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Original Research

Yield-Scaled Nitrous Oxide Emission from Soils Depending on Nitrogen Use Efficiency Characteristics

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Abstract

Nitrogen fertilization of agricultural crops increases nitrous oxide (N_2O) emissions from soils. The data used in this study were obtained from a long-term field experiment for corn, winter wheat and rapeseed cultivated on loam and sandy loam soils, and fertilized with the recommended nitrogen doses (kg N ha^{l}) of 150, 120 and 150, respectively. The purpose of the study was to determine the relationship between yield-scaled N_2O emissions (Eys) and nitrogen yield (Yn), as well as nitrogen use efficiency (NUE) and nitrogen surplus (Ns). It was found that the provisionally determined desired yield values (Yn>80 kg N ha^{-1}), NUE (50-90%) and N surplus (Ns<80 kg N ha^{-1}) can be considered as nitrogen utilization efficiency characteristics, reducing yield-scaled N_2O emissions. Our study showed that these emissions for desired parameters Yn, NUE and Ns were ≤25.6, 28.3-18.6 and ≤30.9 g N_2O_N kg Yn^{-1}, respectively. Estimated Eys were 1.5-2.6 time higher than the minimum emission and 2.2-3.6 times lower than the maximum emission recorded in the analyzed data series. In conclusion, the reduction of nitrogen surplus in our field experiment, significant for environmental protection, did not result in loss of crop yields; on the contrary, it led to their growth.

Keywords: N_2O; emission; yield-scaled; NUE

Introduction

Fertilization of crops with nitrogen (N) contained in natural and/or mineral fertilizers is a common practice that has long been used in agriculture. It is due to the fact that the application of this element in a dose adapted to the plant's nutritional needs has a strong yielding effect. However, plants usually take up and process into yield production only a part of the nitrogen applied. The level of N uptake is plant species-specific and depends on numerous factors, especially N input, soil characteristics and weather conditions [1]. Recently, the efficiency of nitrogen utilization contained in applied fertilizers has been described by the following parameters: nitrogen yield (Yn), nitrogen use efficiency (NUE) and nitrogen surplus (Ns). It has been

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assumed that arable crops use in the most productive way the nitrogen contained in natural and/or mineral fertilizers when Yn>80 kg N ha^{-1}, NUE = 50-90% and Ns<80 kg N ha^{-1} [2]. Nitrogen surplus (Ns) may partially enrich the soil with ammonium nitrogen; however, most of it is lost by leaching into the water in the nitrate nitrogen form, or emitted to the atmosphere in the form of ammonia and/or nitrous oxide (N_2O). Nitrogen losses occurring in the waters contribute to their eutrophication, while gaseous losses cause an intensification of climate change advances. Agriculture, which is one of the major ammonia and N_2O emitters, is required to report these emissions and also to promote practices that limit the leaching and emission of nitrogen compounds to the environment [3, 4]. These activities are primarily aimed at reducing the environmental burden of potentially harmful reactive nitrogen compounds.

The purpose of this study was to determine the relationship between yield-scaled N_2O emissions from soils, on which winter wheat, grain maize and oilseed rape were grown, and nitrogen yield (Yn), nitrogen use efficiency (NUE) and nitrogen surplus (Ns). Moreover, the values of the above indicators of the efficiency of nitrogen utilization, considered desirable to ensure adequate efficiency of N utilization, were verified. It was hypothetically assumed that for all plant crops under study, characterized by diversified nitrogen demand, it is possible to describe the common regression equations.

Materials and Methods

Field experiments were carried out at two experimental stations of the Institute of Soil Science and Plant Cultivation – State Research Institute in Puławy, Poland between 2003 and 2013. Experiments were located in Baborówko, western Poland (19°12'E, 52°01'N), on loam (pseudopodzol and black earth) and in Grabów, eastern Poland (19°37'E, 52°37'N), on heterogeneous sandy loam and loam (brown type). In two factorial experiments, four crops were grown each year in the following rotation: winter oilseed rape – winter wheat – corn – spring barley. The first factor was P, K, Mg, and Ca fertilization in plus or minus variants, and the second one were six levels of N fertilizers applied in split doses. For almost 30 years no manure was applied to the field experiments. In our analysis we used data from treatments with the supply of P, K, Ca, Mg and the following rates of nitrogen (kg N ha^{-1}): oilseed rape – 150, winter wheat – 120 and corn – 150. The nitrogen doses were adapted to the average yields obtained for the conducted field experiment. The data used in our analyses included yields of main products (Yg, t ha^{-1}), yields of by-products (t ha^{-1}) and nitrogen content in main products (%). On the basis of these data, the nitrogen use efficiency parameters were estimated for grains.

Nitrogen utilization efficiency (NUE, %) was assessed by the formula according to the EU nitrogen expert panel [2]:

$$\mathrm{NUE} = \frac{\mathrm{Yn}}{\mathrm{F}} \times 100 \quad (1)$$

…where Yn (kg N ha^{-1}) – nitrogen yield and F (kg N ha^{-1}) – N dose plus N from soil deposition (14 kg ha^{-1}). Thus, defined NUE is usually interpreted as the efficiency of N uptake by plants.

Nitrogen yield (Yn, kg N ha^{-1}) was calculated by the formula:

$$\mathrm{Yn} = \text{grain yield} \times \text{N content in grains} \quad (2)$$

Nitrogen surplus (Ns, kg N ha^{-1}) was assessed by the formula according:

$$\mathrm{Ns} = \mathrm{F} - \mathrm{Yn} \quad (3)$$

Ns is usually interpreted as a partial nitrogen balance. In the crops located on arable lands, about 80-100% of Ns may leach into the waters [5].

To be able to use the presented parameters (Yn, NUE and Ns) in the evaluation of nitrogen fertilization efficiency, it was temporarily assumed that the desired values for them should be: Yn>80 kg N ha^{1}, NUE = 50-90% and Ns<80 kg N ha^{-1} [2].

Direct and indirect N_2O emissions from soil were calculated according to the IPCC tier 1 methodology [3] using a BIOGRACE spreadsheet [6]. In the calculations, the amount of nitrogen contributed by mineral fertilizers, nitrogen interception (natural manure was not used) and straw was included.

The yield-scaled N_2O emission (g N_2O_N kg^{-1} Yn) was estimated by the formula:

$$\mathrm{Eys} = \frac{\text{Emission kg } N_2O\text{_N ha}^{-1} * 1000}{\mathrm{Yn}} \quad (4)$$

Statistical analyses were performed for a total of three studied crop plants using Statgraphics Centurion software ver. 16.1.11.-

Results and Discussion

In the analyzed set, the corn yields (Yg) varied widely from 1.72 to 15.18 t ha^{-1}, with a median value of 8.11±2.21 t ha^{-1} (Median ± MAD) (Table 1). Nitrogen yields (Yn) were generally above the desired value of 80 kg N ha^{-1}, with a median of 124±28 kg N ha^{-1}. However, during the experiment period there were limiting factors (water availability), and reducing yields (weeds, diseases, and pests), which resulted in a minimum nitrogen intake of only 27.0 kg N ha^{-1}

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for the total nitrogen dose of 150 kg N ha^{-1} in the applied fertilizer. On the other hand, in yield-favorable conditions the N uptake reached a maximum value of 195 kg N ha^{-1}. The median NUE value (82.5±18.5%) was within the range of the desired values (50-90%). However, in some years the nitrogen dose was slightly too low because NUE was greater than 90%. It also indicates that plants took nitrogen stored in the soil repository (nitrogen mining). The surplus nitrogen (26.5±28.0 kg ha^{-1}) was in the range of the desired values. The median yield-scaled N_2O emission (Eys) was 18.9±2.7 g N_2O_N kg^{-1} Yn, with a minimum-maximum range of 12.1-67.8 g N_2O_N kg^{-1} Yn. In general, the applied nitrogen dose plus interception (150+14 kg N ha^{-1}) was slightly underestimated in relation to the maize fertilization needs; however, its increase could simultaneously lead to an unwanted increase in the Ns and Eys values.

The yields of winter wheat grain (Yg) in the analyzed collection varied from 2.51 to 8.62 t ha^{-1}, with a median value of 5.18±1.41 t ha^{-1} (Table 2). Nitrogen yields (Yn) were sometimes lower than the desired value (80 kg N ha^{-1}), with a median of 92±24 kg N ha^{-1}. Nevertheless, as in the case of maize, factors strongly limiting yield of grain and nitrogen occurred in some years during the field experiment. Consequently, the minimum Yn was only 44.0 kg N ha^{-1} for the total nitrogen dose of 120 kg N ha^{-1} in the applied fertilizer. On the other hand, in yield-favorable conditions the N intake reached a maximum value of 150 kg N ha^{-1}. The median NUE value (76±21%) was in the range of desirable values (50-90%). Nevertheless, in some years NUE was greater than 90%, which indicates that the dose of N used was slightly too low, and the plants used nitrogen accumulated in the soil. The median nitrogen surplus (Ns) value was 29±24 kg ha^{-1} and fitted to the range of desirable values. The median yield-scaled N_2O emission (Eys) was 22.4±4.1 g N_2O_N kg^{-1} Yn, with a min-max range of 15.8-38.0 g N_2O_N kg^{-1} Yn. In conclusion, it can be seen that winter wheat absorbed less total nitrogen than maize because in some years Yn for wheat was below 80 kg N ha^{-1}.

The yields of winter oilseed rape grains (Yg) in the analyzed collection oscillated between 1.25 and 4.62 t ha^{-1}, with a median value of 2.88±0.79 t ha^{-1} (Table 3). Estimated nitrogen yields (Yn) were higher than the desired value of 80 kg N ha^{-1}, with a median value of 98±23 kg N ha^{-1}. However, as in the case of

Table 1. Parameters of yields, nitrogen use efficiency and emissions for grain maize (n = 44).

Parameters	Yg	Yn	NUE	Ns	E	Eys
	(t ha^{-1})	(kg ha^{-1})	(%)	(kg ha^{-1})	(kg N_2O_N ha^{-1})	(g N_2O_N kg^{-1} Yn)
Median	8.11	123.5	82.5	26.5	2.31	18.9
MAD	2.21	28.0	18.5	28.0	0.20	2.70
Minimum	1.72	27.0	18.0	-45.0	1.60	12.1
Maximum	15.18	195.0	130	123.0	2.90	67.8

Table 2. Parameters of yields, nitrogen use efficiency and emissions for winter wheat (n = 44).

Parameters	Yg	Yn	NUE	Ns	E	Eys
	(t ha^{-1})	(kg ha^{-1})	(%)	(kg ha^{-1})	(kg N_2O_N ha^{-1})	(g N_2O_N kg^{-1} Yn)
Median	5.18	91.5	76.0	29.0	2.0	22.4
MAD	1.41	24.5	20.5	24.5	0.17	4.1
Minimum	2.51	44.0	37.0	-30.0	1.67	15.8
Maximum	8.62	150	125.0	76.0	2.42	38.0

Table 3. Parameters of yields, nitrogen use efficiency and emissions for oilseed rape (n = 44).

Parameters	Yg	Yn	NUE	Ns	E	Eys
	(t ha^{-1})	(kg ha^{-1})	(%)	(kg ha^{-1})	(kg N_2O_N ha^{-1})	(g N_2O_N kg^{-1} Yn)
Median	2.88	97.5	64.5	53.0	2.27	24.0
MAD	0.79	23.0	15.0	22.5	0.17	3.7
Minimum	1.25	42.0	28.0	-11.0	1.48	16.2
Maximum	4.62	161.0	107.0	108.8	2.65	46.8

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maize and wheat, factors strongly limiting yield of grain and nitrogen occurred in some years during the field experiment. This resulted in a minimum Yn of only 42.0 kg N ha^{-1} for the total nitrogen dose of 150 kg N ha^{-1} in the applied fertilizer. In turn, under good yielding conditions the intake was up to 161 kg N ha^{-1}. The median NUE (64.5±15%) and Ns (53±22 kg N ha^{-1}) values were well within the range of desired values. The median yield-scaled N_2O emission (Eys) value was 22.4±4.1 g N_2O_N kg^{-1} Yn, with a min-max range of 15.8-38.0 g N_2O_N kg^{-1} Yn. In summary, the applied nitrogen dose plus interception (150+14 kg N ha^{-1}) was sufficiently adjusted to the fertilizer needs of oilseed rape.

The presented data (Tables 1-3) were characterized by sufficient variability for conducting the intended analyses. The nitrogen yield-forming effects estimated on their basis were as follows: 14.2, 17.9 and 32.9 kg of grain kg^{-1} N for maize, winter wheat and winter oilseed rape, respectively. The above values were slightly better than the average values given for large datasets (15.5, 18.9 and 33.6 kg of grain kg^{-1} N for maize, winter wheat and winter oilseed rape, respectively).

The regression between yield-scaled N_2O emissions from soil (Eys) and nitrogen yield (Yn) was described by a reciprocal-X model according to the equation $Eys = a + \frac{b}{Yn}$ (Fig. 1). The curve was well adjusted, as indicated by the high value of its coefficient of determination (R^2 = 95.1%). According to the regression equation, for the desired nitrogen yield value (Yn>80 kg N ha^{-1}), the Eys values will be ≤25.6 g N_2O_N kg^{-1} Yn.

The regression between Eys and NUE was described by the same type of model based on the equation $Eys = a + \frac{b}{NUE}$ (Fig. 2). The coefficient of determination was R^2 = 97.0%, showing a good curve fitting, and the Eys values estimated from the curve ranged from 28.3 to 18.6 g N_2O kg^{-1} Yn for the desired NUE value (50-90%).

The regression between Eys and Ns was also described by reciprocal-Y model based on the equation $Eys = \frac{1}{a - b * Ns}$ (Fig. 3). The coefficient of determination was R^2 = 88.3%, indicating a good curve fitting. The regression curve showed that for Ns>80 kg N ha^{-1} the emission values (Eys) increase rapidly. For Ns values lower than 80 kg N ha^{-1} the Eys values were below 30.9 g N_2O_N kg^{-1} Yn.

A farmer with the best own economic interest and for environmental reasons should potentially be willing to keep nitrogen surplus (Ns) as low as possible. In the simplest way, it can be implemented by applying nitrogen doses according to the current fertilizer recommendations. For the nitrogen doses used in our field experiment, where the long-term variability of the nitrogen application efficiency characteristics was random, maintaining nitrogen surplus at 39±6.27 kg N ha^{-1} provided yields in the range of 54-60% of the relative maximum harvest (Fig. 4). Thus, our results confirm that efforts aimed at improving the economic efficiency of crop fertilization are consistent with measures to protect the environment, water quality, and climate.

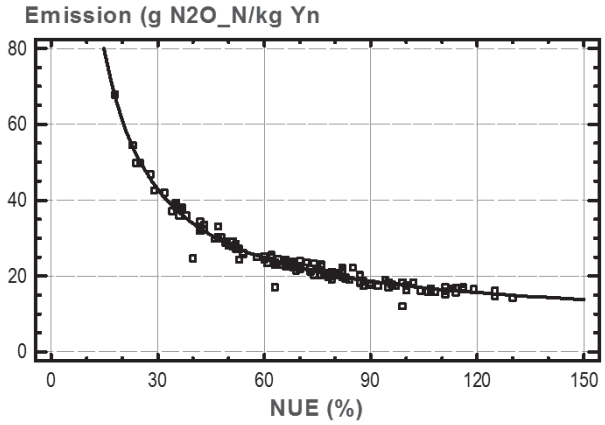

Fig. 2. Regression between yield-scaled N_2O_N emissions (Eys) and nitrogen use efficiency (NUE) (Eys = 6.52 + 1091/NUE).

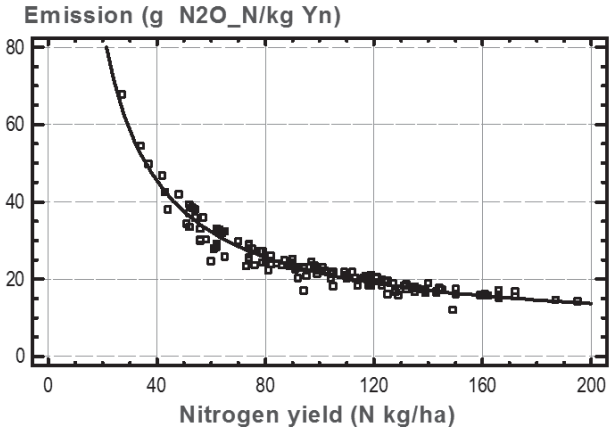

Fig. 1. Regression between yield-scaled N_2O_N emissions (Eys) and nitrogen yield (Yn) (Eys = 5.78 + 1587/Yn).

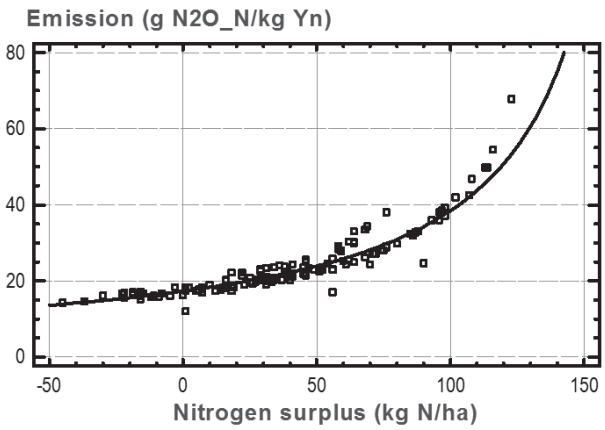

Fig. 3. Regression between yield-scaled N_2O_N emissions (Eys) and nitrogen surplus (Ns) (Eys = 1/(0.0577 – 0.000317* Ns).

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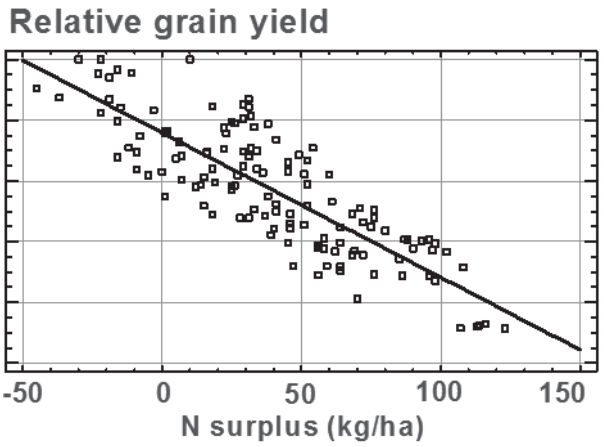

Fig. 4. Regression between relative grain yield (seeds) (Yg relative) and nitrogen surplus (Ns, kg ha^{-1}) (Yg relative = 0.759 - 0.00477*Ns; r^2 = 69.5%).

In 2015, N_2O emissions accounted for 4.9% of total greenhouse gas (GHGs) emissions in Poland [7]. The main sources of nitrous oxide emissions were agricultural land (67.0%) and manure management (11.0%). Hence, agriculture generated 78% of the total emissions of N_2O in 2015. Due to the fact that this gas has a heat equivalent of 298 times higher than carbon dioxide, its emission contributes to the reduction of ozone in the stratosphere and significantly impacts climate change [4]. It is therefore understandable that attempts are being made to limit N_2O emissions in agriculture due to the need to mitigate climate change.

Nitrous oxide emissions from agricultural land depend on several factors such as climate, soil granulometric composition, organic carbon content, and dose and type of applied fertilizer [8, 9]. Moreover, it has been found that emissions are clearly increasing as a result of the application of mineral and/or natural fertilizers [10-12]. The rate of this increase depends on the processes of nitrification and denitrification of nitrogen in the soil. These processes take place due to the activity of soil microorganisms and are part of the natural cycle of nitrogen transformation. Although the farmer has no direct impact on this cycle and N_2O emissions, they can indirectly affect them by increasing NUE. This can be achieved by adapting an appropriate nitrogen dose to the fertilizing needs of the plant crops. For this purpose, commonly available systems of fertilizer recommendations and the long-term analysis of nitrogen use efficiency parameters can be helpful [2].

The conducted research shows that the methods of effective limiting of N_2O emissions from fertilized soils are consistent with the activities promoting agronomic efficiency in general [13]. On the basis of the results of 19 studies, it was found that the yield-scaled N_2O emissions (expressed as g N_2O_N per kg aboveground N uptake) are the lowest at medium N doses [14]. For example, a meta-analysis showed that at N dose of 150-200 kg N ha^{-1} the yield-scaled N_2O emissions decreased by 37% in comparison to the non-fertilized control for rice cultivated in China [15]. Moreover, the lowest emissions from soil were observed for N doses between 100 and 150 kg of N ha^{-1} in sub-Saharan Africa farming [16]. In general, the results of the above studies showed that the N dose that guarantees the optimal yield can simultaneously minimize yield-scaled N_2O emissions from soil. This conclusion is very important because it contradicts the view that the only possible way to limit N_2O emissions is to reduce nitrogen fertilizer dose. Furthermore, analysis of Eys is relevant in view of the global challenges of increasing food production and decreasing emissions concomitantly [17-19].

Despite the fact that recently the number of studies on yield-scaled N_2O emissions have recently increased [14, 15, 19-22], studies on the relationship between Eys and nitrogen efficiency characteristics are still rare. One of the few examples of this type of research is the meta-analysis of the correlation between yield-scaled N_2O emissions and nitrogen surplus and nitrogen use efficiency as described by van Groenigen et al. [13]. The authors used data from 19 publications (147 observations) to estimate the relationship between Eys (expressed as g N_2O_N per kg^{-1} aboveground N uptake) and Ns and NUE. As a result, they found that the regression between Eys and Ns was curvilinear. The emission nearly didn't increase in the range of Eys between -150 and 10 kg N ha^{-1}, then it continued to grow rapidly curvilinear. Eventually, above the Ns value of 90 kg N ha^{-1} N_2O emissions increased threefold.

Our analyses were performed for nitrogen fertilizer doses of 120-150 kg N ha^{-1}, which according to literature should provide the lowest Eys [15, 16]. The field experiment was conducted over a period of 12 years on the same light soils. Hence, the variability of yield (Yg and Yn), NUE and Ns were caused by the random yield-forming conditions.

In our study, the relationship between Eys and Ns was found to be quite similar to that described by van Groenigen et al. [13] (Fig. 3). In the Ns range from -50 to 10 kg N ha^{-1}, the emission increased by less than 1 g N_2O_N kg^{-1} Yn. Subsequently, curved and larger Eys increments started after exceeding Ns = 50 kg N ha^{-1} (Fig. 3). In the study of van Groenigen et al. [13] the relationship between Eys and NUE was a negative linear regression in the NUE range of 20-75%. In turn, in our research the range of NUE's variability was broader (18-130%), and the obtained dependence was non-linear (Fig. 2). As shown in Figure 2, Eys was the lowest at NUE value close to 90%.

In conclusion, our analyses, based on extensive data from the field experiment, demonstrated that the expected values of Yn, NUE, and Ns proposed by EU NEP [2] can also be regarded as the nitrogen efficiency characteristics that reduce the yield-scaled N_2O emissions from soil. Moreover, it was found that the reduction of nitrogen surplus, and thus the Eys, was linked to an increase in relative grain yields (Fig. 4). Our results confirm the thesis of van Groenigen et al. [13],

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according to which actions aimed at effective reduction of N_2O emissions from fertilized soils are coherent with methods promoting the agronomic effectiveness of fertilization in general.

Conclusions

Temporarily determined desired values of nitrogen yield (Yn>80 kg N ha^{-1}), nitrogen use efficiency (NUE = 50-90%) and nitrogen surplus (Ns<80 kg N ha^{-1}) can be considered as nitrogen efficiency characteristics limiting yield-scaled N_2O emissions (Eys) from soils. Our research showed that nitrous oxide emissions for desired parameters Yn, NUE and Ns were ≤25.6, 28.3-18.6 and ≤30.9 g N_2O_N kg^{-1} Yn, respectively. The estimated emissions were 1.5-2.6 times higher than the minimum emissions and 2.2-3.6 times lower than the maximum in the analyzed data series. In conclusion, according to our results, keeping the surplus nitrogen as low as possible, which is important for environmental protection, does not have to result in yield reduction. On the contrary, it may lead to their growth.

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Conflict of Interest

The authors declare no conflict of interest.

References

1. MASCLAUX-DAUBRESSE C., DANIEL-VEDELE F., DECHORGNAT J., CHARDON F., GAUFICHON L., SUZUKI A. Nitrogen uptake, assimilation and remobilization in plants: challenges for sustainable and productive agriculture. Annals of Botany, **105** (7), 1141, **2010**.
2. EU NITROGEN EXPERT PANEL. Nitrogen Use Efficiency (NUE) an indicator for the utilization of nitrogen in food systems. Wageningen University, Alterra, Wageningen, Netherlands. **2015**.
3. IPCC. N_2O Emissions From Managed Soils, and CO_2 Emissions From Lime and Urea Application. In Guidelines for National Greenhouse Gas Inventories, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (Eds.), Japan, IGES, **2006**.
4. IPCC. Climate change 2007: The physical science basis. Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H.L. (Eds.). Cambridge University Press, Cambridge, **2007**.
5. BILLEN G., LASSALETTA L., GARNIER J. Some conceptual and methodological aspects of NUE of agro-food systems. The note at the attention of the EU N-expert panel. Windsor, Sept 15-16, **2014** [manuscript].
6. BIOGRACE, Harmonised Calculation of Biofuel Greenhouse Gas Emission in Europe. 2015. Available online: http://www.biograce.net/content/ghgcalculationtools/recognisedtool (accessed on 02.03.2018).
7. OLECKA A., BEBKIEWICZ K., CHŁOPEK Z., JĘDRYSIAK P., KANAFA M., KARGULEWICZ I., RUTKOWSKI J., SĘDZIWA M., SKOŚKIEWICZ J., WAŚNIEWSKA S., ŻACZEK M. Poland's National Inventory Report 2017. Greenhouse gas inventory for 1988-2015. Submission under the UN Framework Convention on Climate Change and its Kyoto Protocol., Warsaw, KOBiZE, 559, **2017**.
8. BOUWMAN A.F., BOUMANS L.J.M., BATJES N.H. Emissions of N_2O and NO from fertilized fields: Summary of available measurement data. Global Biogeochem. Cycle, **16** (4), 6, **2002**.
9. BUTTERBACH-BAHL K., BAGGS E. M., DANNENMANN M., KIESE R., ZECHMEISTER-BOLTENSTERN S. Nitrous oxide emissions from soils: how well do we understand the processes and their controls? Philosophical Transactions of the Royal Society B: Biological Sciences, **368** (1621), 20130122, **2013**.
10. BOUWMAN A.F. Direct emission of nitrous oxide from agricultural soils. Nutrient Cycling in Agroecosystems, **46** (1), 53, **1996**
11. FORSTER P., RAMASWAMY V., ARTAXO P., BERNTSEN T., BETTS R., FAHEY D., HAYWOOD J., LEAN J., LOWE D. C., MYHRE G., NGANGA J., PRINN R., RAGA G., SCHULZ M., VAN DORLAND R. Changes in atmospheric constituents and in radiative forcing. In: Climate Change 2007: The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change; Solomon S., Qin D., Manning M., Chen Z., Marquis M., Averyt K.B., Tignor M., Miller H. L. (Eds.). United Kingdom and New York, IPCC, 129, **2007**.
12. SNYDER C. S., BRUULSEMA T. W., JENSEN T.L., FIXEN P.E. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. Agriculture, Ecosystems and Environment, **133** (3-4), 247, **2009**.
13. VAN GROENIGEN W. J., OENEMA O., VAN GROENIGEN K. J., VELTHOF G., VAN KESSEL C. Best Nitrogen Management Practices to Decrease Greenhouse Gas Emissions. Better Crops, **95 (**2), 16, **2011**.
14. QIN S., WANG Y., HU C., OENEMA O., LI X., ZHANG Y., DONG W. Yield-scaled N_2O emissions in a winter wheat-summer corn double-cropping system. Atmospheric Environment, **55**, 240, **2012**.
15. FENG J., CHEN C., ZHANG Y., SONG Z., DENG A., ZHENG C., ZHANG W. Impacts of cropping practices on yield-scaled greenhouse gas emissions from rice fields in China: A meta-analysis. Agriculture, Ecosystems and Environment, **164**, 220, **2013**.
16. KIM D.G., THOMAS A.D., PELSTER D., ROSENSTOCK T.S., SANZ-COBENA A. Greenhouse gas emissions from natural ecosystems and agricultural lands in sub-Saharan Africa: Synthesis of available data and suggestions for further research. Biogeosciences **13**(16), 4789, **2016**.
17. FOLEY J.A., RAMANKUTTY N., BRAUMAN K.A., CASSIDY E.S., GERBER J.S., JOHNSTON M.,

MUELLER N.D., O'CONNELL C., RAY D.K., WEST P.C., BALZER C., BENNETT E.M., CARPENTER S.R., HILL J., MONFREDA C., POLASKY S., ROCKSTRÖM J., SHEEHAN J., SIEBERT S., TILMAN D., ZAKS D.P. Solutions for a cultivated planet. Nature, **478** (7369), 337, **2011**.

18. VAN KESSEL C., VENTEREA R., SIX J., ADVIENTO-BORBE M.A., LINQUIST B., VAN GROENIGEN K.J. Climate, duration, and N placement determine N_2O emissions in reduced tillage systems: A meta-analysis. Global Change Biology, **19** (1), 33, **2013**.
19. SAINJU U.M. A global meta-analysis on the impact of management practices on net global warming potential and greenhouse gas intensity from cropland soils. PLoS ONE, **11** (2), 1, **2016**.
20. MOSIER A.R., HALVORSON A.D., REULE C.A., LIU X.J. Net global warming potential and greenhouse gas intensity in irrigated cropping systems in northeastern Colorado. Journal of Environment Quality, **35** (4), 1584, **2006**.
21. VENTEREA R.T., BIJESH M., DOLAN M.S. Fertilizer source and tillage effects on yield-scaled nitrous oxide emissions in a corn cropping system. Journal of Environment Quality, **40** (5), 1521, **2011**.
22. PITTELKOW C.M., ADVIENTO-BORBE M.A., HILL J.E., SIX J., VAN KESSEL C., LINQUIST B.A. Yield-scaled global warming potential of annual nitrous oxide and methane emissions from continuously flooded rice in response to nitrogen input. Agriculture, Ecosystems and Environment, **177**, 10, **2013**.

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