**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:** Point-by-point reply to comments (discussion papers stage)

We thank the anonymous reviewers for taking time to review this discussion paper. Since many major edits were suggested, the entire paper was edited for clearer wording and the clarification/addition of some points presented by the referees. The structure of some sections was also changed. We believe that these suggestions are important in increasing the quality of the text for recommendation for this paper to be published to AMT.

Kindly refer to the following point-by-point replies to the reviewer comments, and we appreciate your kind consideration and highly detailed comments, for improving the content and preparing this discussion paper for publication to the journal.

## I. Author's comment:

An entry in page 1, line 4 has been corrected to show the full name of the Institute of Environmental Science and Meteorology, University of the Philippines-Diliman, where the researchers are affiliated.

## II. Evaluation and response to interactive comment by anonymous referee #1:

### General comments

I think there are some major concerns with this manuscript that have to be taken in consideration before it can be accepted for AMT. The main problem is the language that is not clear, which means that it is difficult to fully validate the scientific content in this study. However, I think relevant scientific questions are addressed that are in the scope of AMT, but they have to better emphasise. I think the authors present a novel idea that deserve to be taken in consideration. The present method is interesting, which can also be used in the developing countries dealing with small budgets and limitation in resources.

### Major concerns

1. Due to limitation in time the review of the language has only been performed for the four first pages. Even so, it is obvious that the language has to be improved, and suggestions to improve the text are given below for these four pages. However, English is not my native language, which means that all my suggestions are probably not the best ones in an attempt to make the text more readable. The main criticism is that too much of redundant words and phrases are used in the text. However, the selection of words are also not always correct, which makes it difficult to understand the text at several places. In addition, I think the structure of the text could be improved by reducing the many paragraphs introduced. This is purely a scientific text and not a popular scientific text. At some places also very long sentences are found, which should be avoided: for example at the lines 4 – 7 on page 10. I suggest that the authors take contact with someone that is able to improve the text and/or ask AMT if they could support with this work.

**Response:** In general, effort was taken to improve the wording of all sentences in the text. This is especially edited with the goal of reducing redundancies in some explanations found in the manuscript itself. Paragraph lengths were shortened in general, as well as splitting long sentences, found in almost all the newly edited sections of the manuscript. Specific details as to what changed can be found in later comments.

2. Paragraph at lines 10 – 19: equation 3 and the corresponding text in this paragraph is very confusing. I suggest to present, where it is missing, units for the different factors included in the equations. Should the three first factors in the bracket actually be multiplied with each other? The factor SDF is not defined. Among other, the following phrase is confusing "PM2.5 per year per square kilometer per kilometer traveled". For this paragraph I will also give here an example when redundant words are used. Line start with "Emissions for motorcycles. . ...", which means that you do not need to repeat this in the following sentence after the equation. The same for equations 1&4.

**Response:** The authors have reworded the section in question. Several major edits were made, the most obvious one the splitting of the former equation (3) to equations (3) and (4). Wording was changed to reflect a focus on "vehicular sources" of $PM_{2.5.}$ Most of the ambiguous factors in question were those intended to serve as the activity data factors for tricycles.

NAF in the previous version was renamed to AVF (association vehicles factor) for clarity. Units were added to the explanation of all emission factor estimation equations (1-5). The new explanation hopefully makes it clear as to why the first three factors ($N_u$, DF, AVF) should be multiplied. The definition for factor SDF (distance/kilometers traveled) was also added. Similar edits were also used for sections containing equations (1) and (4) (now (1) and (5))

**Page 6, Lines 11-20:** *$PM_{2.5}$ emissions for vehicular sources were estimated with the formula shown in Eq. (3) and Eq. (4).*

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

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

*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 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.*

**Page 4, Lines 17-26:** *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)*

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

*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.*

**Page 6, Lines 20-27:** *Emissions for agricultural waste burning were estimated with the formula shown in Eq. (5):*

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

*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).*

3. Lines 18 – 21. Concerning the low percentage values 1%, 5% and 2%, does this means that it was so few respondents that answered the survey? If so, how useful and solid is this information for the present study? You should at least make a comments on this in the manuscript.

**Response:** Edited paragraph starting in page 7, line 19 to comment on this. Also, an edit was made to the paragraph starting in page 10, line 4 as an additional comment:

**Page 7, Line 19 – Page 8, Line 2:** *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.*

**Page 10, Lines 4-10:** *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.*

**Minor concerns**

1. For E and the corresponding equations 2-4 write out the units somewhere in the text. It is not logical to name the emissions with “fuels, vehicles and straw”. Maybe “households, vehicles and agricultural” instead.

**Response:** Relevant sections were edited to include units for all factors. The names of the E factors (i.e. $E_{households}$) for all equations were also changed to reflect this.

**Page 6, Lines 2-27:** *Emissions for household fuel (charcoal) were estimated with the formula shown in Eq. (2):*

$$E_{households} = (N_h \times HF) \times Q_{fuel} \times EF \times 0.01 \, , \quad (2)$$

*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).*

$$E_{MC/TC} = (N_u \times DF \times AVF) \times (EF \times KT \times SDF) \times 0.01 \, , \quad (3)$$
$$E_{PUV} = (N_u \times DF) \times EF \times 0.01 \, , \quad (4)$$

*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 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):*

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

*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).*

**Authors’ comment:** The following corrections suggested by anonymous referee #1 were made in various capacities, taking into account our intent for the study methods, and acknowledging our own writing style and use of the English language.

**Corrections suggested by anonymous referee #1:** 2. “Figure 2. The 2.4 x 4.0 km2 study. . .. . .”

**Response:** Caption edited for technical purposes

**Page 14, Line 2 (caption):** *Figure 2: The 2.4 x 4.0 km study area in Cabanatuan City containing the “city center” (poblacion, highlighted).*

Technical/language corrections Page 1 Line 6, “Exposure to particulate matter (PM) is a serious environmental problem in many urban areas on earth.” Line 8, “. . .. . .involving human exposures to particulate pollutants is rare.” Line 9, ”fine particulate (PM2.5) emissions" Line 10, "Nueva Ecija in the Philippines," Line 11, "The emissions estimated" Line 11, "geographic information system (GIS)" Line 12, "The present results suggest that emissions from" Line 14, I think this is better "applied to any urban area, as long"

**Response:** Abstract section mostly edited as suggested, see full changes below:

**Page 1, Lines 6-15:** *Exposure to air particulate matter (APM) 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 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.*

Line 21, "Particulate matter, especially. . .. . ...haze phenomena, local and regional air quality, and climate." Line 22, "Exposure to pollutants is a risk for many people leaving in urban areas, since the level of pollution frequently exceeds WHO guidelines (Mage et al., 1996)." Line 24, "The presence of high PM2.5 is linked to increased morbidity. . .. . .. . ."

**Response:** Introduction section (paragraph beginning in page 1, line 21) was edited as suggested.

**Page 1, Line 21 – Page 2, Line 2:** *Exposure to air particulate matter, especially fine particles smaller than 2.5 micrometers in size (PM2.5), 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 PM2.5 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). PM2.5 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).*

Page 2 Line 1, "carcinogenic, especially exposed for the finest fraction. . .." I think "for" instead of "at". Line 2. "attributed to particles acting as" Line 4 "Sources of PM2.5 are caused by many man-made activities." Line 4, "A common source of. . .. . ..areas is related to mobile sources, directly. . .. . ." Line 7, Connect this paragraph to the previous one. Line 7, This sentence has to be improved. Line 9, Suggestion "However, PM2.5 emissions from other activities such as burning of agricultural waste occurs as well in Philippines cities. . .. . ..."

**Response:** Various edits for wording, clarity, and content were made to the paragraph beginning in page 2, line 4 as suggested (some edits are not exactly the same as suggested by anonymous referee #1)

**Page 2, Lines 4-9:** *Sources of $PM_{2.5}$ are caused by many man-made activities. A common source of $PM_{2.5}$, 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 CORINAIR and AP 42). 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).*

Line 14, "At present, air quality monitoring and management are based on. . .. . .." Line 15, "Standards for PM2.5 have however not been fully developed and implemented in small cities. Emissions inventories in general have likewise. . .. . ..in many cities." Line 17. "In addition, previous investigations are rare and limited in time, which means that temporally resolved long-term air quality monitoring data are not available."

**Response:** Various edits for wording, clarity, and content were made to the paragraph beginning in page 2, line 11 as suggested.

**Page 2, Lines 11-14:** *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 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.*

Line 20, "This study present a method to estimate PM2,5 by utilising emission factors, satellite imagery and activity data. The latter is obtained from interpretation of geographic information system (GIS) data and by identifying and localising all sources in a city, taking into account the type of emissions (. . .. . .. . .) and activities that produces the emissions. This includes factors such as local population, density of households, number of emission-generating. . .. . .." Line 27, "A limitation with this study. . .. . ...sources, since this is required in the mapping process."

**Response:** Various edits for wording, clarity, and content were made to the paragraph beginning in page 2, line 16 as suggested (spelling differences reflect local usage of English).

**Page 2, Lines 16-22:** *This study presents a method to estimate $PM_{2.5}$ by utilizing locally sourced 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 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.*

Line 30, "This study aims to determine. . .. . ..PM2.5, caused by individual and several aerosol sources. The present method can specifically be used for similar mixture of man-made activities as in the Philippines cities: open burning of agricultural waste and charcoal (rural activity or population) as well as usage of mobile sources (urban activity or population)." Page 3 Line 1, Connect this paragraph with the previous one. Line 1, "Another application of 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."

**Response:** Various edits for wording, clarity, and content were made to the paragraph beginning in page 2, line 24 as suggested (some edits are not exactly the same as suggested by anonymous referee #1)

**Page 2, Lines 24-32:** *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 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 PUVs (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.*

Line 8, "Philippines (Fig. 1)." Line 9, "and an estimated population of 296,584 in 2012." Line 10, "around half each of the total population (Cabanatuan City SEP, 2015)." Line 13, "A 2.4 by 4.0 kilometre area including the city centre and its nearest environs was selected as the study area." Line 14, "of the study area shown in Fig. 2." Line 15, As it is written, marked with grey is not shown in Fig. 2 and what is meant with "point of reference"? I have difficult to understand this sentence. Line 17, "The investigation area includes residential and commercial quarter, and even agricultural areas with less than two kilometres to a main road." Line 19, "A commercial zone and the main industrial district in Cabanatuan City located south and about 8 km from the eastern border of the investigation area, respectively, are not taken in consideration in the study."

**Response:** Various edits for wording, clarity, and content were made to the paragraph beginning in page 3, line 3 as suggested (some edits are not exactly the same as suggested by anonymous referee #1, some spelling differences reflecting local usage of English)

**Page 3, Lines 3-14:** *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 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.*

Line 22, "The investigation area was divided with 24 x 40 grid cells (100 x 100 m or 1 ha / 0.01 km2). For each cell, the type of man-made activity. . .. . ..Detailed images over the ground, taken by Google Street View (examples are shown in Fig. 3), were also. . .. . .. . ..(residential/commercial)." Line 26. "Satellite images were dated 3 March 2016, while street view images. . .. . ..September 2015. Additionally, maps from OpenStreetMap were also used for identifying special landmarks or since it occasionally present more updated information than Google Street View."

**Response:** Various edits for wording, clarity, and content were made to the paragraph beginning in page 3, line 16 as suggested. Some technical edits are also present (some edits are not exactly the same as suggested by anonymous referee #1)

**Page 3, Lines 16-24:** *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. 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. 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.*

Line 30, "Google Earth Images have been used here instead of raw image data from example the Landsat satellite. This is because the method developed in this study is intended. . .. . ..familiar with processing of satellite raw imagery data. The Google Earth images have been processed to exclude the presence of clouds and corrected for aberrations from the camera taken the satellite images." If the images really show some clouds sometimes please modify the latter sentence suggested.

Page 4 Line 2, "These images are not representative for the most current features on the ground, minor . . .. . ..coordinates. It is also difficult to get access to the metadata of the original images. Even so, the Google product is useful enough and then also for the uninitiated considering the present purpose. In addition, other programs such as the Google Street View or OpenStreetMap (community-based initiative) for mapping can be used." Line 6, Sentence starting with "Actual verification. . .." is hard to understand.

**Response:** Various edits for wording, clarity, and content were made to the paragraph beginning in page 3, line 26 as suggested (some edits are not exactly the same as suggested by anonymous referee #1)

**Page 3, Line 26 – Page 4, Line 6:** *Google Earth images have been used here instead of raw image data from, for example, the Landsat satellite (The collaged image used in Google Earth is sourced from processed images from Landsat 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, 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.*

Line 10, "PM2.5 emissions in the 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 quarter, agricultural areas or other surface characteristics. Figure 4 shows that residential land use (households using liquefied petroleum gas as a fuel) are spread widely, although with noticeable commercial districts and open fields (not settled) located within this area. Two large agricultural areas are found in the northwest and east, occupied by small households likely using fuels." Improve the latter with just writing "fuels". Line 19, The Pampa River is marked with blue color in the figure, and in southeast a new residential area near open fields and agricultural areas has been built-up.” Line 23, Connect this paragraph to the previous one. Line 23, “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.”

**Response:** Various edits for wording, clarity, and content were made to the paragraph beginning in page 4, line 8 as suggested (some edits are not exactly the same as suggested by anonymous referee #1). The usage of the wording “household fuels” was fixed overall in this section and in some other parts of the paper to now read “households” or “fuels” depending on context instead.

**Page 4, Lines 8-15:** *PM2.5 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 (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 fuels. 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.*

Line 27, “Estimation of PM2,5 emission Line 28, “All calculations that have been used here to estimate PM2.5 emissions are based on. . .. . .(EPA, 1995): Lines 28 and 31, Emissions of what? Line 31, “where E is equal to emissions, A is the activity rate/data (e.g. quantity of fuel, percentage of households using fuel), EF represents the. . .. .. . .”

**Response:** Various edits for wording, clarity, and content were made to the section beginning in page 4, line 17 as suggested (some edits are not exactly the same as suggested by anonymous referee #1)

**Page 4, Lines 17-26:** *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)*

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

*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.*

## III. Evaluation and response to interactive comment by anonymous referee #2:

This is an interesting paper for those researchers interested in PM2.5 emissions and learns about approaches to estimate the spatial distribution of emissions using activity data, local emission factors and land cover derived from satellite imagery. That would be of interest to the Atmospheric Measurement Techniques readership. However, the manuscript needs to be considerably improved before publication, both from the point of view of its presentation and from the amount of details provided on the data. I think the paper should be accepted after the comments and suggestions below and those from the other reviewer have been addressed.

### Major issues

If the paper is to be published in AMT, I advise a significant revision and restructuring of the manuscript. It was at times difficult to read. The largest issue for me is that the methods section is extremely difficult to follow. The used methods of the paper must be written clearly and explicitly. I would suggest restructuring the article to better streamline the material. There is a wide combination of methods, calculations and data products used. For example, the description of the study area and Google satellite image are first introduced in Section 2.1. And additionally, the used methods have been mentioned in the same Section 2.1. Then, all details of the activity data and emission estimations are given throughout Section 2.2. My suggestion to improve readability and clarity would be to reorganize all the methods and results into the following Sections: 2. Materials and methods 2.1 Study area 2.2 Activity data (with used data and methods) 2.3 Local emission factors (with used data and methods) 2.4 Land cover classifications by using satellite imagery (with used data and methods) 2.5 Validation of emission estimation factors, ground surveys, and sensitivity analysis 3 Results and discussion 3.1 The utilizing of activity data (with the discussions) 2.3 The utilizing of local emission factors (with the discussions) 2.4 The utilizing of Land cover classifications (with the discussions) 4 Summary and conclusion The Section "4.1 Recommendations" just stand there or there are other sessions such as 4.2, 4.3? If not, it must be done with the Section 4.

**Response:** The entire manuscript from section 2 onwards has been restructured using the following headers:

**2 Materials and methods**

- **3.1 Study area**
- **3.2 Land cover classification using satellite imagery**
- **3.3 $PM_{2.5}$ emission estimation**
  - **3.3.1 Local emission factors**
  - **3.3.2 Activity data**
  - **3.3.3 Emission estimation equations**
- **3.4 Validation of activity data factors (ground surveys and sensitivity analysis)**

**3 Results and discussion**

**4 Summary and conclusion**

**5 Recommendations**

**Response (continued):** This was done to help streamline section 2 in particular. New sections were added to sections 2.2, 2.3/2.3.1/2.3.2/2.3.3, and 2.4 to give more detail as to the methods used in the study.

The other prominent issue I have is the not precise definition of "activity data" throughout the manuscript. In page 5 (line 5-6), the "activity data" is written as follows: "this study uses "activity data" to describe this and other relevant factors pertaining to the quantity of fuel used and percentage of households using fuel". Are the activity data estimated? And what are the significant influencing factors of the on-site specific activity data? An important concern is the emission factor. It is not clear, what is the dependence of emission factors on the fuel types. Another problem I have is that there is a little-to-no mention about the used method of land cover classification.

**Response:** The definition of "activity data" is now worded to follow more closely with how it is used in the general EPA equation as explained in the section starting in page 4, line 17, and used as the basis for equation (1). All mentions of "emission estimation factors" or "EEF" used in the previous iteration of the manuscript were removed in favor of wording that includes the factors that make up ER in equation (1) under the definition of "activity data" as well.

**Page 4, Lines 17-26:** *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)*

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

*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.*

In my opinion, the authors not clearly discussed the limitation of Google Earth. It is not clear to me whether there was used any classification method for the land cover classifications. If not, then I think a more significant treatment of the uncertainty in the classification is required. Is there the coordinate transformation considered?

**Response:** The new section 2.2 was created, structured, and edited to address this issue. An additional few sentences were added to the paragraph starting in page 3, line 16 to address the method used in the land cover classification.

**Page 3, Lines 16-24:** *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. 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. 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.*

**Response (continued):** Issues regarding the usage of Google Earth images were laid out in the paragraph starting in page 3, line 26.

**Page 3, Line 26 – Page 4, Line 6:** *Google Earth images have been used here instead of raw image data from, for example, the Landsat satellite (The collaged image used in Google Earth is sourced from processed images from Landsat 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, 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.*

Specific comments: The other reviewer provides excellent comments related to the technical correction that should be taken into account in the revision of the manuscript.

**Response:** The suggestions by anonymous referee #1 were largely taken into account (see previous section) for the editing of this manuscript.

(Attached is a copy of the revised manuscript with markup below).

# 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 (APM) is a serious environmental problem in many urban areas on Earth.~~presently relevant issue that affects the environment and the health of residents of many urban areas globally.~~ In the Philippines, most existing studies and emission inventories have mainly focused on point and mobile sources, while research involving ~~personal~~ human exposures to particulate pollutants is ~~mostly lacking~~rare. This paper presents a method for estimating the amount fine ~~($PM_{2.5}$)~~ 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. ~~The estimated emissions have been mapped using g~~Geographic information system~~s~~ (GIS) software was used to map the estimated emissions in the study area. The present r~~R~~esults suggest that vehicular emissions from motorcycles and tricycles, as well as ~~biomass-based household~~ 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 ~~to any study site~~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 ($PM_{2.5}$), ~~impacts visibility in the form of haze phenomena,~~ can ~~affect~~ reduce ~~local and regional~~ air quality, affect visibility through smog and other haze phenomena, and ~~can have~~introduce lasting effects on climate on a local and regional scale. ~~Many urban dwellers are at risk of high pollutant exposure, living in areas of high outdoor ambient pollution, and in many cities,~~Exposure to pollutants is a risk for many people living in urban areas, since the ~~amount~~ level of pollution frequently exceeds WHO guideline values ~~for air pollutants~~ (Mage, *et al.*, 1996).The presence of $PM_{2.5}$ ~~among other air pollutants urban cities in general represents a significantly high health risk for residents, as it~~ 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 ~~at~~ exposure to the finest fractions (ultrafine particles) (Bocchi, *et al.*, 2016). This can be attributed to ~~fine particulates~~particles acting as carriers of mutagenic and genotoxic compounds (Chen, *et al.*, 2016).

Sources of ~~fine particulates~~$PM_{2.5}$ ~~come from~~are caused by many man-made activities. A common source of $PM_{2.5}$, in urban areas ~~comes from~~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

~~In~~ most of the reports from Philippine cities~~the Philippines~~, ~~percentages of~~ vehicular emissions ~~from mobile sources are~~ reported in inventories ~~and using~~use foreign emission factors ~~from non-local engine sources~~ (such as CORINAIR and~~,~~ AP 42). 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~~In areas where urban and rural land uses are both present, however, especially in the Philippine context, PM$_{2.5}$ emissions can be accounted for by other factors as well, such as particulates generated by the burning of biomass sourced from agricultural waste~~ (Sarigiannis, et al., 2014; Kim Oanh, et al., 2011; Gadde, et al., 2009).

At present, ~~the current basis for most measures for air quality monitoring and management~~air quality monitoring and management are based on PM$_{10}$ and total suspended particles (TSP) as an indicator. Standards for PM$_{2.5}$ ~~in~~ have however not ~~comparison have not been~~ been fully developed and implemented in small cities.~~;~~ ~~e~~Emission inventories in general have likewise not been conducted in many cities ~~and regional centers as well~~. ~~Aside from this, such studies are often conducted every few years, if at all, presenting a lack of temporally resolved long-term historical data for air quality monitoring purposes.~~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 ~~paper~~ study presents a ~~spatial~~ method ~~for the estimation of air~~to estimate PM$_{2.5}$~~,~~ by utilizing locally sourced emission factors, ~~as well as~~ satellite imagery, and ~~"~~activity data~~"~~. The latter is obtained from ~~their~~ interpretation of geographic information system (GIS) data and by identifying and localizing all sources in the city, ~~(with the use of GIS software for mapping). The usage of the term "activity data" stems from the current process of the air pollution emissions inventory in most cities in the Philippines. The current method involves the location and identification of all emission sources in a given city,~~ taking into account the type of emission (point, area, mobile), and ~~nature of activity~~activities which produces the emissions. ~~In this study, "activity data" is defined as not only the type of air pollution generating activity, but also~~This includes factors such as local population, density of households, ~~density~~ 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, ~~as~~ since this is required ~~for~~ 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 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 PUVs (buses and vans). ~~in total and by individual PM$_{2.5}$ sources. This method 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 their land uses tend to be more diverse and more influenced by conventionally "rural" activities such as agriculture and the usage of traditional household fuels such as charcoal.~~

Another application for this study ~~involves its potential use as~~is planning aids for local governments; as the present~~is~~ method can ~~also~~ 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. ~~As such, the methods used in this study were developed for use by relevant personnel with minimal required training, in order to serve as a possible method of expediting the process of gathering emission inventories.~~

## 2 Materials and methods

### 2.1 ~~Gridded study area and land cover from satellite imagery~~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 ~~as of~~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~~ of the city each~~ (Cabanatuan City SEP, 2015).

A 2.4 by 4.0 kilometer area including~~bounded section corresponding to~~ the city center and its ~~immediate~~ 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~~ as~~ shown in Fig. 2.  Grey lines indicate ~~The~~ boundaries of *barangays* (the smallest administrative division of a local government, a similar concept to town wards or districts)~~ are marked in grey~~, and the constituent barangays of the *poblacion* are marked ~~distinctly~~ using thicker grey outlines~~as a point of reference~~. The~~is~~ investigation area ~~represents much of the different land uses present within the city center and its surroundings; these~~ includes residential and~~,~~ commercial zones, and even agricultural areas~~ within the short space of~~ less than two kilometers away from ~~the national~~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.~~The study area, however, does not take into account a relatively sizeable commercial zone south of this enclosed region, as well as the main industrial district of Cabanatuan City located near its eastern border, which is located around 10 kilometers east of the city center.~~

### 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. 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. 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.

Google Earth images have been used here instead of raw image data from, for example, the Landsat satellite (The collaged image used in Google Earth is sourced from processed images from Landsat 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, 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.

PM2.5 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 (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 fuels. 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)

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

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

~~This area was mapped out in a 24 x 40 cell grid of 100 x 100 meter (1 ha / 0.01 $km^2$) cells. For each cell, the type of activity was interpreted from satellite images taken from Google Earth software. Detailed images from the ground level taken by Google Street View (examples are shown in Fig. 3) were also used to verify building types (residential/commercial) when available. Satellite images were dated March 3rd, 2016, while Street View images were dated September 2015. Additionally, maps of the same location from OpenStreetMap were also used as a reference for landmarks not present in the information in Google Earth, or present more updated information compared to ground features from the Street View images.~~

~~The choice to use Google Earth images as opposed to raw image data from sources such as Landsat images was made for several reasons. The method used in this study is intended to be used by personnel not necessarily familiar with or are trained in the processing of satellite imagery data, in which case, the researchers have opted to use Google Earth imagery as a possible source in this manner. Images (in this area, sourced from Landsat and the European Space Agency (ESA)'s Copernicus program since 2015) have been processed and corrected for aberrations of the camera taking said satellite image, as well as collaged to only show higher quality images with minimal cloud cover. However, there are issues with these images that are worth mentioning. For one, the resulting image collage is not necessarily representative of the most current features on the ground. Google Earth imagery is projected orthographically; while this allows for relatively accurate measurements of distance in the small scale, it can also result in the image location being deviated from its actual geographic coordinates. While the images themselves aren't georeferenced, the coordinates provided by the software are accurate enough to represent the actual surface without much deviation. Other issues include the limitations of accessing the metadata of the original images. In spite of these issues, these materials are sufficient for the uninitiated and can be very useful regardless considering their intended purpose. It is very important, then, that other tools such as the Google Street View images or community-~~

~~based initiatives for mapping such as OpenStreetMap 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.~~

~~Land cover features for each 100 x 100 m cell for areas inside the study site were identified and then mapped. These are classified by their possible land uses (i.e. residential/commercial, agricultural areas, roads, other surface features) and are associated with an emission type, to be used for estimating $PM_{2.5}$ levels later in the process. As seen in the map in Fig. 4, residential areas (represented in the map as "residential" cells, which account for households using liquefied petroleum gas (LPG) as fuel) are spread widely throughout the study site, with a noticeable commercial district (represented by cells marked with "commercial") at its very center. At the same time, the cells immediately outside and some even inside the overall bound of the residential areas are categorized as either open space (a term used for characterizing areas that are not considered built-up), or agricultural areas. This is especially noticeable in the northwest and the southeast portions of the map; the northwest section is mostly agricultural, occupied by small households which are likely using fuels, and located adjacent to the Pampanga River. In the southeast portion of the map, a residential area is seen next to cells with open space and agricultural areas; this represents recently built-up areas used for new residential developments that have been constructed in the past few years in Cabanatuan City.~~

~~Note that some cells are marked as land uses by themselves as they are currently considered to be "special" land uses, and the emission factors for these cells are currently being studied: these are the "cemetery" and "terminal" cells, the latter corresponding to the central transport terminal of Cabanatuan City, currently considered a commercial area with a large concentration of vehicular emissions.~~

### ~~2.2 Activity data and emission estimation~~

~~All calculations that have been used to estimate emissions is 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)~~

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

~~where: E is equal to emissions, A is the "activity rate" (term used by EPA; this study uses "activity data" to describe this and other relevant factors pertaining to the quantity of fuel used and percentage of households using fuel), EF represents the emission factor (in this case, for $PM_{2.5}$), and ER is the overall emission reduction factor/efficiency in percent, if applicable. In this study, ER was also used to refer 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). For this study, factors used as "activity data" (A) and "emission reduction" (ER) will be collectively be referred to as emission estimation factors (EEF).~~

Emission factors for ~~fuelwood, charcoal~~ households, vehicular emissions, and agricultural waste burning~~rice straw burning,~~ ~~were~~ is sourced 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

| **Factor** | **Source** |
|---|---|
| **Emission factors for households** | Cayetano and Lamorena (2014) |

| | |
|---|---|
| **(charcoal)** | |
| **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

~~The EEF for each emission type is calculated depending on which metrics are relevant for each source of $PM_{2.5}$. Household and population data were obtained from local government documents, particularly the Comprehensive Land Use Plan(s) and Socio-Economic Profile(s) of Cabanatuan City; information on total amount of fuel used by household is obtained from the national Household Electricity Consumption Survey (HECS), conducted in 2005 and 2011.~~ Table 2~~1~~ compiles the sources of activity data used in this study.~~, in various units such as fuel consumption, population and household data, and agricultural land use data per year.~~ 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; information on total amount of fuel used by household is obtained from the national Household Electricity Consumption Survey (HECS), conducted in 2005 and 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~~1~~.** Data sources for activity data~~, emission factors, and ER factors~~

| | |
|---|---|
| **Population data, land use** | 2016 (provisional) Cabanatuan CLUP<br>Cabanatuan City SEP (2015) |
| **Activity data for households~~ fuels~~; LPG, charcoal consumption** | 2011/2005 Household Energy Consumption Survey (HECS)<br>Ground surveys |
| ~~**Emission factors ($PM_{2.5}$) for fuelwood, charcoal**~~ | ~~Cayetano and Lamorena (2014)~~ |
| **Activity data for PUVs and motorcycles, tricycles (MC/TC),** | Local government documents, Land Transportation Office (LTO) annual reports, ground surveys |
| ~~**Emission factors for PUVs and MC/TCs**~~ | ~~In-house data~~ |
| **Data on rice production and rice land agricultural area** | Cabanatuan City SEP (2015)<br>2016 (provisional) Cabanatuan CLUP |
| **Data on rice straw generated per amount rice produced** | Bakker, et al. (2013) |
| ~~**Emission factor for rice straw burning**~~ | ~~In-house data~~ |

### 2.3.3 Emission estimation equations

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

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

where: ~~$E_{fuels}$ is equal to emissions generated by charcoal fuels,~~ $N_h$ is the estimated number of households (generated from city government data), and HF is the ~~factor (in percent)~~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~~3~~). EF corresponds to the emission factor for charcoal fuel PM$_{2.5}$ ~~per year~~ per square kilometer per year; this is then multiplied by 0.01 to scale to each 0.01 km$^2$ cell.

PM$_{2.5}$ ~~E~~emissions for ~~motorcycles and tricycles~~vehicular sources were estimated with the formula shown in Eq. (3) and Eq. (4)~~. (3)~~.~~:~~

$$E_{\cancel{vehicles}MC/TC} = (N_u \times DF \times \cancel{N}AVF) \times (EF \times KT \times SDF) \times 0.01 \,, \quad (3)$$

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

~~where~~Factors that are the same for both equations include: ~~E$_{vehicles}$ is equal to emissions generated by vehicles (motorcycles and tricycles, PUVs),~~ N$_u$, ~~is~~ the estimated number of vehicle units, ~~(by type: MC/TCs, PUVs); multiplied by density factor~~ DF, the density factor ~~corresponding to(~~ amount of vehicles per km$^2$), and EF, the emission factor. ~~area~~ The in-house emission factor for 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 ~~in the city and non-~~association ~~(~~vehicles~~)~~ factor (AV~~NA~~F), the percentage of vehicles which are officially registered and properly accounted for by the city~~which corresponds to an additional multiplier to the overall number of vehicles taking into account unregistered vehicles (not registered by the city, or are from outside Cabanatuan 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 ~~were sourced and derived from city government data and~~ was verified using sensitivity analysis by ground surveys as detailed in section 2.4~~well~~. ~~EF corresponds to the emission factor for motorcycle and tricycle/PUV PM$_{2.5}$ per year per square kilometer per kilometer traveled. The emission factor is scaled to the average distance traveled by any given vehicle unit, here represented as factor KT (kilometers traveled). Similar to the previous example, also multiplied by 0.01 to scale to each 0.01 km$^2$ cell.~~

Emissions for ~~rice straw burning in agricultural areas~~agricultural waste burning were estimated with the formula shown in Eq. (5~~4~~):

$$E_{\cancel{straw}agricultural} = \left(\frac{RS}{RA}\right) \times EF \times SF \,, \quad (5\cancel{4})$$

where: ~~E$_{straw}$ is equal to emissions generated by rice straw burning,~~ 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.~~acting as~~ T~~t~~his~~e~~ reduction factor is taken from the study of Launio, et al. (2013).~~; this represents the percentage of farming area where burning of rice straw as agricultural waste is used.~~

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. ~~For each emission source, a~~All cells with estimated PM$_{2.5}$ greater than zero ~~assigned values (PM$_{2.5}$ emissions above zero) were~~ are plotted for each land cover type.~~according to the amount of PM$_{2.5}$ generated by the source per cell.~~

**2.4~~3~~ Validation of activity data factors (~~emission estimation factors,~~ ground surveys~~,~~ and sensitivity analysis)**

Ground surveys were conducted to validate specific activity data factors used in the $PM_{2.5}$ estimation process~~the emission estimation factors used to modify activity data factors (represented by A in the general equation in Eq. (1))~~. 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. ~~to determine if the reported factors originally used in the study are within ideal specifications.~~ 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: ~~A total of 98 respondents (32 for household fuels, 33 for tricycles, and 33 for PUVs) were surveyed for the validation of EEFs involving household fuels, tricycle, motorcycle, and PUV (jeeps/vans) usage. Factors included~~ the amount and type of household cooking fuel used ($Q_{fuel}$), registration under a tricycle/PUV riders association (AVF), ~~trips and total travel distance per day~~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. ~~These factors were compared with the activity data (A) and emission reduction (ER) factors used in the general equation (Eq. (1)), and those following the standard following the sensitivity analysis were used as EEFs used in the specific equations for household fuel usage (Eq. (2)) and tricycle fuel usage (Eq. (3)).~~ Table 3~~2~~ shows the list of ~~EEFs~~ activity data factors that have been validated in this activity.

**Table 3~~2~~.** List of ~~emission estimation factors (EEF)~~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 ~~group of~~ respondents that ~~have been~~were surveyed ~~for the sensitivity analysis was~~were taken from specific areas, termed emission ~~"~~hotspots~~"~~. ~~, as in, t~~These are locations where the amount of estimated $PM_{2.5}$ emissions are expected to be high. From the total ~~possible~~ estimated maximum respondents per type (households~~ehold fuels~~, vehicles ~~tr~~(MC/TCs~~icycles~~, PUVs)), the sample group for this study accounts for around 1% of the total for respondents for household~~ fuel~~s, around 5% for total respondents for ~~for motorcycles and tricycles~~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~~ fuel~~-related emissions are located in the fringe of the central residential areas, where ~~low-income households and~~ households using charcoal as fuel are mostly situated. ~~These cells account for~~

~~possible h~~High levels~~amounts~~ of ~~emissions~~$PM_{2.5}$ are expected in these areas, with levels reaching up to one kilogram of $PM_{2.5}$ per~~ 1 hectare cell per~~ year per cell. It is of note, however, that the emissions for ~~a few~~some of these cells is produced by commercial grilling establishments.~~,~~ Similar to households, Eq. (2) was also used to estimate the emissions in these areas.~~and while these emissions were calculated differently from cells for household fuels, they are also included in the map shown in Fig. 3 due to similar emission sources and quantities.~~ 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 ~~open space~~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.~~The emission values themselves are enough to account for a substantial fraction of the total emissions due to the high overall presence of motorcycles and tricycles as a mobile emission source in the study site.~~

Areas of interest concerning the very high density of tricycles and associated emissions include the central ~~“quadrangle” representing much of the~~ commercial zone, located within~~s of~~ 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 ~~particulate~~$PM_{2.5}$ 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 ~~small~~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) ~~usually~~ 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~~In this context~~.~~,~~ ~~PUVs refer to vehicles often referred to as “jeepneys” or “jeeps”, but also more colloquially known as “XLTs” as they are built differently than similar vehicles used in other parts of the country such as in Metro Manila.~~

Emissions for PUVs are estimated to be mostly equal along major roads,~~ such as the national road~~ 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 ~~relatively~~ much lower compared to tricycles~~than that of the emissions of 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 $PM_{2.5}$~~spatial~~ 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. Only a certain fraction of all agricultural land in Cabanatuan 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,~~, notice that~~ 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~~ general~~ ~~study site~~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~~ fuels~~ and vehicular sources (tricycles) account for much of the total $PM_{2.5}$ emissions in the Cabanatuan City ~~study site~~investigation area. PUVs (jeeps) ~~have a comparatively lower level of generated emissions~~account for a small portion of vehicular emissions. $PM_{2.5}$ from burning of ~~rice straw~~agricultural waste ~~accounts for a relatively~~was found to be a large ~~portion~~ constituent of total ~~emissions~~ particulates~~within the study site~~.~~,~~ As the investigation area is only a small fraction of the entire city, this ~~and is l~~likely means that agricultural waste burning is a significant source of $PM_{2.5}$ in the largely agricultural Cabanatuan City. ~~to account for emissions in agricultural zones of Cabanatuan City outside the study site; t~~This is open to future research on air quality management in the city, among others.

~~The equation used to estimate air particulate emissions produced a value~~The amount of $PM_{2.5}$ emissions in the investigation area estimated by this method is comparable to emission levels in urban metropolitan areas~~cities~~.~~,~~ ~~though t~~A possible reason for this is ~~likely due to~~the common usage of biomass-based fuels such as charcoal, or the high levels of particulates from vehicular sources~~being responsible for more PM2.5 emissions as a major source~~. Vehicular emissions and agricultural waste burning,~~The estimated emission levels for tricycles and rice straw burning is of note, as these two factors~~ at their highest levels, are responsible for~~ have produced~~ emission levels~~s~~ of at least 2 kilograms of $PM_{2.5}$ per ~~0.01 km² (~~1 hectare~~)~~ cell per year each. This~~e~~ interface between rural and urban land uses in ~~a highly urbanizing city such as~~ Cabanatuan City has produced~~s~~ a varied environment for research on multiple areas. Household fuel usage, vehicular sources, and agricultural waste burning are a major component~~fronts on possible determinants~~ ~~to~~of the city's air pollution~~n~~ and more research on its management ~~the monitoring of air quality i~~in the region is necessary.

The validation of specific activity data factors is effective at ~~the EEFs used in the general estimation of PM2.5 emissions have~~ adapting~~placed~~ the~~ actual value~~m closer~~s~~ ~~needed for the equations closer~~ to the specific conditions present in Cabanatuan City.~~;~~ ~~w~~While the more general~~ized~~ original in-house values ~~were~~are more appropriate in areas like Metro Manila, the validation procedure has made them more appropriate for ~~helped customize these values toward levels that are closer to what is expected in~~ smaller cities in general. An issue during the ground survey activity~~While the resulting modifications could only be applied to the emission factors for tricycles and household fuels~~ 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. ~~, the estimation for both these sources was at least updated to more current conditions.~~

**5~~4.1~~ Recommendations**

As stated earlier, this method for the estimation of $PM_{2.5}$ emissions is intended for use by~~ the~~ local government stakeholders~~s~~ for smaller cities and regional centers in any study country. While this method was primarily developed to estimate $PM_{2.5}$~~can easily be used as is for particulate matter~~, ~~usage of~~ similar methods can be used for other components of the emission inventory process in the country (~~for example, usage of the method to estimate~~i.e. criteria pollutants and GHGs)~~ is an area of interest~~.

G~~As g~~round verification of surface features is necessary to ensure the accuracy of~~at the gridded~~ land cover maps~~ that will be used to determine the activity data, and~~. ~~a~~Due to this,~~s a result, the~~ ~~emission factors that need to be used,~~ 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.

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

~~s~~The specialization of city environment officers in pollution studies~~ng in air quality in small cities~~ is ~~another~~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. ~~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.~~

Additionally, a method for the ~~ground~~ verification of activity data factors~~ emission factors~~, similar to this study's ~~what was conducted here as used in the~~ sensitivity analysis~~ of EEFs~~,~~,~~ 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 ~~the target households/~~area, would be instrumental in placing the total emission estimate more accurate with regards to specific conditions in a city~~ in the target city~~. 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~~t~~.

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Competing interests

*The authors declare that they have no conflict of interest.*

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**Figure 1: Overview map of Cabanatuan City, Philippines**

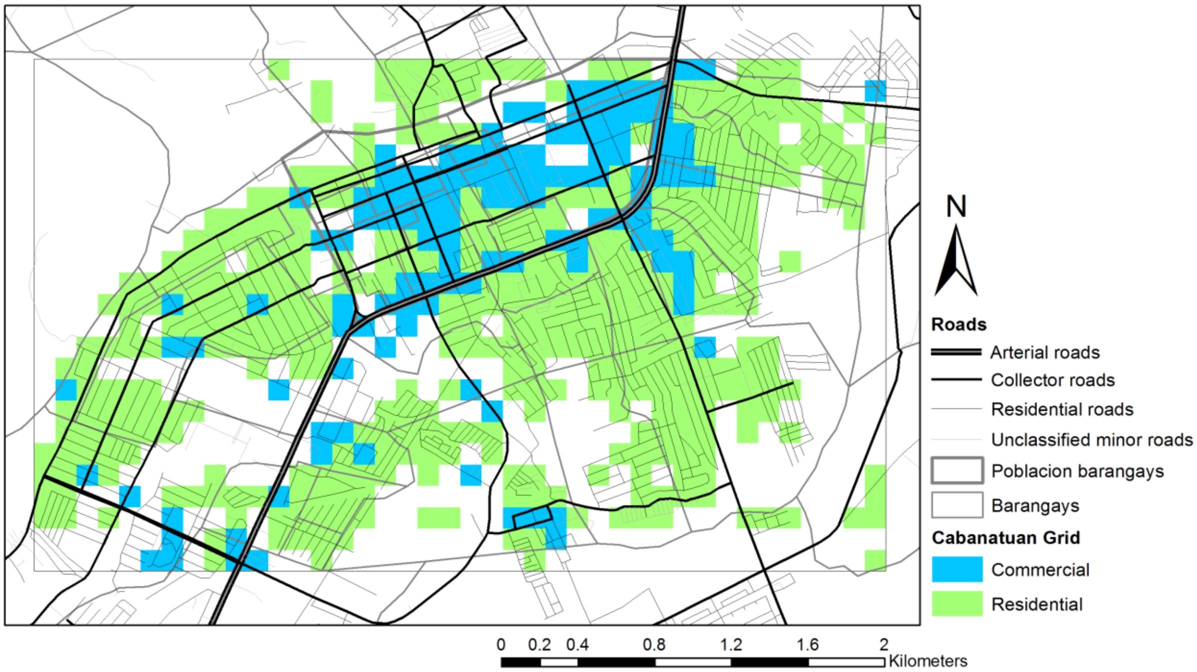


**Figure 2: The 2.4 x 4.0 km study area in Cabanatuan City containing the "city center" (*poblacion,* highlighted).**

5


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

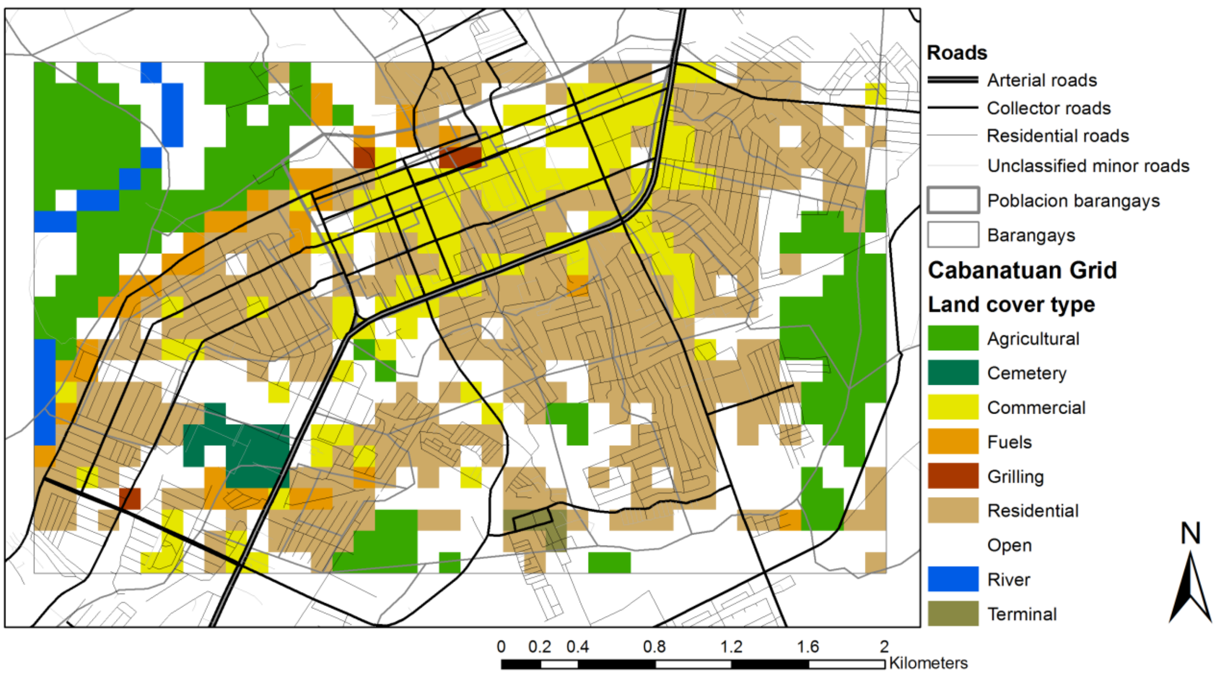


**Figure 4: Land cover/land use map from interpretation of satellite image.**

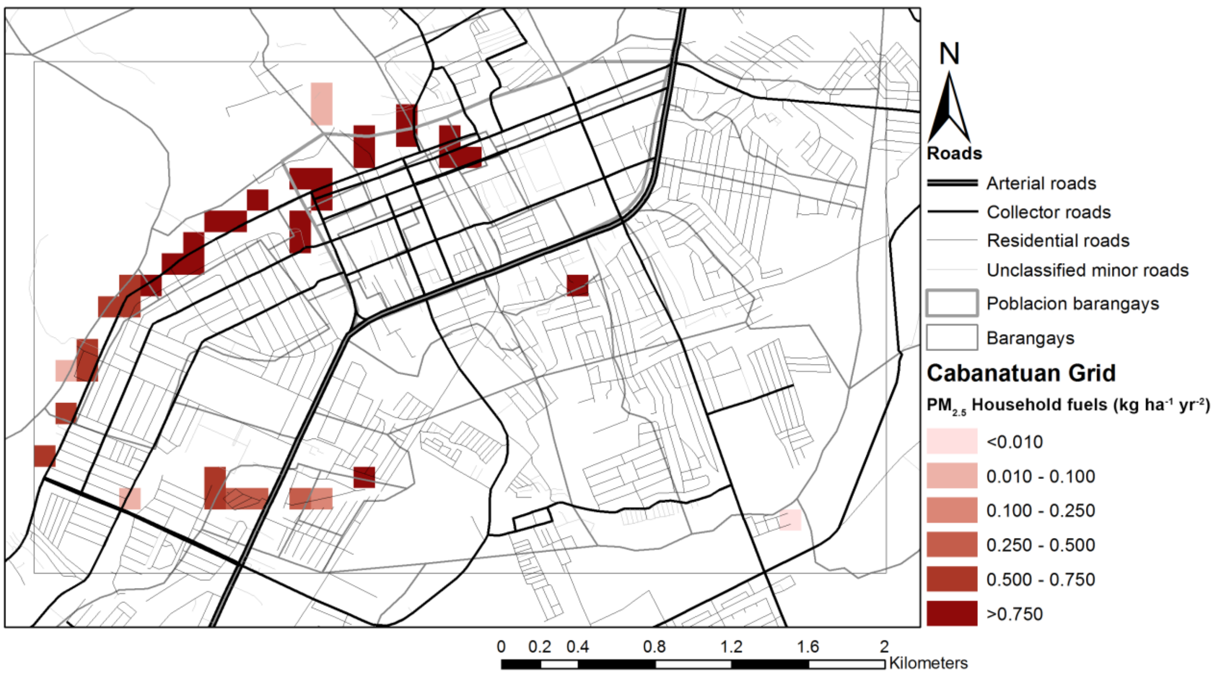


**Figure 5: Map of estimated $PM_{2.5}$ emissions from burning of household fuels.**


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

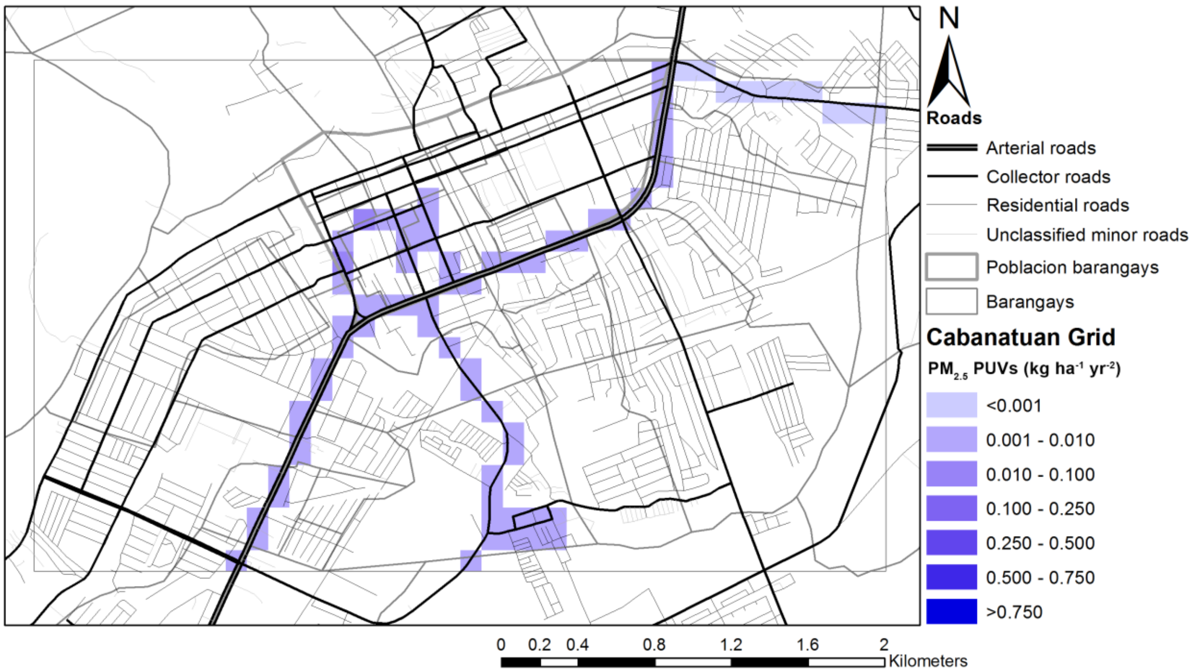


**Figure 7: Map of estimated $PM_{2.5}$ emissions from PUVs (public utility vehicles/jeepneys/XLTs).**


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

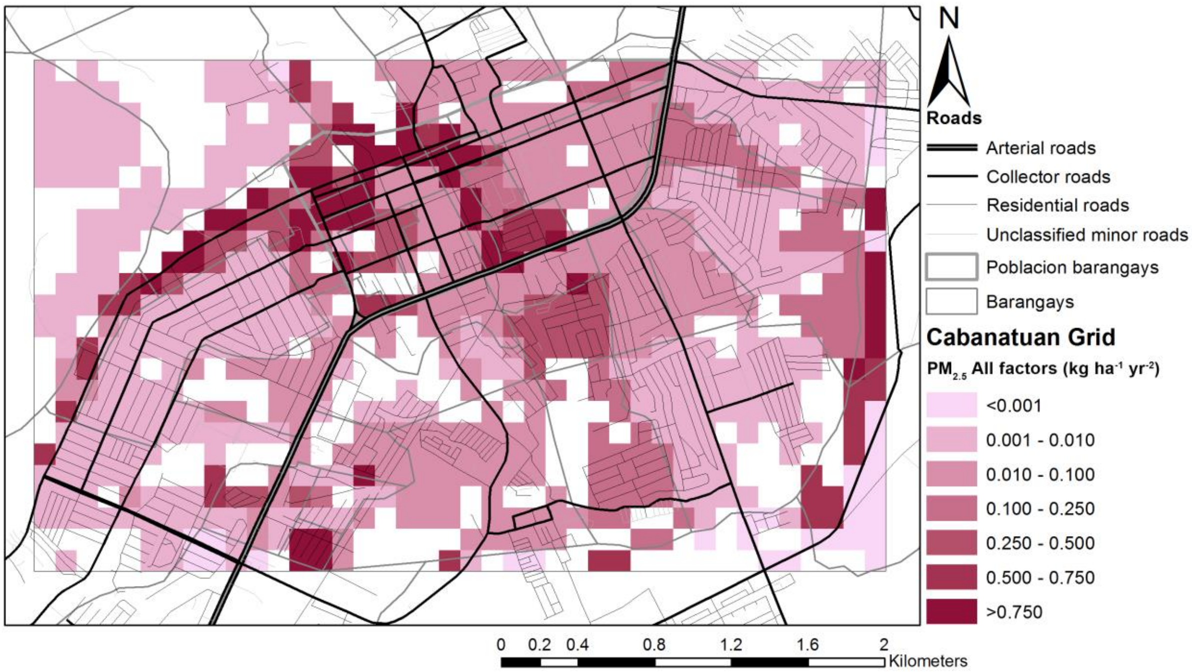


**Figure 9: Map of estimated $PM_{2.5}$ emissions combining all factors in the study.**