Integrated management of a Swiss cropland is not sufficient to preserve its soil carbon pool in the long-term

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Abstract. Croplands are involved in the exchange of carbon dioxide (CO_2) between the atmosphere and the biosphere. Furthermore, soil carbon (C) stocks play an important role in soil fertility. It is, thus, of great interest to know whether intensively managed croplands act as a net source or sink of atmospheric CO_2, and if soil C stocks are preserved over long timescales. The FluxNet site CH-Oe2 in Oensingen, Switzerland has been operational since the end of 2003. This cropland is managed under the Swiss framework of the Proof of Ecological Performance (PEP, a variant of integrated management) with a crop rotation centred on winter wheat, which also includes winter barley, winter rapeseed, peas, potato and intermediate cover crops. In addition to eddy covariance measurements, meteorological and soil measurements were available along with information on C imports and exports from organic fertilisation, sowing and harvesting. This study investigates cropland C budgets over 13 years and assesses whether the PEP regulations resulted in a balanced C budget. Strongest CO_2 uptake was observed during cereal seasons. C export through harvest, however, offset the strong uptake of the cereal crops. The largest net CO_2 emissions to the atmosphere were observed during pea and cover crop seasons. Net biome production, representing the overall C budget (assuming carbon leaching to groundwater to be negligible), typically ranged between close to C neutral to C losses of up to 407 g C m^{-2} per season, with peas being the largest source. Overall, the field lost 1674 g C m^{-2} over 13 years (129 g C m^{-2} yr^{-1}), which was confirmed by soil C stock measurements at the beginning and the end of the study period. Although managing the field under the regulations of PEP did not result in an overall C sink, model simulations showed that the use of cover crops reduced the C losses compared to leaving the field bare. The use of solid manure improved the C budget by importing substantial amounts of C into the soil while liquid manure had only a small effect. We thus conclude that additional efforts are needed to bring Swiss management practices closer to the goal of preserving soil C in the long-term.

1 Introduction

Understanding the net carbon (C) exchange of agricultural fields, which are typically highly managed, is of interest in the context of global warming and rising atmospheric carbon dioxide (CO_2) concentrations (Ciais et al., 2013). Through photosynthesis, CO_2 is removed from the atmosphere, whilst respiration of soils and plants releases CO_2 to the atmosphere. An ecosystem can be a net CO_2 source or sink from an atmospheric point of view, depending on whether photosynthesis or respiration dominates. This exchange of CO_2 between an ecosystem and the atmosphere is typically measured with the eddy covariance technique (Baldocchi, 2003; Eugster and Merbold, 2015) as net ecosystem exchange (NEE).

Soil C concentrations have an important influence on soil fertility by improving the soil water holding capacity, nutrient storage, aggregation and sorption of organic or inorganic pollutants (Smith et al., 2015). Because agricultural land makes up approximately 37 % of the world's land surface (The World Bank, 2017) and holds substantial amounts of C, soil management can be a powerful means of mitigating C losses of croplands (Lal et al., 2011). Therefore, it is of great interest to determine whether agricultural ecosystems are a C source over longer timescales and how this influences the C stocks in the soil.

To understand whether an ecosystem is losing C, all exports (e.g., harvests) and all imports (e.g., organic fertilisers or seeds) of C need to be considered in order to calculate the net biome production (NBP). There have been a number of studies investigating NEE and the C budget of different ecosystems, however, most of them focused on forests (e.g., Turner et al., 1995; Etzold et al., 2010; Adachi et al., 2011; Zielis et al., 2014) and grassland ecosystems (e.g., Allard et al., 2007; Ammann et al., 2007; Gilmanov et al., 2007; Soussana et al., 2007; Li et al., 2008). On the other hand, there are relatively few long-term cropland flux stations resulting in a much lower number of cropland studies. In contrast to forested ecosystems, croplands are often considered overall C sources (Ceschia et al., 2010). Schulze et al. (2009) for example reported a significant source of 33 Tg C yr^{-1} for Continental European croplands. This may lead to a strong decrease in soil C because large amounts of photosynthetically-fixed CO_2 are removed from the field during harvest and only a relatively small amount of biomass, in the form of residues and litter, is returned to the soil (Janzen, 2006). The management type and intensity of agricultural ecosystems strongly influences the net C budget (Ceschia et al., 2010; Eugster et al., 2010). Some studies have found that croplands growing specific crops (e.g., maize) and/or under specific management practices (e.g., no tillage or reduced tillage) were net C sinks or C neutral (e.g., Hollinger et al., 2005; Nishimura et al., 2008; Robertson et al., 2000).

Most cropland studies looked either at short periods of measurements (single years or only one crop rotation) from single field sites (e.g., Anthoni et al., 2004; Moureaux et al., 2006, 2008; Aubinet et al., 2009; Béziat et al., 2009; Schmidt et al., 2012; Chi et al., 2016), combined measurements from different field sites (Janssens et al., 2003; Ceschia et al., 2010; Eugster et al., 2010; Kutsch et al., 2010; Gilmanov et al., 2013; Joo et al., 2016; Jensen et al., 2017) or were based on model simulations (e.g., Parazoo et al., 2014; Vuichard et al., 2016). Prescher et al. (2010) pointed out the need for long periods for investigating management influences on the NBP. Furthermore, only with long-term measurements can a direct comparison with soil C stocks be made, because stocks change only slowly and are typically only measured at decadal intervals. There have been only three studies analyzing the C budget of croplands in detail at a single site over a longer timescale: Suyker and Verma (2012) and Dold et al. (2017) studied maize-soybean rotations in the United States over eight and nine years, respectively, and Buysse et al. (2017) studied a four-year crop rotation field in Belgium over twelve years.

At the Swiss FluxNet cropland site CH-Oe2 in Oensingen, Switzerland, long-term eddy covariance and meteorological measurements have been conducted since 2003. This is the only long-term Swiss FluxNet cropland site. The field is managed under the Swiss integrated management framework of the Proof of Ecological Performance (PEP) (Swiss Federal Council, 2017). The term "integrated management" is here defined as a more sustainable management approach when compared to conventional agricultural practices and does not only focus on economical benefits but also takes ecological aspects into account. These agricultural regulations were introduced in Switzerland in the late 1980s. The PEP regulations include amongst other requirements, the fulfilment of neutral nitrogen (N) and phosphorus budgets, the implementation of a crop rotation, an appropriate soil protection (e.g., by planting cover crops in the autumn, to avoid bare fields during winter), and the reduction and more efficient use of fertilisers and pesticides.

Given that there is little known about the detailed long-term C budgets of crop fields, especially in Switzerland, and to understand whether implementing PEP has also led to a balanced C budget, the objectives of this study were to (1) analyse NBP of the crop field over 13 years, (2) determine the impact of the different crop types on NBP, and (3) assess the differences in C loss by planting a cover crop compared to a bare field.

2 Material and methods

2.1 Measurement site

The CH-Oe2 field site is located in Oensingen, in the canton of Solothurn, Switzerland ($47°17'11.1''$N, $7°44'01.5''$E, 452 m a.s.l.). The crop field has an extend of 1.55 ha with a fluvisol with 42 % clay, 33 % silt and 25 % sand (Alaoui and Goetz, 2008). The average air temperature (T_A) at the site is 9.8 °C, and the average annual precipitation sum ($Prec$) is 1155 mm (Fig. 1, period 2004 to 2016; the diagram was produced in R with the diagwl function of the climatol package). The field has been managed under the regulations of PEP since the late 1990s, featuring a three-year crop rotation (Table 1). The main crop has been winter wheat, which is usually planted every third year followed by winter barley. The third crop in the rotation was either potato, winter rapeseed or peas. Only between autumn 2006 and autumn of 2010, wheat was planted every second year. Before summer crops (potato or peas) were sown, a mixture of summer oat, *Phacelia*, and Alexandrine clover (2005) or *Phacelia* only was planted (2009 and 2015). After every rapeseed harvest, a voluntary regrowth of the rapeseed was allowed and the newly grown rapeseed plants were then mulched and incorporated into the soil later in the autumn before wheat was sown. Before the management under PEP started in the late 1990s, the field had an eight-year arable-ley rotation, including three years of perennial grass-clover mixture.

Management information including dates and type of tillage, sowing dates and seed weights, fertilisation dates and amounts, dates of pesticide applications as well as harvest dates and yield (grain and straw) was regularly provided by the farmer (Table 1). Management timing and field conditions were confirmed with webcam images of the field (since 20 May 2005 taken at 10:30, 12:30 and 14:30 CET (UTC + 1 hour) and since 01 March 2015 at 9:30, 12:30 and 14:30 CET). In the case of wheat, barley and rapeseed, the moisture content of the harvested grains was reported by the farmer. Cover crops were not harvested and, thus, ploughed into the soil. No harvest was conducted for the potatoes in 2006; due to a hail storm on 05 July 2006 the potatoes were of very poor quality, therefore left in the ground and later ploughed under. Between 2004 and 2016, solid manure was applied on three occasions (always at the end of the cover crop seasons), whereas liquid manure was applied on five occasions (at the end of wheat, barley and rapeseed seasons). A crop season is here defined as the period between sowing of a crop and sowing of the following crop. Mineral fertilisers were applied during all crop seasons, except for cover crops and

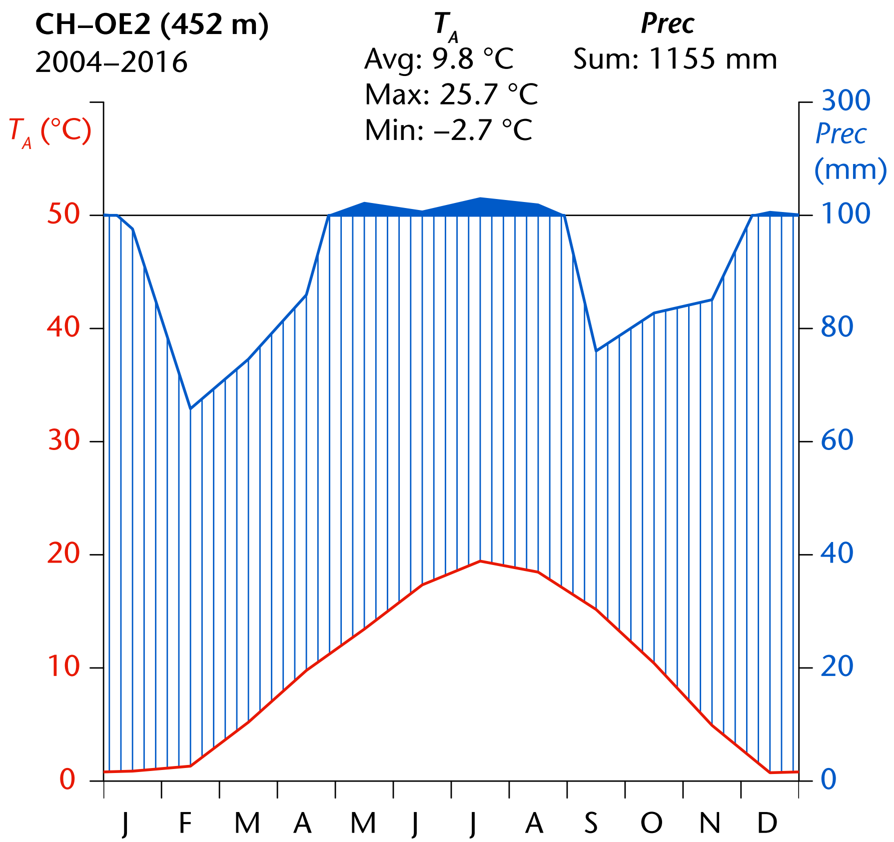

Figure 1. Climate diagram after Walter and Lieth (1960) for the time period of 2004 to 2016. The monthly average air temperature (T_A) and the monthly total precipitation ($Prec$) are shown in red and blue, respectively. Average (Avg), average minimum (Min) and average maximum (Max) annual T_A and average annual total (Sum) $Prec$ are listed at the top of the figure. Note that the scale of the right axis changes above 100 mm.

the 2016 pea season. Herbicides were applied during all crop seasons, except for cover crops and the potato season. Fungicides were only used in spring 2004 (wheat), 2005, 2012 and 2015 (all barley), and insecticides were applied during the rapeseed season in 2007/2008 as well as during the 2010 pea season. Grubbing (shallow secondary tillage) was conducted almost every year, ploughing approximately every third year (typical depth of 30 cm), and harrowing was conducted every year since 2010. In 2005, the cover crop was mulched on 09 November. In 2010 and 2016, the cover crop was incorporated into the ground shortly before the next crop was sown without any preceding mulching.

Table 1. Management information for all 16 crop seasons (defined as sowing of the current crop to sowing of the following crop) between 2003 and 2016 with crop type, sowing and harvest dates and yield (G = grain, P = peas, S = straw). Moisture content of the harvested biomass (MC) is given in brackets. If manure was applied during the crop season, date, manure type and amount are given as well.

Crop	Sowing	Harvest		Manure application	
		Date	Yield, kg ha^{-1} (MC, %)	Date	Type (amount)
Wheat	16 Oct 2003	04 Aug 2004	G: 7980 (13.7), S: 4030 (11.1)	–	–
Barley	29 Sep 2004	14 Jul 2005	G: 6940 (12.3), S: 1700 (11.8)	–	–
Cover crop	09 Aug 2005	not harvested	–	24 Jan 2006	solid (13 t)
Potatoe	05 May 2006	not harvested	–	–	–
Wheat	19 Oct 2006	15 Jul 2007	G: 6140 (11.8), S: 4400 (11.1)	–	–
Rapeseed	28 Aug 2007	16 Jul 2008	G: 3160 (5.8)	–	–
Wheat	07 Oct 2008	21 Jul 2009	G: 6880 (13.1), S: 3660 (11.1)	04 Aug 2009	liquid (33 m^3)
Cover crop	12 Aug 2009	not harvested	–	06 May 2010	solid (10 t)
Peas	09 May 2010	19 Jul 2010	P: 5290 (84.8)	–	–
Wheat	15 Oct 2010	02 Aug 2011	G: 7810 (12.8), S: 3910 (11.1)	02 Sep 2011	liquid (20 m^3)
Barley	24 Sep 2011	09 Jul 2012	G: 8700 (11.6), S: 2130 (11.8)	28 Aug 2012	liquid (30 m^3)
Rapeseed	04 Sep 2012	28 Jul 2013	G: 3920 (9.7)	24 Sep 2013	liquid (30 m^3)
Wheat	19 Oct 2013	24 Jul 2014	G: 7480 (16.2), S: 4400 (11.1)	12 Sep 2014	liquid (30 m^3)
Barley	29 Sep 2014	04 Jul 2015	G: 8110 (11.8) , S: 1580 (11.8)	–	–
Cover crop	03 Aug 2015	not harvested	–	15 Mar 2016	solid (20 t)
Peas	09 May 2016	25 Jul 2016	P: 500 (84.8)	–	–

2.2 Turbulent fluxes

Since the end of December 2003, eddy covariance (EC) measurements have been made at the site. The eddy covariance measurements consist of three-dimensional wind speed and air temperature measurements with an ultrasonic anemometer (R3-50, Gill Instruments Ltd., Lymington, Hampshire, UK) as well as CO_2 and water vapour measurements with an open-path infrared gas analyser (LI-7500, LI-COR, Lincoln, NB, USA) and were recorded at 20 Hz.

The eddy covariance data were processed and quality controlled with the software EddyPro (Version 6.2.0, LI-COR). Thereby 30-min averaged fluxes were calculated and the following corrections and filters were applied: high-frequency despiking and a drop out test (on the raw data) following Vickers and Mahrt (1997), angle-of-attack correction (Nakai et al., 2006), double rotation (Wilczak et al., 2001), lag time compensation via covariance maximisation using a default lag time if a maximum was not attained within a plausible window, density fluctuation correction (Webb et al., 1980), high-pass filter (Horst, 1997), low-pass filter (Moncrieff et al., 2004) as well as a steady state test and test for well developed turbulence conditions (on the processed fluxes). Fluxes were rejected from further analyses when they were outside a physically plausible range ($\pm 50\ \mu\text{mol m}^{-2}\ \text{s}^{-1}$). From November 2015 to May 2016, an angle-of-attack filter was also applied, which discarded half-hourly fluxes if the angle of attack was outside the range of -10 to 30° for more than 10% of the half hours. This additional quality criterion was applied to filter out time periods of an occasional malfunctioning of an anemometer transducer. During times of repair of the R3-50 ultrasonic anemometer, the ultrasonic anemometer was replaced by a model HR-100 ultrasonic anemometer (Gill). CO_2 storage in the air layer below the flux measurement height was calculated according to Aubinet et al. (2001) within EddyPro.

NEE was calculated by adding the half-hourly CO_2 flux and CO_2 storage and subsequently despiked by iteratively removing outliers outside the valid range defined as the mean $\pm$ three times its standard deviation (Rogiers et al., 2004) based on a 30-day moving window. NEE was then gap filled and partitioned into gross primary production (GPP) and ecosystem respiration (R_{eco}) based on Reichstein et al. (2005) using the R software REddyProc by the MPI Jena (Version 1.0.0., Reichstein et al., 2017). Gap filling was done after applying an automatically determined u_* filter (with a threshold ranging between 0.01 and 0.13 m s^{-1}; changed for each crop season). The u_* threshold was automatically determined for each bare soil period and growing period separately within REddyProc by determining the saturation of NEE with u_*. In total, NEE had to be gap filled for 46% of the half hours.

For the beginning of the first wheat season (October to December 2003), the measurement station was not established yet and therefore no flux data were available. From November 2006 until Feb 2007, no reliable NEE measurements were available due to a sonic anemometer malfunctioning. Therefore, NEE was estimated for these two time periods in 2003 and 2006/2007 by averaging gap-filled NEE of the corresponding days of the wheat seasons in 2008, 2010 and 2013 (on a daily basis).

2.2.1 Yield, seed and manure

Moisture contents of straw and seeds were determined in the lab by weighing a subsample with a high precision scale before and after drying in the oven at 55 °C. Elemental C concentrations of dried and ground yield as well as seed samples were measured with a Flash EA 1112 Series elemental analyser (Thermo Italy, Rhodano, Italy) coupled to a Finnigan MAT DeltaplusXP isotope ratio mass spectrometer (Finnigan MAT, Bremen, Germany) according to Brooks et al. (2003) and Werner et al. (1999), with a sample, blank and laboratory standard positioning (Identical-Treatment principle) following Werner and Brand (2001). The performance was tested with laboratory standards. The C concentrations and moisture contents of manure were measured in 2006 (solid) and 2017 (liquid) at the laboratory LBU (Thun, Switzerland) and in 2009 (liquid) by Agroscope (Zurich, Switzerland). The measurements in 2006 were used for all other solid manure applications (2006, 2010 and 2015) as well. In the case of liquid manure, an average of all available liquid manure measurements of CH-Oe2 and the neighbouring site CH-Oe1 (same farm, 2002-2011; Ammann et al., 2009) were averaged when the manure was not analysed during a given year. In cases when the moisture content or C concentration of the harvested biomass were not measured, the value was substituted by the average of all other available seasons of the same crop. In the case of peas, a sample from a neighbouring field in 2017 was used to determine the moisture content of the peas at harvest. To determine the C export and import (g C m^{-2}) through harvest, fertilisation and sowing, first the dry weight of the yields, fertilisers and seeds was calculated and then multiplied by the corresponding C concentration.

2.2.2 Soil carbon and nitrogen

Soil C and N concentrations were measured in 2004 and 2017. On 13 October 2004, soil samples were taken to a depth of 12 cm at 36 locations in the field. Each sample was divided into two parts (0-6 cm, 6-12 cm depth), from which the C and N concentrations were determined with an elemental analyser (LECO CHN-1000, LECO Corp., St. Joseph, MI, U.S.A.) after sieving (1 mm mesh), drying and grinding the soil. Additionally, bulk density of the soil was determined for a 4-cm deep core within the top 12 cm of the soil at the same 36 locations on the field.

In 2017, soil samples for C and N measurements were taken on five days (23 February, 23 March, 05 April, 04 May and 31 May), of which two days were before and three were after the application of liquid manure (31 March 2017). Sampling dates before and after the application of liquid manure were chosen to see if it would change the soil C and N significantly. At 12 locations, the samples were taken to a depth of 30 cm, and at four locations to a depth of 70 cm. These samples were divided into subsamples of 0−15 cm, 15−30 cm, 30−50 cm and 50−70 cm depth on the first 4 sample days, and 0−2 cm, 2−5 cm, 5−10 cm, 10−15 cm, 15−30 cm, 30−50 cm and 50−70 cm on the last sample day. All samples were processed the same way as in 2004. Concentrations of C and N were determined with the same set up as for yield C concentrations. In 2017, bulk density of the soil was determined at four locations for 5.5−9.5 cm depth and 20.5−24.5 cm depth and at one location for 0.5−4.5 cm, 5.5−9.5 cm, 10.5−14.5 cm, 20.5−24.5 cm, 38.0−42.0 cm and 58.0−62.0 cm depth. Averages of C and N concentration and bulk density for each depth layer and year were calculated and soil C and N densities (ρ_C and ρ_N, respectively) were then determined by multiplying the average C and N concentration of a depth layer by the corresponding average bulk density. For stock calculations, the ρ_C or ρ_N of each depth layer was multiplied by the layer thickness and then all depth layers were summed.

The statistical analysis of differences in soil C and N vertically and over time was conducted in R. Significance of soil bulk density as well as soil C and N concentrations, densities and stocks between 2004 and 2017 was determined with a one-sided t-test. To test whether vertical differences in C and N densities in 2017 were significant a one-way ANOVA with following post hoc test was conducted. To test whether the application of slurry in 2017 resulted in a change in C densities, a two-way ANOVA including interactions of the factors time of sampling and depth with following post hoc tests was conducted.

The uncertainty of the LECO CHN 1000 analyser was determined from repeated measurements of two standards and one blank (standard deviations). At concentrations in the range of soil samples the accuracy of the C and N contents is ± 1.7 % and ± 3.9 %, respectively. The uncertainty of the C and N contents measured with the elemental analyser in 2017 were ± 1.5 % and ± 1.7 % of the C and N contents, respectively, determined as the average from 7 batches

2.2.3 Ancillary meteorological and soil measurements

Further ancillary meteorological and soil measurements have been made at the site since the end of 2003. The set up consists of an air temperature and relative humidity sensor (CS215, Campbell Scienctific Ltd., Logan UT, USA; 2 m height), a cup anemometer (A100R, Vector Instruments, Denbighshire, UK; 2 m height) and a wind vane (W100P, Vector Instruments; 2 m height), a four-component net radiometer (CNR1, Kipp & Zonen, Delft, The Netherlands; until November 2014 at 1 m height, afterwards at 2 m height), a sunshine sensor measuring diffuse and total photosynthetically active radiation (until June 2014 BF3, afterwards BF5, Delta T, Cambridge, UK; until November 2014 at 1 m height, afterwards at 2 m height), four heat flux plates (HFP01, Hukseflux B.V., Delft, The Netherlands; 0.03 m depth) with corresponding soil temperature probes (model 107, Campbell Scientific; 0.015 m depth), a soil moisture probe profile (ECH2O, Decagon Devices Inc., Pullmann, WA, USA; 0.05, 0.15, 0.30, 0.50 m depths), a soil temperature profile (Th3-s, UMS GmbH, Munich, Germany; 0.05, 0.10, 0.20, 0.30, 0.50 and 1.00 m depths) and a heated rain gauge (until July 2014 model 10116, Toss GmbH, Potsdam, Germany, afterwards model 15188, Lambrecht GmbH, Göttingen, Germany; 1 m height). These measurements were conducted at a frequency of 1 Hz and 30-min averaged until October 2012. Afterwards 1-min averages were recorded. These data, which were aggregated to 30-minute resolution, were used to support the flux data gap filling and partitioning and to drive the SPA-Crop model (Section 2.2.5).

2.2.4 Estimation of net biome production

NBP was used to determine the C budget of the field between 2003 and 2016. Knowing the C exchange through turbulent CO_2 fluxes (NEE), C exports by harvest (E_{harvest}) and C imports by organic fertiliser ($I_{\mathrm{fertiliser}}$), sowing (I_{sowing}) and other possible pathways (I_{other}), NBP can be calculated as:

$$\mathrm{NBP} = \mathrm{NEE} + E_{\mathrm{harvest}} + I_{\mathrm{fertiliser}} + I_{\mathrm{sowing}} + I_{\mathrm{other}} \tag{1}$$

We use the same sign convention as Buysse et al. (2017): when the field is a C source, NBP is positive, while it is negative if it is a C sink. For the contributing terms, C imports into the ecosystem are negative and exports positive. The term I_{other} can be relevant in rice paddies, where methane fluxes are important (Nishimura et al., 2008) and at sites, where substantial losses via volatile organic compounds (VOC) or dissolved organic carbon losses (DOC) have to be taken into account. At the CH-Oe2 site, however, neither of these fluxes is of relevant magnitude, and I_{other} can be neglected. While VOC emissions (methanol) had been investigated at the nearby CH-Oe1 grassland site (Brunner et al., 2007) and were found to be very small compared to CO_2 fluxes, no estimates were done for DOC at CH-Oe2 so far. A dye tracer experiment by Alaoui and Goetz (2008) at CH-Oe2, however, indicated that the high clay content actually limits the leakage to lower soil layers well beyond the ploughing depth, hence we do not account for potential DOC losses. Cumulative NBP (NBP_{cum}) can then be calculated for our site as:

$$\mathrm{NBP}_{cum} = \int_{t_0}^{t} \mathrm{NEE} + \int_{t_0}^{t} E_{\mathrm{harvest}} + \int_{t_0}^{t} I_{\mathrm{fertiliser}} + \int_{t_0}^{t} I_{\mathrm{sowing}}, \tag{2}$$

where t_0 and t are the starting and end dates of the period of interest, respectively. The first term of this equation is the cumulative NEE (NEE_{cum}).

2.2.5 Modelled net ecosystem exchange

In order to quantify the impact of the cover crop on the C budget, the Soil-Plant-Atmosphere Crop Model (SPA-Crop, Sus et al., 2010) was used to simulate NEE under the same meteorological conditions but without the cover crop (i.e., bare soil). The model simulates cropland ecosystem photosynthesis and water-balance at point-scales over fine temporal (half-hourly) and vertical scales (ten canopy and twenty soil layers). The SPA-Crop simulation of heterotrophic respiration, modelled independently of crop type, includes decomposing surface litter and soil organic C (SOC) pools. The simulations were applied for the three available cover crop periods by running the model for the entire previous year (not shown) until the end of the cover crop season. The results were then compared to the corresponding eddy covariance NEE observations.

3 Results and discussion

3.1 Carbon budgets over 13 years

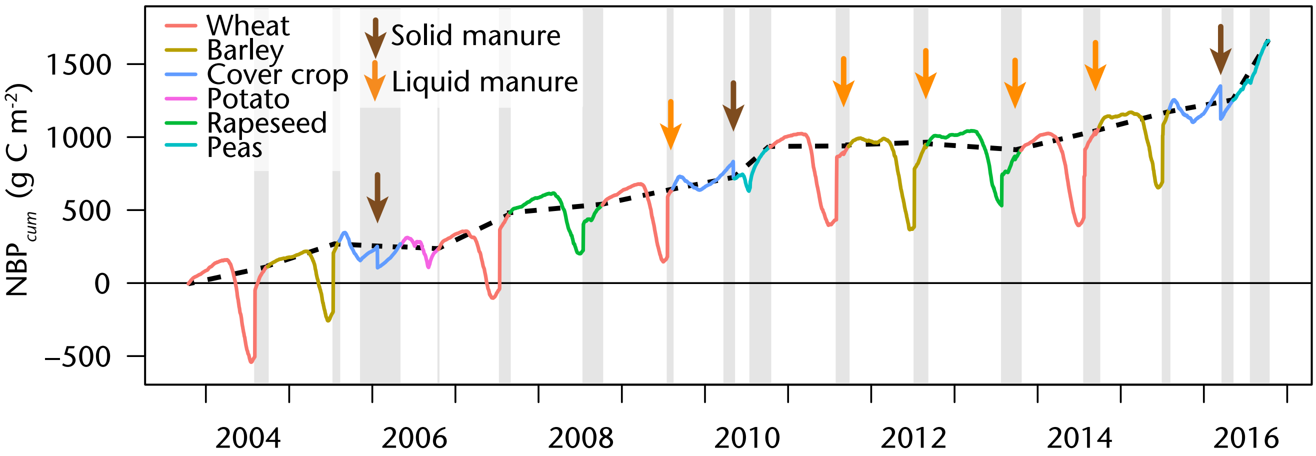

Figure 2. Daily cumulative net biome production (NBP$_{cum}$) between 16 Oct 2003 and 11 Oct 2016. The black dashed line connects NBP$_{cum}$ at the end of each crop season. During time periods with a grey background, the field was bare (from harvest of a crop to sowing of the next crop or from first ploughing after sowing of a crop to sowing of the next crop if the first crop was not harvested).

For all crops, the season (defined from sowing of one crop to the sowing of the following crop) started with a net release of CO_2 until the crop had emerged and became established, after which GPP began to exceed R_{eco} (Fig. 2). A few weeks before harvesting, when senescence started, R_{eco} exceeded GPP again, resulting in a net CO_2 release. At the point of harvest, C was exported from the ecosystem, which can be seen in most years as a sharp increase in NBP$_{cum}$. Organic fertilisation with solid or liquid manure and sowing were C imports into the ecosystem. However, only solid manure applications were large enough C imports to be seen as a sharp decrease in NBP$_{cum}$. While the field was bare, it was almost only respiring and therefore NBP$_{cum}$ increased during these periods. The voluntary regrowth after the harvest of rapeseed (2008 and 2013) resulted in an approximately 2-month long period of uptake in the autumn of the same years.

For peas, the period of net C uptake was quite short (less than one month in contrast to three to four months for the other crops), which is due to their short growing period as they were peas for canning and were therefore harvested relatively early. The period of net C uptake is barely visible during the pea season in 2016 because the field was flooded due to extensive rain. Cover crops were only growing in the autumn resulting in a relatively weak CO_2 uptake followed by a relatively long period of net CO_2 loss during winter season.

NBP$_{cum}$ at the end of each season mostly increased over time. Only during the potato season in 2006 without harvest due to the hail damage and during the crop rotation cycle (wheat, barley and rapeseed) between 2010 and 2013, NBP$_{cum}$ stayed almost constant. NBP$_{cum}$ of the first crop rotation cycle (wheat, barley, cover crop, potato; 2003 – 2006) was 236 g C m^{-2}.

Between 2006 and 2009, wheat was repeated every second year. During the first two-year period (wheat, rapeseed), the field was a net source of 302 g C m^{-2} and during the second two-year period (wheat, cover crop, peas) a net source of 396 g C m^{-2}. During the next full crop rotation cycle (wheat, barley, rapeseed; $2010-2013$), the field was close to C neutral (NBP = -22 g C m^{-2}), while it was a net source of 748 g C m^{-2} during the last crop rotation (wheat, barley, cover crop, peas; $2014-2016$). The cumulative net biome production (NBP_{cum}) for the 16 crop seasons between autumn 2003 and autumn 2016 shows that there was a net C loss of 1674 g C m^{-2} over the 13 years of study (Table B2). The field lost on average 129 ± 50 g C m^{-2} of C per year (unless stated otherwise, we report mean $\pm$ standard error except for soil C and N values, where mean $\pm$ standard deviation is given).

Soil C densities (ρ_C) in the top 12 cm of the field were 0.0355 ± 0.0042 g cm^{-3} (mean $\pm$ standard deviation) in 2004 and decreased significantly ($p < 0.0001$) on average by 18.0 % to 0.0291 ± 0.0031 g cm^{-3} until spring 2017 (average over the top 15 cm and over all measurement days in 2017). The bulk density of the same layer increased insignificantly ($p = 0.25$) from 1.16 ± 0.08 g cm^{-3} in 2004 to 1.21 ± 0.14 g cm^{-3} in 2017. The soil C stock decreased significantly ($p < 0.0001$) on average by 775 g C m^{-2} in the top 12 cm from 4263 ± 507 g C m^{-2} to 3488 ± 374 g C m^{-2}. At the same time, N stock changes were not significant over the 13 years (372 ± 53 in 2004, 382 ± 44 g N m^{-2} in 2017, $p = 0.19$). There were no measurements from deeper soil layers available for 2004. However, measurements in 2017 show that C densities did not vary significantly (adjusted $p = 0.959$) in the top 30 cm (Fig. 3). Also ploughing was done in most years to a depth of 30 cm. If we therefore assume that C stocks changed equally over a depth of 30 cm between 2004 and 2017, the soil C stock decreased in the top 30 cm layer on average by 1980 g C m^{-2}. This corresponds to an annual average loss of 152 g C m^{-2}.

The application of slurry caused such a small C input that it was not only invisible in NBP_{cum} (Fig. 2) but was also not detectable in the soil. Soil C density measurements before and after the application of the slurry in 2017 did not reveal any significant (adjusted $p > 0.05$) changes (Fig. C1). The slurry added only 25.4 g C m^{-2} and 4.7 g N m^{-2} to the soil. When comparing these numbers to the C and N stock of the top 30 cm of the soil, it can be seen that the C and N input is negligible.

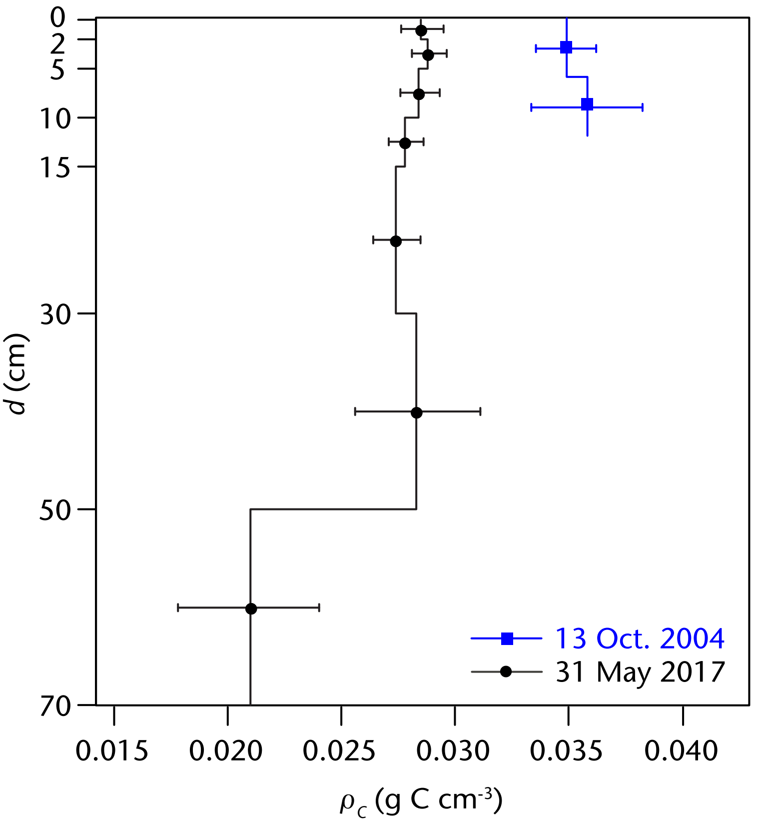

Figure 3. Average soil carbon density (ρ_c) for different depth layers on 13 October 2004 and 31 May 2017. Error bars show standard errors.

The field site was clearly a C source, which was also confirmed by the changes in soil C stocks measured at the beginning and at the end of the measurement period. Depending on the measurement method, the field lost 15.7 ± 4.0 % (based on NBP$_{cum}$ and soil C stock of top 30 cm in 2004) to 18.0 ± 5.3 % (based on soil C stocks in 2004 and 2017, uncertainty is based on standard errors) of C over the 13 years. The differences between the C budget determined by calculating NBP and by measuring C stocks in the soil were remarkably small given that these results are based on two completely independent measurements. The loss strength, however, was likely influenced by the arable-ley rotation, which was used at the field until the late 1990s and which is expected to reach a higher soil C stock than the crop rotation that was used afterwards.

Ceschia et al. (2010) studied the annual NBP (138 ± 239 g C m^{-2} year^{-1}, they call it net ecosystem C budget) and the annual changes in soil C stocks of the top 30 cm (2.4 ± 4.7 % year^{-1}) of European croplands (averaging over 17 croplands and 41 site years ± standard deviation, between 1 and 5 consecutive years per site). In contrast to our results, their findings were not significantly different from a C neutral budget. However, our results were within the range found by Ceschia et al. (2010). Kutsch et al. (2010) determined an average annual NBP of 95 ± 87 g C m^{-2} year^{-1} for 5 crop rotation sites and 2 monoculture sites. There are a number of other studies on European crop fields with crop rotations that found similar or slightly higher annual losses to what we found in this study (e.g., Prescher et al., 2010; Buysse et al., 2017, no cover crops included in these studies). A modelling approach based on soil stock measurements for European croplands also resulted in comparable average annual C losses of approximately 90 ± 50 g C m^{-2} (Janssens et al., 2003). On the other hand, research using a process-based model and soil C inventories (Ciais et al., 2010) and a study combining ecosystem scale measurements with atmospheric greenhouse gas measurements and an inversion model (Schulze et al., 2009) found an average annual source of 8.3 ± 13 to 13 ± 33 g C m^{-2} year^{-1} and 10 ± 9 g C m^{-2} year^{-1}, respectively for croplands. In our study, the management under the regulations of PEP did not result in a neutral C budget or C sink and also not in a significantly smaller average annual loss compared to other European croplands. However, soil N stock measurements showed that the neutral N budget, as required by PEP, was approximately reached.

An uncertainty estimate of NBP calculated with Eq. 1 can be found in Appendix A. In total, the uncertainty adds up to a maximum uncertainty of approximately $\pm$25 % of NBP$_{cum}$. Buysse et al. (2017) listed in detail the uncertainties involved in the different NBP terms in their study, which would add up to a maximum uncertainty of 220 g C m^{-2} over the 12 years of their study (at NBP = 990 g C m^{-2}) corresponding to an uncertainty of 22 %.

3.2 Crop specific budgets

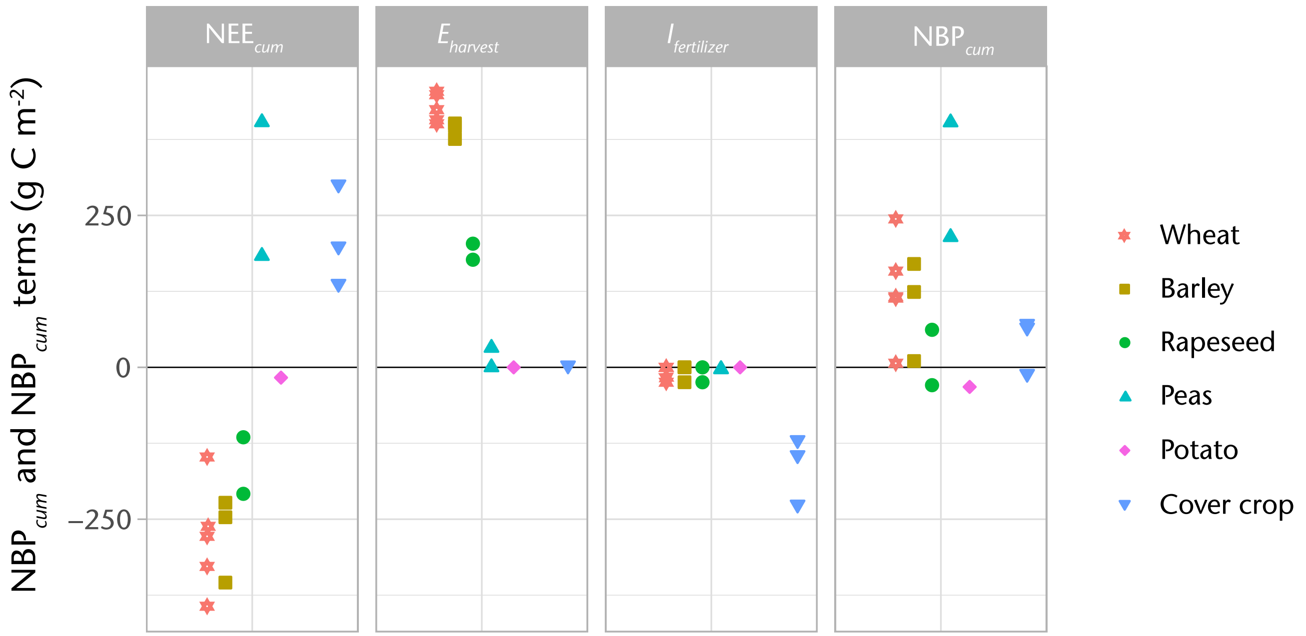

Figure 4. Crop season specific cumulative net biome productions (NBP_{cum}) and their main contributing terms: cumulative net ecosystem exchange (NEE_{cum}), C export by harvest ($E_{harvest}$) and C import by fertiliser ($I_{fertiliser}$). Each symbol stands for one crop season. Not shown is the C import by sowing (I_{sowing}), which is negligibly small except for potatoes. It is however included in the calculation of NBP_{cum}. Please note that cover crops were only grown during autumn and winter.

Table 2. Average and standard error of cumulative net ecosystem exchange (NEE_{cum}), C export through harvest ($E_{harvest}$) and cumulative net biome production (NBP_{cum}) in g C m^{-2} season^{-2} of the five crop types with more than one season. The number (n) of seasons for each crop type is given in brackets. Please note that cover crops were only grown during autumn and winter.

	NEE_{cum}	$E_{harvest}$	NBP_{cum}
Wheat ($n = 5$)	-284 ± 50	427 ± 12	130 ± 49
Barley ($n = 3$)	-279 ± 41	391 ± 8	98 ± 49
Rapeseed ($n = 2$)	-165 ± 47	191 ± 14	13 ± 46
Peas ($n = 2$)	296 ± 112	19 ± 16	311 ± 96
Cover crop ($n = 3$)	205 ± 47	0	38 ± 28

Wheat and barley showed the largest net C uptake from the atmosphere over the crop season and had also the largest C export through harvest (Fig. 4 and Table 2). They were followed by rapeseed, which also had less C exported through harvest. Peas assimilated less C from the atmosphere than the ecosystem released at the same time, and very little was exported from the field during harvest. Also during winter seasons with cover crops, more CO_2 was lost to the atmosphere than was taken up by the ecosystem. For all crops, I_{sowing} was very small to negligible (< 15 g C m^{-2}, Table B1). Also the application of slurry resulted in rather small imports of 16 to 25 g C m^{-2}, whereas solid manure imported 123 to 229 g C m^{-2} (Table 1 and B1).

Taking into account NEE$_{cum}$, $E_{harvest}$, $I_{fertiliser}$ and I_{sowing}, NBP$_{cum}$ of most crop seasons was positive. Pea seasons showed a substantially larger overall C loss than the other crops. Most other crop seasons ranged between close to zero and 160 g C m^{-2}. Since the potatoes were not harvested and did not receive a fertiliser application, this resulted in the only season that had an almost neutral C budget. For one season (2007/08) rapeseed was a weak C source and a very weak C sink in the other season (2012/13). Cover crops were only on the field from the late autumn until the early spring, when less light was available for growth and conditions were generally colder compared to that of the other crops. Their relatively large C loss to the atmosphere was thus a result of the winter growing season, not of the crop type and was strongly compensated by the application of solid manure. Solid manure was always applied at the end of the cover crop seasons. This was done to compensate the expected C losses during the following pea season, which are often referred to by farmers as consumers of soil organic C. Therefore, it could be argued that the application of solid manure should be attributed to the following pea season instead of the cover crop season. With the crop season defined as the time range between first ploughing after the harvest of the previous crop to the first ploughing after the harvest of the current crop, all crops (except potatoes and one barley season) would be in a more similar range (peas: 124 g C m^{-2} in 2010 and 181 g C m^{-2} in 2016; Fig D1). The attribution of the manure application to the pea season is also discussed in Gilmanov et al. (2014). The reduction of the net C loss during the pea season due to the solid manure application shows that the application of solid manure before the growth of peas is useful to compensate the loss of C during these seasons although it can only partly offset the C losses.

Our results for winter wheat and winter barley are comparable to what was found in Europe for these crop types (averaged over several sites, seasonal NEE$_{cum}$ = -304 ± 49 and -303 ± 92 g C m^{-2}, $E_{harvest} = 513 \pm 44$ and 378 ± 71 g C m^{-2}, NBP = 191 ± 58 and 101 ± 104 g C m^{-2}, $n = 12$ and 3, respectively; Ceschia et al., 2010). There are very few studies looking at rapeseed or peas. For winter rapeseed (in Germany) and peas (in France), Ceschia et al. (2010) reported values of NEE = -306 and 278 g C m^{-2}, $E_{harvest} = 560$ and 98 g C m^{-2} and NBP = -2 and 375 g C m^{-2}, respectively, including only one season per crop type. In our study rapeseed assimilated less C in both seasons and also less C was exported with the harvest, however, NBP was again comparable. For peas, NEE was comparable to NBP because the export with the harvest was much smaller than for all other harvested crops. This could be related to the fact that the peas cultivated at CH-Oe2 were peas for canning, which are harvested when they are still relatively small. We are not aware of a study having investigated the C budget of potatoes that does not use data from our own site. The results of our potato season should not be considered representative for regular potato seasons due to the hail damage, which had major impacts on the management, the growth of the plants and resulted in no harvest. In our study, applying solid manure to the cropland was found to import substantial amounts of C to the ecosystem while the import through liquid manure was very small. For a variety of European croplands, Ceschia et al. (2010) found that organic fertilisation tended to lower the C budget even though respiratory losses can slightly increase (less than 10 %) in the first month after the application of solid manure (Eugster et al., 2010).

3.3 The effect of cover crops

During the winter seasons with cover crops, there was always a net C loss. This loss, however, could have been larger not having a crop on the field at all. Having a crop on the field, allows C uptake through photosynthesis, however, also autotrophic respiration (by the plants) and heterotrophic respiration (by providing more soil C matter to decompose) will be enhanced. Depending on whether photosynthesis or respiration is enhanced more, a cover crop may be beneficial in the context of the C budget. In order to asses the benefit of having a cover crop, the CO_2 exchange of the field without crop (i.e. bare field) was modelled with the SPA-Crop model. All other terms of NBP were kept constant since the cover crop was not harvested. SPA-Crop captures the CO_2 exchange from harvest of the previous crop until the start of the cover crop growth quite well (Fig. 5). In contrast to tropical regions (Powlson et al., 2016), where climate during cover crop seasons is not a limiting factor, the field experienced a net loss of C during the cover crop seasons due to the less favorable climate (colder and less light) on the Swiss Plateau in autumn. Nevertheless, in all three seasons, the field with cover crop is overall a smaller net C source than the bare field, even though the NEE_{cum} difference covers a large range of 11 to 163 g C m^{-2}. The cover crop seems to be clearly beneficial (GPP increases larger than R_{eco} increases) to reduce C losses during fallow periods. Furthermore, substantial amounts of C are introduced into the soil by incorporating the biomass at the end of the season when the field is prepared for the next crop. Ceschia et al. (2010) report that also the voluntary regrowth of seeds and weeds after the harvesting of winter wheat at Avignon in the season 2005/2006 reduced the C losses. In a recent review by Chenu et al. (2018) the use of cover crops was discussed. Similar to our findings they conclude based on a number of different studies that the use of cover crops is beneficial for soils because it results in higher soil organic C stocks compared to their absence. The result on cover crops at CH-Oe2 shows that the regulations of PEP requiring a cover crop during fallow periods improved the C budget of the field.

3.4 Solid manure can at least partly compensate the C losses

The more frequent use of solid manure could compensate at least partly the C losses of the crop field and decrease or prevent the loss of soil fertility. Assuming the same average C loss rate for the future but without any organic fertiliser application (also no slurry), the average annual loss would be 174 g C m^{-2}. The average C concentrations in solid manure at CH-Oe2 was 440 g kg^{-1} dry mass (Table E1). Based on these numbers an annual manure application of approximately 15.8 t ha^{-1} would compensate the C losses without any further slurry applications if we assume no increase in R_{eco}. The regular application of solid manure could also reduce the amount of mineral fertilisers applied to the field because substantial amounts of N, phosphorus pentoxide (P_2O_5), potassium oxide (K_2O) and magnesium (Mg) would be supplied by the solid manure (for N approximately half and in all other cases close to the needs as given by the fertilisation plan (Landwirtschaftliche Beratungszentrale Lindau LBL, 2005) averaged over all crop seasons). The application of compost instead of solid manure should be considered if not enough solid manure is produced by the farm. We estimate that 28.6 t ha^{-1} of compost would be needed to compensate the average annual C losses assuming that the net fluxes of compost are similar to manure. Also, in the case of compost, large frac-

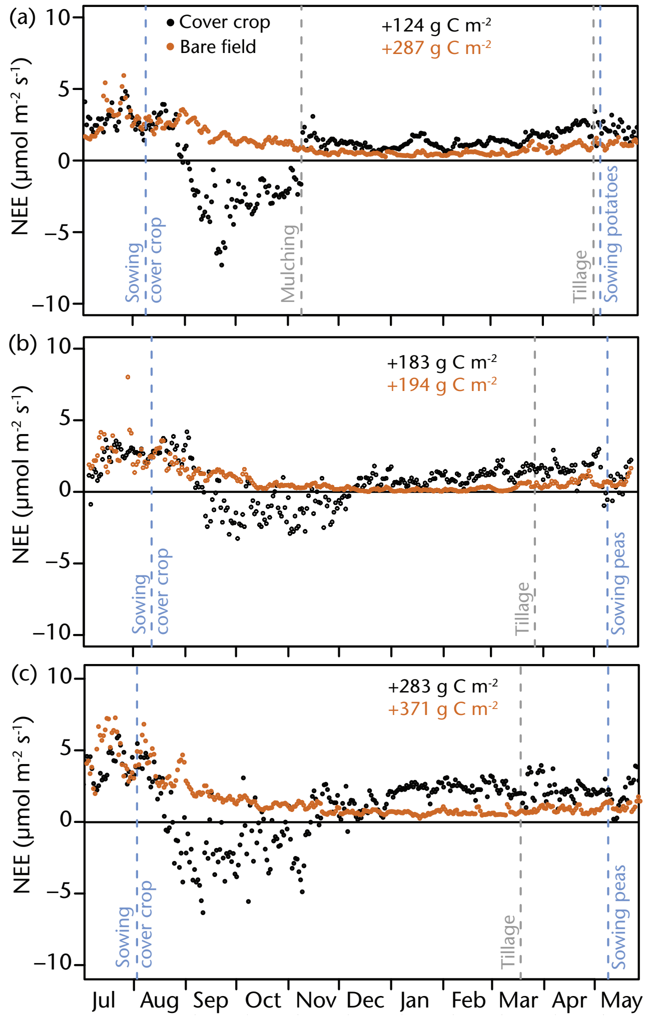

Figure 5. Daily average NEE of the three cover crop seasons: (a) 2005/2006, (b) 2009/2010 and (c) 2015/2016 displaying measured data with cover crop and modelled data with a bare field. NEE was measured with an EC system while modelled NEE was simulated with the model SPA-Crop. Vertical lines indicate sowing, tillage and mulching dates. Numbers in the top right corner of each subfigure are cumulative NEE of the field with cover crop in black and of the bare field in brown.

tions of the N, P_2O_5 and K_2O needs would be met. On the other hand, Mg would be overfertilised. This is however only a rough estimate because the composition of compost and manure can vary substantially. Furthermore, the manure amount needed to compensate C losses should be rather seen as a lower limit because several studies in Switzerland have shown that the C loss reduction can be much less then the C input through manure (10 to 30 % of C inputs; Leifeld et al., 2009; Oberholzer et al., 2014; Maltas et al., 2018), which likely also applies to compost. Including ley in the crop rotation could also be considered to compensate C losses. According to Maltas et al. (2018) green manure or cereal straw application can also be effective measures to prevent or reduce soil degradation, while solid manure has, however, the highest C loss reduction efficiency (compost was not included in the study).

Switzerland's nationally determined contribution (NDC) to the reduction in greenhouse gas emissions lists zero emissions from non-forest lands like croplands (NDC, 2017). Therefore, the C losses should be reduced from a climate change point of view. The use of organic fertilisers could help get closer to the set goal. In the case of CH-Oe2, the grains, peas and potatoes were not used to feed animals on the same farm. However, straw produced on the field at a rate of 78 g C m^{-2} $year^{-1}$ (1013 g C m^{-2} in total during the 13 years of measurements) is used on the farm. If this straw would have been added back to the field (either directly or included in solid manure), it could have compensated a fraction of the C losses over the 13 years. Ammann et al. (2007) studied the C exchange of the neighboring grassland managed by the same farm. Intensive management of the grassland fertilised with liquid manure (mixture of cow dung and urine) from the same farm resulted in a significant uptake of C. Because the grassland was a C sink it could have been considered to apply the manure to CH-Oe2 instead to counteract the higher C loss of the arable field. Therefore, we assume that there is a potential to decrease the field's C losses substantially by increasing the application of the farm's own solid manure to the field. In order to determine if the application of manure would improve the greenhouse gas budget of the cropland as listed by Switzerland's NDC, it would require a complete life cycle assessment which goes beyond the scope of this study.

Table 3. Nutrient requirements and input: Average annual need based on the fertilisation plan (Landwirtschaftliche Beratungszentrale Lindau LBL, 2005), the input of the same nutrients with the annual application of 15.8 t ha^{-1} $year^{-1}$ of solid manure (based on the average concentrations of solid manure given in Table E1) and the annual application of 28.6 t ha^{-1} $year^{-1}$ of compost (based on concentrations from Landwirtschaftliche Beratungszentrale Lindau LBL, 2005) both corresponding to an approximate C_{org} input of 174 g m^{-2} $year^{-1}$. For N an efficiency of 60 % was assumed for manure and for compost as required by the regulations of PEP in the case of farmyard manure (Amaudruz et al., 2014).

	Average annual need	15.8 t ha^{-1} $year^{-1}$ solid manure	28.6 t ha^{-1} $year^{-1}$ compost
N (g m^{-2})	12.7	5.4	6.0
P_2O_5 (g m^{-2})	7.5	6.8	5.7
K_2O (g m^{-2})	14.2	11.3	8.1
Mg (g m^{-2})	1.7	1.7	4.4

4 Conclusions

The combination of direct eddy covariance measurements and management records provided a unique dataset to study the long-term C budget of the crop field over 13 years. The field was managed under the regulations of the Proof of Ecological Performance (PEP) regulations that shift the focus from a purely economical focus to a more ecological one. Our goal was to assess whether the PEP regulations resulted in a more sustainable C budget.

Our study showed that the crop field was a source of C of 1674 g C m^{-2} over 13 years (129 g C m^{-2} per year), which was also confirmed by changes in the soil C stock in the top 30 cm. The loss corresponds to a soil C stock loss of 16 to 19 % over these 13 years of study.

Overall, NBP of most crop seasons was positive (i.e., the field lost C), while the C loss during pea seasons was the largest. Liquid manure had a too small C content to compensate C losses of a whole crop season. Contrastingly, solid manure imported similar C amounts into the ecosystem as the C uptake through NEE of the cereal and rapeseed crops.

The field was a net C source during cover crop seasons, but model simulations showed that the source was smaller than if the field would have been left bare between the autumn and spring before a summer crop was sown.

Managing the field under the regulations of PEP did not result in a long-term C sink. However, some aspects of the regulation seem to improve the C budget of croplands. Even though the application of slurry had very little influence on the C budget, fertilisation with solid manure and the sowing of cover crops during fallow periods provide a potential means to close the C budget of this crop field. More effort than only applying PEP is necessary to reach not only an N-neutral but also a C-neutral budget and to meet Switzerland's NDC. The more frequent application of solid manure or compost should be considered to at least partly compensate the C losses with the side effect of reducing the need for mineral fertilisers.

Data availability. Gap filled observational NEE, SPA-Crop modelled NEE, soil C and N concentrations, harvest exports, sowing and fertiliser inputs and ancillary meteorological and soil data will be made available under https://doi.org/10.3929/ethz-b-000260058.

Appendix A: Uncertainty estimation of NBP calculated with Eq. 1

Several corrections were applied during the calculation of NEE to avoid errors and biases. However, there might be still sources of uncertainties for NBP_{cum}, which are listed in the following.

The uncertainty of NEE_{cum} related to the u_* filtering was assessed within ReddyProc by determining the 5th and 95th confidence interval for the u_* threshold. The gap filled NEE_{cum} using the generally applied u_* threshold were then compared to the gap filled NEE_{cum} based on the 5th and 95th confidence interval for the u_* threshold. This resulted in an uncertainty of -271 g C m^{-2} to $+213$ g C m^{-2} over the 13 years. The uncertainty due to gap filling was assessed by comparing the regularly gap filled NEE using the regular u_* filter to a gap filled NEE where all half-hours were gap-filled (a variable computed with REddyProc). The difference in NEE_{cum} was 32 g C m^{-2} for the 13 years.

The uncertainty of I_{sowing} can be neglected since I_{sowing} itself is already very small. The uncertainty of $I_{\text{fertilizer}}$ is dominated by the uncertainty of the solid manure import (liquid manure imports are small). The uncertainty of the solid manure weight is 5 % according to the farmer and combined with the uncertainty of the elemental C measurement, this results in an uncertainty of ± 70 g C m^{-2} for the 13 years. The uncertainty of E_{harvest} is dominated by the possible loss of harvest material during cleaning before weighing. This loss can be up to 3 % of the yield, which results in a possible underestimation of E_{export} of 99 g C m^{-2}. The uncertainty due to the balance uncertainty and the elemental C uncertainty adds up to ± 31 g C m^{-2} for the 13 years.

Assuming that all these uncertainties add up, the maximum uncertainty of NBP_{cum} calculated with Eq. 1 adds up to -404 to $+445$ g C m^{-2} corresponding to a relative uncertainty of 24 to 27 %. Realistically the uncertainty is however lower because it can be assumed that some of these uncertainties will cancel each other out.

Appendix B: Carbon budget tables

Table B1. Seasonal carbon budget expressed as cumulative net biome production (NBP_{cum}) and its contributing terms of the 16 full crop seasons between 2004 and 2016 (units: g C m^{-2}). A season is defined as the period from the sowing of the current crop until the sowing of the following crop. NEE_{cum} is the cumulative net ecosystem exchange, $E_{harvest}$ is the C export through harvest, and $I_{fertiliser}$ and E_{sowing} are the C imports through organic fertilisation and sowing, respectively. The sums over all crop seasons are also given.

Season	Crop	NEE_{cum}	$E_{harvest}$	$I_{fertiliser}$	I_{sowing}	NBP_{cum}
16 Oct 2003–28 Sep 2004	Wheat	−326	449	0	−7	116
29 Sep 2004–08 Aug 2005	Barley	−226	401	0	−5	170
09 Aug 2005–04 May 2006	Cover	131	0	−148	0	−17
05 May 2006–18 Oct 2006	Potato	−17	0	0	−15	−32
19 Oct 2006–27 Jul 2007	Wheat	−150	401	0	−8	243
28 Jul 2007–06 Oct 2008	Rapeseed	−118	177	0	0	59
07 Oct 2008–11 Aug 2009	Wheat	−286	407	0	−7	114
12 Aug 2009–08 May 2010	Cover	190	0	−123	0	67
09 May 2010–14 Oct 2010	Peas	185	35	0	−4	215
15 Oct 2010–23 Sep 2011	Wheat	−395	424	−16	−7	6
24 Sep 2011–03 Sep 2012	Barley	−360	397	−25	−7	5
04 Sep 2012–18 Oct 2013	Rapeseed	−212	204	−25	0	−33
19 Oct 2013–28 Sep 2014	Wheat	−264	454	−25	−8	157
29 Sep 2014–02 Aug 2015	Barley	−251	376	0	−5	120
03 Aug 2015–08 May 2016	Cover	293	0	−229	0	64
09 May 2016–11 Oct 2016	Peas	407	3	0	−3	407
Sum	All crops	−1400	3728	−591	−76	1661

Table B2. Annual carbon budget expressed as cumulative net biome production (NBP_{cum}) and its contributing terms for the thirteen crop years between 2003 and 2016 (units: g C m^{-2}). A crop year starts here on 16 October of one year and ends on 15 October of the next year. This date was used because the first crop was planted on 16 October 2003. NEE_{cum} is the cumulative net ecosystem exchange, $E_{harvest}$ is the C export through harvest, and $I_{fertiliser}$ and E_{sowing} are the C imports through organic fertilisation and sowing, respectively. The total sum, annual average and standard error of each term is also given.

Season	Crop	NEE_{cum}	$E_{harvest}$	$I_{fertiliser}$	I_{sowing}	NBP_{cum}
2003/2004	Wheat	−351	449	0	−7	91
2004/2005	Barley	−359	401	0	−5	37
2005/2006	Cover/potato	286	0	−148	−16	122
2006/2007	Wheat	−150	401	0	−8	243
2007/2008	Rapeseed	−125	177	0	0	52
2008/2009	Wheat	−371	407	−8	−7	21
2009/2010	Cover/peas	438	35	−115	−4	355
2010/2011	Wheat	−433	424	−16	−7	−32
2011/2012	Barley	−331	397	−25	−7	35
2012/2013	Rapeseed	−185	204	−25	0	−6
2013/2014	Wheat	−274	454	−25	−8	148
2014/2015	Barley	−365	376	0	−5	6
2015/2016	Cover/peas	833	3	−229	−4	603
Sum		−1387	3728	−589	−78	1674
Average		−107	287	−45	−6	129
Standard error		107	49	20	1	50

Appendix C: Soil carbon and nitrogen

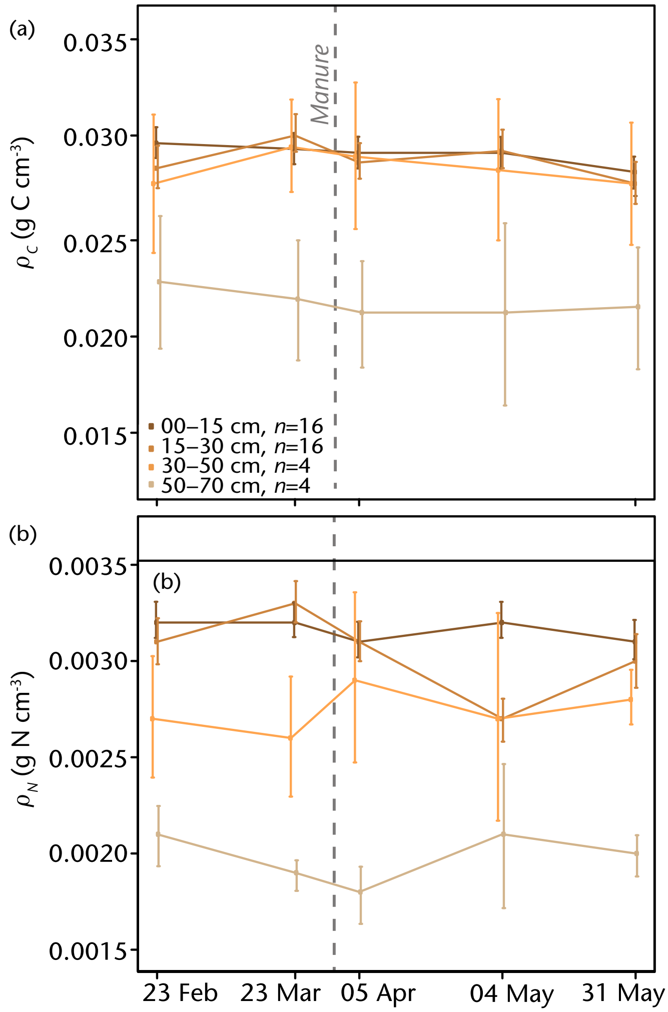

Figure C1. Average soil carbon (a) and nitrogen (b) densities (ρ_C and ρ_N, respectively) in five different soil layers and on two days before and three days after the application of liquid manure in 2017. Standard errors are shown as error bars. The grey dashed line indicates the day of manure application. The number of samples (n) included in the averages is given in the legend.

Appendix D: NEE_{cum} and NBP_{cum} with seasons defined by ploughing

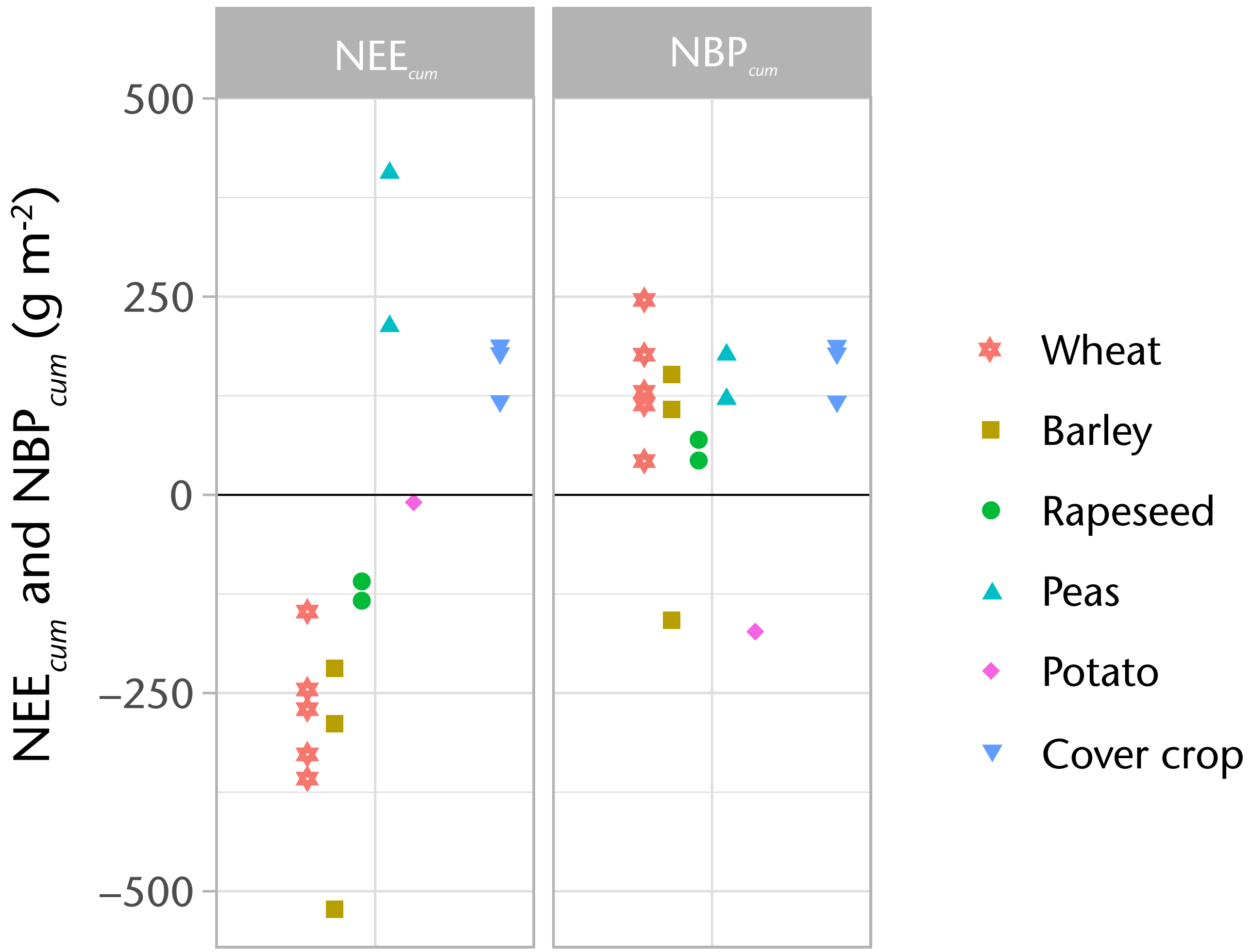

Figure D1. Crop season specific cumulative net ecosystem exchange (NEE_{cum}) and net biome productions (NBP_{cum}) with a season defined as the time range between first ploughing after the harvest of the previous crop to the first ploughing after the harvest of the current crop. Each symbol stands for one crop season. Please note that cover crops were only grown during autumn and winter.

Appendix E: Fertilizer inputs

Table E1. Average nutrient concentrations (per dry matter) of liquid and solid manure. The liquid manure data of 2017 are based on samples from 31 March 2017 and include all variables while for the average over all liquid manure samples between 2002 and 2017 only dry mass, C and N data are available. The solid manure data are based on 5 samples on 24 January 2006. The number of samples included in the average is given as n.

	Liquid 2017	Liquid 2002−2017	Solid 2006
n	2	22	5
Dry mass (%)	2.1	2.4	25.0
C/N ratio	5.4	4.0	18.9
C_{org} (g kg^{-1})	412.5	324.0	440.0
N (g kg^{-1})	76.6	81.0	22.9
P_2O_5 (g kg^{-1})	19.9	n.a.	17.2
K_2O (g kg^{-1})	109.7	n.a.	28.6
Mg (g kg^{-1})	5.5	n.a.	15.4
Ca (g kg^{-1})	15.6	n.a.	4.2

Author contributions. CE designed the study, conducted most parts of the analysis, wrote and revised the manuscript. AW and CE designed and conducted the slurry application study in 2017. CA contributed parts of the field management and manure data. LH was involved in processing the eddy covariance measurements. WE conducted the uncertainty analysis of the elemental analysers and supported CE during all parts of the study. All co-authors were involved in writing and contributed to the study with feedback and critique.

Competing interests. The authors declare that they have no conflict of interest.

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