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Supplement of

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

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Supplementary material

S1 Uncertainty estimation of selected C budget components

S1.1 Animal intake

The uncertainty of dry matter (DM) intake is dominated by the (systematic) uncertainty of the applied empirical model (Eq. 6a/b) based on animal performance and characteristics (milk yield and composition, live weight, etc.). To estimate this uncertainty we used results of a multi model validation study by Jensen et al. (2015). They present in their Table 4 root mean square prediction errors (RMSPE) for different published DM intake models. We selected the results of four models that use similar input data like our model, i.e., the models by NRC (2001), Volden et al. (2011), Huhtanen et al. (2011) and Gruber et al. (2004). We converted their RMSPE to relative errors and averaged them. Finally the systematic model uncertainty (15%) was estimated as twice the average relative error.

Carbon (C) content of pasture forage and concentrates were measured by dry combustion (VDLUFA, 2000) of weekly sampled pasture forage (n = 34, but data from samples contaminated with soil were excluded) and from periodically analyzed concentrate samples (n = 6 over the grazing period). The uncertainties of the average C content was limited by the C analyzer uncertainty of 2%. For the concentrate intake also the average DM to fresh matter ratio needed to be quantified from oven dried samples (n = 6). Its uncertainty (4%) was estimated as 2SE.

Depending on individual production state of the cows they were offered concentrate in weighing troughs. Mean daily fresh matter of concentrate ration amounted to 1.5 kg head^{-1} d^{-1}. We assume a total uncertainty of portion and weighing trough of 15% (expert guess). The uncertainty of concentrate C intake was calculated by error propagation from the uncertainties of C content analysis (2%), the DM content analysis (4%) and the weighing of the fresh matter intake for each cow (15%) resulting in a total uncertainty of 16% for $F_{\text{C-feed,off}} = 0.6 \pm 0.1$ kg C head^{-1} d^{-1}.

Daily grazing C intake $F_{\text{C-grazing}}$ (7.5 ± 1.2 kg C head^{-1} d^{-1}) was calculated from the difference between total required C intake (8.0 ± 1.2 kg C head^{-1} d^{-1}) and the offered C concentrate. The uncertainty of 16% resulted from the error propagation of the uncertainties of total and concentrate C intake.

S1.2 Milk carbon content

The uncertainty of the milk yield related carbon flux was clearly dominated by the estimation of the milk carbon content, which was not directly measured in this study. In a previous experiment Münger (1997) determined the relationship between milk C content and milk gross energy content (Fig. S1). Milk samples were collected during a study comparing energy utilization of three different dairy cattle breeds over a whole lactation cycle. Energy content of the milk (estimated) was calculated according to Arrigo et al. (1999) from sample contents of fat, protein and lactose as determined by mid-infrared spectroscopy (Milkoscan, Foss A/B, Hillerød, DK). Carbon content was determined using the total combustion of freeze-dried samples and subsequent gas analysis (CHN-600 Elemental Analyzer, Leco Inc., St. Joseph MI, USA). A relationship of 21 g C MJ^{-1} was derived from this experiment. The uncertainty was estimated by fitting outer bands to the data comprising 95% of the points (dashed lines in Fig. S1) resulting in a relative uncertainty of 9% (±1.9 g C MJ^{-1}).

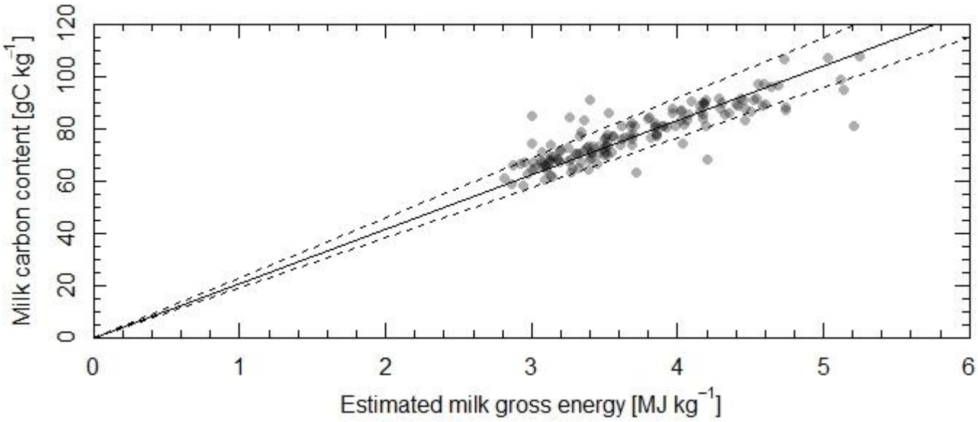

Fig. S1: Relationship between measured milk carbon content and milk gross energy content estimated from measured fat, protein and lactose contents according to Arrigo et al. (1999): $y = 20.8\ x$, $R^2 = 0.99$. The dashed lines indicate the uncertainty range limits ($y = 23\ x$ and $y = 19.2\ x$).

S1.3 CO_2 exchange

Measured CO_2 exchange of the pasture system needed a gap filling procedure to derive an annual data series without gaps. Felber et al. (2016) used the REddyProcWeb online partitioning and gap filling tool (www.bgc-jena.mpg.de/bgi/index.php/Services/REddyProcWeb) with two different data sets: i) a data set with fluxes that include fluxes with cow contribution to quantify $F_{\text{C-CO}_2\text{,tot}}$ and ii) the same data set but without fluxes with cow contributions to quantify $F_{\text{C-CO}_2\text{,past}}$. The total uncertainty of the annual CO_2 fluxes (54 g C m^{-2} yr^{-1} and 44 g C m^{-2} yr^{-1}, respectively) was determined from combined random and systematic uncertainties. As reported by Felber et al. (2016), the existence of a high fraction of gaps and the uncertainty of the filled data was the dominant error source. Its effect was estimated by a series of simulations, in which additional gaps were introduced by randomly shifting the original gap structure time series before gap filling. The corresponding results are presented in Fig. S2.

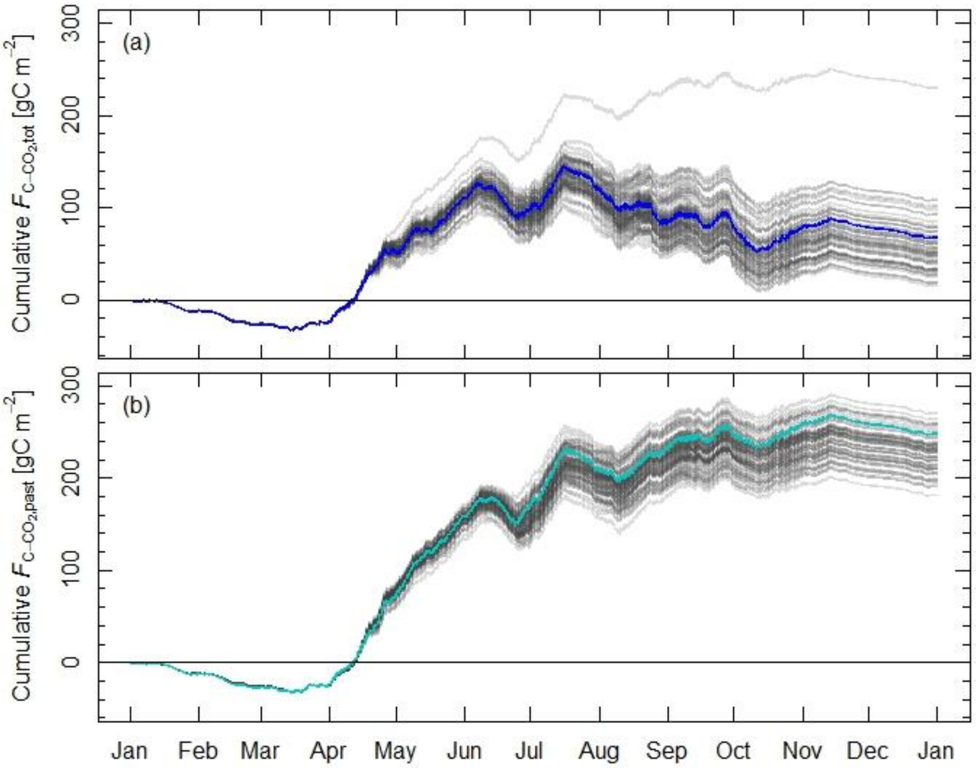

Fig. S2: Cumulative gap filled CO_2 fluxes (a) $F_{\text{C-CO}_2\text{,tot}}$ and (b) $F_{\text{C-CO}_2\text{,past}}$ simulated with additional gaps introduced by randomly shifting the original gap structure time series before gap filling. The colored lines indicate the time series with the original gap structure.

S1.4 Fertilization

The uncertainty of $F_{\text{C-fertil}}$ was combined from the uncertainty of the slurry and the urea application in the study year. The uncertainty of slurry application was estimated from previous studies in Switzerland. Ammann et al. (2009) measured C contents in slurry over several years and we adopted their uncertainty value of 17%. Only by specific sampling and analysis of the applied slurry (see Sect. 2.3.3), 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.

The uncertainty of urea C was assumed to be close to zero because, at one hand, the absolute C amount (2 g C m^{-2} yr^{-1}) was small compared to the amount of C from slurry (75 g C m^{-2} yr^{-1}) and, at the other hand, the C content and the amount of applied urea can be determined very accurately. Thus the uncertainty of $F_{\text{C-fertil}}$ corresponds directly to the uncertainty of slurry C.

S2 Budget results with uncertainties

Table S1: Components of the average carbon (C) and nitrogen (N) budget of the dairy cows (Eq. 5 and 9) with uncertainties (95% confidence range). The N budget was closed by adjusting the amount of excreta loss.

	Animal C exchange rate		Animal N exchange rate	
	(kg C head^{-1} d^{-1})	(% of intake)	(g N head^{-1} d^{-1})	(% of intake)
$E_{\text{C/N-intake}}$	8.0 ± 1.2	100	508 ± 137	100
$E_{\text{C-resp}}$	4.6 ± 1.6	57	-	-
$E_{\text{C-CH}_4\text{,cow}}$	0.3 ± 0.02	4	-	-
$E_{\text{C/N-milk}}$	1.5 ± 0.1	19	124 ± 13	24
$E_{\text{C/N-meat}}$	<0.1	<1	<5	<1
$E_{\text{C/N-excreta}}$	2.6 ± 0.8	32	380 ± 138	75
(Im-)balance	-1.0 ± 2.0	12		

Table S2: Components and uncertainties (95% confidence range) of annual carbon fluxes (g C m^{-2} yr^{-1}) determined for the total system and pasture system approach. 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 of interest.

	Total system (incl. cows)	Pasture only (excl. cows)	Attributed time used in Eq. (4)
$F_{\text{C-CO}_2\text{,tot}}$	+68 ± 54		full year
$F_{\text{C-CO}_2\text{,past}}$		+248 ± 44	full year
$F_{\text{C-CH}_4\text{,soil}}$	−2 ± 1	−2 ± 1	full year
$F_{\text{C-CH}_4\text{,cows}}$ 1)	−17 ± 1		99 days
$F_{\text{C-fertil}}$ 2)	+77 ± 13	+77 ± 13	full year
$F_{\text{C-grazing}}$		−404 ± 65	99 days
$F_{\text{C-excreta,past}}$		+104 ± 30	73.1 days
$F_{\text{C-products}}$	−82 ± 7		99 days
$F_{\text{C-feed,off}}$	+31 ± 5		99 days
$F_{\text{C-resp,off}}$	−65 ± 23		25.9 days
$F_{\text{C-excreta,off}}$	−37 ± 11		25.9 days
NECB	−27 ± 62	23 ± 76 3)	full year

1) including $F_{\text{C-CH}_4\text{,cows}}$ during pasture and off-pasture times

2) 75 g C m^{-2} yr^{-1} as cattle slurry and 2 g C m^{-2} yr^{-1} as urea

3) For the uncertainty calculation of $\text{NECB}_{\text{past}}$ it was taken into account that the errors of $F_{\text{C-grazing}}$ and $F_{\text{C-excreta,past}}$ are highly correlated, because the excretion was calculated as a fraction of the animal intake (Sect. 2.4.3).

Table S3: Comparison of components and uncertainties of the pastures greenhouse gas fluxes (g CO_2-eq. m^{-2} yr^{-1}) and the carbon sequestration determined for the total system ($NECB_{tot}$) and the pasture system ($NECB_{past}$). The ecological sign convention is used: negative values indicate emission from the system to the atmosphere. N_2O emissions are modelled, whereas the other emissions are measurements.

	mean	uncertainty
N_2O	−219	−438/+153
CH_4,cows	−573	±33
CH_4,soil	−50	±38
$NECB_{tot}$	−98	±226
$NECB_{past}$	+85	±179

S3 References

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