Journal: AMTD/AMT
Title: Spatial estimation of air $PM_{2.5}$ emissions using activity data, local emission factors and land cover derived from satellite imagery
Author(s): Hezron Gibe and Mylene Cayetano
MS No.: amt-2017-14

Subject: Authors' comment: point-by-point reply to comments by Associate Editor

We thank the Associate Editor for taking time to oversee the final review for this manuscript. The suggested edits for grammar and use of abbreviations were taken. References and citations to software, usage of satellite imagery, and data sources were also added. A few paragraphs were also included with additional information as suggested. We believe that these suggestions have been important for increasing the quality of the text. We hope that this will be enough for your recommendation for this paper to be published to AMT.

Kindly refer to the following point-by-point replies to these comments. We appreciate your kind consideration and detailed comments for improving the content and preparing this manuscript for publication to the journal.

Evaluation and response to interactive comment by Associate Editor:

Dear Authors,

You have obviously made a great effort to improve the manuscript according to the referees' suggestions. Yet, I still have some comments that I would like to see addressed before the manuscript can be published. These are mostly about missing literature or internet references, the use of abbreviations, and some grammatical corrections. More importantly, I have two scientific questions: first, how can the results of your method be validated? Although your results look very plausible, validation of a new method is crucial. And second, how useful would it be to provide seasonal PM2.5 maps? The contribution of rice straw burning, for example, clearly depends on the time of year.

Detailed comments:

1. Literature (or internet) references to Google Earth/Streetview, OpenStreetmap, and Arcmap / ArcGIS software are missing. Also an acknowledgment for the free use of data (Google and OpenStreetmap) is lacking.

Response: References were added to relevant points, particularly:

Page 3, Line 24-28: *Detailed images over the ground, taken by Google Street View (examples are shown in Fig. 3) was 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; Google Earth Pro, 2016). Additionally, maps from OpenStreetMap were also used for identifying special landmarks or as an additional resource since it occasionally presents more updated information on surface features than Google Earth/Google Street View (OpenStreetMap, 2016).*

Page 7, Line 8-10: *These equations are applied to estimate PM2.5 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 PM2.5 greater than zero are plotted for each land cover type.*

An acknowledgement was added to its corresponding section:

Page 1, Line 19-21: *Map data used in this study is copyrighted (2015, 2016) to Google and data providers: Landsat, Copernicus, ZENRIN, and SKEnergy. Additional map data copyrighted to OpenStreetMap contributors and available from https://www.openstreetmap.org*

Their corresponding citations were also added to the references section.

Also other literature references, particularly to the activity data (Section 2.3.2) are missing. For example, cite the reference for the HECS as "Household Energy Consumption Survey (HECS)", Philippine Statistics Authority, https://psa.gov.ph/hecs, accessed on 7/7/2017.

Response: References were added to the following:

Page 5, Line 12-16: *Household and population data is obtained from local government documents, particularly the Comprehensive Land Use Plan(s) (CLUP) and Socio-Economic Profile(s) (SEP) of Cabanatuan City (Cabanatuan City CLUP, 2016; Cabanatuan City SEP, 2015). Information 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).*

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2. Please pay attention to the abbreviations you use, such as PUV, MC/TC, etc. These need to be explained at least once in the text, preferably when they are first introduced. Alternatively, you can add a table with abbreviations, but as the manuscript contains many tables already I would recommend the first option.

Response: Usage of these abbreviations have been improved for this paper, For all of these listed abbreviations, the sections in which they appear have now been re-written to introduce their meaning when they are first introduced, such as in:

Page 2, Line 31-32: *Sources corresponding to urban activity include vehicular mobile sources such as tricycles, jeepneys, and public utility vehicles (PUVs, which include buses and vans).*

Page 6, Line 15-16: *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).*

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3. Can you comment on seasonality? Your study is done on a yearly basis, but rice straw is only burnt in certain seasons.

Response: A few sentences were added in various sections on seasonality of rice straw burning.

Page 9, Line 12-17: *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 typically occurs around the months of April and October in Cabanatuan City.*

Also, only a certain fraction of all agricultural land in the city is used in the growing of rice (this data is taken from the Cabanatuan City CLUP), and this was taken into account when estimating emissions for this map. […]

Page 10, Line 30 – Page 11, Line 2: *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.*

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4. Please add a paragraph about how these data can be validated to Section 5. Satellite-based monitoring is probably not possible due to the small scale of the study region, so what methods would you suggest?

Response: A substantial edit was made to the latter half of Section 5, reordering paragraphs and adding content with regard to possible methods of validation of data.

Page 11, Line 4-24: *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.*

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 City 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 its capabilities for spatial knowledge and city planning due to the propagation of usage of GIS software by government officials and non-government 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.*

Page 1

Line 6 - "air particulate matter (APM)" -> "particulate matter (PM)"

Line 8 - "...estimating the amount fine..." -> "...estimating the amount of fine..."

Response: These sentences have been corrected, as seen in:

Page 1, Line 6-10: *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 Cabanatuan City, Nueva Ecija in the Philippines, by utilizing local emission factors, regionally procured data and land cover/land use (activity data) interpreted from satellite imagery.*

Page 2

Line 4 - "Sources of PM2.5 are caused by many man-made activities" -> "Enhancements in PM2.5 are mainly caused by various human activities"

Line 5 - "A common source of PM2.5..." -> "A common source of particles contributing to PM2.5..."

Response: These sentences have been corrected, as seen in:

Page 2, Line 5-7: *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)*

Line 7 - "(such as CORINAIR and AP 42)" -> literature references are missing here

Response: References to emission factor guidebooks were added to this section:

Page 2, Line 7-9: *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) (EPA, 1995)).*

Line 13 - "conducted" -> "constructed"

Line 16 - "sourced" -> "determined"

Line 18 - "which produces" -> "producing"

Line 26 - "This method is specifically meant to explore this method " -> "This study is specifically meant to explore this method "

Response: These sentences have been corrected, as seen in:

Page 2, Line 14-15: *Emission inventories in general have likewise not been constructed in many cities.*

Page 2, Line 18-21: *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.*

Page 2, Line 28-30: *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.*

Page 3

Lines 17-19 - do you have literature references for this method?

Response: Sentences were added to the paragraph starting in Page 3, Line 19 to include a reference/influence for the method used in this study.

Page 3, Line 19-23: *The investigation area was divided with 24 x 40 grid cells (100 x 100 m or 1 ha / 0.01 km^2 each). For each cell, the type of man-made activity was interpreted from satellite images 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. […]*

Lines 26-28 - "(The collaged image used in Google Earth is sourced from processed images from Landsat and the European Space Agency (ESA)'s Copernicus program). "The Google Earth images used consist of post-processed Landsat images from the European Space Agency (ESA)'s Copernicus program."

Response: This sentence has been corrected, as seen in:

Page 3, Line 30-31: *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 (ESA)'s Copernicus program.*

Page 4

Line 2 - "Even so, " -> "Despite these disadvantages, "

Response: This sentence has been corrected, as seen in:

Page 4, Line 6-7: *Despite these disadvantages, the Google satellite image product is useful enough for the uninitiated considering the present purpose.*

Lines 8-15 (and accompanying Fig. 4) - Land cover type and expected dominating sources of PM are being mixed here. Please be more consistent, for example by changing the map to contain only the land type (i.e., substituting "fuels" by "traffic" and "grilling" by "market place" (What are commercial grilling establishments?)). Then you can mention the assumed PM sources for each land use type in the text.

Response: The legend for the map shown in Figure 4 has been corrected to substitute certain terms: "Commercial", "Fuels", "Grilling", and "Residential" have been changed to "Commercial (Electricity)", "Residential (Charcoal)", "Commercial (Charcoal)", and "Residential (LPG)", respectively. "Fuels" here in this manuscript refers to household fuels, not vehicular fuels, and this first mention has been corrected to "charcoal" for clarity. The corresponding part of the manuscript has also been edited, as seen in the following:

Page 4, Lines 15-20: *Figure 4 shows that residential land use (cells marked as "Residential (LPG)"; households using liquefied petroleum gas as a fuel) are 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.*

Line 28 - "sourced" -> "estimated"

Response: This sentence has been corrected, as seen in:

Page 5, Line 4-5: *Emission factors for households, vehicular emissions, and agricultural waste burning is estimated from various local studies and projects (Table 1).*

Page 10

Line 15 - "GHGs" -> "greenhouse gases"

Response: This sentence has been corrected, as seen in:

Page 10, Line 21-23: *While this method was primarily developed to estimate $PM_{2.5}$, similar methods can be used for other components of the emission inventory process in the country (i.e. criteria pollutants and greenhouse gases).*

Figure 1. Change the caption to "Map of the Philippines and location of Cabanatuan City and some other major cities.", then add some major cities (or at least Manila) for reference.

Response: Figure 1 has been changed to add local cities for reference. The caption has also now been changed to read:

Caption: *Figure 1: Map of the Philippines and location of Cabanatuan City (with major cities)*

Attached below is the text of the manuscript with markup:

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 ~~air~~ particulate matter (~~A~~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 Cabanatuan City, 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 City. Overall, the method used in this study can be applied in other small urbanizing cities, as long as on-site specific activity data, emission factor and satellite-imaged land cover are available.

1 Introduction

Exposure to air particulate matter, especially fine particles smaller than 2.5 micrometers 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 cardio-pulmonary 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).

S~~ources of~~Enhancements in $PM_{2.5}$ are mainly caused by ~~many~~ various ~~man-made~~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) (EPA, 1995)). However, PM2.5 emissions from other activities such as burning of agricultural waste occurs as well in cities with a mixture of rural and 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 (TSP) 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 ~~conducted~~ 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 ~~sourced~~ 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 ~~which produces~~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 man-made activities present in Philippine cities. This ~~method~~ 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, 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 Cabanatuan City, Philippines ~~(Fig. 1)~~. It is the former capital and largest city of the province of Nueva Ecija, with a land area of 190.67 square kilometers and an estimated population of 296,584 in 2012. On average, the population density is around 1,516 persons per square kilometer. The urban and rural population take up around half each of the total population (Cabanatuan City SEP, 2015). A map of Cabanatuan City with a reference to its nearby major cities is shown in Fig. 1.

A 2.4 by 4.0 kilometer 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 two kilometers away from a main road. A commercial zone and the planned main industrial district in Cabanatuan City 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 x 40 grid cells (100 x 100 m or 1 ha / 0.01 km^2 each). For each cell, the type of man-made activity was interpreted from satellite images taken from Google Earth software. The classification process is similar to ~~what is done for~~ 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) was 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; Google Earth Pro, 2016). Additionally, maps from OpenStreetMap were also used for identifying special landmarks or as an additional resource since it occasionally presents more updated information on surface features than Google Earth/Google Street View (OpenStreetMap, 2016).

~~G~~oogle Earth images have been used here instead of raw image data from, for example, the Landsat satellite. ~~(~~The Google Earth ~~collaged image used in Google Earth is sourced from processed~~ images used ~~from~~ consist of post-processed Landsat images from ~~and~~ the European Space Agency (ESA)'s 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 metadata of the original images. ~~Even so~~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 use plans and land cover maps, as well as actual verification of features at the ground level (ground truth, that is, information on surface features in the study area), is necessary, and was used in this study to verify land cover and land use features at the surface level.

$PM_{2.5}$ emissions in Cabanatuan City highly depend on local activity. Therefore, each grid cell (100 x 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) are 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 City, 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 (EPA, 1995), as shown in Eq. (1)

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

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

Table 1. Data sources for emission factors

Emission factors for households (charcoal)	Cayetano and Lamorena (2014)
Emission factors for vehicular activity (motorcycles/tricycles, jeepneys, PUVs)	In-house data
Emission factor for agricultural waste burning (rice straw)	In-house data

2.3.2 Activity data

Table 2 compiles the sources of activity data used in this study. Household and population data is obtained from local government documents, particularly the Comprehensive Land Use Plan(s) (CLUP) and Socio-Economic Profile(s) (SEP) of Cabanatuan City~~;~~ (Cabanatuan City CLUP, 2016; Cabanatuan City SEP, 2015). ~~i~~Information 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 is obtained from the 2015 Cabanatuan City SEP. The findings of the study of Bakker, et al. (2013) is used as a reference to calculate how much agricultural waste (rice straw) is produced per amount of rice produced.

Table 2. Data sources for activity data

Population data, land use	2016 (provisional) Cabanatuan CLUP Cabanatuan City SEP (2015)
Activity data for households; LPG, charcoal consumption	2011/2005 Household Energy Consumption Survey (HECS) Ground surveys
Activity data for vehicles: PUVs, and motorcycles, and tricycles (MC/TC),	Local government documents, Land Transportation Office (LTO) annual reports, ground surveys
Data on rice production and rice land agricultural area	Cabanatuan City SEP (2015) 2016 (provisional) Cabanatuan CLUP
Data on rice straw generated per amount rice produced	Bakker, et al. (2013)

2.3.3 Emission estimation equations

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

$$E_{households} = (\mathrm{N_h} \times \mathrm{HF}) \times \mathrm{Q}_{fuel} \times \mathrm{EF} \times 0.01\ , \tag{2}$$

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 section 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 Eq. (3) and Eq. (4).

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

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

Factors that are the same for both equations include: N_u, the estimated number of vehicle units, DF, the density factor (amount of vehicles per km^2), and EF, the emission factor. 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 vehicles 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 NAF was verified using sensitivity analysis by ground surveys as detailed in section 2.4.

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

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

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 EEFs 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 City. 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 (Q_{fuel}), registration under a tricycle/PUV riders association (AVF), kilometers traveled per day per vehicle (KT). 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.

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 travelled (KT)	80 (in-house data)	87.21	9.0%
Days in service (SDF)	320 (in-house data)	304.4	4.9%

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 (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 Figures 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 one kilogram of $PM_{2.5}$ per year per cell. ~~It is of note, however, that the emissions for some of these cells is produced by commercial grilling establishments.~~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. ~~Due to this, the map shown in Fig. 5 contains both cells representing households and commercial grilling establishments.~~

The widespread presence of tricycles in Cabanatuan City 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 City. 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, as well. 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 City. 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 public utility vehicles (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 (colloquially known as "XLTs") 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 City. 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 typically occurs around the months of April and October in Cabanatuan City.

Also, Oonly a certain fraction of all agricultural land in Cabanatuan Citythe city is used in the growing of rice (this data is 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 City 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 City. 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 levels, are responsible for emission levels of at least 2 kilograms of $PM_{2.5}$ per 1 hectare cell per year each. This interface between rural and urban land uses in Cabanatuan City 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 City. 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 $PM_{2.5}$, similar methods can be used for other components of the emission inventory process in the country (i.e. criteria pollutants and ~~GHGs~~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.

~~Local governments in the Philippines are continuously upgrading its capabilities for spatial knowledge and city planning due to the propagation of usage of GIS software by government officials and non-government 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.~~

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.

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 City 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 its capabilities for spatial knowledge and city planning due to the propagation of usage of GIS software by government officials and non-government 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.

Acknowledgement

*This study was supported by the research grants from the Natural Sciences Research Institute (2016-ESM-001), and the Office of the Vice Chancellor for Research and Development (***141406 PNSE),** *both from the University of the Philippines, Diliman. The study was also supported by the Ministry of Science, ICT and Future Planning in South Korea through the International Environmental Research Center and the UNU & GIST Joint Programme on Science and Technology for Sustainability* ***from 2014- 2016****. The authors would like to acknowledge the Local Government of Cabanatuan City, the Office of the City Mayor, and the Environmental Protection Division for their assistance in the activities conducted for the purposes of this study.*

Competing interests

The authors declare that they have no conflict of interest.

References

Andrade, M., de Miranda, R.M., Fornaro, A. et al., Vehicle emissions and $PM_{2.5}$ mass concentrations in six Brazilian cities. Air. Qual. Atmos. Health., 5 79-88. doi:10.1007/s11869-010-0104-5, 2012.

Bakker, R., Elbersen, W., Poppens, R., & Lesschen, J. P., Rice straw and wheat straw: potential feedstocks for the biobased economy. Wageningen UR, Food & Biobased Research. NL Agency. 2013.

Bocchi, C., Bazzini, C., Fontana, F., Pinto, G., Martino, A., & Cassoni, F. Characterization of urban aerosol: seasonal variation of mutagenicity and genotoxicity of $PM_{2.5}$, PM_1 and semi-volatile organic compounds. Mutat. Res., 809, 16-23, doi:10.1016/j.mrgentox.2016.07.007, 2016.

Cassidy, B., Alabanza-Akers, M., Akers, T., Hall, D., Ryan, P., Bayer, C., & Naeher, L. Particulate matter and carbon monoxide multiple regression models using environmental characteristics in a high diesel-use area of Baguio City, Philippines. Sci. Total. Environ., 47-58, doi:10.1016/j.scitotenv.2007.03.010, 2007.

Cayetano, M., Hopke, P., Lee, K., Jung, J., Batmunkh, T., Lee, K., & Kim, Y. Investigations of the particle compositions of transported and local emissions in Korea. Aerosol. Air. Qual. Res., 14, 793-805, doi: 10.4209/aaqr.2012.08.0218, 2014.

Cayetano, M., Rosales, C., Lamorena-Lim, R. Determination of particulate and elemental emission factors from selected area and point sources in Metro Manila. 2014 Project Report. Science and Technology for Sustainability: Issues of environmental multi-phase pollutants: from problem understanding to developing innovative solutions. UNU & GIST Joint Programme on Science and Technology for Sustainability, Gwangju Institute for Science and Technology. Vol. 12. 2014.

Chen, H., Goldberg, M., & Villenueve, P. A systematic review of the relation between long-term exposure to ambient air pollution and chronic diseases. Reviews on Environmental Health, 4. 243-297. 2008.

CChen, R., Hu, B., Liu, Y., Xu, J., Yang, G., Xu, D., Chen, C. Beyond $PM_{2.5}$: the role of ultrafine particles on adverse health effects of air pollution. Biochim. Biophys. Acta., 1860, 2844-2855. doi:10.1016/j.bbagen.2016.03.019. 2016.

Emission Factor and Inventory Group (EFIG), U.S. Environmental Protection Agency. Compilation of air pollutant emission factors, volume I; stationary point and area sources (fifth edition). 1995.

ESRI. ArcMap. ArcGIS Desktop: Release 10.1. Redlands, CA. Environmental Systems Research Institute. 2011.

European Environmental Agency. EMEP/CORINAIR Emission Inventory Guidebook. 2007.

Gadde, B., Bonnet, S., Menke, C., Garivait, S. Air pollutant emissions from rice straw open field burning in India, Thailand and the Philippines. Environ. Pollut., 157. 1554-1558. doi:10.1016/j.envpol.2009.01.004. 2009.

Google Earth Pro v. 7.1.5.1557. (September, 2015) Google Street View, Cabanatuan City, Philippines. 15.474329° N, 120.948210° E. ZENRIN (2016), SKEnergy (2016), Google (2016). http://earth.google.com, 20165.

Google Earth Pro v. 7.1.5.1557. (March, 2016) Google Earth imagery, Cabanatuan City, Philippines. 15.474329° N, 120.948210° E. Landsat (2016), Copernicus (2016), Google (2016). http://earth.google.com, 2016.

Goto, D., Ueda, K., Ng, C., Takami, A., Ariga, T., Matsuhashi, K., & Nakajima, T. Estimation of excess mortality due to long-term exposure to PM2.5 in Japan using a high-resolution model for present and future scenarios. Atmos. Environ., 140. 320-332. doi: 10.1016/j.atmosenv.2016.06.015. 2016.

Kim Oanh, N. T., Ly, B. T., Tipayarom,, D., Manandhar, B. R., Prapat, P., Simpson, C., Liu, L.-J. S. Characterization of particulate matter emission from open burning of rice straw. Atmos. Environ., 45. 493-502. doi:10.1016/j.atmosenv.2010.09.023. 2011.

Launio, C., Asis, C., Manalili, R., Javier, E. Economic analysis of rice straw management alternatives and understanding farmer's choices. Cost-benefit studies of natural resource management in Southeast Asia. 93-111. doi:10.1007/978-981-287-393-4_5. 2013.

Lin, C., Li, Y., Lau, A., Deng, X., Tse, T., Fung, J., Li, C., Li, Z., Lu, X., Zhang, X., Yu, Q. Estimation of long-term population exposure to PM2.5 for dense urban areas using 1-km MODIS data. Remote. Sens. Environ., 179. 13-22. doi: 10.1016/j.rse.2016.03.023. 2016.

Mage, D., Ozolins, G. P., Webster, A., Orthofer, R., Vandeweerd, V., & Gwynne, M. Urban air pollution in megacities of the world. Atmos. Environ., 681-686. 1996.

OpenStreetMap contributors. Planet dump (March 2016). Retrieved from https://planet.osm.org. 2016.

Philippine Statistics Authority (PSA). Household Energy Consumption Survey (HECS). Retrieved from https://psa.gov.ph/hecs. 2011.

Sarigiannis, D., Karakitsios, S., Kermenidou, M., Nikolaki, S., Zikopoulos, D., Semelidis, S., Papagiannakis, A., Tzimou, R., Total exposure to airborn particulate matter in cities: the effect of biomass combustion. Sci. Total. Environ., 493. 795-805., doi:10.1016/j.scitotenv.2014.06.055, 2014.

Wu, S., Deng, F., Wang, X., Wei, H., Shima, M., Huang, J., Lv, H., Hao, Y., Zheng, C., Qin, Y., Lu, X., Guo, X. Association of lung function in a panel of young healthy adults with various chemical components of ambient fine particulate air pollution in Beijing, China. Atmos. Environ., 873-884. doi: 10.1016/j.atmosenv.2013.06.018. 2013.

Yuberk, N., Cornet, B., Report: Emission inventory network meeting, Bangkok, 26-27 August 2013. ASEAN – German Technical Cooperation (GIZ). Clean Air for Smaller Cities in the ASEAN Region. 2013.

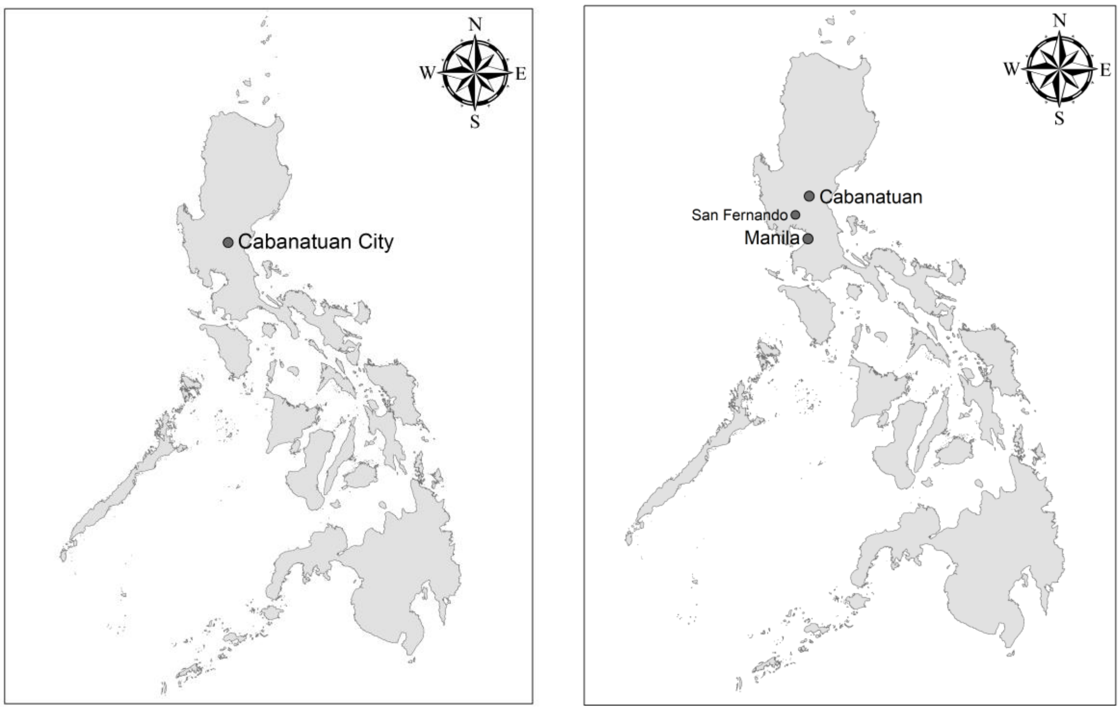


Figure 1: ~~Overview map of Cabanatuan City, Philippines~~Map of the Philippines and location of Cabanatuan City (with major cities)

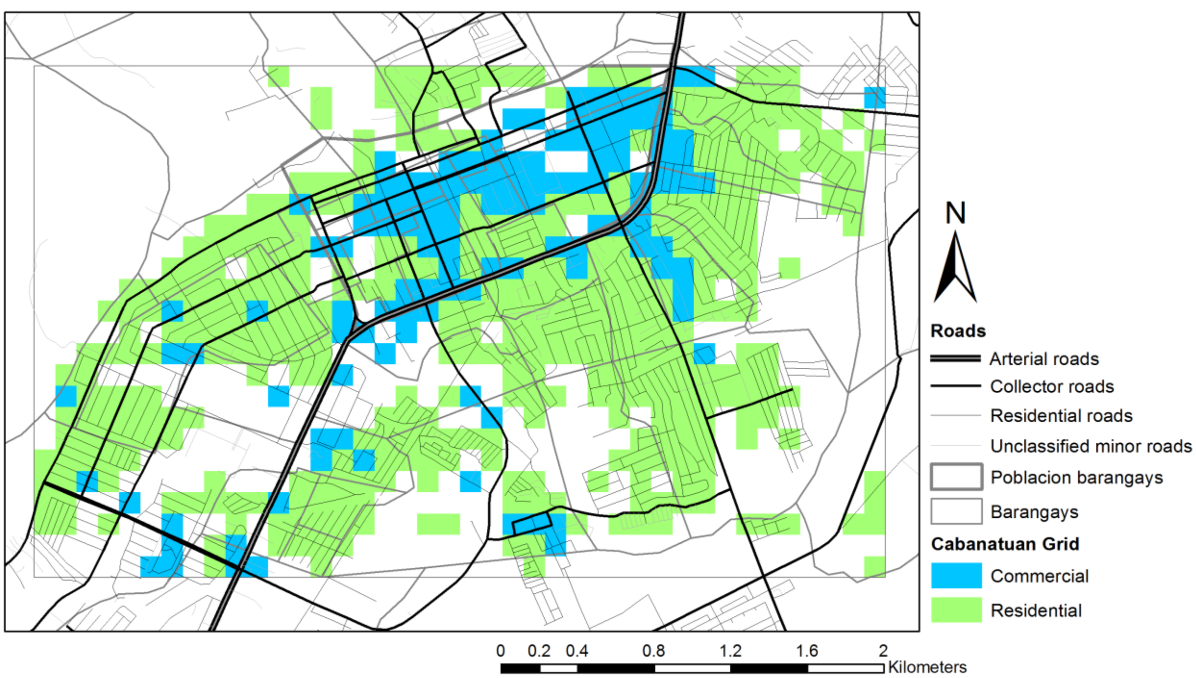
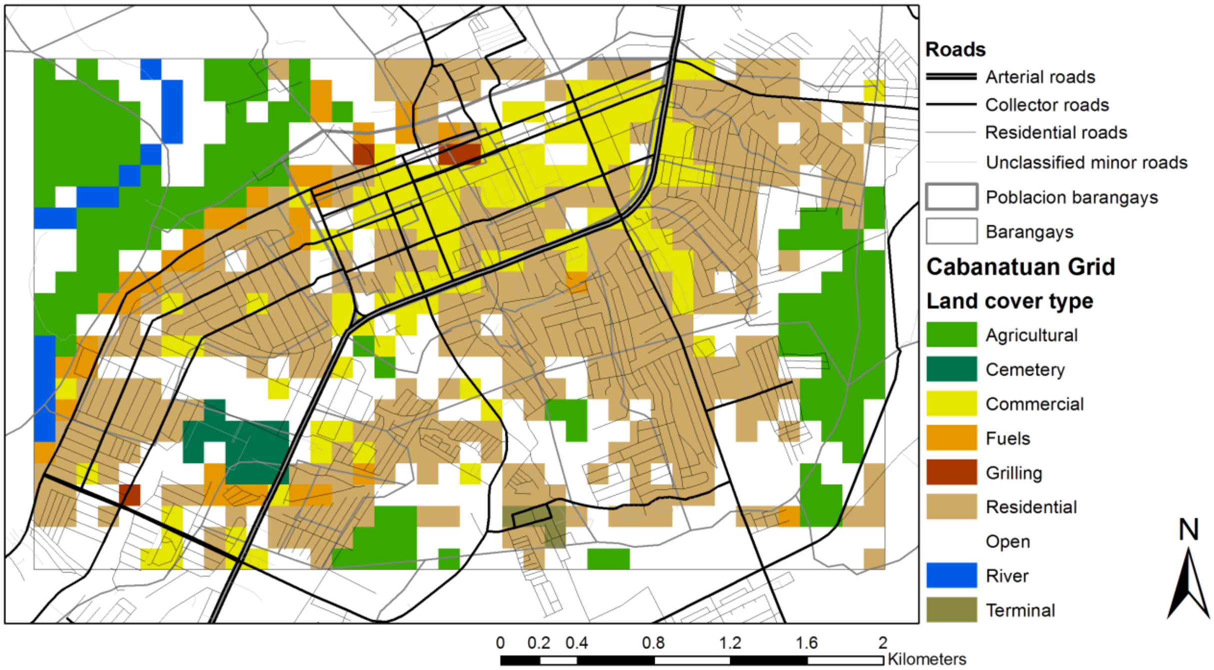


Figure 2: The 2.4 x 4.0 km study area in Cabanatuan City containing the "city center" (*poblacion,* highlighted).

Figure 3: Example of reference image used for Google Street View verification of surface features


Roads
Arterial roads
Collector roads
Residential roads
Unclassified minor roads
Poblacion barangays
Barangays
Cabanatuan Grid
Land cover type
Agricultural
Cemetery
Commercial
Fuels
Grilling
Residential
Open
River
Terminal
N
0
0.2
0.4
0.8
1.2
1.6
2
Kilometers

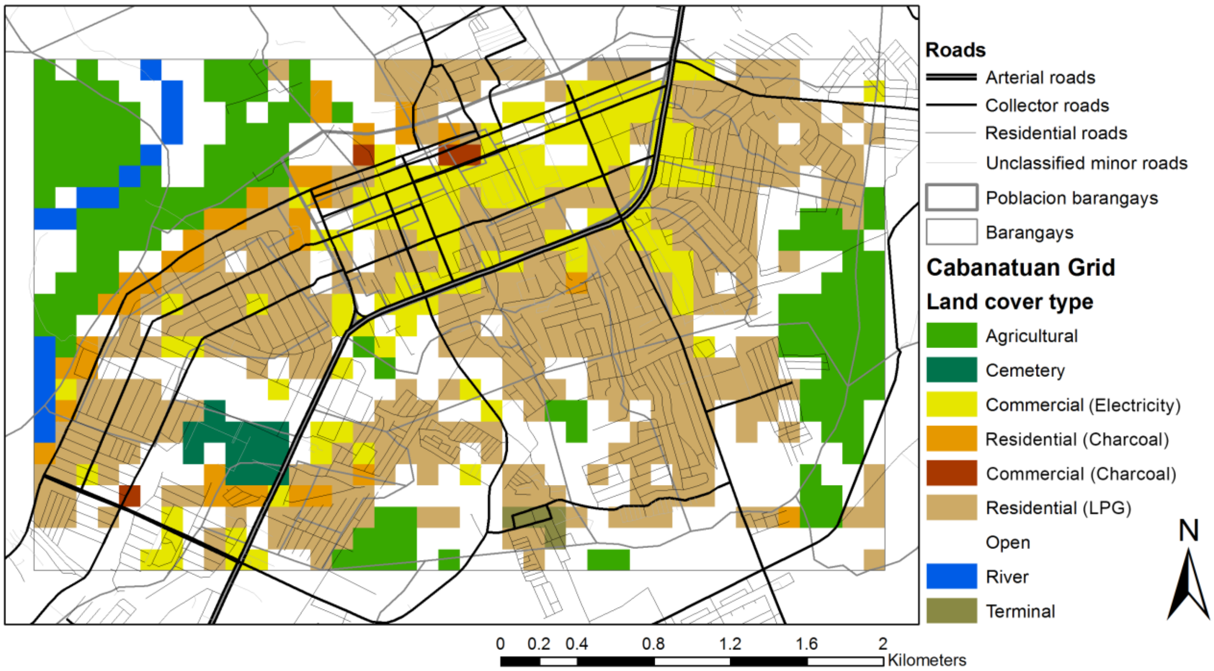


Figure 4: Land cover/land use map from interpretation of satellite image.

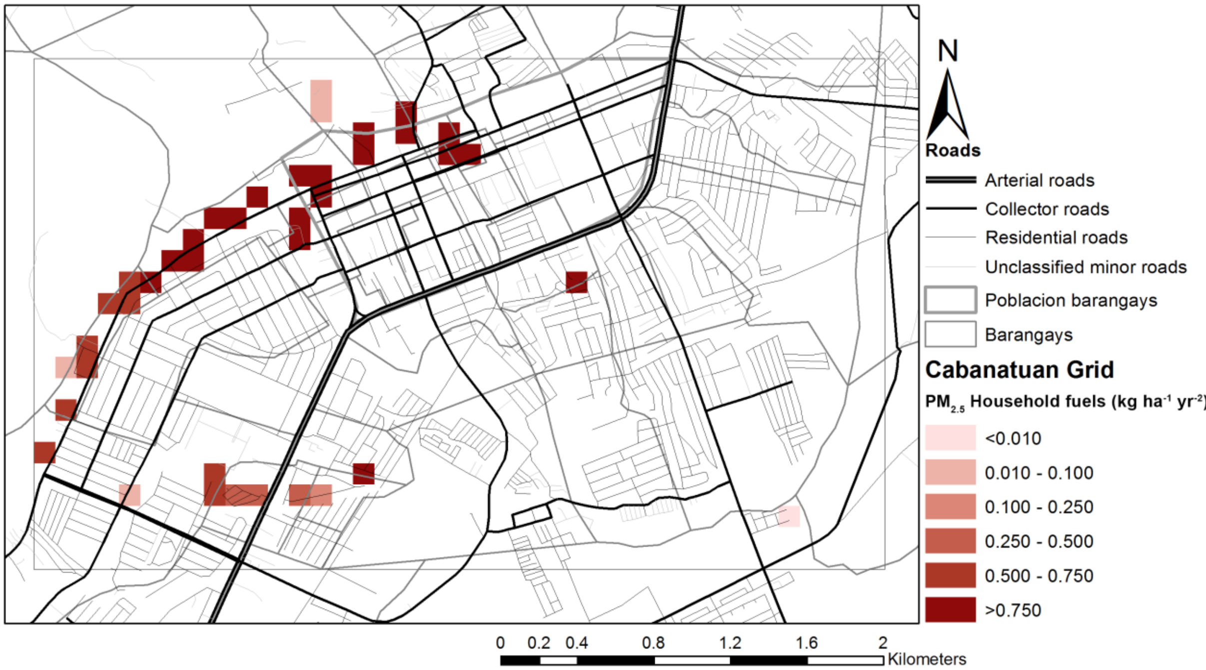


Figure 5: Map of estimated $PM_{2.5}$ emissions from burning of household fuels.

Figure 6: Map of estimated $PM_{2.5}$ emissions from motorcycles and tricycles.

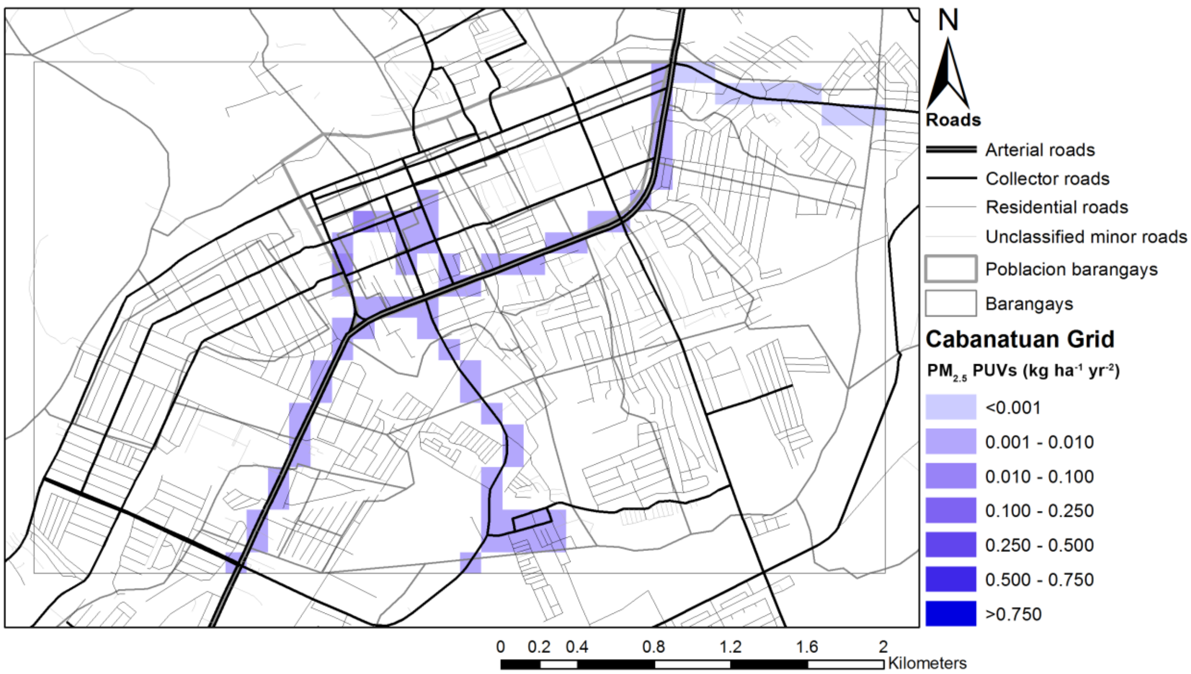


Figure 7: Map of estimated $PM_{2.5}$ emissions from PUVs (public utility vehicles/jeepneys/XLTs).

Figure 8: Map of estimated $PM_{2.5}$ emissions from burning of rice straw as agricultural waste.

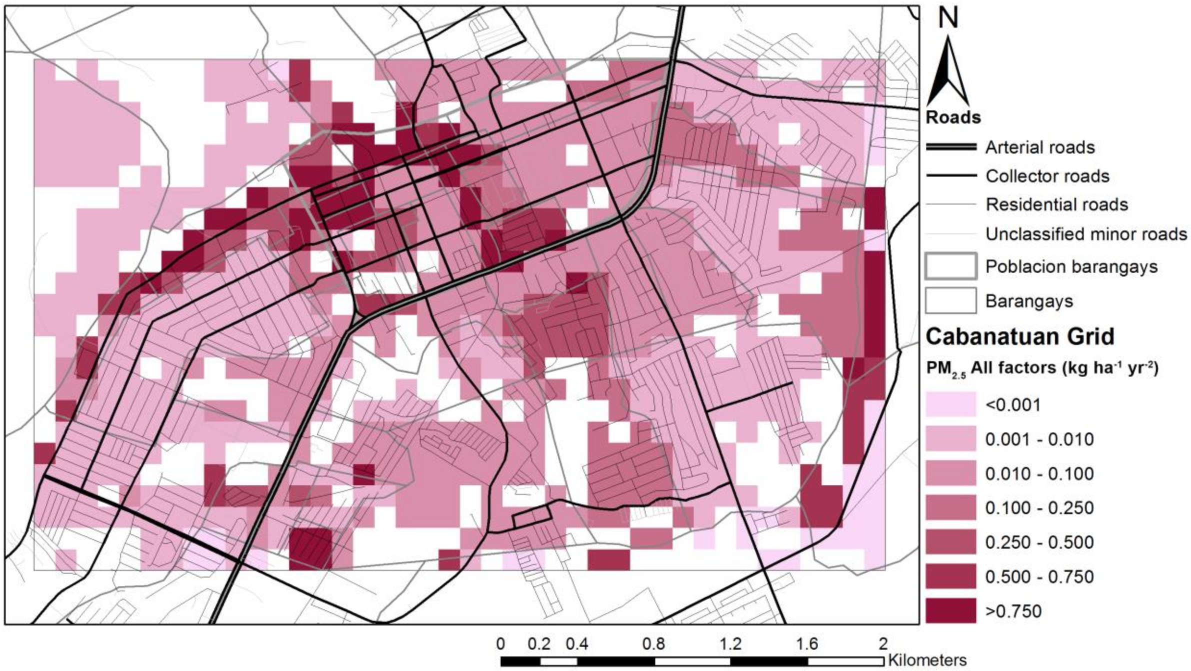


Figure 9: Map of estimated $PM_{2.5}$ emissions combining all factors in the study.