Impact of site history and land-management on CO_2 fluxes at a grassland in the Swiss Pre-Alps

Inauguraldissertation
der Philosophisch-naturwissenschaftlichen Fakultät
der Universität Bern

vorgelegt von

Nele Rogiers

aus Belgien

Leiter der Arbeit:
PD Dr. W. Eugster
Geographisches Institut, Universität Bern
Institut für Pflanzenwissenschaften, ETH Zürich

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Von der Philosophisch-naturwissenschaftlichen Fakultät angenommen.

Bern, den 27. Oktober 2005 Der Dekan:

Prof. Dr. P. Messerli

Es ist schon so: Die Fragen sind es,
aus denen das, was bleibt, ensteht.
Denkt an die Frage jenes Kindes:
„Was tut der Wind, wenn er nicht weht ?“

Erich Kästner

Version 2 - January 2006

Summary

Context

The European CARBOMONT project was initiated to gain insight into the CO_2 exchange of mountainous grasslands in Europe. Within the framework of the CARBOMONT project, CO_2 and water vapor fluxes were measured using the eddy covariance technique above a sub-alpine grassland ecosystem in the Swiss Pre-Alps at Rigi Seebodenalp (1025m a.s.l.). A part of this site is an extensively used grassland with fields used as a meadow (two annual grass cuts) and a pasture (cows grazing), the other part is a wetland with one grass cut at the end of the vegetation period.

For the grassland, a three-year dataset containing eddy-covariance measurements and micrometeorological data from 17 May 2002 to 20 May 2005 was established. This data set is valuable because (1) it comprises information on the CO_2 exchange of a grassland site with a relatively high soil organic content and (2) it contains winter eddy-covariance data, which are relatively rare.

During the three measurement years, considerably high carbon losses were measured at Seebodenalp. In this PhD-thesis, two questions are addressed in detail over the different chapters:

1. What is the influence of microclimate on the CO_2 fluxes and what are the main driving climatological variables steering the CO_2 exchange?
2. How big is the influence of current and historical land-management on the CO_2 exchange?

Driving microclimatological variables on CO_2 exchange

Functional relationships between microclimatic variables and CO_2 exchange have been established. Exponential relationships between nighttime CO_2 fluxes, which are assumed

to represent dark ecosystem respiration, and shallow soil temperature were found. It was not possible to describe the relationship between soil water content and dark ecosystem respiration with a statistical model. The impact of changing light intensities of photosynthetic active radiation on the CO_2 exchange was described by the so called "light response curves". Depending on the leaf area index of the vegetation, which was strongly influenced by land-management, and depending on the age of the vegetation, different light response curves could be determined. Further, it was demonstrated that evapotranspiration at Seebodenalp is mainly energy driven.

Respiration losses during winter accounted for an important share in the total carbon budget at Seebodenalp. Snow pack together with the high content of soil organic matter prevented the soil from freezing thereby creating favorable conditions for microbial activity and thus resulting in substantial respiration losses from the snow covered grassland. As soon as the site became snow-free and a diurnal cycle in soil temperature was observed, the vegetation became photosynthetically active.

Influence of land-management on CO_2 exchange

First the influence of current land-management on the CO_2 exchange was investigated. The carbon budgets for the pasture and the meadow at the extensively used grassland were compared for a 131-day period in summer 2002. It was found that grazing (pasture) resulted in a considerably higher loss (270 ± 24 g C m^{-2}) than harvesting (meadow; 79 ± 17 g C m^{-2}). Further, the carbon budget for this period was modeled under the assumption that no land-management interventions would have taken place. Using site specific functional relationships, a net carbon gain of -128 ± 17 g C m^{-2} was calculated. Also the simulations from the soil-vegetation-atmosphere model SiB2.5 showed that land-management practices strongly influence the annual carbon budget, even turning the site from a net carbon source into a net carbon sink.

In summer 2003, an additional eddy covariance tower was installed to study the CO_2 exchange at the wetland. Here it was demonstrated that even without disturbing the vegetation, the photosynthetic activity of the vegetation decreased from spring to mid-summer due to senescence. Towards the end of summer 2003, this effect was emphasized because plants in the wetland suffered from water stress.

Laboratory measurements of soil samples demonstrated that the annual carbon losses from the wetlands in form of CO_2 due to historical land-management (i.e. draining) ranges between 5.0 to 9.1 t C ha^{-1}, depending of the length of the cultivation period. Although the wetlands are only contributing to a minor part to the eddy covariance measurements from the tower at the extensively used grassland, these results give confidence in the relatively high CO_2 losses measured during all three years (0.9 - 2.5 t C ha^{-1}).

Evaluation

The measurement years 2002 and 2004 were climatologically close to the 10-year mean, although 2002 was wetter than average. The CO_2 fluxes from 2002 and 2004 can therefore be considered to be representative for Seebodenalp. Summer 2003 was warmer and drier than average, which led to some periods were the vegetation at Seebodenalp suffered from drought stress. A reduction in assimilation and also in respiration was measured during these periods, such that the net CO_2 exchange in summer 2003 did not considerably differ from the other measurement years.

Taken together, the studies reported in this thesis demonstrated that Seebodenalp, a cultivated peatland in the Swiss Pre-Alps, is a net source of carbon over all three years both under climatologically average conditions and under extremely hot and dry conditions. By comparing the CO_2 exchange of (1) a meadow with a pasture and of (2) disturbed (extensively used grassland) and undisturbed vegetation (protected wetland), it

has been shown that current land-management indeed has an impact on the CO_2 exchange of the site and can turn the site from a net carbon sink into a net carbon source. Also the importance of measuring the CO_2 exchange outside the vegetation period was pointed out. Finally, by estimating the contribution of historical land-management, the CO_2 fluxes with the eddy-covariance method were put into context.

Table of Contents

1 Introduction

1.1 Political aspect

With the ratification of the Kyoto Protocol, Switzerland has committed itself to reducing its greenhouse gas emissions (Fischlin *et al.*, 2003). Under the Kyoto Protocol, it is possible to take carbon sinks into account to a certain extent in calculating national greenhouse gas balances. Especially the carbon cycling of terrestrial ecosystems has attracted considerable interest of scientists and policy makers because of their potential role as sinks or sources for atmospheric CO_2 (IPPC, 2000; Rosenberger and Azauralde, 2002). In agriculture, mitigation of the greenhouse effect can be achieved by reducing nitrous oxide and methane emissions, and also by sequestering carbon in soils (Leifeld *et al.*, 2005). Through adequate management, it might be possible to increase the quantity of organic matter in soils, thereby offsetting a portion of fossil fuel CO_2 emissions (Drewitt *et al.*, 2002). It is therefore important to have reliable information on current carbon stocks and potential sinks. If carbon sequestration in agricultural land wants to be accounted for in the national greenhouse budget, changes in soil carbon must be measurable and verifiable (Smith, 2004)

1.2 Ecosystem carbon cycle and carbon sequestration

Plants take up carbon dioxide (CO_2) during the day, in a process called assimilation, in order to use them for photosynthesis. In this process plants convert CO_2 and water into sugars, with the help of photosynthetically active radiation. These sugars are then used for growth and maintenance of plants metabolism. Environmental factors such as photosynthetically active radiation, soil moisture availability, air temperature, leaf area index and concentrations of CO_2 in the atmosphere influence the rate of photosynthesis (Pitelka, 1994; Ruimy *et al.*, 1995; Gilmanov *et al.,* 2003a).

Ecosystem respiration takes plays during the day and the night and consists of autotrophic respiration performed by plants and heterotrophic respiration performed by soil microbes and soil fauna. The rate of autotrophic respiration is associated with three major energy-requiring processes: growth, maintenance and transport (Lambers *et al.*, 1998; Buchmann, 2000). The heterotrophic respiration is controlled by soil temperature, soil moisture and substrate quality and reflects the microbial activity rate. Substrate decomposition rates generally increase with increasing temperature in the temperature range -5 °C up to 25 °C (e.g. Clein and Schimel, 1995). Substrate quality is lower the higher the lignin concentrations and the lower the concentrations of soluble carbohydrates (Hobbie *et al.*, 2000).

Carbon sequestration in soils is a climate mitigation strategy based on the assumption that the flux of carbon from the air to the soil can be increased while the release of carbon from the soil back to the atmosphere is decreased (Leifeld *et al.*, 2005). In other words, it is assumed that certain activities can transform soil from a carbon source (emitting carbon) into a carbon sink (absorbing carbon). This transformation has the potential to reduce atmospheric concentrations of carbon dioxide, thereby slowing global warming and mitigating climate change (Fischlin and Fuhrer, 2004). However, carbon sequestration in agricultural soils has a finite potential and is non-permanent. Additionally, the sink strength (i.e. the rate at which carbon is removed from the atmosphere) in soil becomes smaller as time goes on, as the soil carbon stock approaches a new equilibrium (Smith, 2004). Carbon sequestration is a short-time solution from an economical as well as from an ecological point of view. The ecological aspects are discussed by several authors (e.g. Janssens *et al.*, 2003; Smith 2004). Climate models considering the biosphere predict that these worldwide sinks of CO_2 will act as source of CO_2 from the middle of this century, which will result in a serious acceleration of climate change (Fishlin and Fuhrer, 2004). Hedinger (2004) analyzed the economical aspect of carbon sequestration. Dynamical aspects of land use changes and saturation effects are important here. Nevertheless, if atmospheric CO_2 concentrations are to be stabilized at reasonable levels (450 –650 ppm), drastic reductions in carbon emissions will be required over the next decades (Smith, 2004). Thus, sinks can be a part of the solution, but not the whole solution.

Agricultural soils present an important reservoir of organic carbon. In agro-ecosystems, unlike in forest ecosystems, the major carbon pool is located in the soil and not in the biomass. In soils the turnover is relatively slow, allowing the possibility of enhancement through management (Fischer *et al.*, 1994). The amount of carbon stored in agricultural soils depends on climatic and site-specific conditions as well as on management decisions. Several studies have shown that it is not only theoretically possible, but practically feasible to regulate soil carbon stocks through improved management within upper and lower limits, which are determined by natural constraints (Ash *et al.* 1995; Batjes, 1999).

Grasslands cover about 40% of the ice-free global terrestrial surface (Novick *et al.*, 2004) and occupy 38% of agricultural land in Europe (Dziewulska, 1990). Their high root/shoot biomass compared to other biomes and their relatively high reserves of soil organic matter in a predominantly stable form make grasslands play an important role in the Earths global carbon budget (Gilmanov *et al.*, 2003b). From the management standpoint, they also are important because they provide opportunities to facilitate carbon sequestration in a shorter time and at lower costs than afforestation. The IPCC report (IPCC, 2000) demonstrated that grasslands and rangelands offer significant potential for sequestering atmospheric CO_2, especially under future global change scenarios.

1.3 CO_2 flux research

One possibility to measure and monitor soil carbon sequestration is by periodically quantifying the soil organic carbon (SOC) content. This is the most direct approach, but has statistical limitations (Smith, 2004). A large number of soil samples is needed and changes in SOC are only detectable at time scales longer than five years. Another possibility is to measure changes in SOC by using the eddy-covariance method, which is a more complex system. This method collects information about the fluxes released from and entering the ecosystem, as well as information on the underlying processes governing these fluxes.

Baldocchi *et al.* (1996) emphasized the need for regional networks of flux measurement stations covering a broad spectrum of ecosystems and climatic conditions. Since then, continuous measurements of carbon dioxide exchange have been performed at an increasing number of sites throughout the world, covering a wide range of different ecosystems (e.g. Valentini *et al.*, 2000). There is already substantial information on the carbon sequestration of forest ecosystems across Europe (e.g. EUROFLUX, CANIF, CarboEurope). However, site selection in the temperate zone has been focused on forests forest ecosystems (Houghton, 1996; Aubinet *et al.*, 2000; Baldocchi *et al.*, 2000; Valentini *et al.*, 2000) and little emphasis has been put on other ecosystems.

Studies on grassland CO_2 exchange have shown that they may act as either a source or sink of CO_2 (Leahy, 2004). Novick *et al.* (2004) collected information on annual grassland NEE estimates based on eddy-covariance measurements and Bowen Ratio Energy Balance techniques and reported values varying from a net source of +400 g C m-2 to a net sink of -88 g C m^{-2}. A review of available data (Janssens *et al.*, 2003) has shown that large uncertainties remain in resolving whether grassland ecosystems function as CO_2 sources or sinks. This uncertainty is primarily attributable to the sensitivity of grasslands to interannual variability in climate and associated biomass dynamics (Meyers, 2001; Flanagan *et al.*, 2002) and incomplete understanding of the regulation of grassland assimilation and respiration. Since there was still missing a comprehensive synthesis on carbon balances for European mountain grassland ecosystems, two European projects were initiated at the beginning of the third millennium: GREENGRASS investigating management of grasslands and CARBOMONT focusing on grassland in mountainous areas.

1.4 Swiss agricultural structure

When focusing on the possibilities in Switzerland to store carbon in agriculture, we have to take into account that there is a difference between the realistically achievable potentials for carbon sequestration and the potential estimated when considering only availability of land and biological resources and land-suitability (Smith, 2004). Freibauer *et al.* (2004) found that the realistically achievable potentials in Europe are about 10% of the biological potential. Swiss agriculture, however, is already optimized in this respect and the potential here is limited (Leifeld *et al.*, 2005).

The distribution of soil organic matter (SOM) for different land use-types in Switzerland (Fig. 1) was investigated by Leifeld *et al.* (2005). He found that only 23% of the soil organic matter in Switzerland is present under arable land. Most of the soil organic carbon in Swiss agriculture is stored under permanent grasslands, which account for more than 70% of the total agricultural area. The unfavorable permanent grasslands are mainly to be found in mountainous (steep, shallow) areas. Although intact and cultivated peat lands account for only a small percentage of the agricultural area, they play a significant role in Swiss carbon stocks due to the large amounts of carbon stored per hectare. The sequestration potential of organic soils lies mainly in avoiding CO_2 emissions by reducing oxidative peat losses.

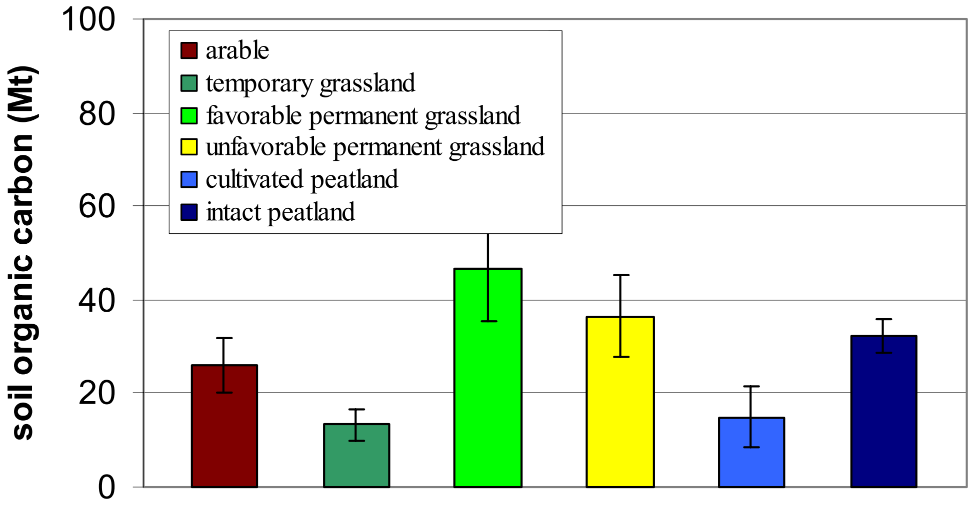

Fig. 1: Distribution of soil organic carbon over different land use- types in Switzerland (Leifeld *et al.,* 2005). Unfavorable permanent grasslands comprise mainly mountainous grasslands.

Economic pressure has had its impact on agricultural practices on European grasslands and has led to an intensification of management of grasslands at relatively low elevation. Less fertile mountainous grasslands suffer from hard economic competition, which has resulted in abandonment of formerly managed grasslands (Cernusca *et al.*, 1999). Semi-natural grassland areas are disappearing at alarming rates in Europe (Dziewulska, 1990). Hopplicher *et al.* (2002) report on a decrease of mountainous grasslands in Austria of about 21% in 30 years. Fundamental changes in the landscape pattern and ecosystem structure can affect the spatial structure of plant canopies, species composition and physiology, nutrient availability and in consequence the biosphere-atmosphere CO_2 exchange (Cernusca *et al.*, 1998).

1.5 Thesis structure

In this thesis, the results are presented of three years of measurements at a Swiss agricultural site at mount Rigi. Among all European flux sites, Rigi Seebodenalp is the one with the highest organic soil content.

This report is built up in chapters, each handling a specific topic.

The first Chapter provides context for this study. It gives an overview of the current state of CO_2 research, especially on grasslands and focuses on the agricultural structure in Switzerland.

In the second Chapter, the measurement site and the measurement technique used to quantify the CO_2 and water vapor fluxes at Seebodenalp are described. The eddy covariance technique with which the carbon fluxes were determined is explained and some technical details about the data handling procedure (calculation of the fluxes, applications of corrections, data filtering and footprint calculation) are described. Also an overview of the available flux and micrometeorological data measured over three years is given.

In Chapter three, the vegetation period 2002 is discussed in detail with a focus on the effect of land management on CO_2 fluxes. The influence of two land-management practices meadow (i.e. grass cuts) and pasture (i.e. cows grazing) on the CO_2 budget is calculated.

In Chapter four, net ecosystem exchange of CO_2 and water vapor are compared for an extensively used grassland and protected wetland. Also the influence of the hot and dry summer 2003 on both ecosystems with respect to eddy-covariance fluxes is investigated.

Chapter five reports on winter CO_2 fluxes with a special focus on the influence of snow cover and micrometeorology on the CO_2 exchange. The CO_2 budgets during three winter seasons are quantified and related to the yearly CO_2 budgets

Chapter six is a synthesis of the measurements made at Seebodenalp during three years. The seasonal and the interannual variation of the carbon fluxes is studied and it is investigated which climatic factors are responsible for the differences in these fluxes. Also the influence of current and historical land-management is estimated.

The main findings of this PhD-thesis are summarized in Chapter seven and recommendations for further research are given.

2 Site description and methodology

2.1 Site description: Rigi Seebodenalp

The Seebodenalp flux site was established in May 2002 as part of the CARBOMONT network. It is located on a subalpine grassland with the local name Seebodenalp on a flat shoulder terrace of Mount Rigi (47°05',38" N, 8°45'36" E) in Central Switzerland at an altitude of 1025 m above sea level (Rogiers *et al.*, 2005). The site encompasses 32 ha of relatively flat terrain (Fig. 2).

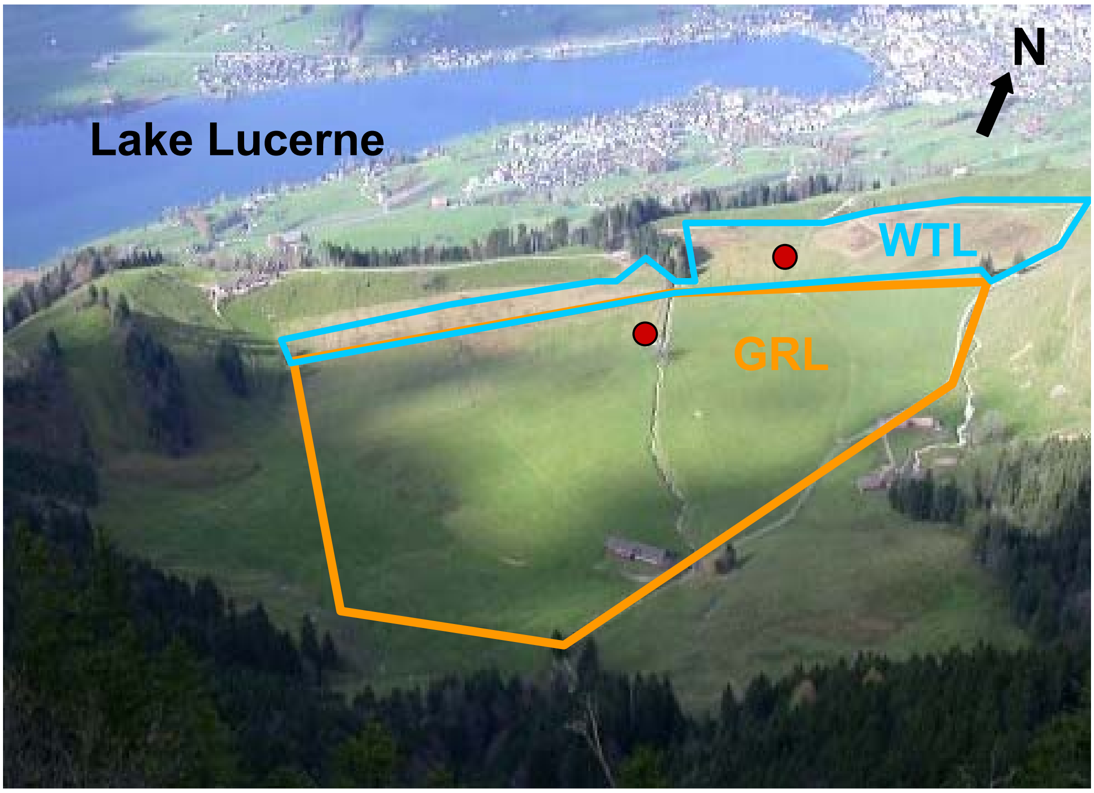

Fig. 2: Aerial view of the Swiss CARBOMONT site Seebodenalp (1025 m a.s.l.) with the indication of both land use types grassland (GRL) and wetland (WTL) and the position of the two EC measurement towers. In the background Lake Lucerne and the city of Küssnacht (440 m a.s.l.) can be seen.

Steep slopes border the area towards south and east, and a moraine rim limits the area towards the northwest. The current terrain is the bottom of a former but vanished lake which was fed by melt water at the end of the last glaciation (Vogel and Hantke, 1989) with a thick sedge peat layer on top. Seebodenalp has been drained since 1886 (Wyrsch, 1988), but is still relatively wet. Nowadays, two different land surface types can be distinguished: grassland and wetland, both with their specific soil properties, plant species composition, and land-management history (Tab. 1).

Tab. 1: Description of the site history, soil type (WRB, 1998), soil characteristics (Müller, 2004) and plant community (Reutlinger, 2004) at the grassland and the wetland at Rigi, Seebodenalp.

	grassland **GRL**	**wetland** **WET**
Area [ha]	23	8
Site history	drained and peat exploited	-
Present land-management	extensively used as pasture and meadow	1 grass at the end of the growing season
Soil type	stagnic Cambisol	folic Histosol (drystic)
Soil organic carbon [%] in upper 10 cm	7.17 ± 0.22	15.73 ± 0.88
Plant community	*Lolio-Cynosuretum cristati*	*Angelico-Cirsietum caricetosum nigrae* and degenerated *Caricetum nigrae*

Seebodenalp lies well exposed towards the Swiss Plateau, at the northwestern edge of the Pre-Alps. Therefore it experiences mainly westerly and northerly wind regimes that carry polar and subtropical maritime air masses towards the Alps. Continental air masses are transported into the area from the east. Southerly flow is usually coupled to foehn, a descending wind in the lee of the Alps bringing dry and gusty winds.

2.2 Flux measurements: Eddy covariance technique

2.2.1 Instrumentation and calculation of eddy covariance fluxes

The eddy covariance (EC) technique was used to measure the vertical fluxes of CO_2, water vapour, sensible heat, and momentum on a continuous basis (e.g. Goulden *et al.*, 1996b; Baldocchi, 2003; Aubinet *et al.*, 2000). Briefly, the vertical turbulent fluxes F_c were calculated as the half-hourly covariance between fluctuations of the vertical wind speed w [m s^{-1}] in a co-ordinate system which is aligned with the mean streamlines, and the CO_2 concentration c [µmol mol^{-1}]:

$$F_c = (\rho_a / M_a) \cdot \overline{w' \cdot c'} \qquad [\mu\text{mol m}^{-2}\ \text{s}^{-1}]\ (\text{Eq. } 1)$$

where ρ_a [kg m^{-3}] is the air density, and M_a [kg mol^{-1}] is the molecular weight of air (28.96). Overbars denote time averages, and primed quantities are the instantaneous deviations from their respective time average. Equation 1 was deduced from the conservation equation of the scalar CO_2, in applying the Reynolds decomposition (Stull, 1988), assuming stationarity and horizontal homogeneity of turbulence, negligible horizontal flux divergence and molecular diffusion and an infinite storage term (Baldocchi, 2003).

The uptake of CO_2 by the vegetation causes a downward CO_2 flux, namely a flux from the atmosphere to the vegetation. Respiration causes an upward CO_2 flux during the day and during the night. The net CO_2 flux or net ecosystem exchange of CO_2

(NEE) is the sum of both processes (Fig. 3). Within the vegetation canopy, a part of the respiration CO_2 is reassimilated. This so called recycling (Buchmann *et al.*, 1994) is not measured by the eddy covariance tower, which measures the fluxes above the canopy at a certain height. We followed the convention that positive fluxes indicate a net upward transport from the vegetation to the atmosphere, whereas negative values signify surface uptake.

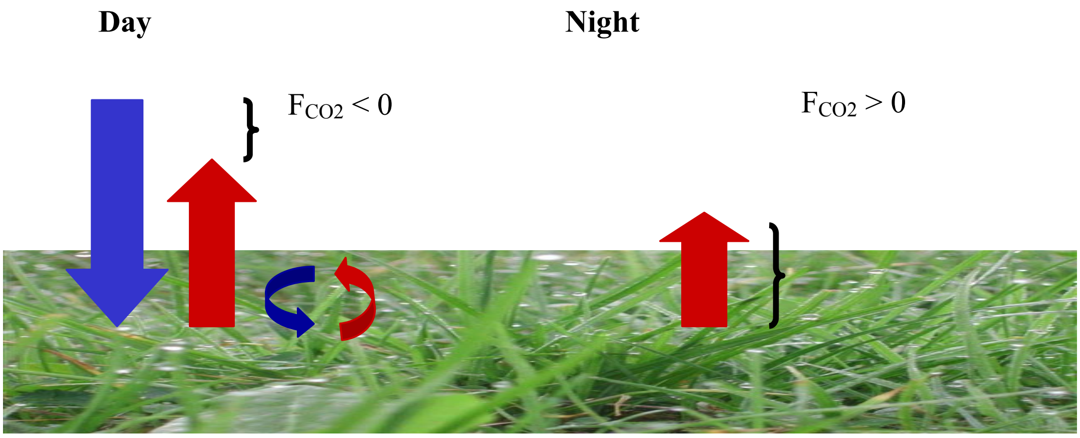

Fig. 3: Net ecosystem exchange (NEE) of CO_2 fluxes or F_{CO2} is the result of the downward assimilation fluxes (negative sign) and the upward respiration fluxes (positive sign). The recycling of CO_2 within the canopy is not detected by the eddy covariance system.

Besides CO_2 fluxes, also water vapor fluxes are measured at Seebodenalp using the same method. The measured water vapor fluxes are the result of plant transpiration and evaporation of soil water. Transpiration of water vapor is a plant physiological process coupled to photosynthesis. Evaporation of soil water is steered by available soil moisture and soil temperature, where the latter is determined by net radiation and by the leaf area index of the vegetation. The inevitable loss of water via evapotranspiration when stomata open to admit CO_2 uptake may lead to a decreased water content in leaves if root water uptake does not compensate the loss from leaves. When the plant water status becomes low stomata close, conserving water but at the same time decreasing photosynthesis and thus reducing the net CO_2 uptake.

Fig. 4: Upper left: The eddy-covariance system in the grassland running on mains power. Upper right: Detailed view on the instrumentation of the EC tower in the grassland: a Solent Gill HS Ultrasonic anemometer, combined with a LiCor LI-7500 open path infrared gas analyzer (IRGA). Lower left: The eddy-covariance system at the wetland (background) running on solar energy. The solar panels are stored in the trailer and the laptop collecting the data is kept in the green cabin. Lower right: instrumentation of the EC tower in the wetland: Solent R2 ultrasonic anemometer (Gill Ltd., Lymington, UK) together with a NOAA open path IRGA.

At the grassland at Seebodenalp, EC fluxes were calculated by combining the measurements of the three-dimensional ultrasonic anemometer (Solent R3-HS, Gill Ltd., Lymington, UK), mounted at a height of 2.4 m above ground level (a.g.l.) (midpoint of the sonic head) with the CO_2 and water vapor concentrations measured with an open path infrared gas analyzer (IRGA) (LI-7500, LI-COR Inc., Lincoln, Nebraska, USA) (Fig. 4, upper left and right panels). In the wetland, a three-dimensional Solent R2 ultrasonic anemometer (Gill Ltd., Lymington, UK) was installed at a height of 2.1 m above a.g.l. together with a NOAA open path IRGA (Auble and Meyers, 1992) which was slightly modified to reduce the electronic noise level (see Eugster *et al.,* 2003) (Fig 4, lower left and right panels.

2.2.2 Webb-correction and damping-loss-correction

The Webb-correction (Webb *et al.*, 1980), which accounts for correlated air-density fluctuations, was applied to the fluxes calculated from Eq. 1. This correction decreases the magnitude of the absolute values of the daytime CO_2 fluxes (Fig. 5), whereas daytime water vapor fluxes are enhanced by the correction (data not shown). The second correction consisted of a compensation for the damping of the high-frequency fluctuations due to sensor path length averaging and separation (± 40 cm) between the sonic anemometer and IRGA gas analyzer. We used the correction model described by Eugster and Senn (1995). A system damping constant called inductance (Li = 2) was derived from a spectral analysis. The application of the damping-loss-correction slightly increased the absolute magnitude of the CO_2 fluxes (Fig. 5).

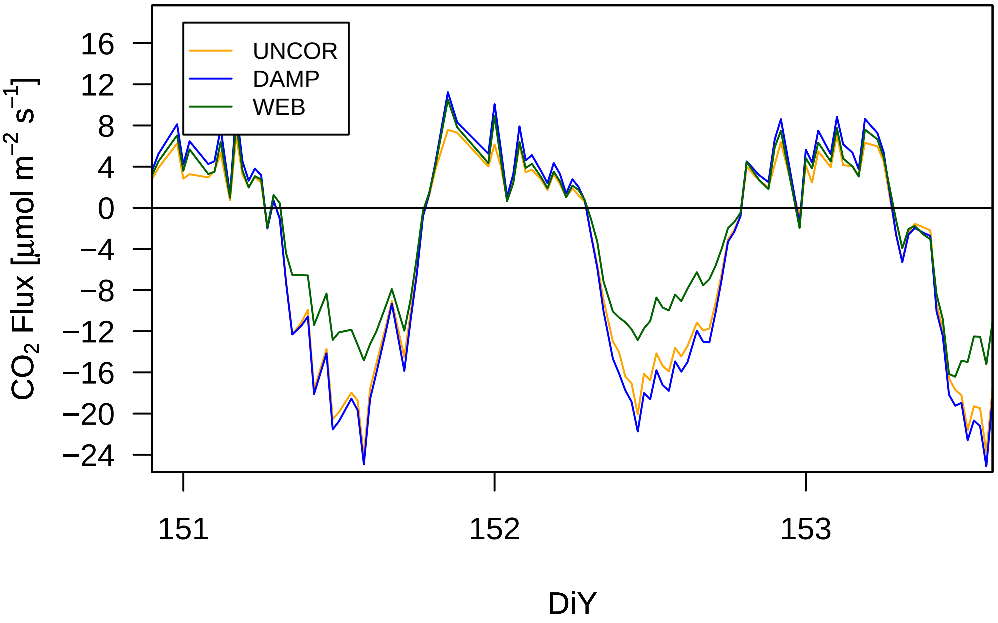

Fig. 5: The damping-loss-correction (DAMP) and the Web-correction (WEB) applied to the CO_2 fluxes calculated from Eq. 1 (UNCOR).

2.2.3 Uncertainties of eddy covariance measurements

The eddy covariance technique has proved to be a successful tool to study net ecosystem exchange of carbon dioxide for forest ecosystems (Baldocchi *et al.,* 2001). Nevertheless, uncertainties in the annual carbon uptake arise from systematic bias errors (Goulden *et al.*, 1996b) and random errors.

Systematic errors represent unknown deviations from the true value that are persistent in sign and size during a longer period and/or certain environmental conditions. Their relative effect is not reduced by averaging or summing up over longer time periods. Two types of systematic bias errors are the lack of energy balance closure and the underestimation of nocturnal ecosystem efflux during low wind conditions (Baldocchi *et al.*, 2003).

The relative effect of random errors, however, gets very small when summing up over several thousand data points and has not to be considered when calculating the carbon budget for Seebodenalp.

2.2.3.1 Problem of nighttime fluxes

Many studies report on poor reliability of nighttime flux measurements during periods with low turbulent mixing (Aubinet *et al.*, 2000; Twine *et al.*, 2000; Wilson *et al.*, 2002). A measure for turbulence is the friction velocity (u_*) defined as

$$u_* = \sqrt{-\overline{u'w'}} \qquad [\mathrm{m\ s^{-1}}]\ (\text{Eq. } 2)$$

where u’ is the deviation from the 30-minute average of the u component of the horizontal wind speed and w’ is the vertical component of the vertical wind speed. Some authors replace the nocturnal CO_2 flux measurements with values derived from the relationship between CO_2 fluxes and friction velocity under good turbulent conditions. The friction velocity (u_*) where “good turbulence” occurs is site specific and many authors define a threshold value for the friction velocity (e.g., Goulden *et al.*, 1996a; Aubinet *et al.*, 2000; Falge *et al.*, 2001; Baldocchi, 2003) to exclude periods of intermittent turbulence, where the eddy-covariance technique is believed to be imperfect in capturing true CO_2 fluxes.

For the Seebodenalp dataset, records where rejected whenever the momentum flux was not directed from the atmosphere towards the surface, in which case the flux measurements are not representative of the local surface. However, no negative effect of low turbulent mixing and measured CO_2 fluxes was found for Seebodenalp. Therefore we did not restrict our dataset with relation to the friction velocity.

2.2.3.2 Energy budget

The closure of the energy budget is a useful parameter to check the plausibility and the quality of the data (Aubinet *et al.*, 2003). The energy budget of the surface is calculated as the difference between the independent measurement of available energy, namely net radiation flux density (Rn) and the soil heat flux (G) on the one side, and the turbulent fluxes measured with the eddy covariance technique latent (LE) and turbulent sensible (H) heat flux on the other side. Many studies have shown that the energy budget tends to be more or less unclosed and that the turbulent fluxes are too small (Flanagan *et al.*, 2002; Greco and Baldocchi, 1996; Nordstroem *et al.*, 2001) which insinuates that the CO_2 fluxes are underestimated too. Some researchers apply a correction for this lack of energy balance closure (e.g. Twine et al, 2000; Griffis et al, 2004). This correction is however still under discussion since other authors argue that the lack of energy might also be the result of the difference in spatial scales (Schmid, 1994). The available energy (Rn + G) is measured at a relatively small portion of the EC footprint area whereas the turbulent fluxes (LE + H) are the result of measurements from the total footprint area.

This closure of the energy budget at Seebodenalp is discussed in detail in Rogiers *et al.* (2005) (See Chapter 3). However, no correction was applied to the dataset.

2.2.4 Data filtering and gap filling

In order to ensure the quality of the data, a careful screening was performed to identify and reject erroneous data. First we checked whether the raw data were within a plausible range. We filtered out values that were outside the range given by their monthly mean ± three times their standard deviation. Second, the relative humidity calculated from the IRGA's water vapor channel (RHi) was compared with the relative humidity measured by a standard device. Whenever RHi deviated by more than 30 % from the reference, the data record was rejected. Third, data records where rejected whenever the momentum flux was not directed from the atmosphere towards the surface, in which case the flux measurements are not representative of the local surface.

For calculating the total annual CO_2 exchange, a continuous flux time series was necessary. The data for Seebodenalp were gap filled using two different techniques, distinguishing between small (< 3 days) and big data gaps (±3 days).

Small data gaps were filled using an in-house developed gap filling tool. In a first flush gaps of maximum two-hours were filled with linear interpolation. In a second flush the remaining gaps were filled by mean diurnal cycles of the respective variable.

Gaps in EC measurements covering more than three days were modeled using functional relationships between CO_2 exchange and micrometeorological parameters determined for the adjacent periods with available data.

Dark ecosystem respiration R_e was modeled using an exponential function of nighttime (PPFD < 10 µmol m^{-2} s^{-1}) CO_2 fluxes (which are assumed to represent ecosystem respiration at night) in response to soil temperature (T_s) at 0.05 m below ground (Wofsy *et al.*, 1993; Schmid *et al.* ,2000),

$$R_e = a \cdot \exp(b \cdot Ts) \ , \qquad \text{(Eq. 3)}$$

where a and b are fitting parameters determined by minimizing the sum of squares of the residuals.

Daytime CO_2 exchange (PPFD > 10 µmol m^{-2} s^{-1}) was calculated from the relationship between gross primary production GPP [µmol m^{-2} s^{-1}] and photosynthetic photon flux density PPFD [µmol m^{-2} s^{-1}]. We used the light response curve described by a rectangular hyperbola (Ruimy *et al.*, 1995; Gilmanov *et al.*, 2003a),

$$GPP = \frac{F_{\infty} \cdot \alpha \cdot PPFD}{\alpha \cdot PPFD \ + F_{\infty}} - R_d \ , \qquad \text{(Eq. 4)}$$

where F_{∞} is NEE at light saturation [µmol m^{-2} s^{-1}], α is the apparent quantum yield and R_d [µmol m^{-2} s^{-1}] is to be interpreted as the best estimate of the average daytime ecosystem respiration (Suyker and Verma, 2001; Gilmanov *et al.*, 2003a).

2.2.5 Footprint analysis

The EC measurement is basically a point measurement, but it enables to study ecophysiological processes of whole ecosystems in order to get insight in the CO_2 exchange (Fischlin and Buchmann, 2004). For a correct interpretation of the measured EC data, the footprints of the EC towers in the grassland and the wetland were determined. The footprint of turbulent flux measurements defines the spatial context of the measurement (Schmid, 2002).

The footprints were determined with the footprint model developed by Kormann and Meixner (2001) using software developed at the Swiss Federal Agricultural Research Center. The assumptions (e.g. vertical and horizontal homogeneous terrain) inherent to the footprint model (see Schmid, 1994; Schmid, 2002) are not perfectly fulfilled at Seebodenalp. Although it is relatively flat for mountainous area, the land surface is rather patchy and heterogeneous.

As discussed in Rogiers *et al.* (2005) (see Chapter 3), the footprint calculations for Seebodenalp should rather be considered a valuable information on the rough extent of the surface area that influenced our tower flux measurements at the two sites. The footprints of the two EC towers cover the grassland and wetland surfaces quite well. At both sites, there was a non-random distribution of wind directions with clear differences between nighttime and daytime footprints for both EC towers.

2.3 Micrometeorological instruments

Along with the eddy flux instrumentation, a weather station was established (Tab. 2). The micrometeorological variables allowed for correction of the EC fluxes of pressure and temperature changes and they provided information on the environmental driving forces. All data were recorded on a datalogger (CR10X, Campbell Scientific Inc. Logan Utah, USA) at 10-minute intervals and 30-minute averages were calculated.

Additional micrometeorological data for the period January 1992 to June 2005 was provided by the National Air Pollution Monitoring Network (NABEL) data. Precipitation data is only available for 1994-2005. The station is located about 1000 m NNE of the Carbomont flux site and has been permanently in operation since the late 1980s.

Tab. 2: Micrometeorological instrumentation at Seebodenalp, measuring height, the units and the instrument brand.

Micrometeorological variable	Height (cm)	Units	Instrument brand
net radiation (Rn)	200	W m^{-2}	NR Lite, Kipp & Zonen, Delft, The Netherlands
short wave radiation (K_{up}, K_{down})	150	W m^{-2}	CM 7, Kipp & Zonen, Delft, The Netherlands
photosynthetically active photon flux density (PPFD)	200	µmol m^{-2} s^{-1}	LI-190SA, LI-COR, Lincoln, Nebraska, USA
relative humidity	100	%	HUMICAP, HMP45A/D, Vaisala, Finland
air temperature	100, 50, 10, 50	°C	copper-constantan thermocouples
soil temperature	-5, -10, -20, -30, -50	°C	copper-constantan thermocouples
soil heat flux (G)	-5, -5	W m^{-2}	heat flux plate, Hukseflux, Delft, The Netherlands
volumetric soil water content (SWC)	-5, -10	%	dielectric aquameter, ECH2O, Decagon Devices Inc., Pullman, WA
wind speed	200, 100, 50, 20	m s^{-1}	switching anemometer (Vector Instruments, UK)
wind direction	200, 100	m s^{-1}	wind vane (Vector Instruments, UK)

2.4 Final data set

In this thesis, 3 years of continuous EC measurements (May 2002 - May 2005) at a sub-alpine grassland site Seebodenalp are presented. The data collection and data processing as described earlier is summarized in Fig. 6. A database containing all quality-controlled and gapfilled EC data and micrometeorological data between 17 May 2002 and 20 May 2005 was constructed. The 30-min average data are incorporated in the CARBOMONT database and are available for the FLUXNET community and for other scientist on request.

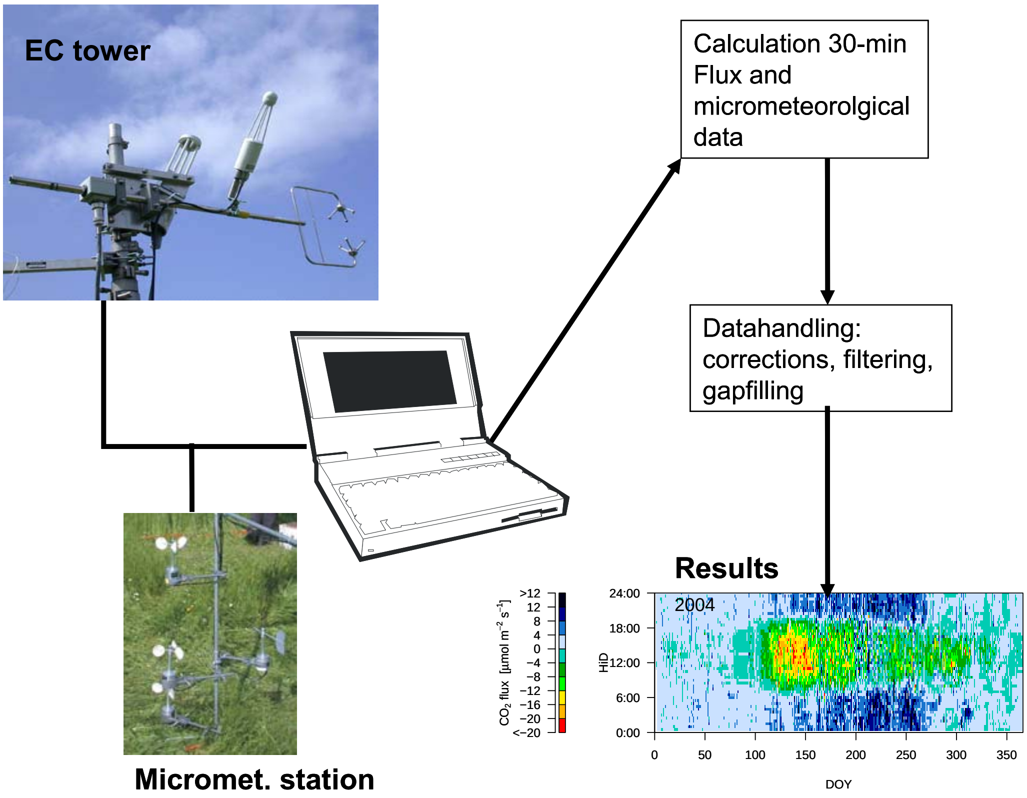

Fig. 6: Structure of the collection and processing of the data collected within the framework of the Swiss CARBOMONT project at Seebodenalp. The EC measurements and the data from the micrometeorological station are collected on a Laptop in the field. These data are than joined together within one database to derive

30-minute averages of flux data and micrometeorological information. After some corrections, filtering and gapfilling a continuous dataset was created.

The fingerprints of the EC flux measurements visualize the seasonal (X-axis) and daily (Y-axis) variation of these fluxes. In the CO_2 fingerprint of 2004 (Fig. 7), the period and the intensity of photosynthetic activity are reflected as an oval pattern, having the form of a fingerprint. In the background of this pattern carbon losses measured during the night and in winter appear.

The winter period is characterized by net respiration losses during the whole day.

As the day length increases, the vegetation becomes photosynthetically active and a net CO_2 uptake is measured during the day.

The period of CO_2 assimilation is restricted by air temperature, light and moisture conditions, as well as leaf area index (LAI). The vegetation at Seebodenalp can develop well in spring, but in summer the vegetation is disturbed resulting in a lower LAI than expected without disturbance. Consequently, a maximum uptake was measured in spring 2004 and the fingerprint was interrupted by the first grass cuts on 6 June (DoY = 158) and a second grass cut on 17 July (DoY = 197). Besides that, it is also visible that respiration during the night reaches higher values in summer than in winter due to higher soil temperatures.

The water vapor fluxes (Fig. 8), which are the result of soil water evaporation and plant transpiration, reveal a similar pattern. Here the influence of the grass cuts is not clear. As will be discussed in Chapter 4, water vapor fluxes over the sub-alpine grassland Seebodenalp are more coupled to day length and energy availability than to the CO_2 exchange.

A detailed comparison and discussion of the three years of eddy covariance data is made in Chapter 6.

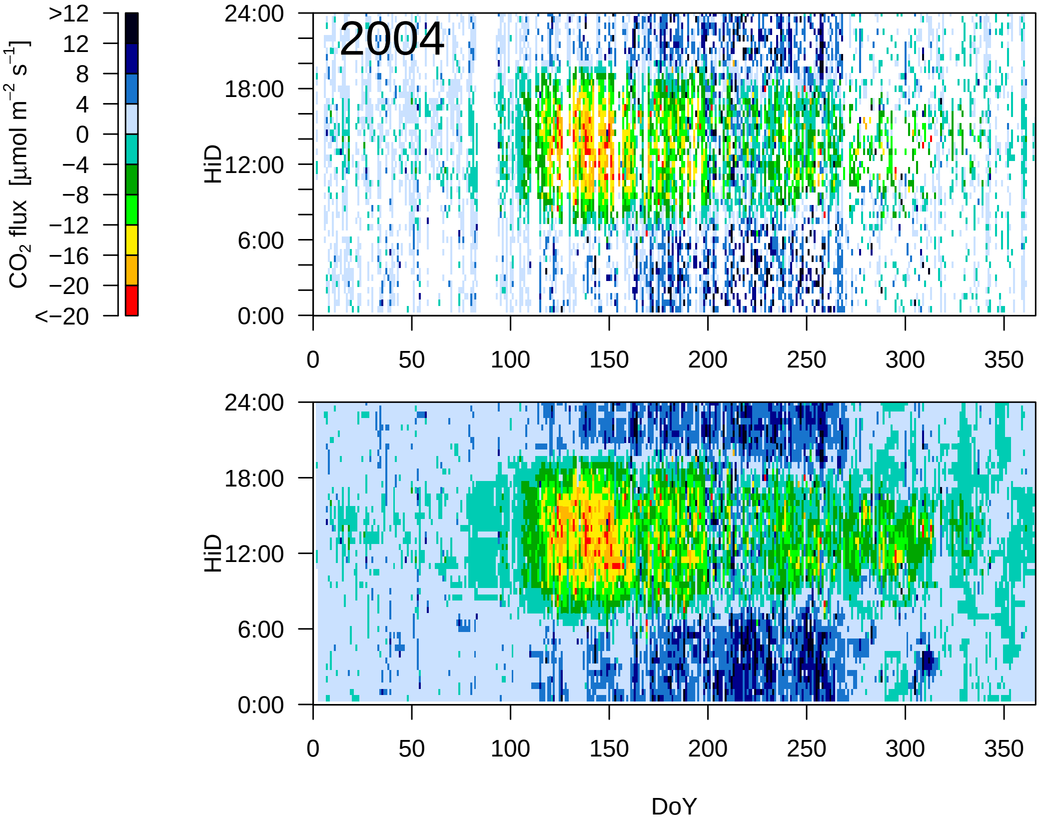

Fig. 7: Fingerprint of the CO$_2$ fluxes for the year 2004 before (upper panel) and after gap filling (lower panel). The diurnal cycles of the EC fluxes (Y-asis; HID = hour in day) are plotted for each day of year (DoY=Julian day of year).

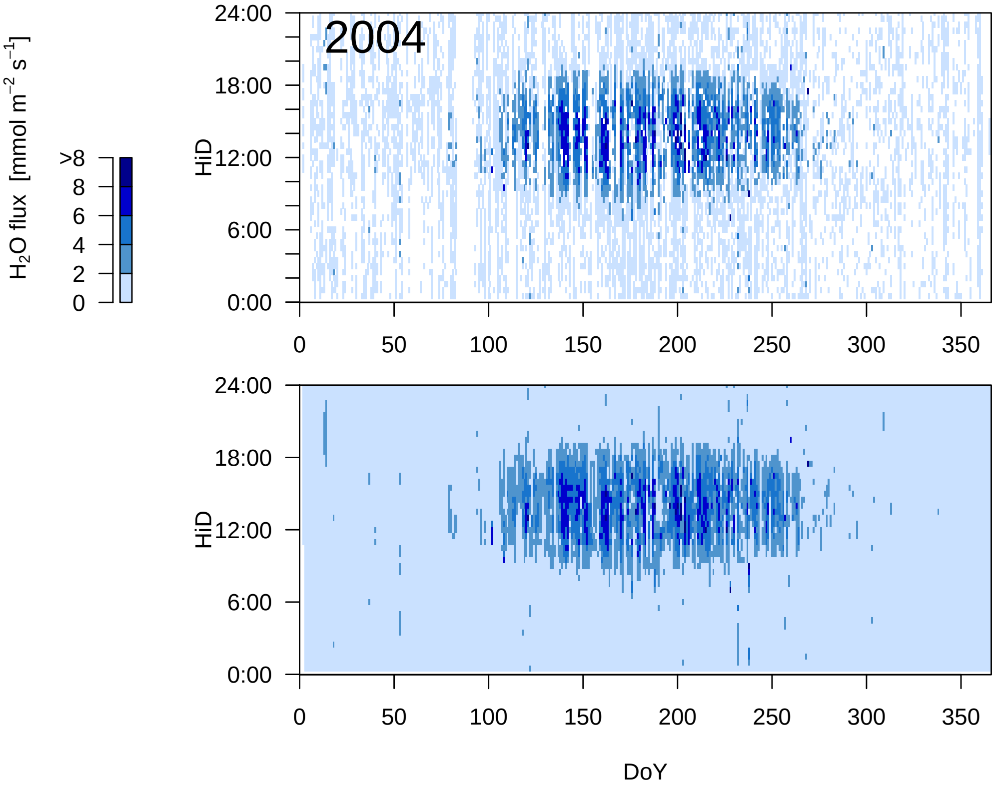

Fig. 8: Fingerprint of the water vapor fluxes for the year 2004 before (upper panel) and after gap filling (lower panel). The diurnal cycles of the EC fluxes (Y-asis; HID = hour in day) are plotted for each day of year (DoY=Julian day of year).

3 Effect of land management on ecosystem carbon fluxes at a subalpine grassland site in the Swiss Alps

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Summary

The influence of agricultural management on the CO_2 budget of a typical subalpine grassland was investigated at the Swiss CARBOMONT site at Rigi-Seebodenalp (1025 m a.s.l.) in Central Switzerland. Eddy covariance flux measurements obtained during the first growing season from the mid of spring until the first snow fall (17 Mai to 25 September 2002) are reported. With respect to the 10-year average 1992–2001, we found that this growing season had started 10 days earlier than normal, but was close to average temperature with above-normal precipitation (125–320% depending on month). Using a footprint model we found that a simple approach using wind direction sectors was adequate to classify our CO_2 fluxes as being controlled by either meadow or pasture. Two significantly different light response curves could be determined: one for periods with external interventions (grass cutting, cattle grazing) and the other for periods without external interventions. Other than this, meadow and pasture were similar, with a net carbon gain of -128 ± 17 g C m^{-2} on the undisturbed meadow, and a net carbon loss of 79 ± 17 g C m^{-2} on the managed meadow, and 270 ± 24 g C m^{-2} on the pasture during 131 days of the growing season, respectively. The grass cut in June reduced the gross CO_2 uptake of the meadow by 50 ± 2 % until regrowth of the vegetation. Cattle

grazing reduced gross uptake over the whole vegetation period (37 ± 2 %), but left respiration at a similar level as observed in the meadow.

3.1 Introduction

Ecosystem carbon sequestration is a climate change mitigation strategy based on the assumption that the flux of carbon from the air to an ecosystem can be increased while the release of carbon from the ecosystem back to the atmosphere can be decreased by choosing an appropriate land management strategy. This transformation has the potential to reduce atmospheric concentrations of carbon dioxide (CO_2), thereby slowing global warming and mitigating climate change (Batjes, 1999).

The Kyoto Protocol establishes the concept of credits for C sinks (IPCC, 2000). It is possible to take carbon sinks into account to a certain extent in calculating national greenhouse gas balances. It is therefore important to have reliable quantitative information on current carbon stocks and potential sinks (Rosenberger and Izauralde, 2001).

Baldocchi *et al.* (1996) emphasized the need for regional networks of flux measurement stations covering a broad spectrum of ecosystems and climatic conditions. Much effort has been put into quantifying these fluxes over forest ecosystems (Aubinet *et al.*, 2000; Houghton, 1996), but not so for other important vegetation types. Here we report on CO_2 exchange of a mountainous pastoral grassland ecosystem in Switzerland that we investigated as part of the European Union's 5th Framework Program project CARBOMONT.

The ability of grassland ecosystems to act as net carbon sinks may result from the continuous turnover of biomass, which supplies C into a 'permanent', inactive and thus stable soil C pool (Schulze *et al.*, 2000). It is not actually believed that agricultural soils and grasslands under normal environmental conditions will ever be managed primarily for the purpose of carbon sequestration for climate change mitigation (Leifeld *et al.*, 2003; Rosenberger and Izauralde, 2001). However, there is a potential to do so in European mountain areas. Recent developments of land management practices in the Alps, for example, are characterized by contrasting exogenic processes. Traditional small-scale farming suffers from hard economic pressure compared to the average European agriculture. This has resulted in abandonment of formerly managed grasslands (Cernusca *et al.*, 1999). Whereas agriculture once was the main source of income in Alpine regions, the main occupation of local people is now mainly in construction, housing, infrastructure, and tourism. Still, grasslands in mountainous areas play an important role in the global carbon balance (Tappeiner and Cernusca, 1998). Fundamental changes in the landscape pattern and ecosystem structure and functioning can affect the spatial structure of plant canopies, species composition and physiology, nutrient availability and in consequence the biosphere-atmosphere CO_2 exchange, which in turn may feed back on the atmospheric CO_2 concentrations (Cernusca *et al.*, 1998).

Most of the soil organic carbon in Swiss agriculture is stored under permanent grasslands (meadows and pastures), which account for more than 70 % of the total agricultural area (Leifeld *et al.*, 2003). Although intact and cultivated peatlands account for only a small percentage of the agricultural area (2.4 %), they play a significant role in Swiss carbon stocks due to the large amounts of carbon stored per hectare. About half of the organic soils have been drained over the past 150 years and are now either managed intensively or used as grassland. Since 1998, however, wetlands in Switzerland are protected by law (BUWAL, 2002).

The amount of carbon stored in agricultural soils and grassland ecosystems depends on climatic and site-specific conditions as well as on management decisions (Batjes, 1999). Thus, it is possible to regulate soil carbon stocks by agricultural management within certain limits, which are determined by natural constraints. In this paper we discuss the results from eddy covariance measurements of CO_2 exchange, made at the Swiss CARBOMONT site during the growing season of 2002.

First, we assess the climatic relevance of this period by comparing standard meteorological variables with their 10-year averages (1992–2001). Then, we quantify the CO_2 fluxes by means of the eddy covariance method and we examine the spatial distribution of the footprints using the Korman-Meixner model (2001). Additionally, we compare the CO_2 fluxes of a pasture and a meadow, and estimate the influence of land management on the amount of carbon dioxide taken up or released. Finally, we analyze the environmental and physiological forcing factors affecting the carbon balance, to gain a better understanding of the processes governing the carbon cycle of grassland ecosystems. Thereby we focus on four key factors influencing the CO_2 budget of a subalpine grassland: respiration as a function of soil temperature, daytime CO_2 flux as a function of photon flux density (PPFD), period of the vegetation season (according to periods covering different air temperature ranges) and land management (meadow vs. pasture).

3.2 Site description

The study site was established in May 2002 as part of the CARBOMONT network. The experimental site is located on a subalpine grassland with the local name Seebodenalp on a flat shoulder of the northwestern slope of Mount Rigi (47°05'38" N, 8°45'36" E) in Central Switzerland at an altitude of 1025 m above sea level (a.s.l.). The site encompasses 32 ha of relatively flat terrain. It is a patchwork of fields with various land-use types (Fig. 9). The majority of the area (22.7 ha) is extensively used pastoral grassland with varying land management practices. In 2002 half of this grassland was managed as meadow and the other half as pasture. 8.8 ha were abandoned in 2000 after the new legislation on wetland protection was enforced. The rest (0.3 ha) is a small forest at the northern boundary (Fig. 9). Steep slopes border the area towards south and east, and a moraine rim limits the area towards the northwest. Having been the bottom of a former lake (which gave the name to the alp), the terrain has been drained since more than 100 years, but is still relatively wet. The soils have a high organic matter content (determined at a depth of 10 cm) of 11.3 % ± 2 % in the drained and managed area and 29 % ± 5 % in the protected wetland area. The plant community is dominated by C_3 plant species such as *Trifolium repens* L., *Trifolium pratense* L., *Dactylis glomerata* L., *Plantago lanceolata* L., *Plantago major*

L., *Taraxacum officinalis* L., *Ranunculus repens* L., *Stellaria media* L., *Polygonum bistorta* L., *Lamium purpureum* L.

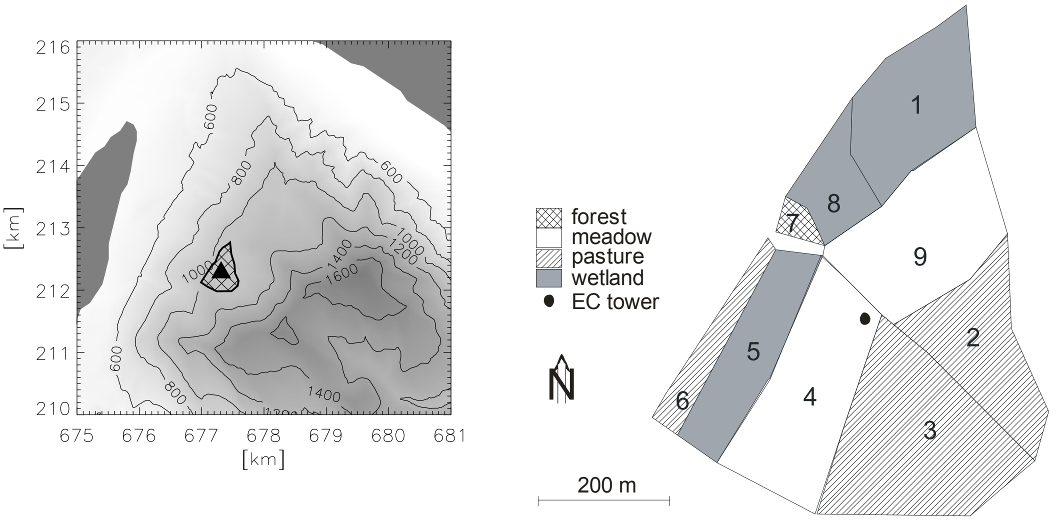


Fig. 9: The topography of the northern part of mount Rigi, the position of the Seebodenalp and the measurement tower are shown (left) on a 25-km grid. The map is in Swiss km-coordinates (DHM25 reproduced with permission, Swisstopo BA046078). A detailed map of the Seebodenalp (right) shows the land use and land-management during the vegetation period 2002 in fields 1-9. The EC tower is located in field 4.

3.3 Instrumentation and methods

3.3.1 Flux measurements

The eddy covariance (EC) technique was used to measure the fluxes of CO_2, water vapour, sensible heat, and momentum on a continuous basis (e.g., Baldocchi, 2003; Goulden *et al.*, 1996b). We calculated the vertical fluxes F_c from the covariance of the measured fluctuations of the vertical wind velocity w [m s^{-1}] and the CO_2 concentration c [µmol mol^{-1}], averaged over 30 minute intervals using Reynolds' rules of averaging (e.g., Arya, 1988). The product expresses the mean flux density of

CO_2 averaged over a time span as the covariance between fluctuations in vertical velocity and the CO_2 mixing ratio

$$F_c = (\rho_a / M_a) \cdot \overline{w' \cdot c'} \qquad [\mu\text{mol m}^{-2}\,\text{s}^{-1}] \text{ (Eq. 5)}$$

where ρ_a [kg m^{-3}] is the air density, M_a [kg mol^{-1}] is the molar weight of air, overbars represent time averages, and primed quantities the instantaneous deviations from their respective time average. Positive fluxes denote net upward transport into the atmosphere, whereas negative values signify atmospheric losses. Similarly we proceed with temperature, water vapour and momentum to obtain the corresponding turbulent fluxes. A three-dimensional ultrasonic anemometer (Solent HS, Gill Ltd., Lymington, UK) that measured wind velocity, wind direction, and temperature, was mounted at a height of 2.4 m above ground level (a.g.l.) (midpoint of the sonic head) on a tripod (diameter = 49 mm), which is expected to exert only a minimum flow disturbance of the flow field and pointed into the prevalent wind direction during the day (north). CO_2 and water vapor concentrations were measured with an open path infrared gas analyser (IRGA) (LI-7500, LI-COR Inc., Lincoln, Nebraska, USA). During the first four weeks of our measurements we used an older NOAA open path IRGA (described in Auble and Meyers, 1992). Calibration of the IRGAs was done every 3 to 4 weeks using CO_2 reference gas and a portable dew point generator (LI-610, LI-COR Inc., Lincoln, Nebraska, USA). The NOAA IRGA was calibrated using a quadratic fit to at least three calibration points, while the LI-7500 has an internal linearization and was thus calibrated with a zero gas and a span gas. Data were recorded at 20 Hz temporal resolution, and all raw data were stored on disk for later processing. The following processing steps were taken to calculate the 30 minute average fluxes with in-house developed software (a further development of the software used by Eugster, 1994; Eugster *et al.*, 1997). First, two coordinate rotations of u, v and w wind components are performed. The first rotation aligns the coordinate system with the mean streamlines of the averaging interval (McMillen, 1988) and the second rotation eliminates the inclination of the streamlines in order to obtain fluxes that are perpendicular to the streamlines. Then the mean values and variances of all variables were computed. Following this, the linear trend was removed from scalar measurements (temperature, CO_2, and H_2O). Then the time lag between CO_2 or H_2O and w was evaluated using a cross-correlation procedure that finds the maximum absolute correlation within a time lag window ranging from 0.0 to 0.5 seconds using all raw data of each averaging interval. CO_2 and H_2O where then synchronized with the wind speed data according to the respective time lag, and the turbulent fluxes were calculated. Damping losses at the high-frequency end of the raw data were corrected using the Eugster and Senn (1995) correction model, and finally the H_2O and CO_2 fluxes were corrected for concurrent density fluctuations according to the method described by Webb *et al.* (1980). The intermediate storage of CO_2 between the grass canopy and the EC measurement height was ignored since it is expected that this only plays a minor role with short vegetation and low sensor height (Baldocchi, 2003). On daily and annual time scales it is even understood that this storage term approximates zero (Aubinet *et al.*, 2000), suggesting that our simplification is justified.

3.3.2 Standard meteorological measurements

To characterize climatic conditions during the flux measurements with respect to longer-term climate we installed additional meteorological sensors on a metal frame next to the EC tower. The all-wave radiation budget was measured with a net radiometer (NR Lite, Kipp & Zonen, Delft, The Netherlands). Photosynthetic photon flux density (PPFD) was measured with a quantum sensor (LI-190SA, LI-COR, Lincoln, Nebraska, USA) at 1 m a.g.l.. Relative humidity and air temperature were measured using a humidity and temperature sensor (HUMICAP, HMP45A/D, Vaisala, Finland) placed in a sunscreen at 2.0 m a.g.l.. Soil temperature was measured at a depth of 0.05 m below ground. At the same depth, volumetric soil water content was measured using a dielectric aquameter (ECH2O, Decagon Devices Inc., Pullman, WA). All data were recorded on a datalogger (CR10X, Campbell Scientific Inc., Loughborough, UK) as 10-minute averages from which 30-minute averages were calculated.

Climate data since 1992 were obtained from the nearby Swiss Air Quality Monitoring Network (NABEL) station (47°04'10" N, 8°27'56" E, 1030 m a.s.l.). With these data we could fill the gaps in the meteorological data at our site, intercalibrate our sensors, and calculate climate statistics for the previous 10 years (1992-2001) to asses the climatic conditions observed during the vegetation period 2002. The soil heat flux was calculated using the measurements of the soil temperature profile and the soil water content (Campbell, 1985). The leaf area index (LAI) was determined periodically with a leaf area meter (LI-COR, LAI-2050, Lincoln, Nebraska, USA).

3.3.3 Data coverage and filtering

Data coverage was 42 % of all possible 30-minute time intervals during our study period. This is rather low compared to the average data coverage of 65 % at the FLUXNET sites (Falge *et al.*, 2001). The low data coverage was due to initial technical problems at the beginning of the measurements. During 28 % of the time our system was down due to hardware and software failures, missing or dysfunctional IRGA, power outages, and planned IRGA maintenance and calibration. Additionally, 30 % of the possible data were rejected, mainly during periods where rain or dew negatively affected the performance of the IRGA.

The data were screened based on certain objectively testable plausibility criteria. First, we rejected values that were outside the range given by their monthly mean ± three times its standard deviation. Second, data were filtered using the relationship between the relative humidity measured with a humicap sensor (RHm) and the relative humidity calculated from the IRGA's water vapour channel (RHi). RHm was used as the reference, because the instrument generally gives reliable mean values, even in rainy and foggy weather. If RHi deviated by more than 30 % from RHm (this threshold was derived from the correlation coefficient between both variables), then the data record was rejected. Third, data records where rejected whenever the momentum flux was not directed from the atmosphere towards the surface, in which case the flux measurements are not representative of the local surface.

3.3.4 Flux footprint analysis

The footprint of turbulent flux measurements defines the spatial context of the measurement (Schmid, 2002). Using the footprint model by Kormann and Meixner (2001), we investigated the actual footprint under all micrometeorological conditions with valid flux data. This analytical model uses an algorithm calculating the density function of the footprint contribution as a 2-dimensional field from measured friction velocity u_*, Monin-Obukhov length L, standard deviation of the wind perpendicular to the mean wind direction σ_v, measuring height z, and zero displacement height d. We calculated the characteristic dimensions of the footprint area that controls 90 % of the EC fluxes. This information was then used to assign the flux measurements to the individual fields (Fig. 9) near our tower site using software developed at the Swiss Federal Agricultural Research Center. Several assumptions have to be fulfilled in order to obtain realistic footprint results from this software. A prerequisite for using this type of model is horizontal and vertical homogeneity (see Schmid, 1994; Schmid, 2002). If the surface is inhomogeneous, the measured signal depends on the part of the surface that has the strongest influence on the sensor, and thus on the location and size of its footprint (Schmid, 2002). It is clear that the assumption of horizontal homogeneity is not perfectly fulfilled at our site. Moreover the influence of topography is certainly important at Seebodenalp, although current footprint models such as the one used here do not explicitly treat this type of heterogeneity. Thus, the footprint model concept has its limitations, which should be considered when the model output is interpreted.

Here we use the footprint model as a tool to find out which fields are contributing mostly to our EC measurements and to split our dataset into subsets for each land management category.

3.4 Results and discussion

The results from the growing season between 17 May and 25 September 2002 are presented. This period encloses all management interventions and goes from the beginning of valid flux measurements from this site until the occurrence of the first snowfall that ended the growing season relatively early in the year. The land management on the pastures was the same over the whole period, although the count of cattle varied over time. We divided this growing season into three distinct periods, which are defined by changes in land management on the pastoral meadows:

- Period 1: from the installation of the EC tower until the first grass cut (17 Mai until 11 June)
- Period 2: after the first grass cut until the second grass cut; this period can be further split into three sub-periods: (2a) the period of regrowth of the vegetation (11 June until 1 July); (2b) the period of regenerated vegetation (1 July until 21 July); and (2c) the period of cattle grazing (21 July until 11 August)
- Period 3: from the second grass cut until the first snow fall that blanketed the site (11 August until 25 September).

We first address the climate anomalies observed during the 2002 growing season. Then we discuss the degree up to which our measurements were successful in closing the surface energy budget. The following section on footprint analysis reports on how our flux measurements from one single tower were used to characterize both the meadow and pasture land-use type at Seebodenalp. This classification will then be used in the rest of the paper to quantify and interpret the growing-season CO_2 fluxes over subalpine meadow and pasture.

3.4.1 Climatological assessment

The year 2002 differed from the 10-year average mainly with respect to precipitation and with minor deviations from the expected temperature. In general, the winter half year (JFM, OND) was warmer than normal, while the summer half year (AMJJAS) temperature was below average (Fig. 10a), except for June, which experienced a heat wave. The first four months (JFMA) obtained the usual amounts of precipitation (Fig. 10b), but from May to December between 125 and 320 % of the 10-year average monthly precipitation were collected each month, with the largest relative deviation in November. The first snow fell on 26 September, but subsequently melted away. Soil temperatures did not fall below freezing until the end of the year.

Thawing degree-days (TDD) (see e.g. Jones 1992) were calculated as the accumulated departure of the daily mean temperatures from 0°C. On any day during the year TDD can be used as an index of past temperature effects upon plant growth. Compared to the 10-year average number, 2002 experienced a warmer spring, reaching the value of 477 TDD 10 days earlier (17 May instead of 27 May) than normal. Between 17 May and 25 September the cumulative difference to the reference value remained about the same. This indicates that the heat gain over the growing season 2002 was comparable to the reference period, despite the June heat wave in 2002. We may conclude that the growing season has started earlier than normal, but that the development during our field campaign was normal, and that our CO_2 fluxes reported here should be considered representative for slightly moister than average climate conditions at Seebodenalp.

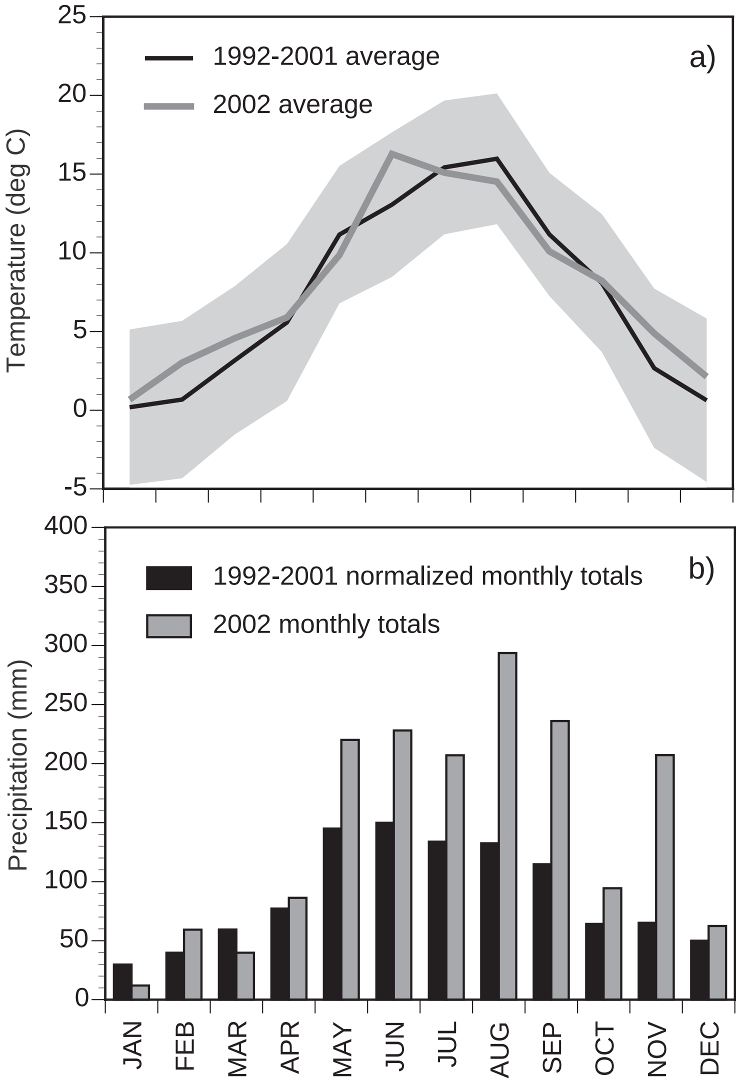


Fig. 10: a) Monthly average temperatures at Seebodenalp for 1992-2001 (black line) and 2002 (grey line). The light-grey area indicates the range of ± 1 standard deviation from the 10-year average. b) Monthly totals of precipitation for 1992-2001 (black) and 2002 (grey). Data obtained from the Swiss National Air Quality Monitoring Network (NABEL).

3.4.2 Energy budget closure

The closure of the energy budget is a useful parameter to check the plausibility and the quality of the flux data (Aubinet *et al.*, 2000) and to investigate whether or not there are other nonturbulent fluxes, such as advective fluxes (Eugster and Siegrist, 2000; Aubinet *et al.*, 2003). The energy budget of the surface is calculated as the difference between the net radiation flux density (Rn) and the soil heat flux (G) on the one side, and the turbulent latent (LE) and turbulent sensible (H) heat flux on the other side,

$$Rn - G = LE + H + \Delta Q \quad . \qquad \text{(Eq. 6)}$$

The budget closure term (ΔQ) accounts for errors in the measurement of any of these components, for the energy storage term, for a difference in source area, and for all unmeasured advective fluxes that might be important for the energy and CO_2 budget of a site.

We calculated the energy budget for all valid half-hourly data in the vegetation period 2002. A large proportion of the data is located in the region with Rn–G in the range 0–100 W m^{-2} with a median of 37 W m^{-2}, which is rather low. We used two methods to evaluate the energy budget closure. In the first method, the intercept and the slope (S1) of the linear regression between the measured 30-minute data of the dependent flux variables (LE+H) against the independently derived available energy (Rn–G) was evaluated (e.g., Wilson *et al.*, 2002). An intercept of zero and a slope of 1 represent ideal closure. The intercept of the linear regression was 27.66 W m^{-2}, and the slope was 0.76 (S1) (Fig. 11). The slope of a linear regression forced through the origin (S2) represents the relative location of the center of the data with regard to the 1:1 line (Aubinet *et al.*, 2000). S2 is 0.83, which means that the dependent variables LE and H underestimate energy balance by 17 %. In the second method, $\Delta Q/Rn$ is examined. Good energy budget closure means that $\Delta Q/Rn$ is small (Eugster and Siegrist, 2000). The energy budget closure was best during the day (PPFD > 5 µmol m^{-2} s^{-1}), with an average $\Delta Q/Rn = 0.17$, while nocturnal data showed poorer energy budget closure, $\Delta Q/Rn = 0.31$ because of weaker turbulent mixing during the night. During sunrise (7–8 AM) and sunset (7–8 PM), $\Delta Q/Rn$ differed greatly from 0, because Rn is close to zero and the ratio is not especially meaningful. Another possible explanation is that during these transition periods, wind direction changes which might cause high uncertainties in measuring the dependent flux variables LE and H. The high uncertainties in the budget closure found during sunrise can also be explained by the venting effect (Baldocchi, 2003) which causes the EC technique to overestimate the time-local flux density.

The results of both methods confirm the common observation found in many studies (Flanagan *et al.*, 2002; Greco and Baldocchi, 1996; Nordstroem *et al.*, 2001) that the energy budget tends to be more or less unclosed. Wilson *et al.* (2002) discusses several hypotheses to explain the lack of energy budget closure. Two of them concern also the interpretation of the CO_2 fluxes at our site. First, there is a possible instrumentation bias of the Sonic and IRGA instruments and second, the unmeasured advective terms might be responsible for the difference.

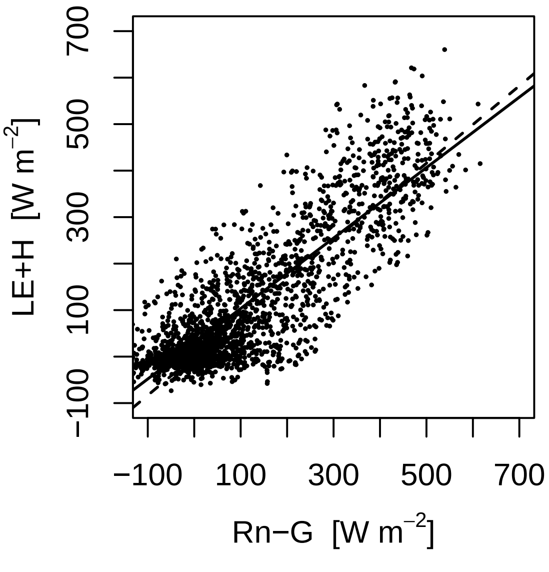


Fig. 11: Relationship between the available energy (Rn-G) and the turbulent flux variables (LE+H) measured by eddy covariance tower. The linear regression (full line) has an intercept of 27.66 W m^{-2} and a slope of 0.76. The slope of a linear regression forced through the origin (dashed line) is 0.83.

3.4.3 Footprint analysis

Depending on wind direction the land use in the flux footprint may be either pasture, meadow, or wetland at our site. Therefore, in theory, it might be possible to acquire information on the carbon balance of all three land-use types with just one EC tower by weighing the measured flux densities according to the fractional footprint of each land-use type. To do this, we ran our footprint analysis separately for each half-hour interval, and collected the results per land-use category for each of the three periods defined above. We found that only four fields on the Seebodenalp (Fig. 9) controlled the CO_2 fluxes measured at our tower during the growing season of 2002: namely, fields 2, 3, 4, and 9. These fields adjacent to the measurement tower are responsible for 95-99 % of the measured CO_2 fluxes. No relevant differences were found between the three periods, which reflects the expected persistence and predictability of the local wind system at this location, which is typical for mountainous areas. There were clear differences between nighttime and daytime footprints, however. This is because the main wind direction changes from northeast during the day to southeast during the night (Fig. 12). Under high pressure weather conditions when thermally driven winds develop, a northeasterly flow establishes over the site during the day. During the night, cold air drainage occurs from the southeast, down slope of Mount Rigi. During the day, 50-55 % and 20-25 % of the footprint are from fields 9 and 4, respectively. During the night, the main sources of measured fluxes are found in fields 3 (55-60 %) and 2 (10-15 %). The fields not adjacent to the measurement tower are rarely contributing to the measured fluxes (1-5 % according to model computations), because they are too far away from the sensor and not upwind of the sensor.

The wetlands were very rarely in the footprint because fields 8 and 9 are situated too far away from the sensor, and field 5 was never in the mean wind direction. Thus, with the setup of 2002, we can not include the protected wetland area with the managed grasslands and pastures. In order to do so in the future, an additional tower needs to be installed in the wet area.

The footprint analysis with the Korman-Meixner (2001) model gave us important information on what our EC flux measurements actually represent. The results of this detailed and time consuming footprint analysis, however, showed that we could easily just use a much simpler method for our further analysis, that is to use the mean wind direction to decide which of the adjacent fields was responsible for each realisation of a 30-minute flux average. We therefore grouped the four fields mainly contributing to the flux measurements into two wind direction sectors, each with its specific land management practice during the growing season 2002. Sector 1 covers northwesterly wind directions between 225° and 80° from geographical north and covers the meadow land-use category. This sector is responsible for most of the daytime flux measurements. Sector 2 with southeasterly winds between 80° and 225° covers the pastures and is the main source of the measured nighttime fluxes.

Working with the sector approach has the advantage that we do not have to worry about the assumptions made in a footprint model, and that it is much easier to calculate. The disadvantage is that we loose some information. We introduce an error of misclassification. However, when considering the fact that we have to make some important assumptions for the footprint calculation, which most likely could also introduce much greater errors, we believe that this does not significantly bias our findings.

Thus, in the following we analyse our dataset separately for the two wind direction sectors, which correspond with different land uses, where “meadow” and “pasture” refer to sectors 1 and 2, respectively.

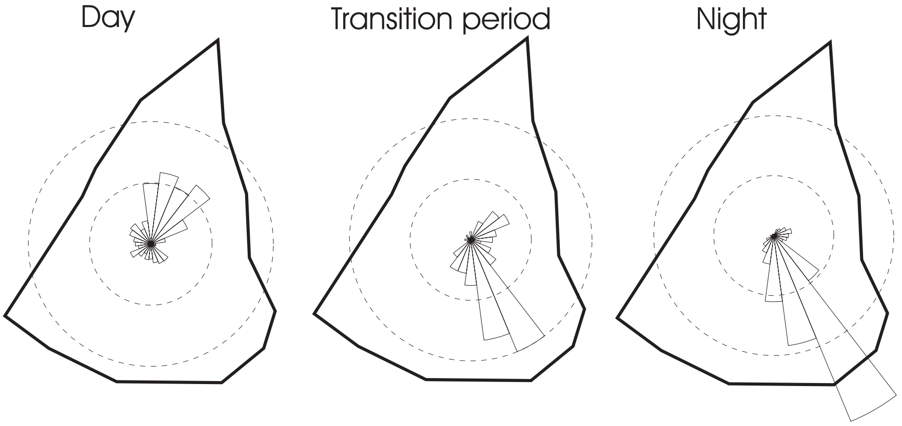


Fig. 12: Wind roses at the flux station with the contour of the site during the day (PPFD > 50 µmol m^{-2} s^{-1}), during the night (PPFD < 5 µmol m^{-2} s-^{1}) and for the transition period with changing wind direction (5 µmol m^{-2} s^{-1} < PPFD < 50 µmol m^{-2} s^{-1}). The wind directions are segregated in sectors of 15°. The circles represent intervals of 20 % of the wind class occurrence.

3.4.4 Processes affecting the carbon budget

We assessed mean diurnal variations in net ecosystem exchange (NEE) of CO_2 for both land-use types and the three periods defined in the previous section. With the prevailing local wind system (Fig. 12) the data coverage for nighttime conditions over meadow was somewhat low, while for the pasture the daytime coverage was a limiting factor. In Fig. 13 the composited mean diurnal cycles are shown. Each 30-minute interval covered by at least three valid flux measurements (i.e. the minimum number of observations needed to calculate a mean and standard variation) was included in the composite. The diurnal variations of the measured NEE are the results of two plant physiological processes: respiration and assimilation. In the following sections, we analyze both processes in detail.

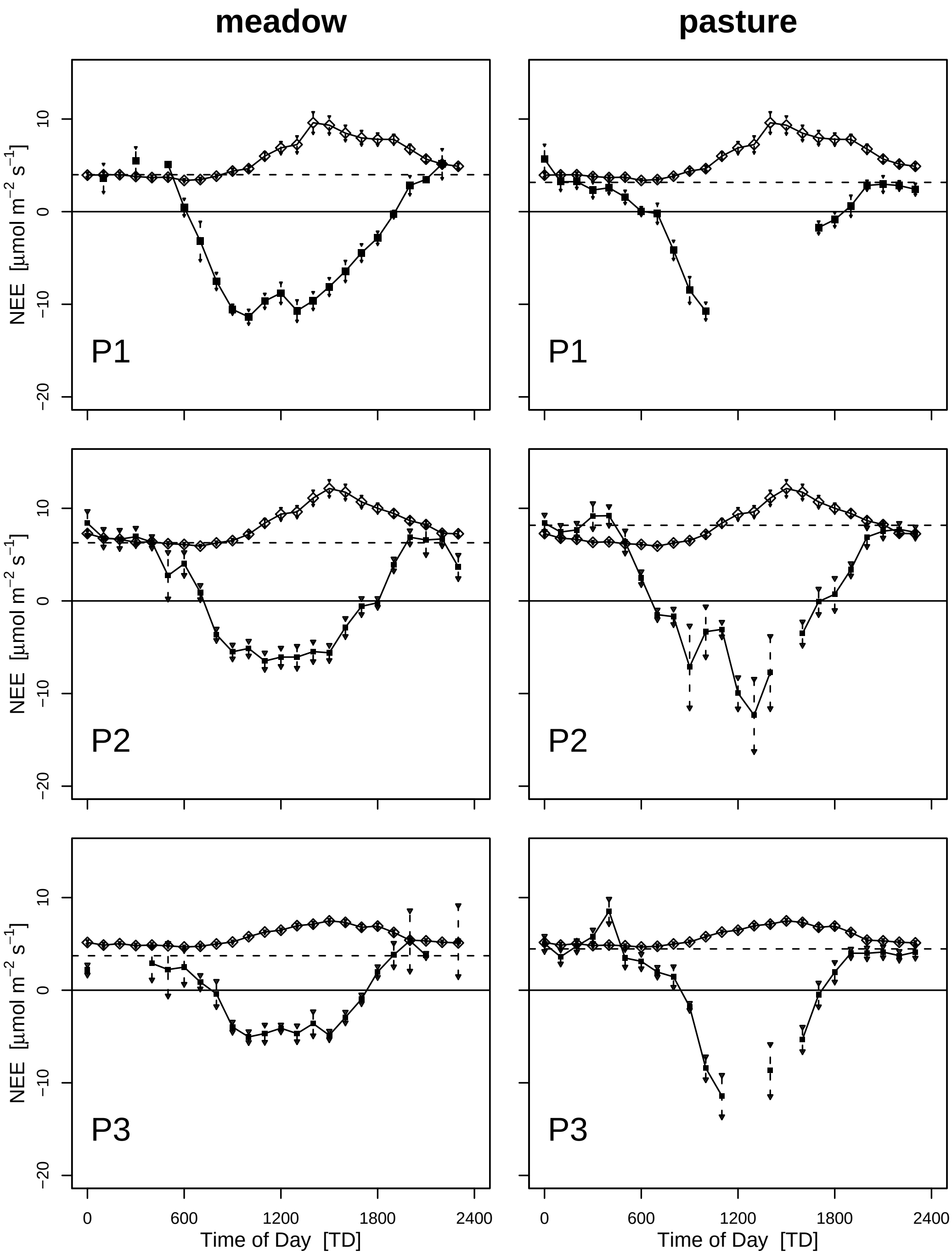


Fig. 13: Mean diurnal courses of the CO_2 flux (closed squares) observed over meadow (left column) and pasture (right column) for the three time periods before the first cut (P1, top), the period between the first and the second cut (P2, centre), and after the second cut before the first snowfall (P3, bottom). The open circles show the

mean ecosystem respiration (derived from Eq. 7). Symbols depict the composite mean of all available 30-minute fluxes, and error bars denote the standard error of the mean. The broken lines indicate the mean dark respiration level derived from flux measurements when PPFD was below 5 µmol m^{-2} s^{-1}.

3.4.4.1 Respiration

In all cases the data coverage during the night appears to be sufficient to calculate reliable mean dark respiration (R_d) (mean CO_2 flux when PPFD < 5 µmol m^{-2} s^{-1}) since the temporal variation is much smaller than during daytime (e.g., Goulden *et al.,* 1996b; Saigusa *et al.*, 2002).

However, rates of ecosystem respiration (R_e) tend to be higher during the day than during the night reflecting additional metabolic activity associated with light-related processes and higher soil temperatures during the day (Gilmanov *et al.*, 2003a). Therefore, we examined the relationship between nighttime CO_2 fluxes and soil temperature (T_s) at 0.02 m below ground to determine R_e as

$$Re = a \cdot \exp(b \cdot Ts) \quad , \quad \text{(Eq. 7)}$$

where a is the fitting parameter. This method is identical to that used by Wofsy *et al.* (1993) and Schmid *et al.* (2000). We block-averaged all data to 1°C temperature intervals to reduce the scatter in the soil temperature data.

Many authors define a threshold value for the friction velocity (e.g., Nordstroem *et al.*, 2001; Schmid *et al.*, 2000) to exclude periods of intermittent turbulence, where the eddy-covariance technique is believed to be imperfect in capturing true CO_2 fluxes. At our site, we did not find a negative effect of low turbulent mixing and measured CO_2 fluxes. Therefore we did not restrict our dataset with relation to the friction velocity (recall that we did not use data when the momentum flux was not directed towards the surface).

It is not possible to compare the fits for the meadow and pasture for the 3 periods, because the temperature range per period is very small, which results in unstable fits.

Therefore we segregated the data into a subsets with and without intervention (Fig. 14). The fitting parameter for the periods with intervention (period 2a, 2c and 3 on meadow and all periods on pasture) is a = 1.122 ± 0.003, and for the period without intervention (period 1 and 2b on meadow) a = 1.113 ± 0.003. We compared the fitting parameter of both models with a t-test based on Wald's confidence ellipsoids. Yet, we could not find any statistically significant differences between the two fits, due to the very high variability in the nocturnal respiration measurements. This high variability could not be explained by variation in soil water content, because no statistical relationship was found between nighttime CO_2 fluxes and soil water content. We determined one curve describing the relationship between soil temperature and respiration with a = 1.123 ± 0.003. Based on this, we could calculate mean values of R_e per period, but we could not distinguish between land management. The diurnal course of R_e is shown in Fig. 13.

The mean values of soil temperature, dark respiration (R_d) and mean ecosystem respiration (R_e) are listed in Table 3. The standard errors on the mean values of R_d are calculated as the sum of the standard errors on the mean R_d and of the standard error on an additional term due to possible random effects, which can be introduced by environmental factors other than soil temperature. The standard error on the means of the ecosystem respiration R_e was calculated using the delta method for smooth functionals of the fitting parameter a (Van der Vaart, 1998).

As well on the meadow as on the pasture, the mean R_d is different for every period. As expected, R_d on the pasture is greater at the end of the season (P3) (4.46 ± 0.19 μmol m^{-2} s^{-1}) compared to P1 (3.16 ± 0.10 μmol m^{-2} s^{-1}), despite the identical average soil temperature in period 1 (13.5 ± 0.3 °C) and in period 3 (13.8 ± 0.3 °C). Interestingly, R_d from the meadow is lower during P3 (3.72 ± 0.08 μmol m^{-2} s^{-1}) than P1 (3.99 ± 0.08 μmol m^{-2} s^{-1}), indicating the importance of the grass cutting that reduces respiration slightly after a certain time lag (no more than a month) compared to pasture. R_d shows a maximum in the second period. This corresponds to the maximum average soil temperature during this period (16.5 ± 0.4 °C) and thus with the maximum mean ecosystem respiration. Mean modeled ecosystem respiration (R_e)

was higher than the mean measured dark respiration (R_d) on the meadow and on the pasture for every period. Mean modeled ecosystem respiration (R_e) is identical for period 1 (5.62 ± 0.10 µmol m^{-2} s^{-1}) and 3 (5.91 ± 0.20 µmol m^{-2} s^{-1}) because of identical mean soil temperatures. In the following, we always used modeled ecosystem respiration R_e.

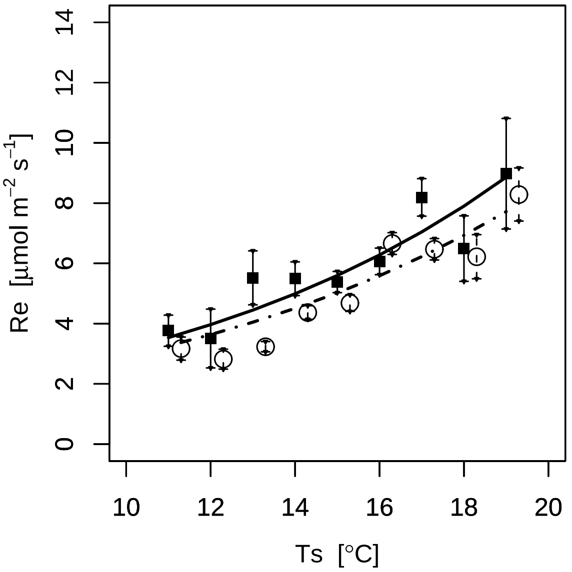


Fig. 14: The relationship between ecosystem respiration (R_e) and soil temperature (T_s) at 5 cm depth. Mean values ± 1 SE were calculated for every 1°C interval, and an exponential curve was fitted to the means. The dataset was split up for the periods with (closed squares, solid line) and without (open circles, dashed line) interventions. To improve legibility the latter data were shifted right by 0.3°C.

3.4.4.2 Assimilation

In our study the ecological main driving variable for assimilation during the day is photosynthetic photon flux density (PPFD) (for comparison see, e.g., Metting *et al.*, 2001; Ruimy *et al.*, 1995). The functional relationship between gross primary production GPP [µmol m^{-2} s^{-1}] and PPFD [µmol m^{-2} s^{-1}] is known as ‘light response curve’ and described by a rectangular hyperbola (Ruimy *et al.*, 1995)

$$\mathrm{GPP} = \frac{F_\infty \cdot \alpha \cdot \mathrm{PPFD}}{\alpha \cdot \mathrm{PPFD} + F_\infty} - R_e \,, \qquad \text{(Eq. 8)}$$

where F_∞ is NEE at light saturation [µmol m^{-2} s^{-1}] and α is the apparent quantum yield. Here R_e [µmol m^{-2} s^{-1}] is to be interpreted as the best estimate of the average daytime ecosystem respiration (Suyker and Verma, 2001; Gilmanov *et al.*, 2003a).

Fig. 15 shows the light response curves for the meadow and the pasture. The curves for the meadow are based on data with PPFD reaching values up to 1800 µmol m^{-2} s^{-1} whereas CO_2 fluxes over the pasture are only available for much lower PPFD values (maximum 700 µmol m^{-2} s^{-1}) due to the previously described local wind directions. The estimated values and the standard deviations of the fitting parameters α, F_∞ and R_e for the light response curves for the different periods on the meadow and on the pasture are calculated using the 'non linear regression' package of the free R-software system and are listed in Table 4. A t-test based on Wald's confidence ellipsoids was used to determine the difference in parameters for the different models.

The estimated values of R_e were significantly different ($p<0.05$) on the meadow for all periods. The differences among the periods found for R_e on the meadow correspond well with the differences in soil temperature. Statistical differences in the model parameter α on the meadow could not be determined. For the meadow, we found significant differences in F_∞ between on the one hand the curves for the period just after the first grass cut (2a), the period with cows (2c), and the period after the second grass cut (3), and on the other hand the fits for the period before the cut (1), and the regeneration period in the second period (2b).

On the pasture, no significant differences for the fitting parameters F_∞, α, and R_e were found between the three different periods. Therefore we fitted the light response curves of the pasture with the same set of parameters for the whole vegetation period. Since this light response curve has very high uncertainties because of lack of data in the range with higher irradiation levels, we assumed that the fit for the pasture is similar to those for the meadow during the period with grazing (2c) and that the difference in GPP is only a result of the lower irradiation levels.

Based on these findings, we segregated the data into two groups and calculated two statistically different light response curves (Fig. 16). One group is associated with the intervals without external intervention (data from the meadow during period 1 and 2b) and the other is associated with the data from periods and fields with external intervention (data from the meadow during period 2a, 2c and 3 and all time periods from the pasture). Again, differences in F_∞ are mainly responsible for the differences in GPP. During managed periods, light saturation of GPP was reached above PPFD values of 500 µmol m^{-2} s^{-1} whereas during unmanaged periods light saturation was reached at PFFD values of 1000 µmol m^{-2} s^{-1}. This fact that light saturation is reached at higher PPFD values is the result of the leaf area index (LAI). Before the grass cut the LAI was 4.4 and in period 2b LAI was 3.3, whereas during managed periods LAI values never approached these values again. The maximum rates of F_∞ (20.12 ± 0.87 µmol m^{-2} s^{-1}) were observed for the period without external intervention. This value is much higher than the F_∞ found for the pasture (10.13 ± 1.42 µmol m^{-2} s^{-1}). The order of magnitude of our values for F_∞ is lower than the values found in literature. Ch. Ammann (pers. comm.) found for the same growing season an average value for F_∞ of 29 µmol m^{-2} s^{-1} during maximum vegetation growth on an extensive managed grassland with similar plant composition on the Swiss Plateau (450 m a.s.l.). The difference is mainly caused by the difference in altitude. A value of 27.5 µmol m^{-2} s^{-1} for F_∞ was found in a northern temperate C_3 grassland ecosystem in June 1998 (Flanagan *et al.*, 2002) and average values for C_3 grasslands of 23 µmol m^{-2} s^{-1} are reported by Ruimy *et al.* (1996).

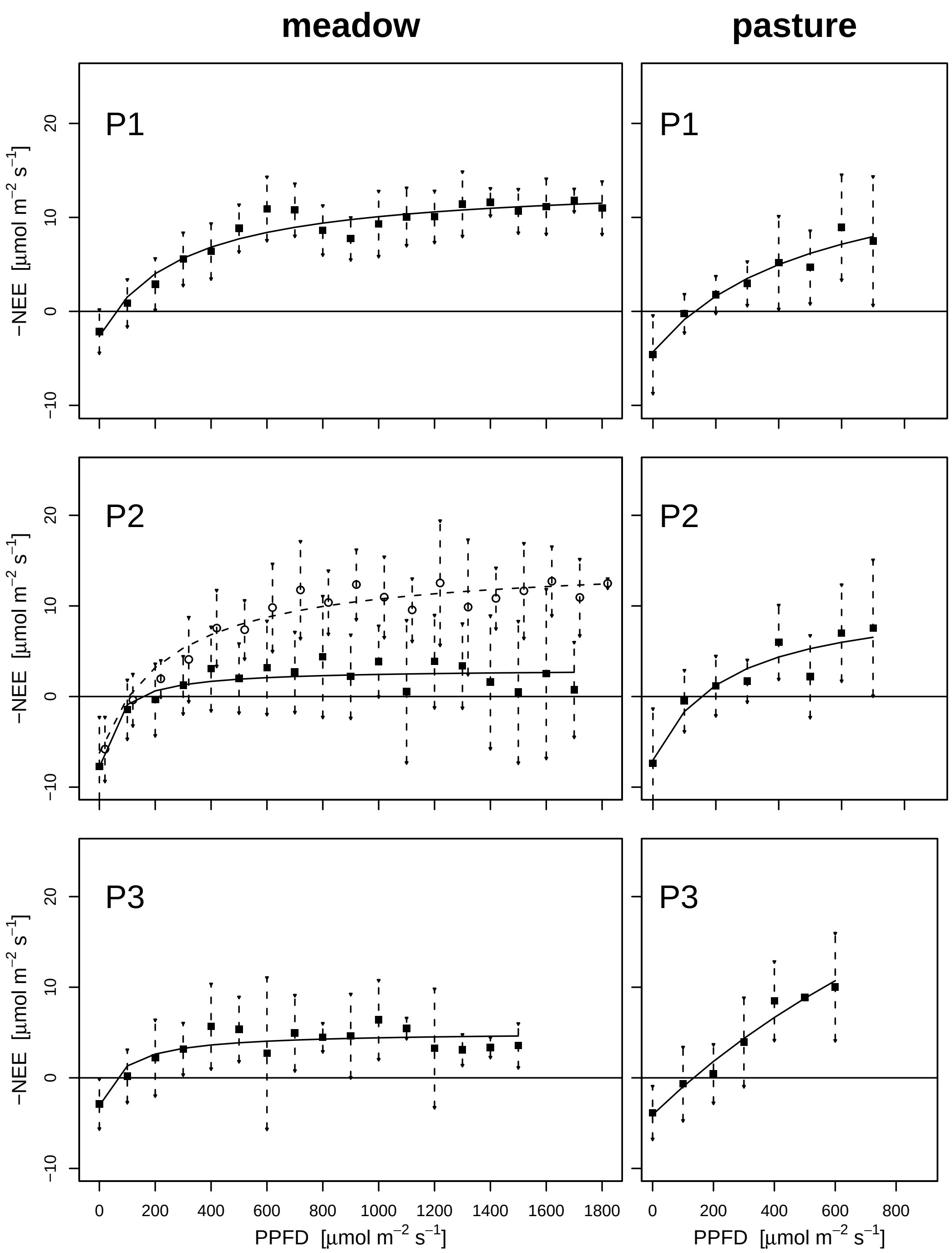


Fig. 15: Light response curves of the CO_2 fluxes measured on the meadow (left) and on a pasture (right) during the 3 time intervals. Symbols depict the mean per 100 µmol m^{-2} s^{-1} PPFD interval, and error bars denote the standard error of the mean. The hyperbolic curves (solid lines) were fitted to the means. Period P2 for the meadow

was divided in 3 intervals and 2 different curves were found: (2a) the period of regrowth of the vegetation together with (2c) the period of cattle grazing (closed squares, solid line); (2b) the period of regenerated vegetation (open circles, dashed line).

Although not statistically different, the apparent quantum yield for the period with intervention is higher (0.116 ± 0.031) than the value for the period of undisturbed growth (0.086 ± 0.014). The mutual shading in the undisturbed canopy was much higher (LAI = 4.4 on meadow before first grass cut) than after the grass was cut (LAI = 0.7 on meadow in period 2a). The higher the mutual shading of a plant community the lower is the probability that all leaves will be exposed to an irradiation level near light saturation, which is also reflected in the quantum yield efficiency. The apparent quantum yield of managed ecosystems generally exceeds that of unmanaged ecosystems (Metting *et al.*, 2001). Whereas α might not be strongly related to the long-term C sequestration, it does represent the carbon uptake efficiency for a given light environment and canopy structure. Our values of apparent quantum yield were remarkably higher than values for other C_3 grassland ecosystems (compare with Flanagan *et al.*, 2002; Ruimy *et al.*, 1995).

No statistical differences were found for daytime R_e between managed and unmanaged periods. This is in agreement with the results obtained for R_e using nocturnal flux measurements (Eq. 7). R_e is thus controlled primarily by soil temperature and not by land management.

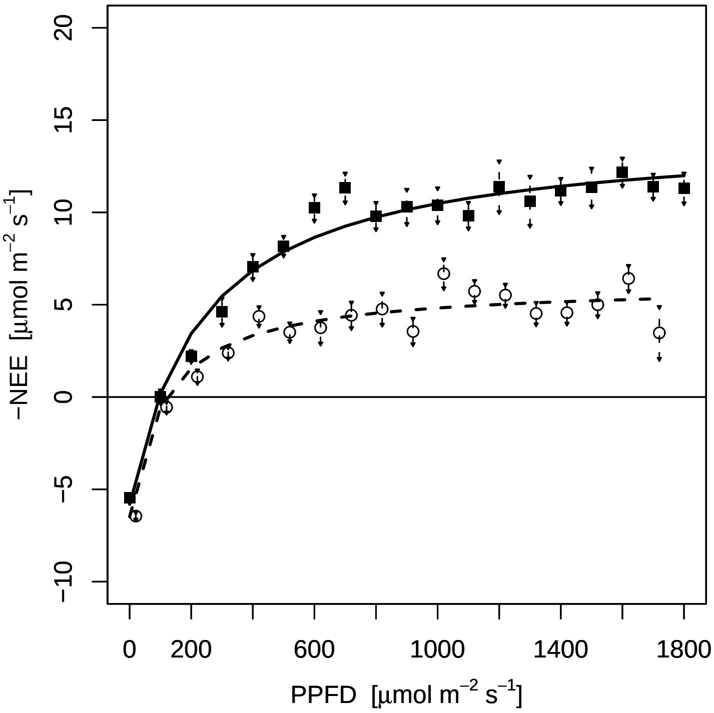


Fig. 16: Light response curves for the data without external intervention (closed squares, solid line) and with external intervention (open circles, dashed line). Symbols depict the mean per 100 µmol m^{-2} PPFD interval and error bars denote the standard error of the mean. To improve legibility the latter data were shifted right by 30 PPFD.

3.4.5 Estimation of the influence of land management on ecosystem carbon fluxes

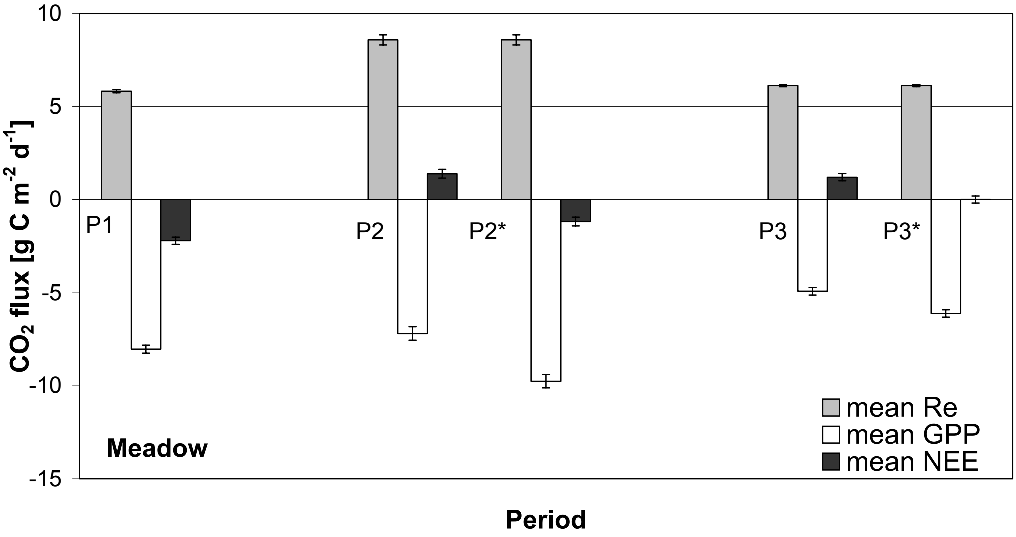
In the following, we assess the influence of land management on the CO_2 fluxes via the comparison of NEE of the different land management practices. Since R_e does not co-vary with land management in this specific case, it is mostly the difference in assimilation that determines the differences in NEE.

Nighttime values were substituted by modeled ecosystem respiration values extrapolated from the relationship derived between soil temperature and nighttime NEE (see above). If we use the term ‘measured NEE data’, we refer to the measured daytime data. ‘Modeled NEE data’ are daytime values for NEE calculated from the light response curves derived in the previous section. Mean daily R_e (Table 3) and mean daily NEE were calculated for both land-use types and the three periods. The assimilation or gross primary production (GPP) was determined by subtracting mean R_e from the daily mean NEE (Fig. 17).

For the meadow, we calculated daytime NEE for the periods with and without external intervention, respectively, based on the light response curves (Fig. 16). The difference between the measured and the calculated values is the amount of CO_2 flux missing due to the land management. GPP shows a decreasing trend from the first (-8.03 ± 0.21 g C m^{-2} d^{-1}) to the third period (-4.92 ± 0.20 g C m^{-2} d^{-1}). Daily mean PPFD was highest in the second period (11 June until 11 August) with 395.3 ± 5.2 µmol m^{-2} s^{-1}, followed by 372.4 ± 4.9 µmol m^{-2} s^{-1} during the first period (17 Mai until 11 June) and the lowest value (323.9 ± 7.1 µmol m^{-2} s^{-1}) during the third period (11 August until 25 September). Without land management, we would have expected a higher assimilation on the meadow in the second period because of the larger LAI, and a better exploitation of the higher mean PPFD in this period. Had the grass not been cut at all, then we would have expected a GPP of -10.45 ± 0.39 g C m^{-2} d^{-1} instead of -5.22 ± 0.39 g C m^{-2} d^{-1} during period 2a. The grass cut reduced GPP on the meadow by 50 ± 2 % between harvest and regrowth of the vegetation and the grazing. Cows grazing in period 2c reduced GPP by 27 ± 1 % from -9.12 ± 0.35 g C m^{-2} d^{-1} till -6.61 ± 0.35 g C m^{-2} d^{-1}. We calculated GPP for the second period as the sum of the measured GPP in period 2b and the GPP for the period after the cut (2a) and for the period with cows grazing (2c; see Fig. 17, P2*). The land management in period 2 reduced GPP by 26 ± 1 % (-9.76 ± 0.36 g C m^{-2} d^{-1} versus -7.19 ± 0.36 g C m^{-2} d^{-1}). Although there was no grazing on the meadow during period 3, the influence of cows grazing is still noticeable because the vegetation was disturbed and NEE was reduced by 20 ± 1 % (-6.12 ± 0.20 g C m^{-2} d^{-1} versus -4.92 ± 0.20 g C m^{-2} d^{-1}).

Pasture GPP could not be determined directly because some considerable gaps in NEE measurements are found during the day (Fig. 13). Therefore NEE was calculated from the light response curve for periods with intervention. We found much lower mean modeled NEE values than on the meadow. In the first period grazing reduced GPP by 44 ± 2 % (-8.03 ± 0.21 g C m^{-2} d^{-1} versus -4.49 ± 0.30 g C m^{-2} d^{-1}). In the second period, GPP on the meadow with undisturbed vegetation growth (here we used the new calculated values of P2*) was higher (-9.76 ± 0.36 g C m^{-2} d^{-1} versus -6.41± 0.43 g C m^{-2} d^{-1}) or 34 ± 2 % of GPP was missing due to grazing. In the third period we found a reduction of GPP of 37 ± 2 % by comparing the calculated values of the meadow (P3*) and the pasture (-6.12 ± 0.20 g C m^{-2} d^{-1} versus –3.83 ± 0.20 g C m^{-2} d^{-1}). Over the entire growing season, the total carbon gain of the undisturbed meadow is -128 ± 17 g C m^{-2}, whereas the total carbon loss for the disturbed meadow is 79 ± 17 g C m^{-2} and for the pasture 270 ± 24 g C m^{-2}. The lower leaf area index of the pasture (for P1, P2 and P3 LAI was 2.5, 1.7 and 0.4) compared to the 'managed' meadow (for P1, P2 and P3 LAI was 4.4, 3 and 0.7) is mainly responsible for the reduction of CO_2 uptake by the grazed vegetation compared to the vegetation with undisturbed growth.

The effect of leaf senescence was not considered in this comparison. However, we can say from other studies that the maximum photosynthetic capacity would decrease within a few weeks below the level that the canopy achieved before the first cut (Tappeiner and Cernusca, 1998).



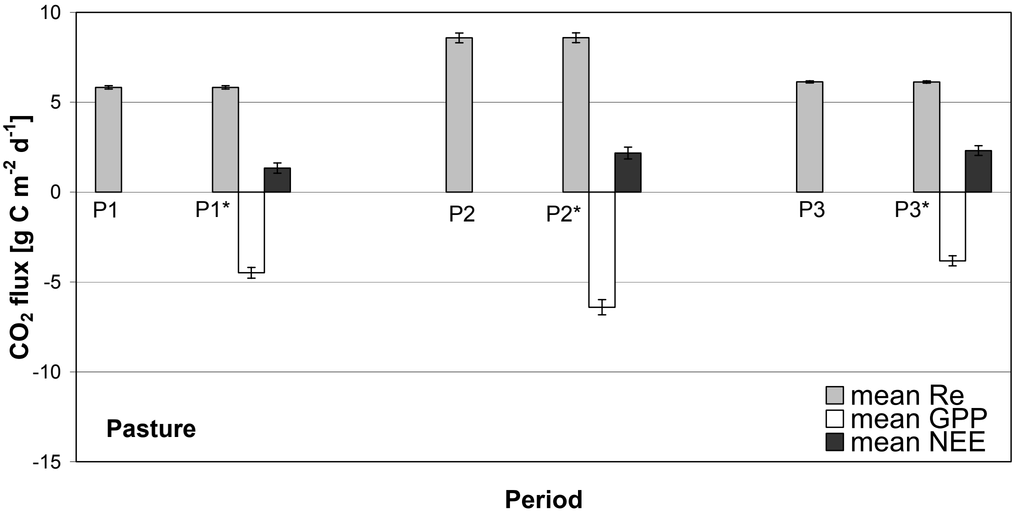


Fig. 17: Comparison of the mean respiration and mean assimilation during the different periods (P1, P2, P3) on the meadow (upper panel) and on the pasture (lower panel). For the period P2 we also calculated a mean assimilation as if no grass cut had occurred and for period P3 we calculated the NEE as if no grazing had occurred in period 2c. These values are labeled P2* and P3*. Mean NEE was also calculated for the pasture for the whole vegetation period. The values are labeled P1', P2' and P3'. The sum of mean GPP and mean Re represents mean NEE.

3.5 Conclusions

CO_2 fluxes were measured by eddy covariance from the mid of spring until the first snow fall (17 Mai to 25 September 2002) above a subalpine grassland land in the Swiss central Alps. The climatic conditions observed during the growing season of 2002 were found to be close to average temperature (10-year reference period) with above-average (125–320 %) precipitation. Despite the heat wave in June, we expect the carbon uptake of the vegetation period 2002 to be comparable to the 10-year average because sufficient water was available.

The energy budget closure of 83 % on average indicates that the CO_2 fluxes reported here could be low estimates and might be 20 % greater in reality, if the lack of energy budget closure is due to advective fluxes.

Based on the Kormann-Meixner footprint results, we were able to show that the much simpler method that uses the mean wind direction is adequate enough to characterize CO_2 exchange from meadow and pasture. This allowed us to escape the justification of debatable assumptions made by such a footprint model (especially when it is applied to complex terrain as we did), without suffering a great loss of confidence in whether pasture or meadow was actually controlling our CO_2 flux measurements. We distinguished two wind sectors each with its specific land management practice during the growing season 2002. One sector covers the meadow land-use category with northwesterly winds during the day and the other sector with southeasterly winds covers the pastures and is the main source of the measured nighttime fluxes.

Ecosystem respiration (Re) was calculated from the relationship between soil temperature and dark respiration, irrespective of land management. Only two significantly different light response curves could be determined: one curve for periods with and another for periods without external intervention (grass cut, cattle grazing). The main controlling factor was F_∞ (NEE at light saturation). Using the light response curves, we were able to calculate daytime NEE for the pasture whenever the data coverage during the day was too poor and for the meadow to calculate hypothetical values as if no land management had occurred. The mean daily assimilation or gross primary production (GPP) could then be calculated by subtracting mean ecosystem respiration from the daily measured or modeled mean NEE. Land management influenced CO_2 fluxes in two ways: (1) via cutting the grass, and (2) via cattle grazing. The grass cut in June reduced the gross CO_2 uptake on the meadow by 50 ± 2 % until regrowth of the vegetation. Cow grazing on the pasture had a strong influence on GPP over the whole vegetation period (reduction between 34 ± 2 % and 44 ± 2 % depending on period).

3.6 Tables

Tab. 3: Mean temperature and respiration fluxes with standard errors calculated for the 3 periods P1, P2 and P3. T_s: mean soil temperature at a depth of 0.02 m; R_d: mean dark respiration; R_e: mean ecosystem respiration (Eq. 8). Means with the same superscript letter do not differ significantly (95% confidence intervals) from one another.

Period	T_s [°C]	R_d meadow [µmol m^{-2} s^{-1}]	R_d pasture [µmol m^{-2} s^{-1}]	R_e [µmol m^{-2} s^{-1}]
P1	13.5 ± 0.3^{a}	3.99 ± 0.08^{c}	3.16 ± 0.10^{f}	5.62 ± 0.10^{i}
P2	16.5 ± 0.4^{b}	6.28 ± 0.39^{d}	7.07 ± 0.45^{g}	8.29 ± 0.30^{j}
P3	13.8 ± 0.3^{a}	3.72 ± 0.08^{e}	4.46 ± 0.19^{h}	5.91 ± 0.20^{i}

Tab. 4: Light response curves (Eq. 8) and fitting parameters α, F_∞ and R_e (best fit ± standard errors) for the different periods on the meadow and on the pasture and for the periods with and without intervention. The asterisk (*) indicates which parameters are significant ($p < 5\%$) in the fit model. Means with the same character do not differ significantly (95% confidence intervals) from one another.

	land management	Period	α [-]	F_∞ [µmol m^{-2} s^{-1}]	R_e [µmol m^{-2} s^{-1}]
meadow	undisturbed growth	1	$0.056 \pm 0.015^{*\ a}$	$16.47 \pm 1.16^{*\ b}$	$2.62 \pm 1.06^{*\ e}$
	grass cut	2a	$0.069 \pm 0.078^{*\ a}$	$12.52 \pm 3.72^{*\ c}$	$7.75 \pm 3.50^{*\ f}$
	vegetation regeneration	2b	$0.085 \pm 0.020^{*\ a}$	$21.24 \pm 1.27^{*\ b}$	$6.23 \pm 1.10^{*\ f}$
	cows grazing	2c	$0.159 \pm 0.111^{*\ a}$	$12.83 \pm 2.30^{*\ c}$	$7.38 \pm 1.81^{*\ f}$
	undisturbed growth	3	$0.095 \pm 0.063^{\ a}$	$8.12 \pm 1.39^{*\ c}$	$3.06 \pm 1.17^{*\ g}$
pasture	cows grazing	1	$0.073 \pm 0.038^{\ a}$	$15.93 \pm 3.22^{*\ d}$	$6.25 \pm 1.55^{*\ h}$
	cows grazing	2	$0.075 \pm 0.043^{\ a}$	$18.19 \pm 4.12^{*\ d}$	$7.01 \pm 1.84^{*\ h}$
	cows grazing	3	$0.033 \pm 0.011^{\ a}$	$60.86 \pm 6.51^{\ d}$	$4.07 \pm 1.11^{*\ h}$
all fields	unmanged	-	$0.086 \pm 0.014^{*\ i}$	$20.12 \pm 0.87^{*\ j}$	$5.81 \pm 0.82^{*\ l}$
	managed	-	$0.116 \pm 0.031^{*\ i}$	$10.13 \pm 1.42^{*\ k}$	$6.53 \pm 1.34^{*\ l}$

4 Comparison of net ecosystem carbon exchange of an extensively used grassland and a protected wetland in the Swiss Pre-Alps during the 2003 heat wave period

To be submitted

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Summary

The effect of the summer 2003 heat wave on two differently managed mountain agroecosystems, a grassland and a wetland at the Swiss CARBOMONT site Seebodenalp are investigated. Direct comparisons of concurrent eddy covariance CO_2 and water vapor flux measurements from 1 June to 30 September 2003 revealed substantial carbon losses at both sites: the grassland, which was extensively used as meadow followed by pasture, was a net carbon source of 204 ± 20 g C m^{-2}, whereas the wetland, where no management took place until late summer, lost 62 ± 6 g C m^{-2}. In June the maximum net uptake of CO_2 was larger in the wetland than in the grassland, which was in agreement with the larger biomass measured in the wetland (162±33 g DW m^{-2}) than in the grassland (104±21 g DW m^{-2}). This difference in biomass is mainly due to the fact that the wetland still had sufficient soil water available during this early phase of the heat wave. Cutting the grass turned the grassland into a carbon source during the peak growing season. The grass cut led to the expected decrease in transpiration but also to a simultaneous increase in soil evaporation. The two changes cancelled out each other and thus had no substantial effect on total evapotranspiration. As a result of the emerging water stress the evaporation of soil water became the dominant component of the water vapor fluxes at Seebodenalp which were mainly energy driven.

The photosynthetic activity of the wetland vegetation decreased steadily from spring to mid-summer due to increasing water stress and early senescence. In the grassland, cattle grazing in the nighttime footprint stimulated dark respiration (RESP). In July, soil water levels were low and reduced both dark and daytime respiration. Daytime respiration rates in the wetland were surprisingly low in the beginning of September, the ending of the heat wave, due to low soil water contents. The fact that the water stress not only lowered assimilation rates but also respiration rates emerged one month earlier in the grassland than in the wetland due to the different hydrological regimes under otherwise similar conditions.

Keywords: summer 2003 heat wave, eddy covariance flux measurements, CO_2 exchange, pastoral grazing ecosystems, mountain regions, CARBOMONT

4.1 Introduction

Grasslands occupy 38% of agricultural land in Europe (Dziewulska, 1990). Grasslands play an important role in the Earth's global carbon budget due to their high root/shoot biomass ratio as compared to other biomes in combination with their relatively large pools of stable soil organic matter (Gilmanov *et al.*, 2003a). Economic pressure has strongly affected agricultural practices in European grasslands and has lead to an intensification of management (Hopplicher *et al.*, 2002). Especially mountainous small-scale farming suffers from hard economic competition, which has resulted in abandonment of formerly managed grasslands (Cernusca *et al.*, 1999). This leads to fundamental changes in the landscape pattern and ecosystem structure in turn affects the spatial structure of plant canopies, species composition and physiology, nutrient availability, and consequently also the biosphere-atmosphere CO_2 exchange processes (Cernusca *et al.*, 1998).
In Switzerland, alpine grasslands account for 40 % of the total agricultural area (Leifeld *et al.*, 2005). Understanding the carbon balance of European grasslands received more and more attention as the EU FP5 projects GREENGRASS and CARBOMONT were initiated. However, there is still a substantial deficit in the understanding of the interactions between climate change and the ecosystem functioning of grasslands and mountainous grasslands in particular (Janssens *et al.*, 2003; Leahy *et al.*, 2004; Novick *et al.*, 2004).

The CO_2 exchange of a specific ecosystem is influenced by several factors such as climate, land-management and the phenological state of the vegetation.
In 2003, Central Europe was experiencing an unprecedented hot summer for at least 500 years (Luterbacher *et al.,* 2004; see also Allen and Lord, 2004; Black *et al.*, 2004; Schär *et al.*, 2004; Ciais *et al.*, 2005). Many ecosystems suffered from water stress due to a deficit in precipitation that had accumulated since early spring 2003. The

heat affected Switzerland to the extent that all previous instrumental records of summer maximum temperatures were broken (Beniston, 2004).
In addition, drought affected the ecosystems even more than did the high temperatures. A decrease in carbon assimilation and ecosystem respiration due to drought has been observed by many comparable studies (e.g. Steduto and Hsiao, 1997; Goldstein *et al.*, 2000; Barr *et al.*, 2002; Griffis *et al.*, 2004; Kljun *et al.*, 2004; Ciais *et al.*, 2005).

Gilmanov *et al.* (2003a) emphasized that from the management standpoint grasslands are important because they provide opportunities to facilitate carbon sequestration in a shorter time and at lower costs than afforestation. Several studies have shown that it is indeed possible to regulate soil carbon stocks by agricultural management (e.g. Ash *et al.*, 1995; Batjes, 1999). Management also influences the state of the vegetation, and the age of the plants affects the photosynthetic activity (Humphreys *et al.*, 2005; Nieven *et al.*, 2005). The wetland vegetation at Seebodenalp was not disturbed until late summer. However, it is expected that the photosynthetic activity was decreased towards the summer as plant structures were ageing (Noodén *et al.*, 1996; Hortensteiner and Feller, 2002; Levey and Wingler, 2005).

In this paper we compare the eddy covariance CO_2 and water vapor fluxes measured during the 2003 heat wave of two differently managed ecosystems at the CARBOMONT site Seebodenalp in the Swiss Pre-Alps. The climate anomaly of the summer of 2003 is analyzed using available standard meteorological data. We then analyze the cumulative CO_2 budgets of the grassland (extensively used as a meadow and a pasture) and of the wetland (grass cut at the end of the vegetation period) over the measurement period 2003 in comparison to the average conditions measured over grassland in years the 2002, 2004 and 2005. The influence of land-management, water stress and senescence on the CO_2 fluxes of both sites under the same climatic conditions is investigated in detail. Further, the behavior of the water vapor fluxes with respect to photosynthetic activity, land-management and available energy is examined. Finally, the results from an independent biomass inventory are put into relationship with corresponding CO_2 fluxes measured by eddy covariance.

4.2 Site description

The Seebodenalp flux site was established in May 2002 as part of the CARBOMONT network. It is located on a subalpine grassland on a flat shoulder terrace of Mount Rigi (47°05’38” N, 8°45’36” E) in Central Switzerland at an altitude of 1025 m above sea level (Rogiers *et al.*, 2005). The site encompasses 32 ha of relatively flat terrain (Fig. 18). Geologically, this area formed at the end of the last glaciation, where the Alpine glaciation bordered at that height, shaping a terrace with moraine debris and meltwater sediments, on which the current landscape and soils could develop. The current terrain is the bottom of a former but vanished lake which was fed by meltwater at the end of the last glaciation (Vogel and Hantke, 1989) with a thick sedge peat layer on top. Seebodenalp has been drained since 1886 (Wyrsch, 1988), but is still relatively wet. Nowadays, two different land surface types can be distinguished, both with their specific soil properties, plant species composition, and land-management history (Tab. 5). Historic land management is mainly responsible for the differences between the two areas. The extensively managed grassland (23 ha) has been drained and peat has been exploited during the Second World War, whereas in the wetland (8 ha), the soil remained more or less undisturbed. A high spatial variability in soil properties is observed at Seebodenalp (Tab. 5). The soil organic carbon content by mass in the grassland (7 – 15%) is substantially lower than in the wetland (20 – 45 %). Both sites have quite different C/N-ratios and pH-values resulting in different levels of decomposition rates. Müller (2004) classified the grassland soil as a stagnic cambisol and the wetland soil as a folic (drystic) histosol (WRB, 1998) depending on mesotopographic conditions.

The present land-management regime is actually the result of the historic developments. Where peat was exploited the grassland is now extensively managed with cows grazing and two annual grass cuts. The wetland area is statutory protected since 2000 and the vegetation is mown only once in late summer.

Reutlinger (2004) characterized the vegetation in the extensively managed grassland as *Lolio-Cynosuretum cristati* and the vegetation in the protected wetland as *Angelico-Cirsietum caricetosum nigrae* and degenerated *Caricetum nigrae* (nomenclature after Ellenberg, 1996).

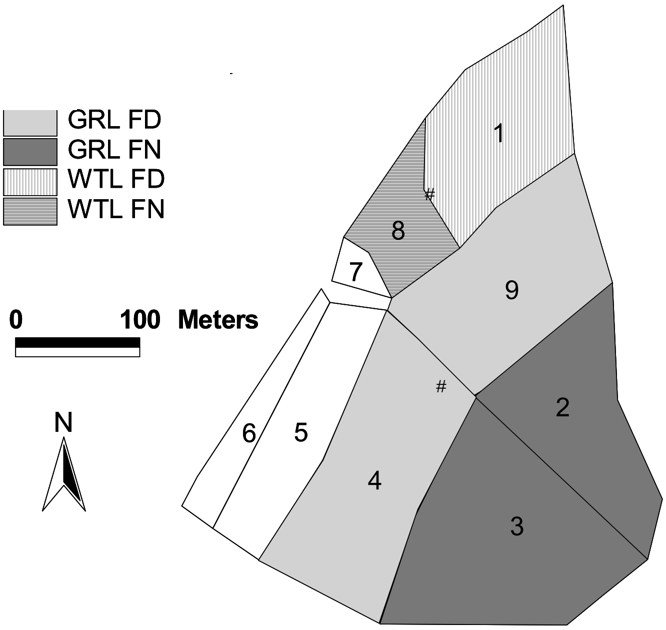

Fig. 18: A detailed map of the Seebodenalp shows the position of the EC towers (marked with dots) in the grassland (GRL) and wetland (WTL) together with the footprint area of nighttime (FN) and daytime (FD) EC measurements. The scale is denoted in the figure.

4.2.1 Biomass of grassland and wetland

Above ground biomass of both ecosystems was determined in June 2003 (Reutlinger, 2004) by clipping 0.1 m^2 areas, with 40 replications at the grassland and 15 replications at the wetland. Dry weight of total aboveground biomass (g DW m^{-2}) was determined by drying the samples during 48 hours at 70°C. At each site, we took 9 soil cores from 0-6.5 and 6.5-13 cm depths to determine the fraction of root biomass in each soil layer. The total above-ground biomass (Fig. 19) was significantly ($p<0.05$) higher at the wetland (162±33 g DW m^{-2}) than at the grassland (104±21 g DW m^{-2}).

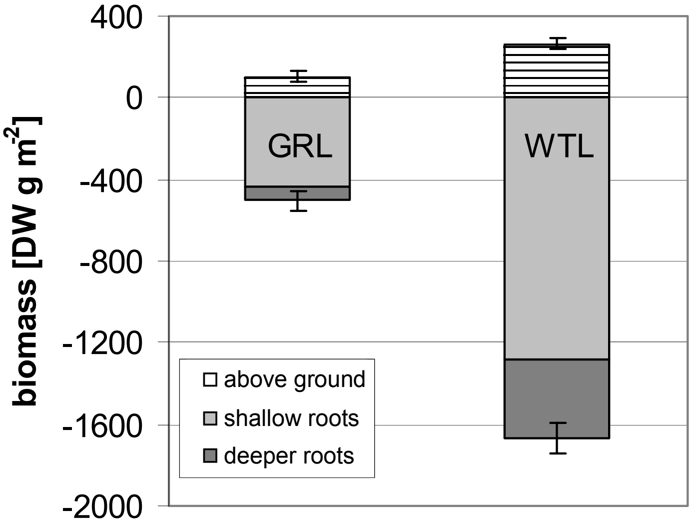

Fig. 19: Above ground biomass and distribution of above and below ground biomass at the grassland (GRL) and the wetland (WTL) in June 2003 (Reutlinger, 2004).

At the grassland 89% of root biomass was found in the upper layer (Fig. 19), while wetland plants rooted somewhat deeper (78% in upper layer). The total root biomass was significantly ($p<0.001$) lower at the grassland (504±41 g m^{-2}) than at the wetland

(1679 ± 213 g m^{-2}). The root to shoot ratio was 4.8 and 6.4 for the grassland and wetland, respectively.

4.3 Instrumentation and methods

4.3.1 Eddy covariance flux measurements

The eddy covariance (EC) technique was used for continuous measurements of the turbulent fluxes of CO_2, water vapor, sensible heat, and momentum (e.g., Baldocchi *et al.* 2000, Aubinet *et al.* 2000) at the ecosystem level.

Two EC towers were operated in summer 2003. One covered the grassland and a second mobile one measured the wetland. Wind velocity, wind direction, and temperature over the grassland were measured with a three-dimensional ultrasonic anemometer (Solent R3-HS, Gill Ltd., Lymington, UK), mounted at a height of 2.4 m above ground level (a.g.l.) (midpoint of the sonic head), and CO_2 and water vapor concentrations were measured with an open path infrared gas analyzer (IRGA) (LI-7500, LI-COR Inc., Lincoln, Nebraska, USA). In the wetland, an older three-dimensional Solent R2 ultrasonic anemometer (Gill Ltd., Lymington, UK) was installed at a height of 2.1 m a.g.l. together with a NOAA open path IRGA (Auble and Meyers, 1992) which was slightly modified to reduce the noise level (see Eugster *et al.* 2003). 20 Hz raw data were saved on a laptop computer and processed off-line.

The data processing and the calculation of the EC fluxes for Seebodenalp is described in detail in Rogiers et al. (2005). Briefly, the vertical turbulent fluxes Fc are calculated from the half-hourly averaged covariances of the measured fluctuations of the vertical wind velocity w [m s-1] in a co-ordinate system which is aligned with the mean streamlines, and the CO_2 concentration c [µmol mol^{-1}]:

$$F_c = (\rho_a / M_a) \cdot \overline{w' \cdot c'} \qquad [\mu mol\ m^{-2}\ s^{-1}]\ (Eq.\ 9)$$

where ρ_a [g m^{-3}] is the air density, and M_a [g mol^{-1}] is the molar weight of air (28.96 g mol^{-1}). Overbars denote time averages, and primed quantities are the instantaneous deviations from their respective time average. Positive fluxes indicate net upward transport from the vegetation to the atmosphere, whereas negative values signify surface uptake. Similarly we proceeded with temperature, water vapor and momentum to obtain the corresponding turbulent fluxes. CO_2 and water fluxes were corrected for high-frequency damping losses (Eugster and Senn, 1995), followed by the necessary density flux correction for open-path instruments according to Webb *et al.* (1980). The intermediate storage of CO_2 between the grass canopy and the EC measurement height was assumed to only play a minor role due to short vegetation and low sensor height (see e.g. Aubinet *et al.*, 2000; Baldocchi, 2003) in long-term budget calculations and thus was not measured separately.

4.3.2 Data availability, filtering and gapfilling

At the grassland, there was mains power available, whereas the wetland EC system was running on solar power only and therefore was not permanently operational. At the grassland, measurements were made continuously, except for a 10-days system failure in August due to a lightning strike during a thunderstorm. In the wetland, measurements were made during several campaigns, starting on 1 June (day 152) to 30 September (day 273). Here, the EC system was running on 85 days out of 121 days, resulting in a data availability of 70% before filtering.

Data were screened for unrealistic values based on objectively testable plausibility criteria as described in Rogiers *et al.* (2005) which are briefly summarized in the following. EC data outside the range given by their monthly mean ± three times its standard deviation, and records where the momentum flux was not directed towards the surface were filtered out. Data coverage after filtering at the grassland during the measurement period (days 152-273) in 2003 was 48% of all possible 30-minute time intervals. At the wetland, 46% of all possible data records within the measurement period were available after the quality check.

Small data gaps (< 3 days) were filled following the suggestions given by Falge *et al.* (2001). In a first flush gaps of maximum 2-hours were filled by linear interpolation. In a second flush the remaining short gaps (< 3 days) were filled by mean diurnal cycles of the respective variable. Gaps in EC measurements covering more than 3 days were modeled using a light response curve of CO_2 exchange as a function of photosynthetic photon flux density PPFD (see below).

Dark ecosystem respiration R_e was modeled using an exponential function of nighttime (PPFD < 10 µmol m^{-2} s^{-1}) CO_2 fluxes which are assumed to represent ecosystem respiration in response to soil temperature (T_s) measured at 0.05 m below ground (see e.g. Wofsy *et al.*, 1993; Schmid *et al.*, 2000),

$$R_e = a \cdot \exp(b \cdot Ts) \ , \qquad \text{(Eq. 10)}$$

where a and b are fitting parameters determined by minimizing the sum of squares of the residuals.

CO_2 exchange (PPFD > 10 µmol m^{-2} s^{-1}) was calculated from the relationship between gross primary production GPP [µmol m^{-2} s^{-1}] and PPFD [µmol m^{-2} s^{-1}]. This light response curve can be described by a rectangular hyperbola (Ruimy *et al.*, 1995),

$$NEE = \frac{F_{inf} \cdot \alpha \cdot PPFD}{\alpha \cdot PPFD + F_{inf}} + R_d \ , \qquad \text{(Eq. 11)}$$

where F_{inf} is NEE at light saturation [µmol m^{-2} s^{-1}], α is the apparent quantum yield and R_d [µmol m^{-2} s^{-1}] is the best estimate of average daytime ecosystem respiration (Suyker and Verma, 2001; Gilmanov, 2003b).

4.3.3 Footprint model

The flux footprints of both EC towers were determined with the Kormann and Meixner (2001) footprint model using a software tool developed at the Swiss Federal Agricultural Research Center. The assumptions inherent to any footprint model (see Schmid, 1994; Schmid, 2002) are however not perfectly fulfilled. Although our sites are relatively flat areas in an otherwise mountainous topography, the land surface is rather patchy and heterogeneous. Thus, as already discussed in Rogiers *et al.* (2005), these footprint calculations should rather be considered a valuable information on the rough extent of the surface area that influenced our tower flux measurements at the two sites.

4.3.4 Additional measurements

Ancillary meteorological measurements are listed in Table 6. All variables were measured every 60 seconds by a datalogger (CR10X, Campbell Scientific Inc., Loughborough, UK), and data were stored as 10-minute averages.

Additional climate data were obtained from the nearby Swiss Air Quality Monitoring Network (NABEL) station (47°04'10" N, 8°27'56" E, 1030 m a.s.l.). This NABEL station is located Northeast of the CARBOMONT site and can be considered representative for the climatic conditions at both sites. The NABEL data can thus be used to assess the climatic conditions observed during the vegetation period 2003 with respect to the 10 years reference period of available data just before starting the EC measurements at this site, i.e. 1992-2001. As precipitation measurements only started in 1994, the reference period is 8 years in this case.

The leaf area index (LAI) was determined periodically with an optical plant canopy analyzer (LI-COR, LAI-2050, Lincoln, Nebraska, USA).

Below-ground respiration was measured periodically with a portable soil chamber system (LI-COR, LI-6400-90 Lincoln, Nebraska, USA).

4.3.5 Canopy-atmosphere decoupling parameter

The canopy-atmosphere decoupling parameter Ω (Jarvis and McNaughton, 1986) is a measure for the relative importance of surface conductance and net radiation to changes in evapotranspiration rates. Ω is expressed by

$$\Omega = \frac{\Delta + \gamma}{\Delta + \gamma(1 + g_a / g_c)} \;, \qquad \text{(Eq. 12)}$$

where Δ is the local slope of the saturation vapor pressure curve (kPa K^{-1}), γ is the psychrometric constant (kPa K^{-1}), g_a is the aerodynamic conductance (m s^{-1}), and g_c is the bulk canopy conductance (m s^{-1}). The value of Ω ranges between 0 (complete coupling) to 1 (complete decoupling), with the control of evapotranspiration by canopy conductance increasing as Ω approaches 0 (Jarvis, 1985; Jarvis and McNaughton, 1986; Goldberg and Bernhofer, 2001, Wever *et al.*, 2002). Complete decoupling is usually found over wet and smooth surfaces (Jarvis and McNaughton, 1986), whereas rough surfaces such as forests yield values of $\Omega < 0.5$ (Schulze *et al.*, 1995).

4.3.6 Senescence

The senescence of the vegetation is investigated by comparing NEE at light saturation F_∞ [µmol m^{-2} s^{-1}] for different time intervals calculated from the light response curves (Eq. 11). A t-test based on Wald's confidence ellipsoids (Van der Vaart, 1998) was used to determine the difference in F_{inf} between time intervals.

4.3.7 Computations

Statistical analyses were carried out using the free R software system version 2.0.1 (R Development Core Team, 2004).

When reporting results we refer to “periods with well developed vegetation canopy” as time intervals before a grass cut or long enough after a grass cut when the vegetation has regenerated. Other time intervals in the measurement periods are referred to as “periods with vegetation under pastoral grazing and shortly after grass cuts”.

Cumulative fluxes per day were calculated by summing up the mean carbon fluxes starting from day 152, the starting day of the measurements in the wetland.

Site comparisons were done using standard ANOVA. We report daily means of CO_2 and water vapor fluxes in the following variants: (a) NEE: net ecosystem exchange of CO_2, (b) NEEMAX: net CO_2 exchange at noon (11 a.m. –1 p.m. CET), (c) RESP: nighttime CO_2-flux or ecosystem dark respiration determined from nighttime data (PPFD < 10 µmol m^{-2} s^{-1}), (d) EMAX: water vapor flux at noon (11 a.m. –1 p.m. CET). We also determined (f) LAI: leaf area index, (g) TS: soil temperature at 5 cm below ground and (g) ENEMAX: energy availability at noon expressed as the difference between net radiation and soil heat flux (Rn-G) (11 a.m. –1 p.m. CET).

4.4 Results

First, the climatic conditions of summer 2003 are assessed with respect to the 10-year climatological mean. Then, the eddy covariance CO_2 and water vapor fluxes are analyzed in detail for the measurement period 1 June to 30 September 2003 with a focus on the influence of land-management, meteorological conditions and phenology (senescence).

4.4.1 Climatological assessment

June and August 2003 were 6.4 °C and 4.2 °C warmer, respectively, than the corresponding months in the years 1992-2001. July 2003 was less extreme with a monthly temperature anomaly of +1.6 °C. In spring 2003 (MAM) Seebodenalp obtained substantially less precipitation compared to the 8-year average 1994-2001 (Fig. 20), with values ranging between 62 and 75 %.

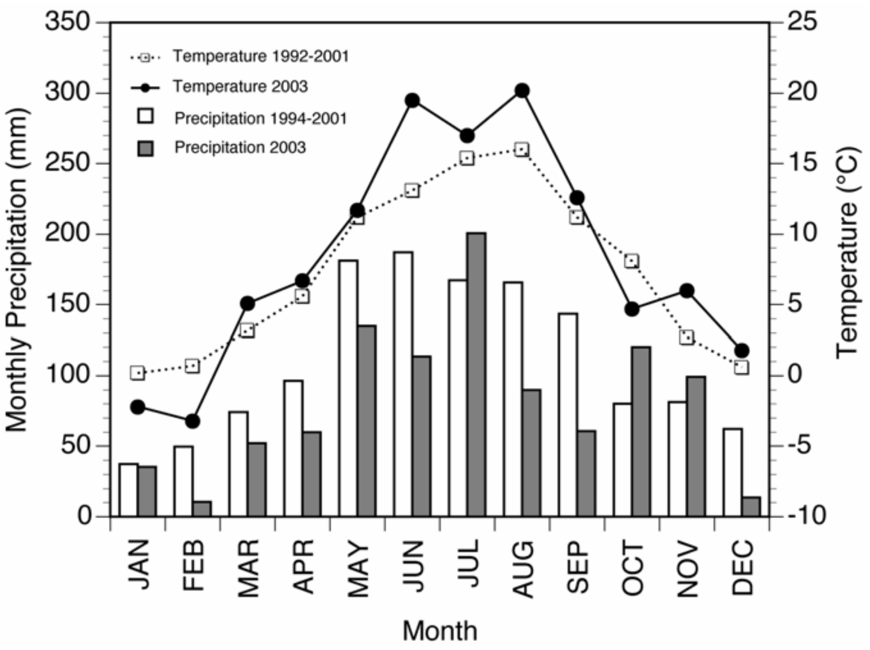

Fig. 20: Monthly average temperatures for 1992-2001 (dotted line) and 2003 (solid line), and monthly average total precipitation 1994-2001 (outlined columns) and 2003 (shaded columns) for Seebodenalp NABEL station.

Consequently, soil water content at the grassland at the beginning of the measurement period (1 June) was relatively low (around 0.20 $m^3 m^{-3}$) (Fig. 21). By then, soil water content was more abundant at the wetland than at the grassland, because the former has not been drained and thus can preserve soil water over a longer time. The maximum volumetric soil water content measured at both sites fluctuated around 0.40 $m^3 m^{-3}$ after snow melt. July in contrast received 120% of the 8-year average monthly precipitation, and soil water reserves were partly replenished (Fig. 21). August and September were again relatively dry (54 and 42 % of the 8-year average). Due to local convective showers in the afternoon or early evening, the number of consecutive days without rainfall was not exceeding 14 days. However, soil water content at the grassland stayed at rather low levels (frequently < 0.20 m^3 m^{-3}) during the whole summer (Fig. 21). The soil water reserves of the wetland also decreased towards the end of the summer, reaching similar low levels as at the grassland at the end of August. In summary, the growing season started with less precipitation than is expected in an average year and thus with a cumulative water deficit of 146 mm (or 33%) by 31 May 2003. Local precipitation, which was observed on a regular basis even during this extraordinary heat weave (see Schär *et al.*, 2004), prevented the soil from drying out completely. The summer 2003 was thus much warmer than the 10-year average 1992-2001, and soil water content levels were relatively low at the grassland over the whole measurement period. Towards the end of August water shortage might have become a problem at the wetland, too. Therefore we must consider that the CO_2 and water vapor exchange during that period was affected by warmer and also dryer conditions (especially at the grassland) than under average conditions.

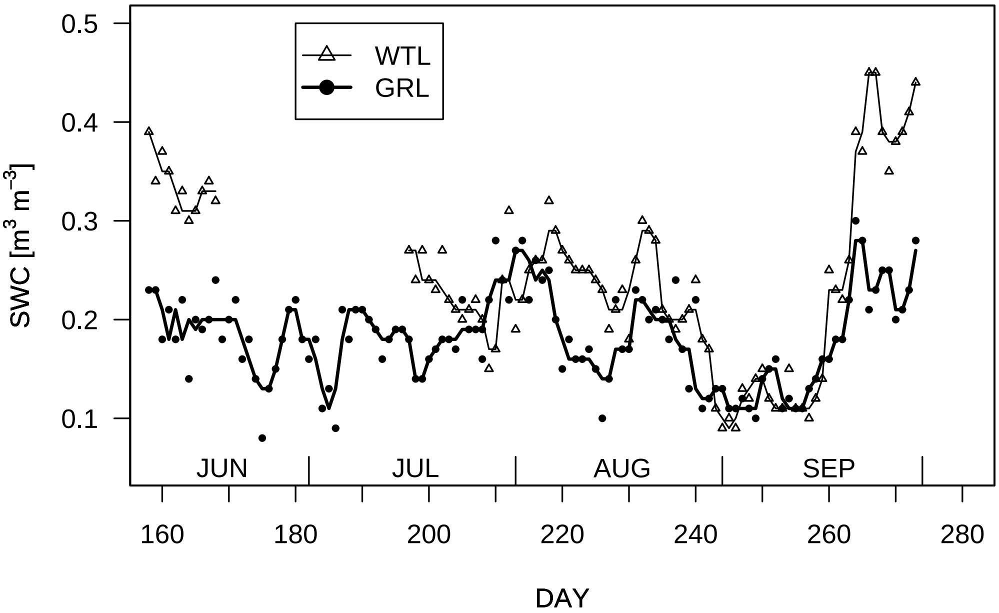

Fig. 21: Volumetric soil water content SWC [m^3 m^{-3}] at the grassland (GRL) and wetland (WTL) in summer 2003 at 5 cm below ground (symbols). The lines represent the 3-days running mean of the volumetric soil water content.

4.4.2 EC ecosystem fluxes

4.4.2.1 Carbon budget

The carbon budgets for both EC stations from 1 June (day 152) to 30 September 2003 (day 273) are shown in Fig. 22. During this period the extensively used grassland lost 204 ± 20 g C m^{-2}, whereas the protected wetland only lost 62 ± 6 g C m^{-2}.

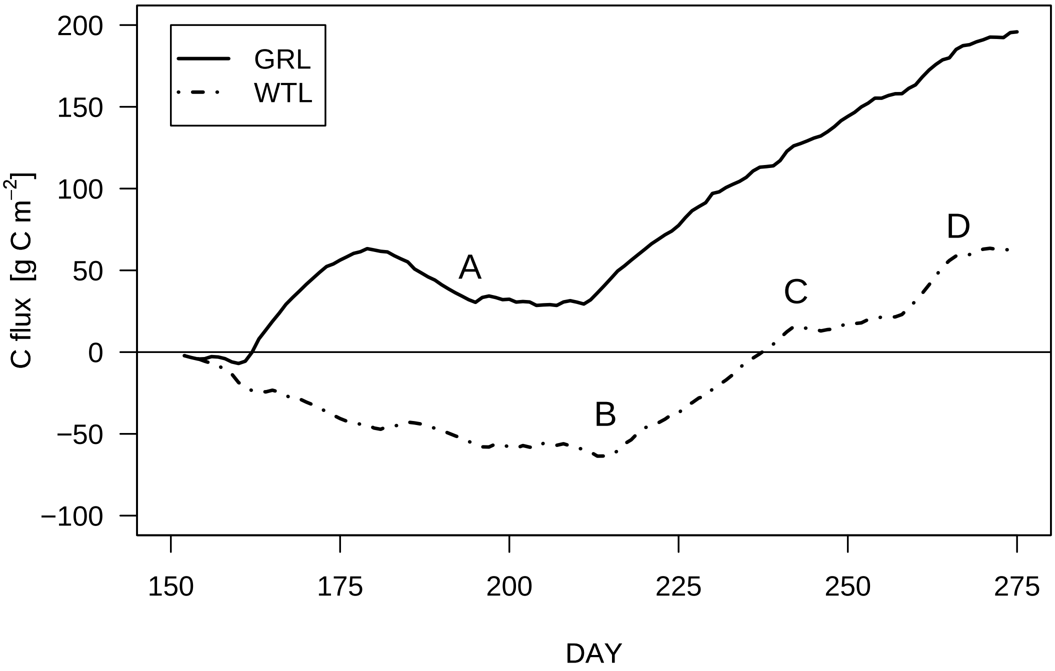

Fig. 22: The cumulative EC carbon budget for the period 1 June (DAY 152) until 30 September 2003 (DAY 273) at the grassland and wetland. A positive sign means carbon losses from the ecosystem. Grass cuts are marked with an arrow; characters are referred to in the text.

Both ecosystems started with a net uptake in the beginning of June. Cutting the grass in the grassland (day 162) dramatically changed the carbon budget and turned the site into a carbon loosing ecosystem. After the cut, there was substantially less photosynthetic active plant material left and assimilation was strongly reduced compared to the wetland. After plants had regenerated after 33 days (day 195; Fig. 22 point A), a zero net carbon flux was measured during the following 17 days. During these days where assimilation and respiration were in equilibrium, there was no further grass cut and no cows were grazing. Soil water levels were however rather low (<0.20 m^3 m^{-3}) (Fig. 21), which is expected to be responsible for a reduction in assimilation. Visual inspection of the vegetation at the grassland site clearly showed signs of drought during this period. The plants were still green, but they showed wilting in the afternoons. The reduction in assimilation is reflected in NEE at light saturation (F_{inf}) as determined from the light response curves for individual two-day periods from day 172 to day 208 (before the second grass cut) (Fig. 23). By day 172, the vegetation was still regenerating from the first grass cut on day 162 and increasing values for F_{inf} were measured. F_{inf} started to decrease from day 190 and especially low values for F_{inf} were determined between day 196 and 202, i.e. the third period with very low soil moistures (Fig. 21). While the regrowth period was characterized by an anti-correlation between F_{inf} and Rd (days 172–196, Fig. 23), the continuation of the heat wave reversed that relationship such that F_{inf} and Rd were in phase from day 196 to the second grass cut, which resulted in an almost neutral carbon budget during these days (Fig. 22).

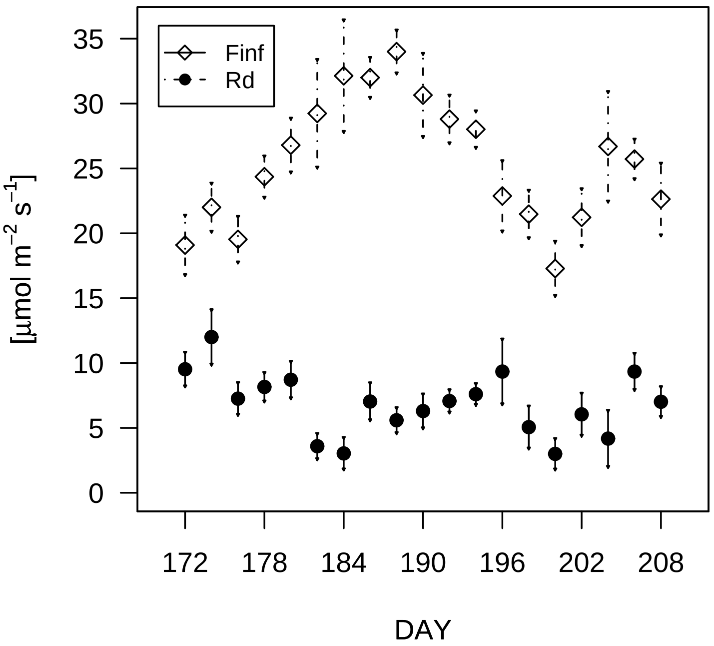

Fig. 23: Fitting parameters F_{inf} and Re derived from the light response curves (Eq. 11) for two-day periods at the grassland with regenerating vegetation between the first and the second grass cuts. Soil water levels became low around day 190.

The second grass cut at the end of July (day 212) changed the direction of the curve again. After that, only net carbon losses were measured in 2003.

At the wetland, there was no grass cut until late summer. Nevertheless, the ecosystem started to lose carbon around 7 August (day 220; Fig. 22 point B) for 30 days. The period of carbon losses was followed by a period with a zero net flux starting on day 248 (Fig. 22 point C). The grass cut on 16 September (day 259) increased the carbon losses of the ecosystem strongly during 13 days before a zero net carbon flux was reached at the end of the vegetation period at day 271 (Fig. 22 point D) while the grassland continued to loose carbon.

4.4.2.2 Footprint areas

In a landscape with small-scale farming such as at Seebodenalp the question arises of whether eddy covariance measurements are sufficiently representative of the respective land surface that they should cover. To answer this question, the footprint areas of both EC towers were determined. In general these footprints covered the grassland and wetland surfaces quite well (shading in Fig. 18). However, there was a non-random distribution of wind directions at both sites, resulting in clear differences between nighttime and daytime footprints for both EC towers. Under high pressure weather conditions when thermally driven winds develop (Whiteman, 2000), a north-northeasterly flow establishes over the site during the day. During the night, cold air drainage occurs from the southeast, downslope of Mount Rigi (Rogiers *et al*., 2005). The tower in the grassland has a footprint that covers four patches which determine 95-99 % of the measured CO_2 fluxes. During the day, 70-80 % of the footprint is in two patches (4 and 9, Fig. 18) north and northeast from the EC tower, which were used as a meadow. Therefore the reduction in assimilation due to the two grass cuts at the grassland and the wetland were clearly visible in the cumulative curves (Fig. 22). During the night, the main sources (65-75 %) of the measured fluxes were southeast from the EC tower (patches 2 and 3, Fig. 18). This area was used as a pasture. The decrease in photosynthetic capacity due to grazing could thus not be detected, since these patches were mainly in the nighttime footprint. The fields not adjacent to the measurement tower rarely contributed to the measured fluxes. The boarder area between wetland and grassland was responsible for 1-5% of the EC daytime data.

In the wetland, 2 patches (1 and 8, Fig. 18) were mainly contributing to the measurements during the day (95-99 %) and patch 8 was in the footprint of the tower during the night (90-95 %). The grass cut on day 259 was affecting the daytime footprint area, and therefore the decrease in assimilation is clearly visible in the cumulative curves.

4.4.2.3 EC exchange under well developed and disturbed vegetation canopy

The CO_2 and water vapor exchange of both sites was investigated for two periods before and after the two grass cuts at the grassland, respectively. For those four periods the diurnal means of NEE, NEEMAX, RESP, EMAX, LAI, TS and ENEMAX of the wetland and the grassland were compared graphically (Fig. 24) and statistically with a one-way ANOVA (Tab. 7).

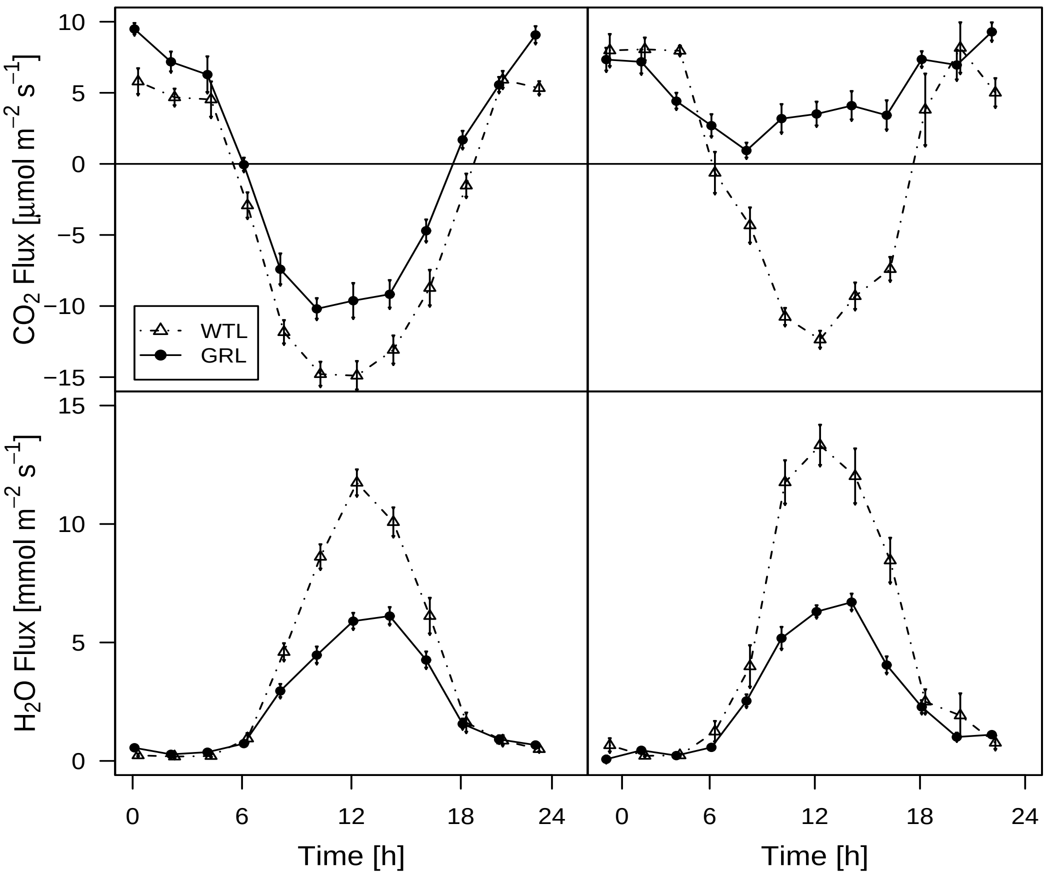

Fig. 24: Diurnal cycles of EC CO_2 (upper panels) and water vapor (lower panels) fluxes measured at the grassland (GRL) and the wetland (WTL) sites before (4-10 June 2003; left) and after the first grass cut (12-17 June 2003; right) in 2003.

In June (days 155-161), significantly higher CO_2 uptake at noon (NEEMAX) was measured at the wetland than at the grassland (Tab. 7; Fig. 24). In addition, dark respiration (RESP) was higher at the grassland than at the wetland, resulting in a small but statistically insignificant net daily uptake (NEE) at the grassland (LAI = 3.6 ± 0.4 m^2 m^{-2}), whereas the wetland (LAI = 3.4 ± 0.4 m^2 m^{-2}) acted as a clear net sink during that period. In mid-summer (days 206-211), after the vegetation at the grassland had regenerated (LAI = 3.0 ± 0.4 m^2 m^{-2}), both sites were more or less CO_2 neutral (Tab. 7; Fig. 22). No statistical difference in NEEMAX was detected between the two ecosystems. RESP was again statistically higher at the grassland, but lower than before the first grass cut (days 155-161), in spite of higher mid-summer soil temperature (TS) at the grassland.

Although the soil organic carbon content (Tab. 5) is significantly higher in the wetland than in the grassland ($p < 0.05$), RESP was higher at the grassland than at the wetland. This can partially be explained by the fact that dark respiration from the nighttime footprint at the grassland, which was used as a pasture in 2003, was stimulated by grazing. Additionally, the relatively low pH-values at the wetland (Tab. 5) limit soil microbial activity and thus result in lower respiration rates than at the grassland (Hobbie *et al.*, 2000).

To evaluate the effect of the grass cut, the EC fluxes of both sites were compared for two periods before and after the grass cut, respectively (Fig. 24). The carbon budget at the grassland was disturbed by the grass cut on 11 June (day 162; see Fig. 24 and Tab. 7). After the grass cut at the grassland (days 163-168), the decrease in photosynthetic active plant material led to a net loss of CO_2. In contrast, the diurnal cycle of the CO_2 flux remained nearly unchanged at the wetland with an insignificant reduction in NEEMAX and a marginally significant increase in RESP, resulting in a small decrease of net daily CO_2 uptake.

At both sites, dark respiration rates were higher after the grass cut than before the grass cut, mainly due to higher soil temperatures (Tab. 7).

Surprisingly, the influence of the grass cut was not directly visible in the diurnal cycles of water vapor (Fig. 24). At the wetland, which is used as a reference for this comparison, the water vapor fluxes at noon (EMAX) were significantly higher in the period after the grass cut took place at the nearby grassland site, whereas no significant decrease in EMAX could be detected at the grassland. We interpret this as an indication that water vapor fluxes over this mountain grassland are not limited by plant photosynthesis but rather by available energy.

4.4.3 Decoupling between ecosystem water vapor fluxes and CO_2 exchange

In the following the decoupling between the water vapor fluxes and the CO_2 exchange will be described in more detail since this appears to be relevant for our understanding of how mountain grassland ecosystems might respond to global climate change of the type resembling the summer 2003 heat wave conditions in Central Europe.

First, the relationship between the CO_2 and water vapor for periods with well developed vegetation canopy was investigated with a one-way ANOVA for the wetland and the grassland. We found no statistically significant coupling between EMAX and NEEMAX (GRL: $p=0.32$; WTL: $p=0.77$), which suggests that a major part of the water vapor flux comes from soil evaporation. At both sites a positive relationship between EMAX and RESP was found ($p < 0.05$). Water vapor fluxes and respiration are apparently governed by the same driving variables. Indeed, an additional ANOVA revealed that there was a very strong positive coupling ($p < 0.05$)

at both sites between on the one hand EMAX and RESP, and on the other hand soil temperature (nighttime and daytime mean) and ENEMAX. Thus, we can deduce that water vapor fluxes are mainly the result of soil evaporation and not of plant transpiration.

Second, the relationship between available energy (Rn-G), and the measured water vapor fluxes was investigated at the wetland for Rn-G > 0 (Fig. 25).

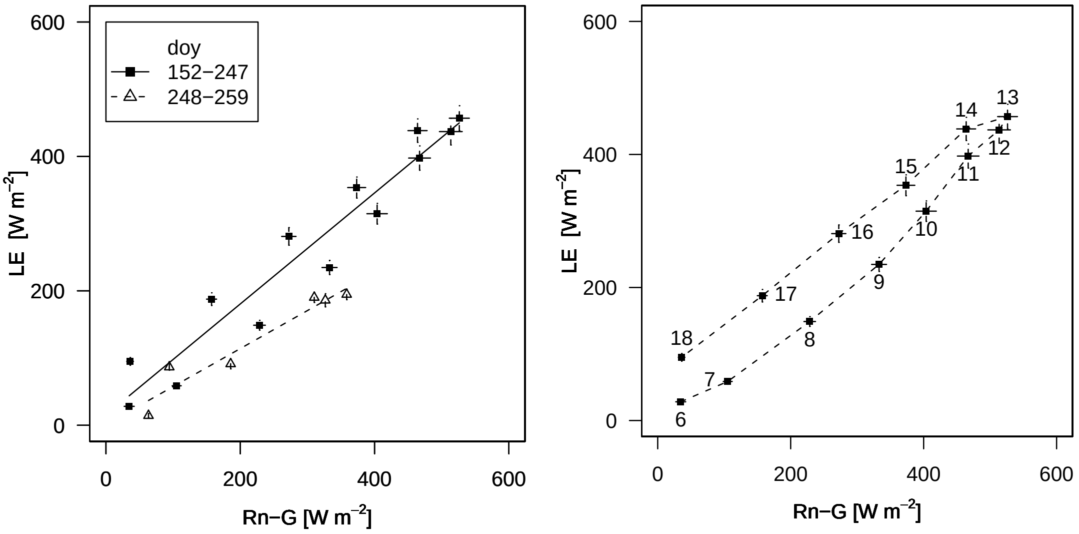

Fig. 25: EC water vapor fluxes at the wetland as a function of available energy (Rn-G). Data were grouped by hour. Two statistically different linear regressions are fitted trough the data (means ± SE) during periods when Rn-G > 0 for vegetation with well developed canopy (left panel). For the period 152-247, the time indication (hour) is added to the graph (right panel).

Two statistically different linear regressions were found for periods with well developed vegetation canopy. For the period from day 152 to 247 there was no significant difference between the two ecosystems. At the end of August (days 248-259) soil water levels were low and the response of water vapor fluxes to available energy changed. The good linear relationship between water vapor fluxes and available energy under optimal (days 152-247: R^2=0.93) and also less optimal soil water conditions (days 248-259: R^2=0.90) shows that water vapor fluxes are mainly energy driven and suggests that a major part of the incoming global radiation is directly converted into latent heat by evaporation. Fig. 25 also illustrates that the diurnal response of latent heat flux to available energy shows a hysteresis effect: the water vapor fluxes at similar available energy are higher in the afternoon than in the morning.

Finally, the mean daytime (PPFD > 10 µmol m^{-2} s^{-1}) Bowen ratio β (H/LE) and the decoupling factor Ω (Eq. 12) of both sites were compared (Fig. 26). During the measurement period 2003, β was always < 1 (Fig. 26). LE was mostly higher in the wetland than in the grassland (Fig. 24) although available energy did not differ significantly between both sites and consequently β of the wetland was generally lower than of the grassland (Fig. 26). Higher Ω values (Fig. 26) were found at the wetland than at the grassland due to the higher soil water content at the wetland (Fig. 21). During the day, both sites had Ω values close to 1, indicating that the canopy was almost totally decoupled from the atmosphere. This means that transpiration and evaporation of these sites are mainly governed by incoming radiation and that the canopy at both sites responds only slightly to changes in canopy surface conductance g_c.

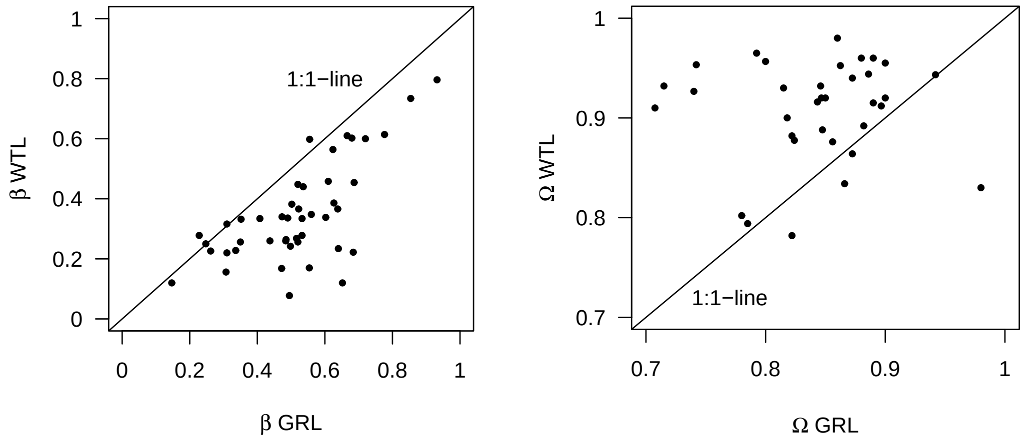

Fig. 26: The Bowen ratio β (left panel) and the decoupling factor Ω (right panel) for the wetland (WTL) compared to the grassland (GRL) during the measurement period 2003.

4.4.4 Senescence

The CO_2 uptake of the undisturbed wetland vegetation declined from spring to mid-summer (Fig. 22, Tab.7). The fitting parameters of the light response curves for selected time intervals with well developed wetland vegetation canopy were compared using the t-test (p=0.05) based on Wald's confidence ellipsoids (Fig. 27; Tab. 8). No statistically significant differences were found between the five time intervals for the values of the apparent quantum yield α, ranging between 0.021-0.036.

In spring (days 155-162), plant photosynthetic activity was highest resulting in the highest NEE at light saturation F_{inf} (24.6±1.4 µmol m^{-2} s^{-1}). No statistical differences were found between F_{inf} at the end of July (days 175-210: 15.5± 1.0 µmol m^{-2} s^{-1}) and the beginning of August (days 212-227: 14.4±0.7) but in both cases F_{inf} was significantly lower than in spring. The lowest F_{inf} were determined at the end of August (days 227-247: 9.1± 0.6µmol m^{-2} s^{-1}) and the beginning of September (days 248-258: 6.4±1.1) as a result of progressed senescence.

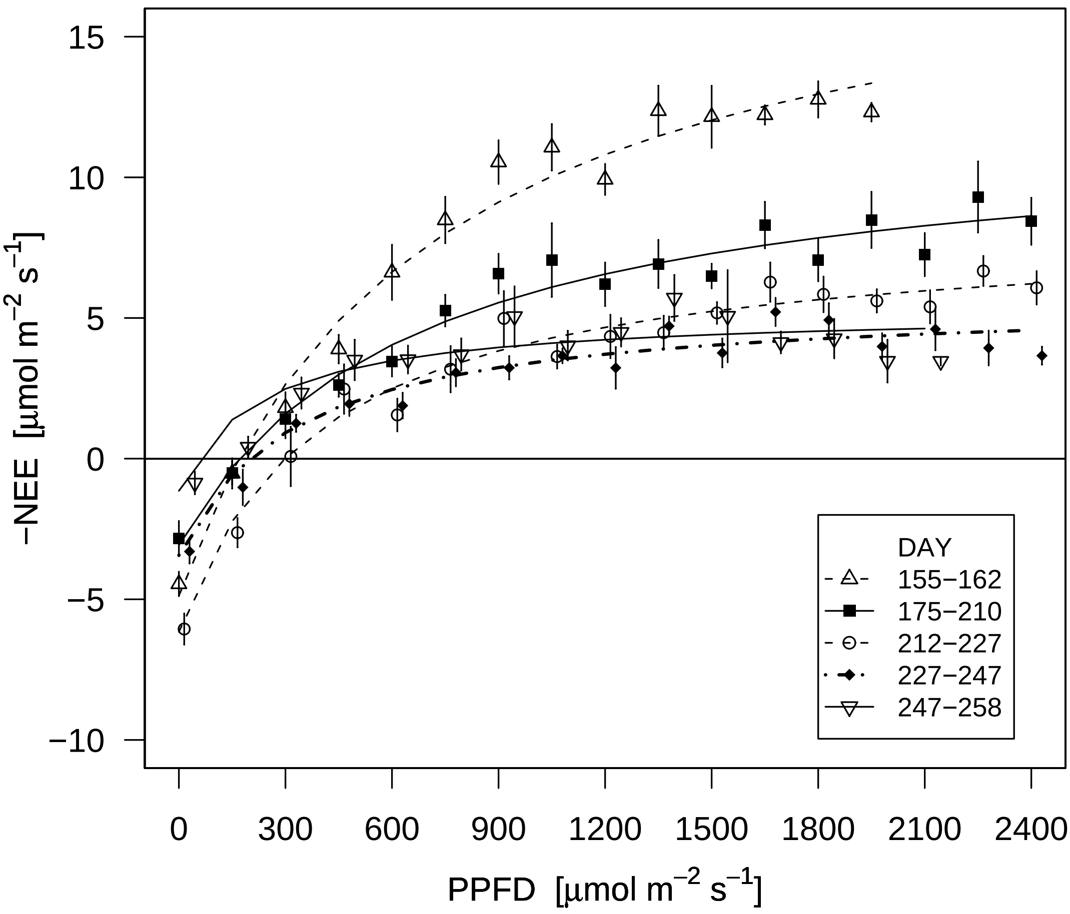

Fig. 27: Response of CO_2 exchange (-NEE) to varying light intensities (PPFD) under well developed vegetation in the wetland in spring (days 155-162), July (days 175-210), at the beginning (days 212-227) and the end of August (days 227-247) and at the beginning of September (days 247-258). Eq.11 is fitted trough the means ± SE. To improve legibility, data from different time periods were shifted right: days 212-227 by 10 PPFD, days 227-247 by 20 PPFD and days 247-258 by 30 PPFD.

There was no water stress at the wetland between day 152 and 247 (Fig. 25) and thus, the reduction in photosynthetic activity can be explained only by the senescence of the vegetation. During the period between days 247 and 258, i.e. just before the grass cut at the wetland, some drought stress effects were observed (flattening of curve in

Fig. 22; Fig. 25) and besides senescence, also water stress might be responsible for the reduced CO_2 uptake in this case.

Besides the reduction in F_{inf} also changes in daytime respiration R_d were observed. There was no clear relationship with soil temperature, but a strong linear correlation was found between R_d and soil water content levels ($R^2=0.80$). Especially low respiration rates were measured at the beginning of September (days 247-258) where soil water content levels were remarkably lower than during the other periods (Tab. 8).

4.5 Discussion

4.5.1 CO_2 budget

At both sites relatively high carbon losses (GRL: 204 ± 20 g C m^{-2}; WTL: 62 ± 6 g C m^{-2}) were detected over the 122-day measurement period 2003 (Fig. 22) in comparison with the annual carbon budget of the grassland for the whole year 2003 (171±17 g C m^{-2}). These high carbon losses are to one part the result of site characteristics (high soil organic carbon content, Tab. 5) and land management, but to an important part also due to the special microclimatological conditions of the summer 2003. The influence of microclimate becomes clear when comparing the interannual variability in CO_2 exchange at the grassland under similar land-management practice. For the corresponding period of other years, smaller carbon losses were measured in 2002 (145±15 g C m^{-2}) and in 2004 (130±13 g C m^{-2}). This shows that during the measurement period 2003, the measured carbon losses must be considered especially high for grassland. Indeed, the low soil water levels in summer 2003 reduced the photosynthetic activity. At the grassland, a reduction in NEE was observed between day 195 (Fig. 22, point A) and day 212 due to low soil water contents (0.17 m^3 m^{-3}) (Figs. 4 and 6). A change in below-ground respiration measured with the portable soil chamber system could not be detected (Müller, 2004; data not shown). Dark respiration rates RESP determined from nighttime EC data were at that time smaller than in spring, despite higher soil temperatures (Tab. 7), as were daytime respiration R_d values derived from light response curves (Fig. 23). Thus, the reduction in NEE is not primarily caused by higher respiration rates, but by dramatically smaller assimilation rates.

At the end of summer (days 247-258), the cumulative CO_2 fluxes of the wetland (Fig. 22) leveled off at a constant value for two weeks, indicating that it took the wetland with well developed vegetation one full month with considerable net CO_2 losses to reach a carbon-neutral steady state. The soil water content reached extremely low levels (<0.15 m^3 m^{-3}) during this period (Fig. 21) which reduced the relative share of available energy that was partitioned into water vapor fluxes (Fig. 25). Under these circumstances water stress became important: remarkably low daytime respiration rates were also derived from the light response curve determined at the beginning of September (days 247-258) (Fig. 27; Tab. 8). Moreover, below ground respiration measured at the wetland with the soil chamber system was substantially lower during this period than earlier in the measurement period under higher soil water content levels (Müller, 2004; data not shown). Since the photosynthetic capacity was already strongly decreased at the end of August due to senescence (Fig. 27), the reduction in respiration losses due to low soil water levels at the end of August explain the reduction in CO_2 losses between days 242 and 258.

For comparison, Ciais *et al.* (2005) determined decreased respiration rates during drought periods, rather than accelerating with the temperature rise. Griffis *et al.*, (2004) found a pronounced decrease in dark respiration in response to a reduction in soil water content in an old aspen forest. Several authors (Barr *et al.*, 2000; Kljun *et al.*, 2004) suggest, however, that this reduction in respiration in response to drought is likely only a transient condition because ecosystem respiration is expected to increase as the soils become rehydrated (Franzluebbers *et al.*, 2000).

The effect of low soil water content levels on CO_2 exchange became apparent much earlier at the grassland (Fig. 22, point A) than at the wetland (Fig. 22, point C). This is the result of differences in historic land-management: soil water is drained more quickly due to presence of draining channels at the grassland site.

The cumulative curves of CO_2 (Fig. 22) clearly demonstrate that present land management still stimulates carbon losses at Seebodenalp. We can assume that even if these areas were abandoned, the grassland would still be a net source of CO_2 under such climatic conditions. The direct comparison with the undisturbed wetland ecosystem, which had more optimal soil water levels and which started to lose carbon under the same climatic conditions due to senescence of the vegetation (Fig. 22, point B), even suggests that restoring the grassland to wetland conditions would not make a big difference in the annual carbon sum during such extreme events, although there would definitely be less carbon loss under less extreme conditions.

4.5.2 Comparison EC data with inventory data

The results of the biomass inventories at the grassland and the wetland in June (Fig. 19) are consistent with the significant differences in NEEMAX found between both areas (Tab. 7). The ratio of dry weight biomass from the grassland compared to the wetland amounted to 0.64 and the corresponding ratio of NEEMAX was 0.81. In the wetland, higher above-ground and root biomass was detected than in the grassland (Fig. 19). The higher NEEMAX measured at the wetland in June (Tab. 7) are in agreement with this difference in biomass, since biomass production is directly related to photosynthetic activity and thus to CO_2 uptake. .

The 13-cm soil cores only covered the upper soil-layer. Since most of the root biomass at Seebodenalp is located in the upper 6.5 cm (Fig. 19: 89% at GRL, 78% at WTL) and since there is generally a linear decrease of root biomass with depth

(Dahlman and Kucera, 1965), we can assume the root biomass determined from the 13-cm soil cores to be representative for the total root biomass.

The root biomass determined at the grassland is extremely low compared to values reported from other grasslands. Coupland and Van Dyne (1979) investigated the below-ground biomass of different ecosystems and found a median root biomass of 1650 g m^{-3} for temperate grasslands and only a few values < 1000 g m^{-3}. Also other studies report values around 1400 g m^{-2} for grasslands under temperate climate conditions (Jackson *et al.*, 1996). Due to land-management over several decades the soil at the grassland might be compacted resulting in the lower root biomass at the grassland. Both sites are characterized by relatively shallow root systems. Polomski and Kuhn (1998) found that shallow root systems are typical for wet grassland vegetation. In spring after snow melt and in autumn, the soil water table at both sites is high (≈20 cm below ground) and probably responsible for these shallow root systems.

4.5.3 Ecosystem water vapor fluxes

Our results show that the water vapor fluxes at our site were not strongly related to the CO_2 exchange (Fig. 24), and that the water fluxes were mainly energy driven (Fig.25,26). Cutting the grass at the grassland had no detectable effect in the total measured water vapor fluxes (Fig 7, Tab. 7). Wolfahrt (2004) observed the same phenomenon for a grass cut at another mountain meadow in the Eastern Alps. Also other studies found that a change in leaf area index did not substantially change the measured water vapor flux (Schulze *et al.*, 1994; Kelliher *et al.*, 1995). Indeed, decreasing leaf area index for unstressed vegetation normally leads to decreased transpiration and increased soil evaporation, such that the total evapotranspiration does not substantially change with LAI for unstressed conditions.

Unlike in forests, the energy storage capacity in grasslands is very low. We showed that the vegetation at Seebodenalp is almost totally decoupled from the atmosphere (high values for Ω at both sites). Theoretical studies (Jarvis and McNaughton, 1986) also indicated that evaporation in short vegetation tends toward an equilibrium rate that is sensitive primarily to net radiation and not to the diurnal variations in vapor pressure deficit and stomatal conductance. By comparing worldwide FLUXNET sites, Wilson *et al.* (2003) found that over short vegetation, the latent heat flux depends mainly on available energy. Thus, our study additionally indicates that this general relationship also holds for water-stressed mountain grasslands in the Alps.

4.6 Conclusions

We compared the eddy covariance CO_2 and water vapor fluxes measured during the hot and dry summer of 2003 at two differently managed ecosystems at Seebodenalp, Switzerland. The grassland site was extensively used as a pasture and a meadow (two grass cuts), whereas the wetland site remained unmanaged until late summer. At the beginning of the measurement period, soil water content levels were rather low at the grassland site (around 0.20 m^3 m^{-3}) compared to the maximum levels reached just after snow melt (0.40 m^3 m^{-3}). Soil water was more abundant at the wetland site (close to saturation, 0.40 m^3 m^{-3}) at the beginning of the measurement period, but gradually decreased towards the end of the summer.

From 1 June to 30 September 2003, substantial carbon losses were measured at both sites: the grassland was a net carbon source of 204 ± 20 g C m^{-2}, whereas the wetland lost 62 ± 6 g C m^{-2}. In June, a higher CO_2 uptake at noon (NEEMAX) was detected at the wetland than at the grassland, which was in agreement with the higher biomass measured at the wetland. Cutting the grass influenced the CO_2 exchange strongly, but the magnitude of the measured water vapor fluxes was not influenced by this disturbance. The grass cut led to decreased transpiration, but also to increased soil evaporation, such that the total evapotranspiration did not substantially change with LAI. At the wetland statistically higher water vapor fluxes were measured resulting in lower Bowen ratios at the wetland. We have shown that evaporation of soil water was the major contributor to the water vapor fluxes. We demonstrated that the water vapor fluxes at Seebodenalp were mainly energy driven: (1) no coupling was found between CO_2 and water exchange, (2) under optimal soil water levels, a good correlation was found between latent heat flux and available energy, and (3) the high values for the decoupling factor Ω (close to 1) indicated that both ecosystems were strongly decoupled from the atmosphere.

Due to senescence of the wetland vegetation, the photosynthetic activity decreased from spring to mid-summer. At the end of July, NEEMAX was higher at the grassland, although photosynthetic activity at the grassland was at that time also reduced due to drought stress. Dark respiration (RESP) at the grassland was stimulated due to grazing. In July, a decrease in both dark and daytime respiration was detected due to low soil water levels. At the wetland, daytime respiration, derived from the light response curves, substantially decreased under low soil water levels at the beginning of September (days 247-259). The effect of low soil water content levels on CO_2 exchange was pronounced earlier at the grassland (end of July) than at the wetland (end of August), which is the result of the draining channels at the grassland leading to a faster draining of the site.

4.7 Tables

Tab. 5: Description of the site history, soil type (WRB, 1998), soil characteristics (Müller, 2004), and plant community (Reutlinger, 2004) at the extensively used grassland and the protected wetland sites at Rigi, Seebodenalp.

	Grassland (GRL)	**Wetland (WET)**
Area [ha]	23	8
Site history	drained and peat exploited	undisturbed
Present land-management	extensively used as pasture and meadow	1 grass cut after growing season
Soil type	Stagnic Cambisol	Folic Histosol (drystic)
Soil organic carbon in upper 10 cm [mass %]	7 – 15	20 – 45
C/N soil [] in upper 10 cm	12 – 20	17 – 45
pH[$CaCl_2$] in upper 10 cm	5.5 – 7	3 – 4
Plant community	*Lolio-Cynosuretum cristati*	*Angelico-Cirsietum caricetosum nigrae* and degenerated *Caricetum nigrae*

Tab. 6: Micrometeorological instrumentation at the extensively used grassland and the protected wetland sites, measuring heights (H) and the physical units.

Micrometeorological parameter	**Height (cm)**	**Units**	**Instrument**
net radiation (Rn)	200	W m^{-2}	NR Lite, Kipp & Zonen, Delft, The Netherlands
photon flux density (PPFD)	200	µmol m^{-2} s^{-1}	LI-190SA, LI-COR, Lincoln, Nebraska, USA
relative humidity	100	%	HUMICAP, HMP45A/D, Vaisala, Finland
air temperature	100	°C	copper-constantan thermocouples
soil temperature	1	°C	copper-constantan thermocouples
soil heat flux (G)	-5*	W m^{-2}	heat flux plate, Hukseflux, Delft, The Netherlands
volumetric soil water content (SWC)	-5	%	dielectric aquameter, ECH2O, Decagon Devices Inc., Pullman, WA

*two sensors were used to better represent small-scale variability

Tab. 7: Means and standard errors of NEE, NEE at noon (NEEMAX), dark respiration (RESP), water vapor flux at noon (EMAX), LAI, soil temperature (TS) and available energy at noon (ENEMAX) at the grassland (GRL) and the wetland (WTL) for periods before and after both grass cuts at GRL in 2003: 4 June to 10 June (days 155-161); 12 to 17 June (days 163-168); 25 July to 30 July (days 206-211) and 1 August to 8 August (days 212-220). Means with the same superscript character within one row do not differ significantly (95% confidence level) from one another.

		Before 1 grass cut		**After 1 grass cut**		**Before 2 grass cut**		**After 2 grass cut**	
		days 155-161		**days 163 -168**		**days 206-211**		**days 213-220**	
Parameter	**Units**	**GRL**	**WTL**	**GRL**	**WTL**	**GRL**	**WTL**	**GRL**	**WTL**
NEE	[μmol m^{-2} s^{-1}]	-0.4 ± 0.7^{a}	-2.9 ± 0.6^{b}	4.9 ± 0.3^{c}	-0.28 ± 0.6^{a}	-0.5 ± 0.4^{a}	0.7 ± 0.4^{a}	3.3 ± 0.2^{d}	0.2 ± 0.4^{a}
NEEMAX	[μmol m^{-2} s^{-1}]	-12.1 ± 0.6^{a}	-14.9 ± 0.7^{b}	1.6 ± 0.8^{c}	$-12.6 \pm 0.6^{a,b}$	-9.7 ± 0.6^{d}	$-7.5 \pm 0.7^{d,e}$	0.4 ± 0.5^{d}	-6.0 ± 0.6^{e}
RESP	[μmol m^{-2} s^{-1}]	$8.6. \pm 0.3^{a}$	5.2 ± 1^{b}	11.0 ± 0.4^{c}	7.6 ± 0.5^{d}	6.6 ± 0.2^{d}	4.3 ± 0.3^{b}	8.5 ± 0.6^{a}	6.4 ± 0.5^{d}
EMAX	[mmol m^{-2} s^{-1}]	5.2 ± 0.4^{a}	11.4 ± 0.8^{b}	5.3 ± 0.4^{a}	13.4 ± 0.6^{b}	4.2 ± 0.3^{a}	6.4 ± 0.4^{a}	4.3 ± 0.6^{a}	13.6 ± 0.9^{b}
LAI	[m^{2} m^{-2}]	3.6 ± 0.4^{a}	3.4 ± 0.4^{a}	0.7 ± 0.2^{b}	3.5 ± 0.3^{a}	3.0 ± 0.4^{a}	4.1 ± 0.3^{a}	1.6 ± 0.4^{b}	3.9 ± 0.4^{a}
TS	[°C]	17.3 ± 0.1^{a}	17.6 ± 0.1^{a}	19.1 ± 0.1^{b}	19.0 ± 0.1^{b}	18.5 ± 0.1^{c}	17.7 ± 0.1^{a}	18.4 ± 0.1^{c}	18.3 ± 0.1^{c}
ENEMAX	[W m^{-2}]	705 ± 65^{a}		699 ± 35^{a}		566 ± 39^{a}		627 ± 29^{a}	

Tab. 8: Light response curves (Eq. 12) and fitting parameters α, F_{inf} and R_e (best fit ± SE) during distinct periods at the wetland. The means ± SE of the volumetric soil water content (SWC) and of the soil temperature at 5 cm below ground (TS) are also given.
The fitting parameters are compared using the t-test (p=0.05) based on Wald's confidence ellipsoids. Means with the same superscript character within a column do not differ significantly (95% confidence level) from one another.

Period	α [-]	F_{inf} [μmol m^{-2} s^{-1}]	R_d [μmol m^{-2} s^{-1}]	TS [°C]	SWC [m3 m^{-3}]
155-162	0.036 ± 0.009 ^{a}	24.6 ± 1.4 ^{a}	4.9 ± 0.8 ^{a}	17.1 ± 0.1 ^{a}	0.35 ± 0.03 ^{a}
175-210	0.021 ± 0.008 ^{a}	15.5 ± 1.0 ^{b}	3.0 ± 0.7 ^{a,b}	18.6 ± 0.1 ^{a}	0.20 ± 0.02 ^{b}
212-227	0.036 ± 0.010 ^{a}	14.4 ± 0.7 ^{b}	6.2 ± 0.6 ^{a,c}	18.9 ± 0.1 ^{b}	0.28 ± 0.01 ^{c}
227-247	0.028 ± 0.011 ^{a}	9.1 ± 0.6 ^{c}	3.4 ± 0.6 ^{a,b,d}	18.0 ± 0.1 ^{c}	0.26 ± 0.01 ^{c}
247-258	0.027 ± 0.025 ^{a}	6.4 ± 1.1 ^{d}	1.1 ± 0.9 ^{e}	16.7 ± 0.1 ^{d}	0.12 ± 0.02 ^{d}

5 Three seasons of winter CO_2 flux measurements at a Swiss sub-alpine grassland

To be submitted

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Summary

Winter carbon losses account for an important share in the annual CO_2 budgets of the sub-alpine Swiss CARBOMONT site Seebodenalp. Here we report on eddy covariance flux measurements obtained during three winter seasons (2002–2005). The cumulative winter respiration and respiration from snow pack determined over the six month period from 15 October until 15 April contributed 23.3 ± 2.4% and 6.0 ± 0.3%, respectively, to the annual respiration. The insulation effect of snow cover and the depression of the freezing point by the high concentration of soil organic solutes prevented the soil from freezing. These favorable soil temperatures resulted in relatively high respiration losses.

CO_2 losses from snow pack, the duration of snow cover, and micrometeorological conditions determining the photosynthetic activity of the vegetation during snow-free periods influenced the size and the variability of the winter CO_2 fluxes. Because of the large variation in length of periods with air temperatures below freezing, the seasonal values are strongly influenced by the days at the edges of the winter period.

Although considerable fluctuations in snow effluxes were recorded, no conclusive and generally valid relationship could be found between CO_2 losses from snow pack and snow depth, rate of snow melt, wind speed or air pressure, suggesting that time lags, and histeresis effects might be more important to understand winter respiration than concurrent environmental conditions.

The CO_2 losses from snow pack were highest in winter 2003–2004. These high losses can partially be explained by the higher temperatures of the topsoil resulting from higher air temperatures just before snow fall and thus are not the consequence of higher soil temperatures registered during the summer heat-wave 2003. However, water stress in summer 2003 might have caused an increment in dead organic material providing additional substrate for microbial respiration in winter.

5.1 Introduction

Winter fluxes are a significant component of the annual carbon budget of ecosystems (Brooks *et al.*, 1997; Oechel *et al.*, 1997; Bubier *et al.*, 2002). Identifying the sources and sinks of CO_2 has been the focus of considerable research over the last decade (e.g. within the FLUXNET project, Baldocchi *et al.*, 2001). Only a small fraction of these studies, however, have focused on quantifying non-growing season fluxes from seasonally snow-covered systems (Brooks *et al.*, 1997; Gilmanov *et al.*, 2004).

Fluxes measured during the growing season provide important information on carbon exchange processes and contribute most to the annual CO_2 budget of an ecosystem. And they may even be dominating annual balances in forest ecosystems, especially under extreme conditions as were observed in 2003 (Ciais *et al.*, 2005). However, in grasslands such a clear response to the European 2003 heat wave has not been reported yet, and fluxes from outside the growing season may even be more critical in grassland ecosystems than in forests. There is however a general consensus that respiratory losses during the cold period may offset the carbon budget measured during the growing season (e.g. Kelley *et al.*, 1968; Oechel *et al.*, 1997; Aurela *et al.*, 2001; Lafleur *et al.*, 2001; Bubier *et al.*, 2002; Schimel *et al.*, 2002; Brooks *et al.*, 2004) in any year, not only during extreme events. Interest in cold-season respiration rates had increased as attempts were started to quantify annual ecosystem CO_2 fluxes (Kelley *et al.*, 1968; Johnson and Kelley, 1970; Zimov *et al.*, 1993; Vourlitits and Oechel, 1999). Gilmanov *et al.* (2004) gives a detailed overview of the existing studies on winter CO_2 fluxes measured over different ecosystems. They conclude that only a limited number of CO_2 flux measurements have been conducted during the winter for northern latitude grasslands. Schimel and Clein (1996) found that wintertime ecosystem respiration in the Western U.S. Mountains can account for carbon losses that total half of the growing season net carbon sequestration, with soil emissions representing a significant fraction of this lost carbon. Quantifying winter CO_2 efflux can thus change both the magnitude and the sign of the overall annual carbon budget. Especially in arctic regions, CO_2 exchange measurements have been made during the last few years. These high latitude ecosystems are particularly vulnerable to climate change, contain large soil C stocks (Oechel *et al.*, 1997), and are therefore of special interest for quantifying the terrestrial CO_2 budget of the Earth. However, in Arctic ecosystems, most annual estimates are still only based on summer CO_2 fluxes (e.g. Oechel *et al.*, 1993; Jones *et al.*, 1998) and do not account for carbon losses during winter, which has been shown to be significant in many snow-covered ecosystems (Jones, 1999; Welker, 2000; Grogan *et al.,* 2001, Swanson *et al.*, 2005).

Environmental conditions, such as rain and snow fall, snow cover, air and soil temperatures, wind speed, and air pressure play an important role in winter CO_2 exchange (Welker *et al.*, 2000; Bubier *et al.*, 2002; Gilmanov *et al.*, 2004) and can vary significantly among years. Bubier *et al.* (2002) discussed the physical factors and biological processes influenced by snow cover. Heterotrophic respiration in the soil appears to be active even under snow cover, releasing significant amounts of CO_2 (Kelley *et al.*, 1968; Zimov *et al.*, 1993; Oechel *et al.*, 1997; Brooks *et al.*, 2004). Via its function as a thermally isolating ground cover, snow may significantly decrease the depth down to which soil freezes, and it can even completely prevent its freezing, thereby increasing the temperature of the active soil layer during winter (Walker *et al.,* 1999; Swanson *et al.*, 2005). These favorable soil temperatures, with a critical threshold for active respiration around –7 and –5 °C, corresponding to the presence or absence of unfrozen water (Brooks *et al.*, 1997; Osterkamp and Romanovsky, 1997) allow significant CO_2 production through a continuation of metabolic activity of soil microorganisms with enzymatic systems that are efficient at low temperatures (Panikov and Dedysh, 2000). Additionally, root respiration may further contribute to the CO_2 flux in winter (Welker *et al.*, 2000; Grogan *et al.*, 2001).

So far no universal relationship between snow pack characteristics and ecosystem respiration has been established. Some authors report on a clear positive effect of snow pack on CO_2 efflux (e.g. Hardy *et al.*, 2001; Gilmanov *et al.*, 2004); others could not determine an effect of snow cover on respiration (e.g. Jones *et al.*, 1999 Of those who identified possible effects of snow cover, the processes governing these effects seemed to be rather specific and not universal. Bubier *et al.* (2002) found a good correlation between declining atmospheric pressure and winter CO_2 efflux; and Kelley *et al.* (1968) demonstrated a positive effect of wind speed on CO_2 efflux, because accumulated CO_2 within the snow pack is more rapidly released under conditions of high wind speed.

Several studies in the Arctic tundra calculated CO_2 fluxes using the diffusion gradients of CO_2 concentrations measured at different heights within the snow and at the snow–air interface (e.g. Kelley *et al.*, 1968; Sommerfeld *et al.*, 1996; Brooks *et al.*, 1997; Welker *et al.,* 2000; Swanson *et al.*, 2005). Others were using automatic chambers (e.g. Zimov *et al.*, 1993; Fahnestock *et al.*, 1999; Christensen *et al.*, 2000; Panikov and Dedysh, 2000; Bubier *et al.*, 2002) or the Bowen ratio energy balance technique (e.g. Frank and Dugas, 2001; Gilmanov *et al.*, 2004) to detect winter CO_2 efflux. In addition, most field studies sampled every few days and cannot assess the importance of short-term variation of the CO_2 flux from snow covered ecosystems. Only a few micrometeorological studies that provide continuous time series of flux data have measured winter NEE so far (e.g. Ham and Knapp, 1998; Vourlitis and Oechel, 1999; Aurela *et al.*, 2001; Lafleur *et al.*, 2001; Suyker and Verma, 2001; Flanagan *et al.*, 2002; Li *et al.*, 2005).

In this study we report on quasi-continuous eddy covariance flux measurements carried out during three years including three winter periods. Measurements were taken at the Swiss CARBOMONT site Seebodenalp, which is snow covered for about 30 % of the year. The objectives of this paper are: (1) to quantify the winter CO_2 fluxes measured during the three winter periods; (2) to evaluate the contribution of the winter CO_2 fluxes to the annual carbon budget of this grassland ecosystem; (3) to investigate the micrometeorological processes controlling winter CO_2 fluxes; and (4) to investigate the temporal evolution of CO_2 fluxes shortly after snow melt.

5.2 Methods and site description

5.2.1 Site description

The Seebodenalp flux site was established in May 2002 as part of the CARBOMONT network, a 5th Framework Program funded by the European Union. The site is located on a sub-alpine grassland on a flat shoulder terrace of Mount Rigi (47°05’38” N, 8°45’36” E) in Central Switzerland at an altitude of 1025 m above sea level (Rogiers *et al.*, 2005). The site encompasses 32 ha of relatively flat terrain (Fig. 28). In summer, the dominant land uses are extensively used meadows and pastures. The current terrain is the bottom of a former but vanished lake which was fed by meltwater at the end of the last glaciation (Vogel and Hantke, 1989) with a thick sedge peat layer on top. The soil has a very high organic carbon content ranging between 7.2 ± 0.2 % and 15.73 ± 0.88 by mass and is characterized as a stagnic Cambisol and a folic Histosol (drystic) (Müller, 2004).

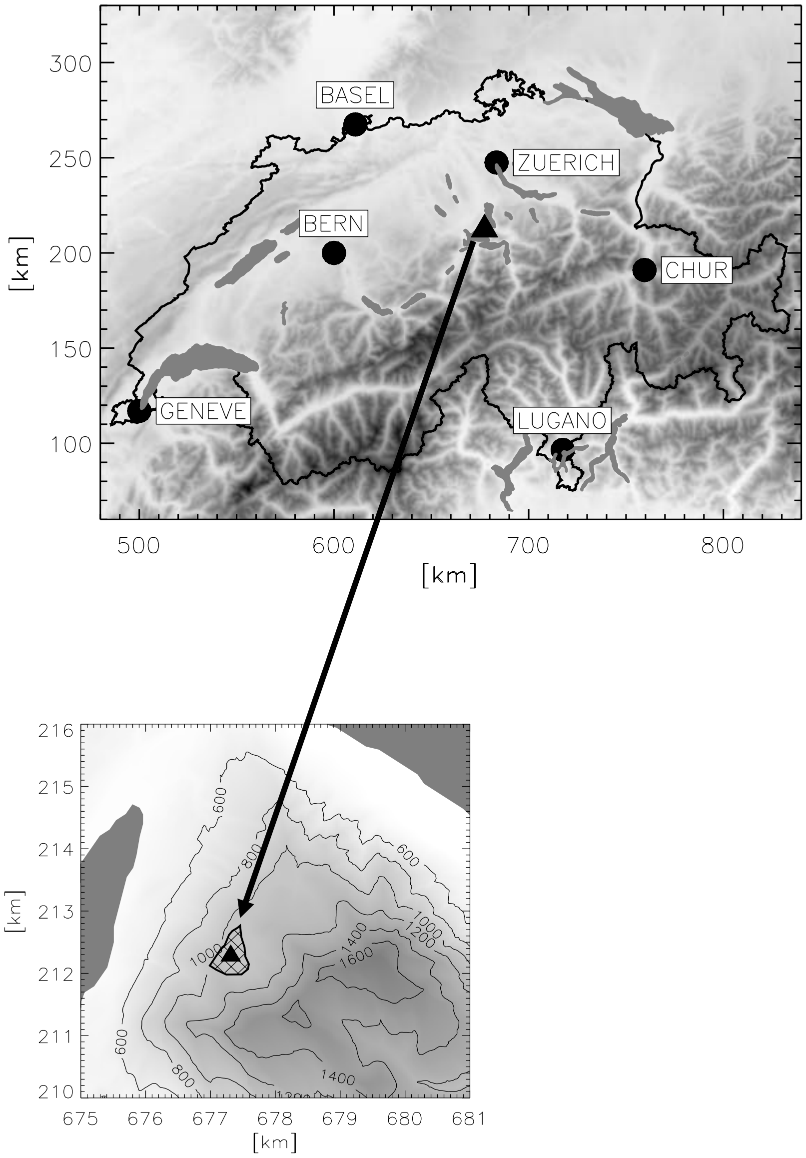

Fig. 28: Map of Switzerland with indication of the CARBOMONT site Seebodenalp (upper). Topography of the northern part of mount Rigi, the position of the Seebodenalp and the measurement tower are shown (lower) on a 25-km grid. The maps are in Swiss km-coordinates (DHM25 reproduced with permission, Swisstopo BA046078).

5.2.2 EC flux measurements

The eddy covariance (EC) technique was used for continuous measurements of the turbulent fluxes of CO2, water vapor, sensible heat, and momentum (see Aubinet et al. 2000, Baldocchi et al. 2003, for methodological details). Wind velocity, wind direction, and temperature over the site were measured with a three-dimensional ultrasonic anemometer (Solent HS, Gill Ltd., Lymington, UK), mounted at a height of 2.4 m above ground level (a.g.l.) (midpoint of the sonic head) and CO_2 and water vapor concentrations were measured with an open path infrared gas analyzer (IRGA) (LI-7500, LI-COR Inc., Lincoln, Nebraska, USA). Both instruments were sampled at 20 Hz temporal resolution. Data processing and the calculation of the EC fluxes for Seebodenalp is described in detail in Rogiers *et al.* (2005). In short, the vertical turbulent fluxes F were calculated from the half-hourly averaged covariance of the measured fluctuations of the vertical wind velocity w [m s^{-1}] in a co-ordinate system which was aligned with the mean streamlines (McMillen, 1988), and the CO_2 concentration c [µmol mol^{-1}]:

$$F = (\rho_a / M_a) \cdot \overline{w' \cdot c'} \qquad [\mu\text{mol m}^{-2}\text{ s}^{-1}] \text{ (Eq. 13)}$$

where ρ_a [kg m^{-3}] is the air density, and M_a [kg mol^{-1}] is the molar weight of air (28.96 g mol^{-1}). Overbars denote time averages, and primed quantities are the instantaneous deviations from their respective time average. To obtain c' the linear trend in CO_2 concentration was subtracted from each half hour interval. CO_2 fluxes were corrected for high-frequency damping losses (Eugster and Senn 1995) using an damping constant of 0.2 s^{-1}, followed by the necessary density flux correction for open-path instruments according to Webb *et al.* (1980). Positive fluxes indicate net upward transport from the surface to the atmosphere.

5.2.3 Micrometeorological data

To characterize climatic conditions additional meteorological sensors were installed near the EC tower on a separate tower. Air and soil temperatures [°C] were measured with copper-constantan thermocouples at the heights 100, 50, 10, 5 above ground and at –5, –10, –20, –30, –50 from soil level. Wind speed at 200 cm height [m s^{-1}] was measured with a switching anemometer (Vector Instruments, UK). All data were recorded on a data logger (model CR10X, Campbell Scientific Inc., Loughborough, UK).

Snow fall and snow depth were measured manually on a daily basis using a graduated measuring rod at the nearby station Oberiberg (1090 m a.s.l.), 6.2 km southeast from Seebodenalp. The quantitative Oberiberg snow data correspond rather well with the qualtitative information on snow cover provided by local people from Seebodenalp from which we could conclude that Seebodenalp experienced the same snow events as the Oberiberg station. The elevation and exposition (north) of that station also closely correspond to the conditions found at Seebodenalp.

5.2.4 Data availability, filtering and gapfilling

The EC tower and the micrometeorological station were continuously operated from 17 May 2002 until 10 May 2005, including three winter periods. Due to some technical failures of the EC system, the data availability before filtering amounted to 88% of all possible 30-min time periods. The data were screened for outliers based on a set of objectively testable plausibility criteria as described in Rogiers *et al.* (2005). Due to snow and rain fall, 6% of the available data had to be discarded. Another 28% of the data were filtered out due to inadequate turbulence conditions (momentum flux was not directed towards the surface), which occurred mainly (65% of these cases) at night (PPFD < 10 µmol m^{-2} s^{-1}). The coverage of high quality data during the three winter periods thus was 54%.

Outside the growing season when there is almost no photosynthesis going on the widely used gap-filling approach using light-response curves (e.g. Falge *et al.*, 2001) failed. Therefore, we filled gaps in our winter data using the median diurnal cycle approach. Short gaps ($\leq$ 2 hours) were filled by linear interpolation, while larger gaps where filled using the median flux value for each hour of the day as determined from available data three days before and after the gap. Gapfilled data only served the purpose to obtain seasonal budgets, but were not used to find relationships between snow cover and CO_2 flux.

5.2.5 Calculations

CO_2 fluxes were calculated as 30-minute averages (eq.13) for a three-year period from May 2002 through May 2005. The annual CO_2 integrals for the three measurement years were calculated by integrating the CO_2 flux data from 15 May until 14 May of the following year. The winter period - or cold season - in this paper was defined as the period from 15 October until 15 April. This period covers all days where snow blanketed the site in any of the years, expect for very few anomalous single-day snow events in autumn and spring. It is to be noted that in the Alps at this altitude snow events can occasionally even happen during the warm season, therefore our choice of the definition of winter differs from the arbitrary definition of winter in climatology (December–February) which would leave too many days with snow cover in the wrong season.

The CO_2 fluxes (NEE) were partitioned into gross primary production (GPP) and ecosystem respiration (RESP). For days where the vegetation was photosynthetically active (i.e. days where there was a clear response of NEE to PPFD), total ecosystem respiration was calculated as the weighted average of dark nighttime respiration (RESPn) and daytime respiration (RESPd). Nighttime (PPFD < 10 μmol m^{-2} s^{-1}) CO_2 fluxes are assumed to represent ecosystem respiration at night (RESPn). Daytime respiration (RESPd) was derived from the light response curves calculated for each day when the vegetation was photosynthetically active. The light response curve defines the relationship between CO_2 exchange [µmol m^{-2} s^{-1}] during the day (NEE; PPFD > 10 µmol m^{-2} s^{-1}) and photosynthetic photon flux density PPFD [µmol m^{-2} s^{-1}] and can be described by a rectangular hyperbola (e.g. Ruimy *et al.*, 1995; Gilmanov *et al.*, 2003),

$$\mathrm{NEE} = \frac{-\,F_{\infty} \cdot \alpha \cdot \mathrm{PPFD}}{\alpha \cdot \mathrm{PPFD} \;+\; F_{\infty}} + \mathrm{RESPd}\,, \qquad \text{(Eq. 14)}$$

where F_{∞} is NEE at light saturation [µmol m^{-2} s^{-1}], α is the apparent quantum yield, and RESPd [µmol m^{-2} s^{-1}] is to be interpreted as the best estimate of the average daytime ecosystem respiration (Suyker and Verma, 2001; Gilmanov *et al.*, 2003).

GPP was than calculated as the difference between NEE and RESP.

For days where no clear response of NEE to PPFD could be determined, total ecosystem respiration was calculated from the exponential relationship between RESPn and soil temperature at –5 cm (Ts in °C) (e.g. Schmid *et al.*, 2000),

$$\mathrm{RESPn} = a \cdot \exp(b \cdot \mathrm{Ts})\;, \qquad \text{(Eq. 15)}$$

where a and b are fitting parameters determined by minimizing the sum of squares of the residuals.

5.3 Results

5.3.1 Winter CO_2 fluxes

Snow coverage at Seebodenalp varied greatly among winters (Tab. 9, Fig. 29). In 2002–2003 the site was snow covered during 88 days, whereas in 2003–2004 snow coverage was more abundant and lasted for 125 days. Winter 2004–2005 took an intermediate position between the two previous years and the site was blanketed with snow during 116 days. On average, Seebodenalp was snow covered during 30% of the year. Also the timing of the first (autumn) and the last (spring) day with snow cover was very variable during the three winter periods. First snow in 2004 (day 313; 9 November) blanketed the site 47 days later than in 2002 (day 266; 23 September). In spring, the last snow melted away much earlier in 2003 (day 102; 19 April) compared to 2004 (day 130; 10 May). Snow depths ranged between 0 and 70 cm (Fig. 34).

Daily CO_2 fluxes during the winter period (15 October–15 April) ranged from a net CO_2 uptake of -15.17 g C m^{-2} day $^{-1}$ in spring 2005 (day 105) to a net CO_2 loss of 12.39 g C m^{-2} day^{-1} in February 2004 (day 51). The mean daily CO_2 flux (F; Tab. 9) varied substantially over the three winter periods. Mean CO_2 efflux was highest during the winter 2003–2004 (3.39 ± 0.19 g C m^{-2} d^{-1}). More moderate mean losses of CO_2 were measured in winter 2002–2003 (2.09 ± 0.21 g C m^{-2} d^{-1}) and in winter 2004–2005 (1.27 ± 0.25 g C m^{-2} d^{-1}). When focusing on snow covered days only, mean CO_2 losses (Fs; Tab. 9) were also remarkably higher in 2003–2004 (4.33 ± 0.18 g C m^{-2} d^{-1}) than during the two other winter periods (3.03 ± 0.31 g C m^{-2} d^{-1} for 2002–2003; 2.63 ± 0.17 g C m^{-2} d^{-1} for 2004–2005). This, together with the greater number of snow covered days (Dts; Tab. 9) in 2003–2004 (125 days) contributed substantially to the observation that the winter 2003–2004 had the highest mean daily CO_2 losses. During snow free days in the winter period, mean daily net CO_2 fluxes fluctuated around zero with some days showing a net uptake but others showing a net carbon loss (Fig. 29). We distinguished between snow free days where there was no photosynthetic activity and thus gross primary production at noon (GPPn) ≥ -0.5 g C m^{-2} s^{-1} (Fnsna; Tab. 9) and snow-free days where assimilation occurred and GPPn < -0.5 g C m^{-2} s^{-1} (Fnsa; Tab. 9). CO_2 fluxes during snow free days without photosynthetic activity at noon (Fnsna) varied among the three winter periods between 1.75 ± 0.24 and 3.32 ± 0.22 g C m^{-2} d^{-1}). Mean daily CO_2 exchange for snow free days with photosynthetic activity (Fnsa) varied substantially.

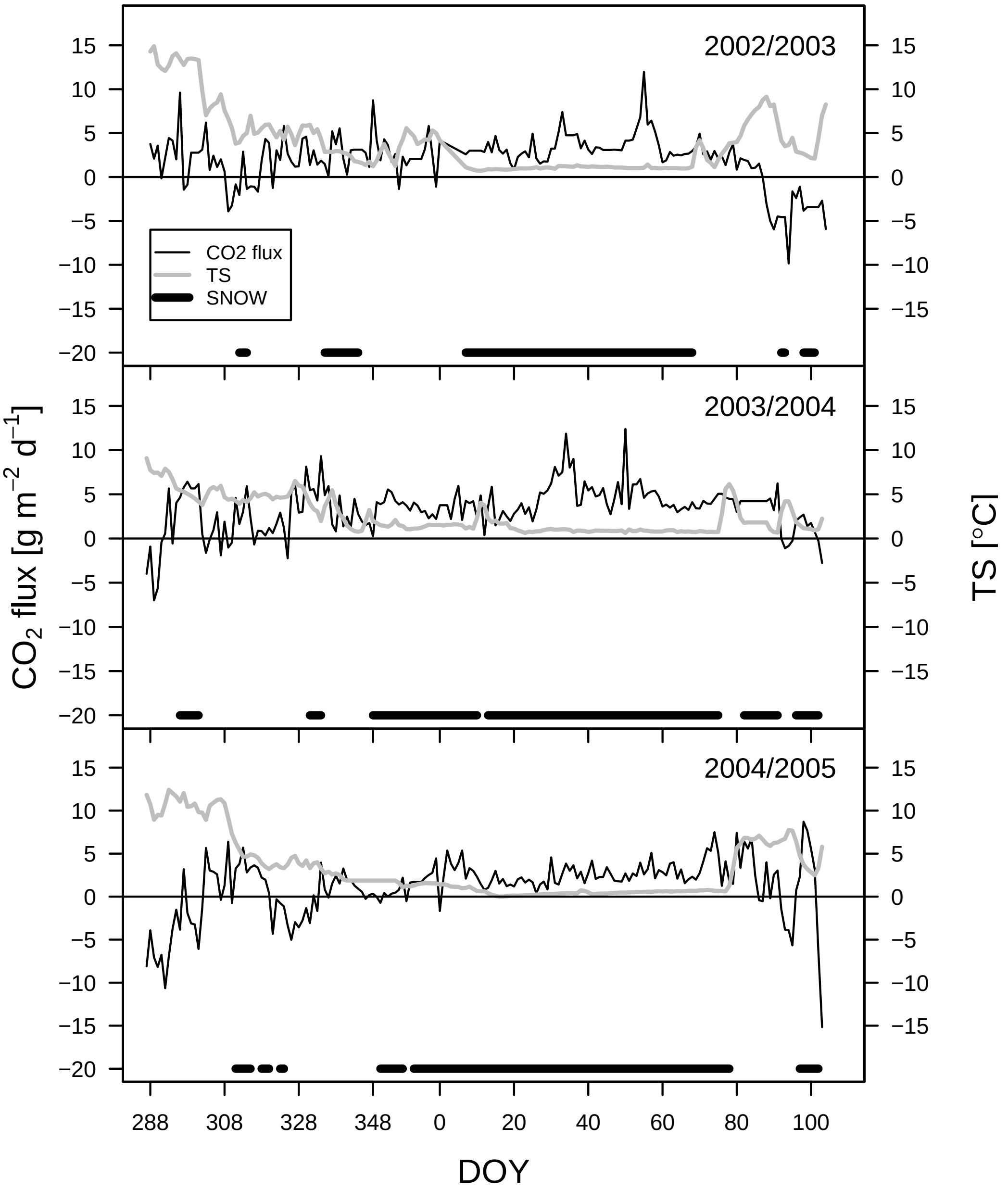

Fig. 29: Mean daily CO$_2$ fluxes (g C m^{-2} d^{-1}), mean soil temperature at –5 cm (°C, TS) and snow cover presence (SNOW) during 3 winter periods 2002–2003, 2003–2004 and 2004–2005. Winter periods start at 15 October (day = 288) until 15 April (day = 105).

Net daily mean losses were measured in winter 2002–2003 (1.35 ± 0.22 g C m^{-2} d^{-1}) and in winter 2003–2004 (1.80 ± 0.22 g C m^{-2} d^{-1}).

In winter 2004–2005 a daily mean uptake was recorded (–0.78 ± 0.32 g C m^{-2} d^{-1}), which actually represent extended autumn and spring growing seasons and thus explains partially the relatively small daily mean loss determined over the whole winter period 2004–2005. The winter period 2004–2005 had the highest number of growing degree days, i.e. days with mean air temperatures > 5°C, (Dgdd = 58 days; Tab. 9).

5.3.2 Contribution of NEE during winter and snow-covered days to the annual CO_2 budget

The interannual variability in CO_2 budgets was very high for the three winter periods (Fig. 30) and strongly depended on the duration of snow free periods where plants immediately became active as soon as soil temperatures were >0 °C (Fig. 35). The annual CO_2 integrals (NEEa; Tab. 10) for the three measurement years demonstrate that the site was a net source of C during all three years. Over the winter period (NEEw; Tab. 10) 2003–2004 the highest carbon loss was observed (169 ± 4 g C m^{-2}), during the other winters lower carbon losses were registered (103 ± 3 g C m^{-2} in 2002–2003 and 63 ± 2 g C m^{-2} in 2004–2005). These values show that the winter situation has a significant impact on the annual CO_2 budget. The share of carbon losses during snow covered days (NEEs; Tab. 10) in 2002–2003 and 2004–2005 amounted to 56 ± 2 and 68 ± 2 g C m^{-2}, respectively. However, the CO_2 efflux in 2003–2004 after the record heat wave summer in Europe (see Schär *et al.*, 2004, Ciais *et al.,* 2005) was twice as much (133 ± 4 g C m^{-2}).

When partitioning NEE into respiration and assimilation, it becomes clear that the highest contribution of snow covered periods (RESPs; Tab. 10) to the annual ecosystem respiration was measured in 2003–2004, partly due to the highest number of days with snow (Ds; Tab. 9) and partly due to the highest CO_2 effluxes measured over snow pack (Fs; Tab. 9) during that period. In 2003–2004, RESPs (Tab. 10) contributed 6.5% to the total annual respiration (RESPa; Tab. 10). The share of RESPs to RESPa was slightly lower in 2002–2003 (5.7%) and 2004–2005 (5.9%).

The highest NEE values measured during the winter period 2003–2004 (F; Tab. 9) are not the result of especially high winter respiration rates (RESPw, Tab. 10), but are rather the result of intermediate respiration rates over the whole winter in combination with relatively low assimilation rates (GPPw; Tab. 10). This due to the fact that the number of growing degree days was lowest in 2003–2004 (Dgdd = 18 days; Tab. 9). The share of ecosystem respiration measured during winter (RESPw; Tab. 10) to the total annual respiration (RESPa; Tab. 10) varied between 28% (in 2002–2003) and 20% (in 2004–2005).

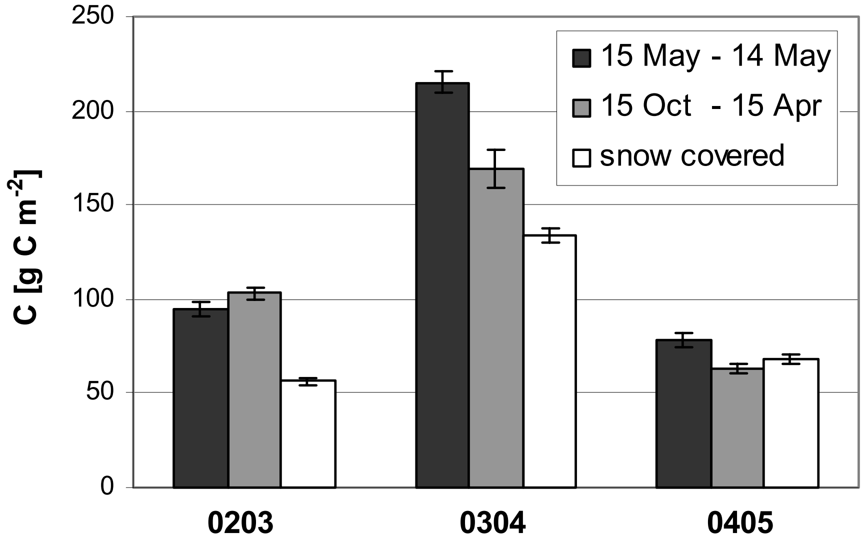

Fig. 30: NEE budgets (g C m^{-2}) at Rigi Seebodenalp, where a positive sign means a net loss. The annual NEE budget (calculated from 15 May until 14 May in the following year), the over-winter NEE budgets (calculated from 15 October until 15 April) and the NEE budget during snow covered periods were calculated for the three measurement years 2002–2003, 2003–2004 and 2004–2005.

There was some photosynthetic activity during snow covered days: GPPs (Tab. 10) < 0. The assimilation was measured towards the end of the snow period were both snow-free and snow-covered patches were found in the footprint of the EC tower.

5.3.3 Soil temperature under snow cover

In winter, air temperatures regularly dropped below 0 °C. However, the soil at Seebodenalp never froze down to –5 cm, where our near-surface soil temperature sensor was located, not even during snow free periods. As an example, air, snow, and soil temperatures for a period with 40 cm snow cover in February–March 2005 was analyzed in detail (Fig. 31). Air temperatures at 200 cm height were constantly below freezing. 10 cm above the snow (at 50 cm height) and in the snow pack (10 and 5 cm) temperatures were less negative and their peak values were slightly lagging air temperature.

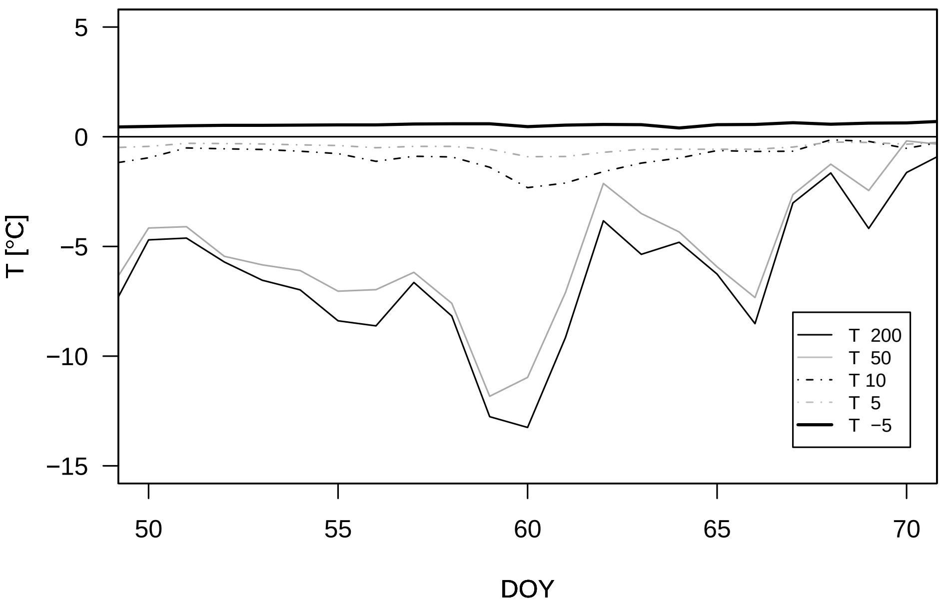

Fig. 31: Air (200, 50 cm), snow (10, 5 cm) and soil temperatures (–5 cm) for a period with 40 cm snow cover in February–March 2005 (days 50–70). Temperature fluctuations were damped from the free atmosphere over the snow towards the soil. The 0 °C-line is added to the graph.

As expected, temperature fluctuations in the air were strongly damped by the snow cover and were thus smallest near the soil. Below the snow cover, soil temperatures increased with depth (Fig. 32). Since we only measured the top 50 cm of the soil, this just indicates that heat which was stored in the ground is released in winter to keep snow basal temperature close to 0 °C under the absence of permafrost (Haeberli, 1973). The temperature of the uppermost soil layer (–5 cm) under the snow cover fluctuated between 0 and 2 °C, but never dropped below 0 °C, as is expected in mountainous areas under absence of permafrost. The temperature of this soil layer under snow pack (TS5s; Tab. 9) was higher in January-February 2004 than during the same months in winter periods 2002–2003 and 2004–2005. Microbial activity increases exponentially with warmer soil temperatures (Mikan *et al.*, 2002). The higher respiration rates under snow cover (Fs; Tab. 9) in 2003–2004 compared to the other two winters can thus be interpreted as the result of the higher soil temperatures (TS5s; Tab. 9). Deeper in the soil, the temperature was not significantly different between spring 2003 and spring 2004 due to cooling of this layer because of the constant soil heat flux towards the upper soil layer.

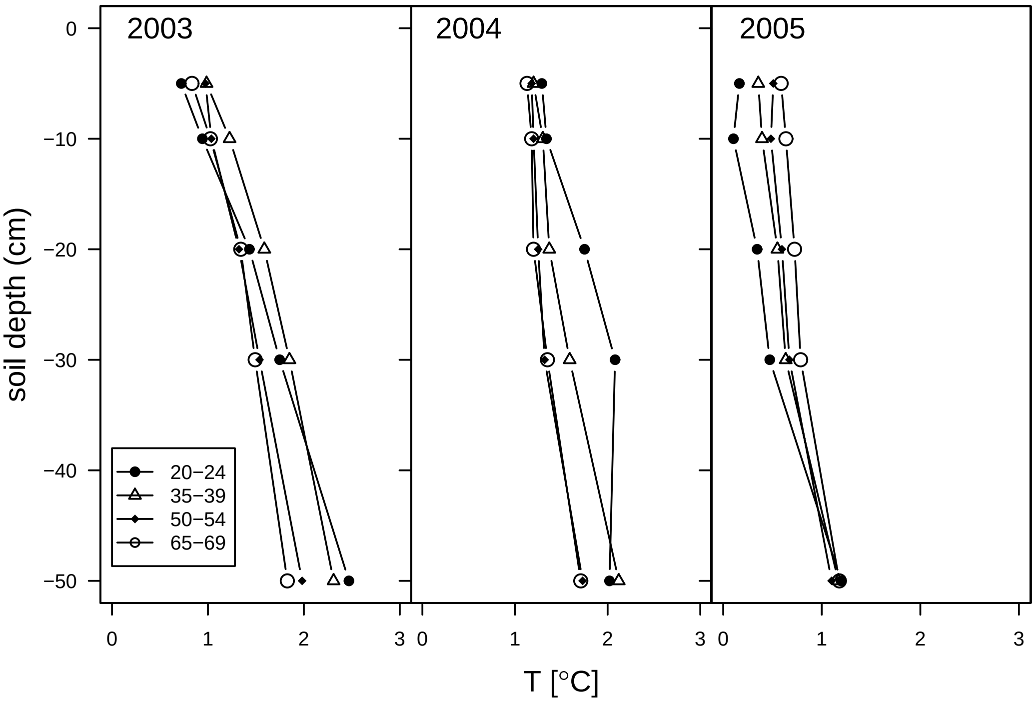

Fig. 32: Soil temperature profiles (°C) for four time intervals in spring 2002, 2003 and 2004. The four intervals are snow covered periods within the period 20 January (day 20) – 10 March (day 69). Before day 20, there was at least 5 days of continuous snow cover in all winters.

Summer 2003 experienced extremely hot temperatures (Schär *et al.*, 2003; Luterbacher *et al.,* 2004; Ciais *et al.* 2005). These high air temperatures in summer 2003 also translated into higher summer soil temperatures (Fig. 33). However, the influence of this extreme event did not persist until the winter period following the hot summer. A cold snap in autumn 2003 (2 October; day 273) reduced soil temperatures considerably, resulting in lower mean values in autumn 2003 than in 2002 and 2004. Thus, the high soil temperatures from summer 2003 did not last until winter and were thus not directly responsible for the relatively high CO_2 losses measured during winter 2003–2004. The high temperature of the uppermost soil layer under snow cover (TS5s in Tab. 9) observed in winter 2004 is more likely the result of the warm air temperatures occurring just before snow fall than the seasonal lag in heat losses from the ground (Fig. 33).

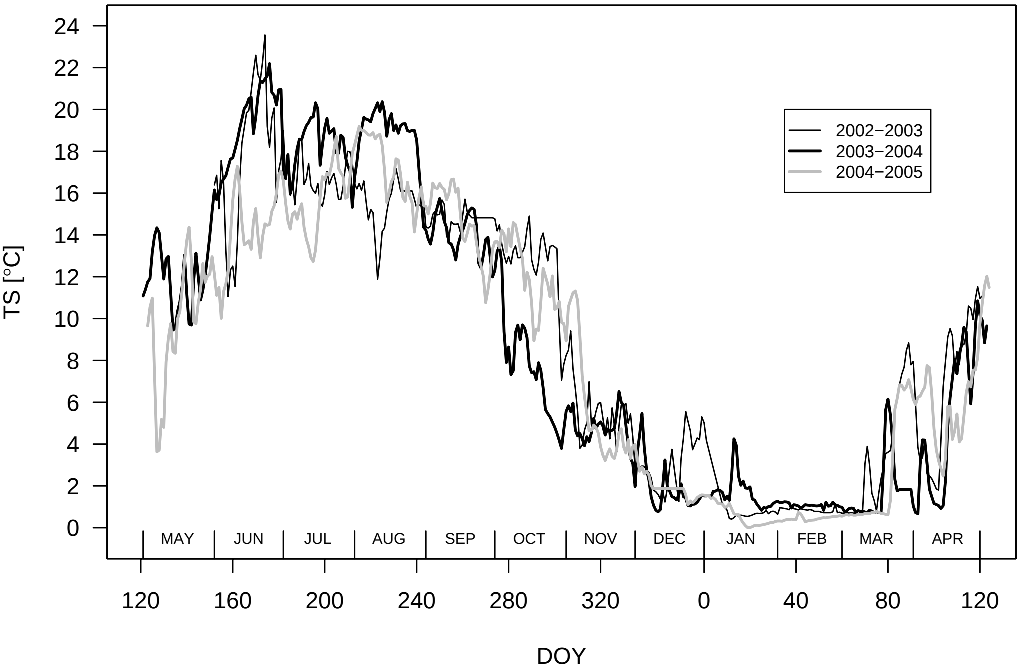

Fig. 33: Evolution of soil temperature TS at 30 cm below ground for the measurement years 2002–2003, 2003–2004 and 2004–2005. Note the extreme hot soil temperature levels in summer and the relatively early drop of TS in winter during the measurement year 2003–2004.

5.3.4 CO_2 fluxes from the snow cover and after snow melt

Since the temperature of the uppermost soil layer under snow cover fluctuated in the range 0 to 2 °C, we expected a rather constant CO_2 efflux from snow cover. However, considerable fluctuations in respiratory losses were measured over snow pack (Fig. 29). We investigated the relationship between respiratory losses from snow covered grassland and meteorological variables such as snow depth, rate of snow melt, wind speed (Fig. 34), soil temperature, and air pressure (not shown). None of these variables explained more than 10% of the total variance in CO_2 efflux during periods with snow cover.

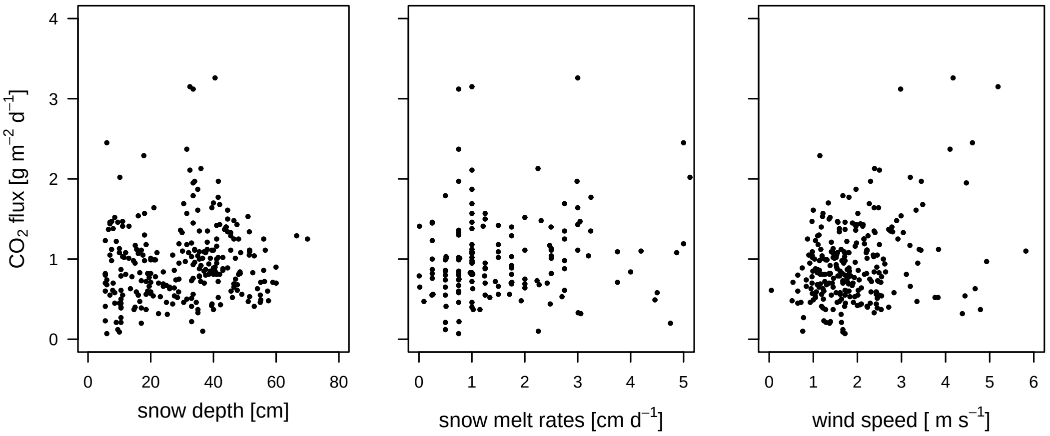

Fig. 34: Relationship between net daily CO_2 efflux (g C m^2 d^{-1}) from snow pack and snow depth, snow melt rates, and wind speed for snow covered days at Seebodenalp. None of the relationships explained more than 10% of the variance and we could thus not determine any statistically significant relationship between CO_2 efflux and the micrometeorological variables.

A more significant relationship was however found between snow melt rates and CO_2 fluxes whenever a snow cover had lasted for at least 7 days (Fig. 35).

The diurnal patterns of the CO_2 flux (NEE) and soil temperature (TS) are best illustrated by the inner 50% range of values (the distance of the 75%-quantile from the 25%-quantile), which we denote as ΔNEE and ΔTS, respectively. As long as the vegetation is inactive, we expect ΔNEE to be close to zero, thus no relevant diurnal course is expected. Similarly, ΔTS is expected to be close to zero whenever the ground is snow covered or frozen. This is due to the fact that the phase change when melting or freezing water at temperatures close to 0°C consumes or produces heat, thereby reducing the daily amplitude of soil temperature fluctuations. To separate conditions with inactive vegetation from such where it should be active, we used threshold values of 1.5 µmol CO_2 m^{-2} s^{-1} for ΔNEE and 0.5 °C for ΔTS.

As soon as the snow pack had disappeared, TS immediately increased and a diurnal pattern (ΔTS > 0.5 °C) was observed (Fig. 35). The increase in TS was correlated with the increase in photosynthetic activity, which is reflected in ΔNEE and in a decrease in GPP The start of assimilation (GPP < 0) and of the measured diurnal pattern of NEE did, however, not coincide precisely with the time of snow melt or the start of a measurable diurnal cycle in soil temperature. In 2004, photosynthetic activity was even observed 3 days before the diurnal pattern in soil temperature was detectable, which can be explained by the spatial heterogeneity of the snow pack during the period of snow melt: the footprint of the EC tower comprised an assemblage of snow covered patches and areas with green vegetation, while our temperature profile was only measured at one location close to the EC tower.

In spring 2004, a clear increase in soil temperature was observed after snow had disappeared, and a net CO_2 uptake (NEE < 0) was measured from the very first day after snow melt. In spring 2003, the increase in soil temperature after snow melt was slower and therefore ΔTS also remained at a modest level. In 2003, it took 19 days from the time when snow had melted near the tower until a daily mean uptake was registered. Immediately after snow melt, changes in mean daily NEE were less pronounced than changes in ΔTS , because assimilation rates balanced and later exceeded respiration rates in the beginning of the growing season.

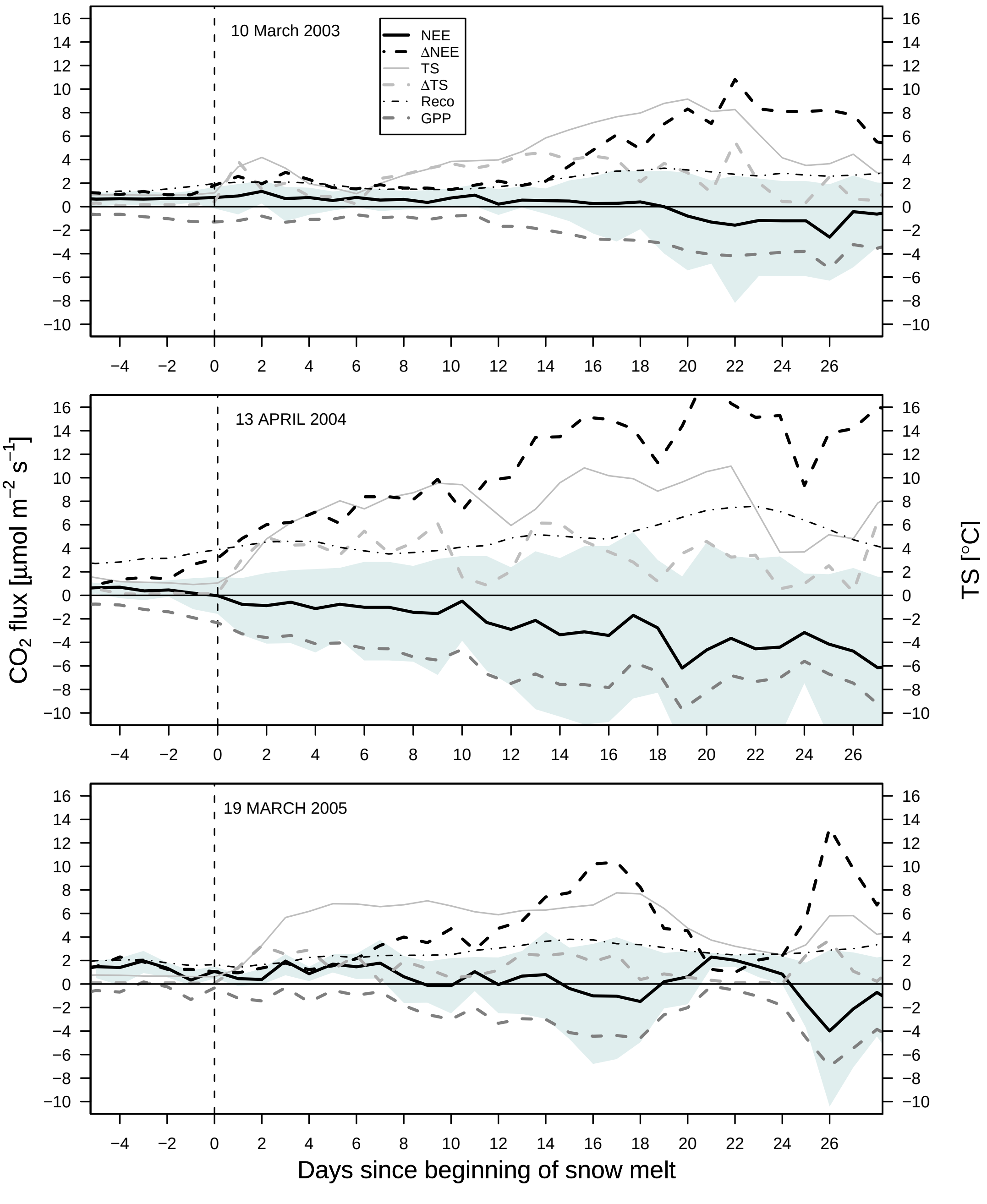

Fig. 35: Daily means of net CO_2 flux (NEE; µmol CO_2 m^{-2} s^{-1}), ecosystem respiration (Reco), gross primary production (GPP) and soil temperature (TS; °C) at the beginning of spring (complete snow melt at day=0) for the three winter periods 2002–

2003, 2003–2004, and 2004–2005. The diurnal patterns of NEE and TS are expressed by ΔNEE and ΔTS and were calculated by subtracting the 25-quantile from the 75-quantile of the respective variable. The grey shaded area covers the range between the 25 and 75% quantiles of NEE.

5.3.5 Photosynthetic activity in spring

The photosynthetic rates in spring after day 104 (i.e. day of snow melt in 2004) were similar during all three years (Fig. 36). After maximum carbon losses in spring and before the first grass cut at the beginning of June, the slopes of the integrated assimilation fluxes (GPP) had similar steepness, indicating that the increment in net daily CO_2 flux is rather constant for the three years. From this we conclude that there were no big differences in nutrient availability or in micrometeorological growth conditions during the early growing season, although the timing of the beginning of the growing season was different, which is seen in the time shift of the three cumulative GPP curves. The interannual variation in the CO_2 budget integrated until 15 April (day 105) was huge. By 15 April 2003, 57 ± 6 g C m^{-2} were lost since 1 January, in 2005 this number was 65 ± 6 g C m^{-2}, and by 15 April 2004 114 ± 6 g C m^{-2} were lost from the ecosystem.

The cumulative net CO_2 curves (NEE) culminate later than the timing of snow melt, because at the beginning of the growing season, respiration losses still exceed photosynthetic uptake rates.

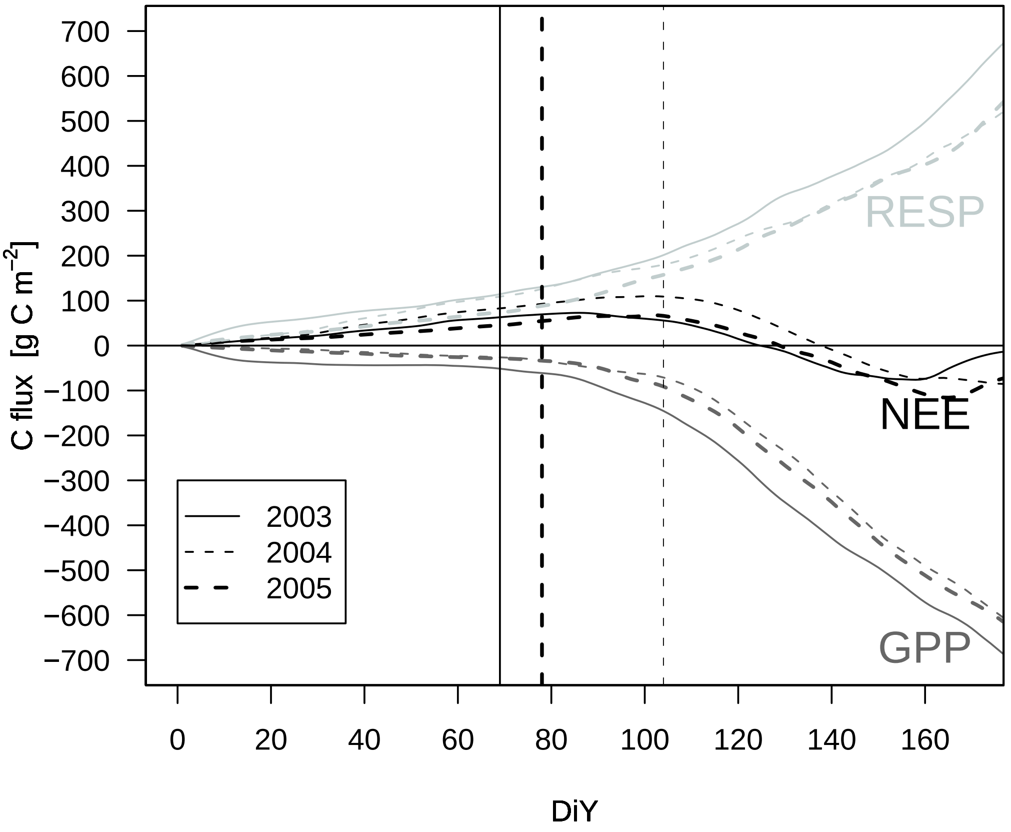

Fig. 36: Cumulative carbon fluxes of net CO_2 flux (NEE), of the respiration (RESP) and the assimilation (GPP) fluxes at Rigi Seebodenalp in spring 2003, 2004, 2005. CO_2 integrals were calculated by integrating the CO_2 flux data from 1 January (day=1). A positive sign means a net C loss. The vertical lines indicate the timing of the snow melt for each year.

5.4 Discussion

During the winter, Seebodenalp was a net sink of CO_2 during all three measurement years (Tab. 10, Fig. 30).Winter respiration (RESPw; Tab. 10) and respiration measured over snow pack (RESPs; Tab. 10) contributed substantially (23.3 ± 2.4% and 6.0 ± 0.3% respectively) to the annual respiration losses at Seebodenalp. The mean daily CO_2 fluxes measured during this winter period strongly depends on the micrometeorological situation.

As noted earlier, we had to choose a special definition for "winter" to match the true pattern of snow cover as good as possible. In this paper, we defined the winter season as the period from 15 October until 15 April. If we were to use another definition for winter, e.g. only the calendar months December, January, and February, then winter CO_2 losses would only account for 11.5%, 9.5%, and 6.5% of the respective annual CO_2 budgets of the three years (May-April). This would lead to a serious underestimation of the importance of winter conditions (which are characterized by snow cover at our location) in the annual balance. Irrespective of the definition of winter, we found that the snow and frost-free days at both far ends of the cold season can contribute considerably to the high interannual variability of mean daily fluxes and thus of the winter or growing season carbon budget.

Other studies also had to adopt the definition of winter to their locality. Therefore, a comparison with literature values not only depends on ecosystem properties, but also on the length of the winter season and micrometeorological conditions. Comparable estimates of winter respiratory losses fluctuate between 3 and 50% of the annual respiratory CO_2 losses for northern wetlands, arctic tundra (Oechel *et al*., 1997; Hobbie *et al*., 2000; Panikov and Dedysh, 2000; Lafleur *et al*., 2001, Hirano, 2005) and 10-20% in alpine and subalpine ecosystems (Mast *et al*., 1998; Wickland *et al*., 2001).

A special assessment of how the definition of winter influences these numbers was published by Bubier *et al.* (2002). They demonstrated that the contribution of winter respiration to the total annual respiration varied between 3 and 25%, depending on the winter period definition.

The mean daily winter CO_2 efflux rates measured at Seebodenalp (Tab. 9) are situated in the upper range of available studies on respiration losses from seasonally snow covered non-forest ecosystems. Ham and Knapp (1998) reported average rates of wintertime CO_2 efflux of 0.95 g C m^{-2} d^{-1} measured at a Tallgrass prairie and Volk and Niklaus (2002) detected respiratory losses of 1.2 g C m^{-2} d^{-1}. The high soil organic matter content at Seebodenalp (between 7.2 ± 0.2 % and 15.7 ± 0.9 % by mass) is certainly one of the relevant factors responsible for these high winter CO_2 efflux rates. Average winter CO_2 rates recorded in the Arctic tundra are substantial lower than the ones measured at Seebodenalp which has no permafrost. Values for the Arctic tundra are reported between 0.06 g C m^{-2} d^{-1} (Fahnestock *et al.*, 1999) and 0.18 g C m^{-2} d^{-1} (Bubier *et al.*, 2002). It appears that although Arctic and Alpine vegetation types are often considered to be similar, the presence (Artic) or absence of permafrost (below 2580 m a.s.l. in the Alps; see Luetschg *et al.*; 2004) are distinct differences for winter respiration rates.

Winter CO_2 efflux is largely the result of microbial respiration, which is sensitive to soil temperature and soil moisture availability (Edwards and Cresser, 1992; Schadt *et al.*, 2003). Liquid water which is a prerequisite for cellular activity (Jones *et al.*, 1999; Mikan *et al.*, 2002) was available at Seebodenalp during winter, due to favorable soil temperatures.

The soil at Seebodenalp was never frozen down to –5 cm, neither during snow covered nor during snow free periods. Snow cover effectively decouples soil temperatures from the atmosphere (Brooks *et al.*, 2004) and keeps soils from deep freezing due to insulation (Haeberli, 1973; Hardy *et al.*, 2001; Walker *et al.*, 1999;

Bubier *et al.*, 2002; Shibistova *et al.*, 2002; Swanson *et al.,* 2005). But also during snow-free days with atmospheric frost, the soil at Seebodenalp didn’t freeze except for the topmost centimeters above our uppermost soil temperature sensor. Brooks *et al.* (1997) observed that in alpine tundra organic solutes act to suppress the freezing point in the organic soil horizon. The same observation was already described before by Edwards and Cresser (1992). They found that a solute depression of the freezing point by ion diffusion as soils begin to freeze may result in thawed soil at temperatures below 0 °C, which in combination with the geothermal heat flux due to the absence of permafrost is most likely responsible for the productive environmental conditions that the soil microorganisms experience in winter.

We could not determine any significant relationship between CO_2 efflux from snow pack and the micrometeorological variables soil temperature, snow depth, rate of snow melt, wind speed and air pressure. In the special case of soil temperature the observed range of values under snow pack was just too narrow (0 – 2 °C) to quantify CO_2 flux over snow pack as a function of soil temperature. Several other studies also did not find good correlations between the two variables (Nadelhofer *et al.*, 1991; Sommerfeld *et al.*, 1993; Winston *et al.*, 1997; Schmidt *et al.*, 1999; Suni, 2003), although they were based on much broader soil temperature ranges. For tussock-tundra soils, Schimel *et al.* (1996) even found that there is generally very little response of soil respiration with temperatures below 10 °C. Laboratory studies (Mikan *et al.*; 2002) however indicate that there should be a strong relationship between soil temperatures and respiration even in frozen soils down to –10 °C. Our data do not disprove this finding, but they clearly show that the observed range in soil temperatures under natural conditions do not allow to establish such a relationship.

That there was also no clear effect of snow depth on CO_2 efflux is in agreement with the findings by Jones *et al.* (1999). Other authors (e.g. Welker *et al.*, 2000; Gilmanov *et al.*, 2004), however determined a positive effect of snow depth on CO_2 efflux.

Gilmanov *et al.* (2004), summarizes two opposing effects of snow cover on CO_2 exchange found in the literature: (1) depending on snow thickness and snow properties, snow cover can act as an almost impermeable coat and can thus significantly decrease the efflux of CO_2 to the atmosphere (Kelley *et al.*, 1968); but (2) a thicker snow cover insulates the soil better and can create a more favorable environment for below-ground respiration during winter (Welker *et al.,* 2000).

During the snow covered periods 2003–2004 higher carbon losses were measured compared to the other two winter periods (Tab. 9, Tab. 10). The higher temperatures of the topmost soil (TS5s; Tab. 9) are partially responsible for these differences. Another possible explanation for the high carbon losses measured during the winter following the summer heat wave 2003 could be the flush of decomposition occurring after rewetting a dry soil (Franzluebbers *et al.*, 2000). During the hot summer 2003 there were some periods where the vegetation at Seebodenalp suffered from water shortage. Due to water stress, a part of the soil microbial biomass and the roots died and this material is respired when the soil is rewetted. The process of drying and rewetting the soil generally results in an increment of the amount of available substrate which forms the feeding basis for microbial respiration.

We could not detected the CO_2 flush following snow melt (Fig. 35, Fig. 36) from the melting snow pack nor from the thawing of the soil, which is different from what was described in literature (e.g. Skogland *et al.*, 1988; Panikov and Dedysh, 2000; Priemé and Christensen, 2001; Bubier *et al.*, 2002). At Seebodenalp, there were several snow-melting events during the winter periods (Fig. 29) and the soil was never frozen and thus no freezing-thawing cycles were observed. From this we conclude that we have a unique dataset that illustrates how environmental conditions in the Alps different from published knowledge with respect to winter CO_2 effluxes.

5.5 Conclusions

Substantial amounts of CO_2 losses were observed at the sub-alpine Swiss CARBOMONT site Seebodenalp during three winter periods (integrated from 15 October until 15 April). Total winter respiration and respiration from snow pack contributed 23.3 ± 2.4% and 6.0 ± 0.3%, respectively, to the annual respiration losses at Seebodenalp. These winter carbon losses account for an important share in the annual CO_2 budgets, which emphasizes the importance of quantifying CO_2 fluxes outside the growing season.

Mean daily CO_2 fluxes in winter ranged from a net uptake to a net loss. The variability in winter fluxes was strongly determined by the CO_2 losses from snow pack, and by the micrometeorological conditions whenever there was no snow. Especially the days at the beginning and the end of the cold season had a strong influence on the seasonal budget, which therefore should be included in the definition of "winter" at this and comparable locations. The highest daily mean losses were recorded in winter 2003–2004. This is the combined result of: (1) the high respiration from snow cover ($Fs = 4.33 \pm 0.18$ g C m^{-2} d^{-1}) measured during this winter; (2) the long persistence of snow cover (111 days); and (3) the relatively low photosynthetic activity ($GPPw = 184 \pm 3$ g C m^{-2}). Although this winter which followed the European summer heat wave 2003 had twice the respiration of the two other winters, we did not find sufficient evidence to attribute this to the special conditions observed during the heat wave, which may be result of the functional difference of grassland ecosystems as compared to forest ecosystems (Ciais *et al.* 2005), a fact which however needs further scientific attention. CO_2 exchange over grasslands in Europe has not been investigated over same long duration as the forest ecosystems analysed by Ciais *et al.* (2005), and therefore it would be too early to generalize our findings to other grasslands in Europe.

With reference to climatic changes it is noteworthy that the grassland ecosystem at Seebodenalp was ready to assimilate even during the winter whenever the snow cover had disappeared. Thus, our data suggest that any changes in duration of the winter snow covers are expected to have a strong impact on the annual CO_2 budget, even if near-surface temperatures do not change considerably.

5.6 Tables

Tab. 9: Daily averages measured at Seebodenalp during three winter periods (183 days) from 15 October (day 288) until 15 April (day 105) in 2002-2003, 2003-2004 and 2004-2005 of soil temperature under snow cover at 5 and 30 cm depth for January-March (TS5s, TS30s), CO_2 flux (F), CO_2 flux over snow pack (Fs), CO_2 flux without snow cover when GPP at noon ≥ -0.5 g C m^{-2} (Fnsna) and CO_2 flux without snow cover when GPP at noon < -0.5 g C m^{-2} (Fnsa). Ds is the number of days with snow coverage within the winter period; Dts is the number of total snow covered days for the three measurement years, Df and Dl are the days on which first (autumn) and last (spring) snow, respectively, occurred. Dgdd is the number of growing degree days (mean air temperature > 5 °C).

Period	TS5s [°C]	TS30s [°C]	F [g C m^{-2} d^{-1}]	Fs [g C m^{-2} d^{-1}]	Fnsna [g C m^{-2} d^{-1}]	Fnsa [g C m^{-2} d^{-1}]	Ds [days]	Dts [days]	Df [day]	Dl [day]	Dgdd [days]
2002-2003	0.88 ± 0.02	1.65 ± 0.08	2.09 ± 0.21	3.03 ± 0.31	3.32 ± 0.22	1.35 ± 0.22	73	88	266	102	26
2003-2004	1.20 ± 0.07	1.61 ± 0.09	3.39 ± 0.19	4.33 ± 0.18	3.22 ± 0.20	1.80 ± 0.22	111	125	278	130	18
2004-2005	0.41 ± 0.02	0.74 ± 0.05	1.27 ± 0.25	2.63 ± 0.17	1.75 ± 0.24	–0.78 ± 0.32	93	116	313	104	58

Tab. 10: CO_2 Budgets [g C m^{-2}] for the three years of measurements at Seebodenalp of net ecosystem exchange of CO_2 (NEE), of ecosystem respiration (RESP) and of gross primary production (GPP). The total annual budgets (suffix a), the budgets of CO_2 fluxes measured during winter from 15 October until 15 April (suffix w) and the budgets during snow cover (suffix s) are listed. RESPw3 is the respiration budget for the three months winter period from 1 December until 28 February.

Year	NEEa	NEEw	NEEs	RESPa	RESPw	RESPs	GPPa	GPPw	GPPs	RESPw3
2002-2003	95 ± 4	103 ± 3	56 ± 2	1337 ± 19	374 ± 7	76 ± 3	–1242 ± 15	–274 ± 5	–15 ± 1	154 ± 5
2003-2004	215 ± 6	169 ± 4	133 ± 4	1602 ± 24	347 ± 7	140 ± 4	–1395 ± 18	–184 ± 3	–11 ± 2	150 ± 6
2004-2005	78 ± 5	63 ± 2	68 ± 2	1331 ± 20	269 ± 5	79 ± 2	–1256 ± 16	–208 ± 3	–13 ± 1	88 ± 4

6 Three years of CO_2 flux measurements at a grassland in the Swiss Alps: assessment of the impact of past and present land-management

In preparation

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6.1 Introduction

In this paper we compare the carbon fluxes and budgets of three consecutive years (May 2002-May 2005) of an alpine grassland. First, the climatology is analyzed for each year and compared with the 10 years mean (1992-2001). This climatological description is then used to assess the representativeness of the measurement years. Second, the carbon fluxes (NEE) are discussed with a special focus on the influence of land-management and microclimate. The NEE fluxes are then partitioned into its components, respiration (RE) and assimilation (GPP). Further, to estimate the influence of current land-management during the vegetation periods, the measurements are compared with model simulations from the biosphere model SiB25. Finally, to assess the impact of historic land-management, the measured annual carbon budgets are related to the laboratory estimates of the annual CO_2 losses from the wetland site, which are the result of the draining of the site.

6.2 Site description

A detailed description of the site can be found in Rogiers *et al.* (2005) and in Chapter 2.

Of special interest for this paper is the draining history of Seebodenalp because it has had a profound influence on the development of the soil, of the vegetation, current land-management practices and consequently, also on the CO_2 exchange of the site. The current terrain is the bottom of a former but vanished lake formed during the last glaciation (Vogel and Hantke, 1989) with a thick sedge peat layer on top. The main meliorations of peatlands in Switzerland were carried out in two phases from 1885 to 1949 (Eidgenössisches Meliorationsamt Bern, 1954). Cultivation of Seebodenalp started in 1886 with the digging of the first draining channels through the site (Wyrsch, 1988). During the Second World War the drainage was intensified. The lowest area of Seebodenalp is still the wettest area and this part is statutory protected as a wetland (Fig. 37). In this part, the peat layer is still thick, whereas the other fields at Seebodenalp degraded to a normal organic soil. Müller (2004) classified the soils in the wetland as a folic Histosol (drystic) and the other soils as stagnic Cambisols according to WRB (1998).

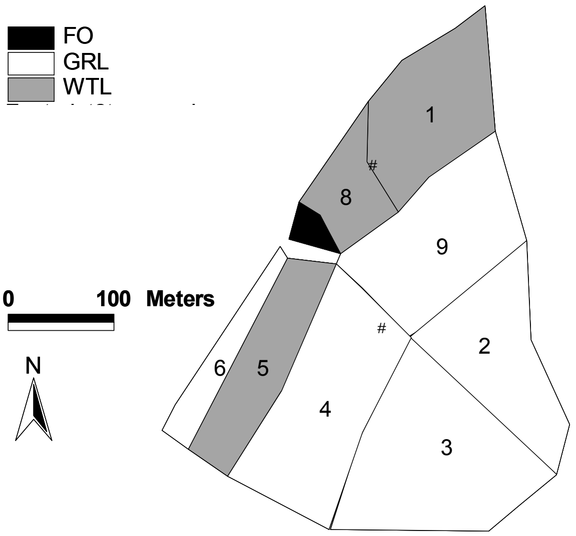

Fig. 37: A detailed map of the Seebodenalp shows a small forest (FO), the grassland (GRL) and the wetland (WTL) area. The EC towers are marked with dots.

6.3 Instrumentation and methods

CO_2 and water vapor fluxes were measured with the eddy-covariance technique and calculated as described in Rogiers *et al.* (2005) and in Chapter 2. There, also a detailed description of the filtering and gapfilling procedure of the eddy covariance data can be found as well as a list of the instrumentation of the micrometeorological measurements. Additional micrometeorological data for the period January 1992 to June 2005 was provided by the National Air Pollution Monitoring Network (NABEL) data. The station is located about 1000 m NNE of the Carbomont flux site. The years 1992-2001 were used as the reference period to which the years 2002-2005 can be compared. Precipitation data was only available for 1994-2005.

For plant growth, growing degree days (GDDs) are a useful measure for the amount of heat accumulated over some time interval. Growing degree days were calculated for a threshold temperature of 5 °C, with each degree of positive difference between the daily mean temperature and the threshold adding one degree day to the sum (Jones, 1992).

Net ecosystem exchange (NEE) was measured by the eddy covariance tower and a continuous dataset containing quality-controlled measurements and gapfilled data was constructed. During the night, measured NEE equals ecosystem respiration. Missing night time measurements and daytime ecosystem respiration was modeled from a 3-days relationship between nighttime NEE and shallow soil temperature (5 cm depth). Ecosystem respiration (RE) was than estimated from direct measurements and modeled data. Gross primary production (GPP) was calculated for each 30-minute interval as the difference between NEE and RE. Whenever the site was snow covered, no photosynthetic activity was possible and GPP was set to zero.

6.4 General climatological assessment

Key meteorological parameters for this study are precipitation, temperature, and growing degree days. Values for the investigated period are given in Table 11 and presented in Fig. 38 and 39.

Both 2002 and 2003 exhibited warmer temperatures than average (7.32 °C; Tab. 11), with 2003 being the warmest year in many places in Central Europe since the beginning of regular measurements (see e.g. Luterbacher *et al.,* 2004; Schär et al., 2004). 2004 was cooler than average. Except for very low temperatures in February, temperature in winter and spring 2005 was close to average.

Precipitation is relevant to plant growth in summer with respect to soil moisture availability. The average annual precipitation amounts to 1327 mm (Tab. 11). The main precipitation season is the summer, with June being the wettest month on average (Fig. 38). The key mechanisms that generate precipitation are frontal and orographic lifting in the winter half year, and convective lifting (thunderstorms) in the summer season. 2002 was the wettest year since 1994, while 2003 was the driest. Rainfall distribution for the year 2002 shows some deviation from the average in that the rainfall surplus occurred in the second half-year. In contrast, 2003 was dry from the beginning, and the water deficit increased monotonically until the end of the year. 2004 started normally with respect to precipitation and accumulated a deficit in the second half-year. 2004 was the third driest year since 1994. The first half of 2005 was also relatively dry.

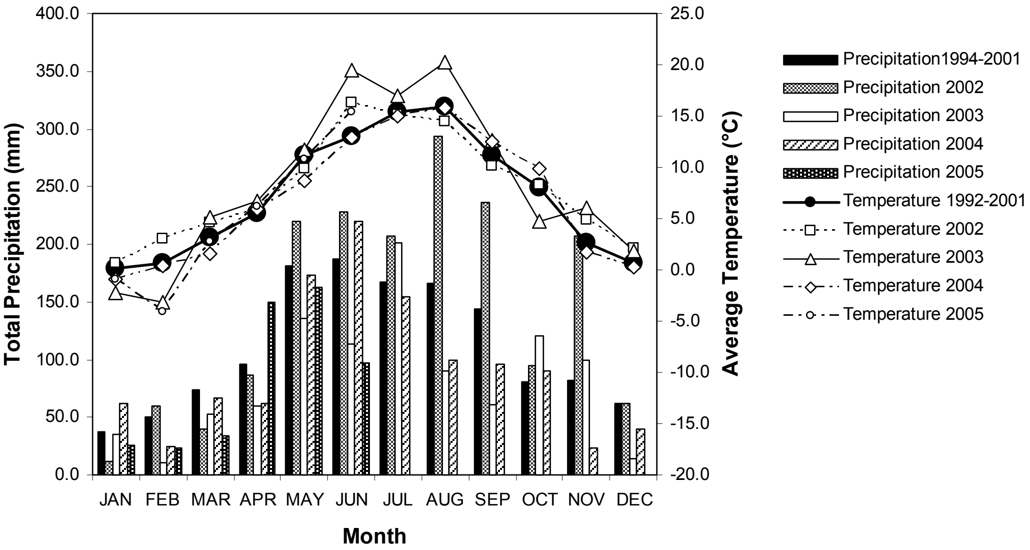

Fig. 38: Monthly average temperatures (symbols and lines) and monthly total precipitation (bars) at Seebodenalp for the years 2002, 2003, 2004 and the first half of 2005 compared to the respective long-term average. Data obtained from the Swiss National Air Quality Monitoring Network (NABEL).

From Fig. 39 it can be seen that although the average value of the growing degree days (GDD) 1992-2001 starts to ascend right on the first days of January, the stronger increase occurs not before day 75 (mid March). The increase relevant for the start of the growing season may begin on day 110 (20 April). Apart from the year 2003, all other curves increase similarly, and 2002 and 2004 reach almost exactly the average value of 1992-2001 (deviations smaller than 5 ‰). This coincidence shows that 2002, 2004 and the first half of 2005 were ordinary years with respect to heat input, but also demonstrates that 2003 was extraordinary. The extreme year of 2003 reaches a value of 1400 GDD 49 days earlier than the mean curve for 1992-2001. The number of days exceeding the threshold temperature of 5 °C was on average 205 days. The year 2002 counted more days with temperatures higher than 5 °C because air temperatures at the beginning of 2003 were rather low.

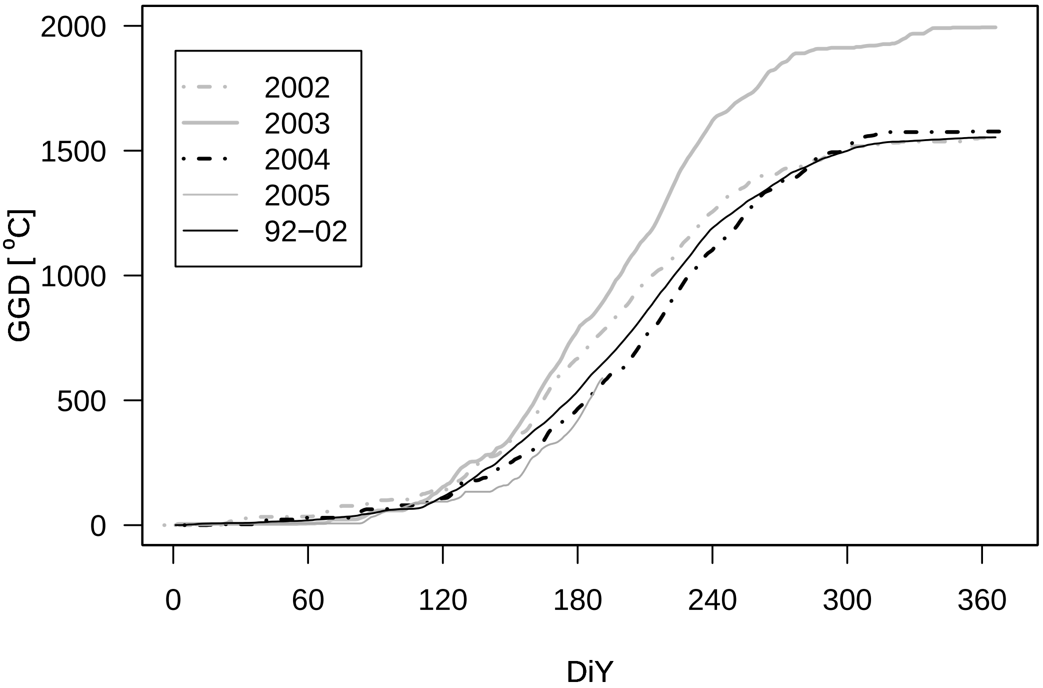

Fig. 39: Cumulative curves of the growing degree days (GGD) for 2002, 2003, 2004 and 2005 compared to the 10-year average. To improve legibility data from 2002 were shifted 5 days forward, data from 2004 5 days backward and data from 2005 10 days backward.

6.5 Results of three years of EC measurements

6.5.1 Data coverage

The data coverage for the measurement period is shown in Fig. 40. Over the whole period, 46% of the time records are covered by original measured EC data. This is rather low compared to the average data coverage of 65 % at the FLUXNET sites (Falge *et al.*, 2001).

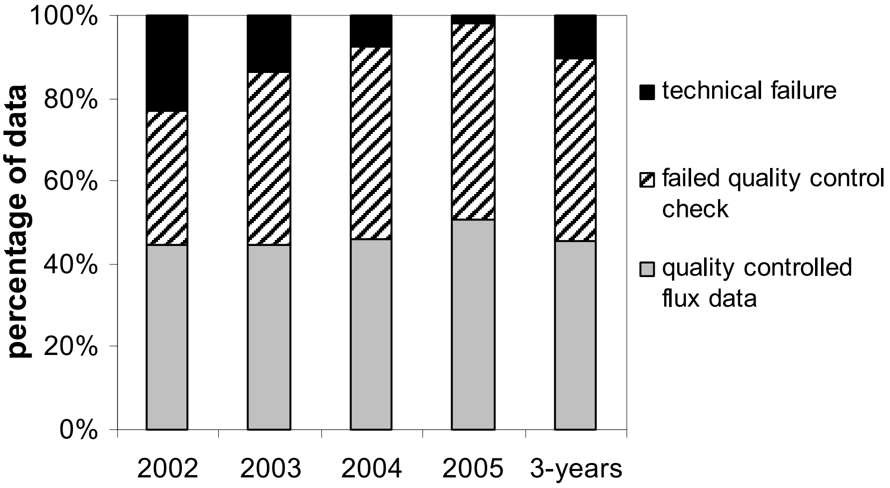

Fig. 40: Data coverage of the EC tower at Seebodenalp for the measurement period May 2002 until April 2005. After gap filling, EC data were available for all time records (=100%), where the share of the measured quality checked data, rejected data and data missing due to system failure is indicated per year.

During 10% of the whole measurement period our system was down due to hardware and software failures, missing or dysfunctional IRGA, power outages, and planned IRGA maintenance and calibration. The share of data gaps due to technical failures decreased from 2002 (23%) to 2005 (2%). Just after EC measurements had started in 2002 there were some periods were the system was not running due to initial technical problems at the beginning of the measurements. In summer 2003 the IRGA was not in use for 12 days due to a lightning strike. In 2004 and 2005 the EC system was rather stable and only calibration or maintenance interventions interrupted the EC measurements.

Data rejection due to failed quality control fluctuated around 45%. Rain or dew negatively affected the performance of the IRGA and around 17% of the rejected data were measured during rainy periods, where most of these data (83%) were measured under good turbulence. Most of the rejected data (70%) were nighttime data. Differences in turbulence between night and day were not found, but rainy events mainly occurred during the night: 13% of the original data were rejected due to night rains and 4% due to daytime rains. In total 56% of the rejected data were measured under low turbulence conditions. Stable, non-turbulent conditions were more frequent in winter (62%) than in summer (38%).

6.5.2 Cumulative fluxes

The cumulative CO_2 and water vapor fluxes were calculated by summing up the gapfilled fluxes from the first day of measurements, i.e. 17 May 2002 until 17 May 2005. The cumulative curves of the CO_2 and water vapor fluxes measured at Seebodenalp between May 2002 (day 137; 17 May) and May 2005 (day 137; 17 May) show a similar pattern in 2002, 2003, 2004 and 2005 (Fig. 41).

In early spring, the cumulative courses of the carbon fluxes reach a plateau meaning that the vegetation period started and assimilation and respiration are in equilibrium. As mentioned in Chapter 5 the cumulative net CO_2 curves culminate later than the timing of snow melt, because at the beginning of the vegetation period, respiration losses still exceed assimilation uptakes. As soon as the assimilative uptake exceeded the respiratory losses, a net carbon uptake was measured.

A direct comparison of the three measurement years from June, the start of land-management at Seebodenalp, is somewhat complicated because of the differences in timing and magnitude in land-management interventions between all years (Tab. 12).

All curves reach maximum uptake rates (i.e. steepness of the cumulative curves) at the beginning of June (around day 150). During the three vegetation periods 2002, 2003 and 2004, the first grass cut at Seebodenalp was executed at the beginning of June. Cutting the grass considerably reduced the leaf area of the vegetation and thus also the assimilative capacity resulting in net carbon losses from the grassland. In 2002 and 2003 the same fields, situated in the daytime footprint, were cut resulting in a similar pattern in the cumulative curves.

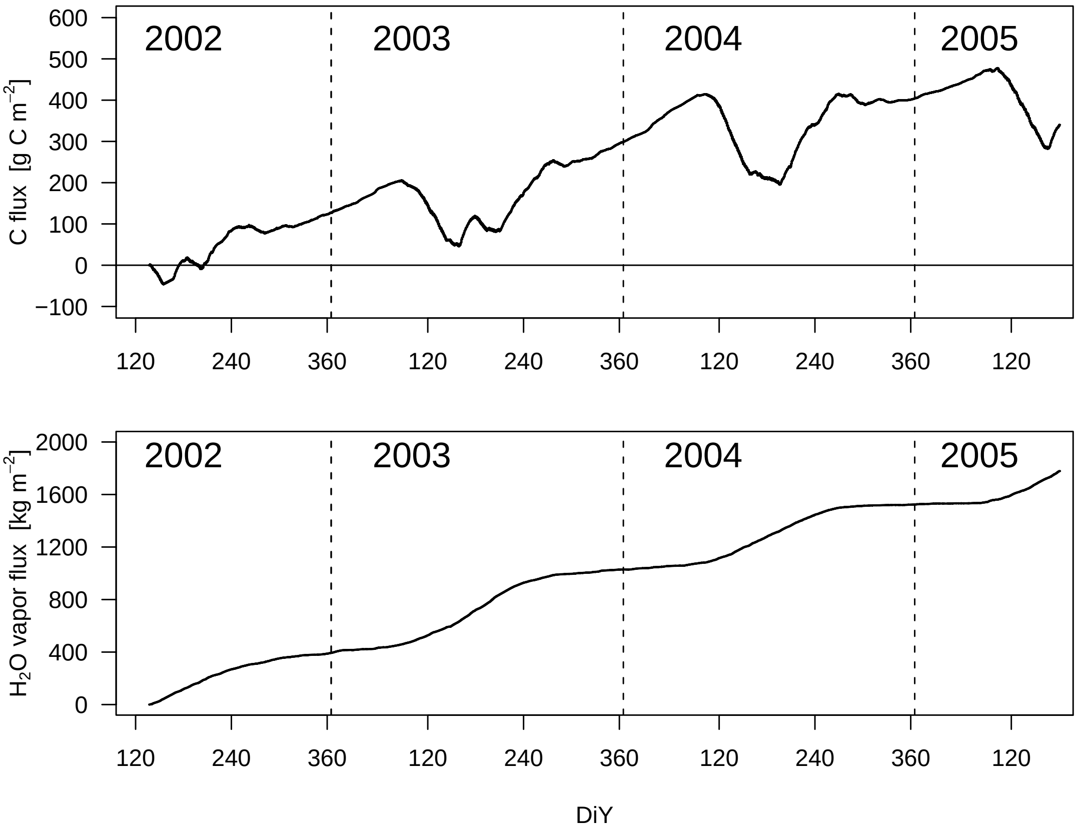

Fig. 41: Cumulative C (upper panel) and water vapor (lower panel) fluxes starting at 17 May 2002 (DiY 137) until 17 May 2005 (DiY 137) based on the gapfilled data of the extensively used grassland at Seebodenalp.

At the breaking point, plants had regenerated and a net carbon uptake was measured again. After the first cut in 2002, it took 23 days until a net CO_2 uptake was measured. In 2003 the vegetation regenerated faster and a net uptake was already registered after 18 days (Fig. 42). In 2004 only half of the fields lying in the daytime footprint were cut. Therefore, there is only a reduction in the steepness of the cumulative courses visible (reduced sink strength compared to the end of May 2004), but not a net carbon loss.

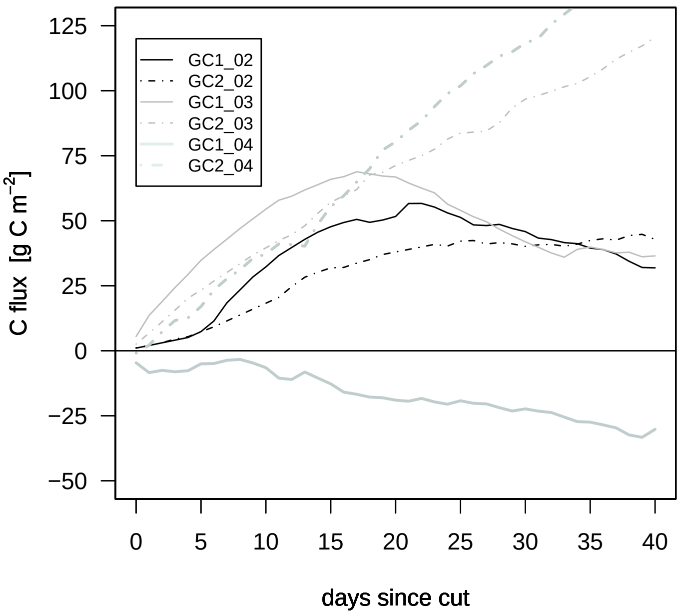

Fig. 42: Cumulative C fluxes after the grass cuts (day = 0). After the first grass cut (GC1) in 2002 and 2003 a net CO_2 uptake was reached after 23 respectively 18 days. In 2004, the ecosystem was still a net sink of carbon. After the second grass cuts (GC2) only carbon losses were measured.

The second grass cut in mid summer (Tab. 12) changed the direction of the curves again and after that, only carbon losses were measured (Fig. 41 and 42). Additional interventions like cow grazing in the daytime footprint also contributed to the reduction in assimilation and thus in the persistence of losing carbon from the ecosystem.

Carbon losses subside towards the end of September. At that time, the heat input into the grassland ecosystem is already strongly reduced compared to the months before (Fig. 39). Lower air temperatures result in lower soil temperatures and thus in smaller respiration rates.

The CO_2 exchange at Seebodenalp during the cold season from 15 October until 15 April is discussed in detail in Chapter 5. Briefly, the highest carbon losses were recorded from snow covered grassland in winter 2003-2004. CO_2 efflux from snow pack was similar in winter 2002-2003 and winter 2004-2005. The periods at the shoulder of winter 2004-2005 were characterized by relatively mild temperatures such that the vegetation was photosynthetically active and quite a few days with a net CO_2 uptake were registered. Therefore, carbon losses during winter 2004-2005 were substantially smaller compared to the other years.

The carbon budgets for the measurement years 2002-2003, 2003-2004 and 2004-2005, calculated from 17 May – 17 May have shown that the site is a net source of carbon. In 2002-2003 95 ± 4 g C m^{-2}, in 2003-2004 215 ± 6 g C m^{-2} and in 2004-2005 78 ± 5 g C m^{-2} was lost from the ecosystem.

In contrast to the cumulative CO_2 fluxes, the management interventions during the different vegetation periods were not detectable in the total measured evapotranspiration (Fig. 41, lower panel).

6.5.3 Partitioning NEE in RE and GEP

The measured CO_2 flux or NEE was partitioned into ecosystem respiration (RE) and gross primary production (GPP) (Fig. 43).

During snow cover, there was no photosynthetic activity (GPP=0) and substantial respiration losses from microbial activity were detected, due to favorable soil temperatures in winter. As soon as snow melted away, plants immediately became photosynthetically active (GPP>0). The grass cuts are visible by a sudden reduction in GPP. After the first cut in 2004, there were cows grazing in the daytime footprint resulting in relatively low values for GPP.

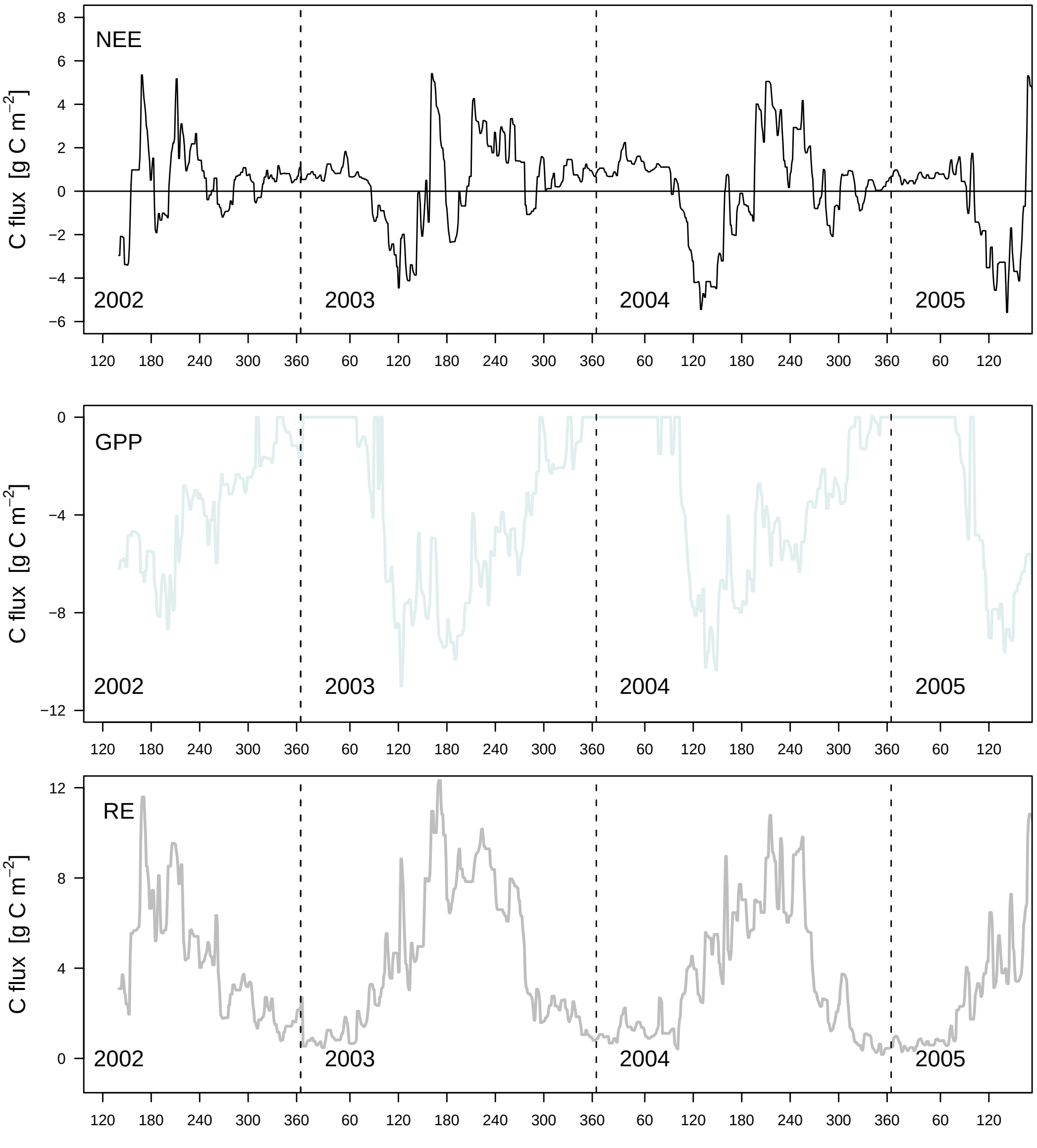

Fig. 43: Net ecosystem exchange (NEE), gross primary production (GPP) and ecosystem respiration (RE) for the three measurement years 2002-2003, 2003-2004 and 2004-2005.

6.5.4 Carbon budget including cows grazing and cuts

To estimate the temporal change in soil organic carbon for a managed grassland, different components have to be considered: (1) the CO_2 exchange between ecosystem and atmosphere measured with the eddy-covariance system, the carbon which is exported by (2) cattle presence and (3) harvesting grass (Fig. 44).

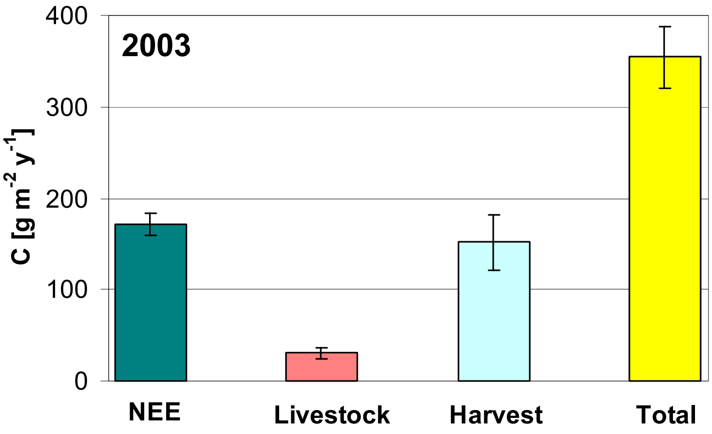

Fig. 44: NEE and the contribution of livestock and harvesting determining the temporal change in soil organic carbon at Seebodenalp for in 2003

With the eddy-covariance system, a net carbon loss was measured (172 ± 12 g C m^{-2}) over the year 2003. The net export of carbon by the cows was calculated to be 31 ± 6 g C m^{-2} and the carbon removed from the ecosystem amounted to 152 ± 30 g C m^{-2}. Thus, for 2003, the temporal change in soil organic carbon is estimated to be 354 ± 13 g C m^{-2}. Thus, the net carbon losses measured with the eddy-covariance tower only reflect half of the real carbon losses from the site.

6.6 Annual CO_2 emissions due to historical land-management

Relatively high carbon losses were measured with the eddy covariance system at Seebodenalp. In order to evaluate the reliability of these results, the measurements are compared with the results of a laboratory method by which the annual CO_2 emissions from the wetland since draining can be estimated. In this section, only preliminary results are presented because some additional calculations are needed for a correct interpretation of the data.

6.6.1 Method

Carbon content of the site before draining was estimated by comparing two laboratory techniques, namely the loss-on-ignition method with the dry combustion method. A rough estimate of net mean annual CO_2 emission can only be made under the following assumptions: (1) ash content (mass ash / mass dry peat) has been the same at all depths before drainage; (2) the peat surface started to oxidize after drainage and is continuing to do so; (3) oxidized C is mainly lost in form of CO_2, directly from the surface of the site; (4) ash from oxidized peat remains on site and accumulates in the surface layer and (5) ash content at greater depth is still the same today as before drainage.

Four replicate cores were sampled near the centre of field 8 (Fig. 37) within a radius of 3 m at the beginning of May 2005. Samples were taken with a 5.4 cm diameter corer with internal plastic liner (Giddings Machine Company, Windsor, Colorado, USA) to a depth between 50 and 60 cm. Compaction was corrected for, assuming linear compaction with depth. Cores were cut into sections corresponding to un-compacted 3 cm depth intervals. These were dried at 40^{o} C for 96 h. Dry weight was determined and bulk density calculated. For determining ash content, complete samples were pulverized in a wolfram mill and sub-samples of around 3 g were

combusted at 600 °C over night. During the first few hours, oven temperature was lower (400-450 °C) to avoid explosive behavior during the process.
Emissions of CO_2 were then estimated from the mass of ash in the surface layer exceeding background concentrations and the proportion of C in the material that has vanished, leaving behind this excess ash. The proportion of C in vanished material was assumed to be the same as the proportion of C in material subjected to the loss-on-ignition method for organic C determination in peat samples (0.52; Bhatti and Bauer, 2002).

Finally, by scaling this result with the relative contribution of the wetland fields to the EC measurements, the contribution of historical land management (i.e. draining) to the CO_2 exchange can be estimated.

6.6.2 Results

A soil pit and coring on field 8 indicated a peat depth of over 1.5 m. At a depth of around 20 cm, peat was decomposed, crumbly, with no visible structure of the original plant material left and with a dark brownish-black color. Below, un-decomposed plant material with lighter brownish color was found. This material was homogenous in structure and appeared from about 20 cm depth to about 1.5 m. No trace of a mineral phase was found. It can be assumed that the top 1.5 m at this site is ombrogenic peat, a Histosol that has received only atmospheric inputs.

Mean dry bulk density (Fig. 45, left panel) was around 0.16 g cm^{-3} at 10 to 20 cm depth and only around half that value below 27 cm (Fig. 45, right panel). Mean ash contents decreased steadily from 13.3 % at the surface to 3.4 % at 27 cm depth. Below 27 cm depth, ash contents remained almost constant with mean values around 2.1 %. Thus, ash contents below 27 cm were considered background values representative for ash contents in the entire profile before drainage and subsequent oxidation of the surface layers. Accumulation of excess ash in the upper 27 cm was calculated individually for each of the four cores and so was total C loss since drainage.

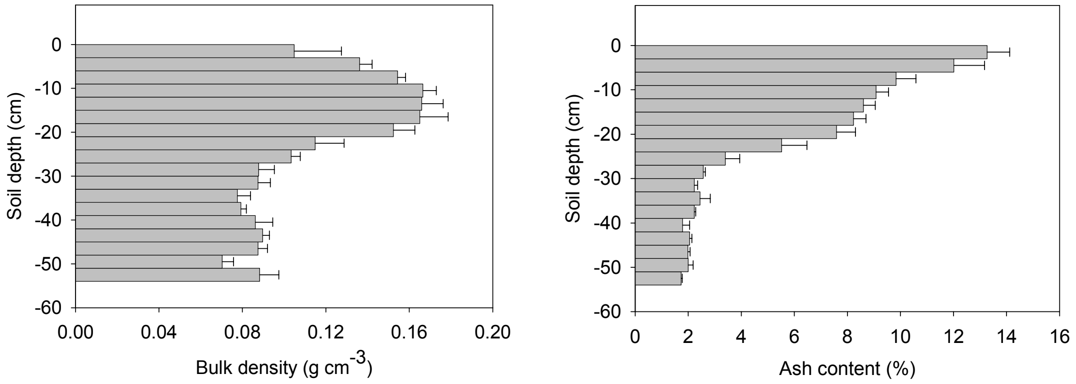

Fig. 45: Mean dry bulk density (left panel) of peat and mean ash contents (right panel) in dry material (in percent of mass) from the surface to a depth of 54 cm (n = 4; bars indicate ±1 standard error).

Estimated mean C loss since drainage was 592 ± 48 t C ha^{-1}. First drainage activities for the site were in 1886. Further improvements on drainage were made around 1940. Therefore, a lower and upper estimate for mean annual C loss in form of CO_2 are 5.0 and 9.1 t C ha^{-1} for a cultivation period of 119 years and 65 years, respectively.

In a next step, this result has to be scaled with the relative contribution of the wetland fields to the EC measurements in order to estimate the contribution of historical land management (i.e. draining) to the measured CO_2 exchange.

6.7 Model estimate of impact of current land-management on CO_2 fluxes

The impact of current land-management can be estimated by comparing the eddy-covariance measurements with simulation results from the model SiB2.5. The model

SiB2.5 is a simple Biosphere Model (Sellers *et al.*, 1996) including a diffusive soil and a Farquhar-type photosynthesis scheme.
In a first step, the model has been initialized with site specific characteristics, including the leaf area index (LAI) measured at the site and using micrometeorological data of 2002 and winter 2003. A very good agreement between observed and modeled energy fluxes (net radiation, ground heat flux, latent and sensible heat flux) was found. Thus, it can be assumed that the model also gives realistic results about the CO_2 fluxes of this site. Indeed, when comparing the measured CO_2 fluxes and the simulation run with the ground truth phenology (LAIGR in Fig. 46), there is a good agreement between both datasets, although in spring, the photosynthetic activity of the vegetation is underestimated by the model. Partially responsible for this deviation, is certainly the input parameter LAIGR. Since Seebodenalp is a patchwork of fields with different land-management interventions, it was difficult to give a realistic estimate of the mean leaf area index during the vegetation period.

In a second step, the CO_2 exchange at Seebodenalp for 2003 was modeled using the leaf area index measured at a part with undisturbed vegetation (LAIUND in Fig. 46). This simulation run gives an idea about the CO_2 exchange as if no land-management interventions (no grass cuts and no cows grazing) would have occurred. By comparing the carbon budget of this simulation with the measured budget it can be estimated how big the impact of the management interventions in 2003 has been.

A yearly carbon budget of 172 ± 12 g C m^{-2} was measured with the eddy-covariance technique over the year 2003. The model run LAIGR estimated a carbon loss of 189 g C m^{-2} and the simulation using LAIUND predicted a net uptake of -141 g C m^{-2}. Thus, grass cuts and grazing at Seebodenalp turned the site from a net carbon sink into a net carbon source. According to the model results, land-management during the vegetation period was responsible for a difference in the carbon budget of 330 g C m^{-2}.

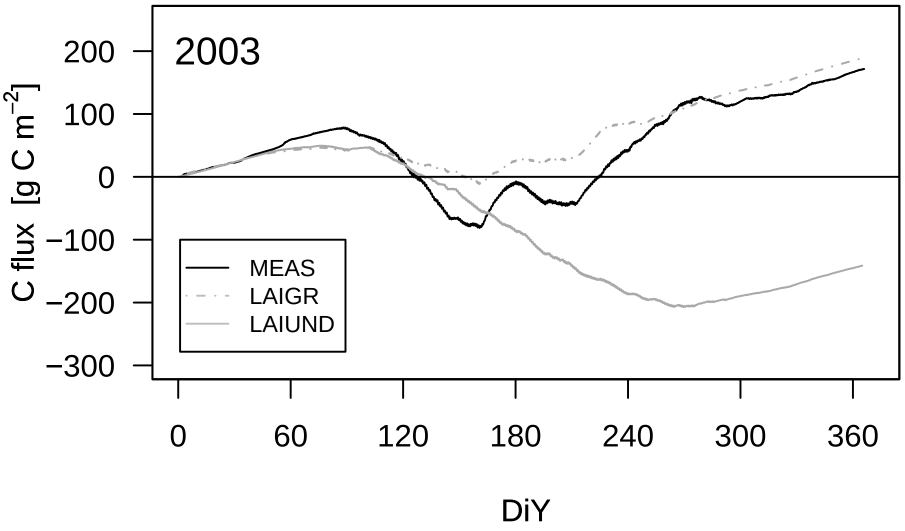

Fig. 46: Comparison of the cumulative CO_2 exchange at Seebodenalp for 2003 measured with the eddy-covariance system (MEAS) and the model simulations SiB25 using ground truth phenology (LAIGR) and using the leaf area index as if no management interventions would have occurred (LAIUND).

6.8 Discussion

The data coverage for the three-year measurement period is moderate: 46% of the time records are covered by screened EC data. Because larger gaps were filled using site-specific functional relationships between micrometeorological variables and CO_2 fluxes, the final matrix contains high-quality measurement and modeled data. Thus, this dataset allowed us to make a good estimate of the carbon budget at this site.

Although the summer 2003 is known as an extremely hot summer in Europe, there is not a clear influence in the cumulative curve of the CO_2 fluxes at Seebodenalp.

At the Swiss CARBOMONT site, extremely high air temperatures were reached in summer 2003 and precipitation was generally lower than average. However, soil water reserves were partially filled up again by night rainfall events (see Chapter 4). Drought at Seebodenalp was only experienced during some short periods. Besides a reduction in photosynthetic capacity during these periods, also a decrease in daytime and dark respiration was observed (see Chapter 4).

CO_2 losses over snow pack were however high in winter 2003-2004 and they might be the result of the warm summer 2003 (see Chapter 5).

As already discussed in detail in Chapter 4, transpiration is reduced after the grass cut due to the decrease in leaf area index. However, evaporation of soil water increases because the ground is not covered by plants and thus heated up more. Moreover, as shown in Chapter 4, water vapor fluxes at Seebodenalp are mainly energy driven. The cumulative curves of water vapor follow more or less the pattern of the heat input shown in Fig. 39: high evapotranspiration rates during the vegetation period and nearly zero evapotranspiration rates during the cold season.

Estimated mean C loss in form of CO_2 since drainage has been estimated to be situated between 5.0 and 9.1 t C ha^{-1} y^{-1}, depending on the length of the cultivation period. The carbon losses measured with the EC system (e.g. 1.72 t C ha^{-1} y^{-1} in 2003) are still clearly below this range and are thus, although relatively high, plausible for this site.

The laboratory results with soil samples from Seebodenalp are in agreement with literature data. Leifeld *et al.* (2005) made a overview of the available data on expected annual losses of organic carbon due to peat oxidation under similar Swiss climatic conditions and found a mean oxidative peat loss of 9.52 t C ha^{-1} y^{-1}.

In future, a detailed footprint analysis of the EC measurements has to be made, to determine the relative contribution of the wetland sites to the EC measurements. So far, a detailed determination of the footprint has only been made for summer periods. It was found that the wetlands were very rarely in the footprint (± 10%). However, two remarks have to be made. First, it has to be considered that it is possible that the local wind system, which is described in detail in Rogiers *et al.* (2005), collapses during the cold season and therefore the footprint in winter is different from the summer footprint. Therefore, a detailed footprint analysis of the winter measurements has to be made. Second, the footprint analysis with the Korman and Meixner model (2001) only gives a rough idea about the contribution of the fields since several assumptions are implicit to the model. Although relatively flat, Seebodenalp is not vertically homogenous. Especially the wetland areas are slightly inclined towards the measurement tower, probably resulting in drainage of CO_2 towards the tower. The contribution of the wetland areas might thus be higher than the results derived from the footprint analysis.

6.9 Conclusions

The EC data from three years of measurement between 17 May 2002 (day 137) and 11 May 2004 (day 131) are presented. All three years were net carbon sources and significant differences in the carbon balance of an extensively used grassland were found between the years. The differences in land-management practices and intensities as well as the differences in microclimate play an important role. With respect to temperature, the measurement years 2002 and 2004 were close to the 10-year average, whereas the year 2003 was clearly warmer and drier than average. The carbon budget during summer 2003 was not completely different from the other two summers, but during the winter period 2003-2004 significantly higher carbon losses were detected.

Besides the CO_2 exchange measured with the eddy-covariance system, also other components such as carbon export by livestock and harvesting have to be considered when calculating the temporal change in soil organic carbon for a managed grassland. In 2003, NEE losses amounted to only half of the total carbon losses.

Measurements of carbon losses under laboratory conditions estimated an annual net carbon loss from the wetland due to draining between 5.0 and 9.1 t C ha^{-1}. These results give a good estimation of the impact of historic land-management on the present CO_2 exchange. They also indicate that the relatively high carbon losses measured at Seebodenalp with the EC tower are realistic.

Finally, model simulations with SiB2.5 have shown that current land-management practices during the vegetation period turn the site from a net carbon sink into a net carbon source.

6.10 Tables

Tab. 11: Basic climatological values for Seebodenalp 2002-2005. Data were taken from the NABEL station.

Parameter	1992-2001	2002	2003	2004
Temperature, °C	7.32	7.96	8.38	6.95
Total precipitation, mm	1327 [1)]	1746	991	1111
Growing degree days (GDD)	1553	1551	1994	1545
Number of days with Temp > 5°C	205	243	230	224

1) only 1994-2001

Tab. 12: Timing of the first and second grass cut at Seebodenalp in summer 2002, 2003 and 2004.

Year	grass cut 1		grass cut 2	
	Date	DiY	Date	DiY
2002	11 June	162	11 August	223
2003	11 June	162	31 July	212
2004	6 June	158	17 July	197

7 Conclusions

Carbon cycling of terrestrial ecosystems has attracted much attention in recent years, because of their potential to act as a net sinks or sources for atmospheric CO2. Agricultural land and grassland ecosystems play an important role in the Earths carbon budget, and studies have shown that through adequate management it is possible to sequester additional carbon in these soils or at least prevent them from loosing carbon.

The main goal of the European project CARBOMONT was to quantify effects of land-management on CO_2 fluxes on mountainous grasslands. Within the framework of the CARBOMONT project, CO_2 and water vapor fluxes were measured using the eddy covariance technique at Rigi Seebodenalp above a subalpine grassland ecosystem in the Swiss Pre-Alps. The site comprises different land-management types. One part is used as an extensively managed grassland with meadows (two annual grass cuts) and pastures (cows grazing). Another part of Seebodenalp is a wetland with one grass cut at the end of the vegetation period. An eddy-covariance system was installed at Seebodenalp in May 2002 supplemented by conventional micrometeorological measurements. The footprint of this tower covered the extensively managed grassland during the vegetations periods quite well. During summer 2003, an additional eddy-covariance system was operational, collecting mainly information from the wetland site.

For the grassland, a three-year dataset containing eddy-covariance measurements and micrometeorological data from 17 May 2002 to 20 May 2005 was established. This data set is unique in two ways. It comprises information on the CO2 exchange of a cultivated peat land. With our site at Rigi Seebodenalp, the grassland with the highest soil organic content was added to the CARBOMONT sites. Furthermore, the dataset compiles continuous data covering three vegetation periods but also three winter periods. Eddy-covariance data during winter and snow-covered periods are relatively rare since measuring during the cold season is often accompanied by logistic and technical problems.

In Chapter 3 of this PhD-thesis, the effect of land-management on the CO_2 exchange was examined during the growing season 2002 by comparing CO_2 fluxes of a pasture and a meadow. The CO_2 exchange of the vegetation period 2002 (17 May until 25 September), is expected to be representative for this site, because it was climatologically close to the 10-year average. Using a detailed footprint model, it was found that a simple approach using wind direction sectors was adequate enough to classify our CO_2 fluxes from the grassland as being controlled by either meadow or pasture.

Functional relationships between CO_2 exchange and micrometeorological variables were determined. Two significantly different light response curves could be determined from the data of both land-management types: one for periods with external interventions (grass cutting, cattle grazing) and the other for periods without external interventions. No differences in the response of dark respiration to soil temperature could be found between meadow and pasture.

By combining the available measured data from a specific windsector on the one hand with the data modeled from the functional relationships between CO_2 exchange and photosynthetically active radiation and soil temperature, respectively, on the other hand, a continuous dataset for each land-management type was constructed. From these datasets, carbon budgets for the vegetation period 2002 (131 days) were calculated for both land-management types. A net carbon loss of 79 ± 17 g C m^{-2} was calculated for the managed meadow and 270 ± 24 g C m^{-2} for the pasture. By comparing measured data with modeled data, the effect of land-management could be quantified. It was found that the site used as a meadow would have had a net carbon gain of -128 ± 17 g C m^{-2} if no grass would have been cut. It was also calculated that the grass cut in June reduced the gross CO_2 uptake of the meadow by 50 ± 2 % until regrowth of the vegetation and that cattle grazing reduced gross uptake over the whole vegetation period by 37 ± 2 %.

In Chapter 4, the eddy covariance CO_2 and water vapor fluxes of the grassland and the wetland area at Seebodenalp were compared. During the hot summer 2003 (1 June until 30 September), both ecosystems were net carbon sources. Due to land-management (grass cuts and cows grazing) the extensively used grassland lost considerably more carbon (204 ± 20 g C m^{-2}) than the protected wetland (62 ± 6 g C m^{-2}).

Summer 2003 at Seebodenalp was characterized by several hot and dry spells. Low soil water levels limited dark and daytime respiration. This reduction was pronounced earlier at the grassland (July) than at the wetland (beginning of September) because of the faster draining of the grassland. The photosynthetic activity of the undisturbed wetland vegetation decreased from spring to mid-summer due to the combined effect of senescence and water stress.

Cutting the grass at the extensively used grassland led to a decrease in transpiration and to a simultaneous increase in soil evaporation, such that there was no substantial change in the total evapotranspiration.

No coupling was found between CO_2 and water vapor exchange. We demonstrated that soil water evaporation was the major contributor to the total measured water vapor fluxes at Seebodenalp and both ecosystems were well decoupled from the atmosphere (decoupling factor Ω close to 1). Under optimal soil water levels, a good correlation existed between latent heat flux and available energy (net radiation-soil heat flux) showing that water vapor fluxes at a grassland ecosystem are mainly energy driven.

Chapter 5 focused on the CO_2 exchange during periods outside the vegetation period. The measurements during three winter periods at Seebodenalp have shown that winter carbon losses account for an important share in the annual CO_2 budgets: total winter respiration and respiration from snow covered grassland contributed 23.3 ± 2.4% and 6.0 ± 0.3%, respectively, to the yearly respiration losses at Seebodenalp. These results emphasize the importance of quantifying CO_2 fluxes outside the growing season.

The insulation effect of snow cover and the high content of soil organic matter prevented the soil from freezing. These relatively high soil temperatures during winter created a favorable environment for microbial activity such that relatively high respiration losses were measured at Seebodenalp.

The highest daily mean losses recorded over snow pack in winter 2003-2004 were the result of higher temperatures of the topmost soil measured during snow covered periods in 2003-2004. These high soil temperatures were the result of the higher air temperatures just before snowfall and were not directly related to the high soil temperatures measured during the hot summer 2003. However an indirect effect of the summer heat wave 2003 was discussed, which might be partially responsible for these higher respiration rates. Water stress in summer 2003 might have caused an increase in dead soil microbial biomass and roots. The process of drying and rewetting the soil generally results in an increment of available substrate for microbial respiration.

In spring, a direct response of soil temperature fluctuations to snow melt at Seebodenalp was observed.

In Chapter 6, a summary of three years of eddy-covariance data is given.

Seebodenalp was a net source of CO_2 during all three measurement years. However, considerable interannual variations were measured due to differences in land-management practices and microclimate. The measurement years 2002 and 2004 were climatically close to average, but the year 2003 was considerably warmer and drier than average. In summer 2003, reduced assimilation rates and respirations rates were measured, such that the total CO_2 exchange did not differ considerably from the CO_2 budgets for the vegetation periods 2002 and 2003. Higher carbon losses were however determined over the measurement year due to extremely high carbon losses from snow pack (see also Chapter 5). It has been shown that also carbon losses by cows grazing and harvesting have to be considered when calculating the total annual carbon budget of a managed grassland site. In 2003, only half of the carbon losses from the site were measured with the eddy-covariance system.

Laboratory experiments have demonstrated that the annual carbon losses from the wetland site at Seebodenalp due to draining are situated within the range of 5.0 to 9.1 t C ha^{-1} which gives confidence in the relatively high CO_2 losses measured at the site. Finally, model simulations with SiB2.5 have shown that land-management practices strongly influence the annual carbon budget and can even turn the site from a net carbon sink into a net carbon source.

Beyond the results presented in Chapter 6, the analysis and interpretation of these data and results is still in progress.

8 Suggestions for further research

The eddy covariance system in the grassland covered a patchwork of fields. It has been demonstrated (Chapter 3) that it is possible to gather information on CO_2 fluxes with only one EC tower by classifying the CO_2 fluxes into two wind sectors. By splitting up the data set, information was collected about the meadow (mainly daytime data) and the pasture (mainly nighttime data). However, for the comparison of the CO_2 exchange of both land-management types some assumptions, inherent to the footprint and modeling procedure, had to be made. To gain better information on the CO_2 exchange of a specific ecosystem it would be better to have one eddy covariance tower surrounded by only one land-management type, such that data from the nighttime and daytime (which do often not overlap because of local wind systems) cover one specific ecosystem. The most ideal situation (but also the most expensive one) to study the CO_2 exchange of one specific site would exist of two EC systems by which the daytime footprint area of one tower covers the nighttime footprint area of the other tower. The respective night- and daytime data are then combined into one dataset. In this way, night- and daytime data from one dataset cover the same area including any possible gradients (for example in soil properties and consequently also vegetation).

Seebodenalp is managed by the land-owning cooperation “Korporation Berg und Seeboden”. Decisions on land-management (grass cuts, grazing) were made by the cooperation. Although they informed the scientific team before interventions, it was not possible to follow a well designed sampling strategy. During the vegetation period 2002 and 2003 similar land-management practices were carried out on the same fields, but land-management slightly changed in summer 2004 (first grass cut was less intensive but followed by grazing). Because of the changes in land-management occurring every few years, it is not possible to study long-term effects of land-management on the CO_2 exchange at this site. It is therefore important to select future measurement sites where a certain level of participation in the decision on land-management interventions is possible.

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