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ORIGINAL ARTICLE

Direct N_2O emission from agricultural soils in Poland between 1960 and 2009

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Abstract Nitrogen fertilization (N) is commonly known as a main source of direct nitrous oxide (N_2O) emission from agricultural soils. An area of 38 % of the total land surface of Poland was covered by agricultural soils in 2009. In this paper, we aimed at analyzing data regarding the land exploitation for 13 selected subareas of Poland between 1960 and 2009. Seven out of the 13 subareas studied are located in the West (area A), and six subareas are located in southeast of Poland (area B). The total area covered by large farms (>20 ha) differed largely, between area A (10.6 %) and area B (0.9 %) in 2009. Both areas varied in terms of the amount of fertilizers used annually, average crop yield and crop structure. Average direct emissions of N_2O from agricultural soils were 1.66 ± 0.09 kg N_2O–N ha^{-1} a^{-1} for area A, 1.39 ± 0.07 kg N_2O–N ha^{-1} a^{-1} for area B and 1.46 ± 0.07 kg N_2O–N ha^{-1} a^{-1} for the whole country between 1960 and 2009.

Keywords Fertilization · Yield · Structure of crops · IPCC methodology

Introduction

The increase in nitrous oxide (N_2O) emission observed from the beginning of the industrial era is most likely to continue in the future (Galloway et al. 2004). N_2O is an atmospheric trace gas belonging to the four major greenhouse gases (GHG), besides water vapor (H_2O), carbon dioxide (CO_2) and methane (CH_4). Nitrous oxide is important due to its global warming potential (GWP) of 298 on a per mass basis (vs. 1 for CO_2) and lifetime of 114 years (the longest of the four GHGs) (Forster et al. 2007). In pre-industrial times (before 1750), the concentration of N_2O in the atmosphere was 270 ppbv (Forster et al. 2007) and has increased to about 322 ppbv until now (WMO 2009). This situation results from the increase in the consumption of nitrogen compounds in fertilization processes (IPCC 2000). Accordingly, larger N_2O concentrations in the atmosphere are a threat to the climate system since N_2O is further responsible for the depletion of the ozone layer in the stratosphere (Crutzen 1970; Crutzen et al. 2007; Ravishankara et al. 2009). Therefore, the reduction in N_2O emissions has become an essential need (Bell et al. 2011). The main sources of N_2O emissions are terrestrial soils and the oceans (Denman et al. 2007; EPA 2010). Natural sources account for 11.0 Tg N_2O–N a^{-1} of

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the emissions, including 6.6 Tg N a^{-1} from soils under natural vegetation. Anthropogenic sources contribute as much as 6.7 Tg N a^{-1}, with the biggest part originating from agriculture (2.8 Tg N a^{-1}, Denman et al. 2007). In the pre-industrial era, about one-third of the total N_2O emission was emitted by the oceans whereas two-thirds originated from terrestrial soils (Fluckiger et al. 2004). Up to date, ocean emissions account for merely a fifth of the total annual emissions, i.e., ~3.8 Tg N a^{-1} out of 17.7 Tg N a^{-1} (natural and anthropogenic) (Suntharalingam and Sarmiento 2000; Denman et al. 2007).

Arable soils among the largest anthropogenic N_2O emitters include cultivated organic soils, drained soils and soils which are either treated with organic or mineral fertilizers (Freney 1997; Rees et al. 2012; Smith et al. 2007). A variety of physical and chemical processes occur in such soils and the most well known are nitrification (ammonia oxidation), denitrification (nitrate reduction) and nitrifier denitrification (Mosier et al. 1998; Mihailovic et al. 2012; Robertson and Groffman 2007).

The provision of nitrogen is a result of its limiting role as a nutrient in intensive cultivation systems (Robertson and Vitousek 2009). Optimization of nitrate fertilization in order to increase crop productivity (Mosier et al. 2001) is a typical phenomenon of contemporary agriculture. Such increases in productivity can be induced by (1) changing the amount of synthetic fertilizers applied, (2) by increasing the amount of leguminous plants in the crop structure (e.g., clover and alfalfa) and (3) by using organic fertilizers (e.g., manure). Today, most crop cultivation systems are based on large doses of fertilizers ensuring the high availability of nitrogen for plants. The consequence of higher yields are bigger amounts of post-harvest residues, which constitute an essential part of organic matter. Due to the high content of organic carbon, these residues may return to the soil and improve its physical, chemical and biological properties (Mary et al. 1996; Kumar and Goh 1999; Bhupinderpal and Rengel 2007). However, a negative consequence of fertilizer application are higher nitrous oxide emissions from soils (Bouwman et al. 1993).

The combination of organic and synthetic fertilizers together with post-harvest residues left in the field are the most important sources of N_2O emission from agricultural soils (IPCC 2000, 2006). In 2009, more than 38 % of the surface of Poland was exploited as agricultural land (GUS—Central Statistical Office in Poland: http://www.stat.gov.pl; access 12.10.2012), indicating that one-third of the total surface of Poland can be considered as a potential source of N_2O emissions.

The methodology recommended by the IPCC (TIER 1 approach) to calculate N_2O emissions requires annual data from national statistics such as mineral and organic fertilization (content of nitrogen), crop yields and crop structure. Unlike the numeric models, which provide more detailed data, it is a much faster and more easily applicable approach to calculate emissions (Olejnik et al. 2001; Butterbach-Bahl et al. 2009; Mihailovic et al. 2009; Lesny 2011). However, significant simplifications such as neglecting meteorological conditions, the types of fertilizers used similar to the agricultural engineering applied, as well as detailed soil characteristics and methods of farm management can lead to uncertain results. To our knowledge, it has not been reported yet how much N_2O is emitted from the agricultural sector in Poland. Therefore, we aim within this paper to (1) quantify current N_2O emission from agriculture subregions of Poland and (2) identify the change in N_2O emissions by comparing current emissions to emissions from the 1960.

Materials and methods

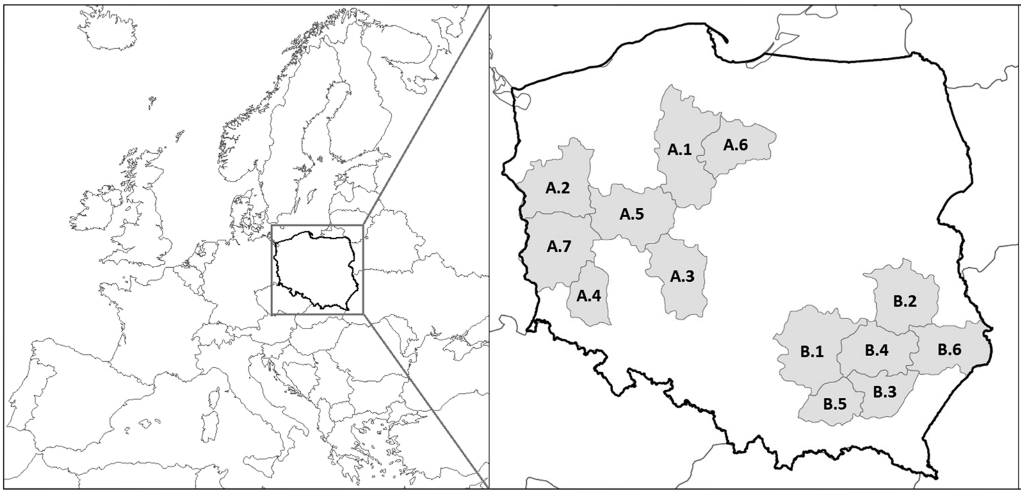
Data collection

The analysis was based on yearly data of land exploitation during 1960–2009 for each of the former provinces and were obtained from publications of the Central Statistical Office (CSO). Statistical data used in this paper were shown in the Table 1 (CSO 1966, 1967a, b, c, 1970, 1971, 1976, 1978, 1982, 1985, 1986, 1987, 1990, 1992a, b, 1993, 1994a, b, 1995, 1996, 1997, 1998, 1999a, b, 2000, 2001a, b, 2002, 2003, 2004, 2005a, b, 2006a, b, 2007a, b, 2008a, b, 2009a, b, 2010).

Thirteen selected subareas were included in this study (former provinces), seven from western Poland (area A) and six from southeastern Poland (area B) (Fig. 1). The total area covered by small farms (<20 ha) was largely different, with 10.6 and 0.9 % for areas A and B, respectively, for the year 2009. Moreover, both areas varied in the amount of fertilizers used annually, average crop yields and crop structure.

Table 1 Parameters obtained from national statistics used in this study

Parameter	Unit
Nitrogen in synthetic fertilizers	kg N ha^{-1} a^{-1}
Nitrogen in organic fertilizers	kg N ha^{-1} a^{-1}
Crop yields (cereals, potatoes, beets, rape, maize)	Mg ha^{-1} a^{-1}
Crop structure (cereals, potatoes, beets, rape, maize)	%
Structure of cereals (oat, barley and wheat together with rye)	%
Percentage of area under crop production	%



Name	Longitude	Latitude
	A	
A.1	17° 56' E	53° 14' N
A.2	15° 19' E	52° 45' N
A.3	17° 51' E	51° 38' N
A.4	16° 03' E	51° 21' N
A.5	16° 52' E	52° 24' N
A.6	19° 00' E	53° 17' N
A.7	15° 21' E	51° 56' N
	B	
B.1	20° 34' E	50° 44' N
B.2	22° 24' E	51° 19' N
B.3	21° 54' E	50° 08' N
B.4	21° 49' E	50° 39' N
B.5	20° 56' E	50° 00' N
B.6	23° 17' E	50° 39' N

Fig. 1 Location of the selected areas and subareas analyzed in this study in Poland

The borders of subareas were defined according to the former administrative division into provinces in the years 1975–1998. This division was effective for about half of the analyzed period and has convenient records concerning agricultural data. Earlier and later (1960–1974 and 1999–2009, respectively) data used were obtained from the official administrative divisions assuming that the percentage of particular crops in the overall crop structure of agricultural soils did not change.

Methods

The methodology we used in this study was described in the Good Practice Guidance (IPCC 2000) and Guidelines for National Greenhouse Gas Inventories published by the IPCC (2006). Estimates of direct emissions of N_2O from agricultural soils were calculated as given in Eq. 1:

$$\mathrm{N_2O - N_{(Direct)} = N_2O - N_{(Fertilizers)} + N_2O - N_{(Animalmanure)} + N_2O - N_{(Cropresidues)}}, \quad (1)$$

where $N_2O–N_{(Direct)}$ presents the direct losses if nitrogen via N_2O emissions from agricultural soils, $N_2O–N_{(Fertilizers)}$ are the emission from synthetic fertilizers application, $N_2O–N_{(Animal\ manure)}$ are the emission from animal manure used as fertilizer and $N_2O–N_{(Crop\ residues)}$ are the emission from crop residues. We used also standard emission factors $EF = 0.01$ (Online Resource 1). When calculating the average value for areas A and B, we used the weighted average for the arable surface in the subareas.

Upscaling of the emissions for the whole of Poland was achieved by collecting data from all 49 provinces that were effective in 1977, which was chosen due to the highest amount of available data. We assume that the areal emission changeability in the 1977 will be the same for the whole period of 1960–2009 and that the value of emission in individual provinces will be proportionate to the mean from the thirteen subareas studied. Based on these assumption, Eq. (2) was determined.

$$M_{\mathrm{Y}} = \frac{A_{\mathrm{Y}} \times M_{1977}}{A_{1977}}, \quad (2)$$

where M_{Y} is the amount of pollution from an area (M)—in this case the agricultural area of Poland—in the year (Y), and A_{Y} means the average emission for areas A and B in year Y.

Uncertainty estimation

Uncertainties in the estimations of direct N_2O emission from agricultural soils occur due to several reasons: (1) the inaccuracy of statistical data, (2) inaccuracy of N_2O emission factor from the applied nitrogen and (3) the equation for aboveground dry matter residues (Online Resource 1) (Bouwman et al. 2002a, b; IPCC 2006; Stehfest and Bouwman 2006).

Description of the areas A and B

Due to historical developments, the two areas differed in the structure of the farms. In area A, 10.6 % (57 % of the area A) of the farms manage an area that is exceeding 20 ha (2009). This situation results from the most important change in Polish agriculture after World War II in 1949 (Banski 2007). The first state-owned collective farms in Poland were created in area A during this time. These collective farms were established on the great territories of former German estates, in particular in northern and western Poland, where the state-owned collective farms accounted for more than 50 % of the total arable land of Poland in the 1980s.

In contrast, in area B, only 0.9 % of the farms (20 % of the area B) are bigger than 20 ha. This is due to huge fragmentation of farms, a consequence of parents' bequests of land to children, which in many cases led to a division of big farms into a number of smaller ones. In this part of Poland, state-owned collective farms did not play an important role in the second half of the twentieth century. The only exception was subarea B.6. After the transformation of the political and economic system in 1989, state-owned collective farms were closed. Still the location and size of the farms did not change. A result of the diversity in the size of farms in western Poland was the intensification of crop cultivation compared to the southeastern part of the country. The differences involve crop structure, the amount of fertilization and consequently also crop yields.

Results

Inorganic nitrogen fertilization

Between 1960 and 2009, the average application of mineral fertilizers applied in area A was 64.36 kg N ha^{-1} a^{-1} (Fig. 2a), which is about 1/3 more than in area B (Fig. 2b), where the average fertilization rate between 1960 and 2009 was 39.52 kg N ha^{-1} a^{-1}. The average application of mineral fertilizers applied in the whole of Poland was 58 kg N ha^{-1} a^{-1} (1970–2009).

Nitrogen fertilizer application in the analyzed areas was correlated with the overall consumption of synthetic nitrogen fertilizer in the territory of Poland (source for national data: faostat.fao.org). The correlation coefficients were 0.85 for area A and 0.87 for area B, respectively (Online Resource 2).

Organic fertilizers

The overall average use of organic fertilizers between 1960 and 2009 was 22.88 kg N ha^{-1} a^{-1} in area A (Fig. 3a) and 20.51 kg N ha^{-1} a^{-1} in area B (Fig. 3b), respectively.

Crop yields

The increased application of fertilizers in area A led to larger yields than in area B (Online Resource 3). The average annual cereal yield was 2.86 Mg ha^{-1} a^{-1} in area A between 1960 and 2009, compared to lower values in area B amounting to 2.48 Mg ha^{-1} a^{-1}. Additional data are given in Online Resource 3.

Crop structure

Between 1960 and 2009, a 10 % increase in cereals in the total crop structure was observed, in both areas (A and B, Fig. 4), from 68.4 to 75.3 % in 1960 to 79.8 to 86.7 % in 2009, respectively. This increase occurred simultaneously with decline in potato production. In 1960, potatoes accounted for as much as 23.5 % in area A and 21.7 % in area B. After 50 years (2009), these areas have decreased dramatically to 3.6 % in area A and 6.7 % in area B, respectively. Additional data for crop structure are given in Online Resource 4.

Components of total direct emission

Total direct emissions consist of six separate components (additional data are given in Online Resource 5). Five of them involve emissions from post-harvest residue of individual plants left on the fields annually (cereals, potatoes, beetroots, maize, and rape). The final sixth component involves the emission resulting from nitrogen (mineral and organic) fertilization. The shares of individual components in total emission in the period 1960–2009 varied considerably, with cereals contributing more than one-third to the total annual emissions (Table 2). Emission from maize and rape were lowest, and the overall largest contribution to the total emissions originated from fertilization.

Larger use of mineral fertilizers led to a 12.2 % increase in N_2O–N emission between 1960 and 2009 in area A. In contrast, emissions originating from fertilization were comparable between 1960 and 2009 in area B (41.8 and 40.9 %, respectively).

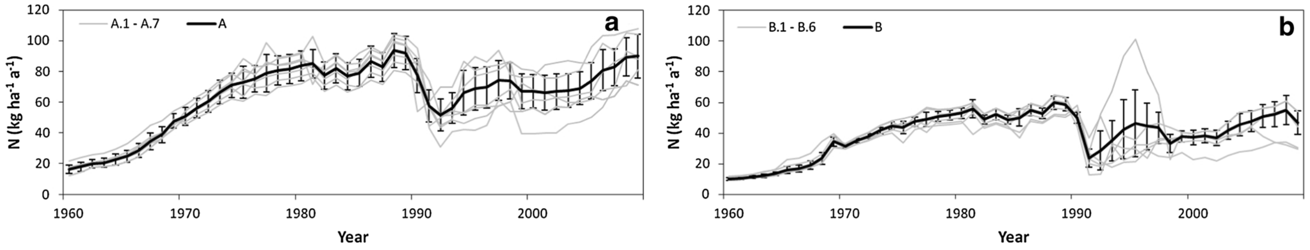


Fig. 2 Application of mineral fertilizers in areas A (**a**) and B (**b**) from 1960 to 2009. *Bars* indicates 95 % confidence interval (A: $n = 7$; B: $n = 6$)

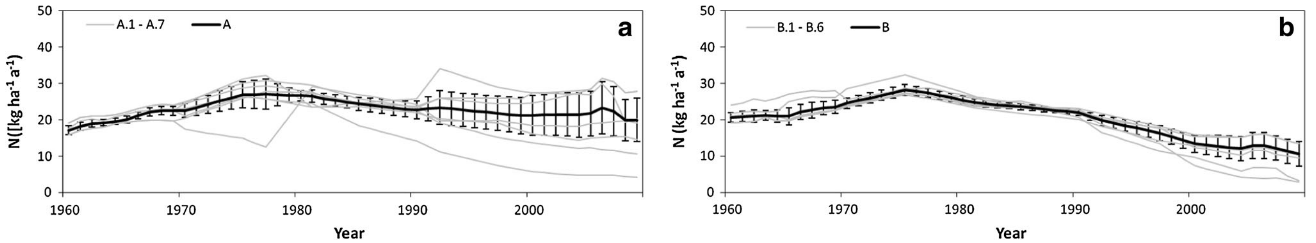


Fig. 3 Application of organic fertilizers in areas A (**a**) and B (**b**) in the period 1960–2009. *Bars* indicates 95 % confidence interval (A: $n = 7$; B: $n = 6$)

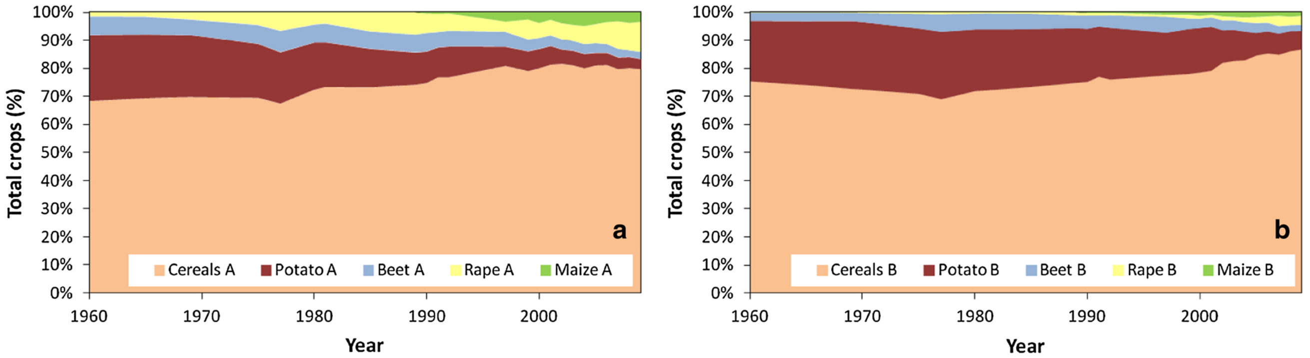


Fig. 4 Crop production (%) separated by type (color coding) in areas A (**a**) and B (**b**) between 1960 and 2009

Table 2 Contribution to total N_2O–N emissions from different components between 1960 and 2009

Area	Components (%)					
	Cereals	Potato	Beet	Maize	Rape	Fertilizers
A	36.8	5.5	2.5	1.6	1.5	52.1
B	44.8	9.0	2.2	0.7	0.3	43.0

A comparison of 1960 and 2009 (Table 3) allows a conclusion that the share of emission components from beetroot and potato crops decreased in both the analyzed areas due to a substantial drop in the area covered by these crops. Emissions from cereals increased significantly in area B and only slight increases were found for area A. The contribution of fertilization originating N_2O–N emissions to total N_2O–N emissions showed an upward trend in both areas. Similar to the pattern found over the years for yields: small reductions in N_2O–N fertilizer emissions were found in 1991 and 1993 in areas A and B, respectively. In 1960, 0.33 kg N_2O–N ha^{-1} were emitted due to fertilizer application. The slump of emission in area A occurred in 1992, when the emissions were 1.00 kg N_2O–N ha^{-1}, whereas were only 0.75 kg N_2O–N ha^{-1} in 1992. In the following years, emissions increased, reaching a maximum value of 1.10 kg N_2O–N ha^{-1} in 2009. Area B was characterized by 0.31 kg N_2O–N ha^{-1} emissions originating from fertilization in 1960. During the following years, an increase was recorded until 1988, when the emissions were as high as 0.82 kg N_2O–N ha^{-1} a^{-1}. Thereafter, the emission decreased and reached a value of 0.45 kg N_2O–N ha^{-1} in 1991. In the following years, the emission fluctuated between the values calculated for 1991–0.66 kg N_2O–N ha^{-1} in 2008. Area B emitted on average 0.60 kg N_2O–N ha^{-1} a^{-1} between the years 1960 and 2009.

Total direct nitrous oxide emission from agricultural soils

The calculated total direct emission of N_2O–N from agricultural soils show larger values for area A than for area B. Between 1960 and 2009, average emissions were as large as 1.66 kg N_2O–N ha^{-1} a^{-1} (Fig. 5a). In 1960, emissions were as low as 0.84 kg N_2O–N ha^{-1}. A relatively sudden increase in N_2O–N emission occurred between 1970 and 1974 reaching 1.77 kg N_2O–N ha^{-1}. Emissions continued to increase until 1989 even though at a much smaller rate (2.05 kg N_2O–N ha^{-1} in 1989). With the political changes in 1989, a sudden decrease was observed and emissions were as low as 1.39 kg N_2O–N ha^{-1} in 1992. Thereafter, considerable fluctuations of emission were observed with a slight upward trend until 2009 (2.12 kg N_2O–N ha^{-1} in 2009).

Total direct N_2O–N emission from agricultural soils in area B were on average 1.39 kg N_2O–N ha^{-1} a^{-1} between 1960 and 2009 (Fig. 5b). Values are 0.27 kg N_2O–N ha^{-1} a^{-1} less than the values calculated for area A. Average

Table 3 Contribution [%; kg] of the different components to total emissions of N_2O–N in 1960 and 2009

Year	Cereals		Potato		Beet		Maize		Rape		Fertilizers	
	A	B	A	B	A	B	A	B	A	B	A	B
Components (%)												
1960	40.6	41.7	14.7	14.0	4.6	2.5	0.0	0.0	0.5	0.0	39.6	41.8
2009	40.0	52.1	1.3	3.2	1.4	1.7	1.8	1.0	3.7	1.1	51.8	40.9
Components from crops/fertilizers (kg of N_2O–N ha^{-1} a^{-1})												
1960	0.50	0.40	0.52	0.47	0.57	0.62	0.00	0.00	0.32	0.30	0.33	0.31
2009	1.06	0.85	0.78	0.69	1.15	1.16	1.06	1.02	0.74	0.51	1.10	0.58

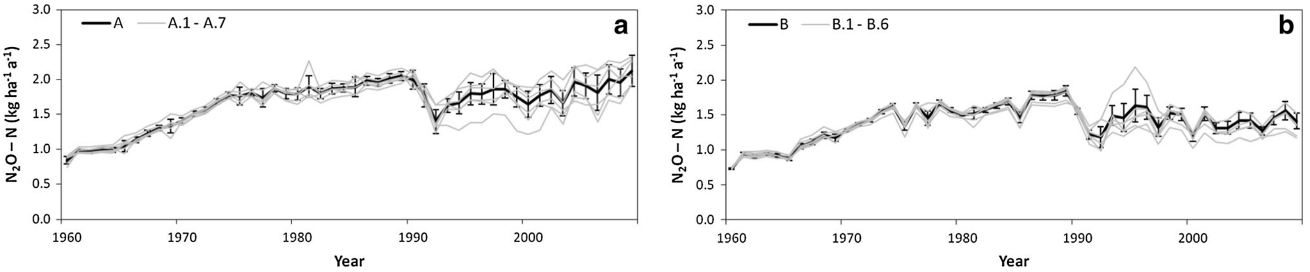


Fig. 5 Total direct emissions of N_2O–N from agricultural soils (kg ha^{-1} a^{-1}) for areas A (**a**) and B (**b**) between 1960 and 2009. *Bars* indicates 95 % confidence interval (A: $n = 7$; B: $n = 6$)

emissions from area B were 0.73 kg N_2O–N ha^{-1} in 1960. Similarly to area A, emissions increased until 1974, reaching 1.62 kg N_2O–N ha^{-1}. The further increase was again slower and lasted until 1989, when the emissions were at a level of 1.84 kg N_2O–N ha^{-1}. A sudden drop in N_2O–N emissions as shown for area A in 1992 was also calculated for area B (1.18 kg N_2O–N ha^{-1}). Between the years 1993 until 2009, N_2O–N emissions remained stable, with slight fluctuations.

Direct N_2O–N emissions for the territory of Poland

The estimated average value of the total nitrous oxide emission from agricultural soils in Poland in the period of 1960–2009 was 1.46 kg N_2O–N ha^{-1} a^{-1}. Between 1960 and 1974, strong increases in N_2O–N emissions were observed, reaching 1.15 kg N_2O–N ha^{-1} a^{-1} in 1974 (Figs. 6, 8). Even though emissions further rose until 1989, the growth rate was much smaller than in previous years (1.68 kg N_2O–N ha^{-1} a^{-1} in 1989). A sudden drop in N_2O–N emission from fertilizers occurred between 1989 and 1992 with N_2O–N emissions decreasing to 1.22 kg N_2O–N ha^{-1}. Emissions from soils fluctuated ranged from 1.32 to 1.68 kg N_2O–N ha^{-1} a^{-1} between 1993 and 2009.

Hot spots and hot moments

Hot spots for all components of emission were observed in the northern, central and southwestern part of Poland and in a few subareas situated in the southeastern part of Poland (Fig. 7), especially in A.5 subarea in western Poland with 1.78 kg N_2O–N ha^{-1} a^{-1} and the south-eastern B.2 subarea with a value of 1.46 kg N_2O–N ha^{-1} a^{-1}. Hot spots were also observed outside areas A and B, and it were subareas described from H.1 to H.6 at the Fig. 7.

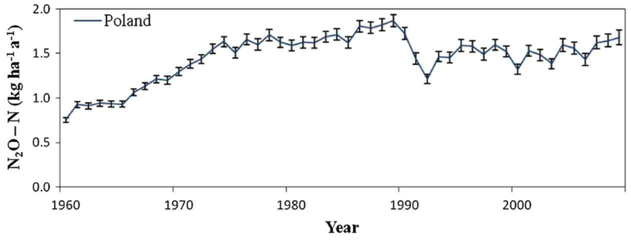


Fig. 6 Average annual direct emissions of N_2O–N from agricultural soils between 1960 and 2009 in Poland. *Bars* indicates 95 % confidence interval ($n = 49$)

The largest emission of N_2O–N in Poland occured between 1986 and 1990 (Figs. 6, 8).

Uncertainty analysis

Estimation uncertainty in the period of 1960–2009 in area A is 307 %, whereas in area B, it is 309 %. Such high uncertainties result mainly from a very high uncertainty for the emission factor. A detailed list of uncertainties for individual regions is included in Online Resource 6.

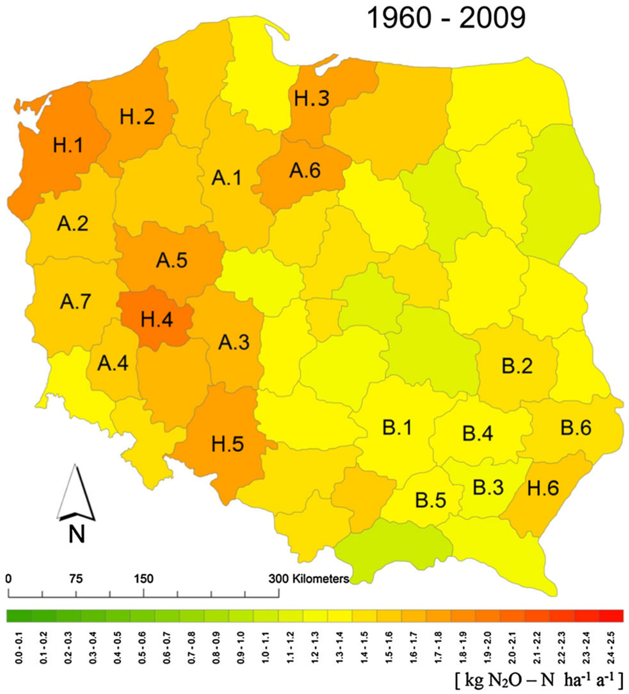


Fig. 7 Average direct emissions of N_2O–N (kg ha^{-1} a^{-1}) from agricultural soils (crop residues, inorganic and organic fertilizers) between 1960 and 2009

Discussion

Between 1960 and 1975, an upward trend in nitrous oxide emissions was observed in both the analyzed areas, largely caused by similar increases in nitrogen fertilization ($r^2 = 0.94$ and $r^2 = 0.80$, respectively) as well as associated increase in yields mostly cereals ($r^2 = 0.81$ and $r^2 = 0.56$, respectively). In 1960, the average application of mineral fertilizers in area A was 16.03 kg N ha^{-1}; in contrast, only 9.97 kg N ha^{-1} were applied in 1960 in area B (Fig. 2a, b). Increases in mineral fertilizer use were observed within both areas between 1960 and 1989. Organic fertilization (Fig. 3a, b) was also favored between 1960 until the mid 1970s. Since this time, the consumption of organic fertilizers has declined in both areas. Two major reasons were identified that could explain this pattern: (1) a large increase in mineral fertilizers production from 1960 on and (2) the decrease in livestock production from mid 1970s (FAO 2003).

A period of smaller increases in nitrous oxide emissions occurred after 1975 and lasted until 1990. The sudden drop in emissions (Fig. 8) was most likely caused by changes in fertilization rates resulting from the political and economical transformations in Poland (Ariaratnam and Antalik 1996). Particularly the costs for synthetic nitrogen fertilizers were more affordable for state-owned collective farms subsidized by the state than for individual farmers. The economy in Poland had been controlled by the government, which prioritized the state-owned collective farms even in terms of the availability of nitrogen fertilizers. Hence, the availability of nitrogen fertilizers was limited for individual farmers.

Collective farms, established in 1949, developed quickly and brought an increasingly higher yield. It was a consequence of the state preferential policy aiming at establishing modern large-area farms at the same time discriminating against family farm holders. In western Poland, state-owned farms were established by replacing former huge farms. As a consequence of establishing large-area state-owned collective farms, bigger doses of fertilizers were used (CSO 1970, 1971, 1985, 1986, 1987), resulting in higher emissions of nitrous oxide.

In the early 1990s, a sudden drop in the yields was observed as a consequence of decreased mineral fertilization (Fig. 2a, b). This reduction in yields was larger in area A, where bigger doses of fertilizers were used than in area B before 1990 and was further represented by the drop in cereal yields in area A between 1990 and 1992 from 3.78 to 2.46 Mg ha^{-1}, respectively. Even though decreasing yields were also found in area B, the reduction was much lower, e.g., cereal yields were 3.03 Mg ha^{-1} in 1990 and 2.48 Mg ha^{-1} in 1994.

Between 1989 and 1994, large-area state-owned farms were closed (gradually sold or rented). The economic transformation after 1989 led to opening trade in Poland and the application of market rules in the agriculture sector, which involved a departure from subsidies for mineral fertilizers. The consequence was a sudden impoverishment of the Polish agriculture (Skarzynska and Augustynska-Grzymek 2000; Wos 2000) and further involved decreasing production and exporting rates to the West of companies producing nitrogen fertilizers (FAO 2003). The sudden decrease in nitrous oxide emissions from agriculture soils between 1991 and 1992 corresponds well with a drop in the overall country emissions at that time (KASHUE–KOBIZE 2011). Since 1992, the consumption of nitrogen fertilizers has been increasing in both areas and therefore providing a significant source for increased emission of nitrous oxide (Fig. 5). Hot spots in the analyzed period between 1960 and 2009 were observed in A.5 and B.2 subareas but also outside areas A and B. Subareas were presented at Fig. 7, in the areas A and B, and from H.1 to H.6 also. Characteristic for subareas A.5 and from H.1 to H.3 were the largest areas farms in the country (many state-owned collective farms), where were applied the highest doses of nitrogen fertilizers. Subareas B.2, H.4 and H.5 had a very high levels of agriculture, so individual farmers were able to force access to synthetic nitrogen fertilizers.

The coefficient determinations for mean emissions from both areas and food supply was higher in the area A

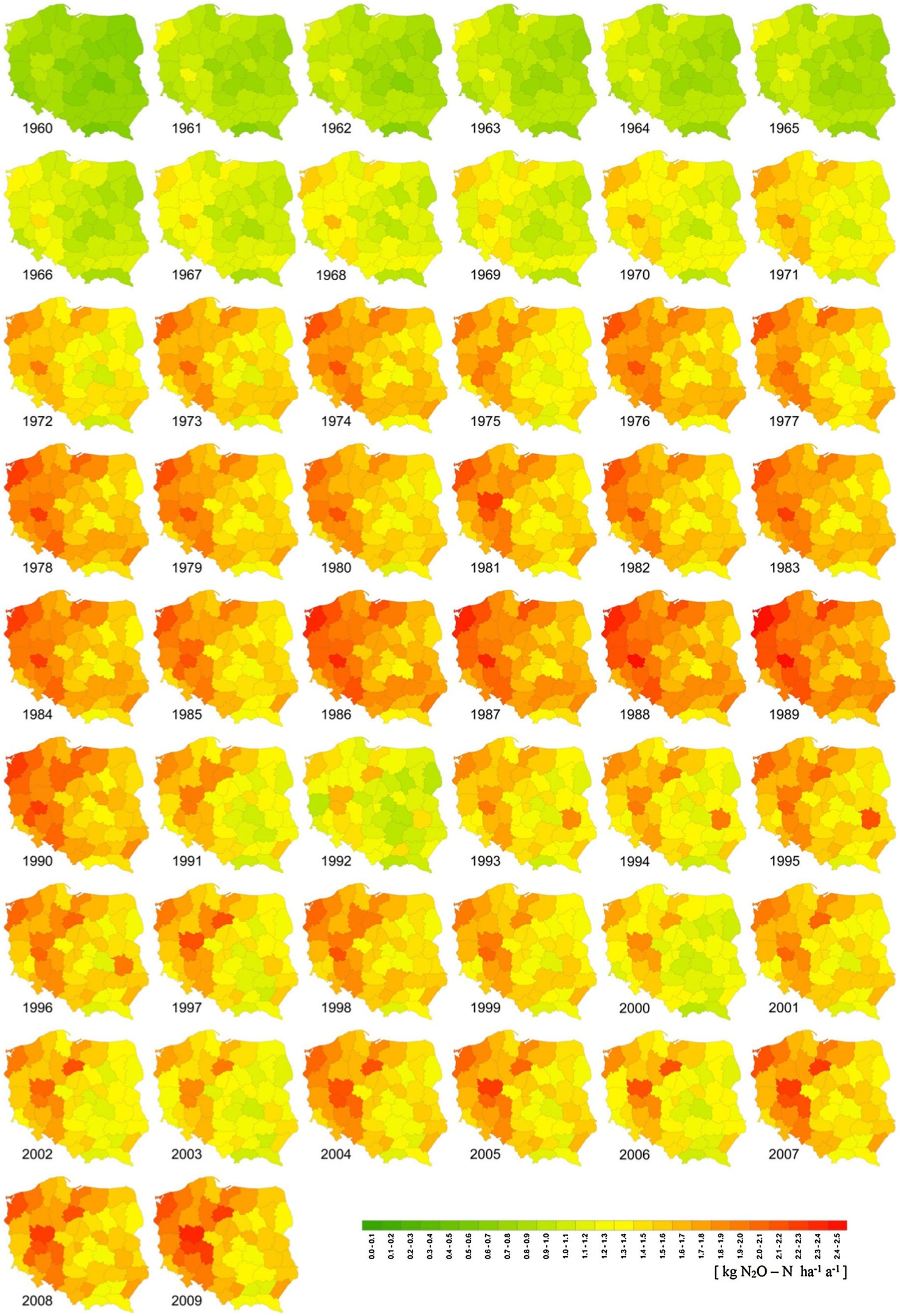


Fig. 8 Spatial and temporal distribution of direct emission N_2O–N (kg ha^{-1} a^{-1}) for Poland during the years 1960–2009

(0.41–0.71) than in the area B (0.12–0.39). One explanation for this situation could be higher quality of economy and life in western Poland resulting from the historical development of the areas. During the period of Poland partitions (period 1772–1918), the western areas (part of Prussia) were better developed than the eastern areas (part of Russia). In this way was obtained higher level of economy and life. Therefore, increasing emissions of nitrous oxide are associated to economic growth of a country.

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