Multi-variable experimental data set of agronomic data and gaseous soil emissions from maize, oilseed rape and other energy crops at eight sites in Germany

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Abstract: Greenhouse gas (GHG) emissions as well as other gaseous emissions and agronomic variables were measured for three years (2011/2012 – 2014/2015) at eight experimental field sites in Germany. All management activities were consistently documented. The database (GHG-DB-Thuenen) stores these multi-variable data sets of gas fluxes (CO₂, N₂O, CH₄ and NH₃), crop parameters (ontogenesis, aboveground biomass, grain and straw yield, N and C content, etc.), soil characteristics (nitrogen content, NH₄-N, NO₃-N, bulk density etc.), continuously recorded meteorological variables (air and soil temperatures, radiation, precipitation, etc.), management activities (sowing, harvest, soil tillage, fertilization, etc.), and their metadata (methods, further information about variables, etc.). In addition, N₂ data were measured and analyzed. Site-specific calculated C and N balances for the respective crops and crop sequences are also available.

Keywords: greenhouse gas emissions, maize, oilseed rape, energy crops, field experiment data.

1 INTRODUCTION AND ORIGINAL PURPOSE: GHG-DB-Thuenen was developed to store and archive a multi-variable data set of two research projects - "Potentials for the mitigation of greenhouse gas emissions from energy crop cultivation for biogas production" (hereafter BGD project) and "Mitigation of greenhouse gas emissions in oilseed rape cropping with particular consideration of nitrogen fertilization" (hereafter OSR project). This database allows flexible data processing and analyses with different disciplinary and interdisciplinary backgrounds. The original purpose of both collaborative projects was to quantify and to evaluate greenhouse gas (GHG) emissions for oilseed rape, maize and other energy crops, considering that oilseed rape is a major renewable resource for biodiesel and that maize plays a key role as feedstock for biogas production in Germany.

Various weekly and event-related measurements of gaseous emissions were conducted. The closed dynamic chamber method was used to measure CO₂ fluxes (Hoffmann et al. 2015), while CH₄ and N₂O were measured using static closed chambers (modified based on Hutchinson & Mosier 1981, Parkin & Vetterena 2010, de Klein & Harvey 2015). The same measuring technique and methods were used at all experimental sites. The field flux measurements are described in detail by Ruser et al. (2017). Emissions of NH₃ after fertilization were recorded using the Dräger tube method (Pacholski et al. 2006). Meteorological parameters such as air and soil temperature, precipitation, wind speed and direction as
well as relative air humidity were continuously recorded at automated meteorological stations at each field site. All management activities at the field sites were documented. Measured soil characteristics include e.g. soil texture, NH$_4$-N, NO$_3$-N, bulk density, pH value, nitrogen and carbon content. Crop parameters such as ontogenesis, aboveground biomass, grain and straw yield, carbon and nitrogen content were measured to supplement the GHG measurements. All crop and soil properties were sampled with documented standard methods. The composition of the used digestate (e.g. total nitrogen content, NH$_4$-N, organic carbon) were also analyzed. Additionally, N$_2$ data were measured in complementary laboratory incubation experiments. More details about the sampling intervals can be found in the database documentation (see supplementary material).

Some results from both projects have already been published, e.g. Fiedler et al. 2015, Fiedler et al. 2016, Fiedler et al. 2017, Heintze et al. 2017, Hoffmann et al. 2018, Huth et al. 2017, Lucas-Moffat et al. 2018, Peter et al. 2016, Pohl et al. 2015, Ruser et al. 2017. Further information is provided in the final project reports (only in German).

The database with the multi-variable data set is stored in the OpenAgrar repository and is publicly via OpenAgrar (Mallast et al. 2018, https://dx.doi.org/10.3220/DATA20180201-080050).

### 2 SITES, FIELD EXPERIMENTS AND THEIR DESIGNS

The BGD and the OSR project each consist of five sites located throughout Germany. Two of these sites, Dedelow and Hohenschulen, are part of both projects, resulting in eight different field sites (see Figure 1). The main climate and soil characteristics of each field site as well as the respective project affiliation are shown in Table 1.

#### Figure 1. Map of experimental sites – OSR project represented by squares and triangles; BGD project embodied by circles and triangles

![Map of experimental sites](image_url)

#### Table 1. Meteorological and soil characteristics of the experimental sites

| Project    | Site          | Latitude | Longitude | Air temp. | Precipitation | Soil type               | Soil texture (%) | pH  |
|------------|---------------|----------|-----------|-----------|---------------|-------------------------|------------------|-----|
| BGD        | Ascha (A)     | 48.99    | 12.66     | 7.5 °C    | 807 mm        | Cambisol               | 55               | 6.2 |
| OSR        | Berge (B)     | 52.62    | 12.78     | 8.7 °C    | 503 mm        | Luvisol                | 75               | 6.6 |
| OSR        | Berge (B)     | 52.62    | 12.78     | 8.7 °C    | 503 mm        | Luvisol                | 75               | 6.6 |
| BGD & OSR  | Dedelow (D)   | 53.38    | 13.79     | 8.4 °C    | 485 mm        | Luvisol                | 59               | 6.8 |
| BGD        | Dornburg (J)  | 51.00    | 11.66     | 8.8 °C    | 596 mm        | Haplic Luvisol         | 3                | 72  |
| BGD        | Gülzow (G)    | 53.81    | 12.07     | 8.4 °C    | 559 mm        | Stagnic Luvisol        | 69               | 8   |
| BGD & OSR  | Hohenschulen (H) | 54.31 | 9.99     | 8.9 °C    | 732 mm        | Haplic Luvisol/Anthrosol | 60               | 11  |
| OSR        | Ihinger Hof (I) | 48.74 | 8.92     | 8.3 °C    | 688 mm        | Haplic Luvisol         | 3                | 78  |
| OSR        | Merbitz (M)   | 51.62    | 11.91     | 9.0 °C    | 520 mm        | Haplic Chernosem       | 16               | 68  |

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The experiments of both projects and their designs are not identical and therefore described separately below.

2.1 THE BGD PROJECT: It is a satellite project of the long-term (2005-2015) EVA project “Development and comparison of optimized cultivation systems for the agricultural production of energy crops under different site conditions in Germany”\(^1\) and uses five of the EVA project sites. Starting in 2011, the BGD project worked on two distinct EVA experiments: the Small and the Large digestate experiment\(^2\). The Small digestate experiment studies one of the EVA energy crop sequences under three different N-fertilizer and digestate treatments: 100 % biogas digestate, 100 % mineral nitrogen fertilizer as well as 50 % digestate + 50 % mineral nitrogen fertilizer. Digestate was applied using a band spreader with a trailing hose (except Gülzow\(^3\)). The basis crop sequence consisted of energy maize (Zea mays L.), winter wheat (Triticum aestivum L.), white mustard (Sinapis alba L. – sown as catch crop), energy maize (Zea mays L.), winter rye used as WPS\(^4\) (Secale cereale L.), sorghum (depending on the site and the regional climatic conditions, either Sorghum bicolor L. MOENCH or Sorghum × drummondi). The replicated crop sequence with a temporal offset of one year was enhanced by winter triticale (×Triticosecale Wittmack) and ryegrass (Lolium perenne L.) (details in Figure 2).

\[\text{Figure 2. Crop sequences of the Small digestate experiment (BDG project)}\]

| Treatments | Maize | Winter wheat | Mustard/ fallow | Maize | Winter rye | Sorghum |
|------------|-------|--------------|-----------------|-------|-------------|---------|
| 100% biogas digestate | | | | | | |
| 50% biogas digestate + 50% mineral N fertilizer | | | | | | |
| 100% mineral N fertilizer | | | | | | |

The Large digestate experiment was designed as an energy maize monoculture with graded biogas digestate amendments and mineral fertilizer (50 % digestate, 75 % digestate, 100 % digestate, 125 % digestate, 200 % digestate, 0 % mineral N as control and 100 % mineral N) at all sites. In contrast to the Small digestate experiment and the OSR project experiment, at each site all seven measuring plots changed their location every year to eliminate N effects from the previous year. For both experiments in the BGD project, absolute quantities of mineral fertilizer (calcium ammonium nitrate - CAN) were calculated relatively to site-specific levels of 100% N fertilization. The N content of the used biogas digestate and a mineral fertilizer equivalent of 70 % determined the applied amount of digestate.

2.2 THE OSR PROJECT: It was established in 2012. The experimental design comprises a uniform field trial with an identical crop sequence consisting of oilseed rape (Brassica napus L.) – winter wheat (Triticum aestivum L.) – winter barley (Hordeum vulgare L.) cultivated at a randomized split-plot design with four replicated blocks (Error! Reference source not found.) and nine fertilizer treatments. Seven of those concern oilseed rape only. Of those, four treatments belong to the intensive monitoring program to analyze and to evaluate N\(_2\)O and CH\(_4\) fluxes\(^5\): (N3) - reduced mineral N-fertilization with 120 kg N/ha, (N4) - mineral N-fertilization with 180 kg N/ha (best management practice treatment), (N6) - full replacement of mineral N-fertilizer by digestate, and (N7) - full replacement of mineral N-fertilizer by biogas digestate and mineral fertilizer equivalent of 70 % determined the applied amount of digestate.

\(^1\) https://energiepflanzen.fnr.de/projekte/anbau/eva/?__mstto=en
\(^2\) Experiment names are agreed among all project partners and are used in the associated database.
\(^3\) Injection technique was used
\(^4\) WPS – whole plant used as silage
\(^5\) Additional N\(_2\)O and CH\(_4\) fluxes was analyzed and evaluated for treatment N1 and N5 in some sites and some years: Berge from 2015 to 2016 (N5), Dedelow from 2013 to 2016 (N1) and from 2014 to 2016 (N5), Hohenschulen from 2013 to 2014 (N1) and from 2015 to 2016 (N5), Ihinger Hof from 2014 to 2016 (N5), Merbitz from 2013 to 2016 (N1) and from 2014 to 2016 (N5).
digestate with nitrification inhibitor (Piadin). The trailing hose technique was used to apply the digestates as in the BDG-project. Three additional treatments were established to analyze the site-specific yield optimum (N1) – No N fertilization as control, (N2) - reduced mineral N-fertilization with 60 kg N/ha, (N5) - high mineral N-fertilization with 240 kg N/ha). For winter wheat and winter barley a site-specific N-fertilization according to best agricultural management practices was applied. As a second control, a long-term grassland without fertilization and management was also monitored.

Figure 3. Spatial scheme of the experimental design of the OSR project (exemplary for one year at one field site, each year crops rotate within each block)

3 DATABASE STRUCTURE AND DATA ACCESS: GHG-DB-Thuenen was developed with Microsoft Access Database 2007-2016. The database provides a combination of a large base of data (in total 43 million records) spread over 48 separate tables (see Table 2). All tables are sorted into six data categories: “experimental design”, “driving forces”, “measurements – raw data”, “measurements - processed data”, “specific statistics” and “metadata”.

| Table 2. All tables of the GHG-DB-Thuenen |
|---------------------------------------------|
| **Table name**    | **Category**       | **Project**       |
| D_Management     | Driving forces     | BGD & OSR         |
| D_Meteo          | Driving forces     | BGD & OSR         |
| D_Soilprofile    | Driving forces     | BGD               |
| E_Block          | Experimental design| BGD & OSR         |
| E_Crop           | Experimental design| BGD & OSR         |
| E_Experiment     | Experimental design| BGD & OSR         |
| E_Plot           | Experimental design| BGD & OSR         |
| E_Site           | Experimental design| BGD & OSR         |
| E_Treatment      | Experimental design| BGD & OSR         |
| E_Variation      | Experimental design| BGD & OSR         |
| M_Below_LOQ_info | Metadata           | BGD & OSR         |
| M_Digestate_info | Metadata           | BGD               |
| M_EVA_Code_ListA_B | Metadata        | BGD               |
| M_EVA_Code_ListC | Metadata           | BGD               |
| M_EVA_Code_ListD | Metadata           | BGD               |
| M_Experiment_info | Metadata           | BGD & OSR         |
| M_Fertilisation_info | Metadata    | BGD               |
Table 2. All tables of the GHG-DB-Thuenen - Continued

| Table name         | Category          | Project     |
|--------------------|-------------------|-------------|
| M_Information      | Metadata          | BGD & OSR   |
| M_Installations_info| Metadata         | BGD & OSR   |
| M_Management_past  | Metadata          | OSR         |
| M_Methods          | Metadata          | BGD & OSR   |
| M_Site_info        | Metadata          | BGD & OSR   |
| M_Soilprofile_info | Metadata          | BGD         |
| M_Units            | Metadata          | BGD & OSR   |
| M_Variables        | Metadata          | BGD & OSR   |
| M_Variable_info    | Metadata          | BGD & OSR   |
| P_Balances         | Processed data - Measurements | BGD |
| P_Emis_CO2_flux    | Processed data - Measurements | BGD & OSR |
| P_Emis_N2O_CH4_daily | Processed data - Measurements | BGD |
| P_Emis_N2O_CH4_flux| Processed data - Measurements | BGD & OSR |
| P_Modelled_CO2     | Processed data - Measurements | BGD & OSR |
| P_Modelled_NO3     | Processed data - Measurements | BGD & OSR |
| P_NO3leaching      | Processed data - Measurements | BGD |
| P_Parameter_CO2    | Processed data - Measurements | BGD & OSR |
| R_Cl_Tracer        | Raw data - Measurements | BGD |
| R_Cl_Tracer_factor | Raw data - Measurements | BGD |
| R_Digestate        | Raw data - Measurements | BGD & OSR |
| R_Emis_CO2_conc    | Raw data - Measurements | BGD |
| R_Emis_N2O_CH4_CO2_conc | Raw data - Measurements | BGD & OSR |
| R_Incubation       | Raw data - Measurements | BGD |
| R_Plant            | Raw data - Measurements | BGD & OSR |
| R_Soil_continuous  | Raw data - Measurements | OSR |
| R_Soil_periodic    | Raw data - Measurements | BGD & OSR |
| S_Statistics_Balances | Specific statistics | BGD |
| S_Statistics_N2O_flux | Specific statistics | OSR |
| S_Statistics_CO2_flux | Specific statistics | BGD |
| S_Statistics_N2O_CH4_flux | Specific statistics | BGD |

Figure 4. Data structure of the database GHG-DB-Thuenen
Figure 4 illustrates the simplified data structure. The detailed structure of the data model is provided as a supplement. More details about the database are provided in the documentation (see supplementary material). In January 2021 the database GHG-DB-Thuenen with the research data will become freely available for (re)use by others at the publication server and data repository OpenAgrar (doi: 10.3220/DATA20180201-080050).

3.1 CATEGORY – EXPERIMENTAL DESIGN: The category “experimental design” contains the basic information (“key of the database”). The table “Plot” represents the organizing principle of the database and contains a Plot_ID (the primary key) describing the unique positioning or affiliation of each measured value and the associated information of the database. For each “Measurements” table in the GHG-DB-Thuenen (with the exception of the tables “Meteo” and “Soil profile”) there is a 1:n relation to the table Plot. This means that the tables are linked by the foreign key Plot_ID.

3.2 CATEGORY – DRIVING FORCES: This table contains mandatory data on management events such as emergence, sowing, harvest with crop name, soil tillage with soil depth and type, applications of mineral and organic fertilization (including total amount of fertilizer and quantity of N-input from the fertilizer) as well as crop protection. Additionally, dates of crop development, damages, irrigation (amount of applied water), mowing and freeze-kill (catch crops) as well as nutrition supply and previous crop are integrated in this table.

The table “Soil profile” contains general soil parameters to characterize the composition of soil horizons at each field site. All meteorological parameters (see Table 3) were collected as hourly values (daily values for precipitation) in the OSR project and half-hourly values in the BGD project at each field site.

### Table 3. Meteorological parameters

| Meteorological parameters       | Unit      | Sampling in/at            | Project     |
|--------------------------------|-----------|---------------------------|-------------|
| Air humidity                   | %         |                           | BGD & OSR   |
| Air pressure                   | hPa       |                           | BGD         |
| Air temperature °C             | 200 cm height | BGD & OSR   |
| Air temperature °C             | 20 cm height | BGD         |
| Global radiation W/m²          |           | OSR                       |
| Photosynth. active radiation µmol/(m²*s) | BGD     |
| Precipitation mm; mm/30 min    |           | BGD & OSR                 |
| Soil moisture %                | 10 cm soil depth | BGD       |
| Soil temperature °C            | 2 cm soil depth | BGD       |
| Soil temperature °C            | 5 and 10 cm soil depth | BGD & OSR       |
| Soil temperature °C            | 20 cm soil depth | BGD (three sites) |
| Sunshine duration h            |           | OSR (one site)            |
| Wind direction °               |           | BGD & OSR                 |
| Wind speed m/s                 | 200 cm height | BGD & OSR       |

3.3 CATEGORY – MEASUREMENTS: All “Measurements” tables follow a similar structure, i.e. the following eight columns are always present and can be complemented by more columns if necessary: Plot_ID: Unique spatial positioning / affiliation of the measured value Date_ or Timestamp_: Point in time of the measured value as date (dd.mm.yyyy) or timestamp (dd.mm.yyyy hh:mm:ss) Variable_ID: Index of the measured variable Value_: The measured value Unit_ID: Index of the unit in which the measured value was recorded Method_ID: Index of the applied methods of the measured value Comments: Comment(s) ID: Unique counter / index of the table

The metadata tables “Variables”, “Units” and “Methods” are always linked to each “Measurements” table. Please note that not all measurements are available across all eight field sites.

3.3.1 Crop, soil and fertilizer data: At all experimental sites event-related plant and soil samples were collected. Soil samples for the analysis of NH₄⁺ and NO₃⁻ contents were taken “parallel” to the gas flux measurements, i.e. each weekly gas flux measurement campaign has a related NH₄⁺ and NO₃⁻ content.
Additionally, the composition of the digestate was also analyzed and stored. All measured variables are provided in the supplementary material. The tables “Plant” and “Soil_periodic” are additionally equipped with two Boolean columns (switching variable). The Boolean column “Aggregated” indicates whether a measured value was aggregated based on several values or not. "Inherited" as a second Boolean shows whether a measured value was adopted from another plot or not. If a value was adopted, a comment states from which plot. A further Boolean column “Below_LOQ” in the tables “Soil_periodic” and “Digestate” displays whether a measured value is below the limit of quantification (LOQ) or not.

The tables “CL_tracer” and “CL_tracer_factor” contain data sets of additional field experiments to quantify NO\(_3^-\) in soil. A further additional laboratory experiment quantified N\(_2\), N\(_2\)O, CO\(_2\) and CH\(_4\) using an incubation method. The experimental results are displayed in the table “Incubation” (a data subset is published by Fiedler et al. 2017). Besides experimental field and laboratory data sets, different modelled measures of nitrate-leaching are stored in the database. All modelled data originate from empirical modelling of soil water and nitrogen dynamics.

**3.3.2 Gas emission data:** The tables contain either raw data of gas flux measurements (e.g. the tables “CO\(_2\)conc” and “N\(_2\)O_CH\(_4\)_CO\(_2\)conc”) or processed data (e.g. “N\(_2\)O_CH\(_4\)_flux”). Different procedures were conducted to calculate gas fluxes. For the OSR project, more details about the N\(_2\)O flux calculation are provided by Ruser et al. 2017. Further information is also given in the metadata table “Methods _”. Due to different calculation procedures, four different statistical tables are stored. The table “N\(_2\)O_CH\(_4\)_flux” displays two statistical indexes. “Stat_N\(_2\)O_ID” is used for the OSR project and links all fluxes with the associated statistical measures from the flux calculation in table “Statistics_N\(_2\)O_flux”. For the BGD project, the N\(_2\)O and CH\(_4\) fluxes (table “N\(_2\)O_CH\(_4\)_flux”) and CO\(_2\) fluxes (table “CO\(_2\)_flux”) are based on weighted linear regressions. Both tables store indexes linking all statistical parameters of the regression procedure. A further statistic table was created for various information on calculated C balance parameters. A link to the table “Balances” is also described by a statistic index. The table “N\(_2\)O_CH\(_4\)_daily_flux” contains interpolated and aggregated daily N\(_2\)O and CH\(_4\) fluxes.

In addition to field emissions, closed chamber measurements from the Small digestate experiment (BGD project) were used to model CO\(_2\) exchange (R\(_{eco}\), NEE and GPP) following a standardized methodology (Hoffmann et al. 2015). The resulting modelled CO\(_2\) fluxes are stored in several tables due to the large amount of data. The data subsets are divided by site and treatment of the Small digestate experiment. A campaign index links all parameters to the measured flux values in table “CO\(_2\)_conc”. Model parameters can be based on data from one or several measurement campaigns. For the OSR project, the closed chamber and the eddy covariance technique were installed in parallel at the Dedelow site and CO\(_2\) fluxes were measured during the crop cultivation period of oilseed rape and winter wheat. The measured and modelled CO\(_2\) fluxes are stored in the database. A description of the setup, the modelling and a comparison of the CO\(_2\) fluxes from the two techniques can be found in Lucas-Moffat et al. (2018).

**3.4 METADATA:** The metadata tables “Variables”, “Units” and “Methods” specify all variables, units and methods used in the GHG-DB-Thuenen. “Variables_info” contains all measured variables used. The variables are explained in a brief description, complemented by information on value plausibility and reference to time and space. It also defines the data type of each variable (raw, processed or general data). The table “Information” lists descriptive information on all columns of the GHG-DB-Thuenen, except for the column “Variable _”. Further metadata tables provide information about sites, experiments, soil profiles, sensor installations, site-specific fertilizations and limits of quantification.

**4 SUMMARY:** GHG-DB-Thuenen provides greenhouse gas emissions (GHG), as well as other gaseous emissions and agronomic variables were measured for three years (2011/2012 – 2014/2015) at eight experimental field sites in Germany. In total 43 million records are stored and archived to quantify and to evaluate greenhouse gas emissions (GHG) for oilseed rape, maize and other energy crops. In January 2021 the database will become publicly available at the OpenAgrar repository OpenAgrar (doi: 10.3220/DATA20180201-080050).

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