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METHANE AND NITROUS OXIDE EMISSIONS FROM AGRICULTURE IN THE PODLASKIE VOIVODESHIP IN YEARS 1999–2015*

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Key words: methane, nitrous oxide, the Podlaskie Voivodeship, agriculture, GHG mitigation.

Abstract

Podlaskie as an agricultural region is expected to face environmental problems, mainly climate-related GHG emissions resulting from intensification of animal production. The aim of this study was to evaluate the methane and nitrous oxide emissions from agriculture in this region in years 1999–2015. The GHG emissions were calculated using methodology by the National Centre for Emissions Management (NCEM). The methane emissions attributed to agriculture in the Podlaskie increased from 59.2 Gg in 1999 to 84.0 Gg in 2015 which was in opposition to the trend for Poland. N_2O emissions in 1999 amounted to 3.05 Gg and increased to 4.14 Gg in 2015.

This growing trend is primarily related to the increasing number of livestock, specifically ruminant animals and increasing N_2O emissions from soils and manure management. In changing food market, farmers will probably be forced to find new niches, which will be profitable but less troublesome for the environment, including GHG emissions.

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EMISJA METANU I PODTLENKU AZOTU Z ROLNICTWA W WOJEWÓDZTWIE PODLASKIM W LATACH 1999–2015

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Słowa kluczowe: metan, podtlenek azotu, województwo podlaskie, rolnictwo, ograniczanie emisji.

Abstrakt

Województwo podlaskie jest regionem rolniczym, a intensyfikacja produkcji mleczarskiej i mięsnej prowadzi do zwiększania obciążenia środowiska m.in. przez emisję gazów cieplarnianych. Celem badań była ocena emisji metanu i podtlenku azotu z rolnictwa w województwie podlaskim w latach 1999–2015. Emisję gazów cieplarnianych obliczono za pomocą metodyki wykorzystywanej w krajowym raporcie gazów cieplarnianych. Emisja metanu z rolnictwa w województwie podlaskim wzrosła z 59,2 Gg w 1999 r. do 84,0 Gg w 2015 r., a emisja podtlenku azotu zwiększyła się z 3,05 Gg w 1999 do 4,14 Gg w 2015 r.

Wzrost emisji gazów cieplarnianych związany jest ze zwiększeniem się liczby zwierząt gospodarskich oraz ze zwiększeniem się emisji podtlenku azotu z gleby i nawozów organicznych. Obecnie należy przeciwdziałać emisji gazów cieplarnianych z rolnictwa, stąd też rolnicy będą zmuszeni do poszukiwania nowych nisz na rynku zbytu, które nadal będą przynosić dochód, a jednocześnie będą umożliwiały zmniejszenie emisji gazów cieplarnianych.

Introduction

Modern agriculture on its way to meet the rising demand for food is challenging many environmental problems such as greenhouse gases (GHG) emissions, losses of biodiversity, pollution of soils and groundwater, acidification and eutrophication. Agriculture is a primary source of non-CO_2 GHG emissions and releases more than 80% of global anthropogenic nitrous oxide (ISERMANN 1994) and more than 40% of total anthropogenic methane (TURNER et al. 2015). Production of food consumed by an individual citizen in Europe leads to the flux of 2,965 kg of $CO_{2\text{-eq.}}$ with the predominant role of agriculture (EC-JRC 2015). The vast majority of N_2O emissions originate from cultivated soils due to the application of organic and synthetic fertilizers. Methane is mainly emitted by livestock, specifically by ruminant animals and during manure management. Dairy and meat (beef, pork and poultry) farming is considered to be the primary sector responsible for GHG emissions (NOTARNICOLA et al. 2017, EC-JRC 2015) whereas crop production is liable for soil eutrophication, acidification and high rates of N_2O discharges. According to ROER et al. (2013), the N_2O from forage production and direct CH_4 emissions from animals contribute mostly to the environmental burdens in both milk and meat production. The conventional pork production in EU-27 contributes significantly to increased land occupancy, eutrophication and global warming (NGUYEN et al. 2012). The amount of energy necessary for poultry production and related global warming effect are similar or only slightly lower than those linked to the production of pork (DE VRIES and DE BOER 2010).

In the European Union agriculture is responsible for ca. 10% of total GHG emissions (EUROSTAT 2016a). Globally increasing food demand may result in 77% rise of GHG flux as a consequence of growing livestock population, deforestation, fertilizers usage and mechanization (BAJZELJ et al. 2014), which indicates a critical role of agriculture in the future climate policy. Poland with the fifth largest area of agricultural land in the EU-28 is the third cereal producer, fourth pork and the biggest poultry meat producer (EUROSTAT 2016b) responsible for 7% of GHG emissions from the EU agriculture (EUROSTAT 2016c). Although the GHG emissions from Polish agriculture decreased between years 1988 and 2014 (NCEM 2016), the trend in the GHG emissions in years 1999-2014 was rather stable and in some regions of the country the methane and nitrous oxide emissions has increased in this period (WYSOCKA-CZUBASZEK et al. 2018).

The Podlaskie Voivodeship is an agricultural region with high dairy and meat production, which is considered as a successful, attractive and promising, hence growing sector (NOWAK 2016). As a result of this tendency, the voivodeship is expected to face severe environmental problems, mainly climate-related emissions of methane and nitrous oxide.

The aim of the study was to evaluate the methane and nitrous oxide emissions from agriculture in the Podlaskie Voivodeship in years 1999–2015.

Methods

Study area

The Podlaskie Voivodeship is located in the NE Poland, has the area of 20,187 km^2 and 1,187,587 inhabitants with a population density of 59 persons per 1 km^2 (LDB 2017). The region is characterized by rather complex topography, changing from a hilly landscape in the north to the vast old--glacial plains cut with the paludified river valleys in the central and southern part of the territory. The climate is rather harsh, with short vegetation period lasting from 190 to 200 days, warm summers and cold winters. The long-term mean annual sum of precipitation ranges from 573 mm in the southern part of the region to 626 mm in the north. The average air temperature is 6.1°C in the north and 7.0°C in the south of the region (GÓRNIAK 2000). More than 60% of the voivodeship is under agricultural use, while almost 31% is covered by forest. Around 32% of the territory is under conservation management (SO 2015a). The number of farms exceeds 79,000 (SO 2015b). The main crops are cereals cultivated on the 70.4% of the cropland. Among livestock, dairy cattle (46.8%), young cattle of 1–2 years old (22.4%) and calves less than one-year-old (23.8%) dominate the cattle population in the region with non-breeding pigs as the main non-cattle livestock (SO 2016).

Calculation of greenhouse gases (GHG) emissions

The GHG emissions for years 1999–2015 in the Podlaskie Voivodeship were calculated using the methodology by the National Centre for Emissions Management (NCEM) for the national inventory for United Nations Framework Convention on Climate Change and Kyoto Protocol. According to the National Inventory Report 2016 (NCEM 2016), the main sources of GHG emissions in agriculture sector are: enteric fermentation from ruminant animals (CH_4), manure management (CH_4 and N_2O), agricultural soils (CH_4 and N_2O) and burning of agricultural residues (CO_2, CH_4, N_2O). In this paper only the first three sources were taken into consideration, because the burning of agricultural residues is of a minor importance, being responsible only for 0.1% of N_2O emissions and 0.2% of CH_4 emissions (NCEM 2016). Methane emissions from enteric fermentation of goats, horses, sheep and swine were calculated according to *Tier 1* method given by the Intergovernmental Panel on Climate Change (IPCC). The emission factors (EFs) were taken from IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006). The CH_4 emissions from enteric fermentation of cattle were calculated according to the *Tier 2* method with emission factors estimated for Poland (NCEM 2016) calculated based on specific gross energy intake values. The cattle population data was collected in livestock categories and the specific EFs, calculated for each cattle category on a basis of specific gross energy intake values, were taken from the National Inventory Report (NCEM 2016). The specific gross energy intake for each cattle category was calculated using the values from national statistics (e.g. pregnancy, milk production, percent of fat in the milk) and from IPCC Guidelines (IPCC 2006). Methane emissions from manure management of cattle and swine were estimated with *Tier 2* method and from manure management of horses, goats, sheep, and poultry with *Tier 1* method. The emission factors for horses, goats, sheep and poultry were taken from IPCC (2006), the EFs for cattle and swine were taken from the National Inventory Report (NCEM 2016). These EFs were calculated based on average daily volatile excreted solids, maximum CH_4 production capacity for manure produced by animal and fraction of livestock category manure in the animal waste management systems. All those parameters were taken from national statistics and Polish publications (NCEM 2016). Nitrous oxide emissions from manure management were calculated according to IPCC (2006) with emission factors based on the amount of nitrogen in animal manure taken from national inventory (NCEM 2016). Indirect N_2O emissions from manure management consist of nitrogen volatilization and nitrogen leaching and were calculated according to IPCC (2006).

Emission from cropland is the sum of direct and indirect fluxes. Direct emissions are due to N inputs from application of synthetic N fertilizers, animal manure, composts, sewage sludge and other N amendments; above and below-ground crop residues, including N-fixing crops returned to soils; mineralization of N due to land use or management change; management or drainage of organic soils; urine and dung deposited by grazing animals on pastures, range and paddocks. Indirect emissions comprise the sum of emissions from atmospheric nitrogen deposition on soils together with leaching and runoff of N that is applied to or deposited in soils (IPCC 2006). All emissions were calculated according to IPCC guidelines (IPCC 2006). EFs were also taken from this publication except the annual amount of N in crop residues, which was calculated according to Corrigenda for 2006 IPCC Guidelines (IPCC 2015) with N content in the above-ground residues, ratio of above-ground residue dry matter to harvested yield and fraction of total above-ground crop biomass removed from the field taken from NCEM (2016). The loss of C stocks from organic soils and mineral soils under cultivation were not calculated because of the virtual lack of data.

The specific for voivodeship data on animals number, crops, synthetic N fertilization, sewage sludge used as fertilizer needed to complete inventory was taken from The Central Statistical Office of Poland from following publications and databases: (i) production of agricultural and horticultural crops in years 1999–2016; (ii) statistical yearbook of the regions – Poland in years 1999–2016; (iii) Local Data Bank (LDB).

Results and Discussion

Total GHG emissions from agriculture

Agriculture in Poland is responsible for 8% of national GHG emissions (NCEM 2016), which is similar to the estimates for Europe, where agricultural flux amounts to 9.9% (EUROSTAT 2016a). Although the share of agriculture in domestic GHG emissions is rather small, Poland is responsible for 7% of GHG emissions from agriculture in EU-28 (Figure 1), following France (18.1%), Germany (15.2%), United Kingdom (10.2%), Spain (8.6%) and Italy (7%; EUROSTAT 2016b).

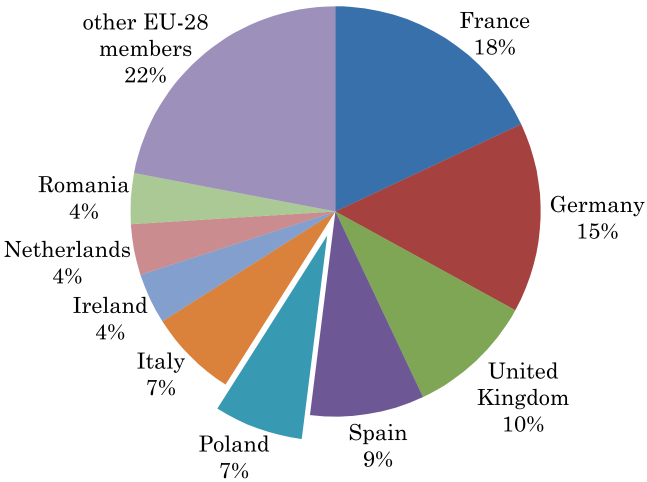

Fig. 1. The share of GHG emissions from agriculture by EU-28 countries

In recent decades the GHG emissions from agriculture in Poland decreased from 25,379 Gg $CO_{2\text{-eq.}}$ in 1999 to 23,949 Gg of $CO_{2\text{-eq.}}$ in 2002 and next peaked at 26,798 Gg $CO_{2\text{-eq.}}$ in 2008. After the decline in 2010 the GHG emissions rose to 26,322 Gg $CO_{2\text{-eq.}}$ in 2014, and subsequently dropped to 25,103 Gg $CO_{2\text{-eq.}}$ in 2015. In the Podlaskie Voivodeship the GHG emissions attributed to agriculture grew from 2,189 Gg $CO_{2\text{-eq.}}$ in 1999 to 3,220 Gg $CO_{2\text{-eq.}}$ in 2009 and stabilized with a slight decrease to 2,937 Gg $CO_{2\text{-eq.}}$ in 2011 (Figure 2). The emissions from the Podlaskie Voivodeship accounted for ca. 10% in 1999 to 16% in 2015 of the total GHG emissions from agriculture in Poland and were related to a high ruminant livestock production. The overall trend observed in the Podlaskie Voivodeship was in opposition to the trajectory of GHG flux from agriculture in the EU-28, which in years 1990–2012 fell by 23.8% (EUROSTAT 2016a). Similar high contribution of agricultural emissions to the total GHG emissions was observed in other agricultural regions of Europe. In the North East Scotland agriculture is responsible for 23% of the total GHG emissions (FELICIANO et al. 2013). In Ireland in 2012 agriculture accounted for 30.7% share of total greenhouse gas emissions and this was the highest contribution from agriculture among any of the EU Member States (EUROSTAT 2016b).

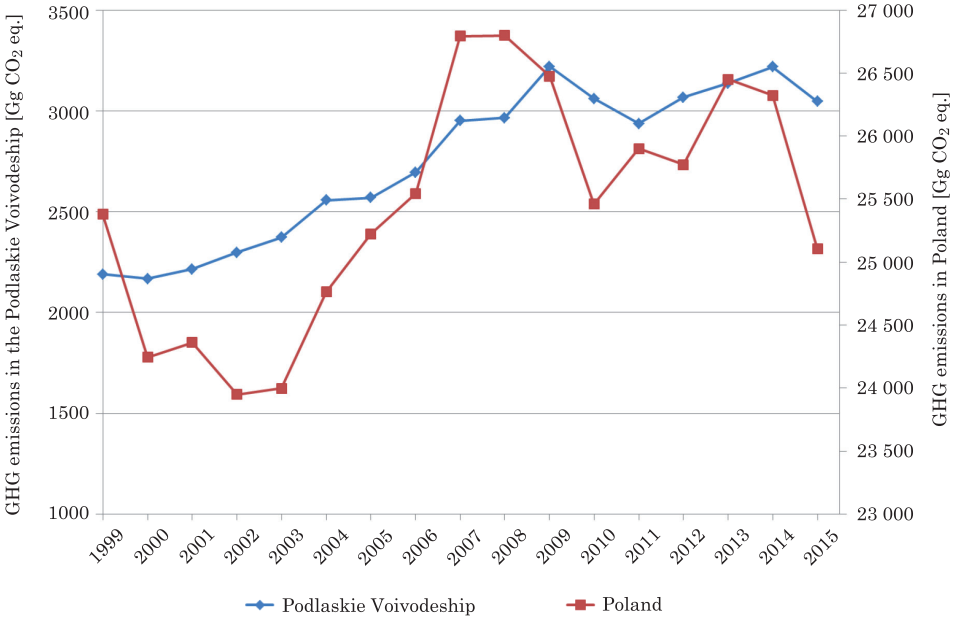

Fig. 2. The GHG emissions from agriculture in the Podlaskie Voivodeship and Poland in 1999–2015

In Italy, four most fertile and exploited agricultural regions (Lombardy, Piedmont, Emilia-Romagna and Veneto) are responsible for 55% of total agricultural emissions in this country (SOLAZZO et al. 2016).

Methane emissions from enteric fermentation and manure management in the Podlaskie Voivodeship

The methane emissions attributed to agriculture in the Podlaskie Voivodeship increased quite rapidly from 59.2 Gg in 1999 to 86.7 Gg in 2009 and then oscillated around 80 Gg in the following years (Figure 3). The overall increasing trend was in opposition to the trend for Poland, where the CH_4 emissions declined from 597.7 Gg in 1999 to 524.1 Gg in 2015. The largest source of methane in the Podlaskie Voivodeship was enteric fermentation of ruminant livestock (Figure 4). Its share in the overall CH_4 flux was 89.9% in 1999 and increased to almost 95% in 2015. In 2014 in Poland 88.4% of methane originated from enteric fermentation (NCEM 2016).

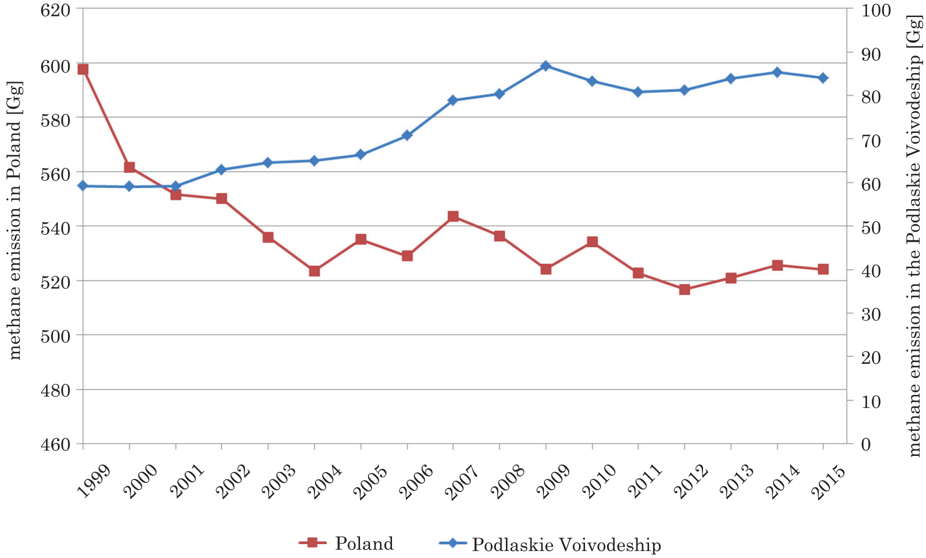

Fig. 3. Methane emissions from agriculture in the Podlaskie Voivodeship and in Poland in 1999–2015

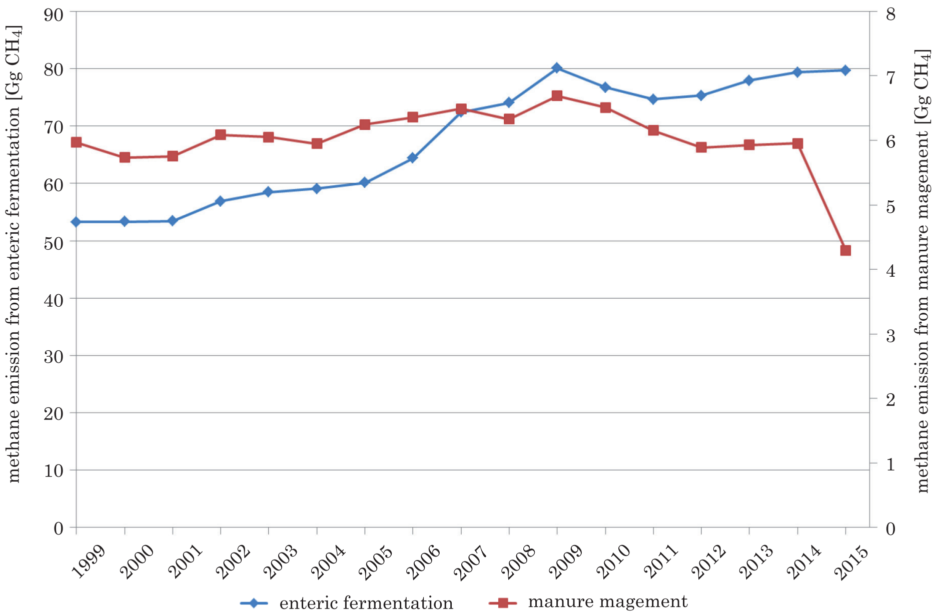

Fig. 4. Methane emissions from enteric fermentation and manure management in the Podlaskie Voivodeship in 1999–2015

The increase in methane emissions from enteric fermentation was due to the growth of livestock population in recent decades. In the Podlaskie Voivodeship the cattle livestock has doubled since 1960, with the highest growth rate between 2005 and 2009 (Figure 5). Since 2009 dairy cattle livestock remained stable but others, mainly calves under one year and young cattle of 1–2 years, grew rapidly. This tendency was similar to the general trend for Poland, where since 2008 dairy cows have been slightly outnumbered by the other cattle categories. The decline in dairy cattle in Poland was caused by low procurement prices for milk, high penalties for exceeding milk quotas and a shortage of forage in regions affected by drought.

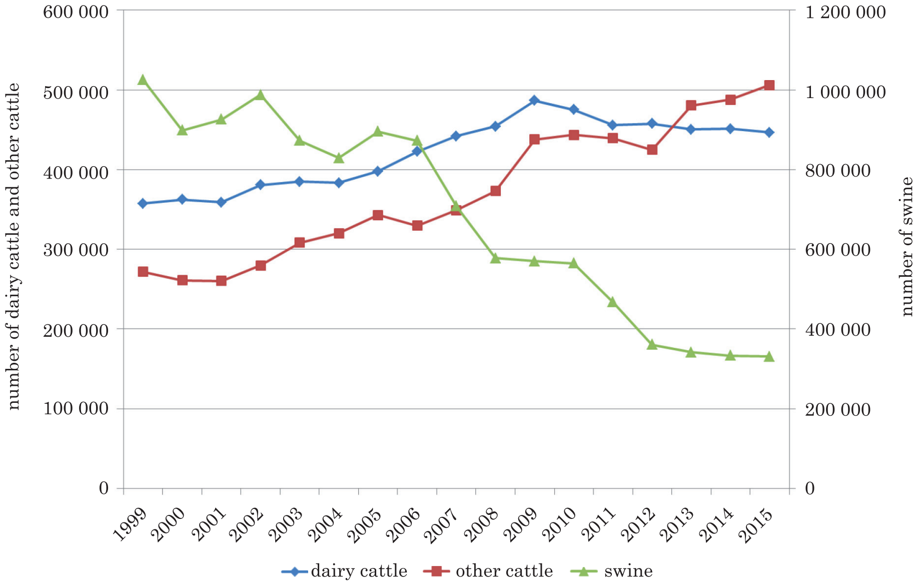

Fig. 5. Changes in cattle and swine population between 1999 and 2015
Source: LDB (2015)

In the Podlaskie Voivodeship, from 1999 the number of pigs slightly decreased as a result of collapsing market prices. The rapid decline in swine population observed since 2006 (Figure 5) was attributed to a high fodder (cereal) prices, and decreasing procurement prices, affected by the import of pork from Germany, the Netherlands, Denmark, and Belgium. This trend stopped in 2009 due to improvement of the market. However, the scarcity of cereals in 2010 caused the increase of fodder prices in the two following years (TRAJER and KOSSAKOWSKA 2013) and further decline in pig number. Even though the procurement prices of swine livestock have raised recently, the number of pigs in the Podlaskie Voivodeship has not increased mainly due to a risk of African Swine Fever (GVI 2016).

The sheep population fluctuated along a decreasing trend; a similar tendency was observed for horse population. Nowadays horses are mainly bred for recreation, medical purposes and meat (KRUSZEWSKI 2011). The number of goats was rather stable, with little increase in years 2005–2010.

The CH_4 emissions from animal wastes decreased slightly from 5.9 Gg in 1999 to 4.3 Gg in 2015. The decline of methane emissions was attributed to the reduction in the number of swine feedstock. The general trend was not affected by an increase in the number of broilers from 248,958 in 1999 to 7,021,285 in 2015.

The increasing trend for CH_4 emissions is typical for those countries and regions, where growing cattle livestock population is observed, because GHG emissions, especially CH_4 emissions are mainly related to the ruminant number, particularly cattle number (O'MARA 2011). In European countries, cattle are the source of 40–70% of the CH_4 emissions which is much higher than methane emissions from other agricultural sources (FREIBAUER 2003, WANG et al. 2011). In China the population of livestock almost tripled in period of 1980–2013 what resulted in CH_4 emissions increase, especially in the 2000s (YU et al. 2018). The growing number of cattle in the Podlaskie Voivodeship accompanying by increasing CH_4 emissions is in the opposite trend to most European countries, where the decline in livestock population results in decrease of CH_4 emissions (FELICIANO et al. 2013, FREIBAUER 2003).

Nitrous oxide emissions from agriculture in the Podlaskie Voivodeship

Nitrous oxide emissions from agriculture in the Podlaskie Voivodeship in 1999 amounted to 3.05 Gg and subsequently increased to 4.14 Gg in 2015 (Figure 6). Almost 70% of N_2O emissions originated from manure management, application of mineral and organic fertilizers, urine and dung left by animals on pastures, sewage sludge used as fertilizer, and decomposition of crop residues. Mineral fertilizers and crop residues generated 20–26% and 16–28% of total nitrous oxide emissions, respectively. Manure management and application were responsible for 21–24% of total nitrous oxide emissions. The indirect emissions resulted from N volatilization and leaching from manure management (34%) and the transformation of atmospheric N depositions and leaching together with runoff from soils (66%).

Nitrous oxide emissions from application of synthetic N fertilizers increased from 0.77 Gg in 1999 to 0.85 Gg in 2015 with the peak around 2013 and 2014 (1.09 Gg and 1.07 Gg, respectively) due to growing fertilizer dosage. In the Podlaskie Voivodeship the fertilization increased from 80 kg NPK ha^{-1} in 2002 to 88 kg NPK ha^{-1} in 2015 with a peak in 2013 (115 kg NPK ha^{-1}). This trend was, however, slower than that observed for Poland as a whole, and fertilizer dose was still lower than the average fertilization rate in Poland (MADEJ 2015) equal to 123 kg NPK ha^{-1} in 2015 (LDB 2016). The other source of N_2O was emission from crop residues, which exhibited an increasing trend from 0.51 Gg in 1999 to 0.93 Gg in 2015, being a result of increased maize cultivation. The share of corn in the total area of cereals had been less than 10% before the year 2005 and then systematically grew up to 29% in 2015. This rapid increase in maize production was related to the growing number of cattle because maize silage is now used as high energetic forage.

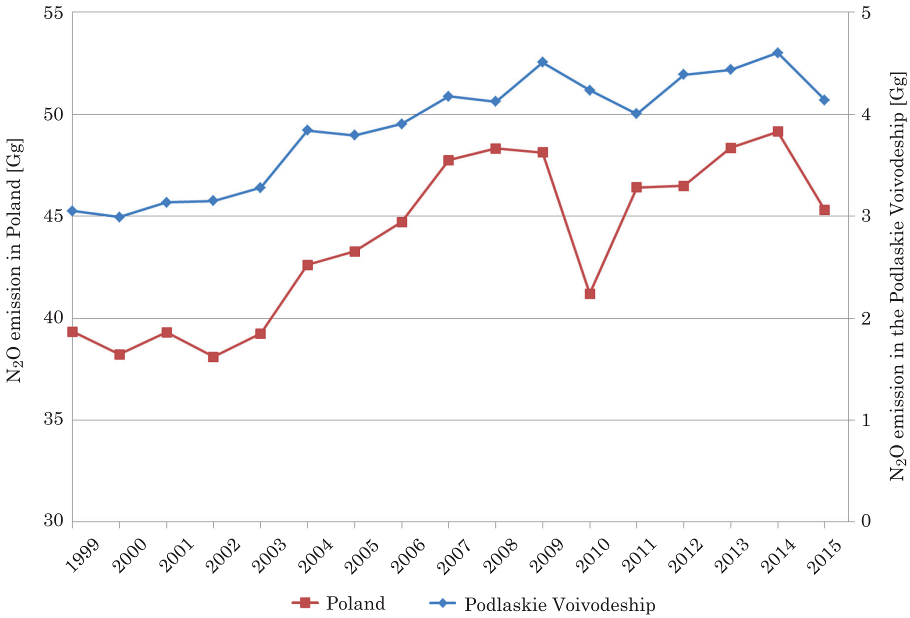

Fig. 6. Total nitrous oxide emissions form agriculture in the Podlaskie Voivodship and in Poland in 1999–2015

Estimated N_2O emissions from manure management grew from 0.33 Gg in 1999 to 0.44 in 2015. The livestock population growth also resulted in the rise of emissions from manure applied to soils and from dung and urine deposited by grazing animals. This was in opposition to CH_4 emissions from animal waste. The increase in N_2O emissions from animal waste reflected the increase in cattle population and growing milk yields from 3,213 L cow^{-1} year^{-1} in 1999 to 5,251 L cow^{-1} year^{-1} in 2014 (PFCDF 2016). This was due to the introduction of new more efficient breeds of cows combined with improved animal diet. Despite the progressive intensification and the shift from small herds housed in straw yards to herds of over 40 cows housed more and more often in slurry-based buildings, most of the herds is still between 10 and 20 cows, which are housed in the deep-straw system (LITWIŃCZUK and GRODZKI 2014). A deep-bedded pack system was reported to have relatively low N_2O losses, which are lower than 1–4% (CHADWICK et al. 2011). The N_2O emissions from sludge used as fertilizer in the Podlaskie Voivodeship were negligible.

A growing trend was observed in the indirect sources of N_2O emissions from manure and soil. The estimated emissions due to N volatilization from manure management rose from 0.25 Gg N_2O in 1999 to 0.33 Gg in 2015 while emissions due to leaching from manure management grew from 0.05 Gg in 1999 to 0.07 Gg in 2015. The atmospheric deposition resulted in an emissions of 0.23 Gg in 1999 and 0.32 Gg in 2015. Leaching was a more important source responsible in 1999 and 2015 for 0.35 Gg and 0.46 Gg of N_2O emissions, respectively.

The highest anthropogenic N_2O emissions are related to cultivated agricultural soils due to application of nitrogen fertilizers, mainly in mineral form, however the climate and soil characteristics also influence the nitrous oxide emissions (FREIBAUER 2003, BELL et al. 2015). However, in regions with high animal production, as in case of the Podlaskie Voivodeship, the contribution of animal derived N_2O emissions may be also very significant. In UK, crops contribute 42% to total N_2O emissions, while cattle 25% (WANG et al. 2011), which is similar to the contributions calculated for the Podlaskie Voivodeship. The increasing trend in N_2O emissions from synthetic N fertilizers is somehow balanced with growing use of manure as fertilizer, however both fertilizers contribute in nitrous emissions.

GHG emissions from agriculture in the Podlaskie Voivodeship compared to Poland

The presented data indicates that area related to GHG emissions tend to be much higher in agricultural regions than an average for the whole country. In 2015 the Podlaskie Voivodeship emitted 16% of agricultural CH_4 and together with the Mazowieckie (18.5%) and Wielkopolskie Voivodeships (16%) was responsible for more than half of CH_4 flux. However, the emissions related to the area of agricultural land give a different picture. The Podlaskie Voivodeship with its 7,939 kg CH_4 100 ha^{-1} a.l. dominated in Poland and outran the Mazowieckie Voivodeship (5,058 kg CH_4 100 ha^{-1} a.l.) and the Wielkopolskie Voivodeship (4,860 kg CH_4 100 ha^{-1} a.l.), which was obviously related to the largest number of cattle per 100 ha a.l. This implicates very good usage of natural conditions in the Podlaskie Voivodeship but also indicates the threat of growing environmental burden from agriculture.

In dairy production the emission per 1 L of produced milk is an important indicator. In the Podlaskie Voivodeship this parameter decreased from 33.9 kg CH_4 L^{-1} to 21.8 kg CH_4 L^{-1} and is similar to the value obtained for the Wielkopolskie Voivodeship (20.5 kg CH_4 L^{-1} in 2015) and the Mazowieckie Voivodeship (22.2 kg CH_4 L^{-1} in 2015), where dairy production is one of main sectors of agricultural production. The intensification of dairy cattle production such as increasing cattle stocking rate, milk yields and cow fertility reduces the emissions (GERSSEN-GONDELACH et al. 2017).

The Podlaskie Voivodeship contributed only to 9% of total N_2O emissions from Polish agriculture. The flux of N_2O per 100 ha a.l. in 2015 equaled to 391 kg N_2O. The nitrogen fertilizers and crop residues were responsible for more than 40% of the emissions, followed by manure management (11%) and organic fertilizers (13%). Agriculture in the Podlaskie Voivodeship is based mainly on the emission-intensive milk and meat production with some crop cultivation. In 2015 the region harvested only 6% of total Polish cereals, while the Wielkopolskie and Mazowieckie Voivodeships produced 13.3% and 12.8%, respectively. However, last year the Podlaskie Voivodeship was a significant maize producer (10% of total yield), although its share only halved that of the Wielkopolskie Voivodeship (21%). To the high emissions of the nitrous oxide in the Podlaskie Voivodeship contributed large livestock number per 100 ha while low consumption of fertilizers slightly decreased the N_2O flux.

The results indicate that in regions where agriculture is the basic economic factor the GHG emissions contribute much more to total emissions than it is assessed for the whole country. It is worth noting that agricultural sector in Poland is still in transformation phase. In the Podlaskie Voivodeship changes in this sector are pronounced in enlargement of farms, shifting from crop production to milk and meat production which is the most suitable direction of agriculture according to the natural conditions, replacement of old equipment, decline in agriculture area per person etc. (MADEJ 2015). However, still there is a need for some improvements such as higher liming, as well as phosphorus and potassium fertilizers rates. Increasing cattle population will cause greater demand for feed which may raise the share of maize in crop structure. Maize production in turn will increase the demand for N fertilizers which may contribute to higher N_2O emissions. On the other hand the increasing amounts of manure may be problematic when its production is overly abundant in regions with intensive livestock production (GARNETT 2009).

GHG mitigation options for agriculture in the Podlaskie Voivodeship

To alleviate the threat of climate change, the Podlaskie Voivodeship needs to introduce measures aiming at significant GHG reduction from agriculture, which should not affect the farmers' income. The list of possible mitigation practices includes improvements in cropland, livestock and manure management, bioenergy production, restoration of degraded land etc. Implementation of those measures can be constrained by physical, political, social, biological, economic, institutional, educational and market barriers (SMITH 2012). In the case of methane reduction from livestock the most common solution is the intensification of milk production through increasing herds, and milk yield (GRESSEN-GONDELACH et al. 2017) or the decreasing of methane production during rumination through the diet. Higher milk production per cow may increase the demand for forage and hence the area of crops (NAYAK et al. 2015) or can lead to intensified meat production from the pure beef system which is characterized by very high GHG emissions (FLYJSÖ et al. 2012). The increasing milk production may be also politically unpopular because it will favour regions and countries where GHG emissions per 1 kg milk are already low through the density of cows and high yield per cow (MCALLISTER et al. 2011). However, the GHG decrease from cows can be obtained not only through milk yield increase or reduced protein diet but also through the combination of those two with longevity to 7 lactations per cow instead of current 3–4 lactations (AUDSLEY and WILKINSON 2014). BACENETTI et al. (2016) reported that increasing only milking procedure from 2 to 3 per day may increase the annual milk yield without changing the diet.

Beef production has the highest global warming potential, thus mitigation strategies in this sector are of main consideration. The study of BURATTI et al. (2017) showed that carbon footprint of conventional beef production is lower than of organic production due to lower enteric fermentation caused by better digestibility of forage and manure management. As BEAUCHEMIN et al. (2011) reported, the dietary modifications such improved forage quality, supplementation, change of forage and improved animal husbandry based on increased reproductive performance and longevity of breeding stock could save up to 20% of total GHG emissions.

On the other hand, there is a growing concern not only about the impact of food production, especially of animal-based products on the environment but also the welfare of farm animals becomes a public concern in many countries (DEEMER and LOBAO et al. 2011) and some treatments performed on farm animals can be seen even as an ethical problem

(LAGERKVIST et al. 2006). The welfare of farm animals has become a subject of public debates and consumers more and more willingly select the products on which the information of farming method is effectively labeled (NAPOLITANO et al. 2010, BENNETT and BALNEY 2002).

In the Podlaskie Voivodeship, even though the density of cows is the highest in the country and milk production is one of the highest, the annual yield from cow (5,673 L per cow, CSO 2017) is lower than those in 3 other voivodeships with dairy production being the main sector, and much lower than EU-28 average (6,898 L per cow, EUROSTAT 2016d). This means that intensification may not be the only solution for farmers. Increasing public awareness of farm animal welfare and growing niche market for food produced with respect to animal rights create the option for milk production without the intensification of the dairy sector but maintaining income on the current level and reducing the GHG emissions from livestock.

Another important issue is mitigation of GHG emissions from manure management, which is related to animal diet (DEL PRADO et al. 2010, COLOMBINI et al. 2015, MONTENEGRO et al. 2016) and technical options (DALGAARD et al. 2011). Easily digestible forage with reduced nitrogen input results in lower N_2O and NH_3 emissions from stored manure (MISSELBROOK et al. 2013, HANSEN et al. 2014). The positive effect can be also obtained by the addition of NO_3 or other supplements such as *Cysteamine hydrochlorid*e to cattle diet (SUN et al. 2017), however care should be taken with new diet supplements. Supplementing cattle feedlot with distillers' grains plus solubles which are the by-product of ethanol production decreases the CH_4 emissions form cattle manure while substantially increasing N amount in excreta results in intensification of N_2O emissions (HÜNERBERG et al. 2014). Many studies on feedlot supplementation with a whole range of substances give now contradictory results, so there is a need for research before application of these supplements in practice.

According to Polish legislation, slurry should be kept in covered and impermeable tanks, while manure is obligatorily stored on the impermeable plate with leachate stored in the tank. However, the uncovered manure is a source of GHG emissions, which can be reduced by covering the manure heaps (HANSEN et al. 2006). The in-house daily flushing of cattle manure thereby transferring the warm slurry to outdoor cooler container may reduce ca. 49% of CH_4 emissions form an in-house stored slurry with some increase from slurry kept outside. The cooling of slurry channels in pig houses combined with the use of excess heat from cooling units may result in 31% reduction of methane emissions (SOMMER et al. 2004), however in practice cooling below 15°C may not be cost-effective

(DALGAARD et al. 2011). Another option is to use slurry and manure for energy generation through anaerobic digestion (MASSÉ et al. 2011). In the Podlaskie Voivodeship with large livestock population, there is a potential for building the biogas plants. However, investment costs, insecure future of this energy production sector and low level of education are the main constrains which slow down the development of agricultural biogas sector.

Several mitigation measures can be implemented to subdue the nitrogen flux from soils, namely decreasing the application of synthetic N fertilizers, nitrification inhibitors in fertilizers, extending the application of organic fertilizers, improving the timing of fertilization, catch crops and intermediate crops, precision farming (MORAN et al. 2011). The precision agriculture is based on the application of all inputs to the soil according to observed intra-field variations (FELICIANO et al. 2013) and includes satellite technologies, mobile devices, weather modeling, sensors for gathering data on soil water availability, soil compaction, soil fertility, leaf temperature, leaf area index, plant water status, local climate data etc.

Some of those measures like the timing of fertilization or application of organic fertilizers or avoiding the excess of nitrogen fertilizers are or should be well known by Polish farmers because they are part of the Good Agricultural Practices Code. However, many of mitigation practices entail the additional cost, which raises the question about farmers willingness to pay and regulatory or subventions that will help to overcome this problem.

It must be stated that focusing on one target such as GHG without considering the whole spectrum of relationships between agricultural food production and environment may create in future new challenges of which we are not aware now. Some mistakes have already been made. Biogas plants based not on agricultural waste but dedicated crops like maize caused the competition for land for forage and energy crops.

Uncertainty and limitation

The IPCC method was designed for national scale inventories of GHG emissions. That is why it does not take into consideration neither the geographic and climatic variations nor the management practices which may vary as a function of climate and soil types as well as farming ideologies and economic factors (HILLIER et al. 2011). Thus this method may not be sufficient option for small scale inventories like community or farm level. However, on the regional/voivodeship scale the *Tier1* and *Tier 2* methods may be sufficient to assess the regional differences in GHG emissions, even though these methods do not relay on geographic variations. Even though, the IPCC method, especially *Tier 1* is fraught with uncertainties. The EFs can be a source of uncertainty, especially those taken directly from IPCC. The direct measurements of soil N_2O emissions after application of various organic fertilizers revealed the influence of manure type and time of application on EFs and their large deviation from IPCC default EFs (BELL et al. 2016). According to CHADWICK et al. (1999) the N_2O emissions from livestock production in UK may be estimated with ±50% error. The changes in livestock population in one year, production per head and average life span in one year contribute to the values of EFs and are not considered in IPCC emission factors (YU et al. 2018). However, at regional scale, the results based on the aircraft Eddy Covariance, Relaxed Eddy Accumulation and wavelet covariance techniques agreed with calculation based on *Tier 2* method (DESJARDINS et al. 2018). It is worth noting that most of emission factors were taken not from IPCC, but from Polish inventories and thus they are more reliable in Polish conditions and give smaller uncertainties in results. The variability of results is mainly explained by the livestock type and number and crop structure, which on the regional/voivodeship level can be easily obtained from statistical office. However it must be emphasized that data for 2015 year are uncertain because only available data were for June 2015 and did not cover the whole year. In case of horses and goats population the data were the same for 2014 and 2015 and that is why the data for 2015 may be underestimated.

Conclusions

1. In last decades intensification and "industrialization" of agriculture induced the increased methane and nitrous oxide emissions in the Podlaskie Voivodeship. Recent transformation of low-intensity agriculture into commercially oriented and competitive economic activity entails the environmental burdens such as increased GHG emissions.

2. The overall growing trend in GHG emissions from agriculture is primarily related to increasing number of livestock, specifically ruminant animals and nitrous oxide emissions from soils and manure management. The expanding number of cattle causes the enlargement of fodder production, mainly the maize crops. This, in turn, entails higher usage of N fertilizers, which in consequence enhances the nitrous oxide emissions.

3. The Podlaskie Voivodeship should introduce measures to reduce GHG emissions from agriculture. However, the mitigation options must not affect farmer's income while reducing the various environmental bur-

dens. In changing food market, farmers are likely to be forced to find new niches, which will be profitable but less troublesome for the environment, including GHG emissions and will take animal welfare into consideration.

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References

Audsley E., Wilkinson M. 2014. *What is the potential for reducing national greenhouse gas emissions from crop and livestock production systems?* J. Clean. Prod., 73: 263–268.

Bacenetti J., Bava L., Zucali M., Lovarelli D., Sandrucci A., Tamburini A., Fiala M. 2016. *Anaerobic digestion and milking frequency as mitigation strategies of the environmental burden in the milk production system*. Sci. Total Environ., 539: 450–459.

Bajzelj B., Richards K.S., Allwood J.M., Smith P., Dennis J.S., Curmi E., Gilligan C.A. 2014. *Importance of food-demand management for climate mitigation*. Nat. Clim. Change, 4: 924–929.

Beauchemin K.A., Janzen H.H., Little S.M., Mcallister T.A., Mcginn S.M. 2011. *Mitigation of greenhouse gas emissions from beef production in western Canada – Evaluation using farm-based life cycle assessment*. Anim. Feed Sci. Tech., 166–167: 663–677.

Bell M.J., Hinton N., Cloa J.M., Topp C.F.E., Rees R.M., Cardenas L., Scott T., Webster C., Ashton R.W., Whitmore A.P., Williams J.R., Balshaw H., Paine F., Goulding K.W.T., Chadwick D.R. 2015. *Nitrous oxide emissions from fertilised UK arable soils. Fluxes, emission factors and mitigation*. Agr. Ecosyst. Environ., 212: 134–147.

Bell M.J., Hinton N.J., Cloy J.M., Topp C.F.E., Rees R.M., Williams J.R., Misselbrook T.H., Chadwick D.R. 2016. *How do emission rates and emission factors for nitrous oxide and ammonia vary with manure type and time of application in a Scottish farmland?* Geoderma, 264: 81–93.

Bennett R., Blaney R. 2002. *Social consensus, moral intensity and willingness to pay to address a farm animal welfare issue*. J. Econ. Psychol., 23: 501–520.

Buratti C., Fantozzi F., Barbanera M., Lascaro E., Chiorri M., Cecchini L. 2017. *Carbon footprint of conventional and organic beef production systems. An Italian case study*. Sci. Total Environ., 576: 129–137.

Chadwick D.R., Sneath R.W., Phillips V.R., Pain B.F. 1999. *A UK inventory of nitrous oxide emissions from farmed livestock*. Atmos. Environ., 33(20): 3345–3354.

Chadwick D., Sommer S., Thorman R., Fangueiro D., Cardenas L., Amon B., Misselbrook T. 2011. *Manure management. Implications for greenhouse gas emissions*. Anim. Feed Sci. Tech., 166–167: 514–531.

Colombini S., Zucali M., Rapetti L., Crovetto G.M., Sandrucci A., Bava L. 2015. *Substitution of corn silage with sorghum silages in lactating cow diets. In vivo methane emission and global warming potential of milk production*. Agr. Syst., 136: 106–113.

CSO 2017. *Means of production in agriculture in the 2015/2016 farming y*ear. Central Statistical Office, Warsaw.

Dalgaard T., Olesen J.E., Petersen S.O., Petersen B.M., Jørgensen U., Kristensen T., Hutchings N.J., Gyldenkærne S., Hermansen J.E. 2011. *Developments in greenhouse gas emissions and net energy use in Danish agriculture – How to achieve substantial CO2 reductions?* Environ. Pollut., 159: 3193–3203.

De Vries M., De Boer I.J.M. 2010. *Comparing environmental impacts for livestock products: A review of life cycle assessments*. Livest. Sci., 128: 1–11.

Deemer D.R, Lobao L.M. 2011. *Public concern with farm-animal welfare. Religion, politics, and human disadvantage in the food sector*. Rural Sociol., 76(2): 167–196.

Del Prado A., Chadwick D., Cardenas L., Misselbrook T., Scholefield D., Merino P. 2010. *Exploring systems responses to mitigation of GHG in UK dairy far*ms. Agr. Ecosyst. Environ., 136: 318–332.

Desjardins R.L., Worth D.E., Pattey E., Vanderzaag A., Srinivasan R., Mauderc M., Worthy D., Sweeney C., Metzger S. 2018. *The challenge of reconciling bottom-up agricultural methane emissions inventories with top-down measurements.* Agr. Forest Meteorol., 248: 48–59.

EC-JRC 2015. *Energy use in the EU Food Sector. State of play and opportunities for improvement.* JRC Science and Policy Report. European Commission, Joint Research Centre, Institute for Energy and Transport and Institute for Environment and Sustainability, Publications Office of the European Union, Luxembourg.

EUROSTAT 2016a. *Greenhouse gas emission statistics.* Eurostat Statistics Explained. http://ec.europa.eu/eurostat/statistics-explained/index.php/Greenhouse_gas_emission_ Statistics, access: 14.11.2017.

EUROSTAT 2016b. *Agriculture – greenhouse gas emission statistics.* Eurostat Statistics *Explained.* http://ec.europa.eu/eurostat/statistics-explained/index.php/Agriculture_-_greenhouse_gas_emission_statistics#Agriculture.27s_contribution, access: 14.11.2017.

EUROSTAT 2016c. *Greenhouse gas emissions by source sector.* http://ec.europa.eu/eurostat/web/environment/air-emissions-inventories/database, access: 14.11.2017.

EUROSTAT 2016d. *Milk and milk production.* Eurostat Statistics Explained. http://ec.europa.eu/eurostat/statistics-explained/index.php/Milk_and_milk_product_ statistics, access: 14.11.2017.

Feliciano D., Hunter C., Slee B., Smith P. 2013. *Selecting land-based mitigation practices to reduce GHG emissions from the rural land use sector. A case study of North East Scotland.* J. Environ. Manage., 120: 93–104.

Flysjö A., Cederberg C., Henriksson C., Ledgard S. 2012. *The interaction between milk and beef production and emissions from land use change – critical considerations in life cycle assessment and carbon footprint studies of milk.* J. Clean. Prod., 28: 134–142.

Freibauer A. 2003. *Regionalised inventory of biogenic greenhouse gas emissions from European agriculture.* Europ. J. Agronomy, 19: 135–160.

Garnett T. 2009. *Livestock-related greenhouse gas emissions: impact and options for policy makers.* Environ. Sci. Policy, 12: 491–503.

Gerssen-Gondelach S.J., Lauwerijssen R.B.G., Havlík P., Herrero M., Valin H., Faaij A.P.C., Wicke B. 2017. *Intensification pathways for beef and dairy cattle production systems. Impacts on GHG emissions, land occupation and land use chan*ge. Agr. Ecosyst. Environ., 240: 135–147.

Górniak A. 2000. *Klimat województwa podlaskiego.* Białystok, IMGW.

GVI 2017. *Komunikat Głównego Lekarza Weterynarii o ogniskach afrykańskiego pomoru świń (ASF) u świń.* General Veterinary Inspectorate, https:// www.wetgiw.gov.pl/main/komunikaty/Komunikat-Glownego-Lekarza-Weterynarii-o-ogniskach-afrykanskiego-pomoru-swin-ASF-u-swin/idn:634, access: 15.12.2017.

Hansen M.N., Henriksen K., Sommer S.G. 2006. *Observations of production and emission of greenhouse gases and ammonia during storage of solids separated from pig slurry: effects of covering.* Atmos. Environ., 40: 4172–4182.

Hansen M.J., Nørgaard J.V., Adamsen A.P.S., Poulsen H.D. 2014. *Effect of reduced crude protein on ammonia, methane, and chemical odorants emitted from pig houses.* Livest. Sci., 169: 118–124.

Hillier J., Walter C., Malin D., Garcia-Suarez T., Mila-I-Canals C., Smith P. 2011. *A farm-focused calculator for emissions from crop and livestock production.* Environ. Model. Software, 26: 1070–1078.

Hünerberg M., Little S.M., Beauchemin K.A., Mcginn S.M., O'connor D., Okine E.K., Harstad O.M., Kröbel R., Mcallister T.A. 2014. *Feeding high concentrations of corn dried distillers' grains decreases methane, but increases nitrous oxide emissions from beef cattle production.* Agr. Syst., 127: 19–27.

IPCC 2006. IPCC *Guidelines for National Greenhouse Gas Inventories.* Intergovernmental Panel on Climate Change, http://www.ipcc-nggip.iges.or.jp/public/2006gl/, access: 15.10.2017.

IPCC 2015. *9th Corrigenda for the 2006 IPCC Guidelines*. Intergovernmental Panel on Climate Change, http://www.ipcc-nggip.iges.or.jp/public/2006gl/corrigenda9.html, access: 5.10.2017.

Isermann K. 1994. *Agriculture's share in the emission of trace gases affecting the climate and some cause-oriented proposals for sufficiently reducing this share*. Environ. Pollut., 83: 95–111.

Kruszewski T. 2011. *Pogłowie koni w Polsce i w województwie podlaskim*. In: *Analiza kierunków rozwoju i aktualna sytuacja w rolnictwie województwa podlaskiego*. Podlaski Ośrodek Doradztwa Rolniczego w Szepietowie, pp. 68–69.

Lagerkvist C.J., Carlsson F. Viske D. 2006. *Swedish consumer preferences for animal welfare and biotech. A choice experiment*. AgBioForum, 9(1): 51–58.

LDB 2015. *Livestock population*. Local Data Bank. Central Statistical Office, Warsaw, https://bdl.stat.gov.pl/BDL/ dane/podgrup/tablica, access: 27.10.2017.

LDB 2016. *Consumption of mineral fertilizers per 1 ha of agricultural land according to the new definition*. Local Data Bank. Central Statistical Office, Warsaw, https://bdl.stat.gov.pl/BDL/dane/podgrup/tablica, access: 27.10.2017.

LDB 2017. *Population by residence (quarterly data)*. Local Data Bank. Central Statistical Office, Warsaw, https://bdl.stat.gov.pl/BDL/dane/podgrup/tablica, access: 22.01.2018.

Litwińczuk Z., Grodzki H. 2014. *Stan hodowli i chowu bydła w Polsce oraz czynniki warunkujące rozwój tego sektora*. Przegląd Hodowlany, 6: 1–5.

Madej A. 2015. *Rolnictwo województwa podlaskiego po 10 latach w Unii Europejskiej na tle Polski*. Zagad. Ekon. Roln., 2(343): 94–111.

Massé D.I., Talbot G., Gilbert Y. 2011. *On farm biogas production. A method to reduce GHG emissions and develop more sustainable livestock operations*. Anim. Feed Sci. Tech., 166–167: 436–445.

Mcallister T.A., Beauchemin K.A., Mcginn S.M., Hao X., Robinson P.H. 2011. *Greenhouse gases in animal agriculture. Finding a balance between food production and emissions*. Anim. Feed Sci. Tech., 166–167: 1–6.

Misselbrook T., Del Prado A., Chadwick D. 2013. *Opportunities for reducing environmental emissions from forage-based dairy farms*. Agr. Food Sci., 22: 93–107.

Montenegro J., Barrantes E., Dilorenzo N. 2016. *Methane emissions by beef cattle consuming hay of varying quality in the dry forest ecosystem of Costa Rica*. Livest. Sci., 193: 45–50.

Moran D., Macleod M., Wall E., Eory V., Mcvittie A., Barnes A., Rees R., Topp C.F.E., Moxey A. 2011. *Marginal abatement cost curves for UK Agricultural Greenhouse Gas Emissions*. J. Agr. Econ., 62(1): 93–118.

Napolitano F., Girolami A., Braghieri A. 2010. *Consumer liking and willingness to pay for high welfare animal-based products*. Trends Food Sci. Tech., 21: 537–543.

Nayak D., Saetnan E., Cheng K., Wang W., Koslowski F., Cheng Y.F., Zhu W.Y., Wang J.K., Liu J.X., Moran D., Yan X., Cardenas L., Newbold J., Pan G., Lu Y., Smith P. 2015. *Management opportunities to mitigate greenhouse gas emissions from Chinese agriculture*. Agr. Ecosyst. Environ., 209: 108–124.

NCEM 2016. *Poland's national inventory report 2016. Greenhouse gas inventory for 1988–2014*. Institute of Environmental protection – National Research Institute, The National Centre for Emissions Management. Warsaw.

Nguyen T.L.T, Hermansen J.e., Mogensen L. 2012. *Environmental costs of meat production: the case of typical EU pork production*. J. Clean. Prod., 28: 168–176.

Notarnicola B., Tassielli G., Renzulli P.A., Castellani V., Sala S. 2017. *Environmental impacts of food consumption in Europe*. J. Clean. Prod., 140: 753–765.

Nowak M.M. 2016. *Baza surowcowa przemysłu mleczarskiego w ujęciu regionalnym*. Rocz. Nauk. Stow. Ekon. Roln. Agrobiz., 18(5): 189–194.

O'mara F.P. 2011. *The significance of livestock as a contributor to global greenhouse gas emissions today and in the near future*. Anim. Feed Sci. Tech., 166–167: 7– 15.

PFCDF 2016. *Evaluation and breeding of dairy cattle, data for 2015. Polish Federation of Cattle Breeders and Dairy Farmers*, http://www.pfhb.pl/uploads/ckeditor/ attachments/208/wyniki_oceny_2016_prev_p.pdf, access: 18.12.2017.

ROER A.N., JOHANSEN A., BAKKEN A.K., DAUGSTAD K., FYSTRO G., STRØMMAN A.H. 2013. *Environmental impacts of combined milk and meat production in Norway according to a life cycle assessment with expanded system boundaries*. Livest. Sci., 155: 384–396.

SMITH P. 2012. *Agricultural greenhouse gas mitigation potential globally, in Europe and in the UK: what have we learnt in the last 20 years*. Glob. Change Biol., 18: 35–43.

SO 2015a. *Environmental protection and forestry of Podlaskie Voivodeship in 2014*. Statistical Information and Elaborations, Year XI. Statistical Office in Białystok, Białystok.

SO 2015b. *Agriculture in Podlaskie Voivodeship*. Statistical Information and Elaborations, Year XI. Statistical Office in Białystok, Białystok.

SO 2016. *Agriculture in Podlaskie Voivodeship*. Statistical Information and Elaborations, Year XII. Statistical Office in Białystok, Białystok.

SOLAZZO R., DONATI M., TOMASI L., ARFINI A. 2016. *How effective is greening policy in reducing GHG emissions from agriculture? Evidence from Italy*. Sci. Total Environ., 573: 1115–1124.

SOMMER S.G., PETERSEN S.O., MØLLER H.B. 2004. *Algorithms for calculating methane and nitrous oxide emissions from manure management*. Nutr. Cycl. Agroecosys., 69: 143–154.

SUN Y.K., YAN X.G., BAN Z.B., YANG H.M., HEGARTY R.S., ZHAO Y.M. 2017. *The effect of cysteamine hydrochloride and nitrate supplementation on in-vitro and in-vivo methane production and productivity of cattle*. Anim. Feed Sci. Tech., 232: 49–56.

TRAJER M., KOSSAKOWSKA J. 2013. *Tendencje zmian w pogłowiu trzody chlewnej w Polsce*. InfoPOLSUS. Ogólnopolski Biuletyn dla Hodowców i Producentów Trzody Chlewnej, 16: 7–11.

TURNER A.J., JACOB D.J., WECH, K.J., MAASAKKERS J.D., LUNDGREN E., ANDREWS A.E., BIRAUD S.C., BOESCH H., BOWMAN K.W., DEUTSCHER N.M., DUBEY M.K., GRIFFITH D.W.T., HASE F., KUZE A., NOTHOLT J., OHYAMA H., PARKER R., PAYNE V.H., SUSSMANN R., SWEENEY C., VELAZCO V.A., WARNEKE T., WENNBERG P.O., WUNCH D. 2015. *Estimating global and North American methane emissions with high spatial resolution using GOSAT satellite data*. Atmos. Chem. Phys., 15: 7049–7069.

WANG J., CARDENAS L.M., MISSELBROOK T.H., GILHESPY S. 2011. *Development and application of a detailed inventory framework for estimating nitrous oxide and methane emissions from agriculture*. Atmos. Environ., 45: 1454–1463.

WYSOCKA-CZUBASZEK A., CZUBASZEK R., ROJ-ROJEWSKI S., BANASZUK P. 2018. *Methane and nitrous oxide emissions from agriculture on a regional scale*. J. Ecol. Eng., 19(3): 206–217.

YU J., PENGA S., CHANG J., CIAIS P., DUMAS P., LIN X., PIAO S. 2018. *Inventory of methane emissions from livestock in China from 1980 to 2013*. Atmos. Environ., 184: 69–76.