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INTERNATIONAL Agrophysics
www.international-agrophysics.org

Int. Agrophys., 2016, 30, 501-507
doi: 10.1515/intag-2016-0013

Assessment of N_2O emissions from rapeseed cultivation in Poland by various approaches**

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Received April 18, 2016; accepted September 23, 2016

A b s t r a c t. The aim of this study was to compare four tools for calculation of nitrous oxide (N_2O) emissions under the renewable energy directive. All the tools follow the methodology of the international panel on climate change. The first calculations of N_2O fluxes were based on the Tier 1 method using the BioGrace tool. The second and the third ones followed the Tier 2 methodology, applying the global nitrous oxide calculator and the Lesschen emission factors, respectively. The last assessment was performed in accordance with the Tier 3 approach by using the denitrification-decomposition model. The N_2O fluxes were calculated for rapeseed cultivation in a 4-year crop rotation in Poland. The same input data were applied in all methods. The average of N_2O emissions varied in the range of 1.99-3.78 kg N_2O ha^{-1} y^{-1}, depending on the approach used (Lesschen emission factors > denitrification-decomposition > global nitrous oxide calculator > BioGrace). This paper illustrates that, at country level, the Lesschen emission factors method worked as well as the denitrification-decomposition model for Poland. The advantage of this approach is the simplicity of collecting the necessary data, in contrast to process-based modelling. Moreover, the Tier 2 method provides mitigation measures similar to the denitrification-decomposition model, related to crop type, climatic conditions, and management practices.

K e y w o r d s: BioGrace calculator, denitrification-decomposition model, global nitrous oxide calculator, international panel on climate change-Tier 1, Lesschen emission factors

INTRODUCTION

In 2010, 56% of biofuel production in Europe was based on rapeseed as the feedstock (Hamelinck *et al.*, 2012). In Poland, the area dedicated to the production of rapeseed amounted to 951 thousand ha, *ie* 7% of agricultural land in the year 2014 (CSO, 2015). This is a nearly two-fold increase since 2005. The increase was the result of implementation of the renewable energy directive (RED) (Directive 2009/28/EC) which requires the use of at least 10% renewable fuel in the transport sector by 2020. In addition, RED contains sustainability criteria for biofuel production concerning the reduction of greenhouse gas (GHG) emissions by 35% when biofuel is used, compared to fossil fuel, and further reduction to 50% in 2017. Nitrous oxide (N_2O) emission is the most important contributor in the GHG balance of biofuel. Its global warming potential is 298-fold higher than carbon dioxide (CO_2) in 100 year horizon, and its average lifespan is 114 years (IPCC, 2006). In Poland, N_2O agricultural emissions are estimated at about 81.3 Gg, which accounts for 85% of the total national N_2O emissions (Olecka *et al.*, 2014). Therefore, it is important to quantify the national N_2O emissions from arable land in support of GHG assessment and climate change policy. Cultivation of rapeseed is characterised by high GHG emissions, which is associated with high nitrogen (N) demands for plant growth (Borzęcka *et al.*, 2011). The calculation of N_2O agricultural emissions can be performed using the guidelines developed by the international panel on climate change (IPCC, 2006). Based on the detailed data held it can be done on three 'Tiers' applying different tools classified as calculators, protocols, guidelines and models (Denef *et al.*, 2012). According to Tier 1, N_2O emissions are calculated based only on N inputs to the soil. Tier 2 method recommends applying country data or region emission factors (EFs). Tier 3 methodology adopts process-based models that present variability in local conditions more clearly. Moreover, the models can simulate the interactions between different management

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**This work was supported by The National Centre for Research and Development within the project BIOSTRATEG1/271322/3/NCBR/2015 support for low carbon agriculture – able to adapt to observed climate change in the perspective of 2030 and 2050 (2015-2018).

practices and climate change. There are several biogeochemical models available, such as CENTURY (Smith *et al.*, 2012), DAYCENT (Del Grosso *et al.*, 2010), CERES (Gabrielle *et al.*, 2006) and DNDC (Li *et al.*, 2001)). The DNDC model was first designed in early 1990s to simulate N_2O emissions from arable soils (Li *et al.*, 2001). Since that time, the original model has been used intensively by many researchers and adopted to different scenarios and ecosystems (Gilhespy *et al.*, 2014; 401 peer reviewed publication in WEB of Science, 2 June 2016). It has been applied at field scale (Abdalla *et al.*, 2009, Beheydt *et al.*, 2007; Peter *et al.*, 2016), country (Li *et al.,* 2001; Lugato *et al.*, 2010; Perlman *et al.*, 2013; Smith *et al.,* 2010) and regional level (Leip *et al.*, 2008). In addition, the DNDC model was adopted to set sustainability criteria for biofuels production in Europe (Directive 2009/28/EC). There is a strong need for biogeochemical models because of the cost and time constrains of field experiments (Syp *et al.*, 2011). Model estimates are reliable if experimental measures agree with model simulations. Based on the literature review, the model validation can be performed in relation to:

– crop yield and biomass;
– soil data: temperature, moisture, organic carbon, water-filled pore space (WFPS);
– gas emissions from the soil-plant system (Gilhespy *et al.*, 2014). Smith *et al.* (2012) used grain yields to calibrate the CENTRY, DAYCENT and DNDC models.

Whereas, Beheydt *et al.* (2007) implied that measured N_2O emission data are necessary to validate DNDC for direct N_2O emissions. The DNDC model was validated in over 100 studies worldwide which showed that it simulates well enough the yields, carbon and nitrogen metabolism and balance sheets of water. Giltrap *et al.* (2010) present details of validation data used for a variety of DNDC-based models.

Irrespective of the possibility of using process based models for N_2O emissions, most countries still use the Tier 1 approach due to the simpler application (Leip *et al.*, 2011). On the other hand, the IPCC recommends using more sophisticated methods of measuring and reporting emissions (*ie* Tier 2 or 3). There are many studies were N_2O field emissions were compared with Tier 1 and 3 methods (Abdalla *et al.*, 2009; Beheydt *et al.*, 2007; Li *et al.*, 2001; Lugato *et al.*, 2010). However, there are only a few studies were differences in N_2O emissions between all three Tiers are presented (Peter *et al.*, 2016; Smith *et al.*, 2010). All the studies present the influence of different climate, soil and management practices on N_2O emissions. To our knowledge, the influence of the variability of weather conditions on N_2O emissions under the application of different Tiers has not been presented. In our study we assume that the soil type and management practices were the same for the whole country. Therefore, the purpose of this study was to quantify the differences in N_2O fluxes using Tier 1, 2 or 3 methods under Polish conditions.

MATERIAL AND METHODS

N_2O emissions were calculated using the BioGrace GHG calculation tool, the global nitrous oxide calculator (GNOC), the emission inference scheme (Lesschen-EF), and the process-oriented denitrification-decomposition (DNDC) model. According to the IPCC Tier 1, the value of N_2O fluxes is proportional to the amount of N fertilizer applied. The emission factor (EF) for this approach is equal to 0.01 kg N_2O-N with the uncertainty range of 0.003 to 0.03 kg N_2O-N (IPCC, 2006). The BioGrace calculator makes use of the IPCC methodology Tier 1 (www.biograce.net). It has been recognised by the European Commission for demonstrating compliance with sustainability criteria for biofuels. The recognition is valid until June 2018 (www.biograce.net). The following data are required by the BioGrace tool: fresh crop and straw yields, humidity (%) and N input. The Tier 1 approach does not take into account environmental or management factors. The next online tool developed to assess soil N_2O emissions from biofuel crops is the GNOC (Köble, 2014). This tool follows the methodology of RED (Directive 2009/28/EC). In the GNOC, the EF from Tier 1 were replaced by Tier 2 disaggregated crop specific emission factors defined on the basis of the Stehfest and Bouwman statistic model (Stehfest and Bouwman, 2006). The resolution of the GNOC default data set is grid cell size of 10 by 10 km based on remote sensing information and FAO crop statistics for the year 2000 (Edwards *et al.*, 2012). To run the calculation, the mandatory inputs include: the place of cultivation, fresh crop yield, soil type, fertilizer input, information about irrigation, environmental and crop residue parameters. Another example of application of Tier 2 for the calculation of N_2O emissions, for the different sources of N input and environmental conditions, is the use of the emission inference scheme (Lesschen-EF) which was developed based on literature reviews and expert knowledge by Lesschen *et al.* (2011). The input of N includes: types of mineral fertilizer and manure, crop residues, atmospheric deposition, biological N fixation, and mineralisation of soil organic carbon (SOC). The environmental factors take into account: land use, soil type, precipitation, and temperature. The parametrisation of Lesschen-EF was done to the reference situation based on the Stehfest and Bouwaman data set (Lesschen *et al.*, 2011). The GNOC and Lesschen-EF represent the Tier 2 method. The Tier 3 approach is represented by the Denitrification-Decomposition (DNDC) model (version 9.2; http:/www.dndc.sr.unh.edu). The basic structure of the model consists of two components incorporated to six sub-models. The first component consists of soil climate, crop growth, and decomposition sub-models. It simulates soil conditions. The second component stimulates the production of GHG based on soil states from the first component. The model requires spatial databases of climatic data (daily air temperature and precipitation), soil parameters (texture, bulk density, pH, SOC content), cropping systems, and agricultural management practices. The DNDC model is very sensitive to climate, size of initial soil C levels, and fertilizer application rates (Giltrap *et al.,* 2010). The calibration of the DNDC model to Polish conditions was performed based on coefficients developed for agricultural crops carried out on a regional scale in the EU-15 (Leip *et al.,* 2008). The coefficients responsible for the control of nitrogen transformations derived from calibration DNDC-Europe were not changed.

In the calibration of the DNDC model, the yield data from a long-term filed experiment from the Grabów Experimental Station (51°21'N, 21°40'E and 167 m a.s.l.) were applied because other data were not available. Input parameters for the DNDC calibration were: heterogeneous sandy loam soil (Cambisols) with pH – 7, bulk density − 1.5 g cm^{-3}, clay fraction − 0.09%, SOC initial value − 0.01 kg C kg^{-1} soil at the depth 5 cm, and average annual precipitation of 614 mm. In this experiment the influence of straw incorporation on yields and soil organic carbon stock (SOC) were studied. Recalibration of the DNDC model for the experimental conditions relied on making changes in the coefficients of allocation of coal to grain (seed), straw and roots, and then, after making any such change multiple, iterative simulations for the periods of field trials. In performed simulations the meteorological data, soil properties and production technology of conducted experiment were applied. The calculated relative root mean squared error (RRMSE) amounted to 19.9%. The DNDC model simulations were made for 20 years, because after this time the allocation of soil organic carbon (SOC) to different pools reaches a balance before estimating N_2O emissions (Perlman *et al.,* 2013). The uncertainties of the model were estimated by Monte Carlo simulations with respect to varied input parameters. The performed simulations showed that the factor to which N_2O emissions were the most sensitive were the SOC values. It was in agreement with studies by Li *et al.* (2001) and confirmed that the DNDC model fits well to the Polish conditions. The obtained results justify the claim that it is acceptable to use the developed DNDC model in further simulations. Validation of the DNDC model was performed in comparison to the yields obtained from surveyed farms located in Poland. The RRMSE of simulated crop yields using the DNDC model amounted to 9%.

In our study the N_2O emissions were estimated for rapeseed cultivation in a 4-year crop rotation including: maize − winter wheat – rapeseed − winter wheat. All the input variables were spatially interpolated to a raster with 50x50 km grid cells for Poland. The grid size was adjusted to obtained climate data for Poland. Due to the small number of weather stations in Poland, the daily weather data (minimum and maximum air temperature, daily precipitation sums, and solar radiation) for the period of 1975-2004 were taken from the Joint Research Centre (http://ies-webarchive-ext.jrc.it/mars/mars/About-us/AGRI4CAST/Data-distribution/Meteorological-Interpolated-Data.html. The interpolation was performed based on the assumption that at least one meteorological station had to be located on three adjacent grid cells. A network of 136 grid squares covered the whole territory of the country. The study included only those squares which were all located within the Polish territory. In all tools the same input data referring to rapeseed cultivation were applied. The rapeseed yields for each grid came from a simulation performed with the DNDC model. The data on rapeseed cultivation were derived from surveys performed in farms located in Poland, included in the farm accountancy data base (FADN). Rapeseed was grown in accordance with good agricultural practices, including sowing, harvesting, fertilisation, and plant protection. N was applied as ammonium nitrate fertilizer at the rate of 180 kg N ha^{-1}. Humidity of the harvested product was 9%. All the crop residues were incorporated.

In the GNOC crop yields from each grid were adjusted to one location within the grid. In the Lesschen-EF methods we applied the following emission factors (EF): 0.8 for nitrate fertilizer, 0.75 for atmospheric N deposition and 0.9 for the soil type.

The necessary soil characteristics for the model were obtained from the soil database of the Institute of Soil Science and Plant Cultivation – State Research Institute in Puławy (IUNG-PIB). Because we wanted to show only the influence of climate conditions on N_2O emissions in Poland, the study covers one type of soil classified by world reference base for soil resources (WRB) as a high clay activity mineral. It has been determined in accordance with a procedure developed by IUNG-PIB for determining the weighted average content of SOC in each square. As the data, physicochemical characteristics of the 15 000 standard soil profiles distributed throughout the Poland were used.

In our research, first, the average N_2O-N emissions for each grid were calculated and simulated. Next, they were converted to N_2O by multiplying the kilogram of N_2O-N by 44/28 (ratio of molecular weight of N and N_2O). The analyses were done using Statistica 10 PL Version 2.1 and ArcGis ver. 10.2 software packages.

RESULTS AND DISCUSSION

The N_2O emissions calculated with different approaches and simulated with the DNDC model, expressed in kg N_2O unit per ha per year (kg N_2O ha^{-1} y^{-1}), are shown on a spatial distribution in Fig. 1. The results illustrate large differences of N_2O fluxes between the methods. The Tier 1 method shows N_2O emissions amounting to over 3.6 kg N_2O ha^{-1} y^{-1} across Poland and a rather homogeneous emission pattern over the entire country. The use of GNOC reduced N_2O emissions in some grids to the range from 2.6 to 3.5 kg N_2O ha^{-1} y^{-1}. It was the result of implementing environmental parameters in the tool, such as climate zone

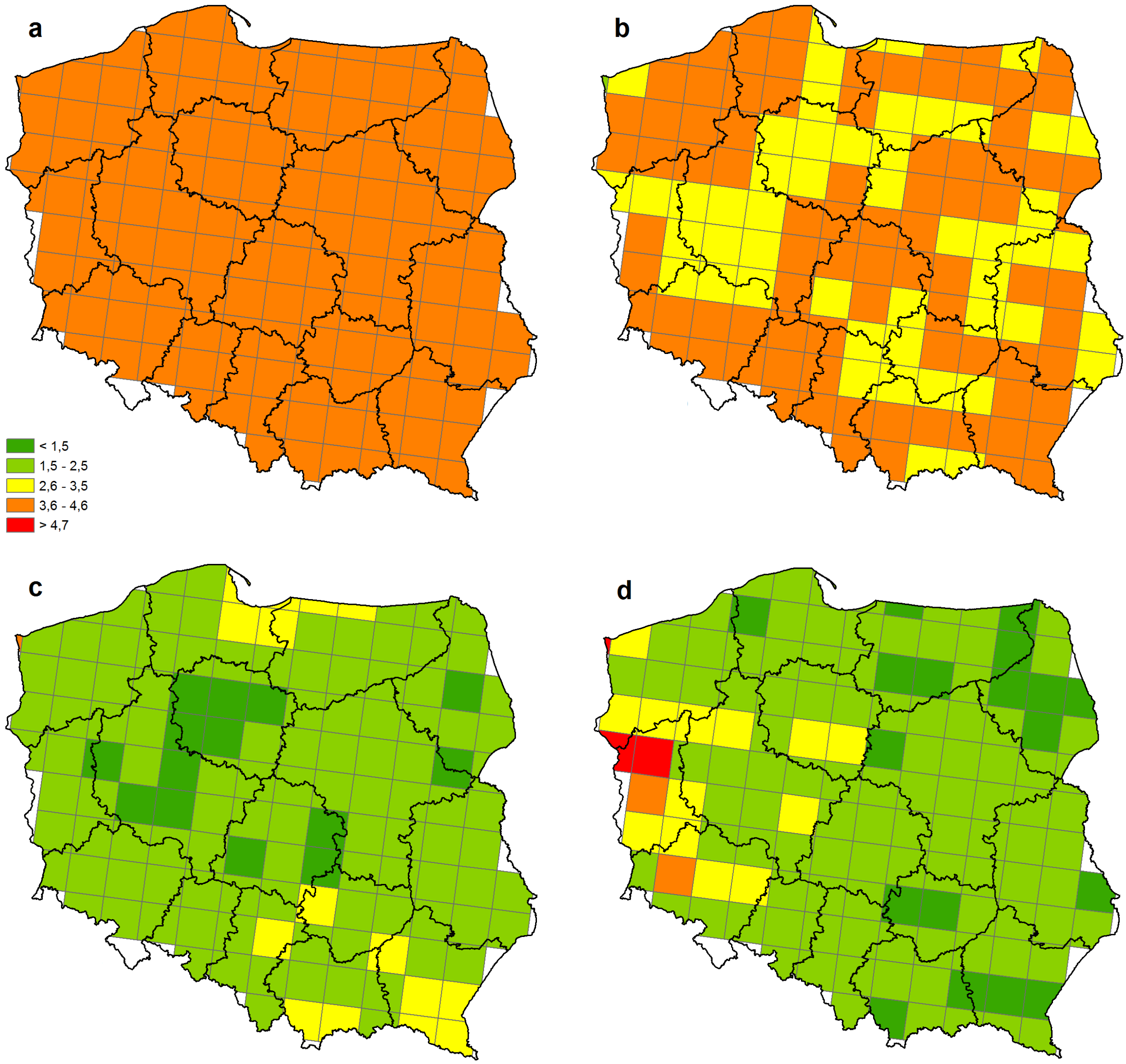

Fig. 1. Comparison of calculated rapeseed N_2O emissions based on: a – BioGrace, b – GNOC, c – Lesschen emission factors and d – DNDC model.

and class, soil pH, soil organic carbon (%), soil texture and information about leaching. The other parameters were the same as in the BioGrace calculator. The application of the Lesschen-EF methods resulted in a further reduction and diversification of N_2O emissions. In some grids, N_2O fluxes were lower than 1.5 kg N_2O ha^{-1} y^{-1}. It was the consequence of using EF with lower value for applied fertilizer, N atmospheric deposition and soil type. The simulations performed with the DNDC model present the most diverse N_2O emissions in Poland. In the western part of Poland, N_2O emissions in some grids exceeded 4.7 kg N_2O ha^{-1} y^{-1}. However, in 18 grids the N_2O fluxes were lower than 1.5 kg N_2O ha^{-1} y^{-1}. This was due to the fact that the DNDC model takes into account regional differences in climate conditions and interactions between various components of the nitrogen cycle. The average N_2O emissions, ranked from the highest to the lowest, based on an applied approach, were as follows: BioGrace, GNOC, DNDC model and Lesschen-EF. In all of the methodologies, the mean and median N_2O fluxes are on the same level, although each method has a different distribution of N_2O emissions (Table 1, Fig. 2). The non-parametric pair-wise multiple comparison based on rank sum test (post hoc Dunn) was performed. The test results showed that differences of N_2O emissions calculated by the Lesschen-EF and DNDC approaches were not statistically significantly different (Fig. 2). The median N_2O emissions from rapeseed cultivation in Poland applying BioGrace – Tier 1 method was 3.68 kg N_2O ha^{-1} y^{-1}, whereas

T a b l e 1. Comparison of N_2O-N emissions (kg N_2O ha^{-1} y^{-1}) over all grid cells in rapeseed cultivation between BioGrace, GNOC, Lesschen emission factors, and DNDC model

Methods	Mean and standard deviation	Median	Min	Max
	N_2O-N emissions (kg N_2O ha^{-1} y^{-1})			
BioGrace	3.78 ±0.15	3.68a	3.60	4.09
GNOC	3.55±0.27	3.54b	2.44	4.56
Lesschen-EF	1.98±0.46	1.89c	1.28	4.43
DNDC	1.99±0.70	1.80c	1.33	5.56

Different letters present differences for median Dunn test p<0.0001.

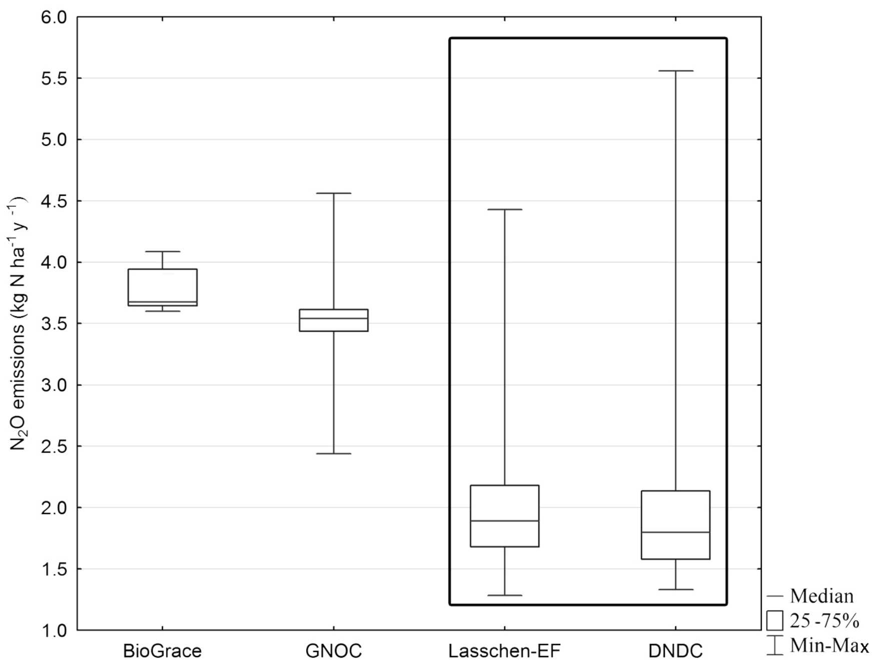

Fig. 2. Median of N_2O emissions for rapeseed over all grid cells between BioGrace, GNOC, Lesschen emission factors and DNDC model. The rectangle on the graph indicates two groups forming a homogeneous group according to the Dunn test p<0.0001.

simulated by DNDC model – 1.8 N_2O ha^{-1} y^{-1}. The results of our research concerning the N_2O soil emissions using Lesschen-EF are in agreement with the calculation emissions for Poland by the INTEGRATOR model (Lesschen *et al.,* 2011). Our outcomes are similar to the studies performed for China, in which the N_2O emissions from the process-based agro-ecosystem model were compared against the IPCC Tier 1 methodology (Li *et al.*, 2001). At sub-regional level in France, the value of N_2O emissions simulated by the CERES model for wheat cropped field were lower than IPCC ones (Gabrielle *et al.* 2006). Abdalla *et al.* (2009) stated that in Ireland modelled and measured N_2O fluxes from arable field for fertilizer input of 70-160 kg N ha^{-1} are comparable, but both significantly lower than the IPCC default value. Similar results were obtained for maize cultivation in Italy (Lugato *et al.*, 2010). However, DNDC is unsuitable for predicting N_2O emissions from grassland due to overestimation of N_2O fluxes (Abdala *et al.*, 2009; Beheydet *et al.*, 2007). The studies performed for ecodistricts in Canada indicated that the DNDC model overestimated N_2O emissions in comparison to Tier 2 estimations (Smith *et al.*, 2010). Peter *et al.* (2016) found out that for winter wheat cultivation in Germany on Stagnic Cambisol (HAC) and Luvisol (HAC) soil type the N_2O emissions calculated with Tier 2 were lower than with the Tier 1 approach. In addition, they stated that the calculation of N_2O emissions for annual crops with a higher Tier approach is particularly important when fertilizer-induced field emission is being estimated. The performed studies confirmed that N_2O emissions depend on local climatic conditions combined with microbiological and physical properties of soil.

The regional modelling studies run their model on a grid size depending on the area covered by the available data sets and scope of simulations. For example, Lugato *et al.* (2010) estimated N_2O emissions from crops in Italy at a grid of 1 x 1 km. This approach is very efficient for fast estimation of large scale emissions. Leip *et al.* (2008) stated that in detail analysis there is no link to realistic land use data and it is difficult to include local heterogeneities. In some papers N_2O emissions are modelled at a high level of aggregation. For example, Smith *et al.* (2010) used Canadian eco-districts as their modelling units (size of 250 km^2). Del Grosso *et al.* (2010) performed N_2O simulation for major crops in the United States for 3 000 counties that reported at least 40 ha of agricultural land. Perlman *et al.* (2013) presented a simulation of N_2O emissions for a large area using maize production in the United States in reference to a raster with 25 x 25 km grid cells. Kesik *et al.* (2005) linked simulation of N_2O emissions from European forest soil to the available climate data set and ran the model on a 50 x 50 km raster. For better land representation, many researchers run models within administrative regions for which regional statistics are available (Li *et al.*, 2001). The 'administrative approach' is also used if a study performs comparison with national GHG estimates based on Tier 1 approach. The usual motivation for using large spatial units is that at least some of the input data set, often crop management data, are only available at coarse resolution (*eg* state, county), and thus modelling is performed at that resolution, even though other data may be available at much higher spatial resolution (Perlman *et al.*, 2013). Grant and Pattey (2003) stated that aggregation of N_2O emissions at higher resolution should be based on 'typical landscape in which surface topography and soil type is accurately represented'.

CONCLUSIONS

1. The introduction of crop rapeseed cultivation and site emission factors to calculate direct emissions of N_2O in global nitrous oxide calculator resulted in lower N_2O fluxes compared to the IPCC-Tier 1 method.

2. The modification of emission factors by Lesschen group following Tier 2 method led to a large decrease of N_2O emissions. The calculated fluxes were on the same level as N_2O emissions simulated by denitrification-decomposition model.

3. Our current work illustrates that Lesschen emission factors methods at country level work as well as denitrification-decomposition model for Poland. Therefore, it is suitable to advise to calculate N_2O emissions using Lesschen emission factors methods. The advantage of this approach is simplicity of collecting necessary data in contrast to process based model needs. Moreover, the Tier 2 method provides mitigation measure similar to denitrification-decomposition model related to crop type, climatic conditions and management practices. The international panel on climate change Tier 1 method, currently used by many countries, ignores factors which are essential in defining current emissions.

Conflict of interest: The Authors do not declare conflict of interest.

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