4th International Workshop on Uncertainty in Atmospheric Emissions

7-9 October 2015, Krakow, Poland

PROCEEDINGS

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About the Workshop

The assessment of greenhouse gases and air pollutants (indirect GHGs) emitted to and removed from the atmosphere is high on the political and scientific agendas. Building on the UN climate process, the international community strives to address the long-term challenge of climate change collectively and comprehensively, and to take concrete and timely action that proves sustainable and robust in the future. Under the umbrella of the UN Framework Convention on Climate Change, mainly developed country parties to the Convention have, since the mid-1990s, published annual or periodic inventories of emissions and removals, and continued to do so after the Kyoto Protocol to the Convention ceased in 2012. Policymakers use these inventories to develop strategies and policies for emission reductions and to track the progress of those strategies and policies. Where formal commitments to limit emissions exist, regulatory agencies and corporations rely on emission inventories to establish compliance records.

However, as increasing international concern and cooperation aim at policy-oriented solutions to the climate change problem, a number of issues circulating around uncertainty have come to the fore, which were undervalued or left unmentioned at the time of the Kyoto Protocol but require adequate recognition under a workable and legislated successor agreement. Accounting and verification of emissions in space and time, compliance with emission reduction commitments, risk of exceeding future temperature targets, evaluating effects of mitigation versus adaptation versus intensity of induced impacts at home and elsewhere, and accounting of traded emission permits are to name but a few.

The *4th International Workshop on Uncertainty in Atmospheric Emissions* is jointly organized by the *Systems Research Institute of the Polish Academy of Sciences*, the Austrian-based *International Institute for Applied Systems Analysis*, and the *Lviv Polytechnic National University*. The 4th Uncertainty Workshop follows up and expands on the scope of the earlier Uncertainty Workshops – the *1st Workshop* in 2004 in Warsaw, Poland; the *2nd Workshop* in 2007 in Laxenburg, Austria; and the *3rd Workshop* in 2010 in Lviv, Ukraine.

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Accounting uncertainty for spatial modeling of greenhouse gas emissions in the residential sector: fuel combustion and heat production

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Abstract

Energy consumption in households has a great potential for energy savings as well as for greenhouse gas emission reduction. As national inventory reports provide estimates at only a country or regional level, we have developed a new GIS approach that increases the resolution of emission inventories. We consider stationary emission sources, such as fossil fuel combustion and heat production for household energy needs that cover energy demand for cooking, water and space heating. We estimate the spatial emissions of greenhouse gases based on IPCC guidelines using official statistics on fuel consumption and spatial data about population density. The heating degree-day method was then used to determine the climatic conditions and spatial variability in energy demand. The results of the spatial inventory are obtained for settlements that are presented as area-type emission sources in a geospatial database. The uncertainties in the inventory results are estimated using a Monte Carlo method. The results show that uncertainties in greenhouse gas emissions at the regional level are significantly higher than at the country level although the uncertainty of emissions in CO_2-equivalent does not exceed 17.0%.

Keywords: Greenhouse gas emissions, spatial inventory, residential sector, heat production, uncertainty of inventory results.

1. Introduction

Climate change refers to a change in the long-term weather patterns that are specific to different regions of the world. Many researchers agree that the most likely reason for climate change is the increasing greenhouse gas emission concentration in the atmosphere [9]. Since the industrial revolution began, the emissions of greenhouse gases have increased by 40% compared with the pre-industrial period [16]. It is therefore important to draw attention to issues of climate change, directing our efforts towards reducing greenhouse gas emissions and mitigating the negative effects of processes that are already happening [9], [18]. However, these can only be achieved through joint efforts that involve as many countries as possible globally.

Greenhouse gas emissions can be reduced through more efficient usage of energy resources, transition to fuels with higher calorific values and lower emission coefficients or increasing the share of renewable energy. However, before investing in these changes, it is important to identify large emission sources, and therefore estimate the potential for emission reduction for those areas. Accounting uncertainty for spatial modeling of greenhouse gas emissions is an important part of such an analysis.

As the residential sector has a great potential for greenhouse gas (GHG) emission reduction compared to other sectors, especially in developing countries, we, therefore, focus in this study on the analysis of emissions from direct fossil fuel use and heat production for household energy needs. We discuss mathematical models and algorithms that have been developed for spatial analysis of GHG emissions and present the method to estimate the influence of the uncertainty of individual inventory components on the total uncertainty of the inventory results. We apply the approach developed here using available statistical data for Poland and present the obtained results.

2. Spatial modeling of greenhouse gas emissions in the residential sector

Greenhouse gas emissions in the residential sector constitute a significant share in total emissions in most countries [20]. The emissions in this sector are caused by burning coal, natural and liquefied gas, wood and other fossil fuels in order to meet the energy needs of the households such as cooking, water and space heating. These needs can be covered from centralized energy supplies (e.g., district heating) or from "individual" energy sources (i.e. energy that is obtained through direct fossil fuel combustion).

The assessment of energy demand is not a new task. There are many global and regional models that analyze energy needs in the residential sector. Some models describe the household energy consumption on global scale for different regions of the world [4], [10], while other models are developed for a particular country [7], [13], administrative district or a city [11-12], [14-15], [19]. However, most of these approaches analyze energy demand and greenhouse gas emissions only on an aggregated level and do not perform an inventory for large areas at a high spatial resolution.

The aim of spatial modeling of GHGs is to obtain geographically distributed information on the amount of gases emitted from different sources [2], [3]. Therefore the inventory process consists of two main steps. First, we identify the emission sources for the sector of interest and then we allocate the amount of fossil fuels that were burned to cover certain energy needs in this sector. Based on this data we can estimate the GHG emissions for every emission source.

A spatial inventory of GHG emissions in the residential sector includes one additional step. As there are no statistical data on energy consumption and fossil fuel use at the level of settlements, statistical data must be disaggregated from the regional level to the level of elementary objects. Therefore, the development of the disaggregation algorithm is an important part of the inventory process.

2.1. Input data

Population density is the most essential input data for the estimation of the spatial distribution of GHG emissions in the residential sector as it is used in the creation of the geospatial database for the spatial GHG inventory. The territory of Poland was first clipped from the map of population density for the European Union and Croatia [8] and then the population estimation was adjusted using official statistical data. The objects of the population map are referred to as elementary, as they contain information about the size of the population at the lowest possible level.

As most of the energy in the residential sector in Poland is used for space heating, heating degree-days are, therefore, another important driving factor for the amount of energy that is used by households. Yearly heating degree-days were estimated as a sum of the daily deviation of the mean temperature from a heating base temperature but were only calculated for those days when the mean temperature was lower than the base temperature [5].

The statistical data on the amount of fossil fuels used in the residential sector was taken from the Energy Statistics Yearbook published by the Central Statistical Office while other input information was taken from online database of official statistical data in Poland [1]. Net calorific values as well as emission coefficients were taken from [17]. In the case where country specific values are available, we use default coefficients from IPCC guidelines [6].

2.2 Estimation of greenhouse gas emissions

In many countries the statistical data about fossil fuels consumption are available only at a country or regional level. Therefore, to obtain the information about the amount of fossil fuel burned at the level of an elementary object, we need to disaggregate the fossil fuels. In the case of direct fossil fuel combustion, the amount of fuel is allocated proportionally to energy demand for cooking, water and space heating, taking into account access to energy sources, the percentage of living area equipped with central heating and the hot water supply.

The total amount of energy required to provide comfortable indoor temperature depends on the characteristics of the building (e.g. the number of floors, the year of construction), climatic features of the region (e.g. amount of heating degree-days), the intensity of building use (e.g. working-time or day of the week factor) and heat energy losses due to several factors such as entrance/exit and ventilation. Heating degree-days are determined based on the daily average temperatures taking into account the duration of the heating period. The total energy demand for space heating in the elementary object (i.e. city, town or village) is determined as the sum of the heat energy needed for space heating for all buildings in the settlement. It is estimated using average indicators of heat energy needed for heating one square meter of living space:

$$Q_h = k_{HDD} \cdot \sum\nolimits_{year} Q_{h,year}^{sqm} \cdot LA_{year},$$

where $Q_{h,year}^{sqm}$ is the energy demand per square meter of living area constructed in *year* in the elementary object, k_{HDD} is the relative change in the amount of heating degree-days and LA_{year} is the living area per person (square meter) in buildings that are constructed in *year*.

District space heating is another source of energy for space heating. It is provided to households from many heat production locations, in most cases within urban areas. As it is complicated to identify the location of these point sources, we consider settlements as area sources of emissions. The statistical data on the amount of heat energy provided to households is available at the district level while the amount of fossil fuel that is used to generate this heat energy is accessible only at the regional level. Therefore, these data are disaggregated to the elementary object level proportional to the living area equipped with central heating.

As fossil fuels for centralized heat production and individual household energy needs were disaggregated to the level of elementary objects, we calculate the emissions of greenhouse gas G from burning fossil fuel i in elementary object n using the following formula:

$$E_{i,n}^{G} = M_{i,n} \cdot EF_{i,n}^{G}, n = \overline{1, N},$$

where $EF_{i,n}^{G}$ is the emission factor of G greenhouse gas and $M_{i,n}$ is the amount of fossil fuel.

At the level of elementary objects, the GHG emissions are determined as the sum of emissions from all sources within this geographical object.

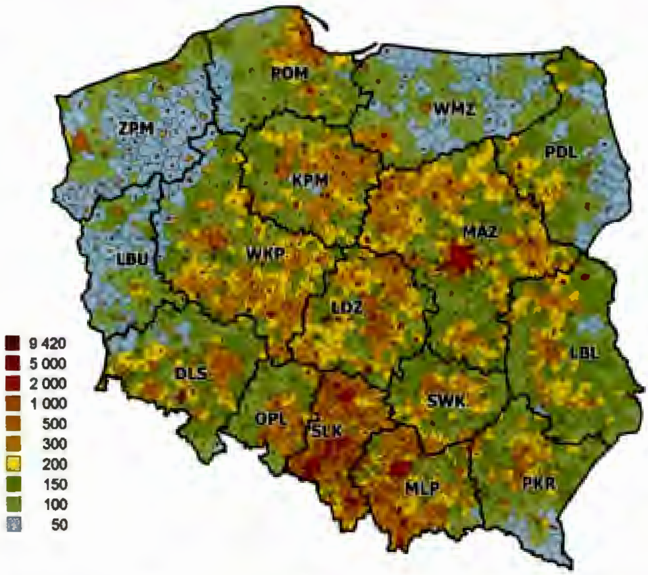

Figure 1. Specific greenhouse gas emissions from direct fossil fuel combustion in the residential sector in Poland at the level of municipalities (tons/km^2, CO_2-equivalent, 2010)

Figure 2. Prism-map of specific greenhouse gas emissions from direct fossil fuel combustion in the residential sector in the Silesia region at the level of elementary objects (tons/km^2, CO_2-equivalent, 2 x 2 km, 2010)

2.3. Results of the spatial inventory of greenhouse gas emissions

The largest emissions from direct fossil fuel combustion in the residential sector are in Masovian (MAZ - 14.4%), Silesian (SLK - 11.9%) and Greater Poland (WKP - 10.3%) regions as shown in Figure 1. Emissions in other regions do not differ significantly and range from 2.03% to 8.12%.

As the region of Silesia is the most urbanized area in Poland and it is a part of the Katowice agglomeration, accounting for more than 3 million people according to the Department of Economic and Social Affairs of the United Nations organization, the emissions in this region are, therefore, high when compared to other territories (Figure 1). Figure 2 presents specific emissions of greenhouse gases from direct fossil fuel combustion in the residential sector of Silesia. The highest specific emissions are in Katowice, Gliwice, Tychy (white circle), and Rybnik and Racibórz (black), Bielsko-Biała (pink) and Częstochowa (blue). The emissions from heat production are the highest in the Silesian region, but as emissions sources are very densely located (Figure 3), we sum up the emissions in this region together to compare with other regions that have much lower emission sources. GHG emissions from heat production in the Silesian region are much higher than in the Masovian region (2360 thousand tons in CO_2-eq., 16.87% of total emissions in this sector, Figure 3) and any other region although emissions in the Masovian region are also relatively high (1790 thousand tons, 12.8% of total emissions).

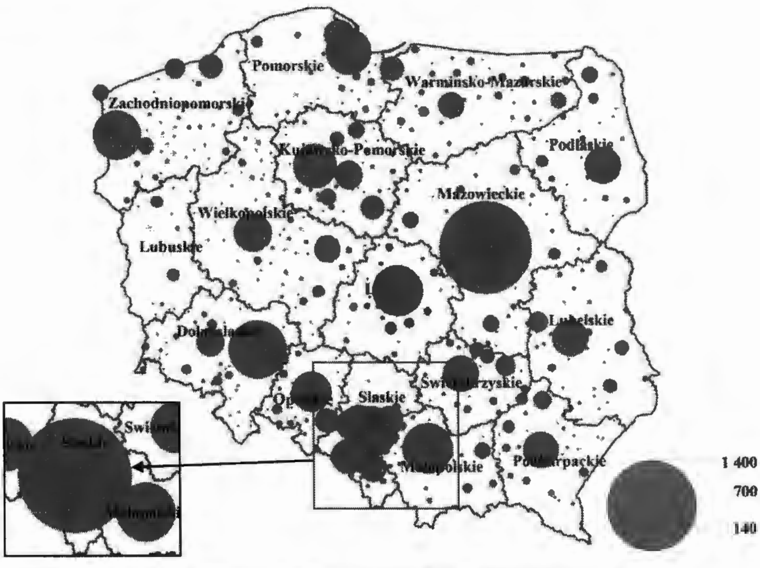

Figure 3. Greenhouse gas emissions from heat production in Poland (thousands tons, CO_2-equivalent, 2010)

3. Uncertainty analysis of inventory results

The obtained results of the spatial inventory are based on a set of input parameters that are not certain and are characterized by normal or log-normal distributions. The uncertainty in the input values of the model can be combined using an error propagation approach, but only in the case when all values are normally distributed and uncertainties are small. In our case, some input values are log-normally distributed (e.g., CH_4 and N_2O emission coefficients). Therefore we used a Monte-Carlo method to sample random variables from these distributions using R. We considered a 95% confidence interval for estimating uncertainty in the emissions. We then performed an uncertainty analysis of the inventory results at the regional level, as most of the fossil fuels are disaggregated from this level downwards.

Table 1. Results of uncertainty estimation of greenhouse gas emissions from direct fossil fuel combustion in the residential sector in Poland (using data from 2010).

Voivodeship	**CO_2,** Gg (uncertainty, %)	**CH_4,** Gg (uncertainty, %)	**N_2O,** Gg (uncertainty, %)	**Total emission** Gg (uncertainty, %)
Lower Silesian	2635,8 (-12,9 : +14,9)	5,4 (-21,4 : +25,5)	0,03 (-19,7 : +23,2)	2780,50 (-13,2 : +15,2)
Kuyavian-Pomeranian	1741,5 (-14,5 :+16,7)	4,0 (-21,5 : +25,5)	0,02 (-19,9 : +23,4)	1848,54 (-14,7 : +16,9)
Lublin	1982,9 (-14,3 : +16,5)	4,5 (-21,5 : +25,6)	0,03 (-19,8 : +23,4)	2103,56 (-14,5 : +16,8)
Lubusz	700,4 (-11,8 : +13,6)	1,3 (-21,3 : +25,4)	0,01 (-19,3 : +22,7)	735,77 (-12,1 : +14,0)
Łódź	2451,2 (-15,0 : +17,3)	5,8 (-21,6 : +25,6)	0,03 (-20,0 : +23,6)	2606,73 (-15,2 : +17,5)
Lesser Poland	3091,0 (-12,7 : +14,7)	6,3 (-21,4 : +25,5)	0,04 (-19,7 : +23,3)	3258,20 (-13,0 : +15,0)
Mazovian	4966,4 (-11,6 : +13,4)	9,2 (-21,3 : +25,3)	0,05 (-19,3 : +22,7)	5211,88 (-11,9 : +13,7)
Opole	893,8 (-14,5 : +16,7)	2,1 (-21,5 : +25,6)	0,01 (-19,9 : +23,5)	948,65 (-14,7 : +17,0)
Subcarpathian	1889,5 (-13,0 : +15,0)	3,9 (-21,4 : +25,5)	0,02 (-19,8 : +23,4)	1994,03 (-13,3 : +15,3)
Podlaskie	759,6 (-14,3 : +16,5)	1,7 (-21,4 : +25,5)	0,01 (-19,8 : +23,2)	805,83 (-14,5 : +16,8)
Pomeranian	1478,1 (-11,7 : +13,5)	2,8 (-21,3 : +25,4)	0,02 (-19,2 : +22,7)	1552,03 (-12,0 : +13,8)
Silesian	4591,5 (-13,8 : +15,9)	10,1 (-21,4 : +25,6)	0,06 (-19,9 : +23,4)	4860,85 (-14,1 : +16,2)
Świętokrzyskie	1106,2 (-14,5 : +16,7)	2,5 (-21,5 : +25,6)	0,01 (-19,9 : +23,4)	1174,20 (-14,7 : +17,0)
Warmian-Masurian	900,1 (-13,0 : +15,0)	1,9 (-21,4 : +25,5)	0,01 (-19,5 : +23,0)	949,97 (-13,2 : +15,3)
Greater Poland	3013,4 (-12,4 : +14,3)	5,9 (-21,3 : +25,4)	0,04 (-19,5 : +22,9)	3172,27 (-12,7 : +14,6)
West Pomeranian	1163,7 (-9,6 : +11,0)	1,8 (-21,0 : +25,1)	0,01 (-18,6 : +21,9)	1210,98 (-9,9 : +11,3)

According to the IPCC classification, the residential sector is part of the 1A4b category in the energy sector. The uncertainty of CO_2 emissions in this sector at the country level is relatively low – around 3.0% (National inventory report of Poland, 2010), as the uncertainty of the activity data is 4% and the uncertainty of the emission factor is 1% for liquid fuels and 2% for gaseous and solid fuels. Such low uncertainties in the input data can be explained by the high level of statistical data aggregation and overall accurate energy statistics at the country level.

However, in our spatial approach, we used data about fossil fuel consumption at the regional level, which is in units of weight. We first converted these data to energy units using national or default (IPCC guidelines) net calorific values, which we later disaggregated and then used for the emission estimations. By using regional statistics on fossil fuel combustion instead of country level data, we reduced the uncertainty due to disaggregation, but at the same time we introduced uncertainty in the net calorific values, which are rather high (e.g. 19.1% for coal). This leads to an increase in emission uncertainty at the regional level (Table 1) compared to the uncertainty in emissions at country level, as mentioned previously.

The statistical data on coal and liquid gas usage at the regional level were available in units of weight while the data on natural gas combustion are available in energy units. As a result, the uncertainty is slightly lower in those regions where natural gas constitutes a bigger share in the total energy consumption in the residential sector (e.g. Wielkopolskie voivodeship) compared to other regions.

4. Conclusions

Uncertainty analysis is an important part of the spatial inventory of greenhouse gas emissions as it gives an understanding of the ranges in which the emission estimates fall and which parameters of the model introduce the highest uncertainty into the model results. This information can be used to find possible ways to decrease uncertainties in the emission inventory when disaggregated to subnational level and to build more certain spatial cadasters of greenhouse gas emissions.

The spatial inventory of greenhouse gas emissions from direct fossil fuel combustion and heat production for residential sector energy needs was conducted using the official statistical data, national emission coefficients and net calorific values (or recommended by IPCC in the absence of national data). The obtained results show that uncertainties of greenhouse gas emissions at the regional level are significantly higher than at the country level; however, the uncertainty of emissions in CO_2-equivalent does not exceed 17.0%.

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