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Biogeosciences Discussions

# Memory effects on greenhouse gas emissions ($CO_2$, $N_2O$ and $CH_4$) following grassland restoration?

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## Abstract

A five-year greenhouse gas (GHG) exchange study of the three major gas species ($CO_2$, $CH_4$ and $N_2O$) from an intensively managed permanent grassland in Switzerland is presented. Measurements comprise two years (2010/2011) of manual static chamber measurements of $CH_4$ and $N_2O$, five years of continuous eddy covariance (EC) measurements ($CO_2$/$H_2O$ – 2010-2014) and three years (2012-2014) of EC measurement of $CH_4$ and $N_2O$. Intensive grassland management included both regular and sporadic management activities. Regular management practices encompassed mowing (3-5 cuts per year) with subsequent organic fertilizer amendments and occasional grazing whereas sporadic management activities comprised

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grazing or similar activities. The primary objective of our measurements was to compare pre-ploughing to post-ploughing GHG exchange and to identify potential memory effects of such a substantial disturbance on GHG exchange and carbon (C) and nitrogen (N) budgets. In order to include measurements carried with different observation techniques, we tested two different measurement techniques jointly in 2013, namely the manual static chamber approach and the eddy covariance technique, to quantify the GHG exchange from the observed grassland site.

Our results showed that there were no memory effects on $N_2O$ and $CH_4$ emissions after ploughing, whereas the $CO_2$ uptake of the site considerably increased when compared to post-restoration years. In detail, we observed large losses of $CO_2$ and $N_2O$ during the year of restoration. In contrast, the grassland acted as a carbon sink under usual management, i.e. the time periods (2010-2011 and 2013-2014). Enhanced emissions/emission peaks of $N_2O$ (defined as exceeding background emissions $< 0.21 \pm 0.55$ nmol $m^{-2}$ $s^{-1}$ (SE = 0.02) for at least two sequential days and the seven-day moving average exceeding background emissions) were observed for almost seven continuous months after restoration as well as following organic fertilizer applications during all years. Net ecosystem exchange of $CO_2$ ($NEE_{CO2}$) showed a common pattern of increased uptake of $CO_2$ in spring and reduced uptake in late fall. $NEE_{CO2}$ dropped to zero and became positive after each harvest event. Methane ($CH_4$) exchange in contrast to $N_2O$ showed minor net uptake of methane seen by the static chambers and small net release of methane seen by the eddy covariance method. Overall, $CH_4$ exchange was of negligible importance for both, the GHG budget as well as for the carbon budget of the site.

Our results stress the inclusion of grassland restoration events when providing cumulative sums of C sequestration and/or global warming potentials (GWPs). Consequently, this study further highlights the need for continuous long-term GHG exchange observations as well as the implementation of our findings into biogeochemical process models to track potential GHG mitigation objectives as well as to predict future GHG emission scenarios reliably.

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## 1 Introduction

Grassland ecosystems are commonly known for their provisioning of forage, either directly via grazing of animals on site, or indirectly by regular biomass harvest and preparation of silage or hay. Simultaneously, grasslands have further been acknowledged for their greenhouse gas (GHG) mitigation and soil carbon sequestration potential (Lal, 2004; Smith et al., 2008). However, greenhouse gas emissions from grasslands, particularly $N_2O$ and $CH_4$ have been shown to offset net carbon dioxide equivalent ($CO_2$-eq.) gains (Dengel et al., 2011; Hörtnagl et al., 2018; Hörtnagl and Wohlfahrt, 2014; Merbold et al., 2014; Schulze et al., 2009). Still, datasets containing continuous measurements of all three major GHGs ($CO_2$, $CH_4$ and $N_2O$) in grassland ecosystems remain limited (Hörtnagl et al., 2018), include a single GHG only, or focus on specific management activities (Fuchs et al., 2018; Krol et al., 2016). At the same time such datasets are extremely valuable by providing key training datasets for biogeochemical process models (Fuchs et al., 2020).

Here we investigate the GHG exchange of the three major trace gases ($CO_2$, $CH_4$ and $N_2O$) over five consecutive years in a typical managed grassland on the Swiss plateau. Our study includes the application of traditional chamber measurements and state-of-the-art GHG concentration measurements with a quantum cascade laser absorption spectrometer and a sonic anemometer in an eddy covariance setup (Eugster and Merbold, 2015). Prior to our measurements we hypothesized continuous (over several years) losses of $CO_2$, $CH_4$ and $N_2O$ following dramatic managements events such as ploughing occurring at irregular time intervals with subsequent high emissions of $N_2O$ in the following years after disturbance. We further hypothesized an increased carbon uptake strength compared to the pre-ploughing years. Methane emissions were hypothesized to be of minor importance due to the limited time of grazing animals on site (Merbold et al., 2014).

Up to date the majority of greenhouse gas exchange research has focused on $CO_2$, with less focus on the other two important GHGs $N_2O$ and $CH_4$, even though an increased interest in these other gas species has become visible in recent years (Ball et al., 1999; Cowan et al., 2016; Krol et al., 2016; Kroon et al., 2007, 2010; Necpálová et al., 2013). The existing exceptions are often referred to as “high-flux” ecosystems, namely wetlands and livestock production system in terms of $CH_4$ (Baldocchi et al., 2012; Felber et al., 2015; Laubach et al., 2016; Teh et al., 2011) and agricultural ecosystems such as bioenergy system with considerable $N_2O$ emissions (Fuchs et al., 2018; Krol et al., 2016; Skiba et al., 1996, 2013; Zenone et al., 2016;

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Zona et al., 2013). Agricultural ecosystems and specifically grazed systems are characterized by GHG emissions caused through anthropogenic activities. These activities lead to changes in GHG emission patterns and include harvests, amendments of fertilizer and/or pesticides and less frequently occurring ploughing, harrowing and re-sowing events. While ploughing has been shown to lead to considerable short-term emissions of $CO_2$ and $N_2O$ (Buchen et al., 2017; Hörtnagl et al., 2018; MacKenzie et al., 1997; Merbold et al., 2014; Vellinga et al., 2004), regular harvests have been shown to lead to increased $CO_2$ uptake (Zeeman et al., 2010) and grazing leads to large $CH_4$ emissions ((Dengel et al., 2011; Felber et al., 2015). Other studies showed contrary results with reduced $N_2O$ emissions following ploughing of a drained grassland when compared to a fallow in Canada (MacDonald et al., 2011).

Still, the full range of management activities occurring in intensively managed grasslands and their respective impact on GHG exchange has not been investigated in detail. In a recent synthesis including grasslands located along an altitudinal gradient in Central Europe, Hörtnagl et al. (2018) highlighted the most important abiotic drivers of $CO_2$ (light, water availability and temperature), $CH_4$ (soil water content, temperature and grazing) and $N_2O$ exchange (water filled pore space and soil temperature). Similarly, the study elaborated the variation in management intensity and subsequent variations in GHG exchange across sites, stressing the need for more case studies based on continuous GHG observations to improve existing knowledge and close remaining knowledge gaps (Hörtnagl et al., 2018). Besides natural variation in environmental variables, irregularly occurring events (e.g. extreme events) such as dry spells or extraordinary wet periods can further impact ecosystem GHG exchange (Chen et al., 2016; Hartmann and Niklaus, 2012; Hopkins and Del Prado, 2007; Mudge et al., 2011; Wolf et al., 2013). While drought has been shown to reduce $CO_2$ uptake in forests (Ciais et al., 2005) whereas dry spells did not affect $CO_2$ uptake in grasslands (Wolf et al., 2013), flooding leads primarily to enhanced $CH_4$ emissions (Knox et al., 2015) and large precipitation events can lead to plumes of $N_2O$ (Fuchs et al., 2018; Zona et al., 2013) similar to freeze-thaw events (Butterbach-Bahl et al., 2011; Matzner and Borken, 2008) to name only some examples. Consequently, understanding both, anthropogenic impacts such as management besides environmental impacts on ecosystem GHG exchange, are crucially important to suggest appropriate climate change mitigation as well as adaptations strategies for future land management with ongoing climate change.

Different measurement techniques to quantify the net GHG exchange in ecosystems are known and the most common approaches are either GHG chamber measurements or the eddy covariance (EC) technique. Static manual chamber measurements have been used for more

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than a century to quantify $CO_2$ emissions (Lundegardh, 1927) and their application has further been expanded during the last decades to quantify losses of the three major GHGs, $CO_2$, $N_2O$ and $CH_4$ from soils, respectively (Imer et al., 2013; Pavelka et al., 2018a; Pumpanen et al., 2004; Rochette et al., 1997). Even though more complex in technology and assumptions made before carrying out measurements, the eddy covariance (EC) technique has become a valuable tool to derive ecosystem integrated $CO_2$ and $H_2O_{vapour}$ exchange across the globe (Baldocchi, 2014; Eugster and Merbold, 2015). The technique has been further extended to continuous measurements of $CH_4$ and $N_2O$ with the development of easy field-deployable fast-response analyzers during the last decade (Brümmer et al., 2017; Felber et al., 2015; Kroon et al., 2007; Nemitz et al., 2018a). Each of the two approaches has its strengths and weaknesses and it is beyond the scope of this study to discuss each of them in detail. However, we refer to a set of reference papers highlighting the advantages and disadvantages of each technique separately (chambers: (Ambus et al., 1993; Brümmer et al., 2017; Pavelka et al., 2018a); eddy covariance: (Baldocchi, 2014; Denmead, 2008; Eugster and Merbold, 2015; Nemitz et al., 2018a).

The overall objective of this study was to investigate the net GHG exchange ($CO_2$, $CH_4$ and $N_2O$) before and after grassland restoration and thus fill existing knowledge gaps caused by limited amounts of GHG exchange data from intensively managed grasslands. The specific goals were: (i) to assess pre- and post-ploughing GHG exchange in a permanent grassland in central Switzerland; (ii) to briefly compare two different measurement techniques, namely eddy covariance and static greenhouse gas flux chambers to quantify the GHG exchange in a business-as-usual year; (iii) to identify changes in GHG exchange after multiple management activities; and (iv) to provide a partial carbon (C) and nitrogen (N) budget of the site. Based on our results we provide suggestions for future research approaches to further understand ecosystem GHG exchange, to mitigate GHG emissions and to ensure nutrient retention at the site for sustainable production from permanent grasslands in the future.

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## 2 Material and Methods

### 2.1 Study site

The Chamau grassland site (Fluxnet identifier - CH-Cha) is located in the pre-alpine lowlands of Switzerland at an altitude of 400 m a.s.l. (47°12′ 37″N, 8°24′38″E) and characterized by intensive management (Zeeman et al., 2010). The site is divided into two parcels (Parcel A and B) with occasionally slightly different management regimes [see also *Fuchs et al., 2018*]. Mean annual temperature (MAT) is 9.1 °C, and mean annual precipitation (MAP) is 1151 mm. The soil type is a Cambisol with a pH ranging between 5 and 6, a bulk density between 0.9 and 1.3 kg $m^{-3}$ and a carbon stock of 55.5–69.4 t C $ha^{-1}$ in the upper 20 cm of the soil. The common species composition consists of Italian ryegrass (*Lolium multiflorum*) and white clover (*Trifolium repens L.*). For more details of the site we refer to Zeeman et al., (2010).

CH-Cha is intensively managed, with activities being either recurrent – referred to as usual/regular - or sporadic. Usual management refers to regular mowing and subsequent organic fertilizer application in form of liquid slurry (up to 7 times per year). In addition, the site is occasionally grazed by sheep and cattle for few days in early spring and/or fall (H.-R. Wettstein personal communication, Table S1). Sporadic activities aim at maintaining the typical fodder species composition and comprise reseeding, herbicide and pesticide application or irregular ploughing and harrowing on an approximately decadal timescale (Merbold et al., 2014). By such activity, mice are eradicated and a high-quality sward for fodder production is re-established following weed contamination. Specific information on management activity (timing, type of management, amount of biomass harvested) were reported by the farmers on site (Table S1). Additionally, representative samples of organic fertilizer were collected shortly before fertilizer application events and sent to a central laboratory for nutrient content analysis (Labor fuer Boden- und Umweltanalytik, Eric Schweizer AG, Thun, Switzerland). Harvest estimates were compared to estimates based on destructive sampling of randomly chosen plots (n = 10) in the years 2010, 2011, 2013 and 2014. The amount of harvested biomass in the year 2012 was based on a calibration of the values presented by the farmer in comparison to the on-site destructive harvests in previous and following years (Table S1).

### 2.2 Eddy covariance flux measurements

#### *2.2.1 Eddy covariance setup*

The specific site characteristics with two prevailing wind directions (North-northwest and South-south east) allows continuous observations of both management parcels. It is

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noteworthy, that the separation of the two parcels is done exactly at the location of the tower. See Zeeman et al. (2010) and Fuchs et al. (2018) for further details. The eddy covariance setup consisted of a three-dimensional sonic anemometer (2.4 m height, Solent R3, Gill Instruments, Lymington, UK), an open-path infrared gas analyzer (IRGA, LI-7500, LiCor Biosciences, Lincoln, NE, USA) to measure the concentrations of $CO_2$ and $H_2O_{vapour}$ and a recently developed continuous-wave quantum cascade laser absorption spectrometer (mini-QCLAS - $CH_4$, $N_2O$, $H_2O$ configuration, Aerodyne Research Inc., Billerica, MA, USA) to measure the concentrations of $CH_4$, $N_2O$, and $H_2O_{vapour}$. 3D wind components (u, v, w), $CO_2$ and $H_2O_{vapour}$ concentration data from the IRGA were collected at a 20 Hz time interval, whereas concentrations of $CH_4$ and $N_2O$ were collected at a 10 Hz rate from the QCLAS. The QCLAS provided the dry mole fraction for both trace gases ($CH_4$ and $N_2O$), and data were transferred to the data acquisition system (MOXA embedded Linux computer, Moxa, Brea, CA, USA) via an RS-232 serial data link and merged with the sonic anemometer and IRGA data streams in near-real time (Eugster and Plüss, 2010). Important to note is that the QCLAS was stored in a temperature-controlled box (temperature variation during the course of a single day was reduced to < 2 K) and located approximately 4 meters away from the EC tower to avoid long tubing. Total tube length from the inlet near the sonic anemometer to the measurement cell was 6.5 m. The inlet consisted of a coarse sinter filter (common fuel filter used in model cars) and a fine vortex filter (mesh size 0.3µm and a water trap) installed directly before the QCLAS. Filters were changed monthly or if the cell pressure in the laser dropped by more than 2 torr. Flow rate of approximately 15 l $min^{-1}$ was achieved with a large vacuum pump (BOC Edwards XDS-35i, USA and TriScoll 600, Varian Inc., USA – the latter was used during maintenance of the Edwards pump). The pumps were maintained annually and replaced twice due to malfunction during the observation period. The infrared gas analyzer was calibrated to known concentrations of $CO_2$ and $H_2O$ each year. The QCLAS did not need calibration due to its operating principles, and an internal reference cell (mini-QCL manual, Aerodyne Research Inc., Billerica, MA, USA) eased finding the absorption spectra after each restart of the analyzer.

*2.2.2 Eddy covariance flux processing, post-processing and quality control*

Half-hourly raw fluxes of $CO_2$, $CH_4$, $N_2O$ ($F_{GHG}$, µmol $m^{-2}$ $s^{-1}$) were calculated as the covariance between turbulent fluctuations of the vertical wind speed and the trace gas species mixing ratio, respectively (Baldocchi, 2003; Eugster and Merbold, 2015). Open-path infrared gas analyzer (IRGA) $CO_2$ measurements were corrected for water vapor transfer effects (Webb et al., 1980). A 2-dimensional coordinate rotation was performed to align the coordinate system

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with the mean wind streamlines so that the vertical wind vector $\dot{w} = 0$. Turbulent departures were calculated by Reynolds (block) averaging of 30 min data blocks. Frequency response corrections were applied to raw fluxes, accounting for high-pass and low-pass filtering for the $CO_2$ signal based on the open-path IRGA as well as for the closed-path $CH_4$ and $N_2O$ data (Fratini et al., 2014). All fluxes were calculated using the software *EddyPro* (version 6.0, LiCor Biosciences, Lincoln, NE, USA) (Fratini and Mauder, 2014).

The quality of half-hourly raw time series was assessed before flux calculations following (Vickers and Mahrt, 1997). Raw data were rejected if (a) spikes accounted for more than 1 % of the time series, (b) more than 10 % of available data points were significantly different from the overall trend in the 30 min time period, (c) raw data values were outside a plausible range (± 50 µmol $m^{-2}$ $s^{-1}$ for $CO_2$, ± 300 nmol $m^{-2}$ $s^{-1}$ for $N_2O$ and ± 1 µmol $m^{-2}$ $s^{-1}$ for $CH_4$) and (d) window dirtiness of the IRGA sensor exceeded 80 %. Only raw data that passed all quality tests were used for flux calculations. Half-hourly flux data were rejected if (e) fluxes were outside a physically plausible range, (f) the steady state test exceeded 30 % and (g) the developed turbulent conditions test exceeded 30 % (Foken et al., 2006).

Between 1st January 2010 and 31st December 2014 64572 (88% of all possible data) raw 30-min flux values were calculated for $CO_2$, of which 42865 (57.8%) passed all quality tests and were used for analyses in the present study (Table 1). The amount of available flux values for $N_2O$ and $CH_4$ were less, since we were only capable to continuously measure both gases from 2012 onwards (Table 1). Flux values in this manuscript are given as number of moles of matter/mass of matter per ground surface area and unit time. Negative fluxes represent a flux of a specific gas species from the atmosphere into the ecosystem, whereas positive fluxes represent a net loss from the system.

## 2.3 Static greenhouse gas flux chambers

### *2.3.1 Manual static GHG chamber setup*

Static manual opaque GHG chambers were installed within the footprint of the site to measure soil fluxes in 2010 and 2011 (n =16) as well as during summer 2013 (n = 10). The chambers were made of polyvinyl chloride tubes with a diameter of 0.3 m (Imer et al., 2013). The average headspace height was 0.136 m ± 0.015 m and average insertion depth of the collars into the soil was 0.08 m ± 0.05 m. During sampling days with vegetation larger than 0.3 m inside the chamber, collar extensions (0.45 m) were used (2013 only). Chamber lids were equipped with reflective aluminium foil to minimize heating inside the chamber during the period of actual measurement. Spacing between the chambers was approximately seven m and an equal number

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of chambers were installed in each parcel. For further details we refer to Imer et al. (2013). Chamber measurements were carried out on a weekly basis during the growing season in all three years (2010, 2011 and 2013), and at least once a month during the winter season in 2010 and 2011. More frequent measurements of $N_2O$ emissions (every day) were performed following fertilization events in 2013 for seven consecutive days after each event. Besides this, an intensive measurement campaign lasting 48 hours (two-hour measurement interval) was carried out in September 2010.

*2.3.2 GHG concentrations measurements*

During each chamber closure four gas samples were taken, one immediately after closure and then in approximately ten-minute time increments. With this approach, we guaranteed that the chambers were no longer closed than 40 minutes to avoid potential saturation effects. Syringes (60 ml volume) were inserted into the chambers lid septa to take the gas samples. The collected air sample was injected into pre-evacuated 12 ml vials (Labco Limited, Buckinghamshire, UK) in the next step. Prior to the second, third and fourth sampling of each chamber, the air in chamber headspace was circulated with the syringe volume of air from the chamber headspace to minimize effects of built-up concentration gradients inside the chamber.

Gas samples were analyzed for their respective $CO_2$, $CH_4$ and $N_2O$ concentrations in the lab as soon as possible after sample collection and not stored for more than a few days. Gas sample analysis was performed with a gas chromatograph (Agilent 6890 equipped with a flame ionization detector, a methanizer - Agilent Technologies Inc., Santa Clara, USA - and an electron capture detector – SRI Instruments Europe GmbH, 53604 Bad Honnef, Germany) as described by Hartmann and Niklaus (2012).

*2.3.3 GHG chamber flux calculations and quality control*

GHG fluxes were calculated based on the rate of gas concentration change inside the chamber headspace. Data processing, which included flux calculation and quality checks, was carried out with the statistical software R (R Development Core Team, 2010). Thereby the rate of change was calculated by the slope of the linear regression of gas concentration over time. Flux calculation was based on the common equation containing GHG concentration (c in nmol $mol^{-1}$ for $CH_4$ and $N_2O$), time (t in seconds), atmospheric pressure (p in Pa), the headspace volume (V in $m^{-3}$), the universal gas constant (R = 8.3145 $m^{-3}$ Pa $K^{-1}$ $mol^{-1}$), ambient air temperature (Ta in K) and the surface area enclosed by the chamber (A in $m^{-2}$) (equation 1 in Imer et al. (2013)).

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303 Flux quality criteria were based on the fit of the linear regression. If the correlation coefficient
304 of the linear regression ($r^2$) was < 0.8 the actual flux value was rejected from the subsequent
305 data analysis. Furthermore, if the slope between the 1st and 2nd GHG concentration
306 measurement deviated considerably from the following concentrations we omitted the first
307 value and calculated the flux based on three instead of four samples. Mean chamber GHG
308 fluxes were then calculated as the arithmetic mean of all available individual chamber fluxes
309 for each date. A total of 60 GHG flux calculations ($CH_4$ and $N_2O$) were available for the years
310 2010 and 2011. Another 52 $N_2O$ flux values were available for the five-month peak-growing
311 season in 2013.
312
313 *2.4 Gapfilling and annual sums of $CO_2$, $CH_4$, and $N_2O$*
314 Up to date a common strategy to fill gaps in EC data of $CH_4$ and $N_2O$ has not been agreed on.
315 The commonly used methods are simple linear approaches (Mishurov and Kiely, 2011) or the
316 application of more sophisticated tools such as artificial neural networks (Dengel et al., 2011).
317 The difficulty of finding an adequate gap-filling strategy results from the fact that emission
318 pulses of either $N_2O$ or $CH_4$ remain challenging to predict. Similarly, different measurement
319 approaches – i.e. low temporal resolution manual GHG chambers compared to high temporal
320 resolution eddy covariance measurements - need different gap-filling approaches (Mishurov
321 and Kiely, 2011; Nemitz et al., 2018). In order to keep the gap-filling methods as simple and
322 reliable as possible, we used a running median (30 and 60 days for eddy covariance based and
323 chamber based $CH_4$ and $N_2O$ fluxes, respectively). A similar approach was recently chosen by
324 Hörtnagl et al. (2018) due to its sensitivity to peaks in the GHG exchange data.
325 In contrast to $CH_4$ and $N_2O$ various well-established approaches to fill $CO_2$ flux data exist
326 (Moffat et al., 2007). Here, we filled gaps in $CO_2$ exchange data following the marginal
327 distribution sampling method (Reichstein et al., 2005) which was implemented in the R
328 package REddyProc (https://r-forge.r-project.org/projects/reddyproc/).
329 Calculation of the global warming potential (GWP) given in $CO_2$-equivalents followed the
330 recommendations given in the 5th Assessment Report of the Intergovernmental Panel on
331 Climate Change (IPCC), with $CH_4$ having a 34 and $N_2O$ a 298 times greater GWP than $CO_2$
332 on a per mass basis over a time horizon of 100 years including climate-carbon feedbacks
333 (Stocker et al., 2013).
334
335 *2.5 Meteorological and phenological data*
336 Flux measurements were accompanied by standard meteorological measurements. These

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included observations of soil temperature (depths of 0.01, 0.02, 0.05, 0.10, and 0.15 m, TL107 sensors, Markasub AG, Olten, Switzerland), soil moisture (depths of 0.02 and 0.15 m, ML2x sensors, Delta-T Devices Ltd., Cambridge, UK) and air temperature (2 m height, Hydroclip S3 sensor, Rotronic AG, Switzerland). Furthermore, we measured the radiation balance including short-wave incoming and outgoing radiation, long-wave incoming and outgoing radiation (CNR1 sensor with ventilated Markasub housing, Kipp and Zonen, Delft, the Netherlands) as well as photosynthetically active radiation at 2 m height (PARlite sensor, Kipp and Zonen, Delft, the Netherlands). All data were stored as 30 min averages on a datalogger in a climate-controlled box on site (CR10X, Campbell Scienctific, Logan, UT, USA).

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## 3 Results

### *3.1 General site conditions*

The Chamau study site (CH-Cha) experienced meteorological conditions typical for the site during the five-year observation period. Summer precipitation commonly exceeded winter precipitation (Figure 1a). A spring drought was recorded from March till May 2011 (Wolf et al., 2013), leading to considerably lower soil water content than in previous and following years (Figure 1a). Average daily air temperatures rose up to 26.7 °C (27$^{th}$ July 2013) during summer and average daily temperature in winter dropped as low as -12.7 °C (6$^{th}$ February 2012, Figure 1b) with soil temperature following in a dampened pattern (Figure 1b). Average daily photosynthetic photon flux density did not differ considerably over the five-year observation period (Figure 1c). The site rarely experienced snow cover during winter (Figure 1b).

The complexity in management activities becomes apparent when comparing business as usual years (e.g. 2011) with the restoration year (2012, Figure 2a and b), highlighting the importance of grassland restoration to maintain productivity yields. Prior to 2012 an obvious decline in productivity with larger C and N inputs was found compared to the outputs in the years after restoration (2013 and 2014, Figure 2a and b).

### *3.2 EC $N_2O$ fluxes vs. chamber derived $N_2O$ fluxes*

In 2013, we had the chance of comparing $N_2O$ fluxes measured with two considerably different GHG measurement techniques, namely eddy covariance and static chambers. The chambers (n=10) were installed within the EC footprint. Our results reveal a similar temporal pattern, with increased $N_2O$ losses being captured by both methodologies following fertilizer application. However, we could not identify a consistent bias of either technique (Figure 3a). Direct comparison of both measurements revealed a reasonable correlation (slope m = 0.61, $r^2$ = 0.4) and larger variation between both techniques with increasing flux values (Figure 3b).

### *3.3 Temporal variation of GHG exchange*

Fluxes of $CO_2$ and $N_2O$ showed considerable variation between and within years. This variation primarily occurs due to management activities and seasonal changes in meteorological variables (Figures 1 and 4). In contrast, methane fluxes did not show a distinct seasonal pattern.

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403 *$CO_2$ exchange*

404 In pre-ploughing years (2010 and 2011), the Chamau site showed 60 % lower $CO_2$ uptake
405 compared to the post-ploughing years (2013 and 2014, Table 2). All four non-ploughing years
406 revealed largest $CO_2$ uptake rates in late spring (daily averaged peak uptake rates were >10
407 µmol $CO_2$ $m^{-2}$ $s^{-1}$, March and April, Figure 4a). Besides the seasonal effects a clear impact of
408 harvest events could be identified, with abrupt changes from net uptake of $CO_2$ to either
409 reduced uptake or net loss of $CO_2$ (light blue arrows indicate harvest event, Figure 4a). A
410 similar but less pronounced effect was found following grazing periods (light and dark brown
411 arrow, Figure 4a). A complete switch from net uptake to net $CO_2$ release was observed during
412 the first three months of 2012, after ploughing and during re-cultivation of the grassland. In
413 this specific year, the site only experienced snow cover for few days (Figure 1c), temperatures
414 below 5 ºC occurred more regularly than in all other years (Figure 1 b). Seasonal $CO_2$ exchange
415 was characterized by net release of $CO_2$ in winter (DJF), highest $CO_2$ uptake rates were
416 observed in spring (MAM), constant uptake rates during summer (JJA) which however were
417 lower than those measured in spring, and very low net release of $CO_2$ in fall (Table 3). Average
418 winter $CO_2$ exchange for the five-year observation period (gap-filled 30 min data) was 0.28 ±
419 5.68 µmol $CO_2$ $m^{-2}$ $s^{-1}$ (SE = 0.04, Table 3). The restoration year 2012 showed a slightly
420 different pattern with relatively large $CO_2$ release in winter and spring and considerably lower
421 uptake rates in summer. The years before the restoration (2010 and 2011) were characterized
422 by smaller net uptake rates during spring and summer when compared to the post-ploughing
423 years (2013 and 2014). Additionally, winter fluxes in 2010 and 2011 were positive (net release
424 of $CO_2$), while winter fluxes in the years 2013 and 2014 were showing a small but consistent
425 net uptake of $CO_2$ (Figure 4a, Table 3).
426
427 *$CH_4$ exchange*
428 While the individual static chamber measurements showed a very small but persistent net
429 uptake of methane, eddy covariance measurements were more than an order of magnitude
430 larger without revealing uptake or release (Figure 4b, different y axis). Overall, methane fluxes
431 were very low at both, the plot (chamber) and ecosystem scale (eddy covariance). Any peaks
432 expected due to freezing and thawing in late winter and early spring could not be found. Also,
433 commonly reported net emissions of methane during grazing were not seen (Figure 4b).
434 Seasonal differences of methane exchange did not show a clear pattern (Table 3).
435
436

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437 *$N_2O$ exchange*

438 $N_2O$ exchange was low during most of the days over the five-year observation period,
439 fluctuating around zero (Figure 4c). However, clear peaks in $N_2O$ emissions were observed
440 following fertilization events or periods with high rainfall after a dry period in summer (i.e.
441 summer 2013 and 2014, Figures 3a and 4c). While event driven $N_2O$ emissions were commonly
442 on the order of 4 to 8 nmol $N_2O$ $m^{-2}$ $s^{-1}$ (Figure 4c), $N_2O$ emissions following ploughing and
443 subsequent re-sowing of the grassland in 2012 lead to up to three times as high $N_2O$ emissions
444 (Figure 4c, year 2012, see also Merbold et al. (2014)). Similar to methane, enhanced $N_2O$
445 emissions in late winter or early spring as reported by other studies could not be identified
446 (Figure 4c).
447 Background fluxes were estimated by analysing all high temporal resolution flux data but
448 excluding the restoration year 2012 and all values one week after a management event. Daily
449 average background fluxes were 0.21 ± 0.55 nmol $m^{-2}$ $s^{-1}$ (SE = 0.02). Differences in $N_2O$
450 exchange over the course of individual years became obvious when splitting the dataset into
451 the four seasons (winter – DJF, spring – MAM, summer – JJA and fall – SON). In contrast to
452 $CO_2$ exchange that showed large net uptake rates in spring, $N_2O$ emissions were largest during
453 summer (JJA) and lowest in winter (DJF). As highlighted for the other gases, the year of
454 grassland restoration showed a completely different picture (Table 3).
455
456 *3.4 Annual sums and Global Warming Potential (GWP) of $CO_2$, $CH_4$ and $N_2O$*
457 Annual sums showed a net uptake of $CO_2$ during the two pre-ploughing years
458 (-695 g $CO_2$ $m^{-2}$ $yr^{-1}$ and -978 g $CO_2$ $m^{-2}$ $yr^{-1}$ in 2010 and 2011 respectively). Up to three times
459 of this net uptake was reached in 2013 and 2014, the two post-ploughing years (-2046 g $CO_2$
460 $m^{-2}$ $yr^{-1}$ and -2751 g $CO_2$ $m^{-2}$ $yr^{-1}$, Table 2). In contrast, the ploughing year 2011 was
461 characterized by a net release of $CO_2$ (1447 g $CO_2$ $m^{-2}$ $yr^{-1}$).
462 The annual methane budget ranged from a negligible uptake in 2010 and 2011 (< 0.1 g $CH_4$ $m^{-2}$ $yr^{-1}$) to a minor release between 2012 and 2014 (26.8 – 55.2 g $CH_4$ $m^{-2}$ $yr^{-1}$).
464 The Chamau site was characterized by a net release of nitrous oxide over the five-year study
465 period. While $N_2O$ emission ranged between 0.34 and 1.17 g $N_2O$ $m^{-2}$ $yr^{-1}$ in the non-ploughing
466 years, the site emitted 4.36 g $N_2O$ $m^{-2}$ $yr^{-1}$ in 2012.
467 The global warming potential (GWP), expressed as the yearly cumulative sum of all gases after
468 their conversion to $CO_2$-equivalents, was negative during all years (between -387 and -2577
469 $CO_2$-eq. $m^{-2}$) except for the ploughing year 2012 (+2629 $CO_2$-eq. $m^{-2}$).

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Overall, $CO_2$ exchange contributed more than 90% to the total GHG balance in 2011, 2013 and 2014. Clearly, $CH_4$ exchange were of minimal importance for the GHG budget (Table 2). In 2010, the contribution of $CO_2$ to the site's GHG budget was almost 70%, and $N_2O$ contributed about 30%. Only in 2012, the year of restoration, $CO_2$ and $N_2O$ exchange contributed almost equally to the site's overall GHG budget (55.1% and 43.9%, respectively).

*3.5. Carbon and nitrogen budgets of the Chamau site between 2010 and 2014*

The Chamau site assimilated on average -441 ± 260 g $CO_2$-C $m^{-2}$ $yr^{-1}$ (4410 kg C $ha^{-1}$ $yr^{-1}$) during the "business as usual" years (2010 and 2011 as well as 2013 and 2014). During the restoration year the site lost 395 g $CO_2$-C $m^{-2}$ (3950 kg C $ha^{-1}$) (Table 2). Carbon losses (and/or gains) from methane were < 1 g $CH_4$-C $m^{-2}$ during all five years. Losses of nitrogen ranged from 0.2 g $N_2O$-N $m^{-2}$ (2 kg N $ha^{-1}$) in the non-ploughing years to 2.7 g $N_2O$-N $m^{-2}$ (27 kg N $ha^{-1}$) in 2012 (Table 2).

Carbon and partial nitrogen budgets showed net gains in both parcels during the pre-ploughing years (Table 4). Considerable net losses of carbon were calculated for the ploughing year, while the same year was characterized by a net input of nitrogen. In contrast, the post-ploughing years were again recognized as years with large net gains in carbon while at the same time showing net losses of nitrogen. Over the observation period of 5 years, the Chamau grassland gained approximately 4 t C $ha^{-1}$, excluding losses via leaching and deposition of C in form of dust. During the same time, the site was characterized by a net input of approx. 70 kg N $ha^{-1}$. However, the nitrogen budget did not consider losses in form of ammonia emissions ($NH_3$), other reactive nitrogen gases ($NO_x$), deposition of N and leaching of N in form of $NO_3^-$ and $NH_4^+$ (Table 4).

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503 **4 Discussion**

504 The five-year measurement period is representative for other similarly managed grassland
505 ecosystems in Switzerland. Climate conditions were similar to the long-term average as
506 described in Wolf et al. (2013). Management activities, such as harvests and subsequent
507 fertilizer applications, were driven by overall weather conditions, (i.e. 2013 late spring, Figure
508 2a and b).
509
510 *4.1 Technical and methodological aspects*
511 Different techniques are currently applied to measure GHG fluxes from a variety of ecosystems
512 (Denmead, 2008), each having its advantages and disadvantages or being chosen for a specific
513 purpose or reason. A common approach to study individual processes or time periods
514 contributing to specific greenhouse gas emissions is to measure with GHG chambers on the
515 plot scale (Pavelka et al., 2018). Chamber methods have been widely used to derive annual
516 GHG and nutrient budgets (Barton et al., 2015; Butterbach-Bahl et al., 2013). Critical
517 assessments of the suitability and associated uncertainty in chamber derived GHG budgets in
518 relation to sampling frequency have been published by Barton et al. (2013). Existing studies
519 have not only compared the two measurement techniques employed in this study (manual
520 chambers and eddy covariance) in grasslands before, but also estimated annual emissions based
521 on differing methodologies (Flechard et al., 2007; Jones et al., 2017). Additional confidence in
522 our approach was obtained from the $N_2O$ emissions during the summer period 2013, where
523 both measurement techniques ran in parallel (Figure 3a and b). Annual budgets derived by
524 applying similar gap-filling approaches to the individual datasets led to comparable results
525 (Table 2).
526 Our study found opposing net fluxes of methane when comparing chamber fluxes (2010 and
527 2011) with eddy covariance methane fluxes. Published studies carried out to investigate
528 grassland methane emissions with chambers mostly show a net uptake of methane (Beyer et
529 al., 2015; Chiavegato et al., 2015; Kim and Tanaka, 2015; Wei et al., 2015), while eddy
530 covariance based studies often show a net release of methane (Baldocchi et al., 2012; Dengel
531 et al., 2011; Hörtnagl et al., 2018; Kroon et al., 2010). We identified three primary reasons for
532 this discrepancy: (1) the difference in spatial scales that the individual methods investigate; (2)
533 the different accuracy of both methods in detecting small fluxes; and (3) the system in which
534 researchers intend to investigate. In more detail: (1) a GHG chamber commonly covers only a
535 small area of the grassland (few $cm^2$ to $m^2$) and unless the chamber is directly placed on a heap

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of manure recently deposited by an animal, net methane fluxes are expected to show a small uptake. Such small fluxes were observed on the Chamau site. We calculated detection limits for the individual GHGs from our manual chambers following (Parkin et al., 2012). Detection limits were 0.34 ± 0.26 nmol $m^{-2}$ $s^{-1}$, 0.05 ± 0.02 nmol $m^{-2}$ $s^{-1}$, and 0.06 ± 0.06 µmol $m^{-2}$ $s^{-1}$ for $CH_4$, $N_2O$ and $CO_2$, respectively, clearly indicating that methane fluxes measured by GHG chambers in 2010/2011 were on average (-0.16 ± 0.16 nmol $CH_4$ $m^{-2}$ $s^{-1}$, see Table 2) and thus below the actual detection limit. The eddy covariance tower on the other hand has a much larger area it "sees". Measurements may include $CH_4$ emissions from ruminants when grazing within the flux footprint area, and nearby stored manure, if the location is still within the flux footprint area. However, we did not identify distinct methane peaks during occurrence of grazing since grazing pressure was very low (Figure 2, Table S2). Consequently, methane fluxes measured with EC fluctuating around zero (Figure 4b). Furthermore, considering the assumptions made when calculating eddy covariance GHG fluxes as well as the precision of the QCLAS used in this study for measuring $CH_4$ (approx. 1.5 nmol $mol^{-1}$ at 10 Hz), $CH_4$ flux measurements at the CH-CHA site primarily consisted of noise measurements. $N_2O$ fluxes in contrast were much better constrained by both methods due to clear $N_2O$ sources (i.e. fertilizer amendments) and better sensitivity of the instruments used by both techniques for $N_2O$ as compared to $CH_4$.

As a third argument on why the sign of the flux differs between studies that used conventional GHG chambers and eddy covariance towers is the researcher and the aim of the research project itself. For instance, if the aim of a project is to study the spatial heterogeneity of GHG emissions within a field a researcher may choose GHG chambers over the eddy covariance approach. Annual budgets of a whole field on the other hand may be better derived with EC measurements due to the continuity of the measurements (Eugster and Merbold, 2015). Besides the aim of a research project, current GHG research primarily tends to quantify GHG exchange from relevant sources, i.e. grazing cattle in the field, which can only be achieved by the EC approach (or with invasive methods such as SF6 as a tracer used in ruminant research) but not with manual GHG chambers as done in existing studies that investigate GHG exchange from pastures (Dengel et al., 2011).

*4.2 Annual GHG and nutrient budgets*

Net carbon losses and gains estimated for the CH-Cha site are in general within the range of values estimated by Zeeman et al., (2010) for the years 2006 and 2007. The slightly higher losses observed prior to ploughing may result from reduced productivity of the sward. This

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570 becomes particularly visible when compared to the net ecosystem exchange (NEE) of $CO_2$
571 values for the years after restoration. Losses via leaching have previously been estimated to be
572 of minor importance at this site (Zeeman et al., 2010) and were therefore not considered in this
573 study. Considerably higher C gains during post-ploughing years were caused be enhanced plant
574 growth in spring and summer. Restoration is primarily done to eradicate weeds and rodents,
575 favouring biomass productivity of the fodder grass composition. Other grasslands in Central
576 Europe, i.e. sites in Austria, France and Germany, showed similar values for net ecosystem
577 exchange. Still, total C budgets as presented here are subject to considerable uncertainty which
578 is strongly depending on assumptions made for gap-filling etc. (Foken et al., 2004).
579 Nevertheless, the values reported here show the overall trend on C uptake/release of the site
580 and clearly exceed the uncertainty of ± 50 g C per year for eddy covariance studies as suggested
581 by (Baldocchi, 2003).
582 Methane was of negligible importance for the C budget of this site. This is primarily due to the
583 low grazing pressure at CH-Cha. Studies carried out on pastures in Scotland, Mongolia, France
584 and Western Switzerland have shown that grazing can largely contribute to ecosystem-scale
585 methane fluxes, in particular if ruminants such as cattle are populating the EC footprint (Dengel
586 et al., 2011; Felber et al., 2015; Schönbach et al., 2012). On the other hand, methane fluxes
587 from a pasture located in Austria at higher elevation showed small methane release and
588 moderate methane uptake, which was an order of magnitude higher than the minimal methane
589 uptake observed in our study by greenhouse gas chamber measurements during the years 2010
590 and 2011 (Hörtnagl and Wohlfahrt, 2014). The nitrous oxide budget reported for the years
591 without ploughing in this study coincides with values reported for other grasslands in Europe,
592 ranging from moist to dry climates and lower to higher elevations in Austria and Switzerland
593 (Hörtnagl et al., 2018; Imer et al., 2013; Skiba et al., 2013).
594
595 Nitrogen budgets varied largely between the years before and after ploughing. While the site
596 was characterized by large N amendments prior to ploughing and with reduced harvest, the
597 picture was completely the opposite during the years after ploughing, with considerably less N
598 inputs compared to the nitrogen removed from the field with the harvests. Farmers aim every
599 year at having a balanced N budget (fertilizer inputs = nutrients removed from the field).
600 Pasture degradation is the main motivation for enhanced fertilizer inputs in order to stabilize
601 forage productivity. Therefore, regular restoration of permanent pastures is absolutely
602 necessary (Cowan et al., 2016). So far, we identified only a single study that investigated the
603 net effects on GHG exchange following grassland restoration (Drewer et al., 2017).

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## 5 Conclusion

This study in combination with an overview of available datasets on grassland restoration and their consequences on GHG budgets highlights the overall need of additional observational data. While restoration changed the previous C sink to a C source at the Chamau site, the wider implication in terms of the GWP of the site when including other GHGs have long-term consequences (i.e. in mitigation assessments). Furthermore, this study showed the large variations in N inputs and N outputs from this grassland and the difficulty farmers face when aiming for balanced N budgets in the field. Still, the current study focused on GHGs only and can only partially constrain the N budget. Losses in form of $NH_3$, $N_2$ and $NO_x$ need to be quantified to fully assess N budgets besides the overall fact that GHG data following grassland restoration remain largely limited to investigate long-term consequences.

Fortunately, these are likely to become available in the near future by the establishment of environmental research infrastructures (i.e. ICOS in Europe, NEON in the USA or TERN in Australia) that aim at standardized, high quality and high temporal resolution trace gas observation of major ecosystems, including permanent grasslands. With these additional data, another major constraint of producing defensible GHG and nutrient budgets, namely gap-filling procedures, will likely be overcome. New and existing data can be used to derive reliable functional relations and artificial neural networks (ANNs) at field to ecosystem scale that are capable of reproducing in-situ measured data. Once this step is achieved, both the available data as well the functional relations can be used to improve, to train and to validate existing biogeochemical process models. Subsequently, reliable projections on both nutrient and GHG budgets at the ecosystem scale that are driven by anthropogenic management as well as climatic variability become reality.

The study stresses the necessity of including management activities occurring at low frequency such as ploughing in GHG and nutrient budget estimates. Only then, the effect of potential best-bet climate change mitigation options can be thoroughly quantified. The next steps in GHG observations from grassland must not only focus on observing business as usual activities, but also aim at testing the just mentioned best-bet mitigation options jointly in the field while simultaneously in combination with existing biogeochemical process models.

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## 6 Tables and Figures

**Table 1:** Data availability of GHG fluxes measured over the five-year observation period. Values are given as all data possible, raw processed values and high quality (HQ) data, which were then used in the analysis. High quality data are data with a quality flag "0" and "1" from the EddyPro output only. Grey shaded areas represent time period where both methods (EC and static chambers) were used simultaneously to estimate $F_{N2O}$.

**Table 2:** Annual average $CO_2$, $CH_4$ and $N_2O$ fluxes and annual sums for the three GHGs as well as carbon and nitrogen gains/losses per gas species. GWP were calculated for a 100-year time horizon and based on the most recent numbers provided by IPCC (2013). Annual budgets were derived from either gap-filled manual chamber (MC) or eddy covariance (EC) measurements.

**Table 3:** Average GHG flux rates per season: winter (DJF), spring (MAM), summer (JJA) and fall (SON). Values are based on gap-filled data to avoid bias from missing nighttime data (predominantly relevant for $CO_2$). Data are only presented when continuous measurements (eddy covariance data) were available.

**Table 4:** Carbon and partial nitrogen budgets (excluding $NH_3$, $NO_x$ and $N_2$ emissions as well as N deposition is not included) for the Chamau (CH-Cha) site in 2010- 2014. Values are given in kg $ha^{-1}$. Inputs/gains are indicated with "-" and losses/exports are indicated with "+". While management information was available for both parcels (A and B), flux measurements are an integrate of both parcels.

**Table 5:** Existing studies investigating the GHG exchange over pastures following ploughing. Results presented show the flux magnitude following ploughing and are rounded values of the individual presented in the papers. Values were converted to similar units (mg $CO_2$-C $m^{-2}$ $h^{-1}$, µg $CH_4$-C $m^{-2}$ $h^{-1}$ and µg $N_2O$-N $m^{-2}$ $h^{-1}$). Based on Web of Knowledge search July 15th 2017 with the search terms "grassland", "pasture", "greenhouse gas", "ploughing" and/or "tillage". Only two studies representing conversion from pasture to cropland or other systems were included in this table.

**Table S1:** Detailed management information for the two parcels under investigation at the Chamau research station. Data are based on fieldbooks provided by the farm personnel as well as in-situ measurements. Organic fertilizer samples were sent to a central laboratory for nutrient content analysis (Labor fuer Boden- und Umweltanalytik, Eric Schweizer AG, Thun, Switzerland). Destructive harvests (n = 10) of biomass were carried out in the years 2010, 2011, 2013 and 2014. Harvest estimates are based on values derived from the in-situ measurements and data provided by the farm personnel. Detailed information on the grazing regime was furthermore provided by the farm personnel in hand-written form (not shown).

**Figure 1:** Weather conditions during the years 2010 – 2014. Weather data were measured with our meteorological sensors installed on site. (a) Daily sum of precipitation (mm) and soil water content (SWC, blue line, $m^3$ $m^{-3}$) measured at 5 cm soil depth; (b) daily averaged air temperature (°C), daily averaged soil temperature (grey line, °C) and days with snow cover (horizontal bars); (c) daily averaged photosynthetic photon flux density (PPFD, µmol $m^{-2}$ $s^{-1}$).

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Days with snow cover were identified with albedo calculations. Days with albedo > 0.45 were identified as days with either snow or hoarfrost cover.

**Figure 2:** Management activities for both parcels (A and B in panels (a) and (b), respectively) on the CH-Cha site. Overall management varied particularly in 2010 between both parcels, whereas similar management took place between 2011 and 2014. Arrow direction indicates whether carbon (C in kg $ha^{-1}$) and/or nitrogen (N in kg $ha^{-1}$) were amended to, or exported from the site ("$F_o$" and "$F_{o*}$"- organic fertilizers, slurry/manure (red); "$F_m$" - mineral fertilizer (light orange); "H" - harvest (light blue); "$G_s$" and "$G_c$" - grazing with sheep/cows (light/dark brown). Other colored arrows visualize any other management activities such as pesticide application ("$P_h$"- herbicide (light pink); "$P_m$"- molluscicide (dark pink); "T"- tillage (black), "R"- rolling (light grey) and "S"- sowing (dark grey) which occurred predominantly in 2010 (parcel B) and 2012 (parcels A and B). Carbon imports and exports are indicated by black and grey bars. Thereby black indicated the start of the specific management activities and grey the duration (e.g. during grazing, "$G_s$"). Green colors indicate nitrogen amendments or losses, with dark green visualizing the start of the activity and light green colors indicating the duration. Sign convention: positive values denote export/release, negative values import/uptake.

**Figure 3:** (a) Temporal dynamics of $N_2O$ fluxes measured with the eddy covariance (white circles) and manual greenhouse gas chambers (black circles measured in 2013) – grey lines indicate standard deviation. Arrows indicate management events ("H" = harvest, "$F_o$" = organic fertilizer application (slurry), "Ph" = pesticide (herbicide) application). (b) 1:1 comparison between chamber based and eddy covariance based $N_2O$ fluxes in 2013. The dashed line represents the 1:1 line. ($y = mx + c$, $r^2 = 0.4$, $m = 0.61$, $c = 0.17$, $p < 0.0001$). Sign convention: positive values denote export/release, negative values import/uptake.

**Figure 4:** Temporal dynamics of gap-filled daily averaged greenhouse gas (GHG) fluxes (white circles): a) ($CO_2$ exchange in µmol $m^{-2}$ $s^{-1}$; (b) $CH_4$ exchange in nmol $m^{-2}$ $s^{-1}$ and (c) $N_2O$ exchange in nmol $m^{-2}$ $s^{-1}$. Coloured circles indicate manual chamber measurements. While both GHGs, $CH_4$ and $N_2O$ were measured in 2010 and 2011 (blue cirlces), $N_2O$ only was measured in 2013 (light blue circles). The grey dashed lines indicate the beginning of a new year. Same color coding as used in Figure 3 a was used to highlight management activities. Sign convention: positive values denote export/release, negative values import/uptake. Grey lines behind the circles indicate standard deviation.

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**Table 1:** Data availability of GHG fluxes measured over the five-year observation period. Values are given as all data possible, raw processed values and high quality (HQ) data, which were then used in the analysis. High quality data are data with a quality flag "0" and "1" from the Eddypro output only. Grey shaded areas represent time period where both methods (EC and static chambers) were used simultaneously to estimate FN2O.

| Year | | $F_{CO2}$ | | | $F_{H2O}$ | | | $F_{CH4}$* | | | $F_{N2O}$* | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | max data availability | raw fluxes | HQ fluxes (0,1) | max data availability | raw fluxes | HQ fluxes (0,1) | max data availability | raw fluxes | HQ fluxes (0,1) | max data availability | raw fluxes | HQ fluxes (0,1) |
| **2010** | | | | | | | | | | | | | |
| | **30min** | 17520 | 16064 | 10171 | 17520 | 13782 | 10117 | 17520 (365) | 0 (44) | 0 (44) | 17520 (365) | 0 (44) | 0 (44) |
| | **%** | 100 | 91.68 | 58.05 | 100 | 78.65 | 57.74 | 100 (100) | 0 (12.05) | 0 (12.05) | 100 (100) | 0 (12.05) | 0 (12.05) |
| **2011** | | | | | | | | | | | | | |
| | **30min** | 17520 | 14873 | 10002 | 17520 | 12868 | 9918 | 17520 (365) | 0 (16) | 0 (16) | 17520 (365) | 0 (16) | 0 (16) |
| | **%** | 100 | 84.8 | 57.08 | 100 | 73.44 | 56.6 | 100 (100) | 0 (4.38) | 0 (4.38) | 100 (100) | 0 (4.38) | 0 (4.38) |
| **2012** | | | | | | | | | | | | | |
| | **30min** | 17568 | 15361 | 10165 | 17568 | 13509 | 10821 | 17568 | 15523 | 10181 | 17568 | 15528 | 12859 |
| | **%** | 100 | 87.43 | 57.85 | 100 | 76.89 | 61.59 | 100 | 88.35 | 57.95 | 100 | 88.38 | 73.19 |
| **2013** | | | | | | | | | | | | | |
| | **30min** | 17520 | 14825 | 10409 | 17520 | 13425 | 10642 | 17520 | 17200 | 11310 | 17520 (365) | 17200 (52) | 11790 (52) |
| | **%** | 100 | 84.61 | 59.4 | 100 | 76.62 | 60.73 | 100 | 98.16 | 64.55 | 100 (100) | 98.16 (14.24) | 67.29 (14.24) |
| **2014** | | | | | | | | | | | | | |
| | **30min** | 17520 | 15719 | 10064 | 17520 | 13903 | 10252 | 17520 | 17207 | 11166 | 17520 | 17207 | 11986 |
| | **%** | 100 | 89.71 | 57.43 | 100 | 79.35 | 58.51 | 100 | 98.2 | 63.72 | 100 | 98.2 | 68.4 |
| **All Years** | | | | | | | | | | | | | |
| | **30min** | **87648** | **76842** | **50811** | **87648** | **67487** | **51750** | **87548 (730)** | **49930 (60)** | **32657 (60)** | **87648 (1826)** | **49935 (112)** | **36635 (112)** |
| | **%** | **100** | **87.67** | **57.97** | **100** | **76.99** | **59.04** | **100 (100)** | **57.03 (8.22)** | **37.30 (8.22)** | **100 (100)** | **57.03 (6.13)** | **41.94 (6.13)** |

* data availability in parenthesis are based on static manual chambers (2010 and 2011, approx. biweekly measurements (n = 16) as well as during summer 2013 (n = 10))

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**Table 2:** Annual average CO2, CH4 and N2O fluxes and annual sums for the three GHGs as well as carbon and nitrogen gains/losses per gas species. GWP were calculated for a 100-year time horizon and based on the most recent numbers provided by IPCC (2013). Annual budgets were derived from either gap-filled manual chamber (MC) or eddy covariance (EC) measurements. **Sign convention: positive values denote export/release, negative values import/uptake.**

| | 2010 (MC) | 2010 (EC) | 2011 (MC) | 2011 (EC) | 2012 (MC) | 2012 (EC) | 2013 (MC) | 2013 (EC) | 2014 (MC) | 2014 (EC) |
|---|---|---|---|---|---|---|---|---|---|---|
| **Average $CO_2$ flux µmol $m^{-2}$ $s^{-1}$** | | -0.5 | | -0.7 | | 1.04 | | -1.4 | | -1.98 |
| **STDEV Average $CO_2$ flux µmol $m^{-2}$ $s^{-1}$** | | 3.11 | | 3.63 | | 3.02 | | 3.52 | | 3.9 |
| **g $CO_2$ $m^{-2}$** | | -695.23 | | -978.16 | | 1447.16 | | -2047.8 | | -2751.66 |
| **g $CO_2$-C $m^{-2}$** | | -189.6 | | -266.77 | | 394.68 | | -558.49 | | -750.45 |
| **Global warming potential in g $CO_2$-eq. $m^{-2}$** | | **-695.23** | | **-978.16** | | **1447.16** | | **-2047.8** | | **-2751.66** |
| **% of the total budget** | | **69** | | **91.4** | | **55.1** | | **92.3** | | **94** |
| | | | | | | | | | | |
| **Average $CH_4$ flux nmol $m^{-2}$ $s^{-1}$** | -0.16 | | -0.16 | | | 1.91 | | 3.67 | | 3.92 |
| **STDEV Average $CH_4$ flux nmol $m^{-2}$ $s^{-1}$** | 0.13 | | 0.16 | | | 11.8 | | 9.77 | | 20.61 |
| **g $CH_4$ $m^{-2}$** | -0.08 | | -0.08 | | | 0.96 | | 1.85 | | 1.97 |
| **g $CH_4$-C $m^{-2}$** | -0.06 | | -0.06 | | | 0.72 | | 1.39 | | 1.48 |
| **Global warming potential in g $CO_2$-eq. $m^{-2}$** | **-2.24** | | **-2.24** | | | **26.88** | | **51.8** | | **55.16** |
| **% of the total budget** | **0.2** | | **0.2** | | | **1** | | **2.3** | | **1.9** |
| | | | | | | | | | | |
| **Average $N_2O$ flux µmol $m^{-2}$ $s^{-1}$** | 0.84 | | 0.25 | | | 3.13 | 0.28 | 0.32 | | 0.32 |
| **STDEV Average $N_2O$ flux nmol $m^{-2}$ $s^{-1}$** | 0.84 | | 0.2 | | | 4.35 | 0.6 | 0.73 | | 0.68 |
| **g $N_2O$ $m^{-2}$** | 1.17 | | 0.34 | | | 4.36 | 0.39 | 0.45 | | 0.45 |
| **g $N_2O$-N $m^{-2}$** | 0.74 | | 0.22 | | | 2.77 | 0.25 | 0.28 | | 0.28 |
| **Global warming potential in g $CO_2$-eq. $m^{-2}$** | **310.05** | | **90.1** | | | **1155.4** | **103.35** | **119.25** | | **119.25** |
| **% of the total budget** | **30.8** | | **8.4** | | | **43.9** | | **5.4** | | **4.1** |
| **Total GWP potential** | **-387.42** | | **-890.3** | | | **2629.44** | **-1892.65** | **-1876.75** | | **-2577.25** |

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**Table 3:** Average GHG flux rates per season: winter (DJF), spring (MAM), summer (JJA) and fall (SON). Values are based on gap-filled data to avoid bias from missing nighttime data (predominantly relevant for CO2). Data are only presented when continuous measurements (eddy covariance data) were available. Sign convention: positive values denote export/release, negative

| | $CO_2$ (µmol $m^{-2}$ $s^{-1}$) | | | | $CH_4$ (nmol $m^{-2}$ $s^{-1}$) | | | | $N_2O$ (nmol $m^{-2}$ $s^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | **DJF** | **MAM** | **JAJ** | **SON** | **DJF** | **MAM** | **JAJ** | **SON** | **DJF** | **MAM** | **JAJ** | **SON** |
| **2010** | 0.56 | -1.75 | -0.79 | 0.01 | | | | | | | | |
| **SD** | 5.39 | 12.07 | 11.34 | 9.31 | | | | | | | | |
| **2011** | 0.48 | -4.29 | 0.39 | 0.66 | | | | | | | | |
| **SD** | 5.47 | 10.54 | 12.52 | 8.97 | | | | | | | | |
| **2012** | 0.98 | 3.64 | -0.33 | -0.13 | 2.2 | 1.38 | 2.76 | 1.32 | 3.1 | 5.61 | 3.06 | 0.73 |
| **SD** | 5.69 | 9.1 | 13.65 | 8.03 | 14.91 | 11.85 | 10 | 9.94 | 4.77 | 5.52 | 3.19 | 0.92 |
| **2013** | -0.2 | -4.49 | -1.3 | 0.13 | 2.18 | 5.3 | 3.79 | 3.4 | 0.12 | 0.19 | 0.73 | 0.26 |
| **SD** | 5.04 | 12.98 | 12.14 | 9.81 | 11.31 | 9.25 | 9.08 | 9.21 | 0.23 | 0.37 | 1.27 | 0.38 |
| **2014** | -0.42 | -5.07 | -2.43 | 0.04 | 6.71 | 5.49 | 0.08 | 3.47 | 0.18 | 0.4 | 0.45 | 0.27 |
| **SD** | 6.56 | 12.93 | 12.98 | 9.45 | 22.93 | 31.37 | 8.5 | 1021 | 0.27 | 0.78 | 0.87 | 0.63 |
| **2010-2014** | 0.28 | -2.39 | -0.89 | 0.14 | 3.69 | 4.06 | 2.21 | 2.73 | 1.14 | 2.07 | 1.42 | 0.42 |
| **SD** | 5.68 | 12.06 | 12.58 | 9.14 | 17.15 | 20.11 | 9.31 | 9.81 | 3.09 | 4.08 | 2.35 | 0.71 |

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**Table 4:** Carbon and partial nitrogen budgets (excluding NH3, NOx and N2 emissions as well as N deposition is not included) for the Chamau (CH-Cha) site in 2010-2014. Values are given in kg ha-1. Inputs/gains are indicated with "-" and losses/exports are indicated with "+". While management information was available for both parcels (A and B), flux measurements are an integrate of both parcels.

| | 2010 | | 2011 | | 2012 | | 2013 | | 2014 | | Total 2010 - 2014 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Carbon | Nitrogen | Carbon | Nitrogen | Carbon | Nitrogen | Carbon | Nitrogen | Carbon | Nitrogen | Carbon | Nitrogen |
| **Fertilizer (kg ha$^{-1}$) - Parcel A** | -1425.53 | -253.09 | -1222.06 | -253.97 | -2242.51 | -271.12 | -926.81 | -213.19 | -385.04 | -122.08 | -6201.95 | -1113.45 |
| **Fertilizer (kg ha$^{-1}$) - Parcel A** | -1487.1 | -194.3 | -1509.9 | -258.3 | -2229 | -293.2 | -1001.1 | -240 | -996.8 | -183.2 | -7223.9 | -1169 |
| **Harvest (kg ha$^{-1}$) - Parcel B** | 3449.26 | 221.85 | 2570.3 | 165.32 | 1684.88 | 108.37 | 4393.9 | 282.61 | 3527.29 | 226.87 | 15625.63 | 1005.02 |
| **Harvest (kg ha$^{-1}$) - Parcel B** | 2018.6 | 129.8 | 1952.2 | 125.6 | 1481.2 | 95.3 | 4174.8 | 268.5 | 6673.4 | 429.2 | 16300.2 | 1048.4 |
| **Flux (CO2-C kg ha$^{-1}$)** | -1896.6 | | -2667.7 | | 3946.8 | | -5584.9 | | -7504.5 | | -13706.9 | |
| **Flux (CH4-C kg ha$^{-1}$)** | -0.6 | | -0.6 | | 7.2 | | 13.9 | | 14.8 | | 34.7 | |
| **Flux (N2O-N kg ha$^{-1}$)** | | 7.4 | | 2.2 | | 27.7 | | 2.8 | | 2.8 | | 42.9 |
| **Total Budget - Parcel A** | **126.53** | **-23.84** | **-1320.06** | **-86.45** | **3396.37** | **-135.05** | **-2103.91** | **72.22** | **-4347.45** | **107.59** | **-4248.52** | **-65.53** |
| **Total Budget - Parcel B** | **-1365.7** | **-57.1** | **-2226** | **-130.5** | **3206.2** | **-170.2** | **-2397.3** | **31.3** | **-1813.1** | **248.8** | **-4595.9** | **-77.7** |

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**Table 5:** Existing studies investigating the GHG exchange over pastures following ploughing. Results presented show the flux magnitude following ploughing and are rounded values of the individual presented in the papers. Values were converted to similar units (mg CO2-C m-2 h-1, µg CH4-C m-2 h-1 and µg N2O-N m-2 h-1). Based on Web of Knowledge search July 15th 2017 with the search terms "grassland", "pasture", "greenhouse gas", "ploughing" and/or "tillage". Only two studies representing conversion from pasture to cropland or other systems were included in this table.

| Publication | Grassland type | Observation Period | Measurement technique | CO2-C | CH4-C | N2O-N | Supporting Information |
|---|---|---|---|---|---|---|---|
| Bertora et al. 2007 | permanent pasture | 62 days | Incubation study of soil cores | 188 - 330 mg kg-1 soil * | NA | 50 - 1000 µg kg-1 soil * | Simulated ploughing, varying moisture contents, earthworm fertilizer application between 36 - 133 kg N ha-1 yr-1, conversion to cropland |
| Li et al. 2015 | managed grassland | approx five years grassland followed by three years of cropland | static GHG chamber | > 600 mg m-2 h-1 & | NA | > 1000 µg m-2 h-1 & | |
| Buchen et al. 2016 | managed grassland | 44 days | 15N isotopic measurements | NA | NA | 100 - 1000 µg m-2 h-1 ^ | 15N gas flux method, restoration, two soil types, conversion to two soil types, N2O emissions |
| Krol et al.2016 | permanent grassland | 17 weeks | static GHG chambers on lysimeter | NA | NA | 3000 µg m-2 h-1 % | and N leaching |
| Cowan et al. 2016 | permanent grassland | 175 days | eddy covariance | NA 250 - 2000 mg m-2 h-1 | NA 1000 - 8000µg m-2 h-1 | 500 - 700 µg m-2 h-1 $ | two adjacent fields (tilled and untilled) |
| Drewer et al. 2016 | permanent grassland | three years | static GHG chambers/eddy covaria | $ | $ | 500 - 7000 µg m-2 h-1 $ | comparing ploughed and un-ploughed grassland |
| MacDonald et al. 2011 | poorly drained grassland | | static GHG chambers | NA | NA | > 6000 µg m-2 h-1 ! 1800 - 5000 µg m-2 h-1 | grassland converted to fallow three treatments with different |
| Estavillo et al. 2001 | permanent pasture | | incubation study of soil cores | NA | NA | § | fertilizer levels, N2O and N2 |
| Merbold et al. 2014 and this study | permanent grassland | five years | static GHG chambers/eddy covariance | > 400 mg m-2 h-1 # | non-different from zero | > 2000 µg m-2 h-1 # | conventional management with restoration occuring after two years |

* cumulative fluxes over 62 days, & conversion from grassland to cropland, ^ approximate value recalculated from figure in the paper, % approximate peak emission following restoration calculated from figure in the paper, $ approximate value recalculated from figures presented in both paper, ! approximate value recalculated from figure in the paper, § approximate value presented in Figure 3 in the publication, # peak emissions

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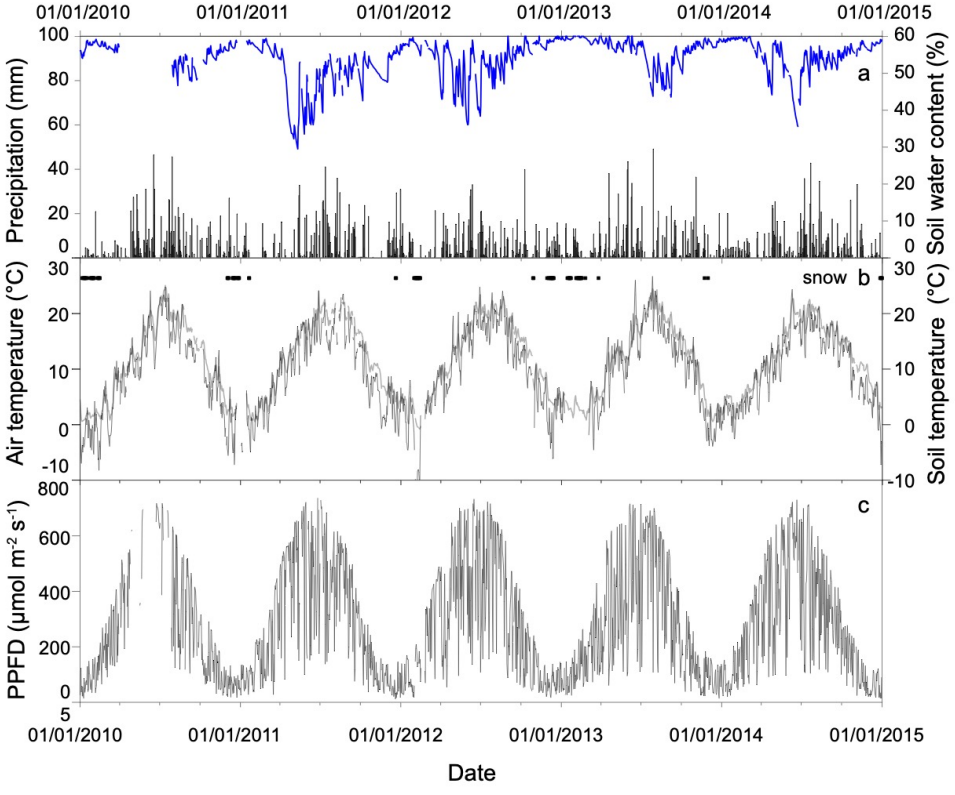


**Figure 1**: Weather conditions during the years 2010 – 2014. Weather data were measured with our meteorological sensors installed on site. (a) Daily sum of precipitation (mm) and soil water content (blue line, %) measured at 5 cm soil depth; (b) daily averaged air temperature (black line, °C), daily averaged soil temperature (grey line, °C) , and days with snow cover (horizontal bars); (c) daily averaged photosynthetic photon flux density (PPFD, µmol $m^{-2}$ $s^{-1}$). Snow covered days were identified with albedo calculations. Days with albedo values > 0.45 were identified as days with either snow or hoarfrost cover.

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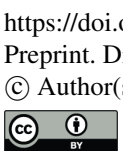



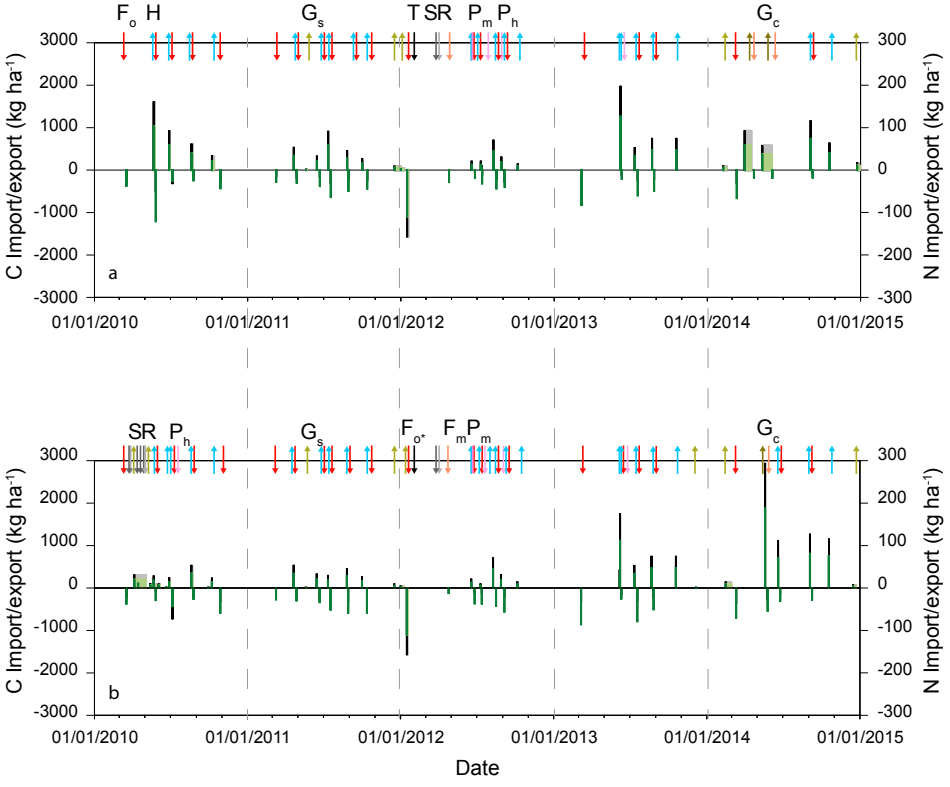


**Figure 2**: Management activities for both parcels (A and B in panels (a) and (b), respectively) on the CH-Cha site. Overall management varied particularly in 2010 between both parcels, whereas similar management took place between 2011 and 2014. Arrow direction indicates whether carbon (C in kg ha-1) and/or nitrogen (N in kg ha-1) were amended to, or exported from the site ("$F_o$" and "$F_{o*}$"- organic fertilizers, slurry/mannure (red); "$F_m$" - mineral fertilizer (light orange); "H" - harvest (light blue); "$G_s$" and "$G_c$" - grazing with sheep/cows (light/dark brown). Other coloured arrows visualize any other management activities such as pesticide application ("$P_h$"- herbicide (light pink); "$P_m$"- molluscicide (dark pink); "T"- tillage (black), "R"- rolling (light grey) and "S"- sowing (dark grey) which occurred predominantly in 2010 (parcel B) and 2012 (parcels A and B). Carbon imports and exports are indicated by black and grey bars. Thereby black indicated the start of the specific management activities and grey the duration (e.g. during grazing, "Gs"). Green colors indicate nitrogen amendments or losses, with dark green visualizing the start of the activity and light green colors indicating the duration. Sign convention: positive values denote export/release, negative values import/uptake.

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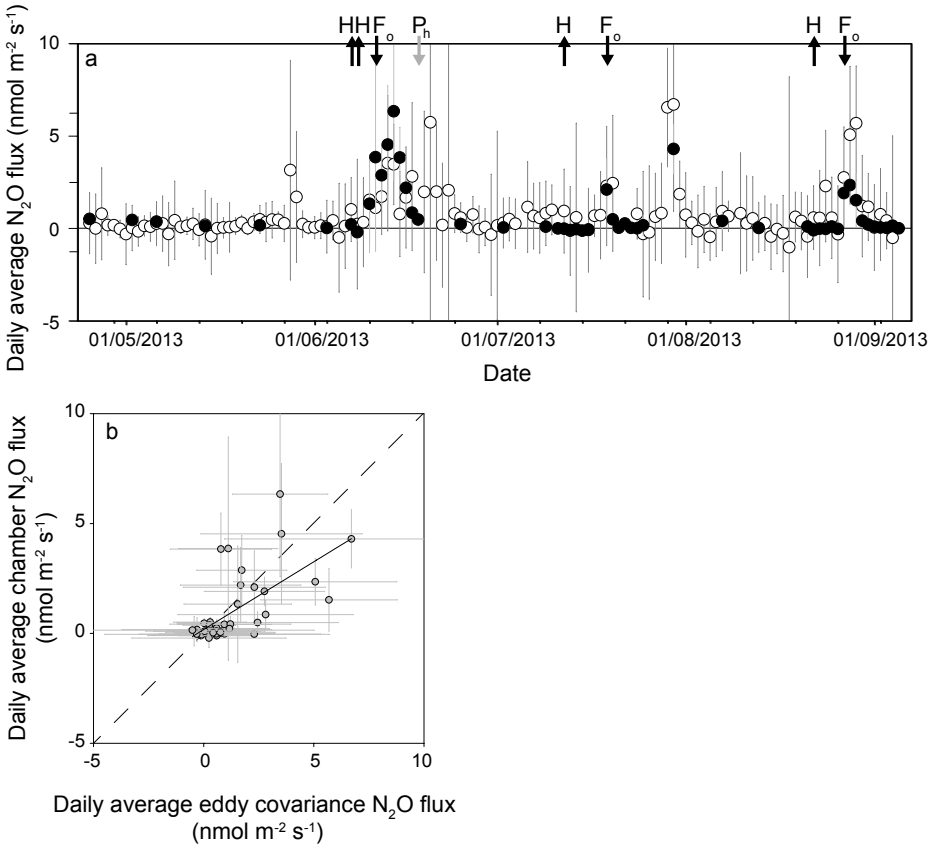


**Figure 3**: (a) Temporal dynamics of daily avergae $N_2O$ fluxes measured with the eddy covariance (white circles) and manual greenhouse gas chambers (black circles) in 2013. Black arrows indicate management events, grey lines indicate standard deviation ("H"= harvest, "$F_o$" = organic fertilizer application (slurry), "$P_h$"= pesticide (herbicide) application);
(b) 1:1 comparison between chamber based and eddy covariance based $N_2O$ fluxes in 2013. The dashed line represents the 1:1 line. (Regression: y = 0.61x+0.17, $r^2$ = 0.4). Sign convention: positive values denote export/release, negative values import/uptake.

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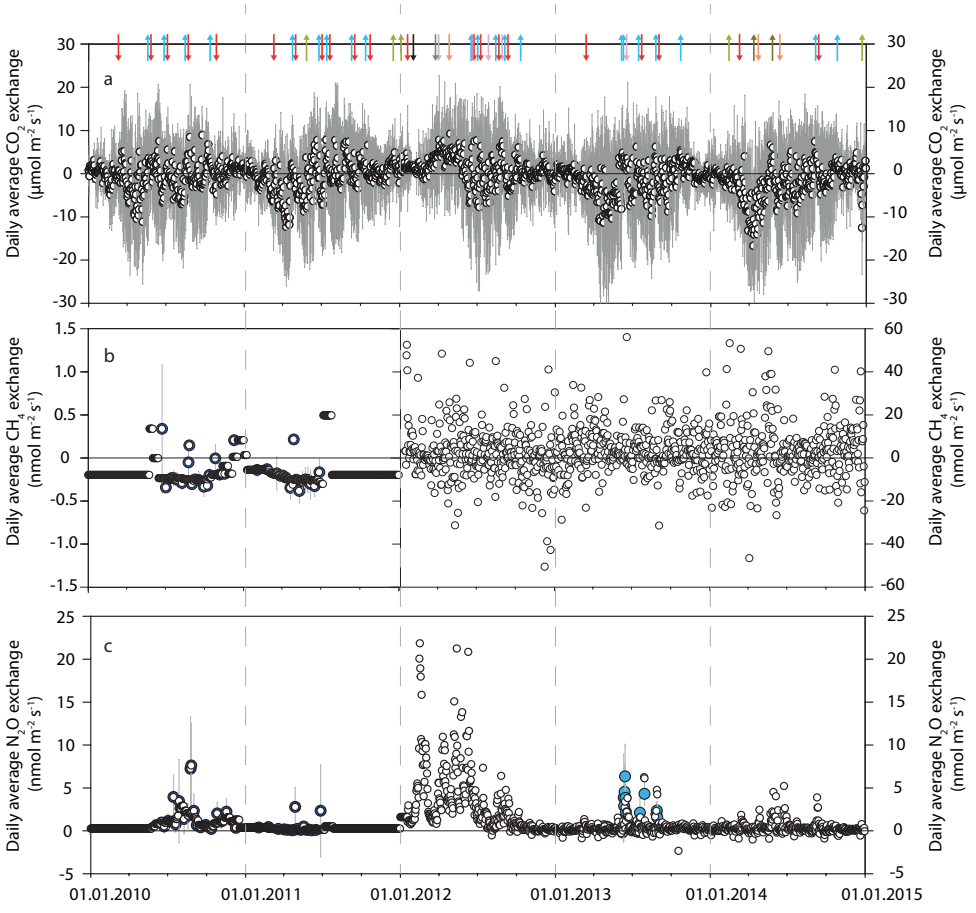


**Figure 4:** Temporal dynamics of gap-filled daily averaged greenhouse gas (GHG) fluxes (white circles): a) (CO2 exchange in µmol m-2 s-1; (b) CH4 exchange in nmol m-2 s-1 and (c) N2O exchange in nmol m-2 s-1. Coloured circles indicate manual chamber measurements. While both GHGs, CH4 and N2O were measured in 2010 and 2011 (blue cirlces), N2O only was measured in 2013 (light blue circles). The grey dashed lines indicate the beginning of a new year. Same color coding as used in Figure 3 a was used to highlight management activities. Sign convention: positive values denote export/release, negative values import/uptake. Grey lines behind the circles indicate standard deviation.