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Modeling and spatial analysis of greenhouse gas emissions from fuel combustion in the industry sector in Poland

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Abstract. This paper describes the development of geoinformation technology for the spatial analysis of greenhouse gas emissions caused by fossil fuel combustion in the industry sector in Poland. Mathematical models and software have been elaborated, which make it possible to calculate the emissions and construct an appropriate geospatial database. The models are based on algorithms of proxy data disaggregation to the level of point- and area-type emission sources. These tools take into account the non-uniformity of anthropogenic activity and spatial distribution of emission sources. Numerical experiments were conducted and the results of spatial analysis are presented in the form of digital maps.

Key words: mathematical modeling, geoinformation technology, GHG inventory, spatial analysis, industry sector, fossil fuel combustion.

INTRODUCTION

Global warming is a problem widely discussed by scientific communities and policymakers worldwide. Most scientists assert that the increase in concentration of anthropogenic greenhouse gases (GHGs) in the atmosphere is the main reason for global warming. The international community has signed a number of agreements to reduce anthropogenic emissions, among them the Kyoto protocol. The main goal of this protocol is to limit GHG emissions and to introduce a mechanism for quota trading. Scientists are actively investigating ways to overcome or at least weaken global climate change. The most significant step in this direction is the reduction of emissions of greenhouse gases. In this regard, there is a need to use GHG inventory guidelines [1] for preparation of national inventory reports [2] and assessment of inventory uncertainties [3], as well as to create spatial inventories of GHG emissions by using GIS technologies [4], which would give an opportunity to evaluate emissions for separate sources [5].

THE ANALYSIS OF RECENT RESEARCHES AND PUBLICATIONS

Many categories associated with production, transportation, storage and distribution of energy belong to the energy sector and related activities. As a result of these complicated processes emissions arise from fossil fuel combustion or from fugitive processes (fugitive emissions). The IPCC Guidelines [1] offer a methodology for conducting an inventory of GHG emissions in this sector separately for each subcategory. According to the IPCC Guidelines the "1.a. Energy" sector is divided into several major subsectors, among which is the subsector "1.A.2. Industry and Construction", which in turn is divided into separate source categories as presented in Fig. 1.

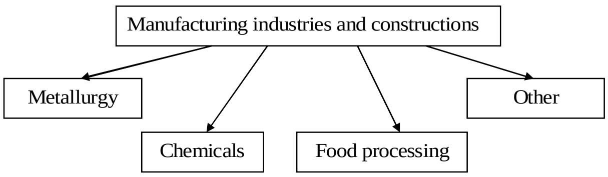

Fig. 1. Structure of GHG emissions from fossil fuel combustion in the industry sector

In 2010, CO_2 emissions (without land use, land-use change and forestry – LULUCF) were estimated as 310.40 million tonnes [2]. The main CO_2 emission source is the fuel combustion subcategory (1.A according to the IPCC Guidelines). This sector accounted for 93.6 % of the total CO_2 emission (without LULUCF) in 2010. The percentages accounted for by the main subcategories in 1.A were as follows: energy industries 53.7 %, manufacturing and construction industries 9.7 %, transport 14.1 %, and other sectors 16.0 %.

OBJECTIVES

There are many categories and sectors of anthropogenic activity with essential GHG emissions (e.g. [6, 7] and many others). In this context mathematical and software tools have been created for a GHG spatial inventory, especially for the energy sector [8], transport [9], chemical transformation in industry [10-12], forestry [13, 14], etc. Nevertheless, a spatial inventory of GHG emissions from fossil fuel combustion in Polish industry at the level of separate emission sources or small territories is not yet available. Therefore the aim of this study was to develop mathematical models that describe emission processes in this sector and to create GIS technology for the spatial analysis of such processes.

THE MAIN RESULTS OF THE RESEARCH

GHG spatial inventory. In this investigation, we used statistical data on fossil fuel combustion at the country level, data on gross value added (GVA) at the subregion level, GHG emission factors for each category under investigation (chemicals, metallurgy, food processing, and other categories), administrative digital maps, and Corine land cover map [15] as input data for modeling GHG emission processes.

Since the data on fossil fuel combustion are available at the national level only, we created mathematical models and algorithms for disaggregation of these data to the level of cities and industrial objects using other statistical data as proxy data (especially gross value added, area of industrial objects/territories, number of inhabitants in cities, etc.).

Let us assume $w=\overline{1,W}$ is the number of voivodeships (W is the total number of voivodeships); $r_w=\overline{1,R_w}$ is the number of subregions in the w-th voivodeship and R_w is the number of such subregions; $\eta_{ind}\left(j_{w,r_w}\right)$ is the j_{w,r_w}-th elementary object (industrial zone) on the land cover map of Poland and $j_{w,r_w}=\overline{1,J_{w,r_w}}$; J_{w,r_w} is the total number of such industrial objects in the r_w-th subregion of the w-th voivodeship. The emission of the g-th greenhouse gas at the i-th elementary object can be calculated by using the formula

$$E_{g,i}=\sum_{Ind\in I}\sum_{f\in F}D_{Ind,f}\cdot K_{f,g,en}\cdot K_{f,g,em}\cdot K_{Ind,d}\,, \qquad (1)$$

where: greenhouse gas $g\in\{CO_2, CH_4, N_2O\}$, i.e. the enumerative variable with carbon dioxide, methane and nitrous oxide; i is the number of the elements in the set $\check{M}=\{m_1,...,m_i,...m_n\}$, which is the set of area-type emission sources (industrial zones or urban territories); $D_{Ind,f}$ is the amount of the f-th type fossil fuel used in the emission category under investigation; F = {solid fuels, liquid fuels, gaseous fuels, biomass}; $K_{f,g,en}$ and $K_{f,g,em}$ are the calorific value of the f-th type fuel, and emission factor of the g-th GHG, correspondingly, in the industry and construction sector; $K_{Ind,d}$ is the disaggregation coefficient; $Ind\in$ {metallurgy, chemicals, food processing, other}.

The disaggregation coefficients depend on the category of anthropogenic activity, because for each category there are other available statistical data.

In some categories of the industrial sector we used point-type emission sources for modeling emission processes from big plants (metallurgy, chemicals, etc.), but in many other cases we used the area-type emission sources for modeling emission processes because we could not identify the location of each small enterprise at the country level. Also, the land cover digital map of Poland was used for identifying industrial zones (territories with industrial activity).

Therefore, the main approach to the disaggregation of activity data (statistical data on fossil fuel combustion) in the industry sector consisted of the following steps (we applied these steps using created software modules for the geoinformation system illustrated in Fig. 2):

1) the national data on fossil fuel combustion were split to voivodeship level and we took into account the coefficients of industrial activity and other available statistical data as proxy data [16-18];

2) at the district level the disaggregation of data on fossil fuel combustion was applied by using data on gross value added as proxy;

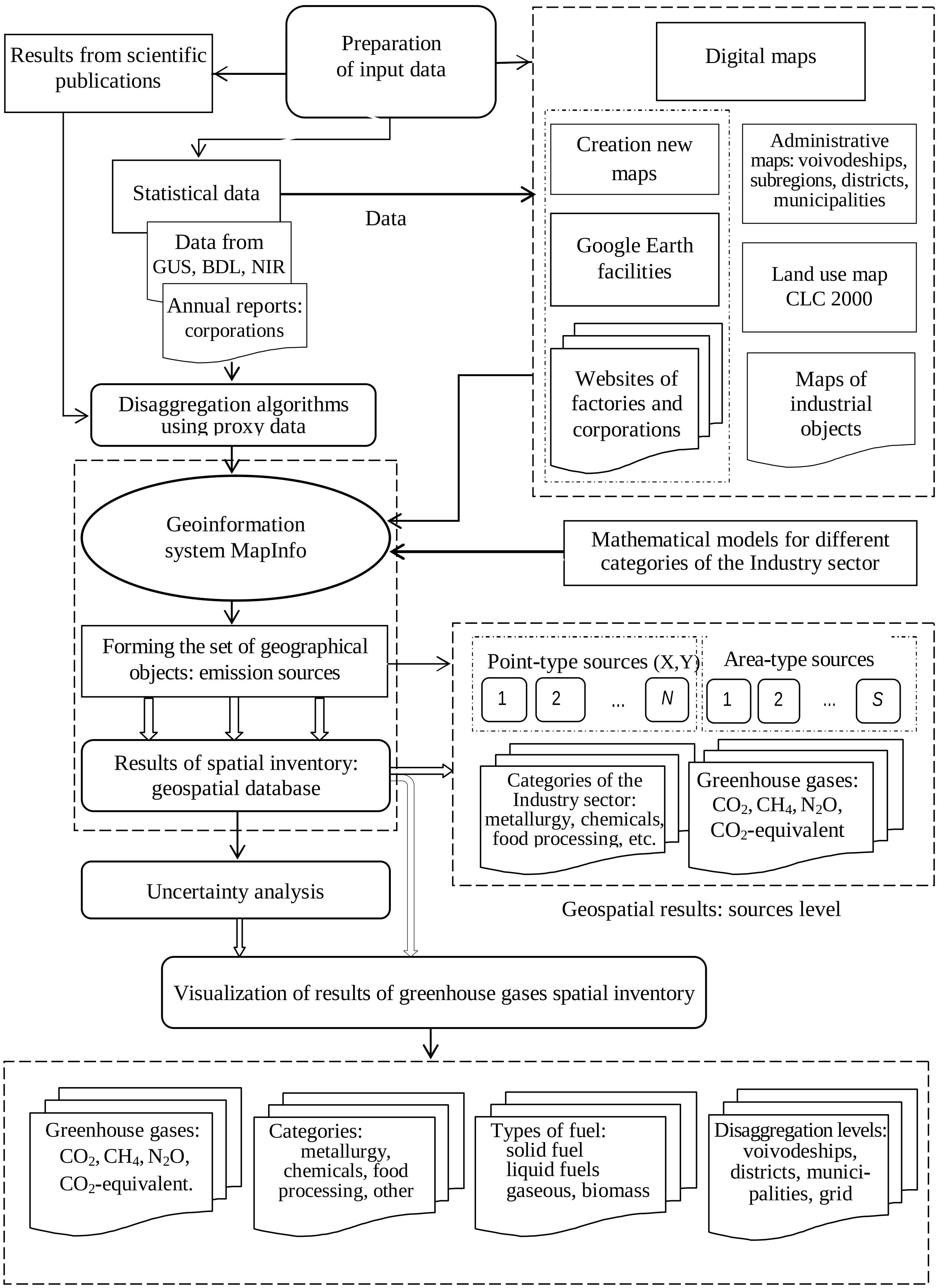

Fig. 2. Structure of the geoinformation technology for a GHG spatial inventory in the industry sector

3) calculated data on fossil fuel combustion at the district level were disaggregated to the level of industrial zones or settlements of the land cover map by using available statistical data as proxy [19] (for example, the number of inhabitants, cost of sales, etc. [20]); the available data on location of big plants as point-type emission sources were also used.

Geoinformation technology. The geoinformation technology for a GHG spatial inventory in the industry sector (see Fig. 2) consists of tools for input data preparation, mathematical models for a GHG emissions inventory, a geoinformation system for handling with geographical objects and spatial analysis, and facilities for visualization of inventory results. As input data the statistical data from GUS [16, 20], BDL [19], NIR [2], and scientific publications were used. For disaggregation of activity data we applied the corresponding proxy data, disaggregation algorithms, and digital maps. We used existing digital maps like administrative maps of voivodeships, districts and municipalities, and Corine land cover map, and also created some new digital maps using Google Earth facilities, especially maps of industrial objects (zones).

Mathematical models for different categories of the industry sector were used in the geoinformation system for forming a set of geographical objects (emission sources) and calculation of emissions in the form of a geospatial database. We took into account point- and area-type emission sources in metallurgy, chemicals, food processing, and other industrial categories. Geospatial results at the sources level included emissions of carbon dioxide, methane, nitrous oxide, and total emissions of these gases in CO_2-equivalent calculated applying their global warming potentials. Results of the GHG spatial inventory can be visualized at the level of greenhouse gases (CO_2, CH_4, N_2O, and CO_2-equivalent), categories of the industry sector (metallurgy, chemicals, food processing, and others), types of fuel (solid fuels, liquid fuels, gaseous fuels, and biomass), and levels of disaggregation (voivodeships, districts, municipalities, and grid).

Emissions from the food processing industry. For this category of anthropogenic activity we assumed that consumed fossil fuel is spatially distributed in proportion to the number of inhabitants in settlements. Only settlements with more than 1,000 inhabitants were taken into account because this industry mainly is developed not far from large number of consumers. In small villages with agriculture possibilities there are less needs for industrial food processing.

Disaggregation of activity data to the level of voivodeships was carried out on the basis some coefficients (indicators of food industry development of regions) as proxy data. Then the disaggregation of activity data to the level of subregions was carried out by using gross value added as proxy data. Finally the disaggregation of activity data to the level of settlements was carried out on the basis of numbers of inhabitants in settlements. In this case the disaggregation coefficient for activity data in the food processing industry K_{food} can be calculated by using the formula:

$$K_{food} = I_w \cdot \frac{G_{r_w}}{\sum_{r_w} G_{r_w}} \cdot \frac{P_i}{\sum_i P_i}, \qquad (2)$$

where: I_w is the indicator of food industry development in the voivodeship, G_{r_w} is the gross value added in the region, P_i is the number of inhabitants in settlement.

Emissions from the metallurgy industry. Assessment of greenhouse gas emissions in the metallurgy industry is very important, because this kind of anthropogenic activity includes technological processes with energy-intensive and raw material-intensive production. Economically it is not profitable to produce this type of product where there is no raw material base. In Poland there are only 22 steel mills, including 10 large ones, producing about 80 % of all steel products. The biggest corporation ArselorMittal includes four major metallurgy plants - Huta Celder (included among the 70 largest steel mills in the world), Huta Florian, Huta im. Sendzimira, and Huta Katowice.

For assessment of GHG emissions in this sector the locations of the 10 largest steel mills as point-type emission sources were identified by using Google Earth facilities. On the basis of these locations the corresponding industrial zones as area-type emission sources were marked in the land cover digital map, and GHG emissions were calculated according to the amount of production (sales) at each metallurgical plant.

The disaggregation coefficient $K_{metal}\left[\eta_{ind}(j_{w,r_w})\right]$ for geographical object $\eta_{ind}\left(j_{w,r_w}\right)$ of the r_w-th subregion of the *w*-th voivodeship, as area-type emission source, depends on available data on production of various types of metals, and it can be calculated by using the formula:

1) for the industrial zone where one of the 10 largest steel mills that produce 80 % of all steel products in Poland is located:

$$K_{metal}\left[\eta_{ind}(j_{w,r_w})\right]\Big|_{\eta_{ind}(j_w, r_w) \mathbf{I} \xi_{n_m} \neq 0; n_m=\overline{1,N_m}} = 0{,}8 \cdot \frac{V_{metal}\left(\xi_{n_m}\right)}{\sum_{l=1}^{N_m} V_{metal}\left(\xi_l\right)},$$

$$j_{w,r_w} = \overline{1, J_{w,r_w}}, \quad r_w = \overline{1, R_w}, \quad w = \overline{1, W}, \qquad (3)$$

where: $V_{metal}(\xi_{n_m})$ is the production capacity of the n_m-th steel mill ξ_{metal,n_m}; $\mathbf{I}$ it the operation that defines a common area of two geographical objects $\eta_{ind}\left(j_{w,r_w}\right)$

and ξ_{metal,n_m}, r_w, is the number of subregion; w is the number of voivodeships;

2) for industrial objects with unknown production capacities we can use the formula:

$$K_{metal}\left[\eta_{ind}(j_w,r_w)\right]\Big|_{[\eta_{ind}(j_w,r_w)]\cap\xi_{n_m}=0;\forall n_m=\overline{1,N_m}} =$$

$$=0,2\cdot K_{\%,metal,w}\cdot\frac{GVA_{r_w}}{\sum_{q=1}^{R_w}GVA_q}\cdot\frac{S(j_{w,r_w})}{\sum_{i=1}^{J_{w,r_w}}S(j_{w,i})},$$

$$j_{w,r_w}=\overline{1,J_{w,r_w}},\quad r_w=\overline{1,R_w},\quad w=\overline{1,W}, \qquad (4)$$

where: $K_{\%,metal,w}$ is the amount of steel production of the w-th voivodeship in this production for the whole of Poland; GVA_{r_w} is the gross value added in the metallurgy sector of the r_w-th subregion of the w-th voivodeship in Poland; $S\left(j_{w,r_w}\right)$ is the area of industrial zones (territories) $\eta_{ind}\left(j_{w,r_w}\right)$ on the land cover map.

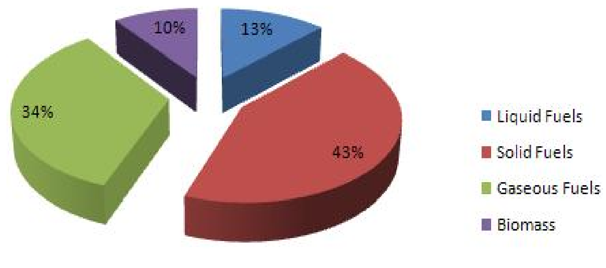

Fig. 3. Structure of fuels used in Polish industry (2010)

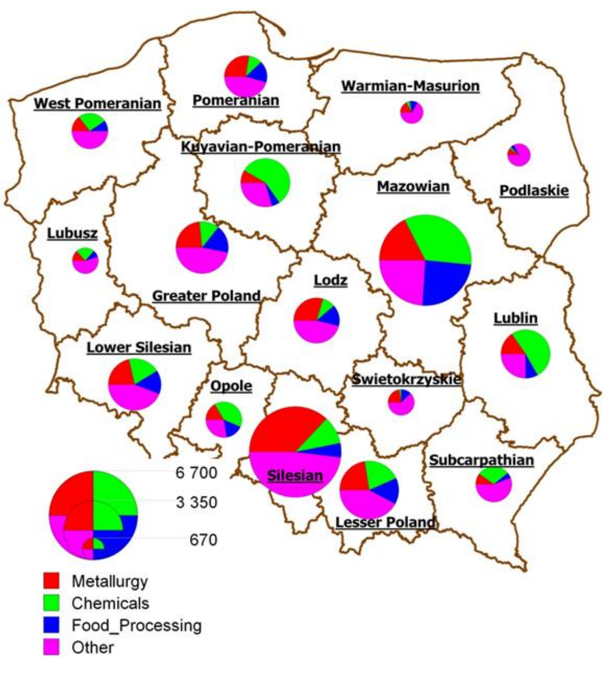

Fig. 4. Total GHG emissions in the industry sector by subsectors (Poland, CO_2-equivalent, Gg, 2010)

Emissions from the chemical industry. The chemical industry in Poland is one of the most innovative but at the same time the most environmentally dangerous sector of the economy. For the chemical industry we took into account the following categories: organic and inorganic fertilizers, plastics, and chemical reagents [21, 22]. The largest sources of GHG emissions in the chemical industry of Poland are: Puławy nitrate fertilizer plant in Lublin voivodeship (Zaklady azotowe Puławy), Anwil SA in Kuyavian-Pomeranian voivodeship and ZAK SA in Opole voivodeship. Anwil SA produces ethylene-based products (EDC and PVC) as a raw material for production of polyamide threads and plastic construction elements (caprolactam), ammonium sulfate as well as non-organic products (sulfuric acid, chlorine, sodium hydroxide). Puławy nitrate fertilizer plant and ZAK SA produce nitrogen fertilizers, plasticizers, oxo alcohols and other chemicals. For example, the annual production capacity of the Puławy plant is about 156,000 t of ammonium sulfate.

The chemical industry is growing in Poland, and it represents all major industries. The inorganic chemical industry is based on rich deposits of rock salt and sulfur. Rock salt is mined near Inowrоław and Kłodawa, sulfur in Świętokrzyskie and Subcarpathian voivodeships. The centers of production of nitrogen fertilizers are Puławy, Włocławek, Kędzierzyn-Kożle and Tarnów. The largest centers of production of phosphate fertilizers are Police, Gdansk and Tarnobrzeg. The center of the country (Warsaw, Lodz, Bydgoszcz, Inowrocław) offers various products of organic and inorganic chemistry.

We analyzed the 14 largest chemical plants, taking into account their GHG emissions. In contrast to the steel industry, the number of chemical plants is much greater. There are 14 largest plants, for which the production capacities are known, and many other plants with unknown capacities. The disaggregation of data on fossil fuel combustion was carried out as follows. The disaggregation of fuel to the level of the voivodeship was fulfilled by using coefficients of economic development. The disaggregation of fuel to the level of subregions was realized according to the gross value added. It was assumed that 60 % of fuel was combusted in industrial areas (since pollution from the chemical industry is quite unhealthy, because most plants are located outside cities), and 40 % of all fuel was combusted by the 14 largest factories. Finally, for the industrial areas (other than those where the largest plants are located) the disaggregation of data on fuel used was accomplished in proportion to the area of zones, and in settlements in proportion to the population.

Emissions from other categories. This category takes into account the greenhouse gas emissions from fuel combustion for industrial purposes by other technological processes than those discussed above. It is unrealistic to analyze each plant separately in this category of industrial activity. Therefore the disaggregation of data on fuel used in this category to the level of voivodeships and subregions was performed in accordance with the gross value added. It was assumed that 60 % of fuel is used in industrial zones. This fuel was disaggregated in proportion to the areas of industrial zones. The remaining fuel was distributed between cities with more than 5,000 inhabitants, in proportion to the population. Accordingly, the disaggregation coefficient for industrial zones can be calculated by using the formula

$$K_{other}\left[\eta_{ind}(i_w, r_w)\right] = I_w \cdot \frac{G_{r_w}}{\sum_{r_w} G_{r_w}} \cdot \frac{S_i}{\sum_i S_i}, \qquad (5)$$

where: I_w is the indicator of other industries development in the voivodeship; G_{r_w} is the gross value added in the region; P_i is the number of inhabitants in the settlement.

CONCLUSIONS

Using the mathematical models described above, and input data from GUS, BDL and NIR, as well as some proxy data and digital maps (a structure of fuels used in Polish industry is presented in Fig. 3), we calculated emissions from fossil fuel combustion in metallurgy, chemical industry, food processing and other categories at the level of area-type sources. Then results were aggregated to the level of voivodeships. The structure of the total GHG emissions in the industry sector by subsectors is presented in CO_2-equivalent in Fig. 4. This figure demonstrates the non-uniform distribution of emissions, the Mazowian and Silesian voivodeships leading the field. Relatively small emissions can be seen in Lubusz, Podlaskie, Świętokszyskie, and Warmian-Masurian voivodeships.

Considering greenhouse gases (see Fig. 5), carbon dioxide causes the most emissions in the industry sector. Amounts of emissions of methane and nitrous oxide are

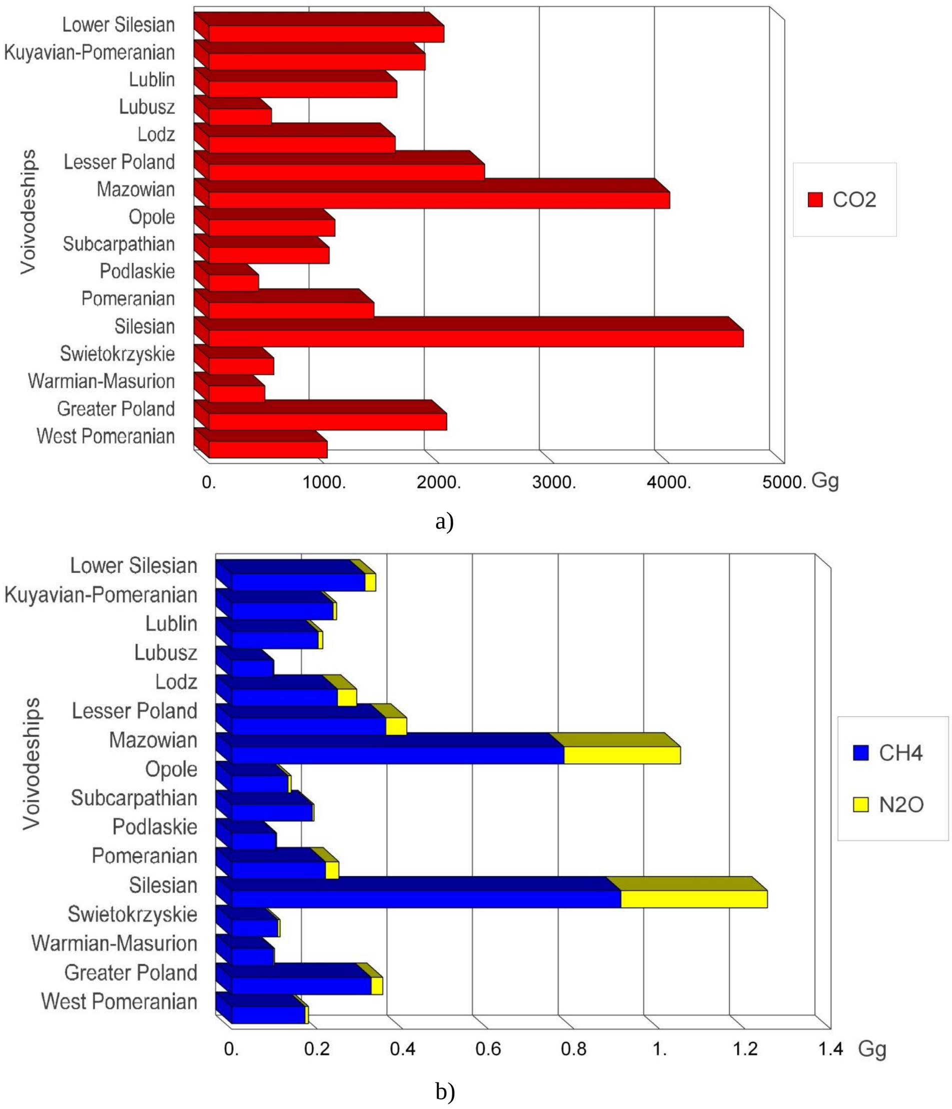

Fig. 5. Emissions of CO_2 (a) and CH_4, N_2O (b) at the level of voivodeships (Poland, CO_2-equivalent, Gg, 2010)

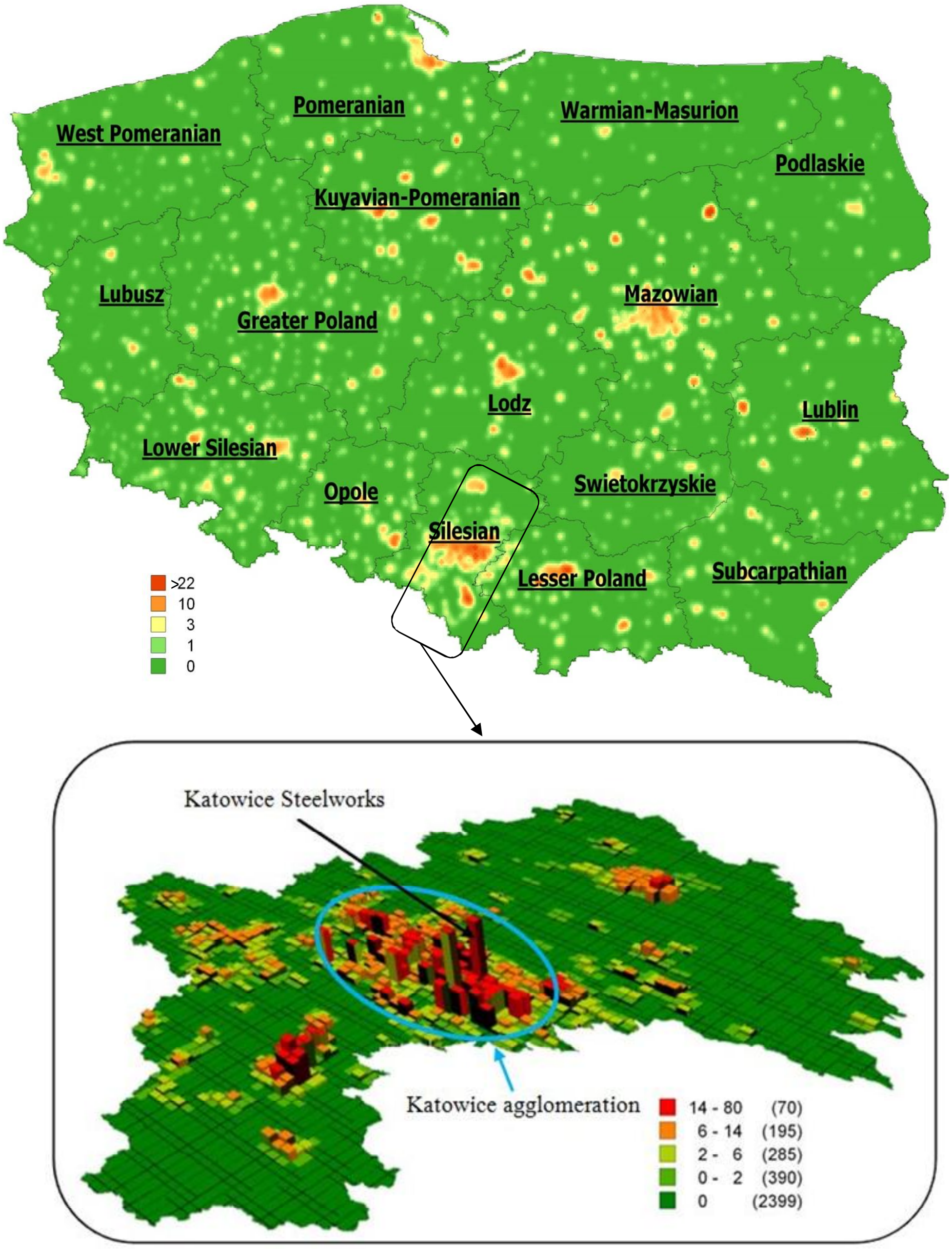

Fig. 6. The total specific GHG emissions in the industry sector in Poland, and detailed visualization of specific GHG emissions in the industry sector in the Silesian voivodeship at the level of industrial zones by using prism-map (CO_2-equivalent, Gg/km^2, grid 2 x 2 km, 2010)

less even if we recalculate them in CO_2-equivalent using global warming potentials of these gases. The spatial distribution of emissions can be seen in Fig. 6, where the total specific GHG emissions in the industry sector in Poland are presented. The most industrialized voivodeship, Silesia, causes the highest emissions. Therefore in this figure a detailed visualization of specific GHG emissions in the industry sector in this voivodeship is demonstrated on grid by using the prism-map. Results in this spatial form are very useful for policymakers because they show emissions where they occur.

REFERENCES

1. 2006 IPCC Guidelines for National Greenhouse Gas Inventories, H.S.Eggleston, L.Buendia, K.Miwa, T.Ngara, K.Tanabe, eds., IPCC, Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan, 2006, 5 volumes. Available online at: www.ipcc-nggip.iges.or.jp/public/2006gl/index.html.
2. Poland's National Inventory report 2011: Greenhouse Gas Inventory for 1988–2009. National Centre for Emission Management at the Institute of Environmental Protection – National Research Institute, Warszawa, May 2011. Available online at: http://unfccc.int/national_

reports/annex_i_ghg_inventories/national_inventories_submissions/items/5888.php.

3. Uncertainties in Greenhouse Gas Inventories - Expanding Our Perspective. 2015. Ometto J.P., Bun R., Jonas M., Nahorski Z. (Eds.), Springer 2015, 239.
4. **Longley P., Goodchild M., Maguire D.** and **Rhind D**. **2005.** Exploring geographic information systems and science, John Wiley & Sons, USA, 517.
5. **Boychuk Kh.** and **Bun R. 2014.** Regional spatial inventories (cadastres) of GHG emissions in Energy sector: Accounting for uncertainty, Climatic Change, vol. 124, is. 3, 561–574.
6. **Osypenko V. 2012.** The algorithm of bifurcation points forecasting in the analytical researches of complex agro-ecological systems, Econtechmod: an international quarterly journal on economics in technology, new technologies and modelling processes. – Lublin–Rzeszow, Vol. 1, No. 2., 35–38.
7. **Zotkiewicz Z**. and **Karwinski A. 2012**. Effect of temperature on the volume of gas emissions, Econtechmod, 2012, vol. 1, n. 2, 75–84.
8. **Hamal Kh.** 2008. Carbon dioxide emissions inventory with GIS, Artificial Intelligence, Donetsk, Ukraine, n. 3, 55–62.
9. **Boychuk P., Boychuk Kh., Nahorski Z. and Horabik J. 2012.** Spatial inventory of greenhouse gas emissions from the road transport in Poland, Econtechmod, Poland, vol. 1, n. 4, 9–16.
10. **Yaremchyshyn O., Bun R. and Hamal Kh. 2009.** The specialized geoinformation system of modelling and analysis of greenhouse gases emission in industrial sector at regional level, Artificial Intelligence, no. 3, 152–159.
11. **Charkovska N.**, **Bun R.**, **Nahorski Z.** and **Horabik J.** 2015. Modelling GHG emissions in the mineral products industry in Poland: An uncertainty analysis, Mathematical Modeling and Computing, vol. 2, is. 1, 16–26.
12. **Charkovska N., Bun R., Nahorski Z.** and **Horabik J. 2012.** Mathematical modeling and spatial analysis of emission processes in Polish industry sector: cement, lime and glass production, Econtechmod, Poland, vol. 1, n. 4, 17–22.
13. **Tokar O., Lesiv M. and Korol M. 2014**. Information technology for studying carbon sink in stemwood of forest ecosystems, Econtechmod, Poland, vol. 3, n. 1, 113–120.
14. **Turkovska O.** and **Gusti M. 2013.** A conceptual scheme for modeling forestry and LUC CO_2 emissions in Ukraine, Econtechmod, Poland, vol. 2, n. 1, 57–62.
15. Corine Land Cover maps. Available online at: http://www.eea.europa.eu/data-and-maps/data/corine-land-cover-2006-raster-2.
16. Rocznik statystyczny przemysłu 2010. Główny Urząd Statystyczny, 2012. Available online at: http://stat.gov.pl/gus/5840_3921_PLK_HTML.htm (in Polish).
17. Mały Rocznik Statystyczny Polski 2010, GUS, Warszawa, 2010, 289. (in Polish).
18. Zużycie paliw i nośników energii w 2010 r., Warszawa, Główny Urząd Statystyczny, 2011. (in Polish).
19. Bank Danych Lokalnych, Warszawa, Główny Urząd Statystyczny. Available online at: http://www.stat.gov.pl/bdl/ (in Polish).
20. Produkcja wyrobów przemysłowych w 2010 r. – GUS,2012. Available online at: http://www.stat.gov.pl/gus/przemysl_bud_PLK_HTML.htm (in Polish).
21. Sektor chemiczny w Polsce, Departament Informacji Gospodarczej Polska Agencja Informacji i Inwestycji Zagranicznych S.A., Warszawa, 2013, 16. (in Polish).
22. Annual report 2010 Chemical Industry in Poland. Available online at: http://www.pipc.org.pl/attachments/article/74/raport_roczny_2010.pdf.