

# Regional spatial inventories (cadastres) of GHG emissions in the Energy sector: Accounting for uncertainty

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**Abstract** An improvement of methods for the inventory of greenhouse gas (GHG) emissions is necessary to ensure effective control of commitments to emission reduction. The national inventory reports play an important role, but do not reflect specifics of regional processes of GHG emission and absorption for large-area countries. In this article, a GIS approach for the spatial inventory of GHG emissions in the energy sector, based on IPCC guidelines, official statistics on fuel consumption, and digital maps of the region under investigation, is presented. We include mathematical background for the spatial emission inventory of point, line and area sources, caused by fossil-fuel use for power and heat production, the residential sector, industrial and agricultural sectors, and transport. Methods for the spatial estimation of emissions from stationary and mobile sources, taking into account the specifics of fuel used and technological processes, are described. Using the developed GIS technology, the territorial distribution of GHG emissions, at the level of elementary grid cells 2 km×2 km for the territory of Western Ukraine, is obtained. Results of the spatial analysis are presented in the form of a geo-referenced database of emissions, and visualized as layers of digital maps. Uncertainty of inventory results is calculated using the Monte Carlo approach, and the sensitivity analysis results are described. The results achieved demonstrated that the relative uncertainties of emission estimates, for CO<sub>2</sub> and for total emissions (in CO<sub>2</sub> equivalent), depend largely on uncertainty in the statistical data and on uncertainty in fuels' calorific values. The uncertainty of total emissions stays almost constant with the change of uncertainty of N<sub>2</sub>O emission coefficients, and correlates strongly with an improvement in knowledge about CH<sub>4</sub> emission processes. The presented approach provides an opportunity to create a spatial cadastre of emissions, and to use this additional knowledge for the analysis and reduction of uncertainty. It enables us to identify territories with the highest emissions, and estimate an influence of uncertainty of the large emission sources on the

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uncertainty of total emissions. Ascribing emissions to the places where they actually occur helps to improve the inventory process and to reduce the overall uncertainty.

## 1 Introduction

Uncertainty estimation is an integral part of a multifaceted process of greenhouse gas (GHG) inventory. A high quality of uncertainty estimates for a GHG inventory is crucial for the implementation of mechanisms under the Kyoto Protocol (such as Emissions Trading, the Clean Development Mechanism and Joint Implementation), as well as for establishing new treaties of environmental protection (Jonas et al. 2014). The importance of this problem is increasing because scientists have outlined a target so that the average global temperature should not increase by more than 2°C from its pre-industrial level. Therefore, the uncertainty of the GHG inventory is an important part of the general problem of uncertainty underlying climate change (Yohe and Oppenheimer 2011).

International agreements regarding the reduction of GHG emissions operate with estimates of emission and absorption on a country scale, and therefore uncertainty estimates of total emissions at country level are of great interest (Winiwarter 2007). However, these uncertainties are not constant, and change constantly (Lesiv et al. 2014). The main two factors of uncertainty changes in relative terms are ‘knowledge increase’ and structural changes in GHG emissions. Therefore, increasing knowledge on uncertainty and on reasons for its change is very important for reducing uncertainties in GHG inventories, and setting realistic emissions targets (Lesiv 2011).

Moreover, for governmental bodies it is desirable to possess an effective tool, enabling the analysis of the separate constituents of complex processes of GHG emissions and absorptions, both at regional (Feliciano et al. 2013), as well as at spatial levels (Hamal 2009; Mendoza et al. 2013). Such a tool would give the possibility of obtaining integrated information on the actual spatial distribution of GHG sources and sinks, and thus of finding optimum ways of solving a number of economic or environment protection problems (Bucki 2010; Bun et al. 2010). Spatial analysis of GHG emissions provides very important information about actual location of anthropogenic sources of emissions at the regional level. Corresponding regions, or large-scale point emission sources with the greatest influence on overall emissions, can be identified, and investments decreasing the uncertainty in input data should increase mainly in these sources. Therefore, referring emissions to the places where they actually occur provides the opportunity to greatly improve the inventory process, and reduce the uncertainty of the overall inventory. This provides very useful opportunities for analysing the separate constituents of inventory results’ uncertainty (Uvarova et al. 2014), using specialised techniques for uncertainty estimations (Joerss 2014) or spatial resolution improvement (Horabik and Nahorski 2014; 2010), and helps to find the most efficient ways for reducing uncertainty (Jonas et al. 2010; Nahorski et al. 2007).

This article discusses the bottom-up inventory of GHG emissions in the energy sector. The approaches to achieving geo-referenced cadastres of emissions are described, and methods of uncertainty reduction are presented. The main idea of the approach is to carry out a spatial cadastre of emissions, and to use the additional information on spatial distribution of emissions for uncertainty abatement.

## 2 GHG spatial inventory

In principle, the approach and methods for the spatial analysis of greenhouse gas emissions presented in this article can be applied to any region. As an example, techniques to analyse and

create spatial emission inventories for the region of Western Ukraine are used in this article. The study area is described in the supplementary material in (see Online Resource 1).

The results of the spatial inventory of GHG emissions contain the emission data for a certain time period, and additional information on geographical coordinates. For climatic models, and for the analysis of the territorial distribution of total emissions, it is desirable to operate with emission estimates at the level of elementary plots of equal, possibly small, areas. The size of a grid cell depends on the purpose of the inventory and on the total size of the territory under investigation. For example, dividing the territory into 30 km×30 km cells is reasonable for a large country, but such cells wouldn't properly reflect the emission distribution in the case of an inventory for a single city or administrative region.

The spatial inventory of GHG emission consists of the following steps: (i) carrying out an inventory for each grid cell, and for each category of activity using the 'bottom-up' approach; and (ii) summing up the inventory results for all activity subsectors. The GHG emissions of a certain economic activity in a single grid cell are, in turn, a sum of emissions from all the emission sources, which are fully or partially located within borders of this grid cell. In order to build a spatial cadastre of a particular gas emission, one calculates the specific emissions (emission per unit area) of this gas on each grid cell. Such specific emission values are calculated using the parameters and data which define the emission process for selected activity, also taking into account the geographical location of the emission sources; that is, for each category of anthropogenic activity characterised by relevant emission coefficients, the specific emission of GHG can be presented as a function of activity intensity in a certain territory (geographical coordinates) and time period.

## 2.1 Point, line and area emission sources

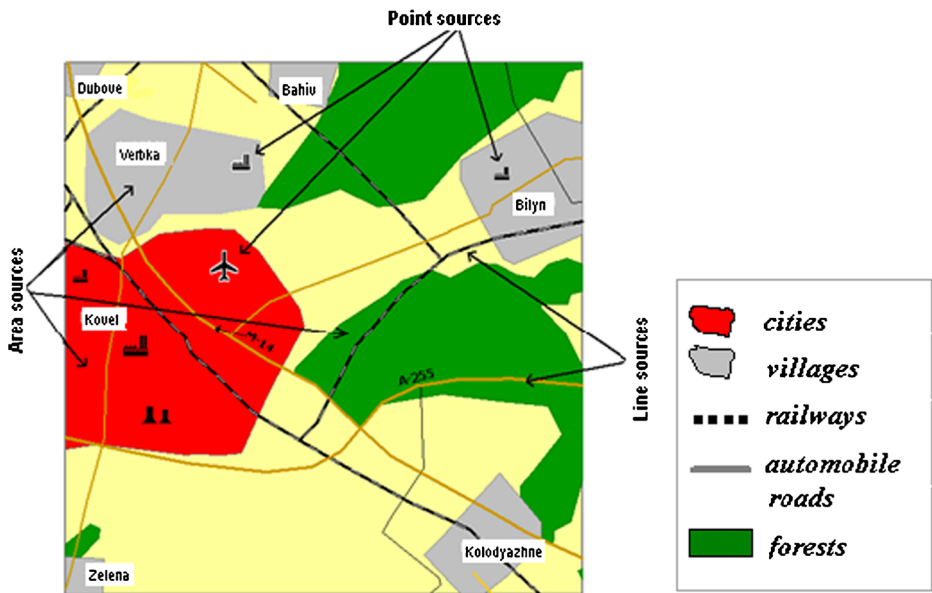
According to the internationally approved methodology of GHG emission inventory, the energy sector, or any other sector, consists of a number of subsectors, which in turn may be divided further into separate emission source groups (IPCC 2006). Within a separate grid cell, the dissimilar emission sources are located: large and small in size; mobile and stationary etc. (see Fig. 1).

To carry out a spatial analysis, it is reasonable to categorise all emission sources into three groups: line, area, and large-scale point sources. Approaches to modelling GHG emissions differ significantly among these.

Large emission sources with significant emissions and relatively small area are treated as large-scale point sources. For example, power stations, large industrial installations, as well as refineries, belong to this group. In the case of an inventory carried out for administrative regions, units or a country as a whole, these emission sources are introduced as large-scale point sources.

Large-scale point sources need to be localised precisely in the territory. Their corresponding emissions need to be positioned directly to the point in space, using geographical coordinates. The approach requires the following information to be available for each plant: activity data (e.g. amount of fuel used in technological process; amount of industrial production sold etc.), and additional parameters influencing emission coefficients (e.g. age and productivity of equipment on a plant; chemical characteristics of fuel used; detailed information on technological processes; efficiency of emission control equipment etc.).

The line emission sources include the sources which are represented in the form of lines. Roads, railways, oil and gas pipelines are treated as line emission sources. These emission sources are divided into sections, using the grid cells that overlap the road or pipeline network.



**Fig. 1** Example of classification of GHG emission sources in separate grid cells, divided into three types of sources: large-scale point sources, line and area sources

Furthermore, for each fragment of line, the corresponding emissions are calculated taking into account a number of parameters. These parameters include: road category; daily or annual traffic capacity; distance from settlements for road segments; presence of railway stations or other objects for railways etc.

The area sources encompass the sources where emissions occur from a surface occupying a certain area. Agricultural fields, forests, oceans, seas etc. are examples of area emission/absorption sources. It is reasonable to also include in this group the territories where a large number of small point or line emission sources are concentrated. For instance, in this paper, the area sources also encompass the urban road network, because of the high density of roads and streets. Other examples include households, territories where agricultural and building work is conducted, small enterprises and plants, small boiler plants, as well as territories where coal, oil or gas are extracted etc.

The spatial approach for GHG inventory takes into account a number of specific features, such as: economic activity for rather small territories; methods and technologies of fossil-fuel combustion in different economic sectors; technological specificity of extraction and refinement of primary fuels; availability and efficiency of cleaning installations etc. Therefore, in comparison to a 'traditional' GHG inventory, based on aggregated emission data for the whole country, the spatially referenced inventory may have a significant impact on the accuracy of the total emission estimates (Bun et al. 2010).

## 2.2 Main objects of geo-referenced inventory

The presented approach requires the possibility to operate with administrative units and separate sources of emissions, such as geographical objects, which have their own set of properties, including geographical characteristics.

Let us define a set of geographic objects and some special operations, which will be used in this paper:

$\tilde{O} = \{O_1, O_2, \dots, O_n\}$	is a set of all administrative regions (such as a province)
$\tilde{R} = \{R_1, R_2, \dots\}$	is a set of all small administrative regions (such as a district)
$\tilde{N} = \{N_1, N_2, \dots\}$	is a set of geographical objects, such as cities of direct regional subordination
$\tilde{S} = \{S_1, S_2, \dots\} = \{\tilde{S}^{Urb}, \tilde{S}^{Rur}\}$	is a set of settlements of all types
$\tilde{S}^{Urb} = \{S_1^{Urb}, S_2^{Urb}, \dots\}$	is a set of cities and towns
$\tilde{S}^{Rur} = \{S_1^{Rur}, S_2^{Rur}, \dots\}$	is a set of villages
$\tilde{D} = \{D_1, D_2, \dots\}$	is a set of geographical features, such as roads
$\Delta = \{\delta_1, \delta_2, \dots\}$	is a set of geographical objects, such as elementary square areas dividing territory into cells — for example 2 km × 2 km — but are also limited by the regional border.

For the GHG spatial inventory, we should also identify some ratios over the geographical features. They will not be used further in the set-theoretic sense, but for a definition of territorial belonging and mutual placement of such objects.

For geographical objects *A* and *B*, let’s define the following operations:

- 1)  $A \in B$  – geographically, object *A* is located entirely within object *B*;
- 2)  $A \cap B = C$  – object *C* is the common territory of objects *A* and *B*; and  $C \neq O$ , if the objects *A* and *B* have at least one common point on the boundary;
- 3)  $A \cup B = C$  – object *C* is the territory that is formed by combining the territories of geographical objects *A* and *B*;
- 4)  $A \setminus B = C$  – object *C* is a territory that was formed after cutting-off the object *B* territory from the object *A* territory.

The following properties of geographic objects are also used: *area(A)* is the area of the object *A*; *len(A)* is the length of linear object *A*; *wid(A)* is the width of object *A*; and *dist(A,B)* is the distance between objects *A* and *B*.

### 2.3 Spatial inventory of GHG emissions from stationary sources

Emissions from stationary sources in the energy sector contain emissions from processes of heat and power production, oil refineries, heating of residential buildings and industry, as well as fugitive emissions from oil, gas and coal extraction processes (IPCC 2006). A common feature for all these sources is that emissions should be located directly in the place where they occur.

In the sectors of heat and power production, as well as in oil refinery processes, all the emission sources should be classified into two types: large-scale point sources; or small territorially dispersed sources (Hamal 2009). For each selected large point source, information has to be collected on fuel consumption, technology of fuel treatment, implemented emission control systems, age of equipment, chemical characteristics of fuel used etc. Based on this, GHG emissions are estimated and geocoded to the elementary cell, using the address of a plant (power stations, big boiler plants, refineries etc.). The total amounts of fuel, combusted in small dispersed sources (small power stations, boiler plants), are ascribed to settlement areas (area emission sources), where these sources are located, proportionally to consumers’ presence or heat production.

The mathematical model of the  $G$ -th gas emission (carbon dioxide, methane, nitrous oxide etc.) for category ‘Power and Heat Production’ at the  $\delta$ -th elementary cell is defined as the amount of emissions from corresponding point and area sources:

$$E_{En}^G(\delta) = \sum_{i=1}^{I_\delta} \sum_{f=1}^F [M_{i,f} * EF_{i,tech}^G(f)] + \sum_{s \in \{\tilde{S}^E \cap \hat{\cap} \delta\}} \frac{\sum_{f=1}^F (M_{R,f}^{En} - \sum_{i=1}^{I_\delta} M_{i,f}) * Q(s) * EF_{En}^G(f)}{\sum_{k \in \{\tilde{S}^E \cap \hat{\cap} R\}} Q(k)}; R = \{R \in \tilde{R} \wedge \delta \in R\},$$

where  $R$  is the administrative region/district, where the  $\delta$ -th elementary cell is located;  $I_\delta$  is the number of point emission sources in the elementary cell belonging to the category ‘Power and Heat Production’;  $F$  is the number of fossil fuel types;  $M_{i,f}$  and  $M_{R,f}^{En}$  are consumption of the  $f$ -th type of fuel, respectively by the  $i$ -th point source, and at the region in total;  $\tilde{S}^E \in \tilde{S}^{Urb}$  is a set of urban settlements, where big power or heat plants are located;  $Q(x)$  is the number of residents in the geographical object  $x$ ;  $EF_{i,tech}^G(f)$  and  $EF_{En}^G(f)$  are the emission factors of the  $G$ -th gas from combustion of the  $f$ -th type fuel, respectively, on the  $i$ -th power plant, taking into account technological process specifics, and the average rate for all small heat and power plants; and index  $En$  reflects belonging to the sector ‘Power and Heat Production’.

As an example, the total specific emissions of carbon dioxide from burning coal, natural gas and other fossil fuels for electricity and heat production, in the Lviv region of Ukraine, are presented in a form of 3D thematic map in Fig. 2 (21.8 ths.km<sup>2</sup> area, 20 administrative districts). For better visual representation, the highest column, corresponding to the Dobrotviraska power station has been cut out from the map. Its emission is so high that makes it impossible to display differences in emissions from other sources.

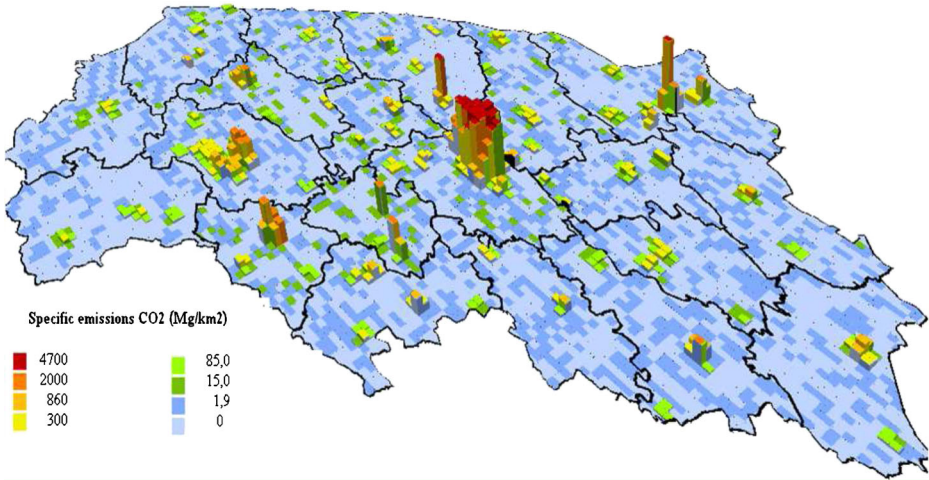
In the residential sector, households constitute small and territorially dispersed emission sources. In the models for this sector, the sources are represented by territories of settlements, and are classified as area sources. For most cities, accurate statistics on fuel usage in the residential sector are available, and the data can be directly related to the city territory. The remaining fuel is distributed among settlements, based on fuel type, settlement type, population density, parameters of average fuel usage for certain types of settlement in rural and urban territories etc.

Mathematical models and spatial inventory results for residential and other sectors are available as supplementary material (see Online Resource 1).

### 2.4 Spatial inventory of GHG emission from mobile sources

Emissions from all types of transport refer to GHG emissions from mobile sources. During fuel combustion in transport, the direct-acting GHG emissions occur; that is carbon dioxide, methane, nitrous oxide etc.

In the sector of road transportation, automobiles are the source of emissions. Since the investigation of emissions from each vehicle is not feasible in practice, it is reasonable to treat



**Fig. 2** Total specific emissions of carbon dioxide from burning all types fossil fuels in sector ‘Power and Heat Production’, at the level of elementary cells 2 km×2 km, Lviv region, 2008

roads and highways as GHG emission sources. According to the classification presented in Section 2.1, roads and highways belong to line emission sources. However, the urban road network is treated as an area source because of very high density, and only main urban roads are treated separately as line sources.

Statistical information on fossil-fuel usage in the road transport sector is available for the level of administrative units and cities from the yearbooks of fuel statistics (TSLR 2009). Other parameters, which will be used in the present model are available from statistical publications containing transport statistics, and from summarising yearbooks. In Ukraine, the input data for the GHG inventory are available either at the level of administrative regions and cities, or at the level of the province as a whole, depending on the administrative province.

In general, the level of GHG emissions in a certain grid cell depends on the amount of fuel consumed by transport within the cell borders. That is, prior to the spatial GHG emission inventory from the road transport, it is necessary to disaggregate the amount of fossil fuel used by transport to concrete emission sources, and to multiply the fuel quantity with the corresponding emission factors, in order to obtain emission estimates for a certain GHG. All the fuel used within an urban road network in a region is disaggregated directly to the territories of cities and suburban areas around cities. Therefore, the suburban territories of three levels are built around administrative borders of each city:  $Z^0(i)$  is a territory of the  $i$ -th city; the first suburban territory  $Z^1(i)$  (the first buffer zone) has a width of half the radius of the city area; the second zone  $Z^2(i)$  has one radius; and the third zone  $Z^3(i)$  has a radius of one and a half parts of the city radius. Then  $\tilde{Z} = \{Z^1(i), i \in \tilde{S}^Z\} \cup \{Z^2(i), i \in \tilde{S}^Z\} \cup \{Z^3(i), i \in \tilde{S}^Z\}$  is a set of analysed buffer zones around the cities, with more intensive automobile traffic. Here,  $Z^n(i)$  is the  $n$ -th level zone for the  $i$ -th city, and  $\tilde{S}^Z \subset \tilde{S}$  is a set of cities, the buffer zones for which have been built.

For big cities, the corresponding fuel consumption in the transport sector is gathered, and the data is located directly in the territory of the city and surrounding suburban areas. For small cities, the disaggregation of fuel used in transport is made proportional to population density.

The rest of fuel used in the transport sector in a region is divided among the automobile roads of a region (including main roads within settlements), according to the developed algorithms. The algorithms take into account the length and width of each road segment, its capacity and current state. In accordance with the above approach, the part of fuel (60 %), which was bought in a region, is used (burnt) within settlements borders, for the needs of internal transport. Moreover, it is assumed that, for cities, this part of fuel is divided additionally on automobile roads in suburban territories, located within a certain distance from the administrative borders of the settlement (zones  $Z^0, Z^1, Z^2, Z^3$  in proportion 40 %, 10 %, 6 %, 4 %, accordingly). The rest of the fuel (40 %) is assumed to be used outside the settlements, and is appointed to the road segments according to the road maps. The values of these coefficients are based on specific statistical data of automobile traffic (TSLR 2009), and on expert opinion.

Emissions for each source type (area and line sources) are calculated using the bottom-up approach. The quantity of a certain fuel type (diesel, gasoline etc.) is multiplied by the corresponding emission factor. Using the above assumptions, the emissions of carbon dioxide per year in the city  $S$  (or in a suburban zone built around it for  $S \in \tilde{S}^Z$ ), which belong to the administrative district  $R$ , are modelled with the formula:

$$E_{Tr}^{CO_2}[Z^n(S)] = \sum_{b=1}^B \sum_{t=1}^T \sum_{f=1}^F \left[ \frac{M_b^O(f, t) \cdot P^R(f, t, b)}{P^O(f, t, b)} \cdot EF_{Tr}^{CO_2}(f) \right] \cdot \frac{Q(S)}{\sum_{s \in \tilde{S}^R} Q(s)} C_n;$$

$$n = \overline{0, 3}; \quad O = \{O \in \tilde{O} \wedge S \in O\}; \quad R = \{R \in \tilde{R} \wedge S \in R\}; \quad \tilde{S}^R = \{\tilde{S} \cap R\},$$

where  $E_{Tr}^{CO_2}[Z^n(S)]$  is the emission of carbon dioxide in the settlement  $S$  (if  $n=0$ ) or in one of the conventionally constructed buffer zones around  $S$  ( $n=1,2,3$ );  $M_b(f,t)$  is the amount of the  $f$ -th type fuel used for vehicles of the  $t$ -th type, owned by  $b$ ;  $P(f,t,b)$  is the indicator used for the disaggregation of the total regional (like province) fuel consumption of the  $f$ -th type for the  $t$ -th type of vehicle, owned by  $b$ , at the level of administrative regions/district (such as mileage of cars using gasoline; diesel fuel sales through service stations; distribution of the number of cars in administrative units; the number of gas filling stations etc.);  $Q(s)$  is the number of habitants in settlement  $s$ ;  $EF_{Tr}^{CO_2}(f)$  is the emission factor for carbon dioxide, which depends on the type of fuel burnt;  $C_n$  is the coefficient, which reflects the proportion of fuel sold in the city for transport activity, in the  $n$ -th zone of this city;  $O$  and  $R$  are, respectively, provinces and regions/districts, where the city is located;  $B$  is the number of vehicle ownership types;  $F$  is the number of fossil fuel types (gasoline, diesel, etc.);  $T$  is the number of vehicle types (motor cars, buses, etc.); index  $Tr$  indicates that the corresponding parameters belong to the road transport sector.

For cities of province/regional subordination, the relevant statistical data about the consumption of fuel for transport activity are reflected separately in statistical reports. Hence for the needs of the spatial inventory, they can be ascribed directly to the territory of city and its suburban zones, in accordance with accepted ratios. For  $n$ -th suburban zone  $Z^n$  of the city  $N$  with regional subordination, the carbon dioxide emissions can be calculated by the formula:

$$E_{Tr}^{CO_2}[Z^n(N)] = \sum_{b \in B} \sum_{t \in T} \sum_{f \in F} [M_b^N(f, t) \cdot EF_{Tr}^{CO_2}(f)] \cdot C_n, \quad n = \overline{0, 3}$$

where  $M_b^N(f,T)$  is an amount of the  $f$ -th type fuel used in the  $N$ -th city of regional subordination, for transport activity of the  $t$ -th type vehicles, owned by  $b$ .



For any section of the road  $d$ , the coefficient  $C_{total}(d)$  is determined, which describes the status and parameters of this road section, and has the following form:

$$len(d) C [k(d), wid(d)] Cond(d),$$

where  $len(d)$  is the total length of the road  $d$ ,  $C[k(d),wid(d)]$  is the coefficient of the road  $d$  capacity, that depends on the road width  $wid(d)$  and category (or type)  $k(d)$ ;  $Cond(d)$  is the coefficient of a road current state (road is used,  $Cond(d)=1$ ; at the stage of repair or construction, or is unusable for any other reasons,  $Cond(d)=0$ ).

For the purpose of emission analysis, the road network is divided into sections within the borders of administrative districts and suburban zones  $\tilde{S}^z$ , located around the cities. The set of zones that includes a corresponding section of the road, can be marked as  $\tilde{Z}_d = \{z \in \tilde{Z} | d \in Z\}$ . It should be noted that the zones of zero order — i.e. territories of the cities — do not belong to this set.

Modelling of carbon dioxide emissions on the road section  $D \in \tilde{D}$  located within the region  $R$  is performed with the formula:

$$E_{Tr}^{CO_2}(D) = \sum_{b=1}^B \sum_{t=1}^T \sum_{f=1}^F \left[ \frac{M_b^O(f,t) \cdot P^R(f,t,b)}{P^O(f,t,b)} \cdot EF^{CO_2}(f) \right] \cdot \frac{C_{total}(D)}{\sum_{d \in \tilde{D}^R} C_{total}(d)} +$$

$$+ \sum_{z \in \tilde{Z}_D} \frac{E^{CO_2}(z) \cdot C_{total}(D)}{\sum_{i \in Z} C_{total}(i)}; \quad O = \{O \in \tilde{O} \wedge D \in O\}; \quad R = \{R \in \tilde{R} \wedge D \in R\}; \quad \tilde{D}^R = \tilde{D} \cap R,$$

where  $E_{Tr}^{CO_2}(D)$  are the carbon dioxide emissions on the road  $D$  section;  $M_b(f,t)$  is the amount of the  $f$ -th type fuel, used by the  $t$ -th type vehicles, owned by  $b$ ;  $P(f,t,b)$  is the indicator used for the disaggregation of the total regional (like province) consumption of fuel of the  $f$ -th type for the  $t$ -th type vehicle, owned by  $b$ , at the level of administrative regions/district;  $C_{total}(D)$  is the parameter of a road  $D$ , that determines its capacity;  $EF_{Tr}^{CO_2}(f)$  is the emission factor for carbon dioxide, that depends on the type of fuel burnt;  $O$  and  $R$  are provinces/regions and districts, respectively, in which a corresponding segment of the road  $D$  is located.

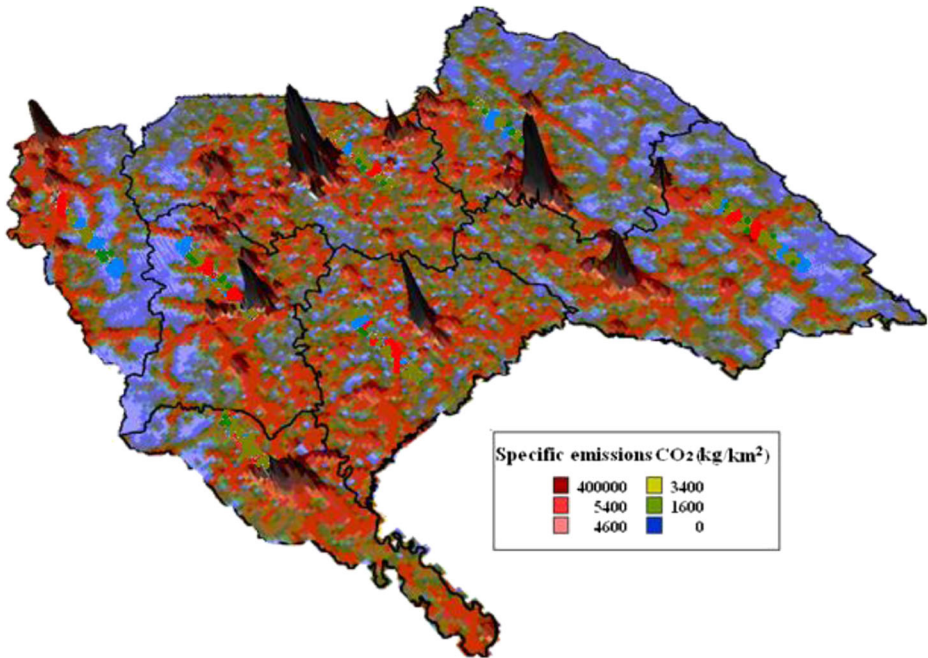
At the level of the elementary plot (i.e. grid cells level), all the emission sources of the transport sector are analysed (the territories of settlements and roads), which are partially or completely located within the corresponding grid cell. Therefore, the total emissions for the line and area sources can be found:

$$E_{Tr}^{CO_2}(\delta) = \frac{1}{2} \left[ \sum_{s \in \tilde{S}} \frac{E_{Tr}^{CO_2}(s) \cdot area(s \cap \delta)}{area(s)} + \sum_{d \in \tilde{D}} \frac{E_{Tr}^{CO_2}(d) \cdot len(d \cap \delta)}{len(d)} \right],$$

where  $E^{CO_2}(x)$  is the carbon dioxide emission, caused by a corresponding geographical object  $x$ ;  $area(x)$  is the object  $x$  area;  $len(x)$  is the length of a linear object  $x$ ; and  $\delta$  is the elementary plot (grid cell).

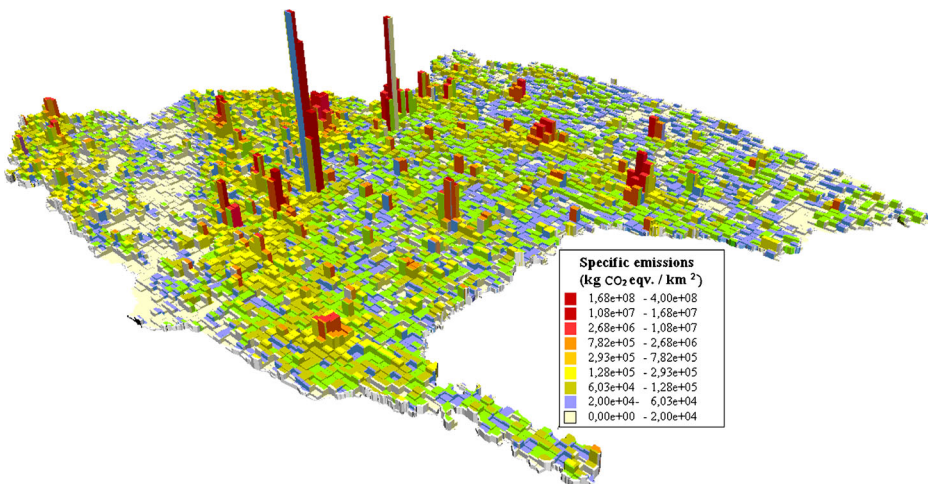
Spatial inventory of gases other than the carbon dioxide, as well as emissions from off-road and railway transport, is described in the supplementary material (see Online Resource 1). As an example of spatial analysis results, the specific emissions of CO<sub>2</sub> from gasoline combustion by road vehicles of firms (not private cars) for the western regions of Ukraine, are presented in a form of 3D thematic map, in Fig. 3.

Based on the approaches presented in (Hamal 2008), the geo-information system is developed for a practical implementation of algorithms for the geo-spatial inventory of GHG emissions, automatic creation of digital maps, visual analysis of obtained results, and



**Fig. 3** Specific emissions of CO<sub>2</sub> from gasoline combustion by road vehicles of firms in Western Ukraine regions (kg/km<sup>2</sup>, 2 km×2 km grid cells, 2009)

for uncertainty analysis. This geo-information system is described in the supplementary material (see Online Resource 1). The results may be visualised as digital maps with various thematic layers (see Fig. 4 as an example).



**Fig. 4** Prism map of specific direct-acting GHG emissions, summarised by all subsectors of the energy sector for Western Ukraine regions (2009, 4 km×4 km; CO<sub>2</sub>-eqv., kg/km<sup>2</sup>; owing to incompatibly high emission rates at Burshtyn and Dobrotvir power plants the scale of power 0.4 is used for visualisation)

### 3 Uncertainty evaluation and sensitivity analysis

Uncertainty of GHG emissions represents a lack of knowledge about the true value of emissions for a certain area. Uncertainties resulting from the assessment of GHG emissions depend largely on the method used, the quality of input data, uncertainties from expert judgements etc. (IPCC 2006).

Increasing knowledge about the investigated process can help to decrease uncertainties (Marland et al. 2009). Therefore, compared to a traditional inventory on the scale of the whole country, spatially referenced emissions have additional parameters: geographical coordinates. This provides new possibilities of analysis and uncertainty reduction. The introduction of new independent information about GHG emission processes, for separate emission sources or groups of sources, leads to a decrease in uncertainty of the total results (Winiwarter 2007).

The verification of spatial emissions disaggregation is described in supplementary material (see Online Resource 1), but uncertainty evaluation and sensitivity analysis is presented below.

Total uncertainty of emission modelling depends on uncertainties of all the input parameters. These uncertainties may be combined into a total uncertainty estimate of inventory results using the statistical tools specified in (IPCC 2006). For such an analysis it is important to have independent uncertainty ranges for emission coefficients, statistical data and other parameters of inventory process (Bun 2009).

In calculations, 'national' uncertainty ranges were used mainly for statistical data, emission coefficients and net calorific values. When the 'national' data were missing, the default IPCC uncertainty ranges were implemented. In the first step, the spatial results of emissions in each category, at the scale of 2 km×2 km, were summarised to a subregional level. Then the uncertainty ranges were estimated for all subsectors and greenhouse gases at the subregional level, using the Monte Carlo procedure. In the next step, these results were used as input data for uncertainty range estimates for the main subsectors in the Western Ukraine, also using the Monte Carlo method. Table 1 contains modelling results of emissions and uncertainty ranges by GHGs, and by economic sectors for Western Ukraine, in 2008.

**Table 1** Uncertainty estimates of GHG emissions by economic subsectors (Western Ukraine, 2008)

Sector	Emissions Uncertainty	CO <sub>2</sub>	CH <sub>4</sub>	N <sub>2</sub> O	Total emissions, CO <sub>2</sub> eqv.
Heat & power production, refinery	E (Gg)	20027,0	0,287	0,286	20122,1
	U(%)	-8,99..+9,45	-31,7..+0,46,74	-68,37..+160,3	-9,02..+9,48
Industry	E (Gg)	1731,5	0,067	0,011	1736,2
	U(%)	-6,61..+6,85	-42,33..+0,66,34	-58,97..+123,3	-6,62..+6,85
Road transport	E (Gg)	5191,5	1,867	0,332	5332,8
	U(%)	-5,65..+5,71	-38,33..+0,61,64	-42,97..+69,3	-5,72..+5,81
Railway and off-road transport	E (Gr)	730,5	0,123	0,315	830,5
	U(%)	-12,35..+12,36	-34,72..+51,64	-58,87..+112,9	-14,53..+17,91
Residential	E (Gg)	8135,1	2,281	0,039	8195,0
	U(%)	-11,44..+11,92	-48,92..+81,64	-62,87..+128,9	-11,47..+11,94
Oil, gas, coal extraction	E (Gg)	34,02	43,431	0,0012	946,43
	U(%)	-78,94..+81,72	-45,82..+48,54	-92,87..+328,9	-44,47..+46,94

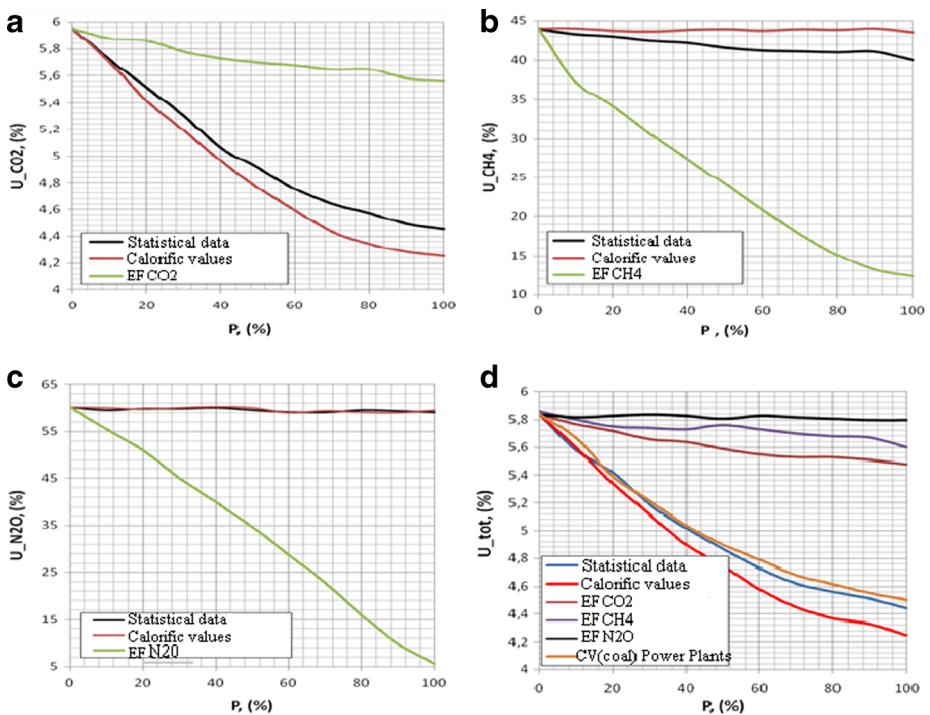
Uncertainty ranges of total GHG emissions from the energy sector in the territory of Western Ukraine are as follows:

- for CO<sub>2</sub>: – 5.76 %..+6.02 %;
- for CH<sub>4</sub>: – 41.45 %..+44.28 %;
- for N<sub>2</sub>O: – 36,93 %..+60.12 %;
- for total emissions taking into account Global Warming Potential factor: –5.74 %..+ 5.97 %.

The highest uncertainty of total emissions is noted for the processes of coal, gas and oil extraction, for transport (with the exception of road transport), and for the residential sector (Table 1). Relatively high uncertainties refer to emissions in the sector of heat and power production, mainly as a result of the domination of solid fuel.

Furthermore, the sensitivity of uncertainty in total emissions to the change of uncertainties in input parameters is investigated. The considered input parameters include: statistical data on economic activity; calorific values; and emission coefficients. Fig. 5 shows the results of analysis and sensitivity graphics of uncertainties of emission estimates for the improvement of accuracy of input parameters as a percentage  $P$ .

The results show that the relative uncertainty in emission estimates for both CO<sub>2</sub> and total emissions in CO<sub>2</sub> equivalent depends largely on uncertainty in the statistical data, and on uncertainty for calorific values of fuel. Uncertainty for total emissions stays almost the same with the change of uncertainty in N<sub>2</sub>O emission coefficients, and it is hardly correlated with an



**Fig. 5** Dependence of total uncertainty of emission estimates on the changes of uncertainty (on  $P$  %) of input parameters of inventory (Monte Carlo approach): **a** CO<sub>2</sub>; **b** CH<sub>4</sub>; **c** N<sub>2</sub>O; **d** total emissions

improvement in knowledge about CH<sub>4</sub> emission processes. For example, with the reduction by half of uncertainty in CH<sub>4</sub> emission coefficients, the uncertainty of total inventory results stays almost unchanged. On the other hand, the uncertainty in overall CH<sub>4</sub> emissions changes from 44 % to 24 %. A similar situation is revealed in the case of the reduction by half of uncertainty in N<sub>2</sub>O emission coefficients. The overall uncertainty of inventory results for all the direct-acting GHGs doesn't change, but there is a considerable reduction of N<sub>2</sub>O emission uncertainty, from 60 % to 35 % (the upper bounds of 95 % confidence intervals).

To summarise, despite large uncertainties in CH<sub>4</sub> and N<sub>2</sub>O emission coefficients, the improvement in their accuracy has no significant impact on the uncertainty reduction of total emissions in CO<sub>2</sub> equivalent. The most efficient way of reducing uncertainty is by improving the accuracy of statistical data on fuel statistics and calorific values.

In the energy sector, a reduction by half of uncertainty in the statistical data leads to a reduction of uncertainty in total emissions from 5.84 % to 4.87 %. An equivalent reduction of calorific value uncertainty leads to a reduction of overall uncertainty, to 4.75 %. Moreover, improvement only in the accuracy of physical and chemical characteristics of coal used in the power plants of Western Ukraine has a significant impact on a reduction of uncertainty in the overall GHG emission cadastre.

#### 4 Conclusions

The spatial analysis of GHG emissions provides important information about the actual location of the main anthropogenic emissions at the regional level. This approach provides an opportunity to carry out a spatial cadastre of emissions, and to use this additional knowledge for the analysis and reduction of uncertainty. Therefore, it enables us to analyse separate constituents of the complex processes of GHG emission and absorption, and also to obtain integrated information on the spatial distribution of the GHG sources. It also provides very useful opportunities for analyzing the distinct components of inventory uncertainty, using specialised techniques for uncertainty estimations, or the improvement of spatial resolution. Hence, in general, it helps to find the most efficient ways for uncertainty reduction.

A spatial integration of the geo-referenced inventory results for all the elementary plots (grid cells) yields a generalised result of the traditional inventory. The approach enables the identification of territories with the highest emissions, and estimates the influence of uncertainty from the large emission sources on the uncertainty of total emissions. Investments for the decrease of uncertainty in input data should be placed mainly in these sources. Therefore, ascribing emissions to the places where they actually occur helps to improve the inventory process and to reduce the overall uncertainty.

The results achieved for the western region of Ukraine demonstrated that the relative uncertainty of emission estimates for CO<sub>2</sub> and for total emissions (in CO<sub>2</sub> equivalent) depends largely on uncertainty in the statistical data, and on uncertainty in fuels' calorific values. The uncertainty of total emissions stays almost constant with the change of uncertainty of N<sub>2</sub>O emission coefficients, and is hardly correlated with an improvement in knowledge about CH<sub>4</sub> emissions processes. Despite great uncertainties regarding CH<sub>4</sub> and N<sub>2</sub>O emission coefficients, the improvement in their accuracy has no significant impact on the uncertainty reduction of total emissions in CO<sub>2</sub> equivalent. The most efficient way of reducing uncertainty is the improvement in the accuracy of data on fuel statistics and calorific values.

In conclusion, the geo-information technology of GHG spatial inventory at the regional level seems to be an effective tool to support decision-making regarding the considered problems of environmental protection.

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