWC	Soil water content
u*	Friction velocity

1. Introduction

Global climate change is a major threat to a stable climate, biodiversity, ecosystem services, water supply, food security, human health and thus to the basics of human life on earth (IPCC, 2014). In order to lower these risks, an international agreement was negotiated 2015 in Paris, which aims to limit the average temperature increase to 1.5 °C (UNFCCC, 2015). This goal can only be achieved if the net greenhouse gas emission is reduced to zero by 2045 – 2060 (Rogelj et al., 2015). In addition to reducing emissions, there is also a second strategy to lower the CO_2 concentration in the atmosphere. Terrestrial ecosystems form an important pool for carbon. This pool is subject to dynamic processes, whereby ecosystems can become sources or sinks of carbon for a limited period of time. Schulze et al. (2009) estimated that 10% of the EU's fossil fuel emissions are compensated by net absorption of terrestrial ecosystems within the EU.

Carbon sequestration effect has been taken into consideration in climate negotiations. Already the Kyoto protocol allowed the inclusion of terrestrial carbon sinks and sources in the greenhouse gas inventory of the participant countries (Smith, 2004). Many countries made use of this scheme. In fact, Switzerland achieved its emissions target, a reduction of 8% compared to 1990, partly because of carbon sink service of Swiss forest. Thereby, nearly 1'800 Mt CO_2 equivalent per year had been sequestered in the tree biomass (FOEN, 2014). This exemplary demonstrates the great influence of such ecosystems on the carbon cycle and their potential use to achieve environmental goals. Detailed knowledge about the processes and the influencing factors are indispensable for policy and decision making. They enable a targeted strategy to promote carbon sinks.

Grassland plays a particularly important role within the carbon absorbing terrestrial ecosystems. It comprises around 40% of total land area and forms one of the major biomes worldwide (Suttie et al., 2005). In Switzerland, Grassland covers about 30% of land area and 80% of agricultural area (Leifeld et al., 2005). Various studies have shown a similar rate of carbon sequestration in grassland and forest (Dilly et al., 2005; Toma et al., 2012; Wei et al., 2012). There is also strong evidence for the generally higher carbon content in grassland soil compared to arable land (Leifeld et al., 2011; Wiesmeier et al., 2013). Despite this knowledge, little effort has been made to increase carbon sequestration by increased cultivation of grass. One possible reason for this is an uncertainty due to the incomplete understanding behind the processes of carbon sequestration.

What factors in grassland lead to a high carbon content in the soil? Generally, we can distinguish between environment and management influence. The environmental factors are usually given and difficult to adapt. However, management alone can already cause large changes in soil carbon content. In grassland, the biggest difference compared to cropland is generally the rare use of the plow. So it is not surprising that an increased frequency of plowing in grassland leads to higher carbon emissions. However, MacDonald et al. (2010) showed that plowing in very wet soils leads to a decline of soil respiration due to carbon incorporation into deeper soil layers. Water prevents the access of oxygen and thus has a crucial role in the slowdown of decomposition. Sulman et al. (2013) calculated that declining soil water table can lead to an increase as well as a decrease of total carbon which mainly depends on the change in living biomass. A general consensus exists on the impact of utilisation and fertilizer intensity. Frequent cutting and high fertilization has a positive effect on carbon sequestration (Conant et al., 2001; Leifeld et al., 2011; Ziter and MacDougall, 2013). However, the effect of fertilizer only applies with manure and not necessarily with mineral fertilizer (Hirata et al., 2013). De Deyn et al. (2011) showed that a substitution of fertilizer with Red Clover (*Trifolium pratense* L.) had an even better effect in terms of soil organic carbon (SOC). Liming has a contradictory effect on the carbon budget. By promoting the microbial activity, it leads usually to higher soil respiration (Biasi et al., 2008) but also to a redistribution of organic carbon into more stable pools (Fornara et al., 2011; Manna et al., 2007).

The aim of this study is a better understanding of the management impacts on carbon budget. With flux data from only one eddy covariance (EC) tower, it is tried to detect CO_2 flux differences between three adjacent parcels. The approach is very different from previous studies, which collected soil samples or used a single eddy covariance tower for each treatment group. We want to test, whether it is possible with such an experimental setup to detect the small flux variations caused by differences in management intensity. The experimental area is situated around 1000 m.a.s.l., covering a still little explored alpine environment. Zeeman et al. (2010) already examined the impact of different altitude levels on the CO_2 exchange of a grassland ecosystem. However, to the best of our knowledge, there are no studies which compares the impact of different management intensities on CO_2 exchange of alpine grassland. Furthermore, many studies have a time horizon which does not allow to uncover long-term effects. From a climate protection view, it is exactly this long-term effect which has the greatest mitigation potential. A currently important task of environmental research is the development of reliable models to predict carbon fluxes. Therefore, it is important to not only discover the connections between environmental variables but also to have a better understanding of the underlying processes. This is achieved by explaining the fluxes with soil properties and biogeochemistry.

With the following research questions, we try to address the issues mentioned: (i) Can we track CO_2 fluxes from three different parcels with only one EC tower? (ii) How do management intensity affect carbon fluxes at high altitude level on different time scales? (iii) To what extent the observed carbon fluxes can be explained with soil properties and biogeochemistry?

2. Theoretical Background

2.1 Eddy covariance

2.1.1 Basics

The EC is a method to measure fluxes of trace gas and energy between surface and atmosphere. It was established around 1990 and is nowadays adopted in more than 400 flux measurement sites worldwide (Baldocchi, 2014). Compared to traditional measurement systems such as chambers it has several advantages mentioned in Eugster and Merbold (2015). The method is non-invasive and non-destructive, meaning that the ecosystem is only very slightly disturbed to perform the measurement. It allows continuous measurements with high temporal resolution. The measured flux represents the spatially integrated carbon exchange of the entire ecosystem. This may be an advantage or disadvantage, depending on whether you want to have a realistic assessment of the whole exchange or spatially separated individual measurements.

2.1.2 Measuring principle

The EC measurement of CO_2 lux is based on two instruments (FIG. 1). An ultrasonic anemometer which measures wind speed in in horizontal and vertical direction and a gas analyzer (Eugster and Merbold, 2015). The gas analyzer estimates the CO_2 concentration or gas mixing ratio by infrared absorption. This can be done directly in the ambient air (open path) or in a partially closed chamber (closed path, Burba et al., 2012). Subsequently, the individual measurement points, often measured with 20 Hz are integrated to one 30 min flux using the following equation

$$F_c = \overline{w'c'_{z_{ec}}} \tag{1}$$

with F_C as carbon flux, w as vertical wind speed

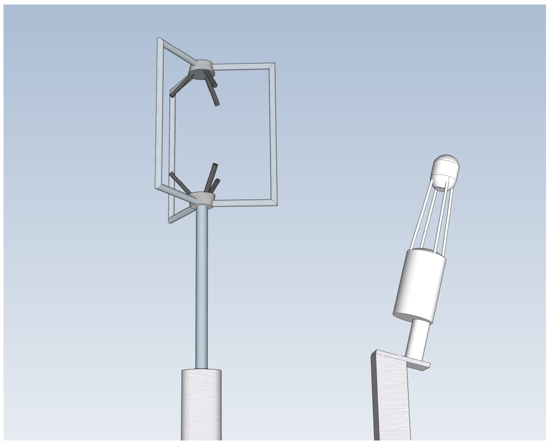

Fig. 1. Instruments of EC to measure CO_2 flux: Ultrasonic anemometer (left) and open path infrared gas analyzer (right)

and c_{zec} as CO_2 concentration at measuring height (Eugster and Merbold, 2015). The apostrophe and overbar indicate the time-averaged deviation of mean. Altogether, it can be interpreted as covariance between turbulent fluctuations of the vertical wind and the fluctuation of CO_2 concentration (Foken et al., 2012). EQ. (1) is derived from the mass conservation equation. To this end, mass conservation equation is separated by Reynold's decomposition and various terms are set to zero. Many assumptions are made in order to simplify the equation. The key assumptions are summarized in TABLE 1. These simplifications must always be considered in the interpretation and in particular in the choice of the location of an EC tower.

2.1.3 Quality insurance and filtering

Even if the EC tower is set at a suitable location, there can always occur environmental condition were the simplification criteria are not met. Foken and Wichura (1996) divides errors in EC measurements generally into (i) situations or sites where the theoretical conditions are not met (e.g. homogeneity or stationarity), (ii) measurements with wrong sensor configurations and (iii) measurements under non-optimal meteorological conditions e.g. low turbulence. For most errors there are

Table 1. Overview of the major simplifications to calculate carbon fluxes with eddy covariance. Adopted from Foken et al. (1996).

Simplification	Explanation
Stationarity	No change of meteorological variables during a measurement interval
Horizontal homogeneity	Flat surface with no obstacles or changes in canopy height
Mass conservation equation	Original equation is satisfied, no chemical reaction of measured gas
Negligible density flux	Only minor fluctuation in air density
Statistical assumptions	Statistical independence and the definition of the averaging procedure
Reynold's decomposition	Possible separation in mean component and instantaneous deviation
Negligible change in gas flux	Only minor change between ground and measurement height

quality tests and correction methods. Although, it has to be emphasized that no correction can rectify the error in the data collection completely. According to Foken and Wichura (1996), there are two tests particularly suitable to check the fulfillment of major theoretical assumptions: the instationarity test and the test with integral turbulence characteristic. The instationarity test compares covariance within a 30 min period with the covariance of a 5 min period. The data can be considered to be stationary with a difference less than 30% between the two measuring intervals. In the second test, the integral turbulence characteristic is calculated. This is a basic similarity characteristic of atmospheric turbulence. The two tests can be transformed into a quality flag (Foken et al., 2004; LI-COR, 2015). Other tests include the recognition of instrument malfunction or data were the footprint exceeds the outreach of the homogeneous surface, also known as fetch. A well-known problem is the underestimation of the flux during periods with low turbulence, especially at night. To this end, data with a friction velocity (u*) lower than a certain threshold are filtered. The threshold is chosen site specific (Papale et al., 2006). During data processing, data spikes should be removed (Foken et al., 2004). Also a correction due to the sensor separation and the air density fluctuation is needed (LI-COR, 2015).

The energy budget closure is oft used to validate the EC measurements (Aubinet et al., 2000). The net energy flux from a system must be equal to zero in the long term. Otherwise, the temperature would increase or decrease to implausible values. This assumption result in the following equation

$$Q_* - Q_G = Q_E + Q_H \qquad (2)$$

with Q_* as net radiation influx, Q_G as soil heat flux, Q_E as latent heat flux and Q_H as sensible heat flux. The right side of the equation can be measured by the EC method, whereas the left side term is measured with other instruments. An energy balance of 80% is still considered to be good. The inaccuracy is related to heterogeneous terrain and the resulting modified turbulent exchange (Foken et al., 2012).

2.1.4 Footprint

The flux footprint is defined as the relative contribution from each element of the surface area to the measured turbulent flux (Rannik et al., 2012). It is not possible to refer the flux to a specific source/sink around the EC tower because the EC measurement of the flux is an integrated product over a large area i.e. a

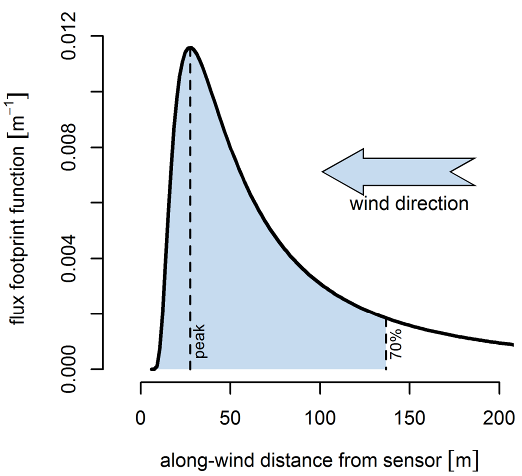

Fig. 2. Typical crosswind-integrated footprint in Fruebuel. The calculation is based on Kljun et al. (2015). The crosswind integrated footprint shows the relative contribution to the gas composition in the measured air parcels as a function of the distance along the upwind direction. 70% of the contribution to the gas composition coming from an area within 137 m upwind, with the largest contribution coming from about 28 m

mixture of several sinks and sources. Therefore, stochastic models are used to trace back a measured flux. They assume that the diffusion is similar to the dispersion of several particles, which all move independently (Kljun et al., 2002). There are also other models which follow a similar approach (Rannik et al., 2012). In all models, advection by wind carrying the turbulent eddies towards the sensor. Thereby, the prevalent wind direction determines the orientation of the footprint. Further factors influencing the footprint are the instrument height of the EC tower, the atmospheric stability and the surface roughness (Leclerc and Thurtell, 1990). The crosswind contributions can be mapped onto the prevalent wind direction and thereby simplify the 3-dimensional flux footprint. An example of such a crosswind integrated footprint is shown in FIG. 2. An unstable atmosphere and thus a high turbulence intensity, resulting in a peak of the footprint function near the EC tower. The quantiles of the function are normally given as the function goes to infinity.

2.1.4 Carbon budget

A flux is defined as the amount of an entity that passes through a closed surface per unit of time (Burba, 2013). In case of CO_2 flux, the quantity of CO_2 passing the sensor is measured. The CO_2 flux is influenced by assimilation and respiration. Respiration can be further divided into autotrophic and heterotrophic respiration. EC mix these processes into one single flux, the so-called net ecosystem exchange (NEE, Moffat et al., 2007). Note that NEE with negative sign indicating a net carbon uptake of the ecosystem as it was defined by atmospheric scientists (Chapin et al., 2006). In literature, the NEE is often equated to the negative value of net ecosystem productivity (NEP, e.g. Ciais et al., 2000; Dragoni et al., 2007). Thereby NEP is defined as

$$NEP = GPP - R_E \tag{3}$$

with GPP as gross primary production and R_E as ecosystem respiration. However, especially for agricultural land, NEP cannot be calculated only with flux data. EC can only detect fluxes related to the CO_2 exchange between ecosystem and atmosphere (Osborne et al., 2010). Additional non-vertical carbon flows like harvest have to be considered (Chapin et al., 2006).

An overview of the most important processes leading to carbon fluxes is given in FIG. 3. Small carbon losses e.g. due to methane emission are omitted for reason of simplification. Assimilation and respiration together account for more than 90% of carbon fluxes. However, there is only a very small residual surplus of around 10% between carbon uptake by photosynthesis and carbon loss through respiration (Schulze et al., 2009). Therefore, even apparent small fluxes e.g. due to manure application play an important role in carbon budget. Leaching of organic and inorganic carbon tends to be higher in grassland than in forest or cropland, and is therefore a crucial component in the net ecosystem carbon balance, shown by Kindler et al. (2011). Ammann et al. (2009) propose the following formula to assess the carbon budget of agriculturally used grassland:

$$\frac{\Delta SOC}{\Delta t} = FC_{CO2} + FC_{org.\ fertilizer} + FC_{harvest} + FC_{leaching} \qquad (4)$$

With ΔSOC/Δt as change of soil organic carbon over time and FC as carbon fluxes.

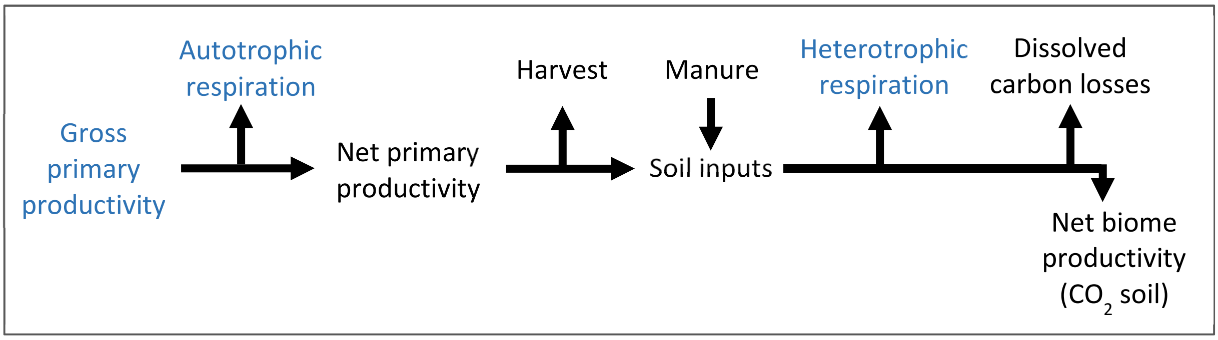

Fig. 3. The main carbon fluxes within a temperate grassland. Upward arrows stand for carbon losses, downward arrows for carbon sequestration. The path from left to right shows possible pathways for a primarily fixed carbon atom. Carbon which is not respired by plant or harvested gets into the soil together with the carbon added by manure. A large part is degraded by decomposers, a small part can be washed out in the form of dissolved organic or inorganic carbon. The remaining carbon at the end is accumulated in the soil. Net biome productivity can also be negative, indicating a loss of soil carbon. The blue printed fluxes are included in the NEE. Adapted from Schulze et al. (2009)

3. Material and methods

3.1 Site description

3.1.1 Location

The experimental site is an agriculturally used grassland at 1000 m.a.s.l in the northern alpine foothills of Switzerland. The exact position of the EC tower is 47°6'57'' N, 8°32'16'' E. The parcels belong to the research farm Fruebuel which is run by the ETH Zurich. The farm is located on the Walchwiler mountain ridge (FIG. 4) and is directly adjacent to a fen. It is part of a traditional three-stage grassland farming system, where the animals are kept in the valley over winter, at the so-called Maiensäss in early and late summer and on the alpine pastures in midsummer (Groier, 1990). The Fruebuel serves as the Maiensäss as it is located at medium altitude level.

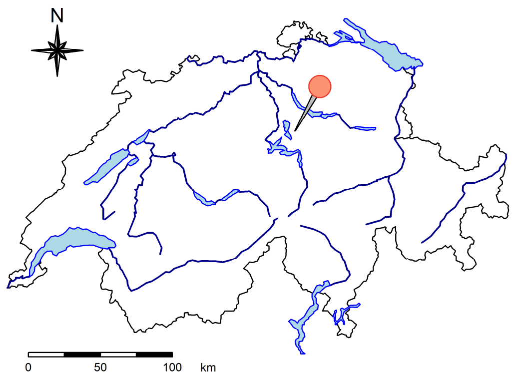

Fig. 4. Location of the Fruebuel within Switzerland.

3.1.2 Climate

The climatic conditions of Fruebuel are characterized by high rainfall and low temperature, which is typical of the alpine foothills. During the study period 2006 – 2013, we measured a mean annual temperature and cumulative annual precipitation of 7.7 °C and 1660 mm, respectively. Between February and July, the mean temperature rises from -1.5 °C to 16.5 °C (FIG. 5A). In early April, the average temperature exceeds 5 °C mark. This is often equated with the beginning of the growing season (Mueller et al., 2015). The mean temperature drops below 5 °C in November. When comparing the annual mean temperatures between the different years, two extreme years are especially striking (FIG. 5B). 2010 was exceptionally cold whereas 2011 was after 2014 the warmest year since the start of measurement in 1864 throughout Switzerland (MeteoSchweiz, 2015a). Nevertheless, there was only a small decline in precipitation on the Fruebuel compared to other sites in 2011, probably due to the Fruebuel's topographic exposure (Wolf et al., 2013).

3.1.3 Soil and vegetation

The major soil type on Fruebuel is Gleysol with a pH value of approximately 4.5. The bulk density of the uppermost 20 cm ranging between 1.3 g cm^{-3} – 1.4 g cm^{-3} (Imer et al., 2013). Due to the rolling topography, parcels have a high variable degree of water logging. Some soils are well drained (Cambisol) while others are highly exposed to groundwater (Gleysol). Thereby also the degradation rate of carbon is influenced, leading to some patches with a very high proportion of SOC. These can be classified as Histosols (Roth, 2006).

The heterogeneous soil conditions provide diverse ecological niches for a relative large number of different plants. Approximately 35 different plant species were identified (Gilgen and Buchmann, 2009). However, there are some predominant species, which cover around 90% of the surface (Sautier, 2007). They include Italian Ryegrass (*Lolium multiflorum*), Meadow Foxtail (*Alopecurus pratensis* L.), Cocksfoot Grass (*Dactylis glomerata* L.), Dandelion (*Taraxacum officinale* L.), Buttercup (*Ranunculus* L.) and White Clover (*Trifolium repens* L.).

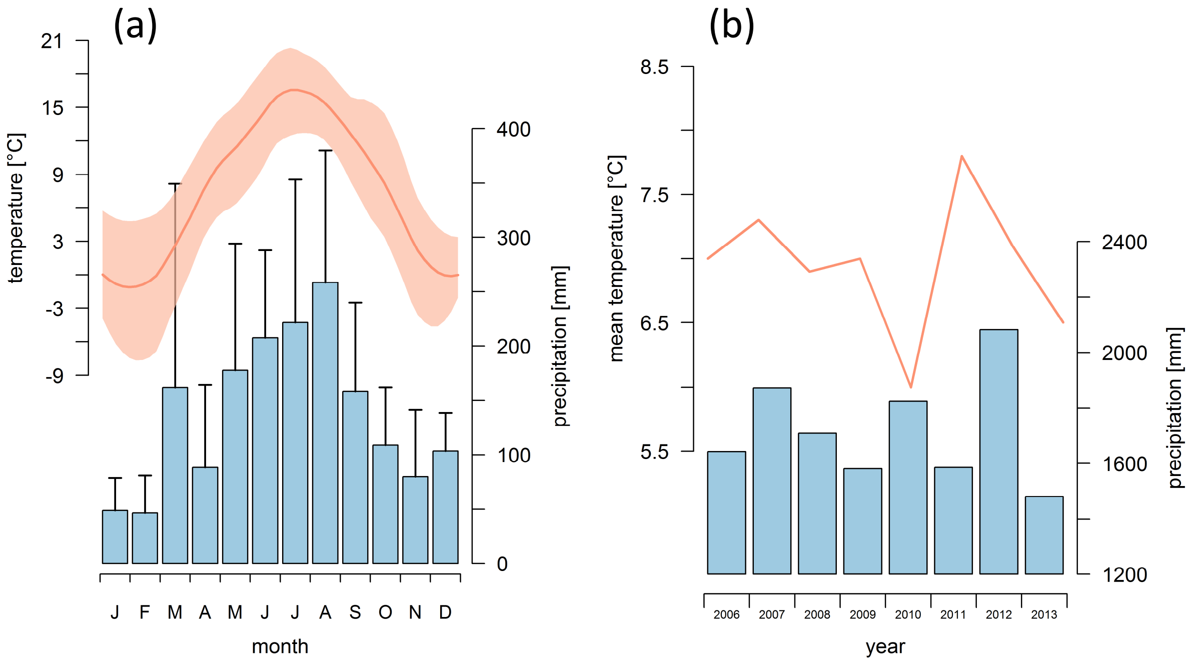

Fig. 5. Climograph of Fruebuel for 2008 – 2013. (a) The red line represents a polynomial fitted curve to the weekly average temperature. The boundaries of the red shaded area represent the warmest respectively coldest average weekly temperature during the time period investigated in this study. The precipitation of each month was added up and averaged over the eight years of data collection (blue). The whiskers show the standard deviation of each month. (b) Mean annual temperature and annual cumulative precipitation of the weather station in Einsiedeln, 16 km east of Fruebuel. Data were provided by MeteoSchweiz. The mean temperature is around 1 °C deeper than in Fruebuel.

3.1.4 Parcels

The experimental site is separated in three parcels: Leitungswiese, Sportplatz and Schutzwiese. The last two include an about 10 m wide conservation headland on the western edge to protect the adjacent fen against nutrient inflow. A map about the separation between the different parcels exists. Unfortunately, it is very imprecise and does not match with the actually boundaries used for management activities. The information about the size of the parcels changed over time. In 2012, they were fundamentally remeasured. For most parcels, there are large changes in the area specified. The difference is mainly due to the imprecise measurement methods before 2012 and not due to a new arrangement of parcels (C. Bovald, pers. comm.). Because of all these uncertainties, we determined the parcel boundaries for this study of a current orthoimage (Fig. 6). Some areas which actually belong to the three parcels were intentionally excluded, particularly areas with trees and areas which lie in the cross section of the two parcels (Table 2).

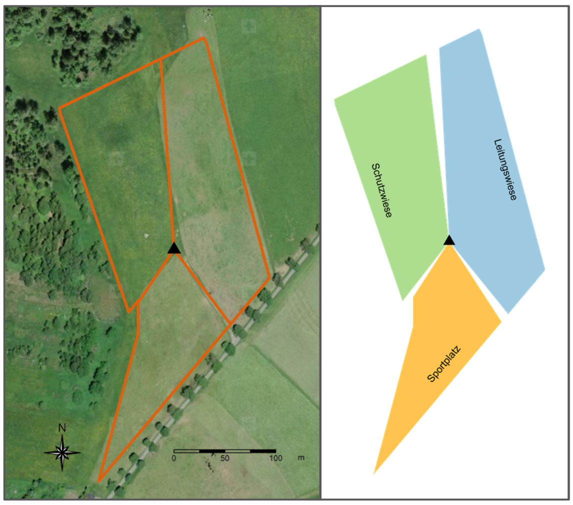

Fig. 6. Parcels of the experimental site. The eddy covariance tower is located in the middle (▲). (a) The borders to surrounding forest, peatlands, road and other cultivated areas, as well as between the different parcels were estimated using the orthoimage. The birch alley in the south-west as well as (b) a buffer zone between each parcel was not included to the individual parcels. Orthoimage of geodata © swisstop

Table 2. Specified and considered area of the different parcels.

Parcel	Bevor 2012	After 2012	Considered in this study	Comment
Leitungswiese	1.80 ha	2.00 ha	1.67 ha	Uncertainty about the boundaries on the northern edge of the parcel. Far away from the EC tower and therefore of little importance.
Sportplatz	1.53 ha	1.49 ha	1.02 ha	The considered area is significantly smaller due to the excluded birch alley.
Schutzwiese	1.80 ha	1.18 ha	1.53 ha	Very large differences in the specified areas. Uncertainty about the boundaries.

3.2 Management

All parcels are managed as permanent grassland. They are hardly ever plowed, which is typical for grassland management in Switzerland. The last tilling has been about 30 years ago when some areas were used as crop land (H.R. Wettstein pers. comm.). In order to close gaps in the canopy and to promote grass with high digestibility and productivity, parcels were occasionally overseeded. In Switzerland, grassland is classified in four intensity levels according to cut frequency, grazing frequency and fertilizer application (AGFF, 2009). The Schutzwiese is classified as extensive, which is the lowest level. No utilization bevor the 1th of July is a prerequisite for these meadows. In return, the farmer is entitled to get contribution payments for ecological value (BLW, 2016). Leitungswiese and Sportplatz are classified as mid intensive which is the second highest level. Such meadows are usually used 3-4 times per year. All management events were actual farm operations not controlled by the research group. The operations were recorded in a field book. Some of them only took place on partial area. If they affected less than 10% of the area of a parcel, they have been omitted for data analysis. One grazing event on the Schutzwiese in 2009 was probably entered incorrectly and was omitted after consultation with the farmer. The continuous control of Alpine Dock (*Rumex alpinus* L.) by hand removal took place on some parcels. It was not considered, since it has only a small influence on the carbon dynamic. FIG. 7 shows all management events within the study period, which have been considered for data evaluation. Certain changes in management practices are visible over the time. Before 2009, the Schutzwiese was not fertilized. The grazing frequency is much higher on Leitungswiese and Sportplatz since 2011.

3.3 Environmental measurements

The EC tower on the Fruebuel is equipped with a large number of sensors (FIG. 8). The air temperature was measured at 2 meters (a shaded, sheltered and ventilated HydroClip S3, Rotronic AG, Basserdorf, Switzerland). To measure the radiation balance, a Photosynthetically active radiation (PAR) Sensor (K&Z PARlite, Kipp & Zonen B.V., Delft, The Nederlands) and a Net-Radiometer (CNR1, Kipp & Zonen B.V., Delft, The Netherlands) was used. Soil measurements included temperature (TB107, Markasub AG, Olten, Switzerland) and humidity (ML2x, Delta-T Devices Ltd. Cambridge, UK) at different depths. Sum of precipitation was measured with a rain gauge (Type 10116, Toss GmbH, Potsdam, Germany). The environmental data were measured every 10 s. Afterwards, 30 min average values or sums were calculated and stored on a field data logger (CR10X-2M, Campbell Scientific Inc., Logan, USA).

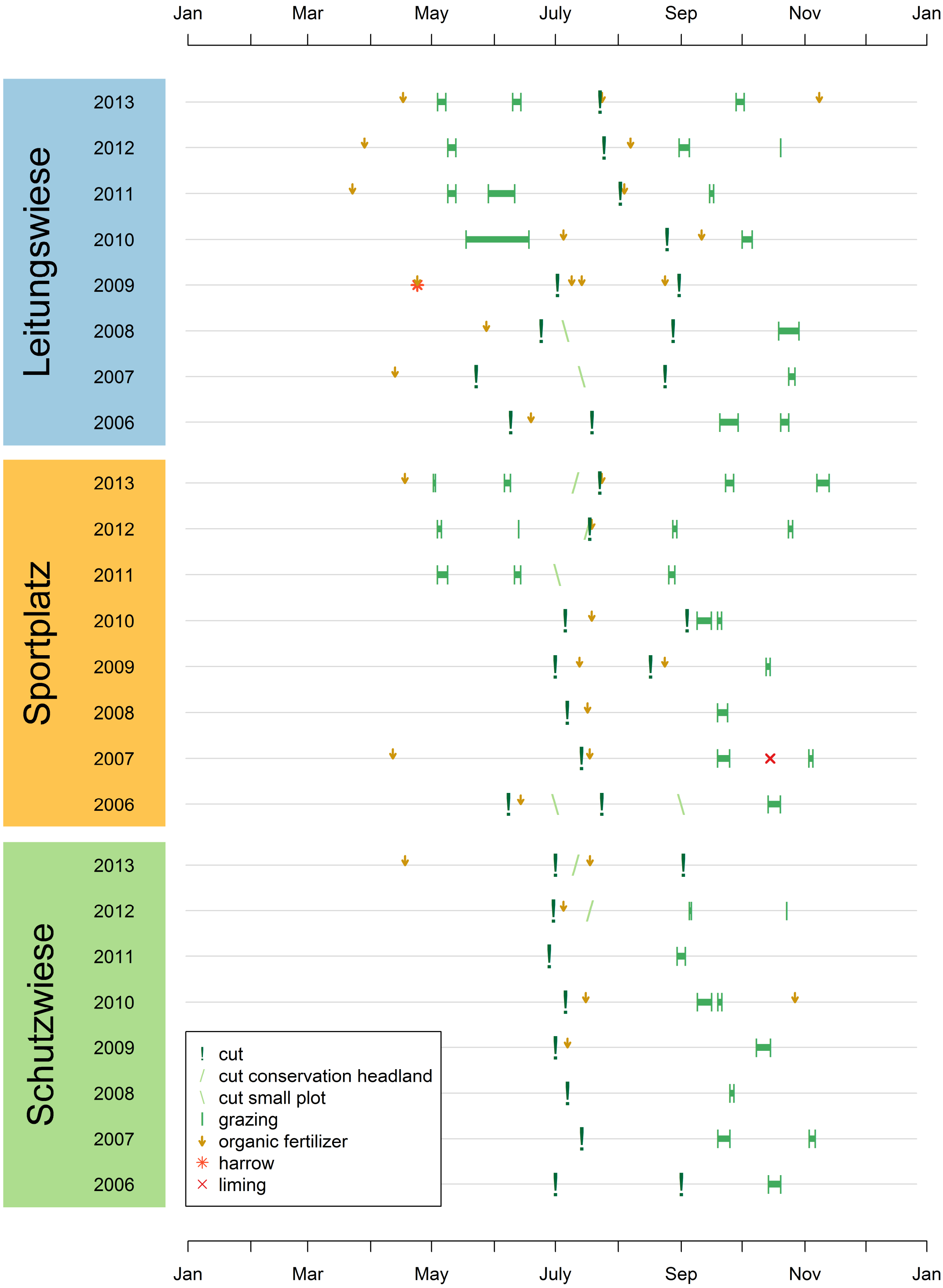

Fig. 7. Management differences at Leitungswiese, Sportplatz and Schutzwiese. The first column lists all usages over the years. There is a conservation headland strip along the forest border of Sportplatz and Schutzwiese, which is managed separately (/). Sometimes only a partial area of a plot was cut. Events, where less than half of the plot was affected are represented by a backslash (\).

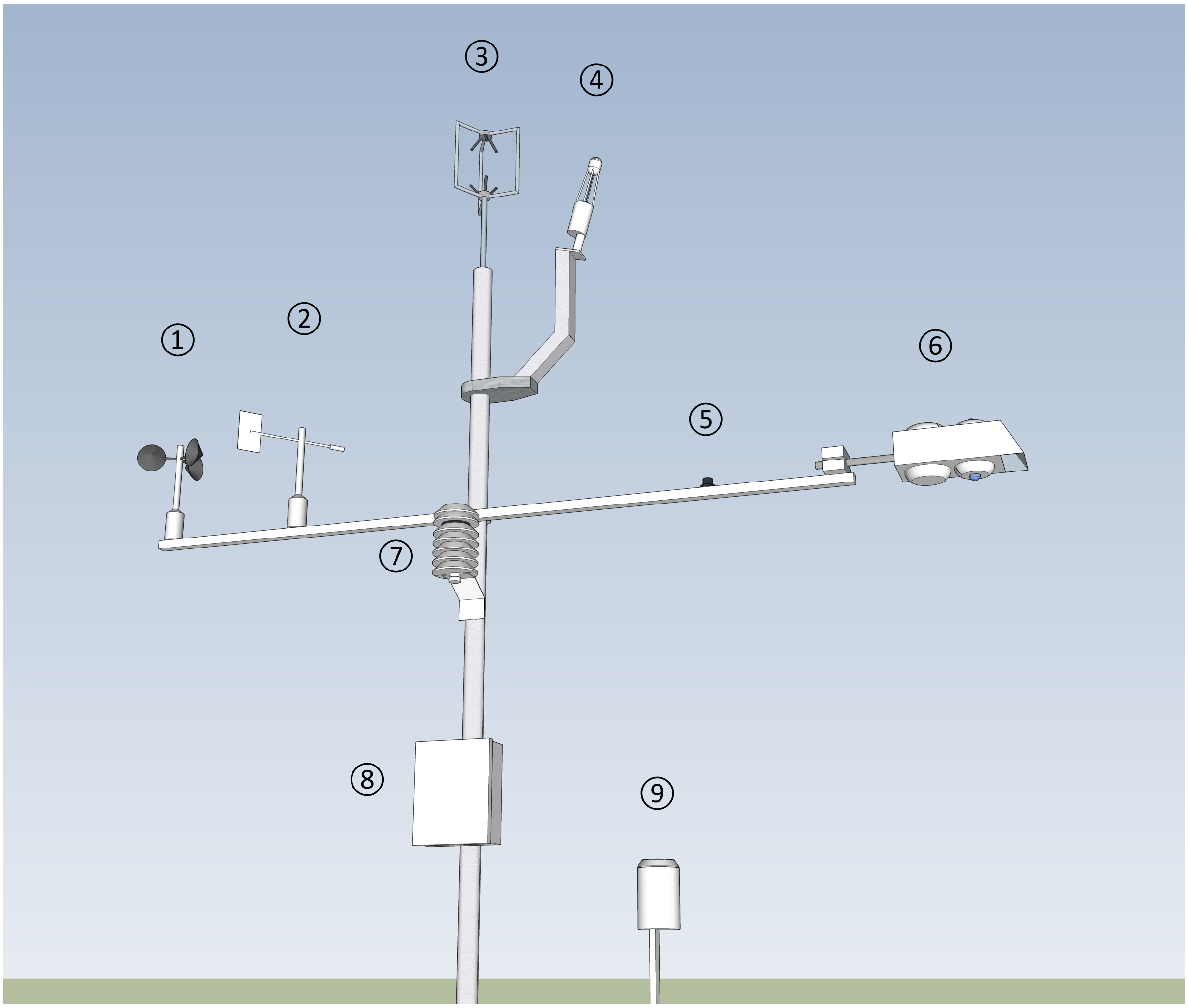

Fig. 8. Setup of the eddy covariance tower at Fruebuel: ① Wind Anemometer Rotor, ② Wind Anemometer, ③ Sonic Anemometer, ④ Infrared gas analyzer, ⑤ PAR Sensor, ⑥ Net-Radiometer, ⑦ Thermometer ⑧ Data Logger, ⑨ Rain Gauge.

3.5 Eddy covariance

3.5.1 Data acquisition

The EC measurements were performed with a three-dimensional sonic anemometer (model Solent R3, Gill Instruments, UK) and an open path infrared gas analyser (Li-7500, Li-Cor, Lincoln, USA). The sonic anemometer was installed on a height of 2.55 m and the measurement frequency of both instruments was 20 Hz. Raw data were processed with the EddyPro software (EddyPro®, 2015). The software calculated half-hourly averaged fluxes and carried out the most important correction e.g. time lag compensation or density fluctuations compensation (LI-COR, 2015). A north offset of 190° was corrected manually.

3.5.2 Filtering

The data were filtered on the basis of data quality criteria. Whenever the CO_2 fluxes took implausible values ($|F| > 50$ µmol s^{-1} m^{-2}) they were discarded as outliers. The instationarity test and the test with integral turbulence characteristic were performed and a quality flag after Foken et al. (2004) was calculated. Data of poor quality (Quality flag = 2) were discarded. Additional filtering eliminated data with too low friction velocity ($u* < 0.08$ m^2 s^{-2}). The threshold was chosen according to previous studies about Fruebuel (Wolf et al., 2013; Zeeman et al., 2010). As FIG. 2 suggests, flux footprint can be quite long, depending on the meteorological conditions. A larger footprint can cause a distortion of measurement by carbon sinks/sources from outside the parcel. In order to prevent this, the crosswind integrated 70% quantile for all half-hour measurements was determined according to the model of Kljun et al. (2004). As this model is not defined for certain atmospheric condition, the remaining footprints were estimated based on a method of Kormann and Meixner (2001). Half-hour measurements with a 70% quantile outside the experimental area were discarded. The threshold distance is given by a function of the wind direction (FIG. 9) since the distance from EC tower to the site edge varies greatly. After the filtering, the data were assigned to one of the three parcels. The assignment was based on the prevalent wind direction within the half-hour measuring period. Data were discarded if the wind direction was coming from a buffer zone between two parcels. Overall, 65% of all data have been discarded (TABLE 3).

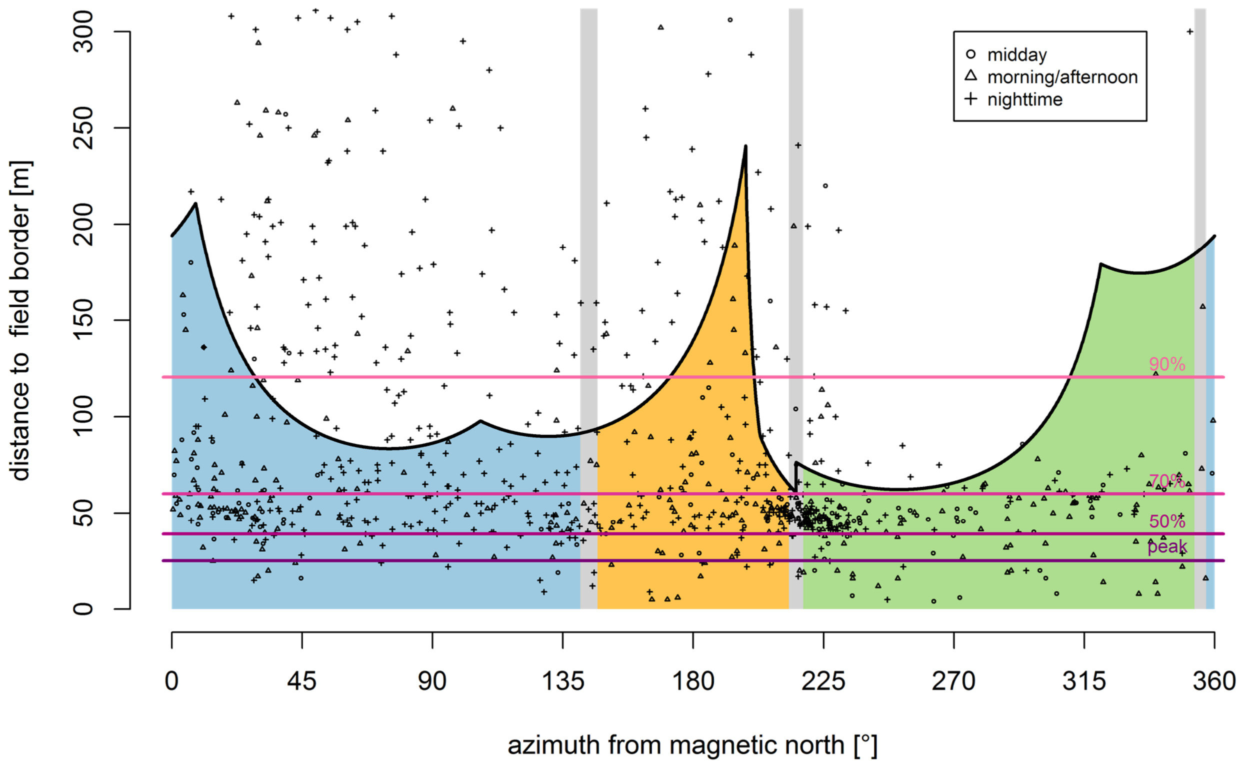

Fig. 9. Distance between EC tower and site edge as a function of azimuth from magnetic north. Everything under the curve belongs to the experimental site. The gray shaded areas represent the buffer zones. 1000 randomly selected 70% quantiles of the crosswind integrated footprint function were plotted as small symbols according to the time of day. All data points which 70% quantile is outside of the shaded area are not included in the data analysis. The horizontal lines correspond to the median of some footprint quantiles (peak, 50%, 70%, 90%) of all measured data. The median of the 70% quantiles lies everywhere within the experimental site.

Table 3. Filtering criteria, absolute number of half-hour measurements and relative to the total number. The whole site has a good quality data coverage of 35%

Criteria	Measurements	% total
Total	140’256	100%
Filtering		
Technical failure	21’156	15%
Outliers	2’739	2%
Quality flag	31’452	22%
Friction velocity	19’167	14%
Footprint	13’112	9%
Buffer zone	3’723	3%
Total filtered	91’349	65%
Good quality data	48’907	35%

3.5.3 Data validation

The energy budget closure for the Fruebuel flux data between 2006 – 2007 has been performed by Zeeman et al. (2010). The result was a budget closure of 78%, which is comparable to other studies (e.g. Wilson et al., 2002). For this reason, no further data validation tests have been carried out.

3.6 Data evaluation

3.6.1 Approach

The EC method is widely used in the scientific community. There are several approaches how to investigate the influence of management on the CO_2 flux. Best practise experimental design includes two or more adjacent parcels, each of them equipped with an EC tower (e.g. Allard et al., 2007; Ammann et al., 2009; Skinner, 2013). The parcels should be as homogeneous as possible and only differ in management. Since those experimental designs are complex and expensive, they cannot be applied to all kind of ecosystems. Another approach compares the fluxes of parcels which are distributed over larger areas or even continents (e.g. Chang et al., 2013; Hirata et al., 2013). However, with this approach it is more difficult to separate the influence of the management from the influence of the environmental factors.

In this study, the three parcels are exposed to very similar environmental condition, due to their geographical proximity. Only one EC tower in the middle of all parcels performs the measurements. The tower measures the CO_2 flux attributed to the area of the footprint. The footprint changes its size and its orientation due to meteorological conditions. In the worst case, the footprint is exactly located between two parcels. Then, the flux corresponds to a mixture of the two experimental treatment groups and cannot be split on each parcel. In the best case, it covers the area of only one parcel. Then, the flux can be directly assigned to one experimental treatment group. This approach never allows the simultaneous and separate flux measurement for multiple parcels. For statistical analysis, this means no paired samples. In addition, the availability of data is very low, since the time series of measurement is divided among the three parcels and some measurements cannot be assigned to a certain parcel.

3.6.2 Gap-filling

One possible option to solve the problem of unpaired samples would be to interpolate the missing data points of each parcel. This approach, usually referred to as gap filling, is widely used and represents a proven process in the EC method (Moffat et al., 2007). The accuracy of the models has increased greatly in recent years (Wang et al., 2015). However, a data coverage of 40% is frequently noted as the lower limit in order to produce defensible annual sums of CO_2 fluxes. The accuracy of the gap filling decreases with low data coverage (Falge et al., 2001). In this study, the gap filling for each parcel would probably lead to a blurring of the CO_2 flux differences between the parcels. For this reason, no gap filling was performed. This makes it impossible to establish an exact carbon budget for each parcel. In return, the existing data will have a higher credibility.

3.6.3 Wind direction and Footprint

The prevalent horizontal wind direction and crosswind integrated peak as well as the crosswind integrated 70% quantile were calculated for 30 min periods with EddyPro® (2015). The wind direction frequency was plotted on a 360° circle for different time of day periods. Thereby, we wanted to detect any temporal pattern in the wind direction. The data coverage of each parcel was calculated and further subdivided for different daytime periods. As mentioned in CHAPTER 3.5.2, the 70% quantiles were used as filter criterion. The crosswind integrated peaks were plotted along their wind direction to get an idea of the annual flux footprint.

3.6.4 CO_2 flux differences between parcels

The half-hourly CO_2 flux measurements were separated into categories based on time of day and the assigned parcel. The time of day was divided into daytime and nighttime according to the photosynthetic photon flux density (PPFD), whereby a half-hourly mean PPFD > 10 µmol m^{-2} s^{-1} was classified as daytime. The category daytime was further divided into midday (10 a.m. – 14 p.m.) and morning/afternoon. Differences in the mean between the categories were determined by Tukey's honest significant difference test.

3.6.5 Annual course

By comparing the data of the entire study period, the incomplete time series of each parcel can lead to a slight distortion in the results. Even if the season has only a small influence on the wind patter, the footprint might not be entirely independent of the season. This could lead to a shift in the data coverage for each parcel over the course of the year. Since the CO_2 flux varies greatly within a year, a changing data coverage has a great influence on the calculated annual mean. This can be prevented by comparing only CO_2 fluxes, which have been collected within a smaller time range.

The CO_2 fluxes were averaged on a monthly and on a weekly basis, separately for each parcel. A polynomial function was fitted to the annual course of the weekly averaged data. A regression was used to evaluate the link between the date of first use and the CO_2 flux in spring months. Also, the influence of use intensity on the typical pattern of CO_2 fluxes during the year was examined by regression. As use intensity, we defined the number of cut and grazing events per year. Events, which took place on less than half of a parcel were counted only half. This is a highly simplified form to indicate the use intensity. It is an approximation of how often the aboveground biomass is removed per year.

3.6.6 Similar environmental conditions

Another problem might be the dependence of wind direction and environmental conditions. Local weather situations (e.g. Bise, Foehn, …) are usually linked to a certain wind direction. At the same time, they influence important environmental parameters such as temperature and precipitation (MeteoSchweiz, 2015b). Wind direction is the determining factor for the assignment of CO_2 fluxes to a certain parcel. If the wind direction is always linked to a specific environmental condition, the measured fluxes would not be comparable across different parcels. Here an example to explain it a bit more visually: north wind is associated with low temperature, whereas south wind is associated with high temperature. The flux of a parcel located north of the EC tower would therefore constantly be measured under lower temperatures compared to a parcel south of the EC tower. The effect influences the measurements all year round. It cannot be eliminated by the evaluation of individual weeks.

In order to exclude this distortion, data must not be compared within the same time period. Instead, the environmental conditions under which they were measured, should be comparable. For this purpose, 24 different environmental conditions were defined. They are the result of the combination of four air temperature ranges (-10 – 5 °C, 5 – 15 °C, 15 – 20 °C and 20 – 30 °C), three soil water content (SWC) ranges (0.3 – 0.5, 0.5 – 0.55 and 0.55 – 0.7) and two ranges of incoming radiation (daytime and nighttime). The ranges with extreme environmental conditions were chosen to be wider, because they should still contain a meaningful number of fluxes. Differences in the mean CO_2 flux between the parcels were calculated for each environmental condition individually.

3.6.7 Single management activity

In addition to the general effects of management intensity also the short-term effect of individual management events was examined. The focus was on the three most common management events in Swiss grassland: cut, grazing and application of organic fertilizer. Events were only considered if they affected at least half of a parcel. The daily mean of daytime CO_2 flux was calculated for 29 days, always 14 days before and 14 days after the management event. The course of the CO_2 flux was fitted by a curve according to weighted last squares. The differences between mean CO_2 fluxes before and after the management event was evaluated using a Student’s t-test. The data for each event was previously tested on normal distribution by a Shapiro-Wilk normality test. For data which did not meet the assumption of normal distribution, a Wilcoxon rank sum test was performed in place of the t-test.

The Sportplatz was limed at the end of 2007. This provided the opportunity to examine the long-term effect of a single liming event. All CO_2 fluxes of the subsequent years after 2007 were compared to the year 2006 before the liming event. The calculation was carried out separately for daytime and nighttime fluxes.

3.6.8 Evaluating Experimental design

The EC tower of Fruebuel lies within a very heterogeneous landscape. The accuracy of the EC measurement could be affected since horizontal homogeneity represents a theoretical prerequisite for the EC methodology. In particular, the adjacent fen on the western edge of the experimental site was expected to affect the CO_2 measurement. The filtering of data with a long footprint should minimize this influence. To evaluate the necessity for this filtering, the mean flux of the discarded data was compared to the mean flux of the data within the parcel. The evaluation was done separately for every month of the year.

Another aim was to investigate the suspected influence of the wind direction on the environmental conditions. Therefore, the air temperature was plotted against wind direction. Individual months were examined in order to recognize seasonal changes.

3.7 Software

All data evaluation and statistical tests were performed using the statistical software R (R Development Core Team, 2016). The processing of the raw EC data has been made with the software EddyPro® (2015).

4. Results

4.1 Wind direction and footprint

There are two main wind directions on the Fruebuel: south-east and north-west (Fig. 10). During the daytime, more than 70% of the winds come along these two directions. Overnight, the average wind speed drops slightly and the wind comes more often from south-eastern direction. The variation of the wind pattern is bigger between night and day than between seasons. A further subdivision of the time of day, for example, in midday and morning/afternoon did not reveal any change in the wind pattern. The wind direction and the wind speed determine the orientation and the proportions of the footprint. The illustrations in Fig. 10 b) and c) correspond to a simplified form of the footprint. They do not show the contribution of each area, but how often a certain point in the area represented the maximum of the footprint. Nevertheless, the figures are suitable to get an idea, from where the largest contribution to the measured flux comes. In the case of Fruebuel it is an area about 25 meters south-west of the EC tower. As it is located directly on the border between Sportplatz and Schutzwiese, many of these measured fluxes cannot be assigned to one of the parcels and are therefore discarded. Fortunately, it also means that the footprint includes fluxes from all three parcels.

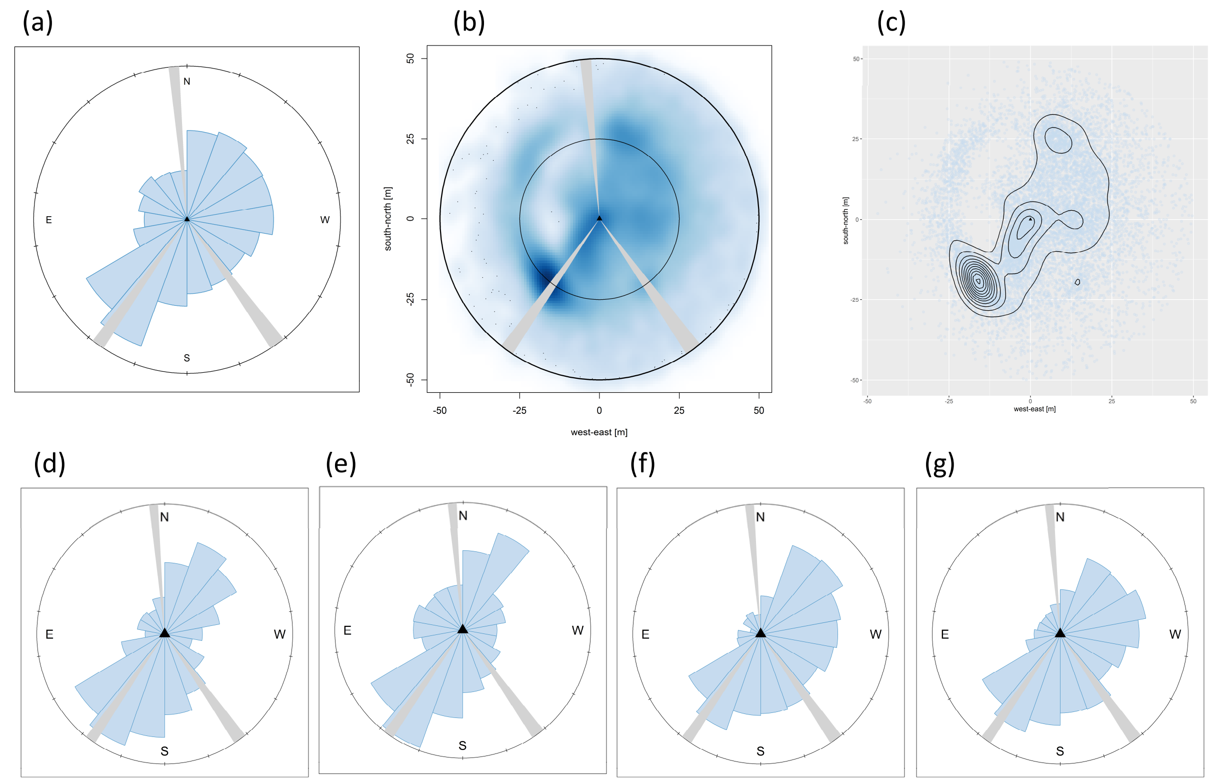

Fig. 10. Wind rose and footprint of Fruebuel. The eddy covariance tower is located in the middle (▲). The gray shaded areas represent the buffer zones. Wind rose diagram shows the relative frequency of horizontal wind directions. Throughout the whole year (a) prevalent wind direction is from south-east and north-west. This is further divided into the wind pattern of (d) January daytime, (e) July daytime, (f) January nighttime and (g) July nighttime. The major wind direction affects the footprint, shown as (b) density plot of the crosswind integrated peaks and (c) isolines, connecting the points with the same crosswind integrated peak density.

Nocturnal low-turbulence conditions are a typical problem on many site. It leads to a rejection of many nighttime fluxes in the filtering process. This effect can also be seen on the Fruebuel. The data coverage for nighttime fluxes is extremely low (TABLE 4). At the same time there are large differences in data coverage for different time of day periods between the parcels. Therefore, it is very important to calculate average values only over a certain time of day period. Otherwise, the different data coverage for a different time of day could affect the mean values greatly. Generally, we notice a higher data coverage in summer months. Of all measured fluxes, only 23% were assigned to Sportplatz. This resulted in a low data coverage of 8.1%.

Table 4. Data coverage and share of total data separately for each parcel

	Leitungs-wiese	Sport-platz	Schutz-wiese
data coverage			
overall	13.2%	8.1%	13.5%
by time of day			
Daytime	20.5%	10.5%	24.0%
Nighttime	8.8%	7.1%	6.1%
by season			
January	7.6%	7.1%	8.5%
July	18.1%	10.5%	19.5%
data share			
Overall	38%	23%	39%
Daytime	37%	19%	44%
Nighttime	40%	32%	28%

4.2 Annual flux differences

4.2.1 Overall differences

The comparison of all half-hourly flux measurements grouped according to different times of day reveals the strong dependence of the CO_2 flux on the time of day (FIG. 11). In all parcels the midday flux is the lowest. At night, all parcels show a positive average CO_2 flux, meaning they are a net source of CO_2 for the atmosphere. The differences between parcels are much smaller than between the time of day. The variation is large and comes along with many outliers in every group. Nevertheless, it is striking that the Sportplatz has the highest CO_2 flux in every time of day category. The Tukey HSD failed in the statistical evaluation of the data. The data are strongly influenced by serial correlation. Even by aggregating fluxes to daily or weekly values, the serial correlation was still too big in order to make robust statistical statements. Attempts to integrate the serial correlation into the model with a generalized least squares approach failed due to the large amounts of data.

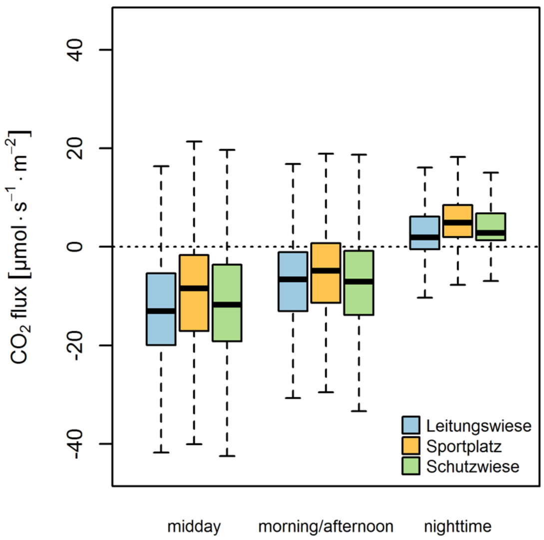

Fig. 11. Boxplots of all half hour CO_2 flux measurements, separated according to time of day (midday, morning/afternoon and nighttime) and parcels. In all experimental groups, there are outliers over the entire span from -50 to 50 µmol s^{-1} m^{-2}. They are not shown in the figure.

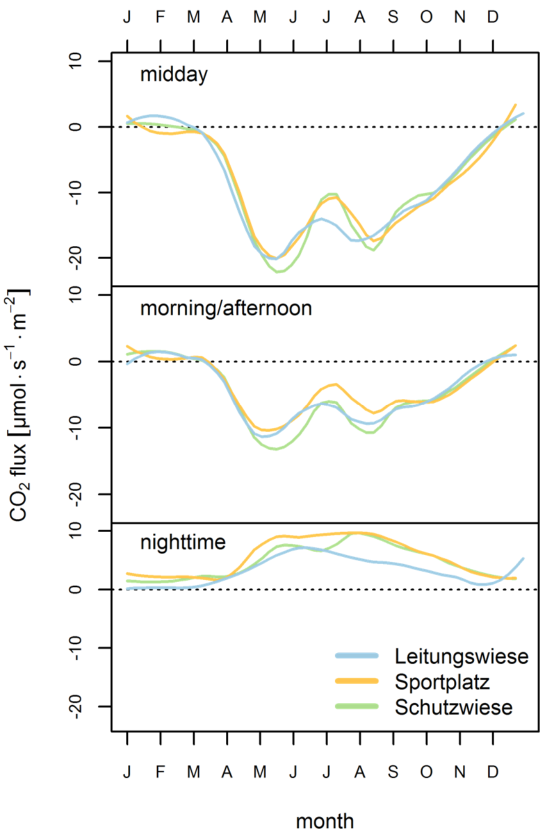

Fig. 12. CO_2 flux course of the year. The weekly mean CO_2 flux separated by time of day and parcel have been fitted by a polynomial function.

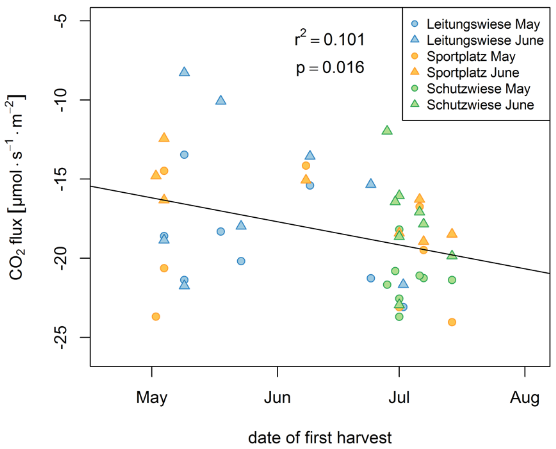

Fig. 13. Mean midday CO_2 Flux aggregated for month May and June plotted against the date of first use (cut or grazing) in the corresponding year. The coefficient of determination for the calculated regression is given as adjusted r^2. The p-value refers to the F-test of the regression.

4.2.2 Annual course

All parcels show a very similar annual course of the CO_2 flux (FIG. 12.). In mid-March, the midday CO_2 flux begins to decline and reach the first minimum in the middle of May. A second minimum is reached in mid-August. In between, during the midsummer months June and July, the CO_2 flux rises very strongly for a limited period of time. This period is also described in the growth rate course of grasses and is in literature referred to as summer depression (Maragni et al., 2000). In most of the years, there was found a plateau phase of the CO_2 flux around September. Subsequently the CO_2 flux rises again just above zero in winter. An annual course of monthly data with associated standard error is shown in the appendix (FIG. 21). The morning/afternoon course is very similar but a bit less pronounced. The courses of the nocturnal CO_2 fluxes are approximately the opposite direction. In winter they are at a similar level as the daytime fluxes. Over the summer, the CO_2 flux rises up to 10 µmol s^{-2} m^{-2}.

Although the three different parcels have a very similar pattern, there are three striking differences to emphasize: (i) Generally a higher nighttime flux on Sportplatz can be observed, indicating a higher respiration rate. It was already suggested in FIG. 11 and has also an impact on the daytime fluxes. (ii) The Schutzwiese reaches a considerably lower minimum in the middle of May compared to the other two parcels. Also the second minima in mid-August is lower than the others. (iii) Like no other parcel, the daytime CO_2 flux of the Schutzwiese rises very sharply in summer and surpasses in July even the midday CO_2 flux of Sportplatz. These observations were recorded in the eight years averaged course. Individual years in some cases differ from these general observations. However, all curves have in common the basic form with two minima.

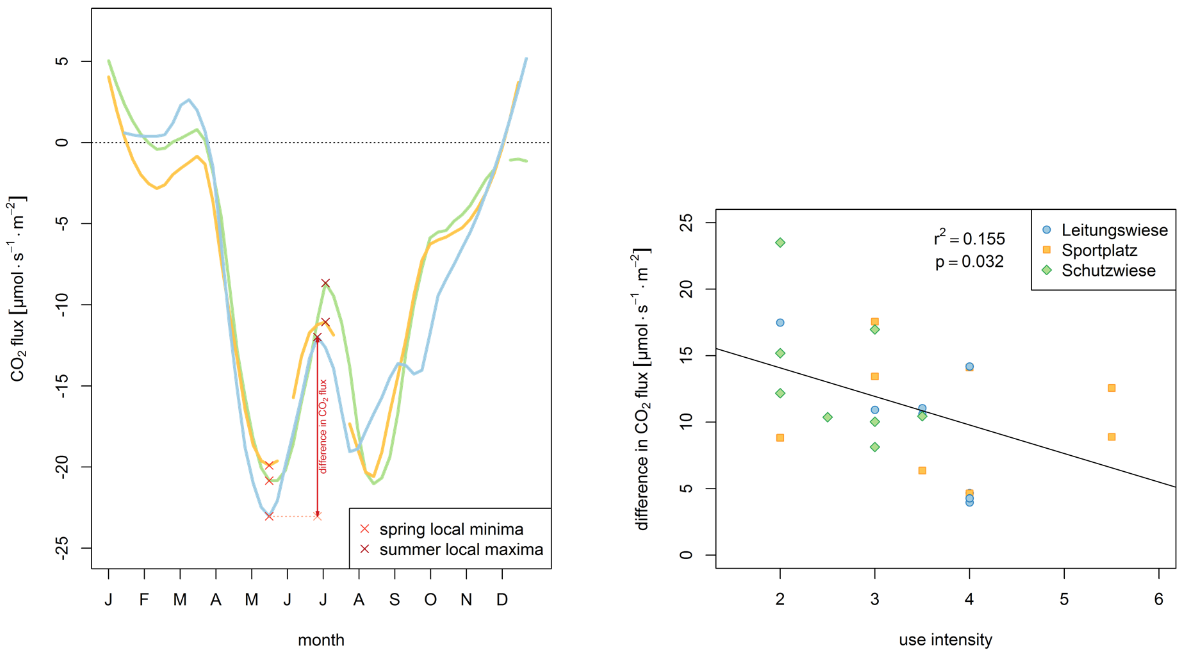

Fig. 14. Summer depression is less pronounced in frequently used grassland. (a) Difference between spring local minimum and summer local maximum of CO_2 flux was calculated for every year and parcel separately (e.g. here shown Leitungswiese in 2008) and (b) plotted against use intensity. Use intensity was measured in number of uses per year. There are some gaps in certain courses of CO_2 flux due to the low data coverage. The coefficient of determination for the calculated regression is given as adjusted r^2. The p-value refers to the F-test of the regression.

The regression analysis between the first date of harvest and the CO_2 flux in May and June show a clear negative relationship between the two variables (FIG. 13). An early cut or grazing event is usually associated with a higher CO_2 flux in the months of May and June. Nevertheless, there is a large scatter around the regression line resulting in a rather small coefficient of determination. The second linear regression which analyses the link between the use intensity and the extent of summer depression was also significant (FIG. 14). As a measure for summer depression, we used the difference between the minimum flux in the spring and the summer maximum. The average difference was 9.6, 10.8 and 13.4 µmol s^{-2} m^{-2} for Leitungswiese, Sportplatz and Schutzwiese, respectively.

4.2.3 Similar environmental conditions

Through the comparison of different environmental conditions, one recognizes the underlying meteorological factor which controls the course of the year. As might be expected, all mean fluxes of the twelve daytime environment are negative, whereas all nighttime mean fluxes are positive (FIG. 15). The nighttime fluxes are constantly increasing with rising temperature, whereas the daytime fluxes are mainly decreasing. However, a saturation effect can be observed around 20 °C during daytime. Based on these data, the impact of the SWC on fluxes is much less clear. No overall trend which would be valid for all temperature ranges can be detected.

By comparing the different parcels, hardly any differences can be observed at temperatures which do not allow plant growth (-10 °C – 5 °C). Within the dominant temperature range on the Fruebuel (5 °C – 15 °C) the CO_2 flux differences between the different parcels are relatively constant, regardless of the SWC and with low standard error. In this temperature range, the Sportplatz has constantly the highest CO_2 flux. At higher temperature ranges, the relative CO_2

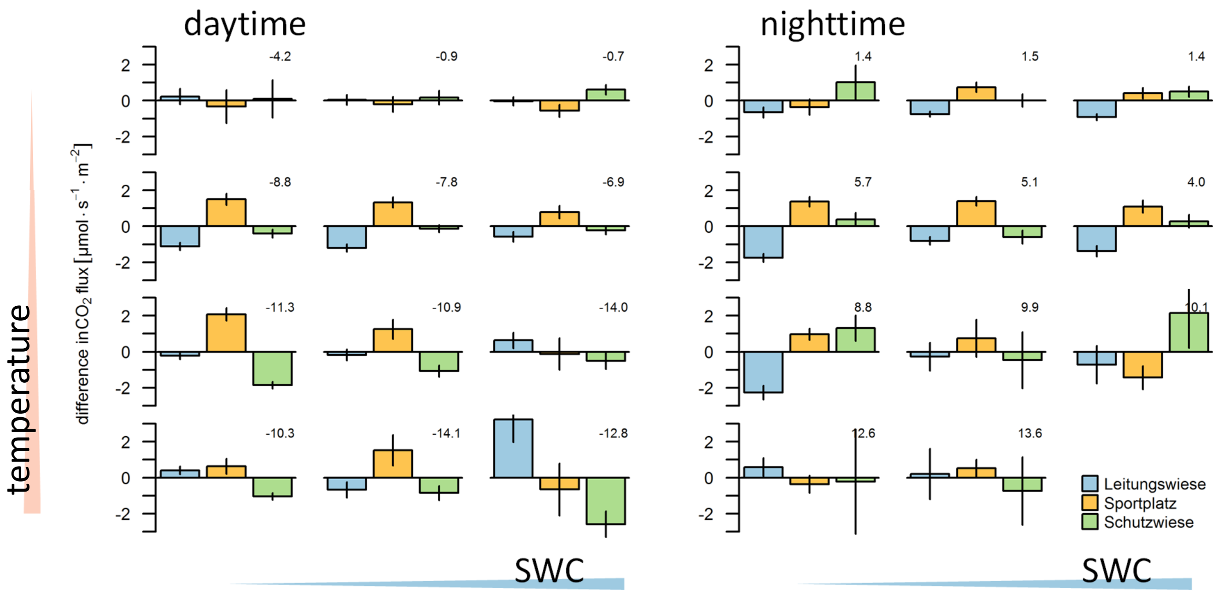

Fig. 15. The CO_2 flux differences between parcels depend on the environmental conditions. The data are spitted into daytime (left panel) and nighttime (right panel). Each of the 12 fields in one panel corresponds to a particular range of air temperature and soil water content (SWC). The temperature conditions change from top to bottom with the following ranges: -10 – 5 °C, 5 – 15 °C, 15 – 20 °C and 20 – 30 °C. The SWC range change from left to right: 0.3 – 0.5, 0.5 – 0.55 and 0.55 – 0.7. The zero line corresponds to the mean CO_2 flux of all three parcels for the specific environmental condition. The mean is stated above each field in µmol s^{-1} m^{-2}. The bar shows the difference to this mean for a specific parcel. The whiskers represent the standard error of a single parcel CO_2 flux.

flux from Sportplatz tends to decrease with higher SWC, whereas the flux from Leitungswiese tends to increase. However, the trend is not entirely clear and the standard error is already quite large due to the low data coverage. Specifically, data with high temperature and high SWC are rare. The last field in the nighttime panel could not be plotted because there was no data for this environmental condition. Therefore, it is not possible to make reasonable statements about the response of the different parcels to such environmental conditions. Furthermore, such extreme conditions are relatively rare and thus the flux within the short time range of this condition have little influence on the whole annual carbon budget.

4.3 Single management activity

4.3.1 Cut, grazing and organic fertilizer

The time series of CO_2 flux after a particular management activity show clearly the substantial effect of management on the short-term CO_2 flux (FIG. 16). Use of grassland leads generally to an increase of CO_2 flux for a limited period of time. The increase is much more abrupt in the case of a cut compared to grazing. It has to be emphasised, that grazing takes place over a longer period of time. The average grazing duration was 4.7 days. Regardless of the type of use, the CO_2 flux start to decline shortly after the event and reach after 20 – 30 days the level as before the management activity. FIG. 16B implies an increase of CO_2 flux even before the actual grazing begin. However, we suspect that these peaks are caused by random fluctuations. Obviously the fitted curve is influenced by the fluxes after the grazing period and begins to rise very early. The time series after an organic fertilizer treatment shows a decline of the mean CO_2 flux from around 6 µmol s^{-2} m^{-2} to 12 µmol s^{-2} m^{-2} within 14 days. When comparing the time series of the different parcels after grazing, we see big differences, especially in the first days. The Schutzwiese has a very rapid and strong response on grazing, whereas the Sportplatz CO_2 flux react considerably slower. The differences between parcels after a cut are more difficult to detect since all fluxes rise very abruptly.

A statistical analysis of the short-term impact of management supports the visual findings of the time series (FIG. 17). The increase due to cut is more apparent than the increase due to grazing. Only 40% of grazing events show a significant ($p < 0.05$) increase of the CO_2 flux, compared to 70% of cut events. Organic fertilizer has the opposite effect than use (cut or grazing), but less pronounced. The comparison between parcels shows only very small differences.

4.3.2 Liming

Evaluating the long-term effects of liming with the data basis of Fruebuel turns out to be a major challenge as there is only one liming event and it took place in 2007. Therefore, we had the data of only one year before the liming event and it would be a challenge to distinguish between the effect of liming and random fluctuations. The result of the comparison between 2006 and the rest of the years is added in the appendix (FIG. 22). The year 2006 is indeed marked by generally higher CO_2 fluxes compared to the other years. However, this can also be observed on the other parcels, which points to an environmental rather than an effect of liming.

4.4 Evaluating experimental design

When comparing data with different footprint lengths we find significant daytime flux differences in most summer months for Leitungswiese and Sportplatz (FIG. 18). Measurements of the two parcels with short footprint generally reveal a more negative CO_2

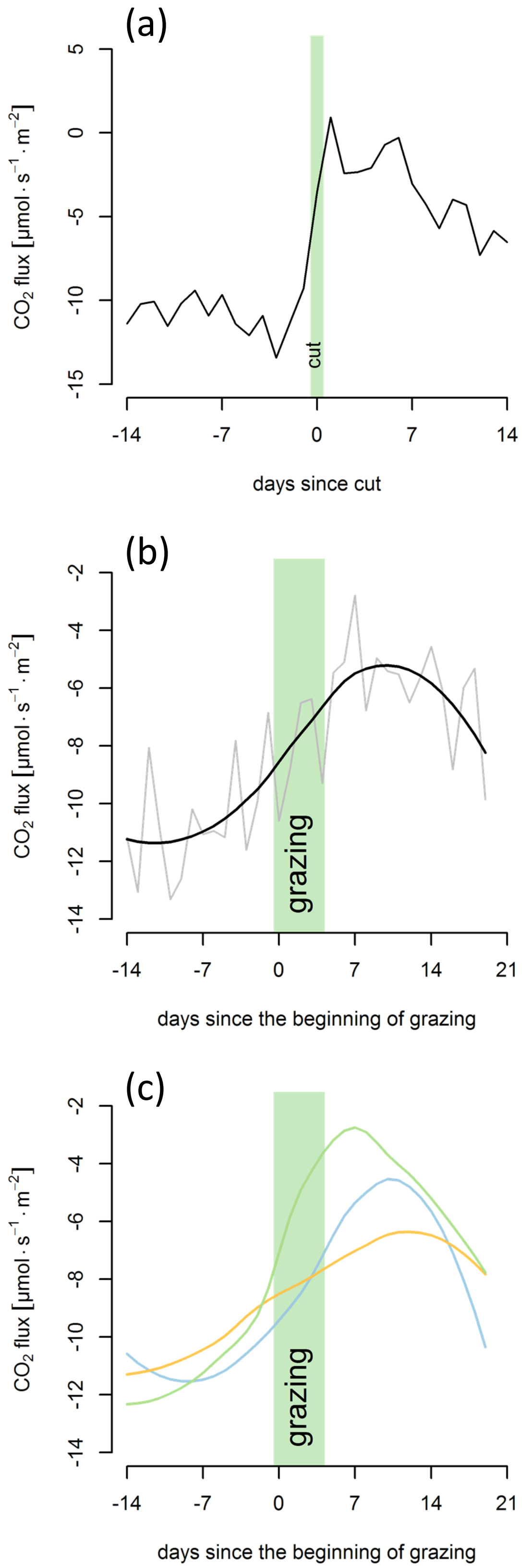

Fig. 16. Course of the CO_2 flux is influenced by management events. Mean daytime CO_2 flux between 14 days before start and 14 after the end of management event are shown for (a) 30 cut events and (b) 38 grazing events. The displayed grazing period corresponding to the average grazing duration of 4.7 days. Smooth lines represent a polynomial fitted curve. (c) A further distinction was made between the three different parcels for grazing.

flux. No such trend can be observed in the Schutzwiese.

The wind patterns on the Fruebuel remains fairly constant over the different seasons (SEE CHAPTER 4.1). Although, the environmental conditions which are linked to a particular wind direction change greatly over the course of the year (FIG. 19). Despite large scatter of the temperature data, we find clear trends associated with the wind direction. South-west wind is generally related to high temperature during winter. The temperature is in the range of -5 °C – 10 °C. The average is 5 °C higher compared to the air temperature of north-eastern direction. This trend reverses in summer. South-west wind is then associated with relatively cool temperatures of about 12 °C. The trend is much less pronounced in summer.

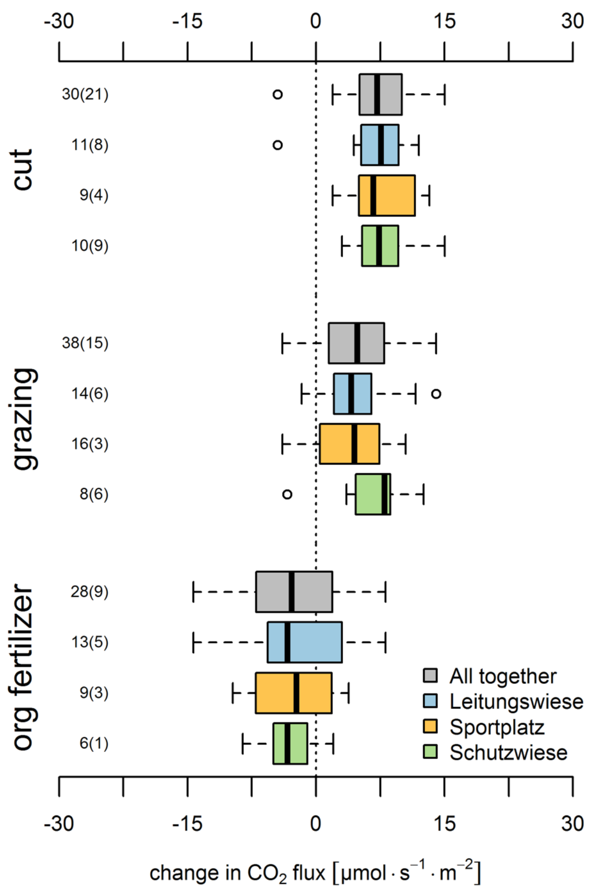

Fig. 17. Effect of major management activities on CO_2 flux. Daily average values of daytime CO_2 flux 14 days before event were compared against values 14 days after event. The day of management is excluded. A positive change in CO_2 flux indicating a higher NEE after the management event. A total of 96 management events within the study period were evaluated, listed separately on the left side for each box. Events which only took place on a minor part of one parcel are not included. The numbers in parentheses specify the number of events which show a significant ($p < 0.05$) difference in mean of CO_2 flux. A Student's t-test was used for normally distributed data and a Wilcoxon rank sum test for the rest of the data. A Shapiro-Wilk normality test determined, whether the data could be assumed to be normally distributed ($p > 0.05$).

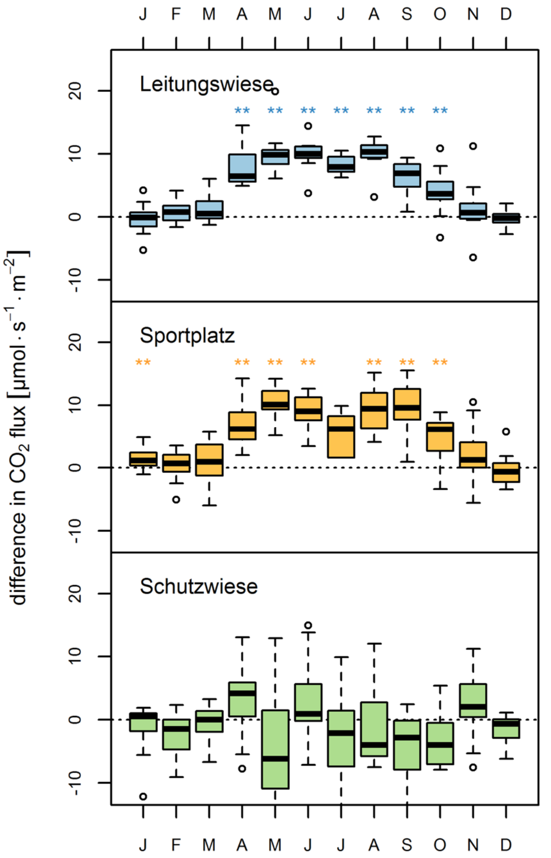

Fig. 18. Differences between fluxes with more than 30% footprint outside the experimental site and fluxes with less than 30% outside. Only daytime data were taken into account. We used monthly averaged flux data. The stars above the box indicate a significant ($p < 0.01$) difference, determined by Wilcoxon rank sum test.

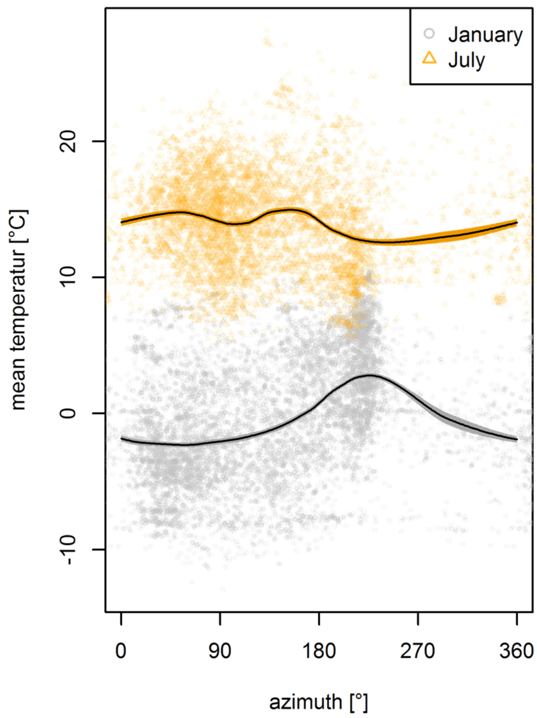

Fig. 19. The mean midday temperature as a function of the main wind direction. The specified degrees are related to the deviation from magnetic north (90° = East, and so on). The black line specifies the locally fitted mean for January and July, respectively. The colored area behind the line shows a local standard error for the local estimated mean values.

5. Discussion

5.1 Annual flux differences

The CO_2 flux of all three parcels was always within a similar range. This suggests that management differences have only a small annual effect on the carbon budget of a meadow at high altitude. It has to be emphasized, that the management differences between the three parcels were also relatively low. Even the mid intensive meadows were never plowed and resowed. Also the average use frequency of 3.5 uses per year is low compared with other grasslands in Switzerland (AGFF, 2009). All analyses showed a great interannual, intraannual, and diurnal variation of the CO_2 flux. Therefore, special care must be taken to only compare parcel fluxes of a similar time range. The annual course of CO_2 flux has great similarities to the course of the growth rate of grasses with reversed sign (Menzi et al., 1991). It suggests that grasses dominate the CO_2 flux by their assimilation. This is not surprising, as grasses are the most important plant functional type in terms of area and biomass on the Fruebuel.

The parcel Sportplatz was generally characterized by a slightly higher CO_2 flux. The effect was also observed at night, suggesting a high respiration rather than a low assimilation rate. Since the climatic conditions are the same for all parcels and the Sportplatz has a similar management intensity as the Leitungswiese, these two factors can be excluded as possible causes. Other important factors which influence soil respiration are SOC and SWC (Yuste et al., 2007). SOC provides the source material which is respired whereas a high SWC in the soil can lead to a shortage of oxygen. Roth (2006) conducted a detailed mapping of SOC in the topsoil around the EC tower. The result of the study is shown in the appendix (FIG. 23). It shows a clearly increased SOC content in the southern part of the experimental site. The region is almost perfectly congruent with the parcel Sportplatz. Moreover, the deeper soil layers are characterized by the abundance of peat. Older maps show that the area was earlier indicated as a marsh, which was heavily waterlogged (Iselin, 1997). Land amelioration took place around 1981 and included the installation of a drainage system. Under anaerobic conditions at earlier times much carbon had been accumulated in the soil which is now decomposed. The decomposition even leads to an observable subsidence (sinking ground level). The drainage pipes had to be lowered in 1996/97 due to the massive loss of organic soil components (Iselin, 1997). Bog subsidence is a highly regarded problem due to drainage in agriculturally used land and leads to a degradation of soil fertility. (Presler, 1993). In addition, it represents a massive source of CO_2 for the atmosphere (Leifeld et al., 2012). Rogiers et al. (2008) conducted a EC study at a comparable site very close to the Fruebuel. Just like Fruebuel, it is located on a carbon-rich soil which is drained to enable agricultural production. The decomposition of SOC is considered to be a major carbon loss on this site. It even leads to the fact that the site represents a net carbon source for the atmosphere. In contrast thereto, carbon budget assessments of Fruebuel indicates that the site is a net carbon sink (Zeeman et al., 2010). However, it would be interesting to evaluate the carbon budget of the parcel Sportplatz alone. Unfortunately, the EC data coverage of only one parcel is very low which would considerably increase the uncertainty in the carbon budget.

The annual course of the CO_2 flux from the Schutzwiese was characterized by a particularly deep minimum in the beginning of the growing season and a subsequent massive increase in the month of June and July. The high productivity of the Schutzwiese in the beginning of the year is probably due to the late first use of this parcel. The first months of the growing season can be better utilized by the plant for biomass production if it is not exposed to disturbance. The negative link between early summer CO_2 flux and the date of the first use support this assumption (FIG. 13). Defoliation of the plant is connected to constant mobilization of nutrients from the roots (Guo et al., 2012). A late first cut allows the plant to build a strong root system that ensures a sufficient nutrient and water supply. This improves the efficiency of photosynthesis and ensures a high rate of carbon assimilation. The following summer depression could have several reasons: (i) The plants switch from vegetative to the generative stage. Thereby, the plant shifts carbon reserves and nutrients from the productive leaves towards the usually photosynthetic unproductive seeds. The photosynthetic capacity of the leaves falls as they are undersupplied and depleted and thus the carbon exchange of the whole canopy rises (Wang, 2001). (ii) The canopy density is constantly increasing. The competition between individual plants increases with higher plant density. Due to the higher biomass, the plant's demand for energy has increased. Some leaves respire more energy than they can produce with the limited amount of light. (iii) The soil resources are depleted after the strong growth in the early stages of the growing season. Plants available soil nutrients were absorbed and the soil water reserve has dropped sharply due to the high transpiration. The effect of decreasing SWC varies greatly from year to year but can often be observed on the Fruebuel around May. (iv) Finally, the onset of senescence. The older leaves and plant tissues die and results in the release of CO_2. An early use can diminish these processes and lead to a more balanced CO_2 flux.

Another special feature in the flux curve is the rapid increase in nocturnal respiration at the Schutzwiese in July. The first cut of the Schutzwiese always takes place around the first of July. Afterwards, the plants need to be regenerated using the reserves from the roots (Schnyder and de Visser, 1999). Large root systems have emerged due to the late use. These can no longer be supplied through the missing leaves. Parts of the root systems are decomposed by microorganisms. This leads to a further increase of respiration.

By comparing similar environmental condition, the strong influence of temperature on the CO_2 flux was shown. Both assimilation as well as respiration are highly temperature-dependent and slow down under cold temperatures (Joseph et al., 2014). This affects all parcels at the same site and reduces the differences between the parcels. The saturation effect at 15 °C is in line with the findings of Dirks et al. (2002) after which the optimum temperature for photosynthesis of grasses such as English Ryegrass (*Lolium perenne* L.) is between 15 – 20 °C. Previous results of a higher CO_2 flux from Schutzwiese were confirmed within the ordinary temperature range of the site.

5.2 Single Management activity

The evaluation of single cut, grazing and organic fertilizer application events covers only the short-term effects within 14 days. It is not necessarily indicative for evaluations of the annual flux. The increase of CO_2 fluxes after a utilization was to be expected. Any use of the grassland results in the loss of photosynthetically active biomass, leading to a lower assimilation rate. Additionally, the removal of the aboveground biomass leads to a warming of the upper soil layers (Guitian and Bardgett, 2000; Wolchansky, 2003). Sunlight is more likely to reach the soil and not to be absorbed previously by the leaves. The black topsoil with high carbon content converts the solar energy efficiently into heat. The cooling effect of transpiration on the canopy is reduced. Thereby, the defoliation triggers an increase of the soil microbial biomass, resulting in an increased soil respiration (Guitian and Bardgett, 2000). The application of organic fertilizer promotes two contradictory processes. On the one hand it promotes microbial growth, on the other hand it is associated with an increased assimilation of plants (Skinner, 2013). Our results imply an outweigh of the latter process in the short term. As grazing leads simultaneously to a fertilization due to animal excretions, it would explain the relatively small increase in CO_2 flux in contrast to cut. The grazing on the Fruebuel is organized as rotational grazing, where parcels are often divided into smaller areas. Not all areas are grazed at the same time. Therefore, the CO_2 flux is increasing continuously. Kirschbaum et al. (2015) report a strong influence of grazer respiration on the CO_2 flux measurements. Thereby, the fluxes from the soil could be overestimated. Also important to mention is, that the measurements are not completely independent. Usually, the application of organic fertilizer takes place shortly after a cut event. In this time span the CO_2 flux would decrease even without application of organic fertilizer. Thus, the effect of organic fertilizer tends to be overestimated in this evaluation. The very rapid and strong increase of CO_2 flux on Schutzwiese after a grazing event could be linked to the long intervals between utilizations. The canopy and root system includes a lot of biomass just before usage. As mentioned in CHAPTER 5.1, the partial degradation of the widespread root system increases the CO_2 flux.

5.3 Experimental design

The approach with several parcels and only one EC tower has already been used by Molodovskaya et al. (2011) to compare nitrous oxide emissions from a Corn and an Alfalfa field. The study results were confirmed by a simultaneous chamber experiment and shows that the wind direction and the flux footprint information may be sufficient to assign the half-hour EC measurements to a certain parcel. Although, from our point of view, there are some considerably disadvantages associated with the approach. By splitting the time series on several parcels, individual parcels have a very low data coverage. As a result, gap filling would lead to a large uncertainty. The buffer zones between parcels lead to discarding of good quality data. Despite buffer zones, the assignment to a certain parcel is associated with uncertainty. Actual wind direction can change several times within half an hour, leading to a mixed flux of different parcels.

Overall, the differences between the parcels are very low. Therefore, it is of particular interest to exclude any systematic distortion, even if it has only a small impact. The various adjoining environments of the parcels could possibly lead to such a distortion. The distortion is largely reduced by filtering the fluxes with long footprint. The analysis between data with different footprint length shows that Leitungswiese and Sportplatz fluxes would be significantly overestimated due to fluxes from outside the experimental area. However, a small distortion still remains despite the filter criterion. Only fluxes with a share of more than 30% from outside the experimental field were discarded. The remaining fluxes can still be influenced by a maximum of 30% from the outside. This is quite a lot in proportion to the small differences between parcels. A stricter filter criterion is impractical as it leads to massive data loss.

Another distortion is conceivable due to the dependence of wind direction and environmental conditions. The wind pattern and its impact on the environment variables of Fruebuel was also examined in Oney et al. (2015). The study attempted to predict wind direction and speed with the help of a meteorological model. The model failed at the Fruebuel, in contrast to three other sites. The authorship suspects a strong influence of the local environment, which is responsible for a redirection of prevailing winds. Despite this redirection, the prevalent wind direction is heavily linked to the measured air temperature as shown our data analysis. Such distortion can only be prevented by comparing fluxes with similar environmental conditions. The evaluation showed an analogous result as the comparisons between similar time ranges. How can this be explained? FIG. 19 implies a dependence of temperature and wind direction mainly in winter but less pronounced in summer. The flux differences between parcels are very low in winter due to the generally low temperature. Thereby, the dependence affects the flux only marginal. In other words: the distortion has a low impact on the flux differences between parcels as the dependency between temperature and wind direction is negligible in summer. An influence would certainly be conceivable in winter but is of little relevance due to the generally low temperature.

5.4 Suggestions for further work

The approach provides a simple method to compare fluxes from different experimental groups with little effort. This opens up the possibility for studies on many different sites. Despite some uncertainties, most distortions can be minimized by a suitable data analysis, e.g. by comparing similar environmental condition days. In order to optimize the analysis with similar environmental conditions, a profound model of the environment is essential with more factor than just time of day, temperature and SWC. Imer et al. (2013) showed that the influence of the management on the CO_2 flux depends on the status of the vegetation, which is currently not included in our analysis. In the study, the status of the vegetation is measured manually by LAI. That is definitely too elaborately for continuous monitoring over several years. A promising approach of Migliavacca et al. (2011) using digital repeat photography (DRP) to optimize prediction models of GPP. Unfortunately, the phenological monitoring of Fruebuel with DRP is restricted to the parcel Schutzwiese (FIG. 24). The implementation of DRP in the environmental condition model should be separately for each parcel. This would result in a combined description of the environmental condition and phenological status and would allow the comparison of fluxes, only different in management.

6. Conclusion

Despite the significant CO_2 flux change shortly after a management event, their effect in the long-term is relatively low. At least, as long as the management is limited to cut, grazing and organic fertilizer application. Much more important is the influence of the previous land use changes, especially the drainage of wetland as the example of Sportplatz shows. Even 35 years after soil melioration, the peat degradation in the soil affects the CO_2 flux of the parcel. A consistent protection of wetlands, could therefore be of greater interest than extensification. Maybe not from the perspective of biodiversity conservation, but from the perspective of climate change mitigation.

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Fig. 20. EC tower on the Fruebuel

8. References

AGFF, 2009. Abgestufte Bewirtschaftungsintensität im Naturfutterbau. Arbeitsgemeinschaft zur Förderung des Futterbaus, Zürich, Schweiz.

Allard, V. et al., 2007. The role of grazing management for the net biome productivity and greenhouse gas budget (CO_2, N_2O and CH_4) of semi-natural grassland. Agriculture, Ecosystems & Environment, 121(1–2): 47-58.

Ammann, C., Spirig, C., Leifeld, J. and Neftel, A., 2009. Assessment of the nitrogen and carbon budget of two managed temperate grassland fields. Agriculture, Ecosystems & Environment, 133(3–4): 150-162.

Aubinet, M. et al., 2000. Estimates of the annual net carbon and water exchange of forests: the EUROFLUX methodology. In: A.H. Fitter and D.G. Raffaelli (Editors), Advances in ecological research. Academic Press, Cambridge, USA, pp. 113-175.

Baldocchi, D., 2014. Measuring fluxes of trace gases and energy between ecosystems and the atmosphere – the state and future of the eddy covariance method. Global Change Biology, 20(12): 3600-3609.

Biasi, C. et al., 2008. Direct experimental evidence for the contribution of lime to CO_2 release from managed peat soil. Soil Biology and Biochemistry, 40(10): 2660-2669.

BLW, 2016. Direktzahlungsverordung. Bundesamt für Landwirtschaft, Bern, Schweiz.

Burba, G., 2013. Eddy covariance method for scientific, industrial, agricultural, and regulatory applications: a field book on measuring ecosystem gas exchange and areal emission rates. LI-COR Biosciences, Lincoln, USA, 331 pp.

Burba, G. et al., 2012. Calculating CO_2 and H_2O eddy covariance fluxes from an enclosed gas analyzer using an instantaneous mixing ratio. Global Change Biology, 18(1): 385-399.

Chang, J.F. et al., 2013. Incorporating grassland management in ORCHIDEE: model description and evaluation at 11 eddy-covariance sites in Europe. Geosci. Model Dev., 6(6): 2165-2181.

Chapin, F.S. et al., 2006. Reconciling carbon-cycle concepts, terminology, and methods. Ecosystems, 9(7): 1041-1050.

Ciais, P. et al., 2000. Global Perspective. In: R.T. Watson et al. (Editors), Land Use, Land-Use Change and Forestry. Cambridge University Press, Cambridge, UK, pp. 375.

Conant, R.T., Paustian, K. and Elliott, E.T., 2001. Grassland management and conversion into grassland: effects on soil carbon. Ecological Applications, 11(2): 343-355.

De Deyn, G.B. et al., 2011. Additional carbon sequestration benefits of grassland diversity restoration. Journal of Applied Ecology, 48(3): 600-608.

Dilly, O., Gnaß, A. and Pfeiffer, E.-M., 2005. Humus accumulation and microbial activities in calcari-epigleyic fluvisols under grassland and forest diked in for 30 years. Soil Biology and Biochemistry, 37(11): 2163-2166.

Dirks, B.O.M., Van Oijen, M., Schapendonk, A.H.C.M., Goudriaan, J. and Wolf, J., 2002. Temperature sensitivity of photosynthesis in *Lolium perenne* swards: a comparison of two methods for deriving photosynthetic parameters from in vivo measurements. Photosynthetica, 40(3): 405-413.

Dragoni, D., Schmid, H.P., Grimmond, C.S.B. and Loescher, H.W., 2007. Uncertainty of annual net ecosystem productivity estimated using eddy covariance flux measurements. Journal of Geophysical Research: Atmospheres, 112(D17112): 1-9.

EddyPro®, 2015. Infrastructure for Measurements of the European Carbon Cycle consortium. LI-COR , Inc., Lincoln, USA.

Eugster, W. and Merbold, L., 2015. Eddy covariance for quantifying trace gas fluxes from soils. SOIL, 1(1): 187-205.

Falge, E. et al., 2001. Gap filling strategies for defensible annual sums of net ecosystem exchange. Agricultural and Forest Meteorology, 107(1): 43-69.

FOEN, 2014. Switzerland's greenhouse gas inventory 1990 – 2012. Federal Office for the Environment, Bern, Switzerland.

Foken, T., Aubinet, M. and Leuning, R., 2012. The Eddy Covariance Method. In: M. Aubinet, T. Vesala and D. Papale (Editors), Eddy covariance : a practical guide to measurement and data analysis. Springer, Dordrecht, Netherlands, pp. 1-438.

Foken, T. et al., 2004. Post-field data quality control. In: X. Lee (Editor), Handbook of micrometeorology : a guide for surface flux measurement and analysis. Kluwer, Dordrecht, Netherlands.

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

Fornara, D.A. et al., 2011. Increases in soil organic carbon sequestration can reduce the global warming potential of long-term liming to permanent grassland. Global Change Biology, 17(5): 1925-1934.

Gilgen, A.K. and Buchmann, N., 2009. Response of temperate grasslands at different altitudes to simulated summer drought differed but scaled with annual precipitation. Biogeosciences, 6(11): 2525-2539.

Groier, M., 1990. Die 3-Stufenwirtschaft in Vorarlberg : Entwicklung, Bedeutung, Perspektiven, Nr. 26. Bundesanstalt für Bergbauernfragen, Wien, Östereich, 185 pp.

Guitian, R. and Bardgett, R.D., 2000. Plant and soil microbial responses to defoliation in temperate semi-natural grassland. Plant and Soil, 220(1): 271-277.

Guo, Y.J. et al., 2012. The effects of defoliation on plant community, root biomass and nutrient allocation and soil chemical properties on semi-arid steppes in northern China. Journal of Arid Environments, 78: 128-134.

Hirata, R. et al., 2013. Carbon dioxide exchange at four intensively managed grassland sites across different climate zones of Japan and the influence of manure application on ecosystem carbon and greenhouse gas budgets. Agricultural and Forest Meteorology, 177: 57-68.

Imer, D., Merbold, L., Eugster, W. and Buchmann, N., 2013. Temporal and spatial variations of soil CO_2, CH_4 and N_2O fluxes at three differently managed grasslands. Biogeosciences, 10(9): 5931-5945.

IPCC, 2014. Climate change 2014: impacts, adaptation, and vulnerability. Part A: global and sectoral aspects. Contribution of working group II to the fifth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, United Kingdom and New York, USA, 1132 pp.

Iselin, G., 1997. Der landwirtschaftliche Versuchsbetrieb Früebel - Anforderungen an eine nachhaltige Landnutzung in einer Morrlandschaft von besonderer Schönheit und nationaler Bedeutung, Diplomarbeit, ETH Zürich, Zürich, Schweiz.

Joseph, T., Whitehead, D. and Turnbull, M.H., 2014. Soil water availability influences the temperature response of photosynthesis and respiration in a grass and a woody shrub. Functional Plant Biology, 41(5): 468-481.

Kindler, R. et al., 2011. Dissolved carbon leaching from soil is a crucial component of the net ecosystem carbon balance. Global Change Biology, 17(2): 1167-1185.

Kirschbaum, M.U.F. et al., 2015. Modelling carbon and water exchange of a grazed pasture in New Zealand constrained by eddy covariance measurements. Science of The Total Environment, 512–513: 273-286.

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

Kljun, N., Calanca, P., Rotach, M.W. and Schmid, H.P., 2015. A simple two-dimensional parameterisation for flux footprint prediction (FFP). Geosci. Model Dev., 8(11): 3695-3713.

Kljun, N., Rotach, M.W. and Schmid, H.P., 2002. A three-dimensional backward lagrangian footprint model for a wide range of boundary-layer stratifications. Boundary-Layer Meteorology, 103(2): 205-226.

Kormann, R. and Meixner, F.X., 2001. An analytical footprint model for non-neutral stratification. Boundary-Layer Meteorology, 99(2): 207-224.

Leclerc, M.Y. and Thurtell, G.W., 1990. Footprint prediction of scalar fluxes using a Markovian analysis. Boundary-Layer Meteorology, 52(3): 247-258.

Leifeld, J., Ammann, C., Neftel, A. and Fuhrer, J., 2011. A comparison of repeated soil inventory and carbon flux budget to detect soil carbon stock changes after conversion from cropland to grasslands. Global Change Biology, 17(11): 3366-3375.

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

Leifeld, J., Steffens, M. and Galego-Sala, A., 2012. Sensitivity of peatland carbon loss to organic matter quality. Geophysical Research Letters, 39(14): 1-6.

LI-COR, 2015. EddyPro® 5 Help and User's Guide. LI-COR, Inc., Lincoln, USA.

MacDonald, J.D. et al., 2010. Plowing a poorly drained grassland reduced soil respiration. Soil Science Society of America Journal, 74(6): 2067-2076.

Manna, M.C., Swarup, A., Wanjari, R.H., Mishra, B. and Shahi, D.K., 2007. Long-term fertilization, manure and liming effects on soil organic matter and crop yields. Soil and Tillage Research, 94(2): 397-409.

Maragni, L.A., Knapp, A.K. and McAllister, C.A., 2000. Patterns and Determinants of Potential Carbon Gain in the C_3 Evergreen Yucca glauca (*Liliaceae*) in a C_4 Grassland. American Journal of Botany, 87(2): 230-236.

Menzi, H., Blum, H. and Nösberger, J., 1991. Relationship between climatic factors and the dry matter production of swards of different composition at two altitudes. Grass and Forage Science, 46(3): 223-230.

MeteoSchweiz, 2015a. Klimareport 2014. Bundesamt für Meteorologie und Klimatologie MeteoSchweiz, Zürich, Schweiz, 80 pp.

MeteoSchweiz, 2015b. Typische Wetterlagen im Alpenraum. Bundesamt für Meteorologie und Klimatologie MeteoSchweiz, Zürich, Schweiz, 28 pp.

Migliavacca, M. et al., 2011. Using digital repeat photography and eddy covariance data to model grassland phenology and photosynthetic CO_2 uptake. Agricultural and Forest Meteorology, 151(10): 1325-1337.

Moffat, A.M. et al., 2007. Comprehensive comparison of gap-filling techniques for eddy covariance net carbon fluxes. Agricultural and Forest Meteorology, 147(3–4): 209-232.

Molodovskaya, M., Warland, J., Richards, B.K., Öberg, G. and Steenhuis, T.S., 2011. Nitrous oxide from heterogeneous agricultural landscapes: source contribution analysis by eddy covariance and chambers. Soil Science Society of America Journal, 75(5): 1829-1838.

Mueller, B. et al., 2015. Lengthening of the growing season in wheat and maize producing regions. Weather and Climate Extremes, 9: 47-56.

Oney, B. et al., 2015. The CarboCount CH sites: characterization of a dense greenhouse gas observation network. Atmos. Chem. Phys., 15(19): 11147-11164.

Osborne, B., Saunders, M., Walmsley, D., Jones, M. and Smith, P., 2010. Key questions and uncertainties associated with the assessment of the cropland greenhouse gas balance. Agriculture, Ecosystems & Environment, 139(3): 293-301.

Papale, D. et al., 2006. Towards a standardized processing of net ecosystem exchange measured with eddy covariance technique: algorithms and uncertainty estimation. Biogeosciences, 3(4): 571-583.

Presler, J., 1993. Die Böden des Betriebes Bellechasse unter Berücksichtigung der Moorsackung, Dissertation, ETH Zürich, Zürich, Schweiz.

R Development Core Team, 2016. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria.

Rannik, Ü. et al., 2012. Footprint Analysis. In: M. Aubinet, T. Vesala and D. Papale (Editors), Eddy covariance : a practical guide to measurement and data analysis. Springer, Dordrecht, Netherlands, pp. 211-262.

Rogelj, J. et al., 2015. Energy system transformations for limiting end-of-century warming to below 1.5 °C. Nature Clim. Change, 5(6): 519-527.

Rogiers, N., Conen, F., Furger, M., Stöckli, R. and 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(11): 2613-2625.

Roth, K., 2006. Bodenkartierung und GIS-basierte Kohlenstoffinventur von Graslandböden: Untersuchungen an den ETH-Forschungsstationen Chamau und Früebüel (ZG, Schweiz), Masterarbeit, Universität Zürich, Zürich, Schweiz.

Sautier, S., 2007. Zusammensetzung und Produktivität der Vegetation im Gebiet der ETHZ-Forschungsstation Früebüel (ZG), Masterarbeit, Universität Zürich, Zürich, Schweiz.

Schnyder, H. and de Visser, R., 1999. Fluxes of reserve-derived and currently assimilated carbon and nitrogen in perennial ryegrass recovering from defoliation. The regrowing tiller and its component functionally distinct zones. Plant Physiology, 119(4): 1423-1436.

Schulze, E.D. et al., 2009. Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance. Nature Geosci, 2(12): 842-850.

Skinner, R.H., 2013. Nitrogen fertilization effects on pasture photosynthesis, respiration, and ecosystem carbon content. Agriculture, Ecosystems & Environment, 172: 35-41.

Smith, P., 2004. Monitoring and verification of soil carbon changes under Article 3.4 of the Kyoto Protocol. Soil Use and Management, 20(2): 264-270.

Sulman, B.N., Desai, A.R. and Mladenoff, D.J., 2013. Modeling soil and biomass carbon responses to declining water table in a wetland-rich landscape. Ecosystems, 16(3): 491-507.

Suttie, J.M., Reynolds, S.G. and Batello, C., 2005. Grasslands of the world. Lavoisier Publishing Inc., New Yourk, USA, 1514 pp.

Toma, Y. et al., 2012. Carbon sequestration in soil in a semi-natural *Miscanthus sinensis* grassland and *Cryptomeria japonica* forest plantation in Aso, Kumamoto, Japan. GCB Bioenergy, 4(5): 566-575.

UNFCCC, 2015. Adoption of the Paris Agreement. United Nation Framework Convention on Climate Change.

Wang, H.-J., Riley, W.J. and Collins, W.D., 2015. Statistical uncertainty of eddy covariance CO_2 fluxes inferred using a residual bootstrap approach. Agricultural and Forest Meteorology, 206: 163-171.

Wang, R.Z., 2001. Photosynthesis, transpiration, and water use efficiency of vegetative and reproductive shoots of grassland species from north-eastern China. Photosynthetica, 39(4): 569-573.

Wei, J., Cheng, J., Li, W. and Liu, W., 2012. Comparing the effect of naturally restored forest and grassland on carbon sequestration and its vertical distribution in the Chinese loess plateau. PLoS ONE, 7(7): e40123.

Wiesmeier, M. et al., 2013. Amount, distribution and driving factors of soil organic carbon and nitrogen in cropland and grassland soils of southeast Germany (Bavaria). Agriculture, Ecosystems & Environment, 176: 39-52.

Wilson, K. et al., 2002. Energy balance closure at FLUXNET sites. Agricultural and Forest Meteorology, 113(1–4): 223-243.

Wolchansky, J., 2003. Effects of simulated grazing on soil temperature, moisture, and respiration in a shortgrass steppe in northeastern Colorado, George Washington University of Colorado, Colorado, USA.

Wolf, S. et al., 2013. Contrasting response of grassland versus forest carbon and water fluxes to spring drought in Switzerland. Environmental Research Letters, 8(3): 035007.

Yuste, C.J. et al., 2007. Microbial soil respiration and its dependency on carbon inputs, soil temperature and moisture. Global Change Biology, 13(9): 2018-2035.

Zeeman, M.J. et al., 2010. Management and climate impacts on net CO_2 fluxes and carbon budgets of three grasslands along an elevational gradient in Switzerland. Agricultural and Forest Meteorology, 150(4): 519-530.

Ziter, C. and MacDougall, A.S., 2013. Nutrients and defoliation increase soil carbon inputs in grassland. Ecology, 94(1): 106-116.

9. Appendix

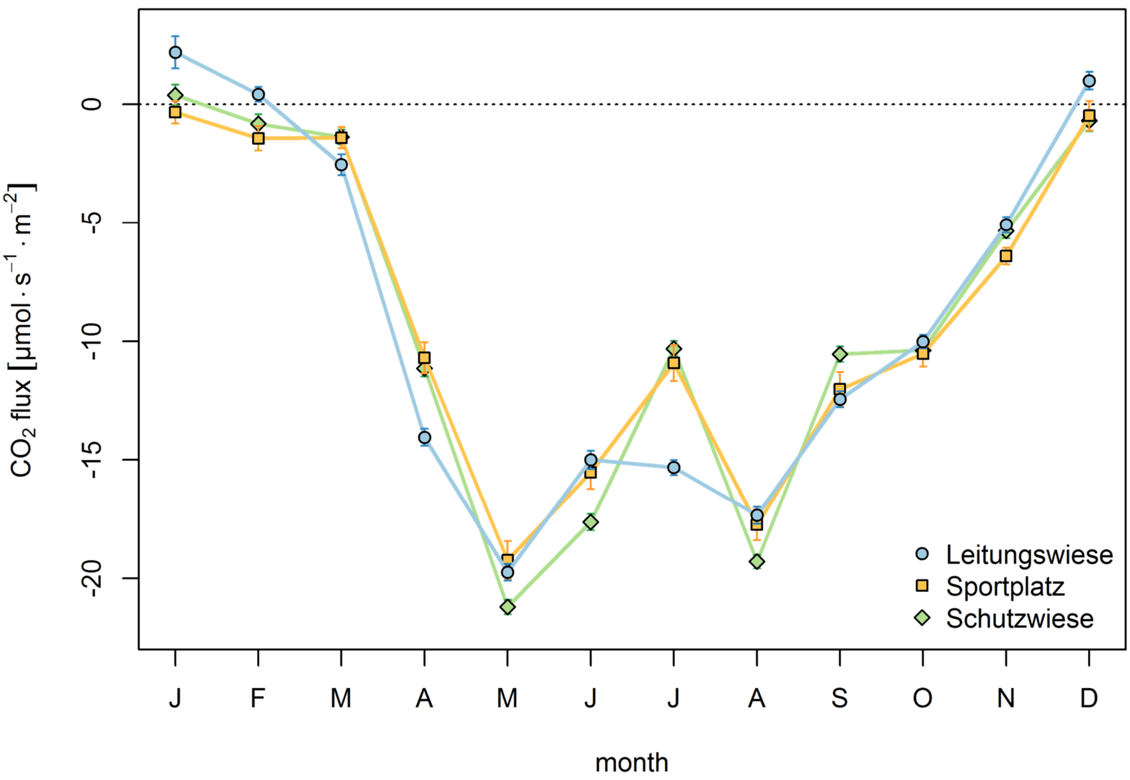

Fig. 21. Course of the year of the midday CO_2 flux. Points representing the mean values of all midday CO_2 Fluxes separated by month and parcel. Whiskers show the standard error of the estimated mean value.

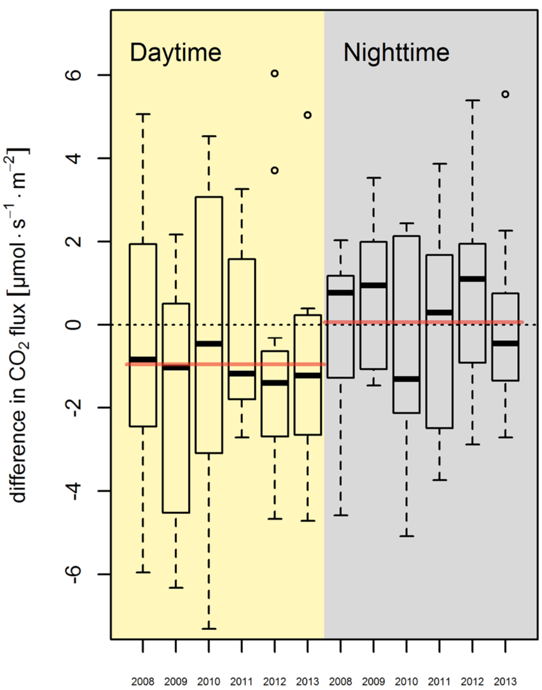

Fig. 22. Liming effect on CO2 assimilation and respiration. Every year after the liming event on Sportplatz (2007) was compared to the year before liming. Boxplot represent monthly mean difference in CO2 flux between 2008 – 2013 and 2006. The red line marks the mean values of all years.

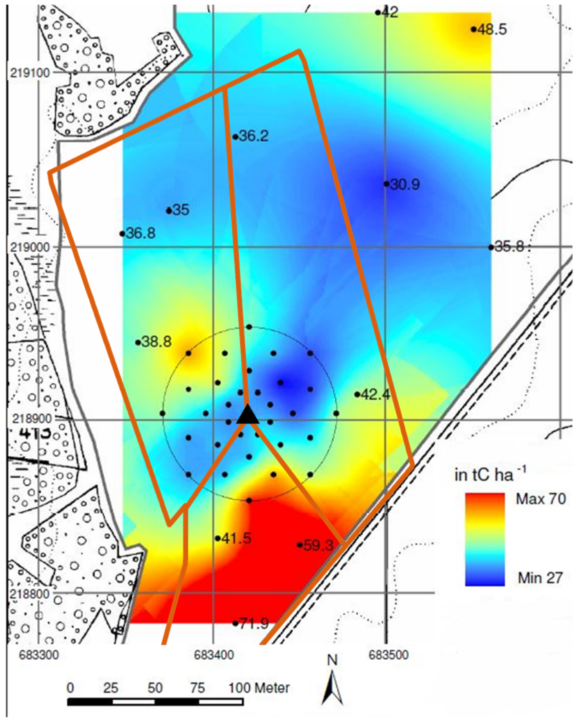

Fig. 23. Organic carbon distribution in the topsoil of Fruebuel. The eddy covariance tower is located in the middle (▲). Points represent location were samples have been taken. The values between the points were interpolated. Adapted from Roth (2006).

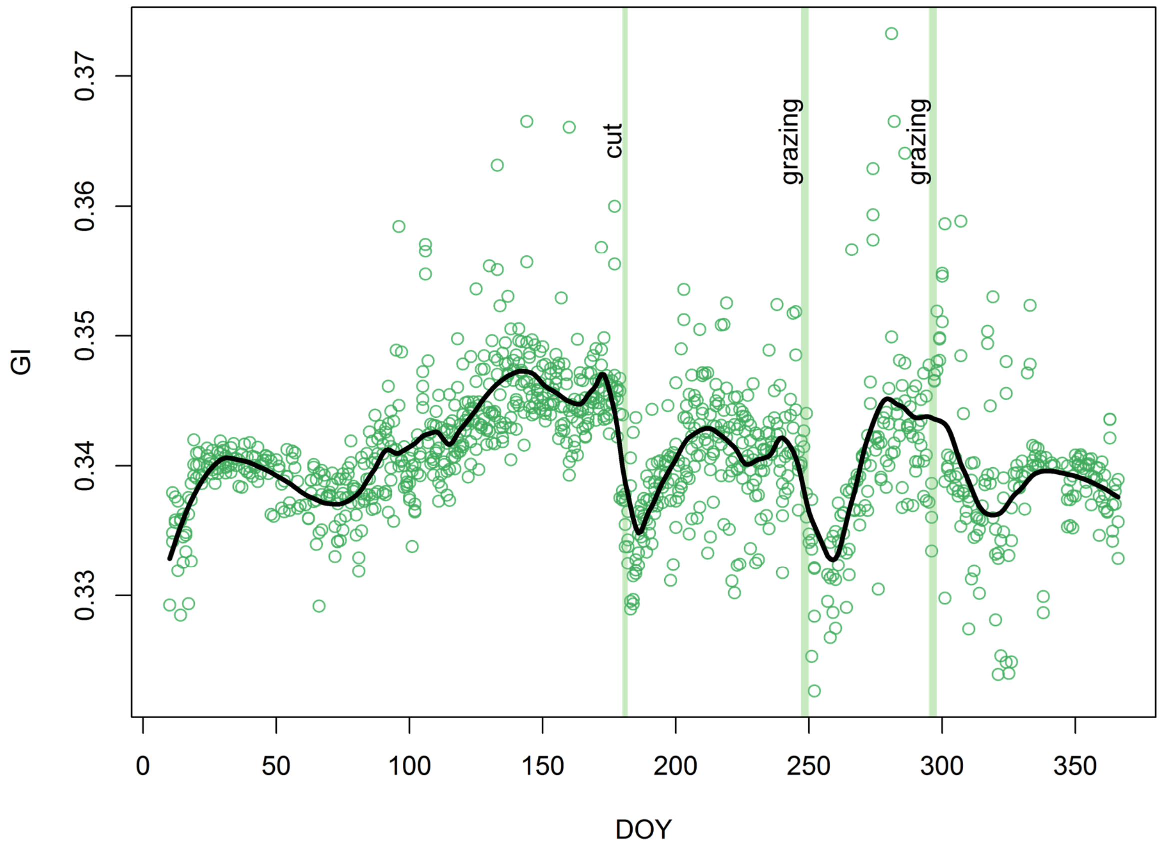

Fig. 24. The greenness index (GI) is derived from RGB images and provide a good proxy is for the status of vegetation. These data refer to the Schutzwiese in 2012. The management events have a clear effect on the course of the GI