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# Determination of the carbon budget of a pasture: effect of system boundaries and flux uncertainties

R. Felber<sup>1,2</sup>, D. Bretscher<sup>1</sup>, A. M $\ddot{u}$ nger<sup>3</sup>, A. Neftel<sup>1</sup>, and C. Ammann<sup>1</sup>

<sup>1</sup>Agroscope Research Station, Climate and Air Pollution, Z $\ddot{u}$ rich, Switzerland

<sup>2</sup>ETH Z $\ddot{u}$ rich, Institute of Agricultural Sciences, Z $\ddot{u}$ rich, Switzerland

<sup>3</sup>Agroscope Research Station, Milk and Meat Production, Posieux, Switzerland

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Correspondence to: R. Felber (raphael.felber@agroscope.admin.ch)

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BGD

12, 20071–20100, 2015

## Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Abstract

Carbon (C) sequestration in the soil is considered as a potential important mechanism to mitigate greenhouse gas (GHG) emissions of the agricultural sector. It can be quantified by the net ecosystem carbon budget (NECB) describing the change of soil C as the sum of all relevant import and export fluxes. NECB was investigated here in detail for an intensively grazed dairy pasture in Switzerland. Two budget approaches with different system boundaries were applied:  $NECB_{tot}$  for system boundaries including the grazing cows and  $NECB_{past}$  for system boundaries excluding the cows.  $CO_2$  and  $CH_4$  exchange induced by soil/vegetation processes as well as direct emissions by the animals were derived from eddy covariance measurements. Other C fluxes were either measured (milk yield, concentrate feeding) or derived based on animal performance data (intake, excreta). For the investigated year, both approaches resulted in a small non-significant C loss:  $NECB_{tot} - 13 \pm 61 \text{ g C m}^{-2} \text{ yr}^{-1}$  and  $NECB_{past} - 17 \pm 81 \text{ g C m}^{-2} \text{ yr}^{-1}$ . The considerable uncertainties, depending on the approach, were mainly due to errors in the  $CO_2$  exchange or in the animal related fluxes. The associated GHG budget revealed  $CH_4$  emissions from the cows to be the major contributor, but with much lower uncertainty compared to NECB. Although only one year of data limit the representativeness of the carbon budget results, they demonstrated the important contribution of the non- $CO_2$  fluxes depending on the chosen system boundaries and the effect of their propagated uncertainty in an exemplary way. The simultaneous application and comparison of both NECB approaches provides a useful consistency check for the carbon budget determination and can help to identify and eliminate systematic errors.

## 1 Introduction

The agricultural sector is the third major contributor of anthropogenic induced greenhouse gas (GHG) emissions and accounts for 14 % of global GHG emissions (IPCC, 2014). Depending on the country and the agricultural production system, agriculture

BGD

12, 20071–20100, 2015

## Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Determination of the carbon budget of a pasture

R. Felber et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



can account for more than 50 % of total national GHG emissions (UNFCCC, 2014). Whereas agricultural activities mainly lead to emissions of CH<sub>4</sub> and N<sub>2</sub>O, agricultural land potentially can be either a source or a sink for atmospheric CO<sub>2</sub> (Tubiello et al., 2015) by changing the carbon (C) storage in the soil. Grazing land management, crop-  
 5 land management and restoration of organic soils are considered as the most cost-effective mitigation options for the agriculture sector (IPCC, 2014), and carbon sequestration, i.e., the increase of soil organic carbon (SOC), in grassland is seen as the key issue (Soussana et al., 2010).

To fully account for the GHG effect of an agricultural system, the exchange of all relevant GHGs needs to be determined. Whereas N<sub>2</sub>O and CH<sub>4</sub> emissions can be directly measured, the carbon source or sink of an agricultural ecosystem is more difficult to quantify. Changes in SOC can be measured from repeated soil sampling over longer time periods (several years) but are difficult to detect for shorter-term assessments because of the generally large background and high spatial variability (Smith, 2004). For  
 15 shorter (e.g., annual) timescales the net ecosystem carbon balance (NECB) approach can be used (Chapin et al., 2006). It determines the carbon storage change as the net budget of all C containing import and export fluxes to/from the ecosystem. In natural ecosystems the NECB is mainly determined by the net CO<sub>2</sub> exchange with the atmosphere including uptake by photosynthesis and release by plant and soil respiration.  
 20 In managed agricultural grasslands additional non-CO<sub>2</sub> carbon imports (e.g., through manure application) and exports (e.g., through biomass removal) in liquid, solid, or gaseous form are important contributions for the determination of NECB. The NECB of a grazed pasture is also strongly influenced by the C cycling in the animals.

While the experimental determination of ecosystem CO<sub>2</sub> exchange and its problems and uncertainties has been investigated in many publications, only few studies have experimentally assessed the NECB of pasture ecosystems and its quality up to now (e.g., Soussana et al., 2007; Mudge et al., 2011; Rutledge et al., 2015). The GHG exchange of agricultural ecosystems is generally determined and described as flux per surface area, whereas the emission of CH<sub>4</sub> and N<sub>2</sub>O of livestock production is





storage in living plant biomass and of uncertainties in the attribution of management related fluxes.

For dairy pasture systems, the choice of system boundaries for the determination of the NECB is not as obvious as for other ecosystems, because of the (temporal) presence of the grazing animals. Two approaches with different boundaries were chosen here to estimate the change of SOC stock expressed as NECB (Fig. 1). In these budget calculations, we neglect C loss due to leaching and erosion because they could not be measured in this experiment, and are assumed to be very small compared to the major fluxes.

The first approach (Fig. 1a) deduces the carbon budget from all relevant C fluxes of the *total* system including the grazing animals ( $NECB_{tot}$ ) similar as applied by Sousana et al. (2007) and Rutledge et al. (2015). In this approach animal respiration and products count as C exports, beside other C losses from the pasture. Since the cows had to leave the pasture twice a day for milking in the barn, this system also comprises cow fluxes during these off-pasture phases.  $NECB_{tot}$  is determined as:

$$NECB_{tot} = F_{C-CO_2,tot} + F_{C-CH_4,soil} + F_{C-CH_4,cows} + F_{C-fertil} + F_{C-products} + F_{C-feed,off} + F_{C-resp,off} + F_{C-excreta,off} \quad (2)$$

where  $F_{C-CO_2,tot}$  is the net  $CO_2$  exchange of the total grazing system including cow respiration (during their presence on the pasture),  $F_{C-CH_4,soil}$  is the  $CH_4$  uptake or loss from the soil including grazing deposited dung on the pasture and  $F_{C-CH_4,cows}$  is the  $CH_4$  emission from enteric fermentation,  $F_{C-fertil}$  is the imported C in organic fertilizers, and  $F_{C-products}$  is the C exported in animal products milk and meat (live weight gain). It has to be noted, that the C stock change in animal live weight is treated here as an export flux and thus it is not part of the resulting net ecosystem budget. For the time share the cows spent off-pasture, the intake of supplementary feed ( $F_{C-feed,off}$ ) as well as the loss by animal respiration ( $F_{C-resp,off}$ ) and excreta ( $F_{C-excreta,off}$ ) are considered.

The system boundaries of the second approach ( $NECB_{past}$ , Fig. 1b) comprise only the pasture (soil and vegetation); the cows are outside the system but contribute to the

## BGD

12, 20071–20100, 2015

### Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



budget by exporting forage and importing excreta. This approach has been applied e.g. by Skinner (2008).  $NECB_{past}$  is determined as:

$$NECB_{past} = F_{C-CO_2,past} + F_{C-CH_4,soil} + F_{C-fertil} + F_{C-grazing} + F_{C-excreta,past} \quad (3)$$

where  $F_{C-CO_2,past}$  is the net  $CO_2$  exchange of the pasture without cow respiration,  $F_{C-grazing}$  is grass biomass C removed by grazing, and  $F_{C-excreta,past}$  is the C import by excreta on the pasture.

The individual flux terms contributing to the budgets in Eqs. (2) and (3) act for different time periods; fluxes related to the pasture field act for the entire year (i.e.,  $F_{C-CO_2,tot}$ ,  $F_{C-CO_2,past}$ ,  $F_{C-CH_4,soil}$ ,  $F_{C-fertil}$ ), while the cow related fluxes act only for the time periods associated with grazing on the investigated pasture (including the adjacent milking time) and were calculated as the attributed temporal fraction. The cows grazed for a total of 99 days on the investigated pasture (hereafter referred to as “total grazing days”) applying to  $F_{C-products}$  and  $F_{C-CH_4,cows}$ . The effective time spent on the pasture of 73.1 days (hereafter referred to as “effective pasture time”), applying to  $F_{C-grazing}$  and  $F_{C-excreta,past}$ , was determined by the sum of all 30 min intervals during which the cows were on the pasture for the entire interval (indicated by the GPS positions) plus one-half of the intervals which were attributed to moving between pasture and barn. The mean time for one milking event (including the time for moving between pasture and barn) was 3.1 h, thus the total time spent outside of the pasture was 25.9 days (hereafter referred to as “off-pasture time”) applying to  $F_{C-feed,off}$ ,  $F_{C-resp,off}$  and  $F_{C-excreta,off}$ .

Annual animal related C fluxes were aggregated from average daily animal exchange rates  $E_{C-x}$  (in units of  $gC\ head^{-1}\ d^{-1}$ ) over the mean number of animals ( $n_{cow} = 19.7$ ) and allocated to the total pasture area ( $A = 36\ 000\ m^2$ ):

$$F_{C-x} = E_{C-x} \cdot \frac{n_{cow}}{A} \cdot T_x \quad (4)$$

where  $T_x$  is the accountable time period for the flux  $F_{C-x}$  as described above. The sign may change between  $F_{C-x}$  and  $E_{C-x}$  depending on the examined system boundaries.

## Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



The uncertainty of the NECB was calculated by Gaussian error propagation of the individual uncertainties of the fluxes contributing to the budget.

## 2.3 Determination of area related fluxes

### 2.3.1 CO<sub>2</sub> fluxes

5 Net CO<sub>2</sub> exchange of the pasture was determined as net ecosystem exchange (NEE) using the EC technique as described in Felber et al. (2016). NEE was determined under the micrometeorological sign convention (negative for downward/uptake, positive for upward/loss), thus  $F_{C-CO_2}$  used here has the opposite sign of NEE. Annual  $F_{C-CO_2}$  was calculated either from gap filled flux data including cases with cow respiration  
10 ( $F_{C-CO_2,tot}$ ) or only from data without cow respiration contribution ( $F_{C-CO_2,past}$ ). The selection of  $F_{C-CO_2,past}$  data was achieved using GPS cow position information and the flux footprint distribution. The uncertainties of the two NEEs were determined from combined random and systematic uncertainties. Random uncertainty was estimated from varying the input data before gap filling (adding random noise or additional gaps)  
15 and systematic uncertainty was estimated from varying the applied selection threshold for low turbulence conditions ( $u_*$  filtering). The difference between the  $F_{C-CO_2,tot}$  and  $F_{C-CO_2,past}$  corresponds to the area related cow respiration flux, which could be converted to an average cow respiration  $E_{C-resp} = 4.6 \text{ kg C head}^{-1} \text{ d}^{-1}$  as detailed by Felber et al. (2016). They estimated different uncertainties for cow respiration, here we  
20 use the rather conservative uncertainty of  $\pm 1.6 \text{ kg C head}^{-1} \text{ d}^{-1}$ .

### 2.3.2 CH<sub>4</sub> fluxes

CH<sub>4</sub> emissions of the pasture soil and surface ( $F_{C-CH_4,soil}$ ) were determined from EC data without direct cow influence (for details see Felber et al., 2015). Flux intervals were selected based on GPS data of cow positions. Small generally positive fluxes in  
25 a typical range of  $0 \text{ to } 15 \text{ nmol m}^{-2} \text{ s}^{-1}$  were found. Even though some temporal vari-

## Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





ations in median diurnal and seasonal cycles were observed, a constant soil/surface CH<sub>4</sub> emission over the year of  $4 \pm 3 \text{ nmol m}^{-2} \text{ s}^{-1}$  is assumed for the budget calculation. This value integrates emissions induced from cow excreta and CH<sub>4</sub> sources and sinks of the soil. The uncertainty of the pasture CH<sub>4</sub> fluxes was estimated from the uncertainty range of  $\pm 50\%$  covering the temporal variation of weekly medians.

Felber et al. (2015) also determined in-situ animal CH<sub>4</sub> emissions from EC data. Cow CH<sub>4</sub> fluxes were corrected by the weights of individual cow position contributions to convert area integrated data into emissions per animal. The average animal CH<sub>4</sub> emission amounted to  $423 \pm 24 \text{ g CH}_4 \text{ head}^{-1} \text{ d}^{-1}$ . This seasonal average animal exchange rate was converted to a carbon exchange and back to a corresponding area related flux  $F_{\text{C-CH}_4, \text{cows}}$  using Eq. (4) for the timespan of total grazing days.

### 2.3.3 Fertilizer application

In the study year, two fertilizer applications took place: before the beginning of the grazing season (6 March) cattle slurry was applied by trailing hose at a rate of  $43 \text{ m}^3 \text{ ha}^{-1}$ . Dry organic matter of the slurry was determined according to VDLUFA (2000) recommendations and the C content of the dry matter of 52% was adopted from previous comparisons with elemental analysis for similar slurry. The uncertainty of the slurry C import was assumed to be 17% (Ammann et al., 2009). Nitrogen applied by the slurry amounted to  $70 \text{ kg N ha}^{-1}$ . An additional  $50 \text{ kg N ha}^{-1}$  was applied as urea in June. Due to the C/N ratio of 1/2 in urea, this corresponds to a very small C import.

### 2.4 Determination of animal related fluxes

The animal related carbon fluxes can be examined under the aspect of the animal C budget (in units  $\text{g C head}^{-1} \text{ d}^{-1}$ ) balancing gain with loss and storage terms:

$$E_{\text{C-intake}} = E_{\text{C-resp}} + E_{\text{C-CH}_4, \text{cow}} + E_{\text{C-milk}} + E_{\text{C-meat}} + E_{\text{C-excreta}} \quad (5)$$

## Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



Ingested C in feed ( $E_{C-intake} = E_{C-grazing} + E_{C-feed,off}$ ) is partitioned into respired  $CO_2$  ( $E_{C-resp}$ ), loss of  $CH_4$  by enteric fermentation ( $E_{C-CH_4, cow}$ ), the C in milk ( $E_{C-milk}$ ) and meat gain ( $E_{C-meat}$ ), and the C in the excreta ( $E_{C-excreta}$ ). The determination of  $E_{C-resp}$  and  $E_{C-CH_4, cow}$  was already described in the previous sections. The quantification of the other terms is explained in the following.

## 2.4.1 Products

The animal production terms  $E_{C-milk}$  and  $E_{C-meat}$  were estimated from monitored daily milk yield and live weights measured after milking. Milk was sampled individually on one day per week and analyzed for fat, protein and lactose content. Energy-corrected milk (ECM) yields were calculated from daily milk yields according to Arrigo et al. (1999) using fat, protein and lactose contents and assuming linear relationship for these components, when no measurements were available. ECM was adjusted to a gross energy content of  $3.14 MJ kg^{-1}$  (Arrigo et al., 1999) and the C content was calculated using an energy to C content ratio of  $21 gC MJ^{-1}$  (determined in previous experiments by Munger, 1997). Using data from the entire grazing period an average milk C output per cow ( $E_{C-milk}$ ) was derived.

The live weight (LW) of the dairy cows slightly increased by only around 6% over the entire grazing season (on average  $0.2 kg LW d^{-1}$ ). This corresponds to a C accumulation in meat of  $< 0.05 kg C head^{-1} d^{-1}$ . Thus for dairy cows  $E_{C-meat}$  was assumed to be negligible compared to  $E_{C-milk}$  (Soussana et al., 2007).

$F_{C-products}$  was calculated from  $E_{C-milk}$  by Eq. (4) using the number of total grazing days. The uncertainty of  $F_{C-products}$  was estimated from the combination of uncertainties of the ECM and the ratio between milk gross energy and C content. The latter effect was dominating and led to a total uncertainty of 10% for  $F_{C-products}$ .

## BGD

12, 20071–20100, 2015

### Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





## Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



per cow was derived.  $F_{C\text{-feed,off}}$  was calculated from the daily concentrate intake alone. The uncertainty (6%) of  $F_{C\text{-feed,off}}$  was derived from the combined uncertainties of the DM content and the C content determination.  $F_{C\text{-grazing}}$  was calculated for the total grazing days from the difference between  $E_{C\text{-intake}}$  and  $E_{C\text{-feed,off}}$  with an uncertainty of  $\pm 15\%$ .

### 2.4.3 Excreta

Excreta output was not measured in this study. But,  $E_{C\text{-excreta}}$  was estimated by closing the average cow C budget (Eq. 5). The uncertainty was estimated to 46% (resulting from the combination of uncertainties of the other budget terms but limited by plausibility considerations).  $F_{C\text{-excreta,past}}$  and  $F_{C\text{-excreta,off}}$  were calculated from  $E_{C\text{-excreta}}$  for the effective pasture time and the off-pasture time, respectively, using Eq. (4).

### 2.5 Greenhouse gas budget

For a consideration of the full GHG budget of the pasture system, the NECB needs to be quantitatively related to  $\text{CH}_4$  and  $\text{N}_2\text{O}$  emissions in terms of global warming potential (GWP). Here we used the 100 year GWPs; 25  $\text{CO}_2\text{-eq.}$  for  $\text{CH}_4$  and 298  $\text{CO}_2\text{-eq.}$  for  $\text{N}_2\text{O}$  (Solomon et al., 2007). The system boundaries were the same as for the determination of the  $\text{NECB}_{\text{tot}}$ , i.e., the effects of the investigated pasture including the animals during pasture days are taken into account. Correspondingly, area related fluxes are accounted for the entire year, while cow related fluxes are accounted for the total pasture days (time spent on the pasture plus the adjacent milking periods).

The average  $\text{CH}_4$  emissions of the soil and the cow emissions were derived by EC measurements as mentioned in Sect. 2.3.2 and allocated to the respective time periods.

Emissions of  $\text{N}_2\text{O}$  in terms of N mass were estimated according to:

$$F_{\text{N-N}_2\text{O}} = (F_{\text{N-fertil}} + F_{\text{N-resid}} + F_{\text{N-dep}}) \cdot f_1 + F_{\text{N-excreta}} \cdot f_2 \quad (8)$$

where  $F_{N-fertil}$ ,  $F_{N-resid}$  and  $F_{N-dep}$  are the N inputs by fertilizers, plant residues, and atmospheric deposition, and  $f_1 = 0.01$  and  $f_2 = 0.02$  are the default  $N_2O$  emission factors due to the respective N inputs according to the IPCC guidelines (IPCC, 2006).  $F_{N-fertil}$  was determined from management records and the analysis of the applied slurry (see Sect. 2.3.3) and amounted to  $120 \text{ kg N ha}^{-1}$  in total for the study year. The amount of N deposited from the atmosphere was estimated to  $25 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  based on EKL (2014).

The other two terms in Eq. (8), were estimated with the help of the animal N balance, which can be formulated in a similar way as the animal carbon balance in Eq. (5) but without gaseous pathways:

$$E_{N-intake} = E_{N-milk} + E_{N-meat} + E_{N-excreta} \quad (9)$$

$E_{N-intake}$  is the uptake of N in the feed and the average value was quantified based on the average N content of pasture forage ( $28 \text{ g N (kg DM)}^{-1}$ ) and concentrates ( $17 \text{ g N (kg DM)}^{-1}$ ). The intake of the cow is portioned into N in milk ( $E_{N-milk}$ ), meat gain ( $E_{N-meat}$ ), and excreta ( $E_{N-excreta}$ ). Average milk N output ( $E_{N-milk}$ ) was determined from the mean ECM yield ( $22.7 \text{ kg head}^{-1} \text{ d}^{-1}$ ) and associated measured protein contents ranging from 2.8 to 4.5 % and a protein-to-N conversion factor of 6.38. Nitrogen accumulation in meat due to weight gain (see e.g., Estermann et al., 2001) was very small and thus assumed negligible (like for C, see Sect. 2.4.1).  $E_{N-excreta}$  was estimated by closing the N balance (Eq. 9) and was used to calculate  $F_{N-excreta}$  in analogy to Eq. (4) for the effective pasture time resulting in a value of  $152 \text{ kg N ha}^{-1} \text{ yr}^{-1}$ .

Nitrogen input from plant residues  $F_{N-resid} = 51 \text{ kg N ha}^{-1} \text{ yr}^{-1}$  was estimated as 25 % of the livestock N intake during the grazing period based on Walther et al. (1994) and AGRIDEA (2007).

## BGD

12, 20071–20100, 2015

### Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



### 3 Results and discussion

#### 3.1 Carbon budget of the dairy cows

Animal C budget considerations serve to estimate, constrain or validate animal related C fluxes that contribute to the pasture system NECB. Results derived for the mean daily C budget for the cows used in this study are shown in Fig. 2 together with the N budget (detailed numbers can be found in Table S1 in the Supplement). The values represent averages over all cows in the herd and over the entire grazing season. The average cow needed a daily feed intake of 18.5 kg DM corresponding to 8.0 kg C. The determination of the feed intake was a very important factor for the assessment of the cow budget. Because in-situ determination of forage intake during grazing is challenging (Undi et al., 2008), the total feed intake was calculated based on the net energy requirements of the animals, which in turn were based on the actual animal performance (milk yield, live weight). The applied models showed only a small difference of 0.3 kg DM head<sup>-1</sup> d<sup>-1</sup>. Gibb et al. (2007) reported intake values for grazing dairy cows between 25 and 30 g DM (kg LW)<sup>-1</sup>. For the live weight of the cows in this study, this would result in intake rates of 16 and 18 kg DM head<sup>-1</sup> d<sup>-1</sup>, which is within the estimated uncertainty range of our result.

From the total C intake the largest share (57%) was emitted as CO<sub>2</sub> and a much smaller part (4%) as CH<sub>4</sub>. A considerable amount (19%) of the C intake was processed into the milk. The residual C was released as excreta (20%). Most of C was lost by respiration, which also has the largest uncertainty. The value was determined from EC measurements and was found to be at the upper range of animal respiration rates for dairy cows reported in the literature (see Felber et al., 2016 and references therein). In contrast to the carbon budget, the largest part of the N intake (75%) was excreted in urine and dung.

The live weight gain of the cows was around 0.2 kg d<sup>-1</sup> (around 6% increase over the grazing season). Applying the value of 0.14 kg C (kg fresh meat)<sup>-1</sup> (Avila, 2006) the C incorporated into meat results in 0.025 kg C d<sup>-1</sup>, which is less than 2% of milk C yield

and thus negligible here. Even for beef cattle,  $E_{C\text{-meat}}$  is generally small (Allard et al., 2007), and thus sometimes neglected in carbon budget calculations (e.g., Soussana et al., 2007).

The amount of C and N in the excreta was estimated by closing the animal budget, because direct measurements were not available and generally difficult for a grazing system. The amount of C in the excreta (mainly in the dung) is strongly related to the digestibility of the forage. In-vitro digestibility measurements of the forage showed that around 71 % of the feed was digested (data not shown). This number has to be considered as lower limit because it does not account for the digestibility of the concentrate. Thus the 20 % of C in the excreta can be considered as a reasonable estimate, although it was determined as a (small) difference from other large animal budget terms. Yet the relative share of excreta loss is considerably lower than the 34 % share in terms of DM reported by Rutledge et al. (2015) for dairy cows. This discrepancy may indicate that the estimated C loss due to respiration may be overestimated. Indeed the values of  $4.6 \text{ kg C head}^{-1} \text{ d}^{-1}$  lies in the upper range of measurements with comparable cows (see Felber et al., 2016). However, Soussana et al. (2010) present C cow budgets in  $\text{g C m}^{-2} \text{ yr}^{-1}$  for cut forage that is feed off-pasture. They also found that 56 to 59 % of intake C is respired as  $\text{CO}_2$ .

### 3.2 Carbon budget of the pasture system

Carbon budget components and balance results for the two different NECB approaches (system boundaries) used in this study are shown in Fig. 3 (detailed numbers are listed in Table S2). Very similar, slightly negative values were determined for  $\text{NECB}_{\text{tot}}$  and  $\text{NECB}_{\text{past}}$ . Yet both values are attributed a considerable uncertainty range and are thus not significantly different from zero.  $\text{NECB}_{\text{past}}$  with the larger uncertainty also resulted from budget components (fluxes) of higher magnitude. A total C import of  $389 \text{ g C m}^{-2} \text{ yr}^{-1}$  to the pasture (soil/vegetation ecosystem) was balanced by a total C loss of  $-406 \text{ g C m}^{-2} \text{ yr}^{-1}$ . For the  $\text{NECB}_{\text{tot}}$  approach, total import ( $176 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) and export ( $-245 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) were less than half as large (it has to be noted that in

**BGD**

12, 20071–20100, 2015

## Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

◀

▶

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



this consideration, the annual net  $\text{CO}_2$  exchange is used, not the gross exchange). This difference is due to the predominantly “internal” processing of the biomass in the  $\text{NECB}_{\text{tot}}$  system. Accordingly, the largest budget term in the  $\text{NECB}_{\text{tot}}$  approach was the milk export ( $F_{\text{C-products}} = -82 \text{ g C m}^{-2} \text{ yr}^{-1}$ ), while the largest term in the  $\text{NECB}_{\text{past}}$  approach, the biomass export by grazing ( $F_{\text{C-grazing}} = -404 \text{ g C m}^{-2} \text{ yr}^{-1}$ ), was five times larger. Additionally, combining the C lost as respired  $\text{CO}_2$  when the cows were off-pasture and the net C imported as  $\text{CO}_2$  into the system resulted in a zero-sum situation for the  $\text{CO}_2$  exchange in the  $\text{NECB}_{\text{tot}}$  approach, but was the main contributor to the  $\text{NECB}_{\text{tot}}$  uncertainty. As discussed in detail in Felber et al. (2016), the difference in the net  $\text{CO}_2$  exchange between the two approaches corresponds to the (annually averaged) effect of cow respiration while on the pasture. Although this annual cow respiration flux ( $180 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) is typically much lower than the respiration of the pasture soil/vegetation (Jérôme et al., 2014), it is larger than many other carbon budget terms and thus very important for the  $\text{NECB}$  quantification.

The time that the cows spent each day in the barn for milking represents an important “disturbance” of the  $\text{NECB}_{\text{tot}}$ . The sum of the three specific off-pasture fluxes ( $F_{\text{C-feed,off}}$ ,  $F_{\text{C-resp,off}}$ ,  $F_{\text{C-excreta,off}}$ ) results in a net off-pasture carbon loss of  $-57 \text{ g C m}^{-2} \text{ yr}^{-1}$ . The relatively small C import due to concentrate feeding only partially balanced the loss through animal respiration and excreta.

While the resulting  $\text{NECB}$  values for a single year cannot be considered as fully representative for the site nor for pasture systems in general, they show the contribution of different C fluxes to the total budget and the effect of their (propagated) uncertainty in an exemplary way. As shown in Fig. 3, the resulting uncertainty of  $\text{NECB}_{\text{past}}$  ( $\pm 81 \text{ g C m}^{-2} \text{ yr}^{-1}$ ) was larger than for  $\text{NECB}_{\text{tot}}$  ( $\pm 61 \text{ g C m}^{-2} \text{ yr}^{-1}$ ). These uncertainties are comparable to the uncertainty ranges reported by Rutledge et al. (2015) for annual  $\text{NECB}_{\text{tot}}$  values of a dairy pasture system ( $\pm 50$  to  $\pm 86 \text{ g C m}^{-2} \text{ yr}^{-1}$ ). Because in the present study the determination of most non-gaseous C fluxes typically have relative errors of 10 to 20 %, it may be concluded that the larger absolute uncertainty of



NECB<sub>past</sub> compared to NECB<sub>tot</sub> was due to the larger individual C fluxes in this approach. This mainly applies to the largest flux  $F_{C\text{-grazing}}$  that dominated the NECB<sub>past</sub> uncertainty. The grazing intake was inferred from the measured milk yield and animal live weight, because more direct intake measurements on the pasture are difficult (see Sect. 3.1) and would probably not yield more accurate results.

The largest uncertainty contribution in the NECB<sub>tot</sub> approach was due to the CO<sub>2</sub> exchange flux, although the magnitude of this term was not very large. The uncertainty of  $F_{C\text{-CO}_2}$  was mainly determined by the gaps in the CO<sub>2</sub> flux measurement and although the calculation of  $F_{C\text{-CO}_2,\text{tot}}$  is based on a larger flux dataset than  $F_{C\text{-CO}_2,\text{past}}$  (for which all fluxes influenced by cows were removed before gap filling) the former had a larger uncertainty (for details see Felber et al., 2016). The uncertainty of the annual CO<sub>2</sub> exchange has an absolute rather than a relative characteristic because, like the NECB, it is itself the result of large compensating fluxes of opposite signs (Ammann et al., 2009; Felber et al., 2016).

Another important component in both NECB approaches was the C import by slurry application, which was also shown for other managed grasslands (Ammann et al., 2007; Soussana et al., 2007). Only by specific sampling and analysis of the applied slurry, the relative error could be limited to < 20 %, because the DM and thus also the C content in slurry can easily vary by a factor of four.

Carbon lost as CH<sub>4</sub> from the soil was the lowest flux in both systems accounting for less than 1 % of total C loss. While this term appears to be negligible, this is not the case for the animal CH<sub>4</sub> emission ( $F_{C\text{-CH}_4,\text{cows}}$ ) with a contribution of 7 % to the total C loss in the NECB<sub>tot</sub> system. In any case the CH<sub>4</sub> fluxes play a much more prominent role in the GHG budget (cf. Sect. 3.4).

Beside the quality and representativeness of the determination of the various C fluxes, also the completeness of the budget with all relevant components is important. In the present study, the loss of C through leaching and erosion were not measured, but assumed to be small compared to the other C fluxes. Carbon loss through leaching in other managed grasslands was found to be in the range of 5 to 11 g C m<sup>-2</sup> yr<sup>-1</sup> (Allard

## BGD

12, 20071–20100, 2015

### Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





feasible; pasture/soil CO<sub>2</sub> and CH<sub>4</sub> exchange ( $F_{C-CO_2,past}$  and  $F_{C-CH_4,soil}$ ) can only be determined, if sufficient and defined periods without cow influence on the EC flux measurement are available.

While the NECB<sub>past</sub> approach necessitates a proper identification of pasture CO<sub>2</sub> fluxes without cow respiration, it does not rely on off-pasture information. However, the import and export of C in excreta and forage needs to be determined. Thus the NECB<sub>past</sub> approach may be suitable for systems with known animal performance and/or short intensive grazing phases, for which the grazing export can be well constrained. The NECB<sub>past</sub> approach is also suitable for grassland systems with mixed management (grazing and harvest), because the harvest export can be treated in the same way as grazing export (Skinner, 2008).

The NECB<sub>tot</sub> approach is more suitable (or even the only choice) for continuous grazing systems (e.g., Allard et al., 2007). For beef cattle pastures, the NECB<sub>tot</sub> approach can even be simplified, because the off-pasture phases are avoidable. While a separation of the fluxes influenced by cow respiration is not necessary in this approach, it needs to be assured that cow respiration contributions are fully represented in NECB<sub>tot</sub>, i.e. that the cows show a temporally representative presence in the flux footprint (see Felber et al., 2015). Otherwise the annual  $F_{C-CO_2,tot}$  would be affected by a systematic error.

Generally, for any pasture system it is advisable to record as detailed information of non-gaseous C fluxes, cow positions, and grazing time schedules as possible, because the simultaneous application of both approaches and their inter-comparison provides the most defensible results for the C budget.

### 3.4 Greenhouse gas budget of the dairy cow pasture

The result for NECB<sub>tot</sub> is compared to the effect of other GHGs in the GHG budget for the investigated pasture system (including cows during pasture time) shown in Fig. 5. In terms of CO<sub>2</sub>-equivalents, the CH<sub>4</sub> emissions from the animals contributed the most to GHG emissions, while the CH<sub>4</sub> emission from soil (including animal excreta) was 10

## BGD

12, 20071–20100, 2015

### Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures

⏪

⏩

◀

▶

Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion





## Determination of the carbon budget of a pasture

R. Felber et al.

[Title Page](#)

[Abstract](#)

[Introduction](#)

[Conclusions](#)

[References](#)

[Tables](#)

[Figures](#)



[Back](#)

[Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)



the C budget results for the investigated single year cannot be considered as fully representative for the longer term, they demonstrate the contribution of the different C fluxes to the total budget and the effect of their (propagated) uncertainty in an exemplary way. The simultaneous application and comparison of both NECB approaches provides a useful consistency check for the NECB determination and can help to identify and eliminate larger systematic errors. Additionally, the consideration of the cow C (and N) budget can be used to quantify and check the consistency of animal fluxes needed in the determination of the NECB.

The NECB result was compared to the effect of the other GHG fluxes from the pasture system ( $\text{CH}_4$  and  $\text{N}_2\text{O}$  normalized to  $\text{CO}_2$ -equivalents). While  $\text{CH}_4$  emission by the cows played a very minor role in the C budget, it clearly dominates the GHG budget due to its larger greenhouse warming potential. Due to the relatively low variability in  $\text{CH}_4$  emission from enteric fermentation (depending on animal state and performance) it has a much lower uncertainty than the NECB, which is the net effect of large fluxes of opposite sign.

While the determination of the non-gaseous fluxes in the C budget could mostly be improved by more comprehensive sampling and analyses, the uncertainty due to the  $\text{CO}_2$  exchange measurements is to a certain part inevitable for the given site and management regime, because the accuracy of the  $\text{CO}_2$  exchange monitoring by EC is limited by the (micro-) meteorological conditions, especially calm nighttime conditions, and by the variability of the animal presence and density in the footprint. However, the uncertainty may be reduced to some degree by better constrained animal C budgets (especially intake and respiration). This may be achieved by prolonged field measurements over several years in combination with C cycling measurements on the individual animals.

The Supplement related to this article is available online at [doi:10.5194/bgd-12-20071-2015-supplement](https://doi.org/10.5194/bgd-12-20071-2015-supplement).

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BGD

12, 20071–20100, 2015

## Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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## Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



## Determination of the carbon budget of a pasture

R. Felber et al.

Title Page

Abstract

Introduction

Conclusions

References

Tables

Figures



Back

Close

Full Screen / Esc

Printer-friendly Version

Interactive Discussion



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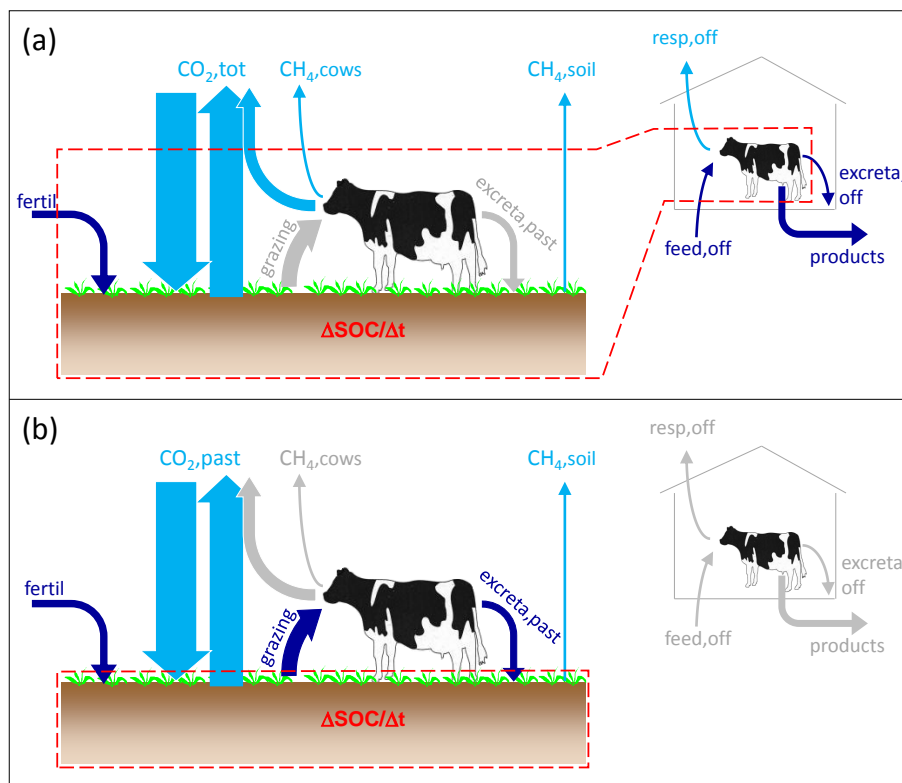
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## Determination of the carbon budget of a pasture

R. Felber et al.



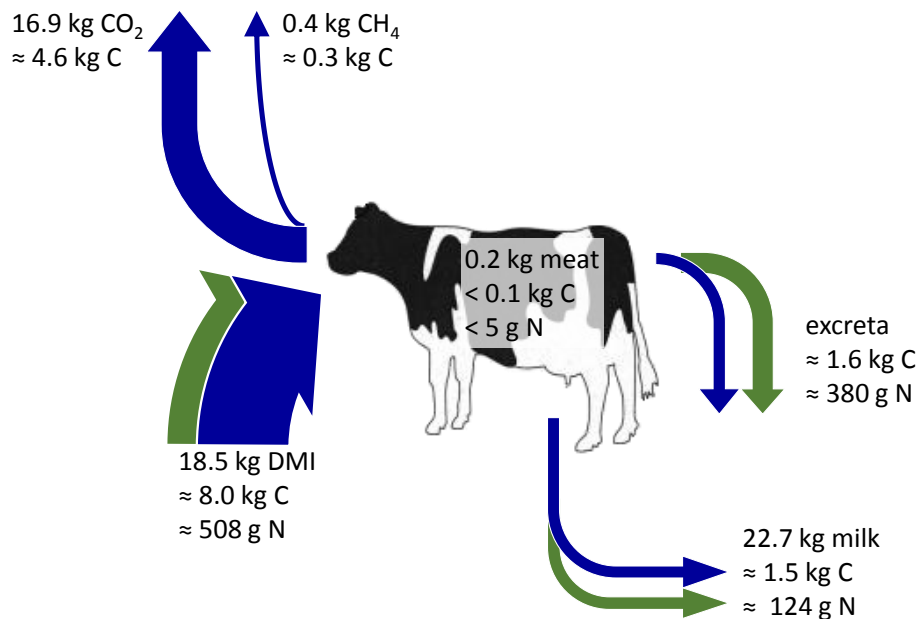
**Figure 1.** Illustration of the two approaches to determine the net ecosystem carbon budget of a dairy pasture using different system boundaries (dashed red line): **(a)**  $NECB_{tot}$  using system boundaries including the cows; **(b)**  $NECB_{past}$  using system boundaries excluding the cows. Relevant carbon fluxes through the system boundaries are marked in blue (gaseous fluxes: light blue, liquid/solid fluxes: dark blue).

## BGD

12, 20071–20100, 2015

## Determination of the carbon budget of a pasture

R. Felber et al.

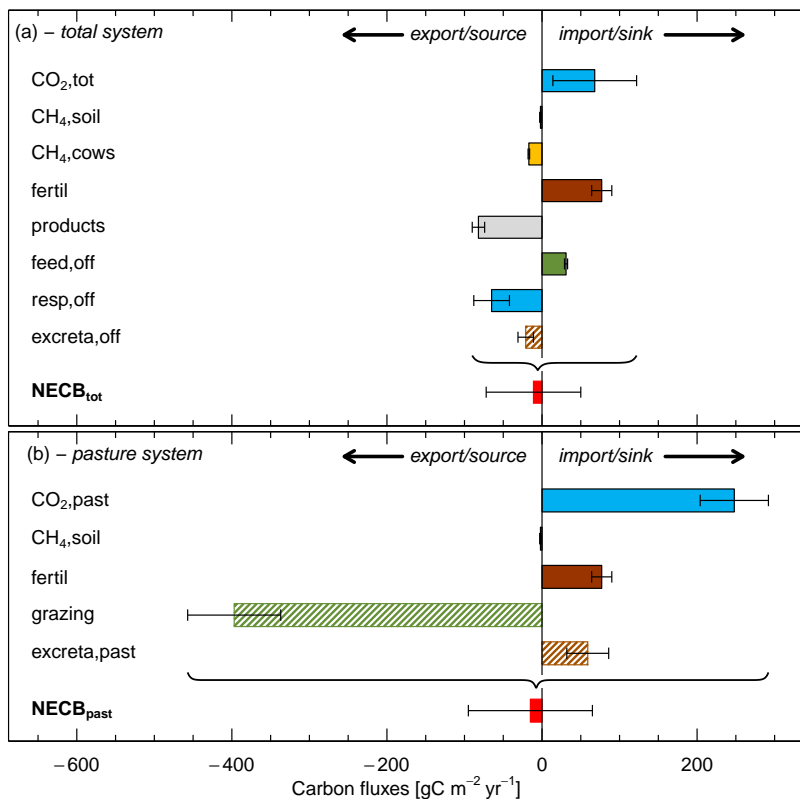


**Figure 2.** Average daily carbon (blue arrows) and nitrogen (green arrows) budget of the studied dairy cows. The budget was closed by adjusting the amount of excreta loss.

[Title Page](#)
[Abstract](#)
[Introduction](#)
[Conclusions](#)
[References](#)
[Tables](#)
[Figures](#)
[Back](#)
[Close](#)
[Full Screen / Esc](#)
[Printer-friendly Version](#)
[Interactive Discussion](#)

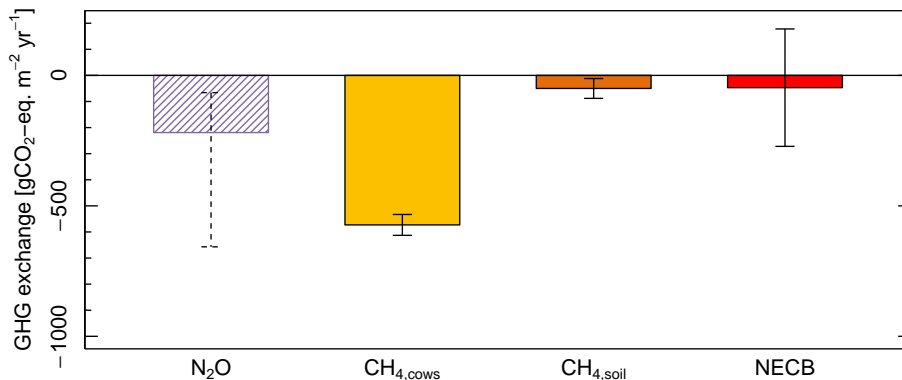
## Determination of the carbon budget of a pasture

R. Felber et al.



**Figure 3.** Components and uncertainties (95 % confidence range) of annual carbon budget determined with **(a)** the total system and **(b)** the pasture system approach as illustrated in Fig. 2. NECB was calculated according to Eqs. (2) and (3). Flux direction is defined according to ecological sign convention: positive values indicate imports to the system, negative values indicate export (loss) from the system. Filled bars indicate values derived from direct measurements, hatched bars indicate values that are modelled with measured and modelled data.





**Figure 5.** Greenhouse gas fluxes of the pasture system including cows during pasture use. The ecological sign convention is used: negative values indicate loss/emission from the system to the atmosphere. N<sub>2</sub>O emissions are modelled, whereas the other emissions are measurements.

**Determination of the carbon budget of a pasture**

R. Felber et al.

[Title Page](#)

[Abstract](#)   [Introduction](#)

[Conclusions](#)   [References](#)

[Tables](#)   [Figures](#)

[◀](#)   [▶](#)

[◀](#)   [▶](#)

[Back](#)   [Close](#)

[Full Screen / Esc](#)

[Printer-friendly Version](#)

[Interactive Discussion](#)

