López-Aparicio, Susana; Vogt, Matthias; Schneider, Philipp; Kahila-Tani, Maarit; Broberg, Anna

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Research article

Public participation GIS for improving wood burning emissions from residential heating and urban environmental management

Susana López-Aparicio a, *, Matthias Vogt a, Philipp Schneider a, Maarit Kahila-Tani b, Anna Broberg c

a NILU – Norwegian Institute for Air Research, Norway
b Department of Real Estate, Planning and Geoinformatics, Aalto University, Finland
c Mapita Ltd., Finland

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C O - B E N E F I T
A B S T R A C T
A crowdsourcing study supported by a public participation GIS tool was designed and carried out in two Norwegian regions. The aim was to improve the knowledge about emissions from wood burning for residential heating in urban areas based on the collection of citizens’ localized insights. We focus on three main issues: 1) type of dwelling and residential heating source; 2) wood consumption and type of wood appliances; and 3) citizens’ perception of the urban environment. Our study shows the importance of wood burning for residential heating, and of the resulted particle emissions, in Norwegian urban areas. Citizens’ localized insights on environmental perception highlight the areas in the city that require particular attention as part of clean air strategies. Information about environmental perception is combined with existing environmental data showing certain correlation. The results support the urban environmental management based on co-benefit approaches, achieving several outcomes from a single policy measure. Measures to reduce urban air pollution will have a positive impact on the citizens’ environmental perception, and therefore on their quality of life, in addition to reducing the negative consequences of air pollution on human health. The characterization of residential heating by fuelwood is still a challenging activity. Our study shows the potential of a crowdsourcing method as means for bottom-up approaches designed to increase our knowledge on human activities at urban scale that result on emissions.

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1. Introduction

While electricity produced from hydropower is the primary means of residential heating in Norway, wood burning stoves are the second most important source of heating. The consequences are significant emissions of particulate matter (PM) and other compounds with negative effects on human health (Chafe et al., 2015). The use of wood as fuel for residential heating is moreover increasing as in the rest of Europe (Viana et al., 2016). The increase at European level is mostly driven by government incentives, as it is a CO2 neutral source of energy, the rising cost of other energy carriers others than fossil fuels or pure electricity. This requirement is for buildings with a calculated heat demand of more than 15 MWh, otherwise the new dwelling does not need to fulfill this minimum share, but it can alternatively be equipped with a fireplace for biofuels (Kipping and Trømborg, 2015). The existing motivations towards the use of fuelwood and the subsequent increased emissions of harmful compounds involve undesirable environmental effects from air pollution (Gan et al., 2013; Karr et al., 2009; Smith et al., 2011), and especially in urban areas characterized by high population density.

Wood burning, along with on-road traffic, is a main contributor to particulate matter in many European cities, and together they often cause high pollution episodes in winter (e.g. Denby et al.,...
In addition, wood burning is an important source of harmful compounds such as benzo(a)pyrene (Bels et al., 2011; Silibello et al., 2012) and black carbon (BC; Bond et al., 2013), a short-lived climate pollutant. As an important emission source, wood burning has received special attention in recent years in social media, the scientific community, and among decision makers. However, designing strategies towards emission reductions and clean air in the urban environment requires better knowledge of emissions and their contribution to pollution levels. Emission inventories from wood burning in small combustion installations are very much uncertain. The uncertainties are associated with emission factors and the activity data, which is commonly derived from statistical methods. In Norway, national emissions from wood burning for residential heating are estimated based on the product of the amount of fuelwood consumed per type of technology (i.e., open fireplace, closed stove produced before 1998 and closed stove produced after 1998) and the corresponding emission factors (Norwegian Environment Agency, 2014). Since 2005, the activity data is derived from responses to questionnaires in the Statistics Norway’s Travel and Holiday Survey, which are distributed quarterly.

Air quality models are essential tools to support urban environmental management and policy formulation by evaluating the possible impact of local and regional emission abatement options on air quality and human health (Thunis et al., 2016). Therefore, when wood burning emissions are used as input data for air dispersion modelling, we need the data at high spatial and temporal resolution, and preferably developed according to bottom-up approaches. However, the development of bottom-up emission inventories is demanding and requires significant amount of input data and resources. In the case of wood burning, the information needs to be regularly updated, as emissions are largely dependent on climatic conditions. For example, long and cold winters will result in higher fuelwood consumption than shorter and milder winters.

The motivation behind our study is on evaluating an innovative crowdsourcing method to collect citizens’ localized data for the understanding of residential heating with fuelwood. Our objectives are 1) to establish the relationship between fuelwood use and other variables (e.g., type of dwelling) to support the data processing as part of the development of emission inventories; 2) evaluate possible correlation between citizens’ perception of the urban environment and air pollution data; and 3) assess the method for regular updates of emission inventories. As crowdsourcing, which was first defined by Howe (2006), we refer to those approaches based on soliciting data, ideas or collaboration to a large group of people, and especially by the use of social media and/or information and communication technologies (ICT). Crowdsourcing or citizen participation is been widely used for applications in environmental monitoring, management and in decision-making processes (Castell et al., 2015; See et al., 2016; Wilkinson et al., 2015).

The novelty of our study is that it combines the elements of crowdsourcing with Public Participation Geographic Information Systems (PPGIS), commonly used for gathering citizen insights in the decision-making process, into a new application that combines localized data collection for environmental research and environmental perception (Brown and Kyttä, 2014; Raymond et al., 2016). In our study, a bottom-up approach was designed to gather citizens’ insights regarding fuelwood use and urban environmental perception. Our study contributes to the understanding of the spatial distribution of wood burning and the type of appliance used, which is essential for the improvement of emission estimates and the evaluation of measures to reduce emissions. This paper shows how a citizen science bottom-up approach may support effective data collection in environmental research and effective urban policy design in the future.

2. Methodology

2.1. Public participation GIS survey

We selected a public participation GIS (PPGIS) tool as method for data collection. The used PPGIS tool originates from Aalto University, where the development of this methodology has been ongoing since 2005 in close cooperation with urban planners (Kahila-Tani, 2016). The Internet-based PPGIS methodology allows residents to communicate local knowledge and experiences (Kyttä et al., 2011). This method has been used in more than 20 research projects in Finland and abroad (Brown and Kyttä, 2014), ensuring the relevance of geospatial information to the planning sector through the involvement of the planners in urban planning processes. The first generation of tools were specially developed and tailored for each project by researchers and information technology specialists. Later, a cloud service, Maptionnaire, was developed as a spin-off company.

The survey carried out in our study was designed using the cloud service Maptionnaire (https://maptionnaire.com), and the participants answered the survey using computers, smart phones and tablets. The GIS-survey focused on residents in Oslo and Akershus, the neighbouring county. We selected the questions around three main themes: 1) Place of residence and characteristics of the living space; 2) Wood burning for residential heating; use of fuelwood for heating, type of wood stove and amount of fuelwood consumed in the last winter season (November 2015–February 2016); 3) Environmental perception associated with air pollution and specifically with wood burning.

The distribution of the GIS-survey was carried out using social media, stakeholder groups, municipalities, the construction sector, universities and educational centres, heating associations, groups and associations of senior citizens, NGOs (e.g. Norwegian Asthma and Allergy Association, Zero - Emission Resource Organization, etc.) and diverse networks (transportation, cultural heritage and archives, researchers, fire and rescue corps, etc.). In addition, posters were displayed in shopping centres, cafes and restaurants. We designed the posters with preliminary results of the GIS-survey and asked for people’s contribution by providing 1) a Uniform Resource Locator (URL) to the survey or 2) a Q-code that allows the access to the survey with smart phones or tablets. Regarding the dissemination and distribution through social media, we primarily used the online networking service Twitter and to a less extent Facebook and LinkedIn. The distribution through social media was supported by preliminary graphs and preliminary results from the survey, in order to guarantee open access and transparency, and to trigger the engagement of citizens answering the survey.

2.2. Participation and survey sample

We have collected approximately 500 individual responses and a total number of geo-located responses of around 1500. Taking into account that the population of Oslo municipality and the bordering county Akershus is 1 252 923 inhabitants in 2016, the number of responses would involve approximately 4.5% margin error for a 95% confidence interval. Table 1 shows an overview of the sample. Approximately the same number of males and females answered the survey, and most of the participants (90%) are over 30 years old.

The level of participation registered in our survey among citizens older than 30 years may indicate that the use of ICT is not constraint to young people. A recent study established that around 85% of American adults between 30 and 50 years old visit the
internet on almost daily basis (Pew Research Center, 2014). The use of ICT in Norway may even be more widespread, as 100% of adults has used internet in the last three month according to the surveys conducted by Statistics Norway (2016).

### 3. Results and discussion

#### 3.1. Dwelling and heating sources

Information about the type of dwelling, their spatial distribution and their heating source is essential for the understanding of emissions associated with residential heating. In countries such as Finland, wood burning is a common heating source in mostly detached houses, whereas in France, Italy or Spain wood burning for residential heating is mostly restricted to rural areas. In Norway, apartments are equipped with wood burning stoves and it can be considered a widespread activity in both urban and rural areas. Regional emission inventories developed through downscaling processes are based on assumptions and proxies to distribute national emissions on much finer spatial resolutions. Hereby, population density, urban and rural population, or dwelling density combined with the type of dwelling are the most common proxies used for the spatial distribution of emissions (Bessagnet et al., 2016; Denier van der Gon et al., 2010; Kuenen et al., 2014). Accordingly, the knowledge about wood burning is crucial, and assumptions developed for one country may not be valid for others.

The sample in our study represents a type of dwelling distribution averaged over two counties (Oslo and Akershus). Approximately 40% of the participants live in apartments, and the remaining 60% reside in different types of houses such as detached (i.e. House, Fig. 1), with two dwellings (i.e. Duplex, Fig. 1), or row houses (i.e. Townhouse, Fig. 1). Houses, including the three main types, represent 20 and 70% of the total dwelling in 2016 in Oslo and Akershus, respectively (Statistics Norway, 2016). The differences are due to the characteristics of both counties. Oslo is a very densely populated urban area (population density of 1456/km² in 2016), with higher percentage of apartments. Akershus is a county that covers an area of around 4579 km², and is less densely populated than Oslo with around 121/km² in 2016. The average national population density is 15.5/km². Akershus includes rural areas and several urban settlements, such as Bærum, Lillestrøm or Skedsmo. Our sample resembles the national statistic level, as around 70% of the Norwegian dwellings are houses (Statistics Norway, 2016).

The energy consumption from electricity in Oslo and Akershus in 2012 and per household was around 4420 kWh and 4795 kWh, respectively (Statistics Norway, 2016). These values represent around 80% of the total energy consumption per household, followed by wood, pellets and wood briquette (7–12%) and gas and district heating (2–7%). The most common space heating method in Norwegian households is direct electricity, and it is used in combination with wood burning stoves and heat pumps. The implementation of the latter has experienced a significant increase in the last years, reaching values of around 44% increase for detached houses. In our survey, the main heating source is reported to be electricity (Fig. 1), which represent 61% followed by heat pump (15%), district heating (9%), wood burning (7%), oil (4%) and others (4%) (Fig. 1). Around 62% of the respondents have wood burning as a secondary heating source, and 7% as primary source. Kipping and Tromborg (2015) already concluded that fuelwood, along with heat pumps, are intensively used in detached houses in Norway and they reduce electricity consumption for residential heating. To our knowledge, our study is the only one that includes multifamily dwellings in urban areas, where the wood consumption for residential heating is more uncertain, and the need for improved knowledge is crucial for the development of air pollution mitigation plans to reduce citizen exposure to harmful levels.

#### 3.2. Emissions from wood burning

Emissions from wood burning are commonly estimated based on the product of fuelwood consumption per type of technology and the corresponding emission factor. In Norway the type of technology includes different wood stove appliances such as open fireplaces, wood stoves produced before 1998 and wood stoves produced after 1998. In order to develop bottom-up emission estimates at urban scale, data on fuelwood consumption per type of appliance need to be available or developed at very fine spatial resolution. However, these approaches are demanding concerning input data availability and therefore updated estimates are uncommon. For instance, the available bottom-up emission estimates for wood burning in Oslo and surrounding areas are more than a decade old.

In our study, we find that wood burning is reported to be used by 66% of the participants (Fig. 2), with around 23% of them reporting to have an old stove, 52–54% a new stove, 14–18% of participants have a closed fireplace and 5–10% of the appliances are open fireplaces (Table 2). We consider an old stove as produced before 1998. However, in our survey, old and new stoves are illustrated with images. The share of old stoves differs from available official information. In Oslo municipality, the number of wood appliances registered by the Fire and Rescue Agency is of about 119 482 stoves and 57% of them are registered as old fuelwood stoves (Norwegian Environmental Agency, personal communication). A possible reason is that the information register at the Fire and Rescue Agency is relatively outdated and it does not register the shift from old stoves to more efficient ones in the latest years, or stoves installed in newly built dwellings.

Based on the information provided by citizens, the share of new stoves (52–54%) is unexpectedly very similar in Oslo and Akershus. Since 1998, there is a scrapping payment plan in Oslo to promote the replacement of old stoves for new ones to increase the share of clean burning appliances. Thereby, an Oslo resident can apply for grants to replace old stoves. The size of the grant varies depending on the place of residence as NOK 3000 (approx. 350 €) is granted to residents in central areas of the city and NOK 1500 (approx. 175 €) to residents in other areas within the outermost road ring. From 1998 to 2015, around 8677 wood stoves have been replaced with granted support. Based on our results, the existence of a scrapping payment plan in Oslo does not seem to increase the share of new stoves compared with areas without grant support. Our findings are relevant for the municipalities, as environmental management toward cleaner wood burning appliances and through economic incentives does not seem to show a significant penetration in the urban environment.

The amount of fuelwood consumed by citizens participating in the PPGIS survey is shown in Fig. 3. The highest density of

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<td>Overview of the GIS-survey sample population.</td>
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consumers is localized in the two most populated urban centres, Bærum and Oslo city and around the localities of Lillestrøm and Skedsmo. The reported fuelwood consumption corresponds to the winter season between November 2015 and February 2016 and the total value reach around 193,515 kg of wood. Around 39% of the fuelwood is reported by residents in Oslo and 56% by residents in Akershus (5% of the wood consumption is reported outside the area of study). The evaluation of the amount of wood consumed per type...
of appliance indicates that around 46%, 35%, 13% and 6% of wood was consumed in new stoves, old stoves, closed fireplaces and open fireplaces, respectively.

Emissions of particles (PM$_{2.5}$) from the sampled population (=500 responders) and within the winter season (November 2015–February 2016) was estimated to reach around 3.13 ton based on the reported amount of fuelwood, the reported type of stove, and the corresponding emissions factors for each type of appliance (SINTEF, 2013). Emissions of PM$_{2.5}$ are scaled to the corresponding counties and to National level based on 1) a linear relationship; 2) that 66% of the population use fuelwood; and 3) the official number of dwellings in 2016 (i.e. 245 852 in Akershus, 326 043 in Oslo and 2 476 519 in Norway). The emissions estimated for Norway and Akershus are comparable with official values (Table 3). National official emissions are reported under the obligations of the Convention on Long-range Transboundary Air Pollution (LRTAP), and emissions in Akershus are based on officially reported fuelwood consumption. The comparison for Oslo shows some discrepancies (Table 3) as PM$_{2.5}$ emissions based on the information reported by citizens is three times higher than emissions based on official statistics (Statistics Norway, 2016).

Evaluating the results from each county independently, we see that the same percentage of citizens (=66%) reported to use fuelwood for residential heating. However, the amount of wood consumed differs between both, as 73 tons of fuelwood were

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<td>Akershus</td>
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Table 2 Percentage (%) of wood appliances in Oslo and Akershus.

Fig. 3. Wood consumption (kg) reported by citizens participating in the PPGIS survey in Oslo and Akershus counties. Each symbol represents the geographical location of the response, and the size is proportional to the reported wood consumption according to the key on the left.
consumed in Oslo versus 105 tons in Akershus. These values result in an average amount of fuelwood per household of around 400 and 1040 kg in Oslo and Akershus, and therefore an estimated total fuelwood consumption of 130 and 344 kton, respectively. This result is significantly higher than the data officially reported. As in 2013 the amount of fuelwood consumed in Oslo and Akershus was about 34 and 86 kton, respectively, 4 times lower than in our study.

Some citizens reported that the wood was taken from the closest forest, their own recreational cabin or from garden waste, and this could partially explain our higher results. Moreover, the GIS-survey was designed focussing on wood burning for residential heating in the city. This focus could involve a certain bias is the percentage of households using fuelwood, as unintentionally we may have targeted citizens that use fuelwood. Based on personal communication with the National Institute for Consumer Research in Norway, a recent survey (2016) on urban environmental issues (N = 1933) in five urban areas in Norway shows that fuelwood is used by around 50% of the households in most of the cities, except in Oslo, where the share of fuelwood consumers is of around 30%. Scaling our PPGIS results to Oslo and Akershus based on 30% and 50% of the population using fuelwood, respectively, derives PM2.5 emissions of around 665 and 836 tons, respectively. The value for Oslo is similar to emissions based on official statistics. Our study shows the importance of PPGIS designing in order to guarantee a representation of the urban population, and especially for highly populated areas.

We evaluate the amount of fuelwood used per type of dwellings and we observe that 46% of the reported fuelwood in Oslo is consumed in apartments. Our study shows the importance of wood burning as a heating source in cities as in Oslo (Fig. 3), and that wood burning is not restricted to rural areas as in other countries. Wood burning is an important heating source in Norwegian cities and agglomerations, and a significant source of air pollutants (particulate matter, PM) and short lived climate pollutants (black carbon). Our study shows the challenges of getting a clear figure about wood consumption in cities characterized with high population density, and the potential of involving citizens to shed light in the understanding of fuelwood consumption. Our approach can be used for other applications, such as mobility patterns and frequency, energy use, or household consumption in general.

### 3.3. Environmental quality perception

Citizens' perceptions of the urban environment was evaluated regarding urban air quality in general and wood burning smell in particular. Around 86% of the participants think that Oslo and Akershus have a problem regarding air quality (Fig. 4). Citizens identified around 700 points as air pollution hotspots and they associated them with traffic, wood combustion and shipping as main pollution sources (Fig. 4).

The spatial distribution of the reported air pollution hotspots clearly indicates that citizens associate urban areas and agglomerations with high air pollution levels. Fig. 5 (top panel) shows a 2D Kernel density maps calculated from the reported air pollution hotspots in Oslo city. The highest density of hotspots is in Oslo downtown and high values are also identified at intersections of roads characterized by a high traffic density. These results highlight the areas that require particular attention in urban environmental management towards the improvement of the quality of life in cities. Fig. 5 (bottom panel) shows a scatter plot of the 2D Kernel density map (Fig. 5 top panel) against the annual average NO2 concentrations computed using the EPISODE dispersion model for 2013 (Heisäkangas et al., 2014; Slordal et al., 2008). The comparison was carried out at an aggregated spatial resolution of 1 km to reduce the number of data points for clarity. A linear regression of the square-root transformed density values against the modelled concentrations exhibits a weak but significant correlation between the two parameters (R2 = 0.59), showing that the hotspots reported by the survey participants to some extent mirror the air pollution hotspots indicated by the model. This result suggests that a crowdsourced dataset of citizens' perception of air quality can be used to obtain an estimate of the approximate location and size of some of the major air pollution hotspots in an urban environment. However, as it can be seen by the significant scatter of the points in Fig. 5 (bottom panel), even though the modelled relationship between the two parameters exhibits a relatively high R2 value, it nonetheless is subject to various sources of uncertainty. This includes for example the fact that the reported hotspots will be biased towards locations that the reporting citizens have personally visited and have memories of experiencing poor air quality. As such, locations that are easily and often accessed by foot and bike will be over-represented in the kernel density map, whereas locations that are never visited by the citizens will be significantly under-represented. Such car-only locations, particularly those along the major highways going in and out of a city in fact very often represent the overall worst air quality conditions within an entire city but since citizens generally do not walk or bike in such areas they tend to not report them as often as significant pollution hotspots. This effect can be clearly seen in the bottom panel of Fig. 5 where the modelled concentrations associated with kernel densities over 2e-8 are lower than would be theoretically expected, whereas the highest modelled concentrations of over 50 µg/m3 are associated with relatively low kernel densities of only between 1e-8 and 2e-8.

As the response of the participants may be biased by their prevalent mobility patterns (e.g. around home and work), and their knowledge of their closest surroundings, we estimated the distance between the citizens' residence and the location of their reported air pollution hotspots. The results show that citizens reported hotspots of air pollution at relatively far distances from their residence (Fig. 6). The average distance is around 8 km, and we are able to identify two main groups of responses, a group that report air pollution hotspots at around 3–5 km from their residence and a second group that report hotspots at around 15–16 km. Long-distance commuters, living outside and working inside Oslo city, could represent the latest group.

Wood burning smoke has been associated with respiratory problems (Janssen et al., 2012; Smith et al., 2011), and especially among asthmatics (Gan et al., 2013). Therefore, we carried out a similar exercise comparing citizen perception to specifically wood burning smell in order to identify the urban hotspots. Fig. 7 shows the 2D Kernel density map obtained based on approximately 300 points identified as locations with persistent wood burning smell in winter season. The highest density of identified locations is within a 5 km radius in downtown (Fig. 7), and in a residential area in Oslo city characterized by multifamily dwellings and buildings from beginning of the 19th century, restaurants and commercial streets. It is
important to highlight that the hotspot for wood burning smell is located in a different area that the hotspot for air pollution (Fig. 5). The evaluation of the distance between the participants’ residence and the reported wood burning smell hotspot shows similar results than those for air pollution perception, and the highest number of responses is obtained at around 3–4 km from their home address (Fig. 6). Fig. 7 (top panel) shows the 2D kernel density plot of the point patterns reported by the participants to exhibit wood burning smell. Fig. 7 (lower panel) shows a scatterplot of the 2D kernel density against the annual average PM2.5 concentrations as provided by the EPISODE urban-scale dispersion model (Høiskar et al., 2014). In addition, the lower panel of Fig. 7 shows a linear regression fit of the square-root transformed density values against concentrations ($R^2 = 0.38$). While the correlation is slightly lower than that observed for air pollution perception and NO2, it nonetheless shows that the overall spatial patterns of wood burning smell are similar to those provided by the model. One of the possible reasons for the slightly weaker correlation can be associated with the fact that wood burning smell is constrained to the winter season and we compare with annual average PM2.5 level. It is also important to take into account that the number of points reported by citizens as characterized by wood burning smell (N = 288) is much lower than the number of hotspots identified for air pollution (N = 683). This relatively small sample size is clearly a major source of uncertainty and explains some of the scatter of the data points seen in Fig. 7 (bottom panel). The related undersampling also explains why some areas with relatively high PM$_{2.5}$ concentrations of over 9 µg/m$^3$ exhibit very low kernel density values of between 0 and 1e-8: There simply were not enough survey participants familiar with these areas to report local wood burning hotspots.

The individual perception of the environment contributes to the perception of our quality of life. The results from our study are relevant for urban environmental management and policy makers, as they show how mitigation measures to reduce urban air pollution will have a positive impact on the citizens’ environmental perception, and on their quality of life, in addition to reducing the negative consequences of air pollution on human health. Moreover, citizen perception of the environment is crucial for the response and acceptance of the implementation of policy measures, such as implementing car-free areas, the ban of diesel vehicles in specific areas or the ban of old wood burning stoves, which may be somehow controversial. The results from our study therefore supports the value of co-benefit measures designed towards a sustainable urban environment.

4. Conclusions

A bottom-up approach for collecting citizen’s localized insights based on public participation GIS was designed and carried out in Oslo and Akershus, two Norwegian regions, aiming at improving the understanding on wood burning for residential heating in urban areas. Our study shows differences between the highly populated urban areas, i.e. Oslo, and the urban-rural combined area, i.e. Akershus, as fuelwood consumption is reported to be higher in the latter one. In spite of this difference, the results show the importance of wood burning as heating source in urban areas, and therefore of the subsequent particle emissions. In Oslo for instance, 46% of the fuelwood is used in apartments. Wood consumption from the sampled population reach around 200 tonnes of fuelwood in one winter season (i.e. November 2015 to February 2016). Wood consumption is scaled to different administrative areas based on the information provided by citizens on use of fuelwood for residential heating and type of wood stove. Wood consumption is estimated to be three times higher than available official data in urban areas, whereas for urban-rural combined areas is estimated to be at the similar level. Our study shows that the characterization of human activity that results on pollutant emissions in highly populated urban areas is still a challenge.

The geographical distribution of wood stoves shows that the share of new stoves ($\approx 53\%$), which are cleaner and more efficient, is almost the same for both regions. This result is unexpected as...
Fig. 5. 2D kernel density maps of air pollution hotspots reported by citizens (top) and scatterplot between the 2D kernel density and annual average concentrations of NO₂ from an urban-scale air quality model. The fitted line shows a linear regression of the square-root transformed density values against the concentrations ($R^2 = 0.59$).

Fig. 6. Histogram and accumulative distribution of distance between the residence of the responders and the points that they identify as air pollution hotspot (left) and wood burning smell (right).
there have been economic incentives for shifting from older to newer appliances in Oslo city since 1998, and our results seem to show a low penetration in the urban environment comparing with areas without economic incentives.

The evaluation of citizens’ environmental perception, and the distance between residence and reported pollution hotspots locations, shows that participants report their perception in the overall urban environment and they do not limit to the surrounding of their neighbourhood. Environmental perception data correlate with air pollution levels. This correlation supports co-benefit approaches in the development of clean air strategies, as the implementation of measures to reduce urban air pollution will have a positive impact on the citizens’ environmental perception and on their quality of life, in addition to reducing the negative consequences of air pollution on human health.

One of objectives of our study was to assess crowdsourcing through a GIS tool as a method to regularly update emission inventories. We are able to conclude that one of the biggest advantages, in comparison with traditional methods, is to obtain information efficiently and localized in space. However, there are two processes that need to be carefully performed to support accurate quantitative outcomes and especially regarding scalability: 1) the design of the survey and 2) the participatory process. Our study shows the potential of public participation GIS as an instrument to gather citizen’s insight on specific activities at fine space resolution, and for its subsequent use in urban environmental research. The method can be easily implemented to provide crucial updates on data collection for specific pollution sources.

**Acknowledgement**

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**References**


![Fig. 7. Density maps of wood burning smell reported by citizens (top) and correlation between wood burning perception and pollution level (i.e. PM2.5 annual average concentration) (bottom panel). A linear regression of square-root transformed density values against concentrations is also shown (R² = 0.38).](image)