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Nitrous oxide emission budgets and landuse driven hotspots for organic soils in Europe

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Abstract

Organic soils are a main source of direct nitrous oxide (N_2O) emissions, an important greenhouse gas (GHG). Observed N_2O emissions from organic soils are highly variable in space and time which causes high uncertainties in national emission inventories. Those uncertainties could be reduced when relating the upscaling process to a priori identified key drivers by using available N_2O observations from plot scale in empirical approaches. We used the empirical fuzzy modelling approach MODE to identify main drivers for N_2O and utilize them to predict the spatial emission pattern of European organic soils. We conducted a meta study with a total amount of 659 annual N_2O measurements which was used to derive separate models for different land use types. We applied our models to available, spatial explicit input driver maps to upscale N_2O emissions on European level and compared the inventory with recently published IPCC emission factors. The final statistical models explained up to 60 % of the N_2O variance. Our study results showed that cropland and grasslands emitted the highest N_2O fluxes 0.98 $\pm$ 1.08 and 0.58 $\pm$ 1.03 $\mathrm{g\,N_2O\text{-}N\,m^{-2}\,a^{-1}}$, respectively. High fluxes from cropland sites were mainly controlled by low soil pH-value and deep drained groundwater tables. Grassland hotspot emissions were strongly related to high amount of N-fertilizer inputs and warmer winter temperatures. In contrast N_2O fluxes from natural peatlands were predominantly low (0.07 $\pm$ 0.27 $\mathrm{g\,N_2O\text{-}N\,m^{-2}\,a^{-1}}$) and we found no relationship with the tested drivers. The total inventory for direct N_2O emissions from organic soils in Europe amount up to 149.5 $\mathrm{Gg\,N_2O\text{-}N\,a^{-1}}$, which included also fluxes from forest and peat extraction sites and exceeds the inventory calculated by IPCC emission factors of 87.4 $\mathrm{Gg\,N_2O\text{-}N\,a^{-1}}$. N_2O emissions from organic soils represent up to 13 % of total European N_2O emissions reported in the European Union (EU) greenhouse gas inventory of 2011 from only 7 % of the EU area. Thereby the model demonstrated that with up to 85 % the major part of the inventory is induced by anthropogenic management, which shows the significant reduction potential by rewetting and extensivation of agricultural used peat soils.

1 Introduction

Nitrous oxide (N_2O) is a natural trace gas with increasing abundance in atmosphere and radiation enforcing properties. Soil processes are the dominant source of terrestrial N_2O and contribute about 70% to the total net emission budget of N_2O (Mosier, 1998). Maljanen et al. (2010) showed that N_2O emissions from organic soils in Nordic countries are four times higher in comparison to fluxes from mineral soils. In Europe about 7% of the land area is covered by organic soils, often also called peat soils, according to Montanarella et al. (2006). The N_2O fluxes from natural, water logged organic soils are low. Drainage and cultivation lead to N mineralisation from degrading peat, and consequently N_2O production (Wild et al., 1998; Regina et al., 2004) via nitrification and denitrification processes (Firestone and Davidson, 1989). So far large scale estimates are based on static emission factor approaches, which only partly reflect land use, climate, soil nutrient or drainage status. A regional study from Estonia found significant land use differences in N_2O emissions from drained organic soils (Mander et al., 2010). The 2013 Supplement to IPCC guidelines for national GHG inventories on wetlands (IPCC, 2013) has recently published new emission factors for different land use types, climate regions and basic soil nutrient and drainage categories for global application. Application of emission factors in GHG inventories can lead to high uncertainties (Pouliot et al., 2012). So far, there are no successful process-based models of N_2O fluxes for organic soils. Klemedtsson et al. (2005) suggested to model N_2O emissions from peatland forest in Sweden with an empirical relationship to C/N ratio of top soil, based on observations from 12 sites. In Great Britain N_2O emissions from agricultural organic soils were modelled with a regression to N input, water filled pore space (WFPS), soil temperature and land use (Sozanska et al., 2002), based on observations from 59 sites predominantly from mineral soils. The long reference lists in the 2013 IPCC Supplement suggest that there is a large amount of N_2O observations in the literature that has not yet been used for model calibration and validation. While some region- and land-use specific empirical relationships have been published (Klemedtsson et al., 2005; Mander et al., 2010), a generic functional relationship between N_2O and environmental and management drivers across land-use categories is missing. This hampers the development of management strategies at local, national and European scale for organic soils that reduce anthropogenic N_2O emissions. This study aims to:

1. Develop generic empirical relationships between human and natural drivers of N_2O applicable across land-use types, by multi-site calibration with all observations published until mid 2013 in Europe.

2. Determine the N_2O budget of organic soils in Europe and its various sources of uncertainty (model, spatial driver data).

3. Determine spatial hotspots of N_2O emissions driven by land-use, other human or natural drivers and priorities for future observations in high N_2O-risk zones.

4. Test whether the new IPCC emission factors are spatially representative of Europe and quantify potential bias.

2 Material and Methods

2.1 Database

The N_2O flux synthesis is based on a meta study of direct N_2O emissions from organic soils. This literature survey contains N_2O observations in Europe published until mid 2013. All incorporated in situ flux measurement studies used the same gas measurement method, the well-established closed chamber technique (Hutchinson and Mosier, 1981). Annual N_2O fluxes were directly taken out of the publications and all fluxes that fulfill the minimum criteria of twelve measurements per year were included in our analysis. The database contains the total amount of 659 annual flux measurements made on 109 sites in temperate and boreal regions in Europe, spread across the main organic soil regions (Figure 1). Numerous measurements came from central Europe (Germany, Netherlands) and from Northern countries like Finland, Sweden and Estonia whereas the British isles and Eastern and Southern Europe are underrepresented in the dataset. The number of measurements per site differs from a minimum of one annual flux period up to a total amount of 59 annual fluxes. Most of the sites include flux measurements from different plots that vary in management and environmental conditions. Partly the experimental design was purposely chosen to distinguish between treatments or influences from different sources, e.g. nitrogen fertilizer (Velthof and Oenema, 1995) or water content of top soil (van Beek et al., 2010). We extracted diverse environmental and management parameters to derive a wide set of parameters that can be tested for potential relationships to N_2O fluxes. The most frequent parameters are listed in Table 1 with units, parameter ranges and fraction of coverage in the studies. Missing values for climate parameters were gap-filled with data from the European Climate Assessment & Dataset (ECAD), described in Haylock et al. (2008). The entire database references are listed in Table 6.

2.2 Model development, calibration and validation

At first the N_2O fluxes and potential drivers were analysed by univariate statistics, respectively. Furthermore we investigated the correlations between fluxes and the corresponding driving parameters to understand interactions and constrain parameter combinations. The specified statistical analyses were carried out with the programming language R (R Development Core Team, 2013). Based on these results we used an empirical fuzzy logic modelling approach to predict N_2O fluxes based on main driving parameters. This data-driven fuzzy logic model has been successfully applied to predict annual N_2O fluxes for agricultural mineral soils in Germany (Dechow and Freibauer, 2011). Bardossy et al. (2003) describe the fuzzy based modelling as fast, transparent and parameter parsimonious alternative to other approaches. These techniques are based on the concept of fuzzy logic, a set theory that extends the binary logic of true (1) and false (0). It allows to have fuzzy sets with truth values in the range between 0 and 1 (degree of fulfilment) and therefore is able to handle partial truth, uncertainties or so called fuzziness. The fuzzy sets can be used to classify factor domains not only by constant crisp sets but also by different function types (e.g. , triangular, quadratic) with variable membership grade over the factor domain. Furthermore it can be utilized to divide factor spaces into sub domains and calculate all possible combinations in fuzzy interference schemes (FIS) by fuzzy logic algebra.

These FIS can be merged in conditional rule systems to model multivariate problems. The approach is able to model non linear relationships and to represent a priori knowledge that limits parameter spaces or constrains directions of relationships. Another advantage of fuzzy sets in comparison to other decision tree approaches is the smooth transition between different sets that allows more accurate modelling of continuous variables. In this study triangular fuzzy sets for driving parameters of annual N_2O fluxes were calibrated by simulated annealing technique to optimize corresponding responses for N_2O flux measurements. We use a forward selection algorithm in combination with a sub dataset, which consists of drivers that are available on European scale, to determine the best fitted and regionalizable parameter combinations. The Nash Sutcliffe Efficiency (NSE) was used for model assessment:

$$NSE = 1 - \frac{\sum_{i=1}^{n}(F_o^i - F_m^i)^2}{\sum_{i=1}^{n}(F_o^i - \bar{F}_o)^2} \quad (1)$$

The coefficient ranges from $-\infty$ to 1, where the value of 1 corresponds to a perfect match and a value of 0 indicates an accuracy comparable to the mean of the observed data. The residual variance of the observed fluxes F_o^i and the modelled fluxes F_m^i must be smaller than the data variance of the observed fluxes to indicate that the model is a better predictor than the mean value of the observed data $\bar{F}_o$. The NSE coefficient is described as a good indicator of model prediction performance because it is a combined measure for scatter and bias (Nash and Sutcliffe, 1970). The automatic selected parameter combinations with the highest NSE measures above 0 represent the best N_2O predictors according to the used parameter set and performance indicator. The NSE_{cali} and NSE_{cv} refer to the NSE coefficient for the model calibration and the validation, respectively.

Further optimisation was performed by setting up model ensembles (MODE) for final parameter combinations, using empirical bootstrapping methods with up to 50 individual models which reduces over-fitting and achieves better averaged model predictions. We followed the procedures described in Dechow and Freibauer (2011).

We validated the model results by a k-fold cross-validation by study sites (Kohavi, 1995). The original dataset was partitioned into k subsets by study site. A single subsample was excluded as validation dataset from the calibration process. All remaining k-1 sites were used for model calibration and could be validated to the independent validation set. This procedure is repeated k times until each site is used once as validation dataset. The study sites subsamples include different number of annual fluxes which can contain up to 15% of fluxes from the total dataset. Hence the unequal sized subsamples can lead to a very strict cross validation result in case of excluding a site with numerous measurements and high proportion of the total dataset. The calibration was weighted by number of measurements per site to avoid over- and under-representation for sites with small and high number of flux measurements, respectively. We also have to take into account that the N_2O fluxes span over several orders of magnitude. Hence we applied a logarithmic transformation,

$$F_o^l = ln(F_o^i + 0.5) \quad (2)$$

to linearise the flux range for better optimisation performance. To generate models useful for upscaling, we considered only driving parameters that can be regionalized. Therefore good predictors of N_2O fluxes like soil nitrate (NO_3^-), ammonium (NH_4^+), mineral N content or CN ratio were not included into the final modelling approach.

2.3 Regionalization

The regionalization describes the application of our validated fuzzy model on EU-wide available input datasets to derive consistent N_2O emissions for Europe. Spatially explicit upscaling of the fuzzy model was realized in a geographic information system (GIS). We used the open source GRASS GIS (Neteler et al., 2012) to process the model input datasets and predict N_2O emissions on EU level. Therefore we developed and implemented several GRASS modules to perform fuzzy logic modelling in this GIS framework. Additionally we conduct time series analysis of climate and landuse data by using the temporal framework TGRASS (Gebbert and Pebesma, 2014). The input data on EU level is predominantly available in raster cell format in Lambert azimuthal equal area (LAEA) projection with the finest resolution of 1x1 km gridded data. Hence we selected the LAEA projection and a resolution of 1x1 km as common unit to avoid data loss by transformation processes and raster cell resampling. The model was applied on peatland areas in Europe which are based on the organic soil distribution map by Montanarella et al. (2006). This dataset serves as basis for all spatial calculations in this study. The following regional datasets were used for driving parameters:

- Land use distribution:
  - CORINE land cover (CLC) from 2006 (Büttner and Kosztra, 2007) differentiated into cropland, grassland, forest, peat extraction and natural areas.
  - Historic Land Dynamics Assessment (HILDA) (Fuchs et al., 2013) differentiated into cropland, grassland (which contains also natural areas) and forest sites for latest available year, 2010.
- Meteorology: Temperature and precipitation from ECAD dataset (Haylock et al., 2008). Based on the daily resolution dataset we calculated the 30 year (1982-2012) longterm annual and seasonal (spring, summer, autumn and winter) minimal, maximal and mean temperatures and precipitations sums.
- Mean annual water table: There is no spatially explicit data available for Europe. Mean annual water table was therefore represented by land use specific frequency distribution functions of observed water table in the database. The mean value of the frequency distributions was used for regionalization, while the distribution served for uncertainty assessment.
- Soil properties: Datasets from European soil portal and Joint Research Center (JRC) (Panagos et al., 2012).
  - Top soil acidity (Reuter et al., 2008).
  - Organic carbon content of top soil (Jones et al., 2005).

  - Bulk density of top soil (Tiktak et al., 2002). The European soil portal provides gridded averages, which mix mineral and organic soils. Consequently, bulk density neither adequately reflects organic soils nor the dependence of bulk density on land use and peat degradation status. As for mean annual water table, land use specific frequency distribution functions of bulk density was used for regionalization.

- Nitrogen fertilization based on Hutchings et al. (2012).

The sum of European wide annual N_2O emissions represents the emissions from cropland, grassland, forest, peat extraction and natural sites on organic soils. Beside the fuzzy model approach land use stratified emission factors can also be utilized to predict annual emission budgets. Emission factors were derived from the N_2O flux synthesis as mean per land use type and compared to the IPCC emission factors from the wetland supplement (IPCC, 2013). We used the good practise guidance of the IPCC Tier 1 approach to calculate the European inventory of N_2O emissions from managed organic soils. The IPCC Tier 1 approach stratifies land use classes by drainage, peat type and climate zone. The delineation between the temperate and boreal zone can be derived from the IPCC definition applied to climate data. Drainage and peat type, however, are not available in a spatially explicit way. We therefore applied the default of nutrient-poor conditions in boreal forests, nutrient-rich conditions in temperate forests, and deep drainage in temperate grasslands. Spatial resolution and land use definitions produce significant uncertainty in the regionalization of N_2O emissions. The uncertainty in land use classifications was assessed by testing the sensitivity of the European N_2O inventory to the choice of the land use map, represented by the two European wide spatially explicit map products CORINE and HILDA. The general land use distribution on organic soils can be separated into the forestry dominated boreal zone, the agricultural temperate zone and the main natural peatland areas in the subarctic Northern parts of Europe. N_2O emission hotspots were identified on the map together with related ranges of drivers separately for each land use specific model. In order to locate N_2O emission hotspots in Europe we computed the flux distributions by land use category from the N_2O emission map and defined the fluxes above the 90th quantile as hotspot emissions for the particular land use category.

2.4 Uncertainty analysis

N_2O emissions can vary largely in space and time and the capabilities to model these variation are restricted to the size of the sample dataset and the data quality. Therefore it is important to propagate the uncertainties during the modelling process to be able to estimate the overall accuracy of the model result. For several ecosystems the confidence interval limits of IPCC emission factors for N_2O emissions from peat soils are greater than the mean values. The modelling approach aims to reduce this variability by using explanatory parameters to predict N_2O fluxes. Uncertainty analysis comprised uncertainties in input parameters and in the model. The model uncertainty was calculated with a fuzzy rule based uncertainty estimation, details in (Dechow and Freibauer, 2011). It can be described as the standard deviation σ_f, which is derived from the rule specific normal like uncertainty distributions in Eq. 3:

$$\sigma_f^2 = \frac{\sum_{i=1}^{n} DOF_i \sigma_{r_i}^2}{\sum_{i=1}^{n} DOF_i} \tag{3}$$

where DOF_i is the degree of fulfilment and σ_{r_i} is the standard deviation of a normal like uncertainty distribution of Rule i. The rule specific uncertainty was estimated by using results from the cross validation over study sites as reference to calculate the model uncertainty. The input parameter uncertainties were estimated by Monte Carlo simulation with parameter variabilities taken from available database. The combination of input and model uncertainty results in the overall uncertainty estimation, which was applied pixel wise for uncertainty analysis on EU level. The resulting map contains average and standard deviation values for a normal like distribution function of N_2O emissions for each raster cell.

The N_2O emission budget is the sum of all raster cell values that are located within a defined area. The corresponding uncertainty of the inventory can be calculated by error propagation. Spatial explicit modelling introduces autocorrelation into the calculation of GHG emission inventories and their uncertainty estimation. Without consideration of the spatial covariance we would underestimate the real uncertainty. This is a methodical problem we solved by integrate the covariance into the error propagation equation to improve the uncertainty estimation:

$$\sigma_b = \sqrt{\sum_{i=1}^{n} \sigma_{f_i}^2 + 2 \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} cov_{ij}} \tag{4}$$

where $\sigma_{i,j}$ is the standard deviation of a raster cell, indexed by i and cov_{ij} the corresponding covariance between all raster cell values, indexed by i and j. We approximated the covariances between raster cells as a function of distance and calculated the corresponding covariance matrix to apply Eq. 4 to the raster map.

3 Results and Discussion

3.1 Statistical analysis

The N_2O fluxes were log normal distributed with predominantly minor fluxes between -0.1 to 0.1 and few high peaks up to 8.11 $\mathrm{g\,N_2O\text{-}N\,m^{-2}\,a^{-1}}$from grasslands in the Netherlands (Koops et al., 1997). We found significant differences in flux data between land use categories, that are shown in Fig. 2. In general the highest fluxes occurred on cropland and grassland sites, whereas natural and rewetted organic soils feature low emissions in average. Fluxes from forest sites were in average lower than the emissions from cropland and grasslands, but included some high outliers of up to 6.06 $\mathrm{g\,N_2O\text{-}N\,m^{-2}\,a^{-1}}$from Slovenia, (Danevčič et al., 2010). The peat extractions sites were only represented by 35 annual flux measurements, which indicated an average flux of 0.47 $\mathrm{g\,N_2O\text{-}N\,m^{-2}\,a^{-1}}$for active and abandoned extraction sites. Table 2 lists the correlation coefficients for N_2O fluxes and main driving parameters. The mean annual groundwater tables for different land use categories were correlated to N_2O fluxes with a correlation coefficient of r = 0.32 ($p < 0.05$). In addition Fig. 3 (a) shows that high N_2O fluxes occurred in the range of mean groundwater table of 0.2 to 0.9 m below the surface. The groundwater table has been found as driving parameter for N_2O in several other studies, (Martikainen et al., 1993;

Regina et al., 1996; van Beek et al., 2010). Drainage increases emissions of N_2O, in particular for nutrient rich organic soils and fertilized and grazed grassland. The seasonal fluctuations of the water table could be better predictor for the magnitude of N2O emissions but these informations were only available for a small fraction of the data set. Therefore we were restricted to use only the mean annual water table in our analysis. The N-fertilization amount was also correlated with N_2O fluxes ($r = 0.43$, $p < 0.05$). Figure 3 (b) suggests that this relationship is especially strong for emissions from grasslands. The N_2O fluxes plotted against C/N Ratio indicated a ratio threshold at approximately 30-35 below which high fluxes occur in the dataset, see Fig. 3 (c). This result provides evidence and supports the findings of Klemedtsson et al. (2005) that the C/N ratio can be a strong predictor for N_2O emissions from organic soils. Peat mineralization releases carbon as CO_2 while nitrogen preferentially remains in the soil. Nitrogen fertilization has a similar net effect, so that both processes reduce the soil C/N ratio. Therefore the C/N ratio can be utilized as indicator for soil processes and conditions that trigger N_2O emissions. Figure 3 (d) shows that low pH values were related to high C/N ratios and vice versa. The collected site data revealed a non linear relationship between pH values and corresponding soil C/N ratios. Due to unavailable data for C/N ratios on European scale, the soil pH relationship to C/N ratios was used as partial proxy for C/N ratio in the regionalization. There is a general trend that managed organic soils with low C/N ratio occur on fertile, minerotrophic peat soils with higher pH values while high C/N ratios are found in nutrient poor ombrotrophic peatlands. Nevertheless, the wide scatter of pH values for a given C/N ratio indicates more complex spatial patterns and pH has an independent direct influence on N2O formation, too (see below). Several other studies found evidence for climate influence at particular peatland sites or regions (Dobbie et al., 1999; Sozanska et al., 2002; Lohila et al., 2010) which can be confirmed in the following landuse stratified models.

3.2 Model calibration and validation

3.2.1 Complete dataset

We applied the fuzzy logic model approach on the entire flux dataset, which results in the best fitted model ensemble ($NSE_{cv} = 0.12$) for four covariates (bulk density, groundwater table, mean winter temperate and annual precipitation). The stochastic variability within the data hampers the generic model approach to predict the measured fluxes accurately. Thus validation results were unsatisfactoy and we investigated further improvements by data partitioning with categorical parameters e.g. land use category, peat type and climate zone. The peat type stratified data set, separated into bog, fen and shallow peat soils, results in improved model fits for each peat type. Peat type, however, cannot be regionalized due to lack of European spatially explicit maps. In contrast to Freibauer and Kaltschmitt (2003), where N_2O fluxes from temperate and sub-boreal climates on mineral soils showed different mean and maximum emissions, we found no significant differences between climate zones for N_2O fluxes on organic soils. Hence the data partitioning by climate zones had no improving effect on the model performance. We achieved the best model results for land use stratification and developed fuzzy logic models for cropland, grassland, forest and extraction sites, separately. Therefore each land use model has different number and range of observations, as well as different covariates. Table 3 gives an overview for the land use specific N_2O flux data and corresponding model performances.

3.2.2 Cropland

The best fitted cropland model was calibrated for three parameters: top soil pH, the mean groundwater table and the annual precipitation amount with a model efficiency of NSE = 0.63. These model covariates were validated for 40 observations from 20 sites on which all three model parameter were available in our dataset. The range of N_2O fluxes from the cropland sub dataset (-0.02, 3.70) in $\mathrm{g\,N_2O\text{-}N\,m^{-2}\,a^{-1}}$was comparable to the range of the complete cropland dataset (-0.02, 6.10). Only few extreme high fluxes were excluded, so that the mean values are equivalent. Using this sub dataset, we were able to achieve the best model fit of $NSE_{cv} = 0.41$ in terms of an independent cross validation, compare Fig. 4.

As mentioned before in section 3.1, the top soil pH of croplands was not only correlated to N_2O emissions (r = -0.53, p <0.001) but also significantly to the C/N ratio (r = -0.68, p <0.001). Mørkved et al. (2007) suggested the soil pH as strong controlling factor for N_2O fluxes, because it affects the N_2O production processes of both denitrification and nitrification. Additionally they stated that low pH soils have higher N_2O/N_2 production ratios and thus higher potential N_2O emissions. The described effect is also observable for fluxes from croplands on organic soils. Weslien et al. (2009) found also a strong negative correlation of soil pH and N_2O emissions in their data. They argued that the Di-nitrogenoxide reductase is inhibited by acidic pH and thus can enhance N_2O emissions (Firestone and Davidson, 1989; Skiba and Smith, 1993). This result is supported by the findings of Liu et al. (2010). They found a strong negative correlation between the N_2O/N_2 product ratio of denitrification and soil pH.

The second important parameter in the model, the groundwater table, is well known as proxy for oxygen availability in top soil and therefore can significantly control the N_2O production processes, (Regina et al., 1996; van Beek et al., 2010). We found a correlation between N_2O and groundwater table in the cropland dataset which confirmed this significance (r = 0.31, p <0.05). The model indicates that deep drainage induces higher fluxes of N_2O. In contrast to Fig. 3 (a), which include all land use categories, the model structure for the relationship of groundwater table and N_2O fluxes for croplands only was linear and not in form of a hump shaped, non-linear curve. The sub dataset for croplands indicated a linear increase in N_2O fluxes with deep drainage. Furthermore precipitation turned out as the third model component. Precipitation increases the WFPS in top soil and can trigger N_2O flux peaks immediately after the rain events (Dobbie et al., 1999; Dobbie and Smith, 2003). High annual precipitation amounts can increase the probability of such N_2O peak flux events in drained agricultural used organic soils.

The expected role of N-fertilizer, as N_2O emission amplifier on croplands (Velthof and Oenema, 1995; Skiba et al., 1998), could not be confirmed in our modelling approach. Both the statistical analysis, shown in Fig. 3 (b), and the fuzzy modelling approach found no significant relationship of N_2O fluxes and N-fertilization. Organic soils under croplands had C/N ratios below 30 and are likely strong sources of nitrogen by peat mineralisation. Assuming a soil carbon loss from mineralised peat of 7.9 $\mathrm{t\,C\,ha^{-1}\,a^{-1}}$, as suggested by the IPCC (IPCC, 2013) (Table 2.1), it would result in a mean N mineralization of approximately 424.7 $\mathrm{kg\,ha^{-1}\,a^{-1}}$ for cropland sites in our database with average C/N ratios of 18.6 $\pm$ 5.8. This exceeds the maximum amount of N fertilizer (288.8 $\mathrm{kg\,ha^{-1}}$) that has been applied to cropland sites. The estimated mean N mineralization suggests that independent of fertilizer application sufficient substrate for N_2O production is available and the N_2O production is not limited by external N-input. All high fluxes from croplands were measured on deeply drained sites, which is also reflected in the regionalization by using the groundwater distribution with mean water table of 0.58 m below surface. In summary sensitivity analysis shows, that the cropland model predicts highest emissions on sites with deep drainage, soil pH around 4.0 and high amount of annual precipitation in combination, whereas the lowest emissions occur for soils with higher pH values and water table near the surface, regardless of rainfall.

3.2.3 Grassland

Grasslands are the best observed land use category represented by 217 annual flux measurements. The automatic calibration results in a fuzzy model with three parameters, which can explain about 68% of the variability in the flux data (NSE = 0.68). The parameters are nitrogen fertilizer amount, mean winter temperature and precipitation in autumn. The required parameter combination is available for 96 observations from 44 sites that cover the N_2O flux range of (-0.03, 4.10) with a higher mean ($\bar{x}$ = 0.67) than the complete grassland dataset ($\bar{x}$ = 0.58 $\mathrm{g\,N_2O\text{-}N\,m^{-2}\,a^{-1}}$). The cross validation could reproduce nearly sixty percent of the variability in the data, (NSE_{cv} = 0.58), (Fig. 5). In agreement with the statistical analysis, (Fig. 3 (b)), we also found the significant relationship of N_2O fluxes and N-fertilization for the grasslands fuzzy model approach. The amount of N-fertilization was directly correlated ($r = 0.54$, $p < 0.05$) to the fluxes from grassland sites, whereas no relationship was found for croplands. In fact the N-fertilization amount was the most important model parameter. The importance of N-fertilization has been recognized in several other studies on organic soils, (Velthof and Oenema, 1995; Skiba et al., 1998). The different responses for grassland and cropland also have been observed and modelled for N_2O fluxes from mineral soils (Dechow and Freibauer, 2011). Furthermore different sensitivities to N-fertilization on temperate and subboreal agricultural mineral soils are discussed in (Freibauer and Kaltschmitt, 2003; Roelandt et al., 2005).

In addition to the management influence the mean winter air temperature is also correlated to N_2O fluxes ($r = 0.40$, $p < 0.05$) and was identified as second important model parameter. The emissions increased with raising winter air temperatures up to maximum values approximately around 0 °C. This relation of N_2O fluxes to mean temperatures in winter months (December, January and February) can be a proxy for the amount of released emissions due to freeze-thaw cycles as described in Freibauer and Kaltschmitt (2003) and Jungkunst et al. (2006). Although the interaction of parameters, e. g. air temperature, WFPS and snow cover, that can induce freeze-thaw cycles is complex and highly variable, the model successfully worked with winter temperature as simple input parameter. This is especially useful regarding model upscaling attempts, because the temperature, as well as the winter temperature only, is easily available on European scale.

Autumn precipitation turned out as the third model component. We observed a positive correlation ($r = 0.50$, $p < 0.05$) between the rainfall amount in autumn months (September, October and November) and the N_2O fluxes on grassland sites. As stated before, precipitation can increase the WFPS in top soil and trigger N_2O fluxes (Dobbie et al., 1999). This strong statistical relation between autumn precipitation and N_2O has not been described before for organic grasslands, but agrees with evidence in mineral croplands Dechow and Freibauer (2011). High precipitation in autumn leaves wet soils in winter, which is a preconditions for freeze-thaw peaks of N_2O emissions. In summary grasslands N_2O fluxes are sensitive to N-fertilization and seasonal precipitation and temperatures. Highest emissions are expected for intensive managed grasslands with high N-input, that are controlled by winter temperature and rainfall events in autumn.

3.2.4 Forest

The measured forest N_2O fluxes in the dataset (n = 170) are dominantly located in boreal (61 %) and subboreal regions (22%), whereas temperate forest sites have only a small percentage (17%). These climatic regions have different mean N_2O emissions 0.51, 0.33 and 0.26 in $g\,N_2O\text{-}N\,m^{-2}\,a^{-1}$ for temperate, subboreal and boreal climates, respectively. However the range within the climatic regions are comparable and no significant difference between mean N_2O fluxes is recognizable. The best fitted forest model consisted of three parameters: mean groundwater table, top soil pH and the annual mean air temperature with a model efficiency of NSE = 0.66. The corresponding sub dataset consisted of 60 observations from 38 sites that cover the N_2O flux range of (0.01, 6.06) in $g\,N_2O\text{-}N\,m^{-2}\,a^{-1}$, which is almost identical to the complete forest dataset. The cross-validation left significant variability unexplained (NSE_{cv} = 0.25). Obviously, the validation data set is too small to robustly describe general relationships.

Top soil pH turned out as most important driver with higher N_2O emissions for pH values lower than 5.5. In forests we observed C/N ratios below 30 also under acid conditions and therefore the relationship between pH and C/N, that has been stated before, exhibits too much variation to get utilized. Nevertheless the soil pH can be selected directly as driver for N_2O emissions because it explains a major part of the variability. The response of N_2O in organic soils under forests thus resembles the response under cropland.

The mean annual groundwater table was modeled as hump shaped function, similar to Fig. 3 (a) and predicted the highest N_2O fluxes in a drainage range from 0.4 - 0.8 m below ground. Martikainen et al. (1993) and Regina et al. (1996) stated that lowering the water table in boreal peatlands increases the N_2O fluxes from soils, especially more in minerotrophic than in ombotrophic sites. The presented forest model can reproduce this effect, due to the combination of groundwater table and pH-value, which can be utilized as proxy for nutrient supply.

Mean annual air temperature was identified as third model parameter with increasing N_2O emissions in warmer regions. In general the model predicts lower N_2O fluxes from forest sites in comparison to crop- and grassland sites and only few hot spot emissions appeared under drained, nutrient rich and warm conditions.

3.2.5 Peat extraction

N_2O flux data were only represented by 35 observations from 20 different peat extraction sites. The N_2O fluxes from extraction sites ranged from -0.01 to 3.69 with the mean of 0.47

$g N_2O\text{-}N m^{-2} a^{-1}$. The fuzzy logic model calibration achieved the best performance (NSE = 0.89) with three parameters: the top soil bulk density, the annual precipitation and the winter temperature. The required parameters were available for 21 observations from 12 sites with similar mean and range for N_2O fluxes in comparison to the complete peat extraction dataset. The best fitted model achieved a model performance of $NSE_{cv} = 0.28$. Comparable to the forest model validation, the data set is also too small to robustly describe general relationships for extraction sites. The bulk density of top soils were strongly correlated ($r = 0.9$, $p < 0.05$) to N_2O fluxes from extraction sites with highest N_2O emissions from compacted sites. The range of bulk densities from extraction sites covered loosely packed natural peat densities, as well as densities of high compaction which indicate strong peat degradation. This wide range of bulk densities could be related to variations in management intensity on extraction sites. The N_2O response to winter temperature and annual precipitation agrees with patterns found for croplands and grasslands. The limited data availability for peat extraction sites can provoke a systematic bias and thus can restrict the model upscaling accuracy. On the other hand, peat extraction sites only have a small percentage of land area and relatively low flux rates in comparison to other land use categories, e. g. cropland, grassland or forest. Therefore the impact on the European N_2O emission budget is very small.

3.2.6 Natural peatland

Natural, pristine peatlands are characterized by wet conditions and peat growth. In these ecosystems the groundwater table is the limiting factor for N_2O emissions, because generally waterlogged soils have low amount of oxygen available, which decreases the N_2O production rate (Firestone and Davidson, 1989). We have 132 observations from 64 different sites with a mean flux of 0.07 $g N_2O\text{-}N m^{-2} a^{-1}$in a range of -0.43 to 0.45 in our database. Thereby we included also rewetted peatlands that exhibit the majority of the sparsely occurring higher fluxes. Some of these restored sites are still in a transitional phase after recent restoration and in some rewetted sites shallow drainage persists. These human influences could explain outlier N_2O emissions. We were not able to find a significant statistical relationship between gathered driving parameters and N_2O fluxes. The automatic calibration of the fuzzy model also could not identify a parameter combination that has a greater explanatory power than the mean flux. Therefore we used the mean value of N_2O fluxes for calculating emission budgets in further model applications. In general the N_2O fluxes from natural organic soils are very low and even consumption can occur in wet, nitrogen-poor soils (Chapuis-Lardy et al., 2007). Hence the contribution to the European N_2O emission budget is comparatively small. The IPCC wetland supplement even reported zero fluxes of N_2O for natural peatlands, (IPCC, 2013). Nonetheless fluxes from natural peatlands represent the background N_2O emission that are expected from peatland areas without any anthropogenic management and therefore could provide useful information for estimating human influence.

3.3 Uncertainties

The quality of the spatial datasets for the regionalization adds an unknown bias. The pixel information in the soil map contains aggregated data, which may not be representative of the peat soils. Bulk density data in the European soil map was in the range of mineral soils and thus considered implausible and inadequate for regionalization. The pH range of the European soil map agreed with the pH range in the observational data set but it remains unclear whether agricultural practices such as liming have been considered and whether the pH values given in the soil map are representative of the land uses on the peat soils.

A sensitivity analysis of the fuzzy models showed that driving parameter uncertainty dominated over model uncertainty except for the forest model. Our approach to estimate the driving parameters mean water table and bulk density, which are unavailable at European level, is not necessarily spatially representative of Europe. Water table constitutes the major source of uncertainty and likely bias in the European N_2O inventory. Improvements in the spatial representation of water table annual mean values as those by Bechtold et al. (2014) and also seasonal fluctuations would strongly enhance inventory accuracy.

3.4 Hotspots of N_2O emissions

Figure 8 shows the European N_2O emission map of organic soils with pixel-wise uncertainties derived by regionalisation of the models presented in Section 3.2. For all land use types computed distributions were positively skewed. N_2O emission hotspots from croplands (1.8 - 2.43 $\mathrm{g\,N_2O\text{-}N\,m^{-2}\,a^{-1}}$) were located in North Denmark, Poland, Estonia and in South Finland. All hotspot regions were related to low soil pH < 4.7, which seems to be the main driving parameter for cropland N_2O emissions at continental scale. N_2O emissions from croplands are generally highest and have also the highest N_2O hotspots of all land use categories. Approximately 35 % of N_2O emissions from cropland exceeded the maximum grassland and 87 % exceeded the maximum forest emissions.

The grassland emission hot spots (0.54 - 1.64 $\mathrm{g\,N_2O\text{-}N\,m^{-2}\,a^{-1}}$) were predominantly located in the Netherlands, Germany, Ireland and in the Baltic states. They were linked to high N-fertilization rates larger than 250 $\mathrm{kg\,ha^{-1}}$, warmer winter temperatures above $0\,^{\circ}\mathrm{C}$ and more than 160 mm rainfall in autumn.

Forests had a relatively small span in N_2O emissions and low peak emissions (0.59 - 0.8 $\mathrm{g\,N_2O\text{-}N\,m^{-2}\,a^{-1}}$), which only reached one third of the cropland maximum and half of the grassland maximum, respectively. The highest flux rates were scattered all over European forest sites on peatlands and were related to pH values lower than 5 similar to the pattern of cropland N_2O hotspots. In addition, the forest N_2O emissions increased especially for annual mean temperatures above $6\,^{\circ}\mathrm{C}$, which coincides with a higher fraction of minerotrophic peat soils.

The hot spot emissions from extraction sites (0.78 - 0.87 $\mathrm{g\,N_2O\text{-}N\,m^{-2}\,a^{-1}}$) were in the same range as forest hotspots and were evenly distributed across Finland and the Baltic states. They were driven by annual precipitation above 500 mm and winter temperatures around $0\,^{\circ}\mathrm{C}$.

Natural sites were represented with the mean N_2O flux of 0.07 $\mathrm{g\,N_2O\text{-}N\,m^{-2}\,a^{-1}}$ from natural sites in the database and therefore set constant across Europe.

The hotspot locations of N_2O fluxes from cropland sites can be confirmed by measurements in the database from Denmark (Petersen et al., 2012), South Finland and Germany. Observed

N_2O fluxes of up to 6.11 $g\,N_2O\text{-}N\,m^{-2}\,a^{-1}$ from soils with low pH between 4.0 - 5.5 support the model results. Unfortunately the modelled hotspot regions in Poland can not be validated with observations. Grassland emission hotspots in the Netherlands and Germany have been observed in several studies (Velthof and Oenema, 1995; van Beek et al., 2010; Wild et al., 1998) and are well represented in our dataset. In general the grassland model (Section 3.2.3) and the spatial patterns show a strong signal from anthropogenic induced emissions which is slightly modified by seasonal climate conditions. The contrasts between croplands and grasslands have not been described before on organic soils but agree with N_2O responses described for mineral soils at national and European level (Jungkunst et al., 2006; Dechow and Freibauer, 2011). In forests, the highest forest N_2O flux measurements were found in boreal peatlands from Finland and Sweden (Klemedtsson et al., 1997; Weslien et al., 2009), as well as in a forest from Slovenia, Danevčič et al. (2010) which exceeds the highest fluxes by the forest model. Remarkably all these N_2O hotspot fluxes are related also to low soil pH under 4.7 and C/N ratios below 20 which is consistent with the relation of N_2O fluxes, pH values and C/N ratios for the whole dataset in Fig. 3(d). In extraction sites, N_2O emission hotspots occurred in the Baltic region. They were in the same magnitude as the highest flux data from extraction sites observed in Estonia (Salm et al., 2011). The cropland model hot spot uncertainties ranged from 0.90 up to 1.01 and were comparable to the grassland uncertainties (0.92 - 1.07 $g\,N_2O\text{-}N\,m^{-2}\,a^{-1}$) for hot spot emissions. In both land use types, modelled N_2O flux rates clearly exceed the uncertainty range. The N_2O emission pattern from croplands and grasslands can thus be considered robust. This finding gives important information where to focus N_2O mitigation since croplands and grasslands represent the main source of N_2O emissions per area and for the total European emission inventory (see Section 3.5). In contrast, the highest forest and peat extraction fluxes had higher uncertainties (1.31 - 1.51) and (0.96 - 1.38 $g\,N_2O\text{-}N\,m^{-2}\,a^{-1}$) than modelled N_2O flux rates. The high uncertainty in the distribution functions of water table and bulk density contributes most to the total uncertainty estimation. The large forest areas in the boreal zone had the highest relative uncertainty but low N_2O flux rates (Fig. 8). The uncertainty of fluxes from natural sites was calculated by using the standard deviation (0.27 $g\,N_2O\text{-}N\,m^{-2}\,a^{-1}$) of the distribution for all available N_2O fluxes from natural sites.

3.5 European N_2O budget for organic soils

The European N_2O budget from organic soils calculated by the fuzzy model, the average emission factors (EF) derived from the European observations and IPCC approach range between 149.5 and 87.4 for the CLC land use data and between 132.7 and 121.1 $\mathrm{Gg\,N_2O\text{-}N\,a^{-1}}$for HILDA land use data (Table 4). The 95% confidence intervals (Table 4) indicate no distinct differences between the three flux estimates. The total N_2O budget from organic soils is remarkably robust despite large differences in assumptions, underlying data and land use representation.

Only the fuzzy model is spatially explicit. The emission factor based approaches assume that the observational basis is representative so that the mean observed flux represents the land use class. This assumption is obviously inadequate for N_2O emissions from organic soils in Europe because the mean N_2O emission by land use class calculated from the fuzzy model implied emission factor (IEF) deviates from the average EF of the underlying observations (Table 5). Obviously, forests and croplands high N_2O emissions and unfertilized grasslands with low N_2O emissions are underrepresented in European observations. Robust inventories therefore should strive for a good representation of driving parameters, in particular soil pH and N-fertilization, which determine the high N_2O emissions from cropland and grassland.

The IPCC EFs strongly disagree with the two European based IEFs. For forests, the low IPCC EF for boreal nutrient-poor forests seems too low for Europe because if it is replaced with the EF for boreal nutrient-rich forests the forest N_2O budget becomes similar to the results of the fuzzy model. The IPCC EF for cropland is between the fuzzy model IEF and the average EF. Additional measurements in the undersampled hotspot regions are, however, necessary, to interpret these differences. The IPCC EF for grassland exceeds the European based IEFs, but comes close if a reasonable fraction of shallow drained grassland is included. The IPCC EF for extraction sites is at the low end of European observations. This strongly points to missing hotspot observations in the worldwide IPCC database, which are partly included as unpublished data in our database. We conclude that the IPCC EF for extraction sites is not representative for Europe while the EFs for forests, croplands and grasslands seem to match when the land stratification of nutrient status and drainage level is known.

The areas by land use class vary between CLC and HILDA due to differences in classification methods. Whereas forest areas represent approximately 50% of total peatland area in both classifications, crop- and grassland areas greatly differ due to different classifications. Natural and extraction sites are only available for the CLC land cover dataset. The land use differences provoke proportional differences in N_2O budgets for croplands and grasslands. Nonetheless, the IEF derived from the spatially explicit fuzzy model remains relatively stable so that the fuzzy model can be considered to yield robust IEFs independent of land use definitions. These IEFs would also qualify as national or European wide Tier 2 approach for greenhouse gas inventories. N_2O emissions from organic soils represent up to 13% of total European N_2O emissions reported in the European Union (EU) greenhouse gas inventory of 2011 (European Commission, 2013) from only 7% of the EU area. N_2O emissions from croplands alone on organic soils contribute 13 to 17% to the direct N_2O emissions from agricultural used soils (European Commission, 2013).

3.6 Anthropogenic N_2O emissions

Clearly, the N_2O budget of organic soils is dominated by emissions from managed land use systems, in particular cropland and grassland. The natural background emission can be estimated by assuming that the total area of organic soils in Europe would be in pristine, natural status. This natural baseline emission budget would amount to 21.53 (7.58 - 35.16) $\mathrm{Gg\,N_2O\text{-}N\,a^{-1}}$. The difference between these baseline emissions and the emission budget with realistic land use can be interpreted as anthropogenic part of the N_2O emissions budget. Accordingly, the anthropogenic contribution to N_2O emissions amounts to 80 to 85 percent of the total European N_2O budget.

4 Conclusions

We compiled an extensive European dataset of N_2O observations on organic soils, made a fuzzy model based analysis of anthropogenic and natural drivers and presented the first European spatially explicit N_2O budget from organic soils. The total budget was consistent with inventories based on static emission factors provided that the emission factors were applied in a way that was representative of regional and land use specific emissions.

N_2O emissions from organic soils are dominantly driven by human management, in particular water table. Soil properties such as C/N ratio, pH and bulk density modify the response strength of organic soils to human management. Climatic parameters such as seasonal or annual temperature and precipitation only have a secondary role in N_2O emissions.

Organic soils in Europe emit more N_2O than suggested by the IPCC default methodology. Less than 100,000 km^2 of agriculturally used organic soils emit about 80 $\mathrm{Gg\,N_2O\text{-}N\,a^{-1}}$, equivalent to 20% of European direct soil N_2O emissions from agriculture.

Acid croplands e.g. in Denmark or Poland, and intensively fertilized grasslands, e.g. in the Netherlands or Germany were identified as strongest hotspots. The hotspots from acid croplands are backed only by few measurements and need further investigations.

Drainage is a main driver for N_2O emissions and therefore the groundwater table has been integrated in the model although it was not available for upscaling. This created additional uncertainty in the calculated regionalized N_2O budget but also highlights that the largest source of uncertainty does not come from the N_2O observations but from the uncertainty in spatial driver data. Improved spatial information on water table is critical for reducing uncertainty in inventories and targeting GHG mitigation measures. The sensitivity of N_2O emissions on mean annual water table across land use classes indicates that water table management is one of the most effective ways to mitigate N_2O emissions from land use of organic soils.

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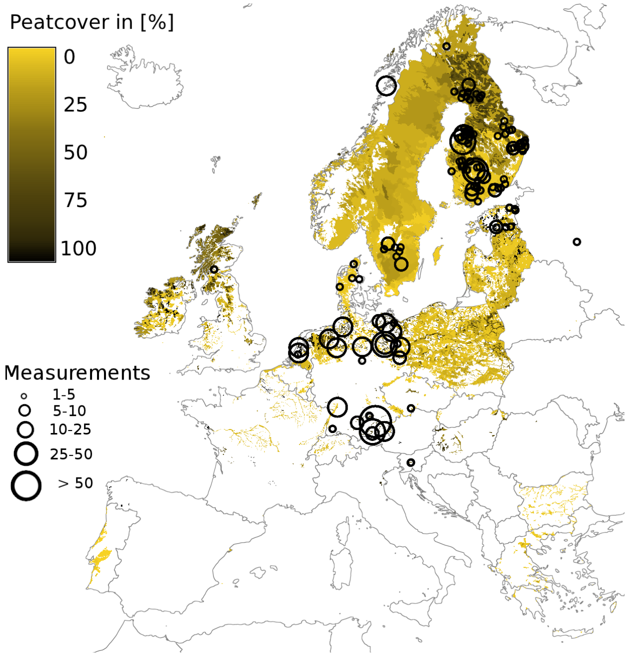

Fig. 1. Overview for measurement sites. Size of points indicates number of measurements per site. Background map displays peatland distribution in Europe with peatcover per square kilometre from Montanarella et al. (2006).

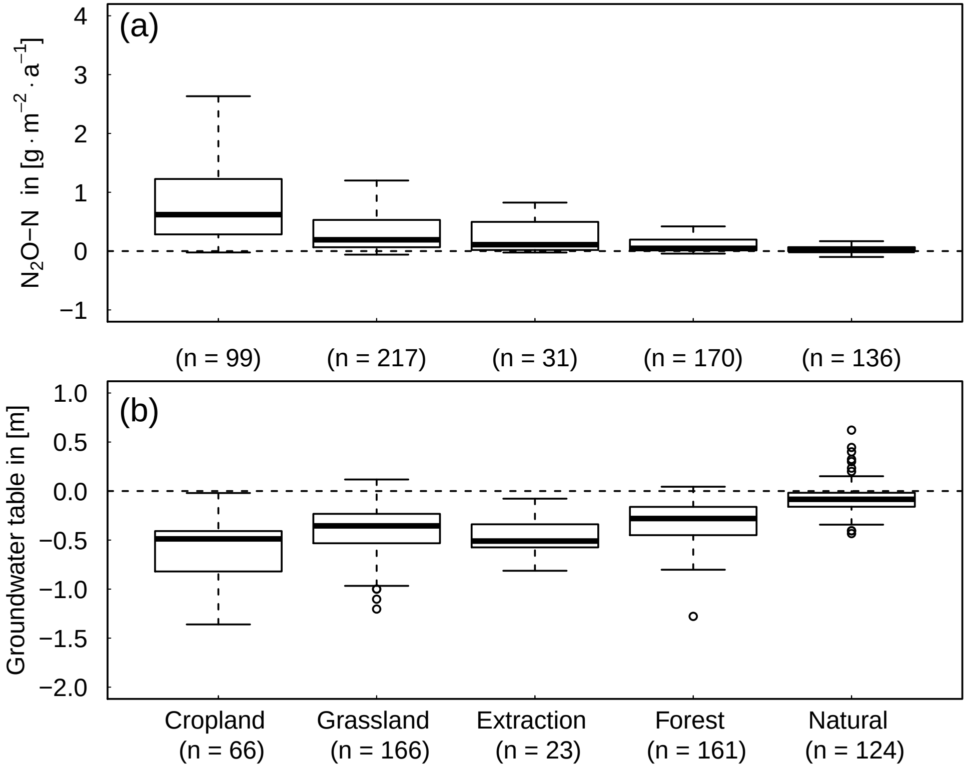

Fig. 2. Boxplots for N_2O fluxes (a) and mean annual groundwater table (b) for five different land use categories (cropland, grassland, peat extraction, forest and natural sites). N_2O fluxes are shown without outliers and *n* indicates the number of measurement per category.

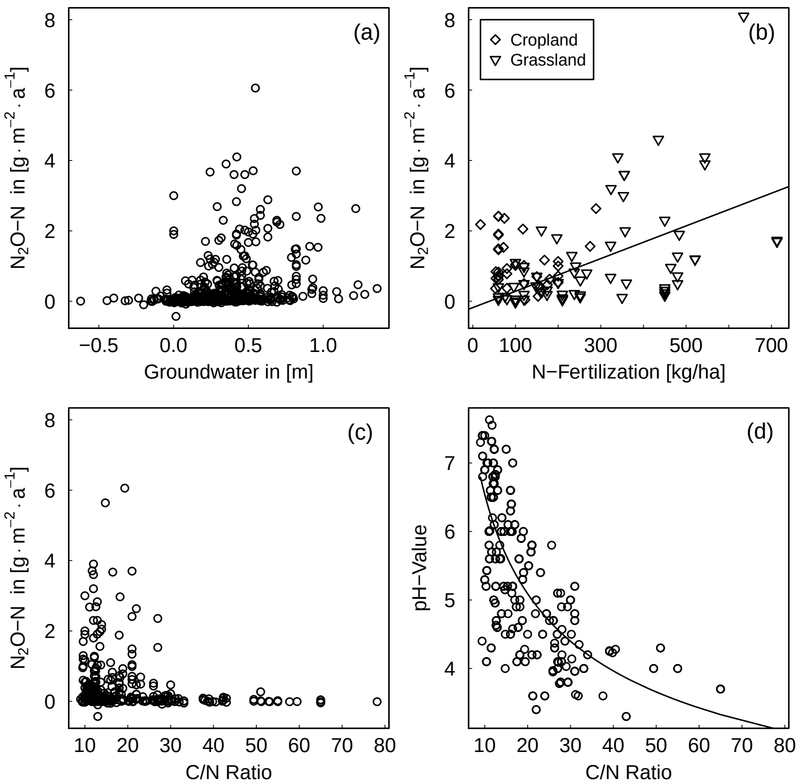

Fig. 3. The scatter plots shows (a) the N_2O flux relationship to mean annual groundwater table, (b) the relationship between N-fertilization and N_2O fluxes for crop- and grassland with significant ($P<0.001$) linear relationship for grassland ($r^2 = 0.26$), (c) the N_2O fluxes plotted against the C/N ratios and (d) pH-values in relationship to this C/N ratios including the fitted non linear function ($ph = 15 \cdot cn^{-0.36}$) ($r^2 = 0.5$).

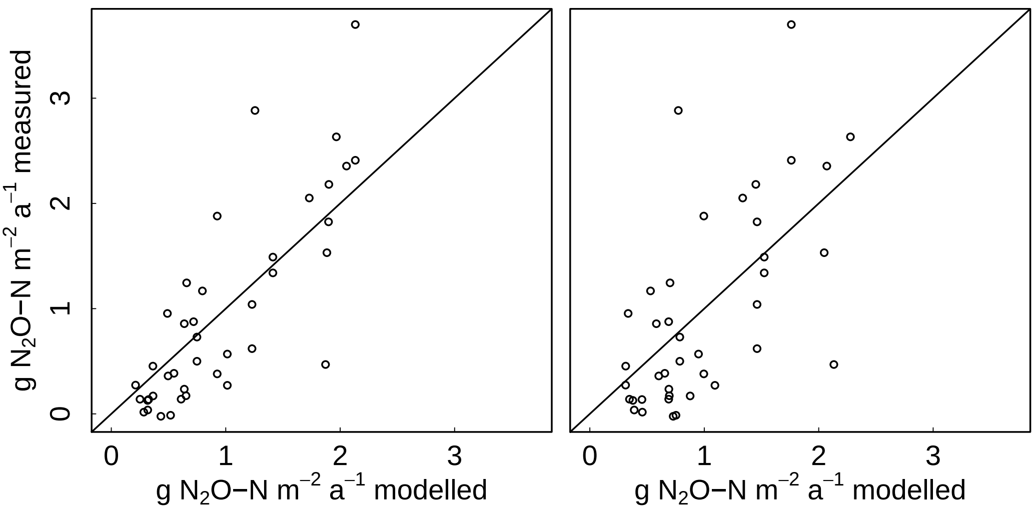

Fig. 4. Fuzzy model performance for calibration and cross validation of N_2O fluxes from cropland on organic soils. The modelled fluxes (x-axis) represent the mean flux rates from a model ensemble of 50 individually bootstrapped models. The cross validation was performed by excluding one site per iteration.

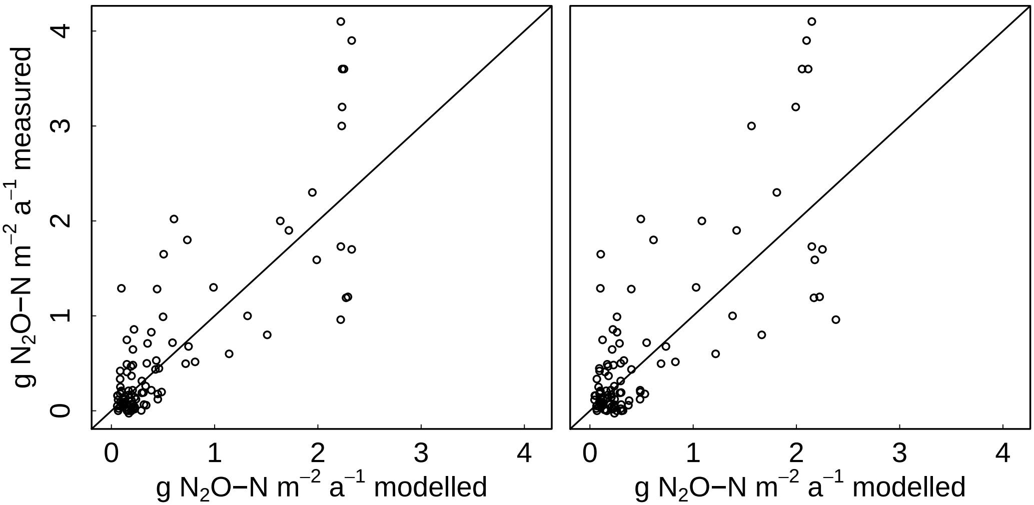

Fig. 5. Fuzzy model results for calibration and cross validation for N_2O fluxes from grassland on organic soils. The modelled fluxes (x-axis) represent the mean flux rates from a model ensemble of 50 individually bootstrapped models. The cross validation was performed by excluding one site per iteration.

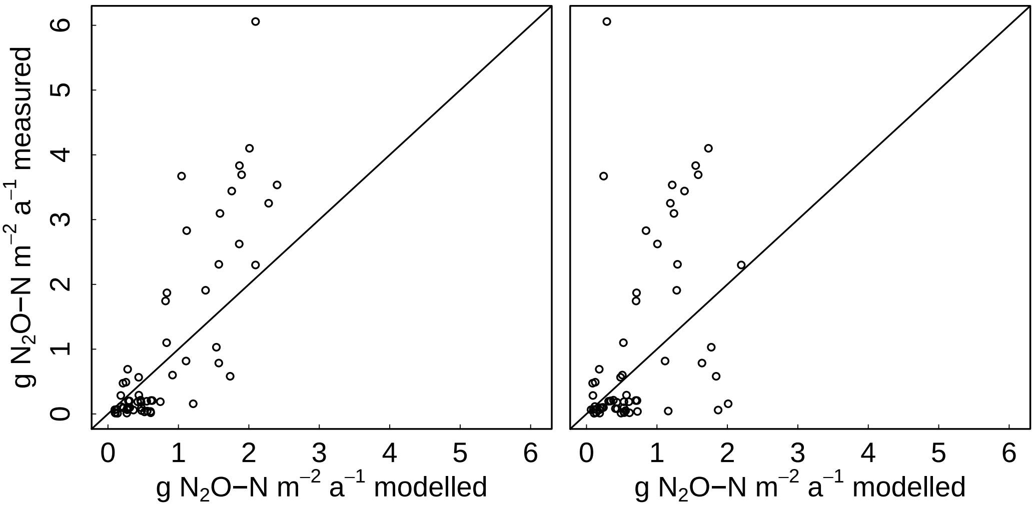

Fig. 6. Fuzzy model results for calibration and cross validation for N_2O fluxes from forest sites on organic soils. The modelled fluxes (x-axis) represent the mean flux rates from a model ensemble of 50 individually bootstrapped models. The cross validation was performed by excluding one site per iteration.

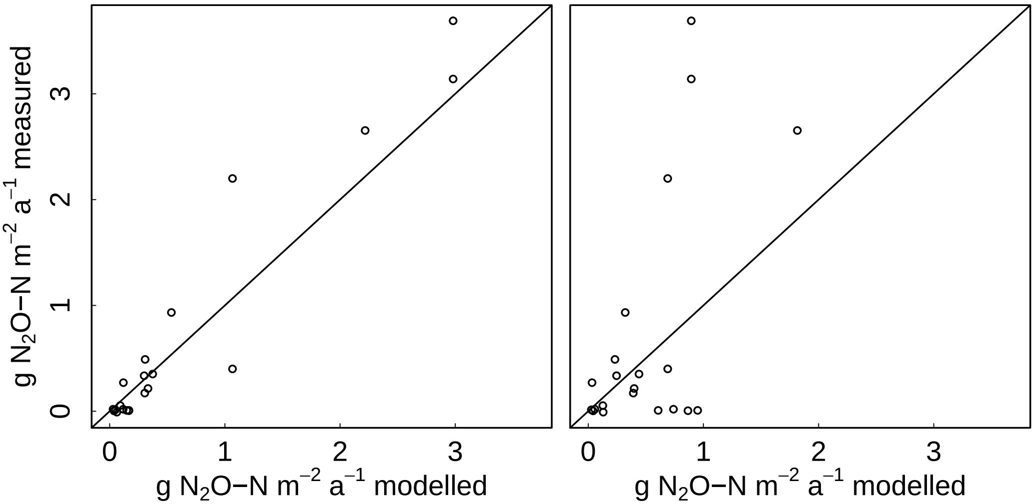

Fig. 7. Fuzzy model results for calibration and cross validation for N_2O fluxes from peat extraction sites on organic soils. The modelled fluxes (x-axis) represent the mean flux rates from a model ensemble of 50 individually bootstrapped models. The cross validation was performed by excluding one site per iteration.

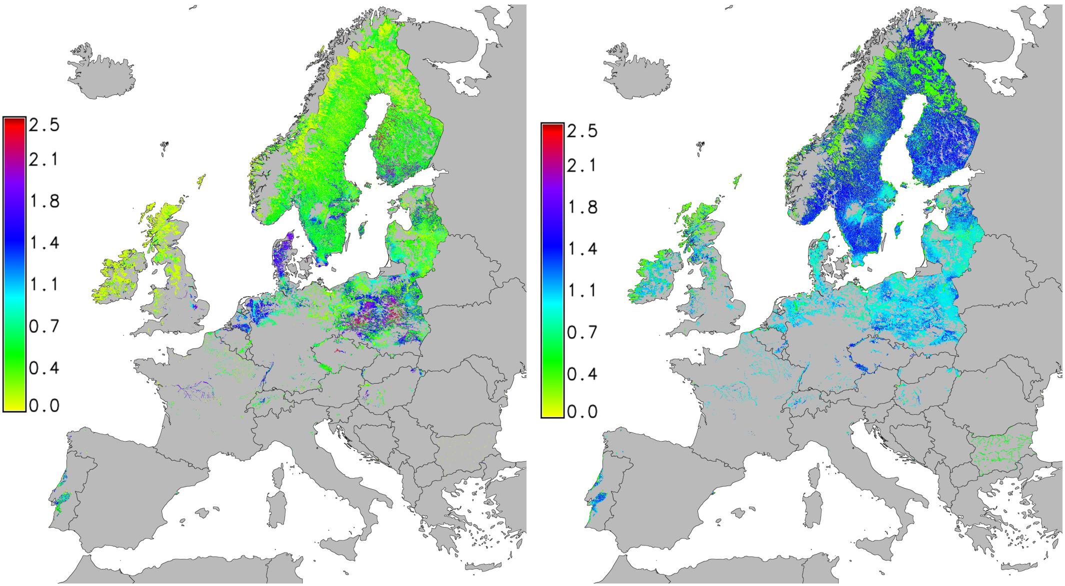

Fig. 8. European N_2O fluxes for 1x1km raster grid cells calculated with the fuzzy logic model approach (left) and the corresponding pixel wise model uncertainty as standard deviations (right) for organic soils in $\mathrm{g\,N_2O\text{-}N\,m^{-2}\,a^{-1}}$. The land use classification is based on CORINE land cover.

Table 1. List of potential driving parameters for N_2O with units, value mean/range and fraction of measurement studies that cover each parameter. Soil parameters are related to top soil layer of 100 cm depth and all parameters are calculated as annual average values. With the exception of precipitation and nitrogen fertilization which are calculated as annual sums.

Name	Description	Unit	Mean	Min	Max	Fraction (%)
bd	Bulk density	$g \cdot cm^{-3}$	0.34	0.03	1.36	69.2
corg	Organic carbon content	%	36.11	6.7	57.5	79.8
ntot	Total nitrogen content	%	1.82	0.3	3.9	71.8
ph	pH value	-	5.34	3.3	7.63	61
cn	Ratio of carbon and nitrogen	-	21.29	9	78.17	80.4
pd	Thickness of peat layer	m	1.61	0.2	10.2	38.7
tair	Air temperature	°C	6.22	-0.23	11.2	83.5
tsoil	Soil temperature	°C	8.8	1.94	11.78	19.1
pp	Precipitation	mm	645.2	0	1840	81.6
wt	Groundwater table	m	0.32	-0.62	1.36	82.2
wfps	Water filled pore space	%	76.48	41.25	100	13.7
no3	Nitrate concentration	$kg \cdot ha^{-1}$	32.97	0	211.7	13.1
nh4	Ammonia concentration	$kg \cdot ha^{-1}$	28.4	0.33	241	13.1
nmin	Mineral nitrogen concentration	$kg \cdot ha^{-1}$	61.37	2.21	241	14.3
nfert	Organic and mineral nitrogen fertilization	$kg \cdot ha^{-1}$	43.77	0	713	80.7

Table 2. Correlation matrix of N_2O fluxes and potential driving parameters for the available dataset from organic soils in Europe. The parameter names are described in Table 1.

	N_2O	bd	corg	ntot	ph	cn	pd	tair	tsoil	pp	wt	wfps	nmin	nfert
N_2O	1.00	0.17	−0.10*	0.07	−0.05	−0.19	−0.14*	0.06	0.07	0.11**	0.32	−0.30	0.10	0.43
bd		1.00	−0.80	−0.39	0.37	−0.48	−0.32	0.34	−0.08	−0.17	0.46	0.07	−0.04	0.25
corg			1.00	0.38	−0.50	0.59	0.27	−0.32	−0.08	0.15	−0.31	−0.12	−0.12	−0.13**
ntot				1.00	0.14*	−0.40	0.34	0.04	0.11	−0.04	−0.21	0.07	0.26*	0.16
ph					1.00	−0.64	−0.31	0.06	0.22*	−0.30	0.29	−0.03	0.29**	0.19
cn						1.00	0.02	−0.22	−0.18	0.15	−0.20	−0.19	−0.36	−0.18
pd							1.00	0.17**	0.29*	0.10	−0.39	−0.06	−0.20	−0.22
tair								1.00	0.77	0.02	−0.11*	−0.01	0.15	0.16
tsoil									1.00	0.44	0.15	−0.26	0.27	0.07
pp										1.00	−0.13**	−0.14	0.24*	0.01
wt											1.00	−0.39	0.08	0.17
wfps												1.00	0.10	−0.01
nmin													1.00	0.10
nfert														1.00

Level of Significance:

** Significant at $P \leq 0.01$

* Significant at $P \leq 0.05$

Table 3. List of calibrated and validated N_2O fuzzy logic models with covariates that are described in Table 1 (Parameters), number of flux measurements (N_{flux}) and model performances of calibration (NSE_{cali}) and cross validation (NSE_{cv}) for different land use categories, respectively.

Landuse	Parameters	N_{flux}	NSE_{cali}	NSE_{cv}
Crop	wt, ph, pp	40	0.63	0.41
Grass	nfert, tair winter, pp autumn	96	0.68	0.58
Forest	wt, ph, tair	60	0.66	0.25
Extraction	bd, pp, tair winter	21	0.89	0.28
Natural	-	132	-	-

Table 4. N_2O emission budget for European peatlands by different approaches: Fuzzy logic model (Fuzzy), average emission factors of flux data from this study (Average) and IPCC emission factor approach (IPCC) are shown as mean and 95 % confidence interval of the budgets in $\mathrm{Gg\,N_2O\text{-}N\,a^{-1}}$. The land use categories are based on CLC 2006 (top) and HILDA 2010 (bottom).

	Fuzzy			Average			IPCC		
Landuse	Mean	95% Conf. Int.		Mean	95% Conf. Int.		Mean	95% Conf. Int.	
Crop	71.734	63.903	79.565	42.443	33.113	51.730	56.417	35.586	78.116
Grass	7.848	2.856	12.841	15.687	12.036	19.365	22.780	13.080	31.180
Forest	64.005	37.980	90.031	42.157	26.730	57.583	8.196	0.524	15.612
Extraction	0.099	-0.045	0.240	0.134	0.050	0.218	0.009	-0.001	0.018
Natural	5.795	2.078	9.513	5.795	2.041	9.469	0.000	0.000	0.000
Sum	149.482	93.718	205.246	106.216	68.701	143.732	87.402	53.980	120.824
Crop	40.446	36.282	44.609	22.512	17.563	27.438	29.924	18.875	41.433
Grass	29.103	12.530	45.675	53.768	41.253	66.376	82.143	43.971	116.158
Forest	63.115	36.031	90.199	45.814	29.050	62.579	9.070	0.524	17.334
Sum	132.663	76.899	188.428	122.095	84.579	159.610	121.137	72.515	169.758

Table 5. Overview of land use areas on organic soils in Europe and corresponding implied emission factors (iEF) for the Fuzzy logic model (Fuzzy), the average emission factors of flux data from this study (Average) and IPCC emission factor approach (IPCC). The land areas are shown in km^2 for CLC 2006 (top) and HILDA 2010 (bottom), respectively. The emission factors are derived from the mean N_2O flux budget divided by particular land use class area and are displayed in $g\,N_2O\text{-}N\,m^{-2}\,a^{-1}$.

Landuse	Area	Fuzzy iEF	Average iEF	IPCC iEF
Crop	43,397.84	1.653	0.978	1.300
Grass	27,046.10	0.290	0.580	0.842
Forest	132,986.80	0.421	0.317	0.062
Extraction	283.35	0.349	0.473	0.032
Natural	81,626.15	0.071	0.071	0
Crop	23,018.50	1.757	0.978	1.300
Grass	92,703.48	0.314	0.580	0.842
Forest	144,525.03	0.410	0.317	0.062

Table 6. List of sites with number of flux measurements and references that are included in the presented meta study.

Name	Number of sites	Number of fluxes	Start date	End date	Reference
Aardlapalu	1	2	2009-01-01	2010-12-31	Salm et al. (2011)
Ahlenmoor	6	17	2008-01-01	2011-12-31	Beetz et al. (2013), + unpublished data
Alkkia	1	1	2003-05-01	2004-04-30	Mäkiranta et al. (2007)
Apukka	1	6	2001-01-01	2002-12-31	Regina et al. (2004)
Asa	4	6	2000-01-01	2001-12-31	Arnold et al. (2005)
Benediktbeuern	6	6	2005-01-01	2005-12-31	unpublished data
Bodin	5	8	2003-01-01	2003-12-31	Kløve et al. (2010)
Bodo	3	8	2003-01-01	2004-12-31	Grønlund et al. (2006)
Central Finland	12	35	1991-01-01	1992-12-31	Regina et al. (1996)
Donaumoos	7	7	1994-01-01	1999-12-31	Wild et al. (1998)
Donauried	5	5	2004-01-01	2004-12-31	unpublished data
Dümmer	6	16	2008-01-01	2011-12-31	unpublished data
Dummerstorf	5	6	2010-01-01	2011-12-31	unpublished data
Falköping	9	9	1995-01-01	1997-12-31	Weslien et al. (2009), Klemedtsson et al. (2009)
Falla	1	1	2008-01-01	2009-12-31	Strömgren et al. (2014)
Finland	50	69	2007-01-01	2008-12-31	Ojanen et al. (2010)
Flanders Moss	4	4	2009-01-01	2009-12-31	Yamulki et al. (2013)
Flugebo	1	1	2008-01-01	2008-12-31	Strömgren et al. (2014)
Freising	29	50	2007-01-01	2012-12-31	Eickenscheidt et al. (2014b), Eickenscheidt et al. (2014a), + unpublished data
Fyodorovskoye	1	3	2009-01-01	2011-12-31	unpublished data
Graben-Neudorf	5	10	2010-01-01	2011-12-31	Peichl-Brak (2013)
Grosses Moor	6	12	2011-01-01	2012-12-31	Leiber-Sauheitl et al. (2014), + unpublished data
Gullhult	1	1	2008-01-01	2008-12-31	Strömgren et al. (2014)
Gumnitz	2	10	1995-01-01	1999-12-31	Augustin et al. (1998)
Halolanmaeki	5	6	1996-01-01	1997-12-31	Maljanen et al. (2003)
Harz	2	2	2002-01-01	2002-12-31	Tauchnitz et al. (2008)
Heinrichswalde	6	18	1995-01-01	1999-12-31	ZALF unpublished data
Hiiesoo	1	4	2009-01-01	2009-12-31	Salm et al. (2011)
Ilomantsi	2	5	1991-01-01	1992-12-31	Nykanen et al. (1995)
Jokioinen	1	9	2000-01-01	2002-12-31	Regina et al. (2004)

Table 6. Continued.

Name	Number of sites	Number of fluxes	Start date	End date	Reference
Kannus	15	47	2000-01-01	2007-12-31	Maljanen et al. (2012)
Kasesoo	1	3	2009-01-01	2009-12-31	Salm et al. (2011)
Kendlmühlfilze	13	13	1999-01-01	1999-12-31	Drösler (2005), + unpublished data
Kuresoo	1	5	2009-01-01	2009-12-31	Salm et al. (2011)
Kuuma	1	9	2000-01-01	2002-12-31	Regina et al. (2004)
Lakkasuo	2	16	1991-01-01	1992-12-31	Laine et al. (1996)
Linnansuo	2	8	2004-01-01	2007-12-31	Hyvönen et al. (2009)
Ljubljana Marsh	2	4	2005-01-01	2005-12-31	Danevčič et al. (2010)
Lompolojaenkkae	1	3	2006-01-01	2008-12-31	Lohila et al. (2010)
Mooseurach	18	33	2007-01-01	2011-12-31	unpublished data
Mørke	1	3	2008-01-01	2008-12-31	Petersen et al. (2012)
Nørreå	1	1	2009-01-01	2009-12-31	unpublished data
Orramossen	1	1	2008-01-01	2008-12-31	Strömgren et al. (2014)
Paulinenaue	17	59	1995-01-01	2011-12-31	Augustin et al. (1998), Bell et al. (2012), Rees et al. (2013), + unpublished data
Puhatu	1	3	2009-01-01	2009-12-31	Salm et al. (2011)
Reeiwijk	1	3	2006-01-01	2008-12-31	Kroon et al. (2010)
Rovaniemi	1	6	2001-01-01	2002-12-31	Regina et al. (2004)
Sangla	1	1	2009-01-01	2009-12-31	Salm et al. (2011)
Sernitz	2	4	1998-01-01	1999-12-31	ZALF unpublished data
Skjern	1	2	2008-01-01	2008-12-31	Petersen et al. (2012)
Spreewald	4	8	2010-01-01	2011-12-31	unpublished data
St. Vildmose	1	3	2008-01-01	2008-12-31	Petersen et al. (2012)
Valgeraba	1	4	2009-01-01	2009-12-31	Salm et al. (2011)
Vesijako	8	8	2003-01-01	2003-12-31	Minkkinen unpublished data
Westermoor	8	16	2010-01-01	2011-12-31	Beyer and Höper (2014), + unpublished data
Wildmoos	2	4	2001-01-01	2002-12-31	Jungkunst and Fiedler (2005)
Zarnekow	5	21	2005-01-01	2011-12-31	unpublished data
Zegveld	6	27	1992-01-01	2007-12-31	Velthof et al. (1996), Koops et al. (1997), van Beek et al. (2010)