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Original Research

Using Different Models to Estimate N_2O Fluxes from Maize Cultivation in Poland

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Abstract

This paper presents a comparison of N_2O fluxes calculated using empirical and biogeochemical models at the country level applying different climatic conditions. The empirical tools follow Tier 1 and 2 IPCC methods, whereas the process-based model follows Tier 3. In our study the following tools were applied: for Tier 1 – BioGrace calculator, Tier 2 − Lesschen emission factors (Lesschen-EF), and Tier 3 − denitrification-decomposition (DNDC) model. The N_2O fluxes were calculated for maize grown in four-yr crop rotation in Poland. The same input data were applied in all methods, and the sequence of N_2O fluxes from largest to lowest was: BioGrace calculator > Lesschen-EF > DNDC. The average N_2O emission from maize cultivation applying IPCC default value was 3.17 kg N ha^{-1} yr^{-1}. Almost two-fold lower fluxes were calculated based on the Lesschen-EF and DNDC model. At a regional level, the Lesschen-EF as well as DNDC model were performed. Therefore, the Lesschen-EF could be recommended for countries to calculate N_2O emissions. The advantage of this approach is simplicity of obtaining the necessary data compared to the process-based model requirements. Additionally, the Tier 2 method offers mitigation measures comparable to the DNDC model, related to crop type, weather conditions, and management practices.

Keywords: BioGrace calculator , DNDC model, IPCC methodology, Lesschen emission factors, N_2O emissions

Introduction

Maize (*Zea mays* L.) is one of the major staple foods in the world. In 2000-13 global maize production increased by 72% to 1,017 million tons, and cultivation area and yield growth, respectively, by 38% (to 186 million ha) and 26% (to 54.7 hg ha^{-1}) [1]. About 10% of world's production is located in Europe. In the analysed period, the growth of production, cropping area, and yield of maize have been higher in Europe than in other regions of the world. Poland – after France, Romania, Hungry, and Italy – is one of the biggest maize producers in Europe [2]. In the last 13 years maize cultivation in Poland has quadrupled from 152 to 614 thousand ha [3]. The increase of maize area cultivation resulted from its comprehensive use for food, as well as animal feed and industry. Recently, the demand for maize has grown due to expansion of the ethanol industry. This trend will be continued, because Poland, as other European countries, is obliged to fulfil sustainability criteria for biofuels set in the Renewable Energy Directive (RED) [4], which defines that at least 10% of the transport fuel

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must come from renewable sources by 2020. Furthermore, the mandatory target is greenhouse gas (GHG) emission savings of at least 35% from the use of biofuels compared to fossil fuels. This number should increase to at least 50% by 2017, and 60% for biofuels produced in installations in which production started in 2017 or later. Nitrous oxide (N_2O) is an important gas in the GHG budget because its global warming potential (GWP) for more than 100 years has been 298-times larger than of carbon dioxide (CO_2), and its lifespan is 114 years [5]. Agriculture is the main anthropogenic source of N_2O emissions [6] and is characterised by the largest uncertainty [7]. The major source of N_2O emissions is arable land. The N_2O emissions in the soil come from a variety of physical and chemical processes, of which the best known are nitrification and denitrification. Today most farming systems are based on large fertilizer applications that provide high availability of nitrogen (N) for plants. A positive effect is higher yields and larger amounts of crop residues, which are an essential part of organic matter. The high content of organic carbon in the post-harvest residue returning to the soil improves its physical, chemical, and biological properties [8]. The negative consequences of fertilizer use are higher soil N_2O fluxes, which are directly related to the amount of N applied [9]. In 2014, in Poland N_2O fluxes from arable soils were reported at 45.2 kt CO_2 eq. and contributed to 68.2% of the total national N_2O agricultural emissions [10]. The countries which have ratified the United Nations Convention on Climate Change (UNFCCC) are obligated to publish national inventory of GHG emissions, including assessment of N_2O agricultural emissions [11]. The reports should include the information on methods used in estimating emissions [12]. Solar radiation in urban area affects human health. Indoor plants also are affected by solar radiation. This leads to climate change on the environment as well as forested, coastal, and urban areas [13-15]. A recent study shows that carbon emissions affect thermal comfort and lead to the climate change problem [16].

Thus, it demands natural areas and coastal areas [17-19]. There are a lot of studies for carbon emissions, including indoor and outdoor specially urban cities and parks. This shows that $PM_{2.5}$ affects human health [20-26].

The Intergovernmental Panel on Climate Change (IPCC) guidelines provide three calculation pathways (tiers) described by various levels of complexity based on available data [11]. Tier 1 methodology uses the default emissions factor provided by the IPCC. The Tier 2 approach requires the use of national or regional emission factors representing local pedoclimatic conditions. The IPCC Tier 1 and 2 methods represent an empirical modelling approach showing the statistical relationship between N input and N_2O emissions [7]. These models require lower input information, assuming that the samples of data represent the full population and are suitable for large-scale applications. In addition, a common feature of these methodologies is that the model structure is defined a priori. The Tier 1 and 2 methodologies are applied in 56% and 26% of countries, respectively, whereas 18% of the countries did not estimate or provide information about N_2O agricultural emissions [12]. Tier 3 methods use process-based model simulation or in-situ measurements. Direct measurement of GHG emissions for reporting is unfeasible as it would require a large number of measurements over a long period of time [27]. Additionally, it is nearly impossible to collect data including all possible conditions [28]. Therefore, there is a great demand for biogeochemical models that could predict the N_2O emissions underlying physical, chemical, and biological processes. To date, the denitrification-decomposition (DNDC) model is one of the most commonly applied process-based models.

The DNDC model was developed by Li et al. [29] to predict N_2O emissions from agricultural soils in the United States as a function of organic carbon content, fertilizer type, and weather conditions. Many researchers have tested the model and adopted it to country-specific management, climate, and soil conditions [30-34]. The DNDC model was used by the European Union (EU) to set sustainability criteria for biofuels with the legislation of the RED [4]. Detailed model development is presented by Gilhespy et al. [35], and Zhang and Niu [27]. The DNDC model was validated globally in over 100 studies, which has demonstrated accurate predictions of crop yields, climate, nitrogen losses, carbon sequestration and GHG emissions from agro-ecosystems [27, 36-37]. Due to reasonable data requirements, the model is suitable for simulation at temporal and spatial scales [32, 38]. The food crops frequently simulated by the DNDC model are: rice (14.36%), maize (13.12%), winter wheat (11.25%), and barley (8.12%) [27].

In maize cultivation, DNDC estimations mainly concentrate on N cycling, which indicates that management practices significantly influence nitrogen fluxes and nitrate leaching [38]. Therefore, in our study we have decided to use the DNDC model to assess the impact of the variability of climate conditions on N_2O fluxes, applying different tools following Tier 1, 2, and 3 methodology. There is much research applying Tier 1 and 3 methods to a comparison of N_2O fluxes [30-32, 36], while the differences in N_2O emissions between all three Tiers are presented only by Smith et al. [33] and Peter et al. [39]. In our study we assumed that the soil type and management practices were the same for Poland's territory in the whole country. The objectives of this paper were to assess and compare the influence of the variability regional climate data on N_2O emissions from maize cultivation, applying empirical and process-oriented biogeochemistry models.

Material and Methods

In our study the following empirical models were applied: the BioGrace calculation tool, the emission inference scheme (Lesschen-EF), and the biogeochemical DNDC model.

BioGrace Calculation Tool

The BioGrace calculator was developed within the Intelligent Energy Programme in order to calculate GHG emissions in compliance with the RED for biofuel chains [40] following the IPCC default methodology (Tier 1). In this method the N_2O emissions from soil are the sum of direct and indirect N_2O emissions. The direct N_2O fluxes are an estimation based on the use of nitrogen (N) fertilizers and decomposition of above- and belowground crop residues, whereas the indirect N_2O emissions are assessed due to N_2O leaching, runoff, and volatilisation. The value of N_2O fluxes is equal to 1±1.0% of N applied, which means that 1% of N added to the soil is lost as N_2O with the uncertainty range of 0.003 to 0.03 kg N_2O-N [11]. The main uncertainties on N_2O emissions from agricultural soil come from: 1) the amount of applied N, 2) N_2O emission factor to applied N, and 3) the equation for above dry matter residues [9, 11]. In the IPCC-Tier 1 method, there is a simple linear relationship between N applied and N_2O emissions. The Tier 1 methodology does not require data on cropland area, soil type, climate, and management practices (fertilizer type, tillage, irrigation). It does not consider time delay in direct emissions from N in crop residues but is allocated to the year in which the residues are returned to the soil [41]. In order to calculate N_2O emissions by the BioGrace tool, the following data are necessary: fresh crop and straw yields, humidity (%), N input, and information about the use of crop residues.

Lesschen Emission Factor

Emission inference scheme (Lesschen-EF) is the Tier 2 method applied to calculate N_2O emissions that are developed based on reviewed literature and expert knowledge [42]. The Lesschen-EF takes into account differences in N sources and environmental conditions. The N sources comprise types of mineral fertilizers and manure, crop residues, atmospheric deposition, biological N fixation, and mineralization of soil organic carbon (SOC). The controlling factors associated with environmental conditions include land use, soil type, precipitation, and temperature. The parametrisation of emission factors was performed relative to the reference based on the Stehfest and Bouwaman data set [42]. The Lesschen-EF were incorporated in the INTEGRATOR model adopted version of MITERRA-Europe model [43]. In the Lesschen-EF methods the following emission factors (EF) were applied: 0.8 for nitrate fertilizer, 0.75 for atmospheric N deposition, and 0.9 for soil type.

Denitrification Decomposition Model (DNDC)

In this study, the DNDC model (version 9.2; www.dndc.sr.unh.edu) was applied. The model consists of two components that integrate ecological drivers and soil environmental factors. The ecological features include climate, soil vegetation, and human activity. Those components form three sub-models that assess soil physical and chemical status, plant growth, and organic carbon mineralization. The second component consists of denitrification, nitrification, and fermentation submodels. It stimulates the production of GHG. The DNDC model can run at field or regional scales. The basic input parameters required by the model include: location (latitude), meteorological data (e.g., daily air temperature and precipitation), and soil properties (e.g., texture, bulk density, pH, soil organic content (SOC)), and crop type and management practices (e.g. tillage, fertilization, and irrigation). A key part of model development is its validation against field measures. The model simulates processes acceptable only if field data are compliant with model calculations.

According to the literature, the validation of the model could be done based on: (i) crop yield and biomass, (ii) soil data, and (iii) gas emissions [35]. The calibration of the DNDC model to Polish terms performed on the foundation coefficients developed for crops at regional scale in the EU-15 [44]. The indicators in charge of nitrogen transformations derived from calibration DNDC-Europe have not been modified, whereas the coefficients responsible for the allocation of carbon to grain (seed), straw, and roots were adjusted to Polish conditions through iterative simulations for the 23-year period of field trials. In the simulations the soil, crop, and farming practices were unchanged. Calibrating the DNDC model was performed on the yield data from a long-term field experiment from the Grabów Experimental Station (51°21'N, 21°40'E and 167 m above sea level) because the 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%, and SOC initial value 0.01 kg·C per kg soil at 5 cm depth. Daily weather data (rainfall, maximum, and minimum temperatures) were collected from the weather station located in Grabów Experimental Station. The annual participation at this location is 614 mm. The calibration was performed on the basis of three different crop rotations. In the first one, the crop sequence was as follows: barley – rapeseed – winter wheat, the second crop rotation included: maize – barley – winter wheat, and the third one: maize – spring wheat – rapeseed. In this experiment we studied the influence of straw incorporation on yields and SOC. The calculated relative root mean squared error (RRMSE) amounted to 19.4, 20.2, and 19.9%, respectively, for maize, winter wheat, and rapeseed. The uncertainties of the model estimated by Monte Carlo simulations presented SOC as the most sensitive factor to N_2O emissions [30]. The acquired results confirmed that it is allowed to apply 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 were as follows: maize 26%, winter wheat 21%, and rapeseed 9%.

Data Input

The N_2O emissions were estimated for maize. The spatial database of input variables for all tools (referenced to a raster with 50x50 km grid cells for Poland) was created. For each cell we recorded: yields, soil properties, daily weather conditions, N fertilization, and management practices. Because of a small number of meteorological stations in Poland the daily climatic data for the time from 1975 to 2004 were acquired from the Joint Research Centre (http://ies-webarchive-ext.jrc.it/mars/mars/About-us/AGRI4CAST/Data-distribution/Meteorological-Interpolated-Data.html), which are available for European countries. It was done by selecting the best combination of weather stations for each grid. The interpolation was based on the statement that at least one weather station had to be placed on three neighbouring grid cells. Therefore, the research includes a network of only 136 grid squares placed within Polish territory.

In all calculators we used the identical input data referring to maize cultivation. The maize potential yields for each grid were simulated by DNDC model at the daily time step, based on pre-defined functions representing the path of maximum possible nitrogen uptake and biomass carbon [44]. The data detail about maize production came from surveys conducted in Polish agricultural holdings included in the Farm Accountancy Data Base (FADN). The maize was produced according to requirements of the Code of Good Agricultural Practices as regards to management practices (sowing, fertilization, protection, and harvesting). In Poland, the common practice in maize cultivation is conventional tillage with straw incorporation and rain-fed irrigation. The mineral fertilization included ammonium nitrate application at a dose of 140 kg N ha^{-1}. Humidity of the harvested grain was 32%. The incorporated straw and crop residues have had an influence on N_2O emissions. The DNDC soil model data were collected from a database developed at the Institute of Soil Science and Plant Cultivation-State Research Institute in Puławy (IUNG-PIB). For the establishment of SOC data in kg C^{-1} of soil we used the database of reference soil profiles. The database contains 15,000 georeferenced soil profiles utilized in 1960-70 in production of an analogue soil agricultural map of Poland.

A set of information describing the profiles include: land use, location of profile, soil type, texture, SOC content, pH, and available nutrients. Because the main aim of our research was to present the impact of weather conditions on N_2O emissions in Poland using different tools, the analysis focused on one soil type classified by the World Reference Base for Soil Resources (WRB) as a high clay activity mineral. This type has been selected on the basis of SOC content in the arable layer of soil for each square. In each grid, we calculated mean N_2O-N emissions over 20-year simulations. Furthermore, N_2O-N fluxes were converted to N_2O by multiplying the kilogram of N_2O-N by a 44/28 (ratio of molecular weight of N and N_2O). In order to express the calculations and modelling results spatially, an N_2O emissions map was produced in ArcGis ver. 10.2 software. The analyses were performed by applying Statistica 10 PL Version 2.1

Results and Discussion

Fig. 1 presents the spatial patterns of N_2O fluxes calculated with different statistical approaches and simulated with a DNDC model expressed in kg N unit per ha per year (kg N_2O ha^{-1} yr^{-1}). The clear differences of N_2O emissions between the methods were observed. The highest N_2O fluxes (> 3 kg N ha^{-1} yr^{-1}) through the whole territory of Poland were indicated when IPCC Tier 1 methodology was applied. There were particularly apparent lower values of N_2O emissions for the Lesschen-EF and DNDC approaches. Moreover, there were differences in the distribution of emissions between both methods. According to Lesschen-EF, in the central part of Poland N_2O emissions under 1.5 kg N ha^{-1} yr^{-1} were estimated, whereas in the northern part emissions between 1.5-2 N ha^{-1} yr^{-1} dominated. In the southern part of the country there was an equal number of squares with emissions ranging between 1.5-2 and 2-2.5 kg N ha^{-1} yr^{-1}. Based on the DNDC model simulation, Poland was divided into two part: east and west. The eastern part of the country was characterized by low homogeneous emissions. In the western part layout was not uniform. The sequence of N_2O fluxes from the largest to the lowest based on the applied methods was as follows: BioGrace, Lesschen-EF, and DNDC.

The average N_2O emissions from maize cultivation in Poland applying IPCC default amounted to 3.17 kg N_2O ha^{-1} yr^{-1}. Almost two-fold lower fluxes are calculated based on Lesschen-EF and DNDC model simulations. These resulted from implementation of crop and site emission factors to the calculation of N_2O direct emissions. In all methodologies the mean and median N_2O fluxes were on the same level, but each methodology had an unlike 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 outcomes of our studies referring to the difference between N_2O emissions calculated by Tier 1 and simulated in Tier 3 were consistent with results of Li et al. [30] studies performed for China, where DNDC model and default values were compared. The obtained results were in line with N_2O soil emissions for Poland predicted by the INTEGRATOR model [42]. In our study, the IPCC Tier 1 method gave a 105% larger value compared to Tier 3 methodology, whereas Dufosse et al. [45] while comparing the Tier 3 and Tier 1 methods obtained 73 and 48% difference, respectively, for sugar beet and Miscanthous cultivated in France. Gabrielle et al. [46] stated that in France model-based estimates of direct N_2O emissions from wheat-cropped field were from 39% to 81% lower than IPCC ones. In Ireland, for a spring barley field, predicted and measured fluxes of

N_2O were agreed for fertilizer doses from 70 to 160 kg N ha^{-1}, but did not match when the rate of N fertilizer was not applied [31]. For the cut and grazed pasture the differences of N_2O fluxes were recorded at 150 and 360%, respectively. Beheydt et al. [36] also stated that this is a better agreement between simulated and measured total N_2O emissions from cropland than from grasslands, even though the cropland fluxes are systemically overestimated. This statement is based on studies performed in Belgium. In the presented studies, not only climate conditions varied across the region but also soil properties. The results of Smith et al. [33] research accomplished for eco-districts in Canada showed that the DNDC model overestimated N_2O emissions in reference to Tier 2 results, while Peter et al. [39] presented N_2O emissions for Stagnic Cambisol (HAC) and Luvisol (HAC) soils in Germany calculated with Tier 2 methods as being lower compared with Tier 1 results. Furthermore, they found 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. According to Cardenas et. al [47] the modelled emission factors for N_2O emissions from soils in the United Kingdom gave similar values to IPCC for inorganic N, and lower values for organic N. These researchers even suggested that the effects may be used to improve the inventory of N_2O in agriculture. However, Lugato et al. [32], based on the research performed in Italy, reported lower values of emission factors from fertilizers compared to IPCC default. Beheydt et al. [36] stated that the regression-based model underestimates total N_2O emissions. The executed analysis pointed out that N_2O emissions depend on local variability of soil, climate, and crop management conditions.

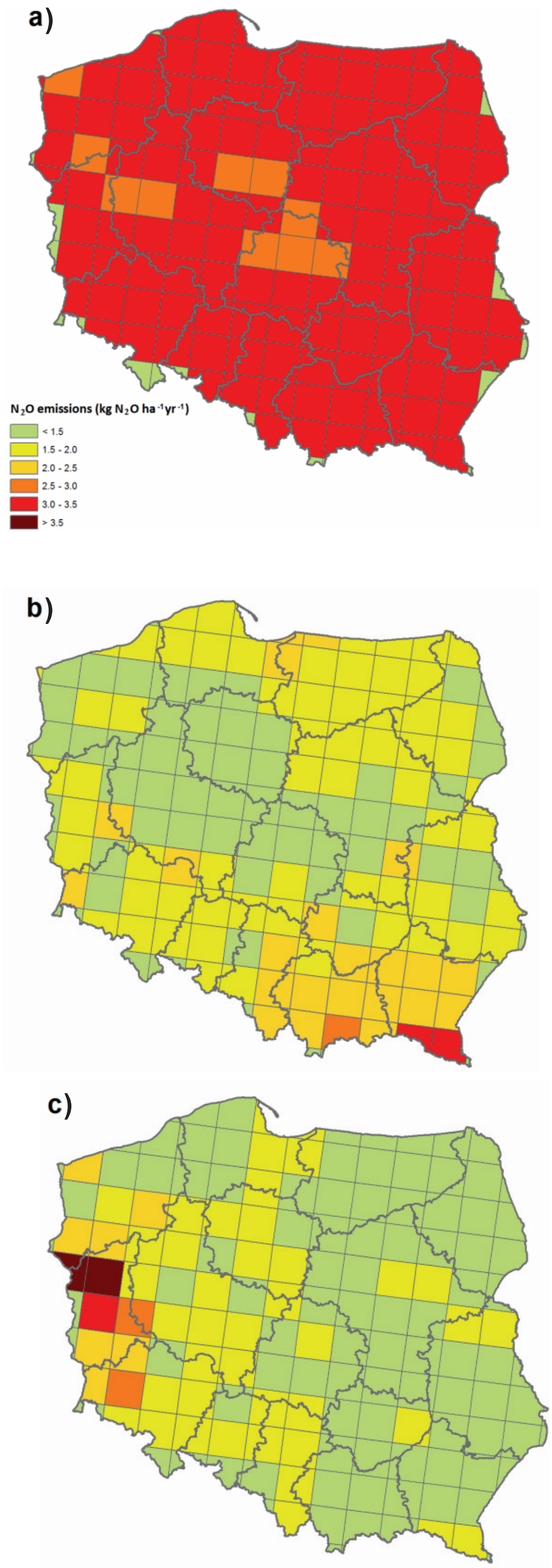

Fig. 1. Comparison of N_2O emissions in maize cultivation between a) BioGrace calculator, b) Lesschen emission factors, and c) DNDC model.

Table 1. Comparison of N_2O emissions in maize cultivation between the BioGrace tool, Lesschen emission factors, and DNDC model.

Methods	Mean and standard deviation	Median	Min.	Max.
	N_2O emissions (kg N_2O ha^{-1} yr^{-1})			
BioGrace	3.17±0.11	3.17a	2.91	3.41
Lesschen-EF	1.68±0.39	1.73b	0.90	3.28
DNDC	1.54±0.48	1.41b	1.04	4.51

Values with different letters show significant difference for median Dunn test p<0.01; ± standard devation

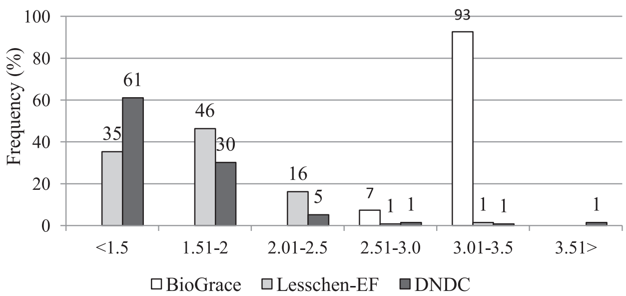

Fig. 2. Frequency distribution of N_2O emissions for maize for BioGrace tool, Lesschen emission factors, and DNDC model.

The regional modelling studies are conditioned by the area covered with the available data sets and scope of simulations. The modelling simulations domain is divided into units such as grid cells, where each unit runs with its own input data [38]. The spatial resolution grids depend on available information necessary to perform simulations for each cell. Lugato et al. [32] estimated N_2O emissions from crops by adopting a grid of 1 x 1 km covering Italy. The purpose of using such a detailed level specialization was to develop a tool that could be used by local administration to provide information about a small area. However, the main limiting factor in these simulations was lack of a geographical database related to such a small scale, and negligence of local heterogeneities. This confirms the opinion presented by Leip et al, [44] that in detail analysis there is no link to realistic land use data. Therefore, the researcher more frequently used high-level data aggregations. For example, simulation of N_2O emissions for major crops of 63 regions of the United States was performed in counties that had at least 40 ha [48]. The larger raster (25 x 25 km) was used by Perlman et al. [38] to model N_2O fluxes from maize cultivation in the United States. The modelling unit for simulations applied to eco-districts in Canada was 250 km^2 [33]. The same size of spatial resolution as we used in our study was applied by Kesik et al. [49] to present N_2O emissions from European forest soil. However, many scientists decided to perform model simulations within administrative regions because of the availability of regional statistical data [30]. Furthermore, the 'administrative approach' is applied if the analysis study includes a comparison with national GHG inventories that elaborated on the Tier 1 methodology. Generally, using large spatial units is more common due to easily accessible databases at the regional level (climatic and crop management data), despite the fact that it is possible to acquire data at much higher spatial resolution [38]. Grant and Pattey [50] stated that the aggregation of N_2O emissions at a higher resolution should be based on a typical landscape in which surface topography and soil type is accurately represented.

Conclusions

The advantage of IPCC default methods is a simple structure. However, it does not take into account regional differences in soil, climate conditions, and interactions between various components of the nitrogen cycle or a possible impact of agricultural practices other than N application. As a result, there is a large uncertainty about sufficient estimates. Also, a consequence of this approach is a possibility to build mitigation strategies based only on reducing fertilizer use. Today there is a need for more detailed methods to describe spatial and temporal patterns of ecosystem GHG exchange. At a regional level the Lesschen inference scheme performs similarly to the DNDC model. Therefore, it could be recommended for countries as a tool to calculate N_2O emissions. The advantage of this approach is the relative ease of obtaining the necessary data compared to process-based model requirements. Additionally, applying Lesschen-EF as a Tier 2 method provides more mitigation measures, such as changes in management practices, fertilizer, or manure type.

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