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Spatial emission modelling for residential wood combustion in Denmark

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HIGHLIGHTS

- A new model for high resolution spatial distribution of RWC emissions is prepared.
- Using detailed heating installation data from the Building and Dwelling Register.
- Improved accuracy by changing to high spatial resolution of 1 km × 1 km.
- Model verification for Copenhagen against the previous model and a case study.
- Improved accuracy independently of the weighting factors chosen.

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ABSTRACT

Residential wood combustion (RWC) is a major contributor to atmospheric pollution especially for particulate matter. Air pollution has significant impact on human health, and it is therefore important to know the human exposure. For this purpose, it is necessary with a detailed high resolution spatial distribution of emissions. In previous studies as well as in the model previously used in Denmark, the spatial resolution is limited, e.g. municipality or county level. Further, in many cases models are mainly relying on population density data as the spatial proxy for distributing the emissions. This paper describes the new Danish model for high resolution spatial distribution of emissions from RWC to air. The new spatial emission model is based on information regarding building type, and primary and supplementary heating installations from the Danish Building and Dwelling Register (BBR), which holds detailed data for all buildings in Denmark. The new model provides a much more accurate distribution of emissions than the previous model used in Denmark, as the resolution has been increased from municipality level to a 1 km × 1 km resolution, and the distribution key has been significantly improved so that it no longer puts an excessive weight on population density. The new model has been verified for the city of Copenhagen, where emissions estimated using both the previous and the new model have been compared to the emissions estimated in a case study. This comparison shows that the new model with the developed weighting factors (76 ton $PM_{2.5}$) is in good agreement with the case study (95 ton $PM_{2.5}$), and that the new model has improved the spatial emission distribution significantly compared to the previous model (284 ton $PM_{2.5}$). Additionally, a sensitivity analysis was done to illustrate the impact of the weighting factors on the result, showing that the new model independently of the weighting factors chosen produce a more accurate result than the old model.

1. Introduction

Residential wood combustion (RWC) is an important emission source in Denmark contributing in 2013 with more than 60% of the emission of fine particles ($PM_{2.5}$), more than 70% of the emission of benzo(a)pyrene (BaP) and about 50% of the emission of dioxins and furans (PCDD/F) (Nielsen et al., 2016b). The corresponding shares for the 28 Member States of the European Union (EU-28) for residential combustion are 50% of $PM_{2.5}$, 71% of BaP and 37% of PCDD/F (CEIP, 2015a). RWC therefore has a significant effect on air quality and adverse impacts on human health. The World Health Organization (WHO) estimates that there were 3.7 million premature

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deaths in 2012 from urban and rural sources worldwide due to outdoor air pollution (WHO, 2014). Recent results (Brandt et al., 2013a, 2013b) show that outdoor air pollution caused a total number of 570.000 premature deaths in the year 2011 in Europe and around 3.500 premature deaths in Denmark alone. In Denmark, the RWC contributes with 30–40% of the premature deaths and the health related external costs due to air pollution from Danish emission sources alone, taking into account both primarily emitted particles and secondary formed inorganic aerosols (Brandt et al., 2013a).

High quality emission inventories of air pollutants are essential input to air pollution models. Likewise, air pollution modelling is an important input in human exposure models, which can further be applied for estimation of health effects and related costs used for decision support and air quality policy development. For modelling of air pollution on regional, national or local scale, there is a demand for high quality emission inventories on high spatial resolution. Modelling based on detailed spatially distributed emissions provides the opportunity to estimate effects of potential and implemented reduction measures and as such can be used as a decision support tool as described by e.g. Jensen et al. (2001) and Elbir et al. (2010).

Due to the need for spatially detailed emissions a number of high spatial resolution emission inventories have been prepared. Few studies have been prepared and documented to handle emissions at the national level, e.g. for Cyprus (Tsilingiridis et al., 2010), the United Kingdom (Tsagatakis et al., 2013) and Japan (Kannari et al., 2007), while more studies have been published documenting high resolution spatial emission inventories for single pollutants and/or sectors such as agricultural NH_3 emissions in Denmark (Skjøth et al., 2001) and in the UK (Hellsten et al., 2008), NMVOC emissions in China (Bo et al., 2008), PM emissions in Delhi (Sahu et al., 2011) and CO emissions in India (Dalvi et al., 2006).

Relatively few studies focusing specifically on residential combustion, or where the methodology behind the spatial distribution is thoroughly documented, have been published. Tian et al. (2004) presented a model for spatial variations of $PM_{2.5}$ emissions from residential wood burning in a study area in the central part of California. The model took into account several variables including demographic and climatic information. Also, information on forest accessibility and distinction between urban, suburban, and rural areas were considered in the modelling. Tian et al. (2004) found that the number of households using wood combustion was a more critical variable than the unit consumption. This indicates that the most critical issue is to estimate number and location. While the unit consumption (i.e. weighting between the installations) is still important, it is less critical to the overall result.

In 2010 the model “Spatial high resolution distribution model for emissions to air” (SPREAD; Plejdrup and Gyldenkærne, 2011) was developed in its first version, which has since then been improved continuously. The SPREAD model provides emissions on a 1 km × 1 km resolution grid, covering all pollutants and all anthropogenic sources in the Danish national emission inventories.

The SPREAD model is a relational database model handling emissions on source or sector level. National emissions are allocated geographically using source specific spatial distribution keys, i.e. normalised shares of the national emissions to be allocated to each single grid cell in the Danish territory. The level of detail reflects the importance of the source to total emissions and the spatial data available. One of the most important sub-models for emissions of several pollutants is the model for residential combustion.

In order to assess RWC's impact on local, national and regional air pollution levels, there has been an increased attention from policymakers and air pollution modellers to improve the spatial distribution of emissions from RWC and hereby decreasing the uncertainty of the input to air pollution models. Therefore, a new RWC distribution methodology has been developed. The new methodology does not rely on population density, which is the case in most published studies, as this is deemed to give an incorrect spatial distribution in Denmark, where the most densely populated areas are covered by district heating. Guttikunda and Calori (2013) used population density and income groups to spatially distribute emissions from the residential sector, and also, Wilson et al. (2006) used population density as the proxy for the spatial distribution. Ghilardi et al. (2007) combined supply and demand modelling to estimate consumption of fuelwood used in Mexico.

Compared to Tian et al. (2004) and to the previous model used in Denmark, the new model presented here is at a much higher resolution (1 km × 1 km) rather than on county or municipality level. Excluding population density from the spatial distribution and instead using location of RWC installations has further improved the model.

2. Methodology

2.1. National emission inventory methodology

Aarhus University prepares the official Danish emission inventories for greenhouse gases and air pollution according to the international technical guidelines (EEA, 2013; IPCC, 2006) for reporting to international conventions, i.e. the Convention on Long-Range Transboundary Air Pollution (CLRTAP) under the United Nations Economic Commission for Europe and the United Nations Framework Convention on Climate Change. Details on the methodologies used in preparing the emission inventories are documented elsewhere (Nielsen et al., 2016a; 2016b).

The Danish air emission inventory for RWC is based on information on the total number of appliances and a distribution on the types of wood burning appliances in Denmark, the wood consumption as included in the official Danish energy statistics (DEA, 2014) and technology specific emission factors (EFs). The Danish approach corresponds to the Tier 2 methodology in the EMEP/EEA Guidebook (EEA, 2013). However, the methodology has been modified to take into account the specific RWC technologies used in Denmark.

Information on the number and type of the stoves and boilers is obtained from a number of national surveys (Evald, 2012; previous versions; Illerup et al., 2007; Hansen, 2015). The inventory distinguishes between five different technologies for stoves and four different technologies for boilers. The emission factors (EFs) are for some combinations of technology and pollutant country-specific and refers to Danish measurements while others are referenced to measurements carried out for similar technologies abroad. Finally, there is a number of EFs that is based on EEA (2013).

The number of appliances, unit consumption, and emission factors used in the estimation of emissions from RWC for 2013 is included as additional information. For particulate matter it is important to note that Danish measurements are carried out in a dilution tunnel, which means that the derived emission factors include a contribution from condensables.

The resulting national emissions for 2013 are shown in Table 1. While wood pellets account for about 30% of the fuel consumption, the emission shares for this technology ranges between 2.1% for $PM_{2.5}$ and 8.5% for PCDD/F.

2.2. Spatial emission distribution methodology

According to the reporting guidelines under the LRTAP convention (UNECE, 2014), Denmark is obligated to report the

Table 1
Emissions of $PM_{2.5}$, PCDD/F and BaP from RWC in Denmark.

Technology	Description	$PM_{2.5}$ tonnes	PCDD/F g I-TEQ	BaP tonnes
Old stove	Stove pre-1990	2495	2.1	325
New stove	Stove with DS mark 1990–2005	5001	5.4	818
Modern stove	Stove conforming with Danish legislation	1572	0.6	156
Eco labelled stove	Advanced stove	801	0.4	39
Other stove	Including fireplaces	184	0.2	30
Old boiler	pre-1980 with accumulation tank	454	0.3	61
Old boiler	pre-1980 without accumulation tank	621	0.2	42
New boiler	post-1980 with accumulation tank	704	0.3	34
New boiler	post-1980 without accumulation tank	657	0.3	32
Pellet boilers/stoves		266	0.9	92
Total		12,755	10.8	1628
National total		21,237	21.8	2276

emission inventory spatially distributed on the EMEP (European Monitoring and Evaluation programme) grid with a resolution of 50 km × 50 km, changing to 0.1° × 0.1° from 2017 (CEIP, 2015b; UNECE, 2012). Furthermore, there is a request from the air pollution modelling community for emissions on an even higher resolution, for modelling of air quality, exposure and health impacts. To meet these requirements the SPREAD model was developed.

Spatial distribution is made on the most disaggregated source level obtainable by the available data related to allocation of emissions, taking into account availability of spatial data, and quality of the resulting spatial distribution. Distribution keys are set up using spatial analysis tools in a geographical information system, GIS. The emission distribution is made on the Danish Grid Net, designed in an orthogonal coordinate system referring to the UTM projection zone 32N using EUREF89, with a spatial resolution of 1 km × 1 km (NSC, 2012).

Denmark is a relatively small country (~43,000 km^2), and a high resolution grid must be applied to cover the national variations. The SPREAD model builds on detailed national data, which is necessary when operating on such high resolution, and which complies with the finding by Maes et al. (2009), that use of country specific methodology and data improves spatial emission distribution, especially on high resolution.

Spatial distribution of emissions from RWC is handled in a separate sub-model of SPREAD. The RWC model has undergone a large improvement since the latest official reporting of spatial emissions to CLRTAP, and it is therefore of importance to introduce both the previous and the new model, focusing on the differences in data basis, methodology, and results.

The following will describe the development of distribution keys for RWC, which holds the share of emissions to be allocated to each grid cell in the Danish part of the EMEP grid. A description of the methodology behind the spatial distribution of emissions from other sources in SPREAD is included in Plejdrup and Gyldenkærne (2011).

According to the previous methodology, spatial distribution of RWC was carried out on a resolution corresponding to the 271 municipalities in Denmark before the structural reform in 2007. The spatial distribution was based on wood consumption in the residential sector in each municipality, estimated from population density and from information from the Danish Building and Dwelling Register (BBR) regarding building age, building size, building type, and heating installations.

Among several reasons to update the RWC model, the most distinctive is implausible large emissions in the two municipalities in the capital (Copenhagen municipality and Frederiksberg municipality), due to including population density in estimating municipal wood consumption. Even though there are numerous wood burning appliances in the capital, the wood consumption is lower than the national average (Andersen, 2015), which is not reflected, but rather counteracted by including the high population density.

While other studies (e.g. Guttikunda and Calori, 2013; Wilson et al., 2006) have relied mainly on population density in their spatial distribution of emissions from the residential sector, this is not appropriate in Denmark. In Denmark the most densely populated areas are covered by district heating and as such the use of RWC is mainly for supplementary heating and in most cases related to creating a cosy atmosphere.

The updated RWC spatial emission model is based solely on information in BBR. To locate addresses with RWC, all records in BBR are analysed and classified according to the relevant information being:

- Building type, e.g. single-family house, apartment building, and holiday house.
- Heating installation, e.g. district heating, central heating, electricity heating, and stoves.
- Fuel, e.g. liquid fuel (i.e. gas oil), natural gas, and solid fuel (predominantly wood; in later years wood has accounted for more than 99.9% of the solid fuels consumption).
- Supplementary heating, e.g. woodstove, fireplace, and oil and gas radiators.

Through the following sequence of criteria, the RWC addresses are divided into three categories, covering primary RWC in stoves (criteria 1), primary RWC in boilers (criteria 2), and supplementary RWC (criteria 3).

1. Heating installation: ‘stove’, fuel type: ‘solid fuel’.
2. Heating installation: ‘central heating from private one-chamber boiler’, ‘central heating from private two-chamber boiler’, fuel type: ‘solid fuel’.
3. Supplementary heating: ‘stoves for solid fuels’ or ‘fireplace’.

BBR holds detailed data on both building and address level. However, the register still to some degree suffers from errors and lack of data. Biennial surveys on RWC in Denmark, carried out by the Danish Energy Agency (Hansen, 2015), estimate a rather constant number of residential wood fired appliances in Denmark around 750.000. By comparison less than 400.000 addresses have been classified as having RWC according to the analysis of BBR. Further, data from the chimney sweepers in the city of Copenhagen include ~16,000 wood stoves (H. B. Jensen, personal communication, 2015), but the BBR classification only returned ~2100 addresses.

In the BBR several different types of residential buildings are reported to have wood combustion installations. For the purposes of the spatial modelling these building types are classified into three groups as the wood consumption is assumed to differ between these groups. The three groups are: 'single-family house', 'apartment building', and 'holiday house'.

While Tian et al. (2004) found that the number and location of the appliances is most important, the differences in unit consumption for different building types are still considered to be important. This is cooperated by the study for Copenhagen (Andersen, 2015) that found differences of up to 30% for unit consumption between building types with district heating and an even larger difference when considering buildings without district heating. Therefore, weighting factors are applied in the model to account for the different wood consumption in building types. These factors have in this first model revision been based on expert judgement, as data to support this subdivision is not available on a national level. However, the assumptions are supported by findings by the Danish Energy Agency (DEA) (Hansen, 2015), that unit consumption in permanent residence is approximately twice of that for holiday houses (28 GJ vs. 17 GJ).

For primary RWC with wood boiler, a factor of 1 is applied for single-family houses and apartment buildings, while holiday houses have a weighting factor of 0.8, see Table 2. The relatively high factor allocated to holiday houses is assumed because the economic cost of installing a boiler and corresponding heat distribution system in the house means that the holiday house will be used for the majority of the year or even permanently inhabited, which is possible for retired people in Denmark. The corresponding factors for wood stoves for primary RWC are 0.8 for single-family houses and apartment buildings, and 0.2 for holiday houses. The factors for holiday houses are lower as they are generally smaller and occupied only part of the year mainly in warmer periods.

For supplementary RWC in single-family houses a weighting factor of 0.4 is applied, based on the assumption, that the wood consumption for supplementary heating is half the amount of primary heating with wood stoves, see Table 3. The wood consumption in apartments are assumed to be one tenth for supplementary heating (0.08) compared to primary heating, as the space for wood storage is limited, and access to and transport of the stored wood is often inconvenient. For holiday houses the same weighting factor is applied for supplementary RWC as for primary RWC with wood stove.

Numerous buildings have more RWC installations, e.g. apartment buildings and some are registered having RWC as both primary and supplementary heating source, mainly with wood boilers for primary heating. For these addresses, the contribution from each RWC installation are summarised in the calculation of distribution key, giving the share of the total emissions from RWC to be included in the separate grid cells.

According to the results from weighting of RWC at separate addresses, a normalised distribution key has been developed and included in the SPREAD model. In the distribution key, resulting weightings for all addresses in each grid cell is summarised and normalised. The final distribution key thereby include only two variables for each grid cell; the grid cell ID and the share of national RWC to be allocated to it. The normalised distribution key is multiplied with the national total emissions for RWC to calculate the resulting emissions in each grid cell.

Table 2
Weighting factors for RWC as primary heating per technology and building group.

Technology	Building group	Primary RWC
Boiler	Single-family house	1
Boiler	Holiday house	0.8
Boiler	Apartment building	1
Stove	Single-family house	0.8
Stove	Holiday house	0.2
Stove	Apartment building	0.8

Table 3
Weighting factors for RWC as supplementary heating per building group.

Technology	Building group	Supplementary RWC
Stove	Single-family house	0.4
Stove	Holiday house	0.2
Stove	Apartment building	0.08

As the distribution key includes only data on the shares of the national total emission to be allocated to the predefined grid cells, implementation of a new methodology for spatial distribution does not influence the national total emissions, but only the allocation of emissions. In this way, it is ensured that the spatial emissions are consistent with national total emissions, even though the distribution key undergoes an update.

3. Results and discussion

The new distribution key is based on the 400.000 identified appliances, assuming that the distribution is representative for the missing 350.000 appliances as well. The majority are categorised as supplementary heating (84%) mainly in single-family houses and holiday houses, which was expected, as district heating with mandatory connection is widespread especially in densely populated areas, and as wood stoves are widely used for cosiness. In contrast, only few RWC installations are expected in apartments, due to limited space for storage of wood, and the inconvenience of carrying wood to higher floors, which is in accordance with the finding that less than 1% of the RWC installations are located in apartments.

Many holiday houses are located outside the district heating areas and as they are mainly used in warmer periods and for short term stays, a large number are expected to use RWC for heating, which correspond with the finding that 25% of the RWC installations are located in holiday houses, see Table 4. Less than 2% of all addresses with RWC are categorised as using RWC for both primary and supplementary heating, the main part using wood boilers for primary heating.

Selection of weighting factors is a crucial part of the methodology and partly based on expert judgements. To verify the selected factors, a sensitivity analysis has been elaborated using

Table 4
Distribution of RWC based on building type and primary and supplementary heating.

Primary RWC	Supplementary RWC	Building type	% of RWC
Stove	Yes	Single-family house	0.20%
Stove	Yes	Apartment	<0.01%
Stove	Yes	Holiday house	0.29%
Stove	No	Single-family house	3.29%
Stove	No	Apartment	0.04%
Stove	No	Holiday house	3.99%
Boiler	Yes	Single-family house	1.42%
Boiler	Yes	Apartment	0.01%
Boiler	Yes	Holiday house	0.01%
Boiler	No	Single-family house	6.90%
Boiler	No	Apartment	0.04%
Boiler	No	Holiday house	0.07%
No primary RWC	Yes	Single-family house	62.19%
No primary RWC	Yes	Apartment	0.80%
No primary RWC	Yes	Holiday house	20.74%

Copenhagen as an example. As primary RWC is of minor importance in Denmark, only the weighting factors for supplementary RWC are analysed. The sensitivity analysis includes eight scenarios where the weighting factors have been increased or decreased by 50% for the three building types separately and for all three building types collectively (Table 5). As expected, the largest changes are identified when changing the factor for single-family houses, which are the dominant building type for RWC. Changing the factor for holiday houses leads to a inverse change of the emissions in Copenhagen. This is due to the fact that holiday houses are far more important in other parts of Denmark than in Copenhagen, and e.g. increasing the weighting factor will allocate a larger part of the national RWC emission to other parts of the country, leaving lower emissions in Copenhagen. Changing the factor for single-family houses cause the emissions in Copenhagen to change proportional, though to a lesser degree.

Introducing the new methodology for RWC has greatly improved the resulting emission pattern, by increasing the spatial resolution from municipality level to 1 km × 1 km. It can be seen that the impact of the weighting factors is limited, which is the same conclusion as reported by Tian et al. (2004).

The national total emissions of $PM_{2.5}$, PCDD/F and BaP from RWC in Denmark, as given in Table 1, has been allocated according to the previous model and the new model, and the resulting spatial $PM_{2.5}$ emissions are shown in Fig. 1a and b. According to the previous model, large proportions of the emissions from RWC are allocated to the capital area (Fig. 1a), but large emissions are also estimated for less populated municipalities, which is driven by parameters included from BBR (building age, building size, building type, and heating installation). Important in an air quality perspective is also the fact that emissions are allocated evenly on the area of each municipality, without any notice of where neither the population nor the RWC appliances are located. This results in emissions being allocated to areas where no people live, and hence to allocation of fewer emissions in populated areas of the municipalities. When used for air quality modelling, the concentration levels will be too low in populated areas, and the human exposure will be underestimated. Using the new methodology, emissions are allocated only to areas with RWC appliances (Fig. 1b), and air quality modelling will lead to more accurate concentrations and thereby more realistic estimates of human exposure. By excluding population density from the model, and by including weighting factors for apartment buildings, the high emission levels in the capital area (284 ton $PM_{2.5}$) are avoided, and the estimated emissions (76 ton $PM_{2.5}$) are more consistent with the results from the case study for Copenhagen municipality (95 ton $PM_{2.5}$), based on detailed data from the chimney sweepers and survey information (Andersen, 2015). The new model gives large emission levels along parts of the coastline, which corresponds to areas with many holiday houses, where RWC for heating is very common.

The emission inventory for RWC is subject to large uncertainties, both regarding the number of appliances, distribution across technologies, fuel consumption (national total as well as per technology), and emission factors, the latter significantly being affected by user behaviour. Additional uncertainty is added when emissions are spatially distributed, as the mentioned details are not known for each single appliance. Consequently, it is necessary to treat households with RWC at an aggregated level using average assumptions. Furthermore, the BBR data, which are the basis for the spatial distribution, are known to have errors and missing information, which is caused by the fact that property owners are expected to update information in BBR themselves. It is plausible that the first registration is mainly correct, but updates after reconstructions or replacements of e.g. heating installations might be neglected.

Case studies have previously shown that the number of wood stoves registered in BBR is too low. This is supported by new comparison of the number of RWC appliances based on data from BBR and from the chimney sweepers, where the chimney sweepers have registered 16,349 RWC appliances in the municipality of Copenhagen, but only 2047 has been classified using BBR data. Correspondingly, the chimney sweepers have registered 6843 RWC appliances on the Danish island Als (located of the east coast of the southern part of Jutland) (K. L. Christensen, personal communication, 2015), but only 2661 has been classified in BBR. In these two cases the BBR classification underestimates the number of RWC appliances by 87% and 61%, respectively. Data from the chimney sweepers are available for only very few areas of limited size, and is unusable as basis for the national model, but applicable for quality control and uncertainty assessment. In the future, efforts will be made to further verify the model by checking the model against data provided by chimney sweepers.

For the city of Copenhagen the new model estimates the emission of $PM_{2.5}$—76 ton in 2013. This compares to 284 ton using the previous model. Considering the high population density in the city of Copenhagen, the new model result will significantly change the estimated air quality and human exposure. The detailed information collected in the case study for Copenhagen, showed a higher number of appliances than the new model, but lower unit consumption than the national average. In the new model, the difference in unit consumption across building types was addressed using the weighting factors. In the case study for the city of Copenhagen the $PM_{2.5}$ emission was estimated to 95 ton (Jensen et al., 2015). The case study used the same basic methodology as the national model, e.g. the same definition of technologies. So in spite of the discrepancy in the number of appliances, the chosen weighting factors cause a good agreement between the new model result and the case study.

Table 5
Weighting factors and $PM_{2.5}$ emissions for supplementary RWC in the new methodology, and changes of $PM_{2.5}$ emissions for the sensitivity analysis scenarios.

Scenarios	Weighting factor for supplementary RWC			$PM_{2.5}$ emissions in Copenhagen, tonnes	Change of $PM_{2.5}$ emissions in Copenhagen
	Single-family house	Holiday house	Apartment building		
Baseline	0.4	0.2	0.08	76	
All −50%	0.2	0.1	0.04	65	−15%
All +50%	0.6	0.3	0.12	81	7%
Single-family house −50%	0.2	0.2	0.08	61	−20%
Single-family house +50%	0.6	0.2	0.08	84	11%
Holiday house −50%	0.4	0.1	0.08	80	5%
Holiday house +50%	0.4	0.3	0.08	73	−5%
Apartment building −50%	0.4	0.2	0.04	76	−1%
Apartment building +50%	0.4	0.2	0.12	77	1%

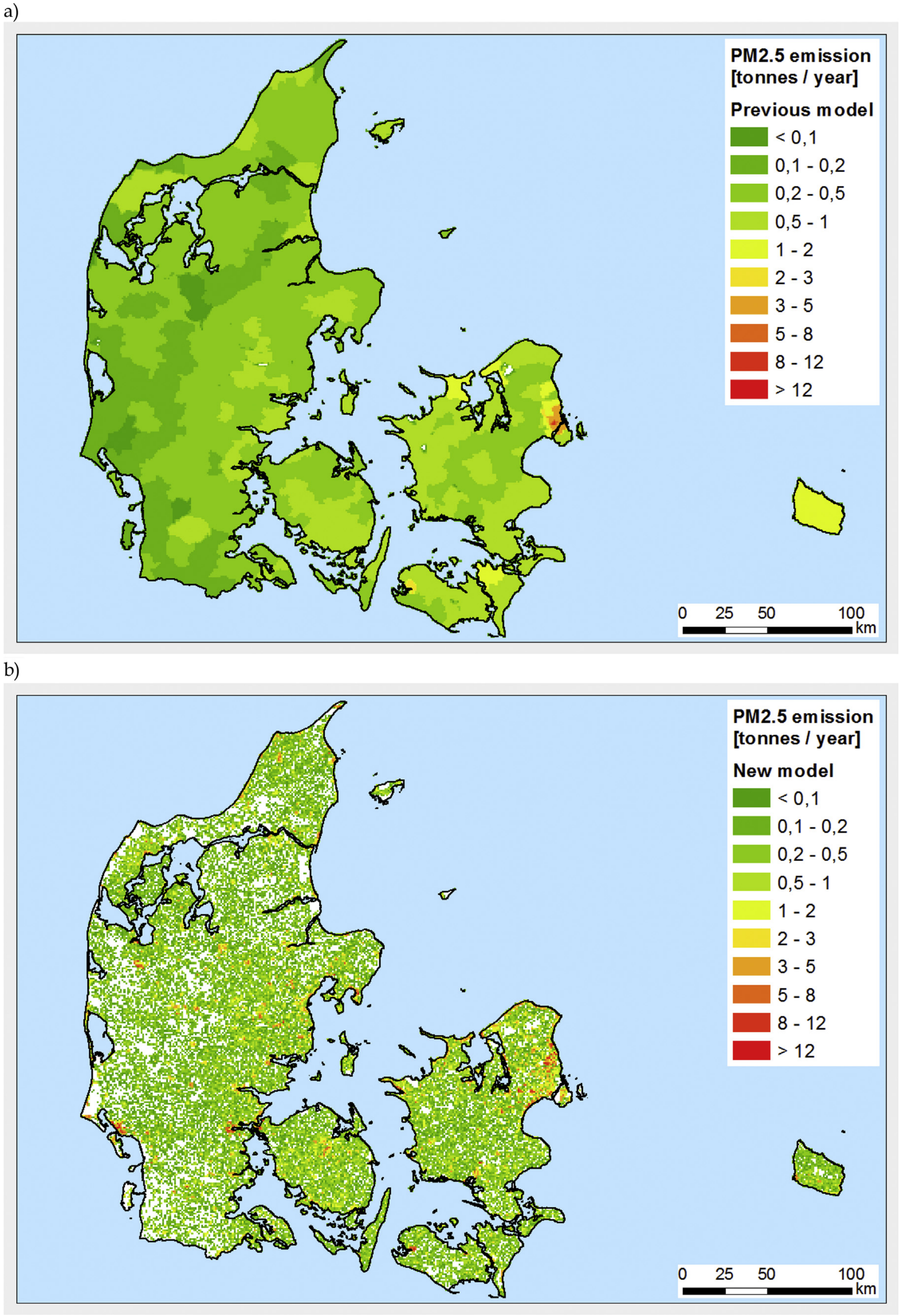

Fig. 1. $PM_{2.5}$ emissions from RWC based on a) the previous model and b) the new model.

4. Conclusions

This paper presents a new detailed methodology for high resolution spatial distribution of emissions for RWC, which has significantly improved the spatial allocation of emissions. The most striking improvement is that emissions are no longer accumulated in the densely populated areas in and around Copenhagen, due to the exclusion of population density from the model. The lower emission level in Copenhagen is in line with information from the chimney sweepers and the recent study of RWC in Copenhagen (Andersen, 2015). Further, the new improved distribution is based on exact location of the RWC appliances classified from BBR aggregated on a 1 km × 1 km resolution grid, instead of average estimated wood consumption per municipality. This leaves uninhabited areas with no emissions, and includes the variation inside the separate municipalities.

Due to the large significance of RWC on the emission of air pollution there will be a continuous demand for improvements both to the emission inventory and to the spatial distribution. An important improvement would be to ensure a mandatory update of the BBR with information on buildings with RWC but also an expansion of the register to cover the age of the RWC appliance. Alternatively, a new register could be created based on information from chimney sweepers. Chimney sweepers inspect all wood burning appliances at least once a year and are tasked with approval every time a new appliance is installed. The improvement of the BBR or the creation of a new register would improve the emission inventory as well as the spatial distribution.

The current work represents a large improvement compared to the previous methodology. However, more work is needed to further refine and improve the spatial distribution, e.g. heat demand modelling can be used to verify or improve the assumptions regarding the weighting factors between the different building types and between primary and supplementary RWC. Also, more case studies should be carried out to verify the new model for other areas than the city of Copenhagen.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2016.09.013.

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