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Spatial estimation of air $PM_{2.5}$ emissions using activity data, local emission factors and land cover derived from satellite imagery

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Abstract. Exposure to particulate matter (PM) is a serious environmental problem in many urban areas on Earth. In the Philippines, most existing studies and emission inventories have mainly focused on point and mobile sources, while research involving human exposures to particulate pollutants is rare. This paper presents a method for estimating the amount of fine particulate ($PM_{2.5}$) emissions in a test study site in the city of Cabanatuan, Nueva Ecija, in the Philippines, by utilizing local emission factors, regionally procured data, and land cover/land use (activity data) interpreted from satellite imagery. Geographic information system (GIS) software was used to map the estimated emissions in the study area. The present results suggest that vehicular emissions from motorcycles and tricycles, as well as fuels used by households (charcoal) and burning of agricultural waste, largely contribute to $PM_{2.5}$ emissions in Cabanatuan. Overall, the method used in this study can be applied in other small urbanizing cities, as long as on-site specific activity, emission factor, and satellite-imaged land cover data are available.

1 Introduction

Exposure to air particulate matter, especially fine particles smaller than 2.5 µm in size ($PM_{2.5}$), can reduce air quality, affect visibility through smog and other haze phenomena, and introduce lasting effects on climate on a local and regional scale. Exposure to pollutants is a risk for many people living in urban areas, since the level of pollution frequently exceeds WHO guideline values (Mage et al., 1996). The presence of $PM_{2.5}$ is linked to increased morbidity and mortality risk, especially in incidences of various cardiopulmonary diseases (Chen et al., 2008; Lin et al., 2016; Wu et al., 2013), birth defects (Goto et al., 2016), and cancer (Cassidy et al., 2007). $PM_{2.5}$ pollution is also considered carcinogenic, especially exposure to the finest fractions (ultrafine particles) (Bocchi et al., 2016). This can be attributed to particles acting as carriers of mutagenic and genotoxic compounds (Chen et al., 2016).

Enhancements in $PM_{2.5}$ are mainly caused by various human activities. A common source of particles contributing to $PM_{2.5}$ in urban areas is related to mobile sources, directly emitted by internal combustion processes inside vehicles of all types (Andrade et al., 2012; Ahanchian and Biona, 2014; Chen et al., 2016). In most of the reports from Philippine cities, vehicular emissions reported in inventories use foreign emission factors (such as the 2007 version of the CORINAIR emission guidebook, EEA, 2007, and the Compilation of Air Pollutant Emission Factors (AP 42), EFIG, 1995). However, $PM_{2.5}$ emissions from other activities such as burning of agricultural waste also occur in cities with a mixture of rural and

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urban land uses (Sarigiannis et al., 2014; Kim Oanh et al., 2011; Gadde et al., 2009).

At present, air quality monitoring and management are based on PM_{10} and total suspended particles as an indicator. Standards for $PM_{2.5}$ have, however, not been fully developed and implemented in small cities. Emission inventories in general have likewise not been constructed in many cities. In addition, previous investigations are rare and limited in time, which means that temporally resolved long-term air quality monitoring data are not available.

This study presents a method to estimate $PM_{2.5}$ by utilizing locally determined emission factors, satellite imagery, and activity data. The latter is obtained from interpretation of geographic information system (GIS) data and by identifying and localizing all sources in the city, taking into account the type of emission (point, area, mobile) and activities producing the emissions. This includes factors such as local population, density of households, number of emission-generating events, and the type and amount of various fuels used. This, in conjunction with various local emission factors, will be used to estimate total $PM_{2.5}$ emissions. A limitation of this study is that all emission sources are treated as being area sources, since this is required in the mapping process.

From the resulting maps, the study aims to determine areas of high concentration of $PM_{2.5}$, caused by individual and several aerosol sources. The present method can specifically be used for similar mixtures of manmade activities present in Philippine cities. This study is specifically meant to explore this method for use in relatively small regional urban centers and cities in the Philippines, especially due to these cities being situated in locations where there is a mixture of rural and urban activities. Sources corresponding to rural activity include open burning of agricultural waste and the usage of household cooking fuels such as charcoal. Sources corresponding to urban activity include vehicular mobile sources such as tricycles, jeepneys (colloquially known as XLTs), and public utility vehicles (PUVs, which include buses and vans). Another application for this study is planning aids for local governments, as the present method can be used in emission inventories for small cities. The method was developed to be used with minimal required training and effort by stakeholders in order to create emission inventories of aerosol sources in the cities.

2 Materials and methods

2.1 Study area

The test study was conducted in the city of Cabanatuan, Philippines. It is the former capital and largest city of the province of Nueva Ecija, with a land area of 190.67 km^2 and an estimated population of 296 584 in 2012. On average, the population density is around 1516 persons per square kilometer. The urban and rural populations each constitute about half of the total population (CPDO, 2015). A map of Cabanatuan with a reference to its nearby major cities is shown in Fig. 1.

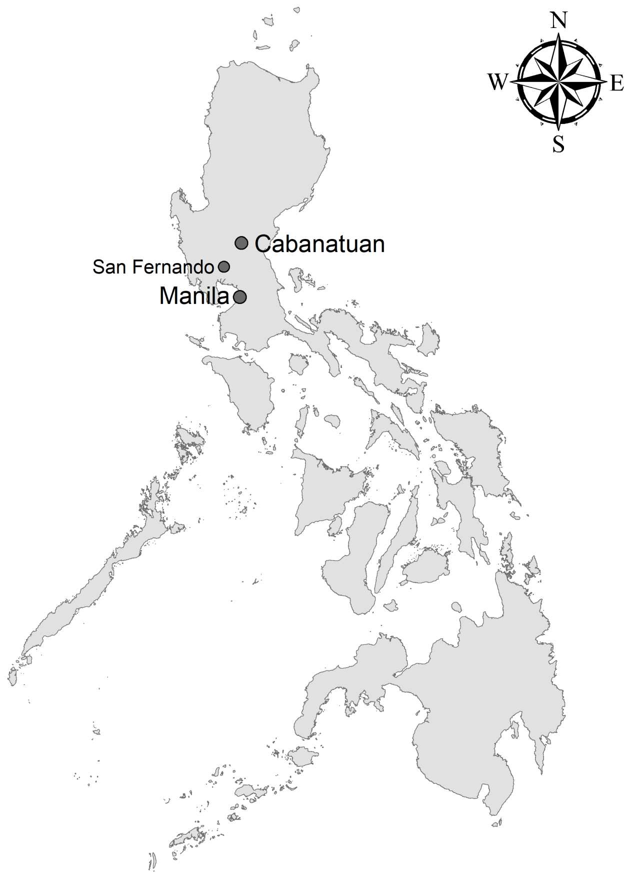

Figure 1. Map of the Philippines and location of Cabanatuan (with major cities).

A 2.4 by 4.0 km area including the city center and its nearest environs was selected as the main study area. The town proper (locally known as the *poblacion*) is highlighted in the map of the study area shown in Fig. 2. Grey lines indicate boundaries of *barangays* (the smallest administrative division of a local government, a similar concept to town wards or districts), and the constituent barangays of the *poblacion* are marked using thicker grey outlines. The investigation area includes residential and commercial zones and even agricultural areas less than 2 km away from a main road. A commercial zone and the planned main industrial district in Cabanatuan located south and about 8–10 km southeast of the investigation area, respectively, are not taken into consideration in the study.

2.2 Land cover classification using satellite imagery

The investigation area was divided with 24×40 grid cells (100×100 m or 1 ha/0.01 km^2 each). For each cell, the type of manmade activity was interpreted from satellite images

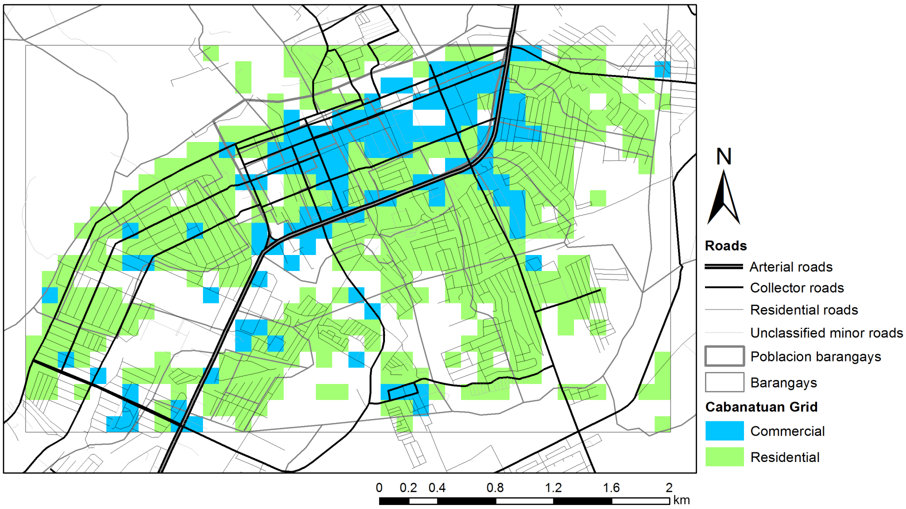

Figure 2. The 2.4 × 4.0 km study area in Cabanatuan containing the "city center" (*poblacion*, highlighted). Base map derived from satellite imagery (Google Earth Pro, 2015, 2016). Additional data from OpenStreetMap (OpenStreetMap contributors, 2016).

taken from Google Earth software. The classification process is similar to methods of supervised classification of land cover, as utilized by current local training activities on emission inventories such as the Clean Air for Smaller Cities (CASC) project (Yuberk and Cornet, 2013). The image of the surface feature is compared to a reference area of known land cover. Due to the size of each cell, the detail of each ground feature can be clearly seen. Detailed images over the ground, taken by Google Street View (examples are shown in Fig. 3), were used to verify building types (residential/commercial). Satellite images were dated 3 March 2016, while ground level (Street View) images were dated September 2015 (Google Earth Pro, 2015, 2016). Additionally, maps from OpenStreetMap were also used for identifying special landmarks or as an additional resource since they occasionally present more updated information on surface features than Google Earth or Google Street View (OpenStreetMap contributors, 2016).

Google Earth images have been used here instead of raw image data from, for example, the Landsat satellite. The Google Earth images used consist of post-processed Landsat images from the European Space Agency's (ESA) Copernicus program. This is because the method developed in this study is intended to be used by personnel not necessarily familiar with processing of satellite raw imagery data. The Google Earth images have been processed to minimize the presence of clouds and corrected for aberrations from the camera taking the satellite images. These images are not representative of the most current features on the ground. There is also a slight deviation of the actual coordinates representing the location of the area due to the orthographic projection of the satellite image. This is consistent with geolocation deviations present in most consumer-grade satellite/GPS products. It is also difficult to get access to the meta-

Figure 3. Example of reference image used for Google Street View verification of surface features (Google Earth Pro, 2016).

data of the original images. Despite these disadvantages, the Google satellite image product is useful enough for the uninitiated considering the present purpose. In addition, other data products such as Google Street View or OpenStreetMap (community-based initiative) can be used. The usage of supporting documents such as existing local government land

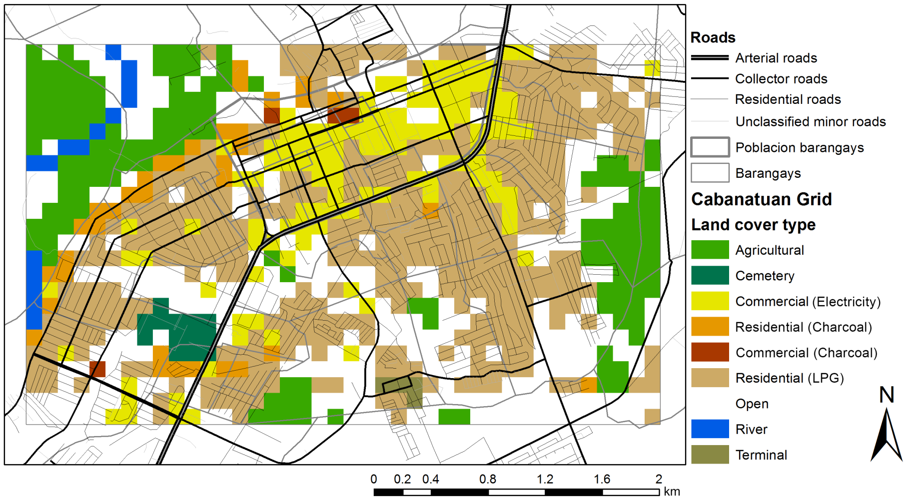

Figure 4. Land cover/land use map from interpretation of satellite image. Base map derived from satellite imagery (Google Earth Pro, 2015, 2016). Additional data from OpenStreetMap (OpenStreetMap contributors, 2016).

use plans and land cover maps, as well as actual verification of features at the ground level (ground truth, i.e., information on surface features in the study area), is necessary and in this study verified land cover and land use features at the surface level.

$PM_{2.5}$ emissions in Cabanatuan depend highly on local activity. Therefore, each grid cell (100×100 m) within the study area has been classified with respect to the land cover features, i.e., residential/commercial zones, agricultural areas, or other surface characteristics. Figure 4 shows that residential land use (cells marked as "Residential (LPG)"; households using liquefied petroleum gas as a fuel) is spread widely, although with noticeable commercial districts and open fields (not settled or occupied) located within this area. Two large agricultural areas are found in the northwest and east, occupied by small households likely using biomass-based fuels like charcoal (cells marked as "Residential (Charcoal)"). Another kind of commercial area is also indicated using cells marked as "Commercial (Charcoal)". These are areas with commercial establishments specializing in grilling foodstuffs highlighted as a possible specific source of $PM_{2.5}$ emissions. The Pampanga River is marked in blue in the figure, and in the southeast a new residential area near open fields and agricultural areas has been built up. Note that some of the grid cells are marked as land uses directly: cemetery and terminal, the latter corresponding to the central transport terminal of Cabanatuan, where high vehicular emissions are expected.

2.3 $PM_{2.5}$ emission estimation

All calculations that have been used to estimate $PM_{2.5}$ emissions are based on a general formula used by the US EPA in the AP 42 Compilation of Air Pollutant Emission Factors (EFIG, 1995), as shown in Eq. (1)

$$E = A \times \mathrm{EF} \times \left(1 - \frac{\mathrm{ER}}{100}\right), \quad (1)$$

where E is equal to $PM_{2.5}$ emissions, A is the activity rate/data (e.g., quantity of fuel used, percentage of households using fuel), EF represents the emission factor, and ER is the overall emission reduction factor/efficiency in percent, if applicable. In the present method, E is estimated as being the quantity of $PM_{2.5}$ per unit cell: micrograms per 0.01 km^2 (1 ha) per year. ER refers to other factors affecting the total amount of $PM_{2.5}$ emissions (such as factors not directly accounting towards the quantity of fuel used; ER factors also incorporate the activity of those using quantities of fuel lower than average). This comprises the various factors that are also part of activity data (as in, factors that modify the amount of emissions generated) as used in this study.

2.3.1 Local emission factors

Emission factors for households, vehicular emissions, and agricultural waste burning are estimated from various local studies and projects (Table 1). For households, the study of Cayetano et al. (2014b) is used as a reference for its $PM_{2.5}$ emission factor. The emission factors for vehicular sources and agricultural waste burning are sourced from in-house laboratory studies.

2.3.2 Activity data

Table 2 compiles the sources of activity data used in this study. Household and population data are obtained from local government documents, particularly the Comprehensive Land Use Plan(s) (CLUP) and Socio-Economic Profile(s) (SEP) of Cabanatuan (CPDO, 2015, 2016). Informa-

Table 1. Data sources for emission factors.

Factor	Source
Emission factors for households (charcoal)	Cayetano et al. (2014b)
Emission factors for vehicular activity (motorcycles/tricycles, jeepneys, PUVs)	In-house data
Emission factor for agricultural waste burning (rice straw)	In-house data

Table 2. Data sources for activity data.

Factor	Source
Population data, land use	2016 Comprehensive Land Use Plan (Provisional; CPDO, 2016), 2015 Socio-Economic Profile (SEP; CPDO, 2015)
Activity data for households; LPG, charcoal consumption	2011 and 2005 Household Energy Consumption Survey (HECS; PSA, 2011); on-site ground surveys
Activity data for vehicles: PUVs, motorcycles, and tricycles	Land Transportation Office annual reports (LTO, 2016); on-site ground surveys
Data on rice production and rice land agricultural area	2016 Comprehensive Land Use Plan (Provisional; CPDO, 2016), 2015 Socio-Economic Profile (SEP; CPDO, 2015)
Data on rice straw generated per amount rice produced	Bakker et al. (2013)

tion on total amount of fuel used by household is obtained from the national Household Electricity Consumption Survey (HECS), conducted in 2005 and 2011 (PSA, 2011). Data on rice production as an indicator for agricultural waste production are obtained from the 2015 Cabanatuan SEP. The findings of the study of Bakker et al. (2013) are used as a reference to calculate how much agricultural waste (rice straw) is produced per amount of rice produced.

2.3.3 Emission estimation equations

Emissions for household fuel (charcoal) were estimated with the formula shown in Eq. (2):

$$E_{\mathrm{households}} = (N_{\mathrm{h}} \times \mathrm{HF}) \times Q_{\mathrm{fuel}} \times \mathrm{EF} \times 0.01, \tag{2}$$

where N_{h} is the estimated number of households (generated from city government data), and HF is the percentage of all households using charcoal as fuel, obtained from the HECS. Q_{fuel} is the quantity of fuel in kilograms used per year by each household, sourced from the HECS and verified using sensitivity analysis by ground surveys (see Sect. 2.4). EF corresponds to the emission factor for charcoal fuel $PM_{2.5}$ per square kilometer per year; this is then multiplied by 0.01 to scale to each 0.01 km^2 cell.

$PM_{2.5}$ emissions for vehicular sources were estimated with the formula shown in Eqs. (3) and (4).

$$E_{\mathrm{MC/TC}} = (N_{\mathrm{u}} \times \mathrm{DF} \times \mathrm{AVF}) \times (\mathrm{EF} \times \mathrm{KT} \times \mathrm{SDF}) \times 0.01 \tag{3}$$

$$E_{\mathrm{PUV}} = (N_{\mathrm{u}} \times \mathrm{DF}) \times \mathrm{EF} \times 0.01 \tag{4}$$

Factors that are the same for both equations include the estimated number of vehicle units (N_{u}), the density factor (DF; amount of vehicles per km^2), and the emission factor (EF). The in-house emission factor for motorcycles and tricycles (here abbreviated as MC/TCs) is measured as $PM_{2.5}$ per kilometer traveled (per vehicle). Due to this non-standard EF unit, additional factors are required in Eq. (3). These include the association vehicle factor (AVF), the percentage of vehicles which are officially registered and properly accounted for by the city. To scale the EF to its proper units, it is multiplied by factor KT (kilometers traveled per day) and SDF (days in service per year). Similar to the previous example, the total is also multiplied by 0.01 to scale to each 0.01 km^2 cell. The DF and AVF were verified using sensitivity analysis by ground surveys as detailed in Sect. 2.4.

Emissions for agricultural waste burning were estimated with the formula shown in Eq. (5):

$$E_{\mathrm{agricultural}} = \left(\frac{\mathrm{RS}}{\mathrm{RA}}\right) \times \mathrm{EF} \times \mathrm{SF}, \tag{5}$$

where RS is the amount of rice straw produced per year, divided by RA, which is the total area in hectares (0.01 km^2) used for growing of rice. EF is the in-house obtained emission factor for rice straw burning $PM_{2.5}$ per year per square kilometer. SF is the survey factor, representing the percentage of farming area where burning of rice straw as agricultural waste is used. This reduction factor is taken from the study of Launio et al. (2013).

These equations are applied to estimate $PM_{2.5}$ emissions for each cell, determined by its land cover type (households, vehicles, agricultural). After the estimated emissions for each cell have been calculated, they were mapped using ArcMap (ArcGIS 10.1) software (ESRI, 2011). All cells with estimated $PM_{2.5}$ greater than zero are plotted for each land cover type.

2.4 Validation of activity data factors (ground surveys and sensitivity analysis)

Ground surveys were conducted to validate specific activity data factors used in the $PM_{2.5}$ estimation process. A total of 98 respondents (32 for households, 33 for tricycles, and 33 for PUVs) were surveyed for the validation of activity data factors involving household fuels, tricycle, motorcycle, and PUV (jeeps/vans) usage. This process was used as a form of sensitivity analysis, intended as a way to fine-tune these factors to the setting of Cabanatuan. For reference, the sensitivity analysis procedure reported by proponents of the Clean Air for Smaller Cities project (ASEAN-GIZ) used a margin of 5 % to determine variability of traffic data collection while surveying roads for mobile air emissions (Yuberk and Cornet, 2013).

This survey was the source of some of the factors used in the estimation process. These include the amount and type of household cooking fuel used, registration under a tricycle/PUV riders association, and kilometers traveled per day per vehicle. While not directly impacting the study, the usage of gasoline fuels and engine maintenance options was also surveyed. Table 3 shows the list of activity data factors that have been validated in this activity.

The respondents that were surveyed were taken from specific areas, termed emission hotspots. These are locations where the amount of estimated $PM_{2.5}$ emissions are expected to be high. From the total estimated maximum respondents per type (households, vehicles like MC/TCs, PUVs), the sample group for this study accounts for around 1 % of the total for respondents for households, around 5 % for total respondents for MC/TCs, and around 2 % for the total for respondents for PUVs. This proportion of the sample size is very low, so the proponents have implemented stratified sampling intended to make the small sample as representative of the entire study area as possible.

3 Results and discussion

The resulting maps of the estimated $PM_{2.5}$ emissions can be seen in Figs. 5 to 9. As seen in Fig. 5, the cells indicating the locations of household-related emissions are located in the fringe of the central residential areas, where households using charcoal as fuel are mostly situated. High levels of $PM_{2.5}$ are expected in these areas, with levels reaching up to 1 kg of $PM_{2.5}$ per year per cell. As this map focuses on charcoal as a fuel source, emissions from commercial establishments using charcoal were also included. Similar to households, Eq. (2) was also used to estimate the emissions in these areas.

The widespread presence of tricycles in Cabanatuan is made evident in the map shown in Fig. 6; almost all cells aside from those indicating non-built-up areas or agricultural areas have assigned values. Due to the high overall presence of motorcycles and tricycles as a mobile emission source in the study site, $PM_{2.5}$ levels are expected to be considerably high as a factor of total emissions in the city.

Areas of interest concerning the very high density of tricycles and associated emissions include the central commercial zone, located within the poblacion barangays of Cabanatuan. A portion of the city center around the old capitol and the public market has a high density of tricycles contributing to $PM_{2.5}$ emissions. High concentrations of $PM_{2.5}$ emissions can also be seen in major roads extending from this central area. Of notice is an isolated four-cell segment in the southwest corner of the map; this is an area near a crowded intersection of the national highway and a road leading to the central transport terminal of Cabanatuan. In addition, this area is also a substantial terminal for tricycles on its own (such terminals are often referred to in the vernacular as *toda*) servicing the immediate vicinity and the growing commercial zone to the south of the study site.

In contrast, emissions coming from PUVs (map shown in Fig. 7) are found only on certain routes, as they are usually used for inter-city transport compared to tricycles. The map indicates emissions from both jeepneys and buses. Emissions for PUVs are estimated to be mostly equal along major roads, marked with cells representative of higher emissions. However, as the number of PUVs servicing the portion of the city near the study site are not as high as that of the number of tricycles, the estimated emissions generated from PUVs are expected to be much lower compared to tricycles.

A factor not usually present in major urban areas is the presence of agricultural land uses, which are more common in regional centers, especially those of provincial centers. These land uses characterize cities that hybridize both rural and urban elements such as Cabanatuan. In this context, a candidate source of $PM_{2.5}$ emissions, burning of agricultural waste, was taken into account in this $PM_{2.5}$ estimation study. Agricultural wastes such as rice straw are frequently still burned as part of a farmland management practice in these regions, an activity that contributes to harmful emissions of particulate matter.

The map of estimated emissions from rice straw burning is shown in Fig. 8. The amount of $PM_{2.5}$ here is assumed to represent the entire year, despite rice straw only being burned as agricultural waste in certain seasons. In particular, rice straw burning only occurs at the end of each planting season. This

Table 3. List of activity data factors validated by ground survey sensitivity analysis.

Factor	Value before validation	Value after validation	% deviation (from sensitivity analysis)
Household fuels			
Quantity of (household) fuel used (Q_{fuel})	194 kg yr^{-1} (HECS, 2011)	173.3 kg yr^{-1}	10.7 %
Vehicular emissions			
Kilometers traveled (KT)	80 (in-house data)	87.21	9.0 %
Days in service (SDF)	320 (in-house data)	304.4	4.9 %

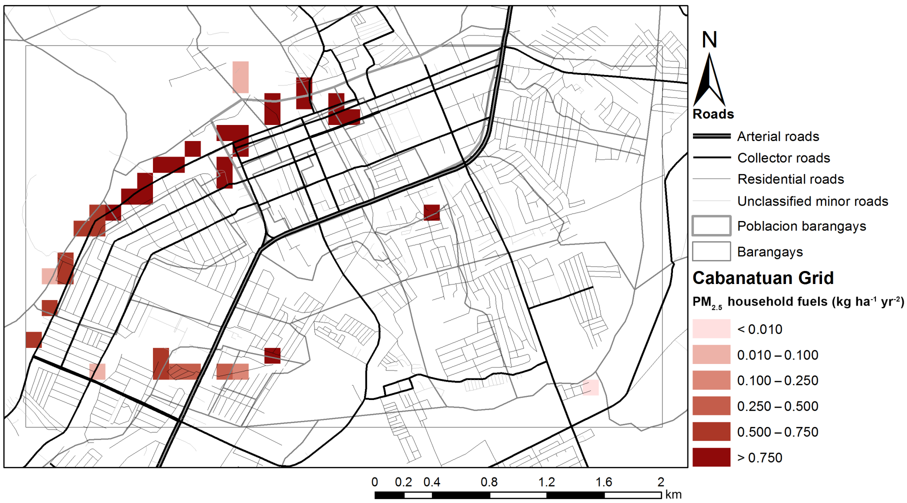

Figure 5. Map of estimated $PM_{2.5}$ emissions from burning of household fuels. Base map derived from satellite imagery (Google Earth Pro, 2015, 2016).

typically occurs around the months of April and October in Cabanatuan.

Also, only a certain fraction of all agricultural land in the city is used in the growing of rice (these data are taken from the Cabanatuan City CLUP), and this was taken into account when estimating emissions for this map. A point to note is the fact that nearly all of the cells tagged as agricultural are only the fringes of larger zones used for this purpose; larger agricultural areas can be found to the northwest, southeast, and east of the study site. More importantly, these areas are very close to the city center itself; it can be observed that the residential, commercial, and agricultural land uses are located very close to each other, almost intersecting inside the investigation area.

A map showing combined emissions for all four factors used in this study is shown in Fig. 9. With the combined contributions visible in this map, areas of high concentration of $PM_{2.5}$ emissions become more evident. Both residential and commercial zones, as well as the dense transportation (by tricycle) network within the *poblacion* and the area immediately to its southeast contribute much of the emitted particulates; definite areas of high $PM_{2.5}$ concentrations can be seen in this location, likely from the high contributions of combustive fuels for both households and agricultural waste burning.

4 Summary and conclusion

As seen in the resulting maps, households and vehicular sources (tricycles) account for much of the total $PM_{2.5}$ emissions in the Cabanatuan investigation area. PUVs (jeeps) account for a small portion of vehicular emissions. $PM_{2.5}$ from burning of agricultural waste was found to be a large constituent of total particulates. As the investigation area is only a small fraction of the entire city, this likely means that agricultural waste burning is a significant source of $PM_{2.5}$ in the largely agricultural Cabanatuan. This is open to future research on air quality management in the city, among others.

The amount of $PM_{2.5}$ emissions in the investigation area estimated by this method is comparable to emission levels in urban metropolitan areas. A possible reason for this is the common usage of biomass-based fuels such as charcoal or the high levels of particulates from vehicular sources. Vehicular emissions and agricultural waste burning, at their highest

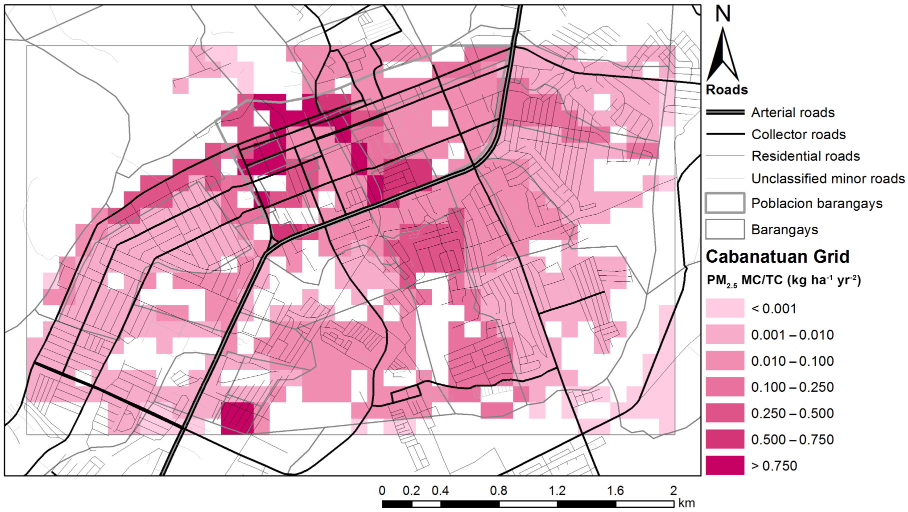

Figure 6. Map of estimated $PM_{2.5}$ emissions from motorcycles and tricycles. Base map derived from satellite imagery (Google Earth Pro, 2015, 2016).

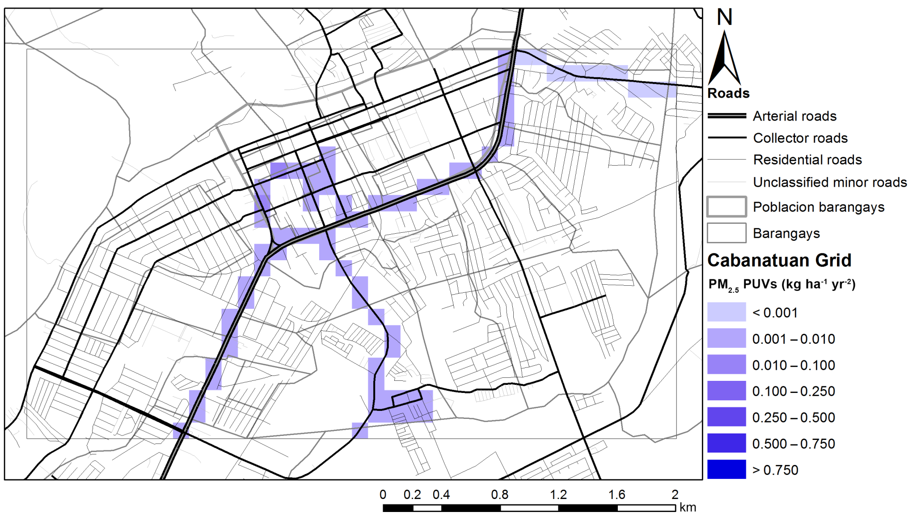

Figure 7. Map of estimated $PM_{2.5}$ emissions from PUVs (public utility vehicles/jeepneys/XLTs). Base map derived from satellite imagery (Google Earth Pro, 2015, 2016).

levels, are responsible for emission levels of at least 2 kg of $PM_{2.5}$ per 1 ha cell per year each. This interface between rural and urban land uses in Cabanatuan has produced a varied environment for research on multiple areas. Household fuel usage, vehicular sources, and agricultural waste burning are a major component of the city's air pollution and more research on its management in the region is necessary.

The validation of specific activity data factors is effective at adapting them closer to the specific conditions present in Cabanatuan. While the more general original in-house values are more appropriate in areas like Metro Manila, the validation procedure has made them more appropriate for smaller cities in general. An issue during the ground survey activity involves its small sample size compared to the possible maximum number of respondents in the investigation area. However, the benefits of fine-tuning the activity data with this analysis outweigh its disadvantages. Also, in future researches, the ground survey and sensitivity analysis validation will highly be improved if the sample size is greatly increased.

5 Recommendations

As stated earlier, this method for the estimation of $PM_{2.5}$ emissions is intended for use by local government stakeholders for smaller cities and regional centers in any study country. While this method was primarily developed to estimate

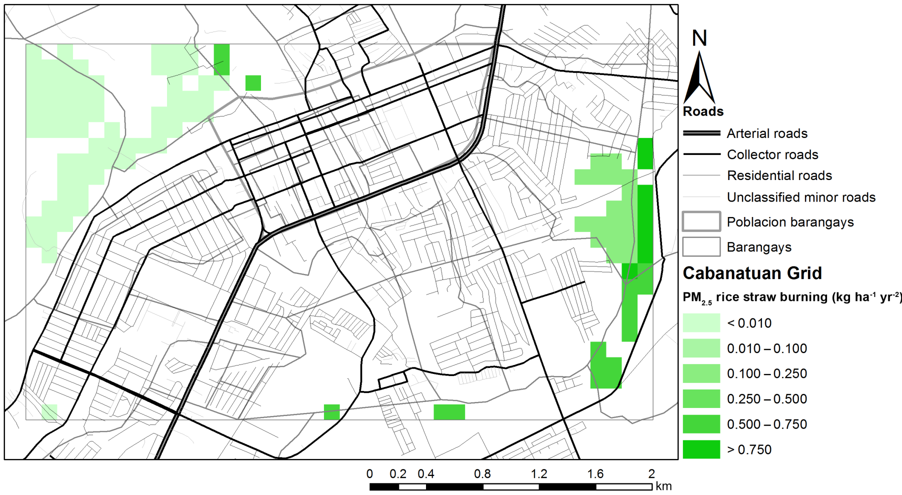

Figure 8. Map of estimated $PM_{2.5}$ emissions from burning of rice straw as agricultural waste. Base map derived from satellite imagery (Google Earth Pro, 2015, 2016).

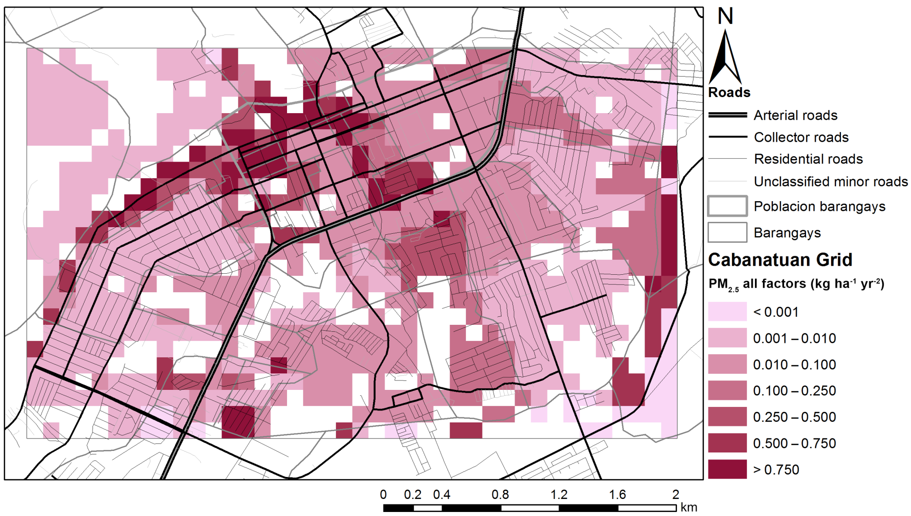

Figure 9. Map of estimated $PM_{2.5}$ emissions combining all factors in the study. Base map derived from satellite imagery (Google Earth Pro, 2015, 2016).

$PM_{2.5}$, similar methods can be used for other components of the emission inventory process in the country (i.e., criteria pollutants and greenhouse gases).

Ground verification of surface features is necessary to ensure the accuracy of land cover maps. Due to this, the researchers recommend a detailed field survey on the ground level with surveyors equipped with GPS units to ensure that the gathered information on surface features is up to date. This will also provide a way to offset the possible inaccuracy of the Google Earth satellite image in terms of its coordinates.

This method currently compiles estimated emissions on a yearly basis. The presence of seasonal factors such as agricultural waste burning, however, can indicate the possible usefulness of seasonal mapping of $PM_{2.5}$ emissions. Since it is equally important to investigate air pollution emissions through different temporal scales, such an option is worth looking into in the future.

Additionally, a method for the verification of activity data factors, similar to this study's sensitivity analysis, is highly recommended for future studies. A focus on such studies but on a much larger scale (a ground survey that represents a much larger portion of an investigation area) would be instrumental in placing the total emission estimate more accurate with regards to specific conditions in a city. Actual in situ measurement of $PM_{2.5}$ emissions is also possible for a small study area like this one. Such a validation activity would require the use of air samplers or particle counters to actually measure the amount of $PM_{2.5}$ present. A limitation of this method, however, lies in the fact that it can only measure total particulate emissions and cannot differentiate between different sources of $PM_{2.5}$. Because of this, any follow-up study that involves actual in situ $PM_{2.5}$ measurements must also include chemical analysis of sampled particulates as well as source apportionment in order to determine the actual amounts of air pollutants by source. A reference study was conducted by Cayetano et al. (2014a), and research projects with methodologies similar to this study are currently being conducted in Cabanatuan and other cities.

Lastly, as this method is primarily geared towards the estimation of particulate emissions, the planning of mitigation strategies to increase air quality in target cities such as in Cabanatuan must also be pursued in tandem with emission inventories conducted by the local government and other stakeholders. Local governments in the Philippines are continuously upgrading their capabilities for spatial knowledge and city planning due to the propagation of usage of GIS software by government officials and non-governmental organizations (NGOs). This particular study has used ArcGIS, a proprietary software that requires a paid license, which may prove to be an issue for units with small financial capabilities. As this method can just as easily be executed using free and open-source GIS software such as QGIS, studies using this software may be used in the future for organizations seeking a less costly alternative for GIS. The specialization of city environment officers in pollution studies is a process that is both ongoing and needing more attention. For future studies and efforts, it will be worthwhile to increase the capability of local stakeholders to plan for environmental issues like air pollution.

Data availability. Excel spreadsheets containing the calculations of the estimated $PM_{2.5}$ emissions, as well as those used as attribute tables for GIS mapping, are attached as the Supplement of this paper.

The Supplement related to this article is available online at https://doi.org/10.5194/amt-10-3313-2017-supplement.

Competing interests. The authors declare that they have no conflict of interest.

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