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# The nitrogen, carbon and greenhouse gas budget of a grazed, cut and fertilised temperate grassland

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**Supplementary information to the methodology**

**Site description and grassland management**

The field has a mean slope from NW to SE, with the steepest slope some 100 m to the NW of the eddy covariance tower. The maximum gradient in the field is 2.5%, so although not completely flat, the topography is only gently sloping. The grass was sown as a grass mixture (no clover) and no grassland renovation measures have taken place in the last 20 years. Animals were moved to neighbouring fields when the grass was too short for grazing to allow the recovery and growth of pasture plants and moved back to the field when the grass was high enough, which represent a common management practise by farmers in this region. Animals were counted several times per week and it was assumed that the animal number stayed constant between observations.

**Nitrogen and carbon leaching ($FN_{leaching}$ + $FC_{leaching}$)**

To reduce microbial transformation in the sampling bottles, the leachate passed a filter with very fine pores, (the suction cup, pore width < 1.6 µm), before it entered the sampling bottle and the bottles were placed in an insulated aluminium box that was placed in a soil pit in order to keep the bottles as cool as possible.

The soil water model which was used to derive the leachate volume did not allow the calculation of upward water fluxes with capillary rise from groundwater. We therefore only used the data for the upslope position for the calculation of leaching losses. The data of the hollow position were not used, because the soil was frequently water logged and likely influenced by capillaries from shallow ground water and lateral flow of groundwater. LandscapeDNDC, which was used to simulate N leaching for years where no N leaching was measured is a process based biogeochemical model with unifying functionalities of the agricultural-DNDC (e.g. Li et al., 1992; Li 2000) and the ForestDNDC model (e.g. Kesik et al., 2005; Stange et al., 2000), particularly suitable for ecosystem N turnover and associated losses of N trace gases and nitrate leaching (Wolf et al., 2012; Chirinda et al., 2011; Kiese et al., 2011).

**N deposition ($FN_{dep}$)**

**Wet N deposition**

The precipitation collector to collect samples for wet N deposition analysis was only open during rainfall and closed automatically when precipitation ceased. For years where no data were available (2002, 2003), an average mineral N concentration per mm rainfall for 2004-2009 was taken and adjusted to the annual rainfall amount at Easter Bush in 2002 and 2003.

**Dry N deposition**

The DELTA system used to collect cumulative monthly concentrations of gaseous and aerosol N species ($NH_3$, $HNO_3$, particulate $NH_4^+$ and $NO_3^-$) comprised of a denuder filter sampling train, an air pump (providing a sampling flow rate of 0.2-0.4 L $min^{-1}$) and a high sensitivity dry gas meter to record sampled volumes (Tang et al., 2009) set at 1.5 m height above ground. The four inferential models used to calculate N dry deposition fluxes were; the UK CBED scheme (Concentration Based Estimated Deposition technique)(Smith et al., 2000), the Dutch IDEM model (Integrated Deposition Model) (Erisman et al., 1994), the dry deposition module of the

Environment Canada model CDRY (Zhang et al., 2001; Zhang et al., 2003) and the surface exchange scheme EMEP (Simpson et al., 2003; Tuovinen et al., 2009), as described in detail by Flechard et al. (2011).

**$N_2O$ fluxes ($FN_{N2O}$)**

The detection limit for the TDL used for EC measurements was estimated to be 1 ppbV and the detection limit for a 30 min averaging period of the $N_2O$ flux measurement was estimated at 11 ng $N_2O$-N $m^{-2}$ $s^{-1}$. The mean flux footprint reflects the prevailing wind direction from the SW and secondarily from the NE, with the bulk of the contribution coming from within 50 m. The EC measurements thus sample the flatter areas of the field. Standard corrections were applied in processing to rotate co-ordinates relative to the mean wind flow in each half hour period. In this way, the fluxes were measured relative to the plane where mean vertical wind speed is zero, rather than assuming a horizontal ground surface.

For the chamber measurements four chambers (0.4 m diameter, 0.2 m height) were inserted into the soil to 0.03 – 0.07 m depth and were accessible for animals to graze and deposit excreta. Chambers were closed usually between 10:00 and 12:00 for 60 minutes with an aluminium lid fitted with a draft excluder. Samples of 200 ml were collected by syringe and injected into Tedlar bags at the beginning and the end of the closure time through a three way tap fitted into the lid. In the laboratory samples were transferred to glass vials using a syringe fitted with a 3-way tap; vials were flushed with the sample using two needles in order not to over pressurise the vials. Fluxes were calculated from the change of gas concentration with time of closure, multiplied by the volume of enclosed space and divided by its surface. Linearity tests were performed in between measurements showing a linearity of up to 120 minutes with an average $R^2 = 0.96$. The minimal detectable flux was 12 ng $N_2O$-N $m^{-2}$ $s^{-1}$.

**NOx fluxes ($FN_{NOx(soil)}$)**

The autochamber system used for NOx flux measurements consisted of four Perspex chambers (0.5 m x 0.5 m x 0.15 m; total volume 0.0375 $m^3$). They were fastened onto shallow frames and moved fortnightly to a second position to allow free grazing of the first chamber set. One control chamber was placed onto a Perspex surface to account for ozone/NOx reactions inside tubing and chamber. An in-house Labview program controlled chamber closure and activated a solenoid valve system to sample from the 4 chambers in sequence, interlaced with sampling from the control chamber. PTFE tubing (25 m in length, ID x OD; 4.35 x 6.35 mm) connected chambers to the NOx (42i-TL Trace Level NOx Analyzer, Thermo Scientific US) and ozone (Model 49i Ozone Analyzer, Thermo Scientific, US) analysers located inside the mains-powered field cabin. Fluxes were calculated from the difference between control (on Perspex) and sample chambers (on grass), the flowrate into the analysers (11 lpm) and the surface area of the frames (0.25 $m^2$).

**$NH_3$ + NOx volatilisation ($FN_{NH3/NOx\ (fert.,manure,\ animal)}$)**

The animal excretion amount was estimated in accordance with the IPCC Guidelines (IPCC, 2006a). The amount of N excretion (N*ex*) from animals depends on the total N intake ($N_{intake}$) and total N retention ($N_{retention}$) of the animal. $N_{intake}$ (amount of N consumed by the animal) depends on the gross energy (GE) intake and the crude protein content (*CP%*) of the feed. The GE intake (based on digestible energy of feed intake, milk production, pregnancy, current weight, mature weight, rate of weight gain and IPCC constants) in our study was estimated at 19.5 MJ $animal^{-1}$ $d^{-1}$ for ewes, while it ranged from 7.9 to 14.9 MJ $animal^{-1}$ $d^{-1}$ for lambs and from 160.9 to 169.7 MJ $animal^{-1}$ $d^{-1}$ for heifers. CP was calculated using the measured N content in the herbage.

Herbage N content was measured monthly in most years, where data were missing we used an averaged value calculated over all years. Ewes were fed standard cake concentrate during lactation (see sect. 2.5). This additional CP was added to the CP% of the herbage. $N_{retention}$ represents the fraction of N intake retained by the animal as meat, milk or wool. For lactating ewes the milk production was estimated at 0.618 l animal$^{-1}$ d$^{-1}$ and the milk protein content (*Milk PR%*) at 5.3% (Atti et al., 2006). Daily N excretions were thus calculated as 0.0263 kg N animal$^{-1}$ d$^{-1}$ for ewes and varied between 0.0019-0.0106 kg N animal$^{-1}$ d$^{-1}$ for lambs and 0.096-0.1013 kg N animal$^{-1}$ d$^{-1}$ for heifers, depending on animal weight.

**Exchange of $CO_2$ ($FC_{CO2}$)**

Wind velocity components were measured at 2.5m above ground and data were logged at 20 Hz by a PC running a custom LabView data acquisition program. Air was sampled 0.2 m below the sensor head of the anemometer using 6.3 mm (1/4 in. OD) Dekabon tubing. The IRGA was located in a field laboratory ca. 10 m from the mast. Lag times between wind data and trace gas concentrations were synchronised and taken into account in the offline data-processing (Helfter et al., 2014). Quality control of the eddy covariance data followed the procedure proposed by Foken and Wichura (1996). Data were filtered out if the friction velocity ($u_*$) was smaller than 0.2 m s$^{-1}$ (insufficient turbulence), $CO_2$ concentrations fell outside a plausible interval (330– 450 ppm), $CO_2$ fluxes fell outside the range -50 to 50 µmol m$^{-2}$ s$^{-1}$ and latent (LE) and sensible (H) heat fluxes fell outside the range -250 to 800 W m$^{-2}$. Missing NEE data were gap-filled using the online tool developed at the Max Planck Institute for Biogeochemistry, Jena, Germany (http://www.bgc-jena.mpg.de/~MDIwork/eddyproc/upload.php, Reichstein et al., 2005).

**Methane fluxes ($FC_{CH4}$)**

Methane emissions from grazing animals, i.e. animal excretion and enteric fermentation, were estimated following the IPCC Tier 2 methodology (IPCC, 2006a: Stewart et al., 2009). For animal excretion only solid volatile production was considered, as urine has no effect on $CH_4$ emissions (Jarvis et al., 1995). The calculation of $CH_4$ emissions from excretion was based on the amount of volatile solids (VS) excreted, the maximum $CH_4$ producing capacity ($B_o$) of the manure and the $CH_4$ conversion factor (MCF), which is specific to the storage type (pasture, in our study). The amount of VS excreted depended largely on the GE intake of the animal (for GE calculations, please see appendix, section $NH_3$ + NOx volatilization). Emission factors for excretion were calculated as 0.198 kg $CH_4$ head$^{-1}$ y$^{-1}$ for ewes and varied between 1.64-1.73 kg $CH_4$ head$^{-1}$ y$^{-1}$ for heifers and 0.081-0.152 kg $CH_4$ head$^{-1}$ y$^{-1}$ for lambs. Methane emission factors for enteric fermentation were calculated from GE intake and $CH_4$ conversion factors ($Y_m$). Depending on animal type and live weight, emission factors were 7.6 kg $CH_4$ head$^{-1}$ y$^{-1}$ for ewes and varied between 60.1-63.8 kg $CH_4$ head$^{-1}$ y$^{-1}$ for heifers and 2.0-4.0 kg $CH_4$ head$^{-1}$ y$^{-1}$ for lambs. Annual emissions from excretion and enteric fermentation were calculated from daily $CH_4$ emissions per animal multiplied by the animal number.

**2.12 Soil N and C measurements**

The soil sampling grid was positioned independently from slope and potentially preferred areas to avoid biased sampling. For the resampling in 2011 the same grid was used, but the transect was chosen two meters further to the NW in order not to meet the same place we already sampled and disturbed before.

**Table S1.** Systematic uncertainties attributed to each budget component. Combined uncertainties were calculated according to simple Gaussian error propagation rules.

| Nitrogen budget component | N [%] | Carbon budget component | C [%] |
|---|---|---|---|
| Mineral fertiliser | 1 | | |
| Cake feed for ewes | 5 | | |
| Organic manure[a] | 20 | Organic manure[a] | 20 |
| Harvest[b] | 16 | Harvest[b] | 11 |
| Leaching[c] | 32 | Leaching [c] | 32 |
| Animal (wool and meat)[d] | 12 | Animal (wool and meat)[d] | 12 |
| Wet deposition | 30 | $CH_4$ soil | 160 |
| Dry deposition[e] | 80 | $CH_4$ enteric | 20 |
| $N_2O$ | 30 | $CH_4$ excretion | 20 |
| NOx soil | 30 | $CH_4$ organic | 120 |
| $NH_4$ volatilisation | 30 | | |
| NOx volatilisation | 50 | | |
| $N_2$ | 30 | | |

[a]combined uncertainties of C and N analysis (17%) and volume spread (10%)
[b]combined uncertainty of total C (4%) and N (12%) analysis and farmer's estimate in harvest amount (10%)
[c] combined uncertainty of modelled data (30%) and measurements (10%)
[d]combined uncertainties from animal numbers (5%), animal weight (10%) and literature values for C and N content for meat and wool (3%)
[e]combined uncertainty of DELTA sample analysis (7%) and variation of outputs from the four models (80%)

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