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Improved rice residue burning emissions estimates: Accounting for practice-specific emission factors in air pollution assessments of Vietnam☆

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Abstract

In Southeast Asia and Vietnam, rice residues are routinely burned after the harvest to prepare fields for the next season. Specific to Vietnam, the two prevalent burning practices include: a). piling the residues after hand harvesting; b). burning the residues without piling, after machine harvesting. In this study, we synthesized field and laboratory studies from the literature on rice residue burning emission factors for $PM_{2.5}$. We found significant differences in the resulting burning-practice specific emission factors, with 16.9 g kg^{-2}(±6.9) for pile burning and 8.8 g kg^{-2}(±3.5) for non-pile burning. We calculated burning-practice specific emissions based on rice area data, region-specific fuel-loading factors, combined emission factors, and estimates of burning from the literature. Our results for year 2015 estimate 180 Gg of $PM_{2.5}$ result from the pile burning method and 130 Gg result from non-pile burning method, with the most-likely current emission scenario of 150 Gg $PM_{2.5}$ emissions for Vietnam. For comparison purposes, we calculated emissions using generalized agricultural emission factors employed in global biomass burning studies. These results estimate 80 Gg $PM_{2.5}$, which is only 44% of the pile burning-based estimates, suggesting underestimation in previous studies. We compare our emissions to an existing all-combustion sources inventory, results show emissions account for 14–18% of Vietnam's total $PM_{2.5}$ depending on burning practice. Within the highly-urbanized and cloud-covered Hanoi Capital region (HCR), we use rice area from Sentinel-1A to derive spatially-explicit emissions and indirectly estimate residue burning dates. Results from HYSPLIT back-trajectory analysis stratified by season show autumn has most emission trajectories originating in the North, while spring has most originating in the South, suggesting the latter may have bigger impact on air quality. From these results, we highlight locations where emission mitigation efforts could be focused and suggest measures for pollutant mitigation. Our study demonstrates the need to account for emissions variation due to different burning practices.

Keywords

Biomass burning; Rice straw; Emission factors; Remote sensing; SAR; $PM_{2.5}$

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1. Introduction

Rice (*Oryza* sativa) is one of the prevalent staple crops for the majority of the people in Southeast Asia and Vietnam. Paddy rice production in Vietnam has consistently increased over the past decade, from 32.5 million tons in 2000 to 45.2 million tons in 2015 (Vietnam GSO, 2017). Concurrently, the area under cultivation has negligibly increased with 7.67 million ha in 2000 to 7.83 million ha in 2015 which indicates agricultural intensification.

Rice residue (rice straw) is defined as the inedible fibrous plant material left in the field after the harvest. It is routinely burned throughout many rice growing regions such as Philippines, China, India, and Thailand in addition to Vietnam (Badarinath et al., 2006, 2009; Sahai et al., 2007; Zhang et al., 2008; Gadde et al., 2009; Vadrevu et al., 2011; Kharol et al., 2012; Kanokkanjana and Garivait, 2013; Hong van 2014; Huang et al., 2016). While other uses for the residue exist such as for animal feed, mushroom cultivation, or bioenergy production, the residue is routinely burned in order to clear the fields for the next crop season. Burning results in emissions of trace gases and aerosols (Streets et al., 2003; Wiedinmyer et al., 2011; Zhang et al., 2017). Unlike most urban or industrial sources, rice burning emissions are focused in a short time period, which has implications for emission inventories, and impacts on local air quality and public health. Studies have suggested significant impact of biomass burning emissions on air quality including rice-wheat residue burning in Punjab, India (Badarinath et al., 2009; Vadrevu et al., 2011; Vadrevu and Lasko, 2015); peat and palm plantations in Indonesia (Gaveau et al., 2014; Hayasaka et al., 2014; Vadrevu et al., 2014; Marlier et al., 2015), vegetation fires in southeast Asia (Vadrevu and Justice, 2011; Reddington et al., 2014; Shi et al., 2014; Crippa et al., 2016), agricultural waste burning in China impacting regional and local haze (Cheng et al., 2014; Zhang and Cao, 2015; Liang et al., 2017; Yin et al., 2017). Studies have also shown variation and uncertainty in emissions inventories for biomass burning in agricultural lands (Kurokawa et al., 2013; Saikawa et al., 2017; Shi and Matsunga, 2017; Yadav et al., 2017; Lasko and Vadrevu, 2018). In addition to local and regional transport, agricultural biomass burning events have been found to transport air pollution such as black carbon through long-range transport, for example with impacts on the Himalayas and across other remote locations (Eckhardt et al., 2007; Ramanathan and Carmichael, 2008; Jeong et al., 2011; Vadrevu et al., 2012; Lin et al., 2013; Cayetano et al., 2014; Ikeda and Tanimoto, 2015; Yadav et al., 2017). The local and regional effects of biomass burning episodes can persist for weeks to months, impacting atmospheric chemistry, weather, biogeochemical cycles, and animal health (Yan et al., 2006; Badarinath et al., 2009; Cristofanelli et al., 2014; Ponette-Gonzalez et al., 2016; Sanderfoot and Holloway, 2017).

High concentrations of fine-particulate matter ($PM_{2.5}$) have been found in urban areas across Southeast Asia including Vietnam, Singapore, Thailand, India, and Indonesia with $PM_{2.5}$ concentrations averaging 44–168μg/m^3, routinely exceeding World Health Organization air quality standards (Oanh et al., 2006). Moreover, $PM_{2.5}$ can have a high proportion of very fine particles less than 1 μm in diameter with elements such as Pb and Cr, detrimental to human health (Khan et al., 2016; You et al., 2017). These high concentrations in Southeast Asia can be attributed to a variety of sources such as industry, transportation, and biomass burning. Moreover, the detrimental health effects of $PM_{2.5}$ are even linked to health conditions such as Tuberculosis, as well as premature death (Lu et al., 2015; Pope et al., 2007; You et al., 2016).

Use of satellite data for quantifying biomass burning emissions has been demonstrated by earlier studies (van der Werf et al., 2006, 2017; Langmann et al., 2009; Mieville et al., 2010; Kaiser et al., 2012; Randerson et al., 2012). However, monitoring small-holder agricultural fires and resulting emissions is difficult mainly due to the ephemeral nature of agricultural fires, combined with timing of satellite overpass, small flaming fire size, and cloud cover obstructing observations (Justice et al., 2002). For example, in Vietnam, using the MODIS Collection 6 active fires averaged for 2003–2015 and MODIS cloud fraction (Giglio et al., 2016; Platnick et al., 2003), we highlight that relatively low numbers of agricultural fires are detected in regions with known agricultural fires, especially during cloudy months and peak burning times (Fig. 2). While in some other biomass burning regions, significantly more agricultural fires are detected such as in India, China, Myanmar, Thailand, and the Mekong River Delta (Korontzi et al., 2006; Bonnet and Garivait, 2011; Giglio et al., 2013; Vadrevu and Lasko, 2015; Chen et al., 2017). Thus, because of the difficulty to detect agricultural fires in much of Vietnam, other approaches may be necessary to indirectly estimate approximate date and location of burning.

In Vietnam, rice is either harvested by machine such as a combine harvester, or by manual cutting (hand-harvest) using sickles or knives to cut the rice crop below the panicle. An example of a hand-harvested field and machine-harvested field with associated pile burning and non-piled burning in Vietnam are shown in Fig. 1. For hand-harvested fields, the rice straw is placed into a pile immediately after it is harvested and threshed, retaining moisture. Whereas in machine-harvested fields the rice is cut and threshed in one collective action, resulting in the rice straw in neat and thin rows within the field leaving the residue more exposed to dry out faster. These harvest practices are important because the resulting residue is burned differently (large, wet piles versus drier and less dense spreading fires). These different burning practices (pile burning versus non-piled burning) result in different combustion behavior such as smoldering or flaming with varied combustion efficiency resulting in different emissions (Korenaga et al., 2001; Christian et al., 2003; Hays et al., 2005; Shen et al., 2010; Akagi et al., 2011; Hayashi et al., 2014; Oanh et al., 2015; Arai et al., 2015; Zhang et al., 2015). Additionally, field studies have been found to have higher EFs than lab studies, attributed to more realistic field conditions such as residue moisture content (Holder et al., 2017).

Considering the above emissions variations specific to different rice residue burning practices and difficulty in estimating emissions using optical remote sensing data in Vietnam, we specifically addressed the following questions: 1) How do the different emission factors compare between pile burning and non-pile burning? 2). How much do $PM_{2.5}$ emissions vary for different scenarios based on the different rice straw burning practices; and how do they compare with estimates provided by global studies? 3) How much residue burning emissions are emitted based on synthetic aperture radar (SAR) satellite-based estimates of rice area under cultivation? 4) Considering the limitations of satellite fire detections in this area, are there any indirect approaches useful to estimate rice residue burning dates? 5) What is the general trajectory of polluted air parcels into Hanoi city during the rice residue burning events, and are there any patterns? We addressed the above questions specific to the Hanoi Capital Region and Vietnam by integrating ground based measurements, SAR data and combining emission factors for different theoretical rice residue burning scenarios based on 100% pile burning, 100% non-pile burning, and half of each. The first is represents historical measurements prior to burning, while the 2nd may represent future mechanized emissions, and the third is the estimated current status.

2. Study area

We conducted this study for two focus regions: 1) the entirety of Vietnam to arrive at national-scale rice residue burning emissions; and 2) the rice-dominated provinces of the Hanoi Capital Region (HCR), to highlight spatial location and transport of emissions into this urban area. The HCR includes a large portion of the Red River Delta, Vietnam's oldest and 2nd largest rice producing hub after the Mekong River Delta and includes the provinces adjacent to Hanoi. In this study, we included all of the rice-dominated provinces of the HCR with rice area occupying more than 20% of land area according to the Vietnam General Statistics Office: Bac Ninh (44% rice), Hung Yen (43%), Ha Nam (39%), Hanoi (33%), and Vinh Phuc (23%). In the Red River Delta, rice is planted with 2 main seasons: the first in February after the *Tet* holiday and harvested and burned around June, while the second is planted around July and harvested and burned around October. The typical field size in the region is wide ranging, but averages about 800 m^2 (Lasko et al., 2017). While rice in the Red River Delta and most of Vietnam is grown in two seasons, in the Mekong River Delta, many farmers practice three rotations of rice resulting in a large amount of rice residues (Kontgis et al., 2015). Much of the rice residues including straw and stubble are subjected to burning to clear the land for the next planting (Pham, 2011; Hong Van et al., 2014). Specifically, after the harvest, the rice residues are either pile burned or non-pile burned (Fig. 1). In addition to rice, the densely populated region is home to over 10 million inhabitants with a vibrant economy including aquaculture, fisheries, mangrove forestry, manufacturing, and construction industries (Devienne, 2006).

In this region, local climate conditions of nocturnal radiation inversions during the October burning time, can contribute to an amplified emission effect (Hien et al., 2002). Hanoi, the city with the highest $PM_{2.5}$ concentration in Vietnam, has exceedingly high concentrations of $PM_{2.5}$ ranging daily from 26 to 143μg/m^3 with sources especially attributed to secondary pollutant formation, diesel traffic, cookstoves, and industry (Hai and Oanh, 2013). Hanoi's monthly $PM_{2.5}$ concentrations consistently exceed 35ug/m^3 with the highest during Dec–Mar attributed to drier weather conditions, as well as local traffic and industrial pollution (Oanh et al., 2006; Nguyen et al., 2015).

3. Methods

3.1. Emission factors

To date, studies have not comprehensively addressed the variation in $PM_{2.5}$ emissions from different residue burning practices, a factor which may result in significantly higher emissions than previously thought. Thus, we compiled results from laboratory and field burning emissions estimates of rice straw to address this issue; as these studies have directly or indirectly emulated either pile burning (associated with hand-harvested fields) or non-pile burning (associated with machine-harvested fields). Previous studies typically burn the residues in controlled lab conditions with about 0.1 kg–1 kg of rice, whereas field studies are more natural and burn based on actual amount found in the field using in situ devices. With non-pile burning, the residues are mostly dry and burn under flaming conditions with complete combustion. With pile burning, the residues are usually burned with wetter residue biomass, often resulting in smoldering conditions and incomplete combustion. All selected studies are shown in Table 1 including a detailed list of emission factors for comparison.

We averaged the emission factors from all selected $PM_{2.5}$ studies in Table 1 to generate the pile burning and non-pile burning emission factors (Table 2). For pile burning, we selected studies with moisture contents exceeding 20% or if the study mentioned that residues were burned in piles. Whereas for the non-pile burning, we included studies with lower moisture contents (~15% or less) or if pile burning was indicated in the study description. The exact moisture content in the field varies, but averages about 13% in machine-harvested fields with non-pile burning, and about 25% in hand-harvested fields with pile burning as measured from rice residues in Hanoi province prior to burning (Lasko et al., 2017). We note some seasonal variation is also likely. To generate burning-practice specific combustion factors, we averaged combustion factors from three different studies for non-pile burning (Aalde et al., 2006; Sanchis et al., 2014; Romasanta et al., 2017), and 1 study from pile burning (Sanchis et al., 2014). We included fewer studies for combustion factors than emission factors due to lack of availability, or results not interpreted to be representative of the burning practice.

3.2. Rice area estimates

3.2.1. Rice area for Hanoi Capital Region (HCR)—For the spatially-gridded $PM_{2.5}$ emissions in the Hanoi Capital Region (HCR), we derived rice areas from Sentinel-1A C-band SAR imagery for the year 2016 (Lasko et al., 2018). We used a time series of 22 Sentinel-1A IW GRD data obtained from the Alaska Satellite Facility, a direct mirror of ESA's scihub. The Sentinel-1A SAR satellite has a local repeat overpass of approximately 12 days and increasing to 6 days with growing availability of Sentinel-1B imagery. We classified the time series stack of imagery using a random forest classifier with bootstrap aggregated sampling with 1000 trees populated in the forest. Random forest is robust against outliers and over-fitting, nonparametric, has high classification accuracy, and can yield a measure of variable importance (Breiman, 2001). In order to highlight spatial variation in emissions resulting from using different SAR datasets for crop area, we processed the SAR imagery into 6 different datasets based on varied SAR polarizations and spatial resolution. They are: Vertical-Vertical (VV) polarized bands at 10 m spatial resolution (VV10m), Vertical-Horizontal (VH) polarized bands at 10 m spatial resolution (VH10m), and both polarizations at 10 m resolution (VVVH10m), as well as the same polarization combinations for 20 m imagery (VV20m, VH20m, and VVVH20m). In addition, a robust accuracy assessment following good practices was carried out with overall accuracy exceeding 90% for each dataset (Olofsson et al., 2014) with further details in Lasko et al., (2018).

3.2.2. Rice area for the entirety of Vietnam—We obtained rice area from the Government of Vietnam for the year 2015 (Vietnam GSO, 2017). The dataset is based on a set of surveys conducted by local officials at the commune-level and has been found to have good overall agreement, and relatively similar results to other rice mapping studies in Vietnam (Kontgis et al., 2015; Nguyen et al., 2015). The data shows a total of 7.8 million ha of rice for Vietnam with 4.3 million ha in the Mekong River Delta and 1.1 million ha in the Red River Delta.

4. Emissions estimation and scenarios

We calculated the $PM_{2.5}$ rice residue burning emissions for both the HCR and entirety of Vietnam based on the following equation.

$$E_{PM2.5} = A * FL * EF * PB * CF \quad (1)$$

Where E is the total $PM_{2.5}$ burning emissions for either pile burning or non-pile burning calculated from: A, the area under cultivation for rice in hectares, FL is the post-harvest rice residue amount in kg/ha, EF is the fine-particulate matter emission factor in g kg^{-2}averaged from the different studies (Table 1), PB is the proportion of rice residue subjected to burning (i.e. not used for cattle feed, cook stoves, etc.), and CR is the combustion factor indicating the completeness of the combustion (i.e. 0 is failed to burn, and 1 is a complete burn). Combustion factors can be influenced by moisture content, density, and other factors mentioned in the introduction section. For example, a higher combustion factor is seen with non-pile burning found in machine-harvested fields due especially to lower moisture content. We obtained rice area from SAR maps for the HCR and government statistics for the entirety of Vietnam (Vietnam GSO, 2017). Following the method in Lasko et al., (2017), we used rice FL of 2700 kg/ha (straw), and 6100 kg/ha (stubble) and FL of 3470 kg/ha (straw) and 3860 kg/ha (stubble) from Hong Van et al., (2014). As the latter FL is representative of triple-cropped fields, it is used for the calculation in the Mekong River Delta. Whereas, the former FL is representative of the common double-cropped rice fields found in the rest of Vietnam. PB is assumed as 50% for straw and 10% for stubble gathered from previous field studies in Vietnam (Trach, 1998; Hong Van et al., 2014; Duong and Yoshiro, 2015; Oritate et al., 2015).

We calculate the emissions for four hypothetical scenarios where: 1) 100% pile burning associated with hand-harvested fields, pre-mechanization of agriculture; 2) 100% non-pile burning associated with machine-harvested fields, post-mechanization; 3) Approximated current amount based on government data (Vietnam GSO, 2017); and 4) Using generalized agriculture emission factors (one factor for all types of croplands) employed in global and regional biomass burning studies. We also calculate emissions uncertainty based on the provided error rates from each study and the approximated error propagation equation for multiplication of quantities where fractional uncertainties add in quadrature (Harvard, 2013) as shown in equation (2):

$$\delta E_{PM2.5} = |E_{PM2.5}| * \sqrt{\left(\frac{\delta A}{A}\right)^2 + \left(\frac{\delta FL}{FL}\right)^2 + \left(\frac{\delta EF}{EF}\right)^2 + \left(\frac{\delta PB}{PB}\right)^2 + \left(\frac{\delta CR}{CR}\right)^2} \quad (2)$$

Where $\delta E_{PM2.5}$ is the uncertainty for the $PM_{2.5}$ emissions equation (1) and the uncertainty (δ) for each variable in equation (1). Proportion burned and crop area data from Vietnam government statistics do not have reported error. Thus, we conservatively assumed twenty percent error in these data.

We also compare our resulting emissions estimates with the Regional Emission inventory in ASia 2.1 (REAS), selecting only the combustion sources from the emissions inventory, available for $PM_{2.5}$ for the latest year of 2008 (Kurokawa et al., 2013). The REAS is based on reported industrial activity data and existing survey data as well as other sources. This comparison will yield improved insight into the contribution of rice residue burning to all $PM_{2.5}$ emissions.

5. Date of burning and pollutant transport

Due to consistent cloud cover and ephemeral agricultural fires in Vietnam, with only an average of about eighty fires detected during the residue burning season within the Red River Delta, other methods are needed to estimate burning (Fig. 2). We employ an indirect approach to estimate date of burning using time series of Sentinel-1A imagery as described in the previous section (Fig. 3). We used a total of 22 VH-polarized images starting on 3rd February 2016 and ending on 24th October 2016 with images for every 12 days excluding approximately June 28th due to no data. The phenology of rice fields has been highlighted in a number of recent studies, where minimum VH-polarized backscatter is observed during sowing because of inundation, and the maximum occurs at or near harvest attributed to removal of water prior to harvest and biomass removal, as well as double-bounce between rice plants and underlying surface and dielectric conditions of the canopy (Inoue et al., 2002, 2014; Choudhury and Chakraborty, 2006; Bouvet et al., 2009; Lopez-Sanchez et al., 2014; de Bernardis et al., 2015; Yuzugullu et al., 2015; Boschetti et al., 2017; Izumi and Demirci, 2017; Mansaray et al., 2017). We note that incident angle is constant throughout study area and is not a factor on backscatter variation.

Within 4 km grid cells, we calculate the approximate harvest date based on the date of maximum backscatter within a window of each season based on local growing conditions (i.e. Feb–June for season 1, and Jun–Oct. for season 2). Based on our field experience, we found that rice residues were typically burned within 3 days of harvest (Lasko et al., 2017). Thus, we estimate the burn date by adding three days to the date of maximum backscatter. We then use these dates as the basis for air pollutant transport within the heavily populated study area, where air quality impacts would be strong due to the dense urban population (Hopke et al., 2008).

Back trajectories have been implemented by a number of studies attributing air quality to different biomass burning events in south/southeast Asia and abroad (Reiner et al., 2001; Eck et al., 2003; Kim et al., 2006; Badarinath et al., 2009; Sharma et al., 2010; Li et al., 2010; Sonkaew and Macatangay, 2015; Zhao et al., 2015). For the back-trajectory analysis we use the NOAA Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Draxler and Hess, 1998; Stein et al., 2015; Rolph et al., 2017) with hourly archived meteorological data from the US National Center for Environmental Prediction (NCEP) Global Data Assimilation System (GDAS). Back-trajectories were calculated during each estimated burn date and 1 day before and after, to account for variation in estimated burn date. The model parameters included: starting a new ground-level (5 m), 6 h back-trajectory every 3 h with start times selected during the day from 9AM to 6PM within the typical range of burn times and distances (Tipayarom and Oanh, 2007; Chen et al., 2017). We ran the HYSPLIT model for a total of 18 different dates.

6. Results

6.1. Rice area estimates

The rice area maps generated from each of the six datasets had mapped rice areas (in thousand ha) of 214.5 (VVVH10m), 220.3 (VVVH20m), 212.4 (VH10m), 218.8 (VH20m), 208.2 (VV10m), 214.9 (VV20m). Whereas the Vietnam Government data indicated 198.9 ha, showing similar results, with about 7.3% less than our most accurate VVVH10m data. Additional variation due to polarization and spatial resolution is described in Lasko et al., (2018). The rice map together with the field-based fuel-loading factors were used to estimate total rice residue using the factors shown in Table 2. The resulting rice residue map was the basis for emissions estimation in the Hanoi Capital Region of Vietnam. The total $PM_{2.5}$ emissions for the HCR from rice residue burning are shown in Table 3 and Fig. 4b including the contribution to total estimated rice residue burning emissions for Vietnam with associated uncertainties in parentheses.

6.2. Burning practice specific emissions factors

The $PM_{2.5}$ EF’s for rice straw burning range from as low as 4.2 g kg^{-2} to 20.67 g kg^{-2}, whereas the generalized agricultural emission factors used in various global and regional biomass burning studies are 3.9 g $kg^{-2}$and 6.26 g kg^{-2}. The pile burning EFs have an average EF of 16.8 g kg^{-2}(±6.9), as compared to 8.8 g kg^{-2}(±3.5) from non-pile burning often found in machine-harvested fields, suggesting pile burning emits almost double the $PM_{2.5}$ than non-pile burning fire emissions. An even starker contrast is seen between the general agriculture emission factors (i.e. 6.26 g kg^{-2}in Akagi et al., 2011 and 3.9 g kg^{-2}in Andreae and Merlet, 2001). These results demonstrate a shortcoming and potential underestimation in global studies. While challenging, larger-scale biomass burning studies should employ crop and burning practice specific emission factors in order to best capture biomass burning emissions variation and to avoid significant potential underestimation in the emissions. For example, using the general agriculture emission factor in Akagi et al., (2011) for this study instead of the pile burning emission factor, would yield a 77% difference in the resulting emissions.

The combustion factors ranged from 66.7% to 98.7% with generally lower factors for pile burning. The average for non-pile burning is 89% (±8%), and 67% (±7%) for pile burning. We note that combustion factor measurements are difficult to measure in the laboratory, and thus, may not be completely representative of field conditions with inherent uncertainty. The combustion factor used in general agricultural studies and global studies is 80%, i.e., eighty-percent burned as reported in the IPCC report on greenhouse gas emissions (Aalde et al., 2006).

6.3. $PM_{2.5}$ emission scenarios

The $PM_{2.5}$ emissions estimates for non-pile burning, pile burning, and current status scenarios are shown for each region of Vietnam (Fig. 4a). The majority of emissions are from the Mekong River Delta (72 Gg $PM_{2.5}$ and 100 Gg $PM_{2.5}$) for non-pile burning and pile burning respectively. The lowest emissions are found in the Central Highlands which is characterized by slash and burn agriculture and coffee plantations (Le et al., 2014). In total, for Vietnam 180 Gg of $PM_{2.5}$ would be emitted if rice residues were burned following the pile burning method with fields harvested by hand, whereas 130 Gg would be emitted if rice residues were non-pile burned, a scenario assuming all fields are mechanized and harvested using combine harvesters or similar equipment. The most-likely current emission scenario (50% pile burn, 50% non-pile burning) estimates 150 Gg $PM_{2.5}$ emissions for the entirety of Vietnam. Overall, there is a 32% difference between pile burning and non-pile burning emission scenarios suggesting that the burning practice plays a very important role in total emissions. The specific emission scenarios with associated uncertainty are shown in Table 3.

We also compared our emission estimates to an existing all combustion-sources inventory (Kurokawa et al., 2013). The results show rice residue burning contributes to 14%, 18%, and 16% of all combustion sources in Vietnam respectively for non-pile burning, pile burning, and most-likely current status. This suggests that rice residue burning is one of the major emissions contributors in Vietnam, and is the second largest contributor after fuelwood burning. However, the REAS emission inventory does not account for other biomass burning such as forest or shrubland, therefore emissions are likely somewhat high.

Many large-scale biomass burning studies rely on generalized agriculture emission factors due to currently limited availability of crop, region, or burning-practice specific data (Andreae and Merlet, 2001; Akagi et al., 2011). To estimate emissions for the entirety of Vietnam, we used the 2015 rice area from Vietnam office of statistics and the general agriculture emission factor from Akagi et al., (2011) with general agriculture combustion factor from IPCC (Aalde et al., 2006). The resulting rice residue burning $PM_{2.5}$ emissions for Vietnam using these factors would be: 80 Gg which is only 44% of pile burning and 62% of non-pile burning. This large difference demonstrates burning practice specific and crop-specific factors are important to improve existing global and regional emission inventories.

6.3.1. Emissions transport—Based on the time-series SAR imagery for 2016, seasonal date of maximum backscatter per grid cell, and 3 day estimate between harvest and burn, we mapped the estimated burn date for each season (Fig. 5). The estimated burn dates were May 24th, June 5th, and June 17th for season one. For season two, the dates of burn were October 3rd, October 15th, and October 27th. These dates are constrained by the 12-day overpass for Sentinel-1 and burn date uncertainty. We subsequently ran the HYSPLIT back-trajectories over Hanoi City, Vietnam on these dates of burning as well as 1 day before and after to account for some variation.

Results from the HYSPLIT back-trajectory maps are shown in Fig. 6 and were conducted for the spring and autumn rice burning seasons. Trajectories generally originate from all directions outside of Hanoi City, suggesting potential rice residue burning impacts. Results stratified by season show that for autumn most trajectories originate from the North while for spring most originate from the South, likely due to synoptic weather patterns. A breakdown for the top 3 wind directions in the spring are: 31% South, 17% southeast, and 17% east; whereas for autumn: 26% North, 24% southeast, and 15% east. The biggest difference was 26% of trajectories originated north of Hanoi in Autumn, but only 6% during Spring as illustrated in the map. Thus, depending on the season, the emissions from different regions and directions will be more impactful in Hanoi City, highlighting the importance of accurate spatial maps of emissions. Overall, the air quality in Hanoi City could be linked with rice residue burning events, but the level of impact will be dependent on seasonal variability and timing and locations of burning. This suggests a need for further research on atmospheric chemical and concentration modelling in Hanoi.

7. Perspectives and conclusions

Our study conducted improved estimates of emissions for rice residue burning, and for the first time, accounted for burning practice in the resulting assessment. The results illustrate that when burning practice specific emission factors are employed, a large difference is seen in the emission estimates. Moreover, our study highlights that previous large-scale studies using general emission factors could be significantly underestimating emissions. Our latest estimates for the entirety of Vietnam for year 2015 show that the $PM_{2.5}$ emissions likely fall somewhere between 130 Gg (100% non-pile burning) and 180 Gg (100% pile burned). Therefore, our rice residue burning estimates on $PM_{2.5}$ will add significantly to the overall $PM_{2.5}$ emissions, such as in the REAS emission inventory (Kurokawa et al., 2013). Our findings also show that rice residue burning contributes to 14% (non-pile burning), 18% (pile burning), and 16% (current status) of total combustion $PM_{2.5}$ emissions in Vietnam in comparison with the REAS. These findings are important for improving upon existing emissions inventories and source apportionment.

These results have an important implication in terms of policy measures and for estimating future emissions. Both our field visit and the literature showed an increasing use of mechanized farming (Oanh et al., 2011; Lasko et al., 2017; Vietnam GSO, 2017). As harvesting practices transition from manual to machine-harvesting with non-pile burning, and assuming a constant rate of burning, the emissions could naturally decrease to the non-pile burning level. In addition, it’s possible to further mitigate emissions by improving crop residue management practices such as incorporating residues into the field and avoiding GHG emissions from residue burning. Whereas, the pile burning emissions estimates for Vietnam would be representative of historical emissions amounts prior to mechanization of agriculture.

The HYSPLIT trajectory model demonstrates common spatial patterns of rice residue burning emissions transport. With this knowledge, focusing emissions mitigation efforts in areas impacted by rice residue burning could be most beneficial. Some efforts to alleviate emissions impact have included: rice straw mushroom cultivation, enforcement of rice residue burning laws, and education on alternative uses such as for fertilizer, cattle feed, etc.

Our study is limited by several factors. Hanoi experiences higher rainfall during June burning time than during the October burning time. This rainfall could impact the moisture content of the rice residues and resulting emissions. However, with current data limitations we are unable to quantify this effect in a meaningful way. In addition, we found in our field experience that farmers may wait to burn the residues after rain events have cleared and dried up. Another limitation in our study is the combustion factor. Only a few studies had combustion factor measurements representative of the different burning practices, and there is a lot of uncertainty in this factor. Future work should explore this factor in more detail to reduce uncertainty. Rice fuel-loading factors may also differ for machine-harvested and hand-harvested fields, however, the data is currently unavailable; considering this, our emissions estimates are still an improvement on the existing studies. Additionally, the rice area estimates for Vietnam have inherent error, however, there are not any available error rates. Although, recent studies have demonstrated relatively high accuracy with the government rice area estimates in Vietnam (Kontgis et al., 2015; Nguyen et al., 2016; Man et al., 2018; Torbick et al., 2017). Additionally, we note there is moderate variability and therefor reliability between the different residue burning studies for each burning practice. For example, pile burning EFs ranged from 9.6 g kg^{-2} to 20.7 g kg^{-2}, whereas non-pile burning ranged from 6.3 g kg^{-2} to 12.1 g $kg^{-2}$of $PM_{2.5}$. Future work could improve upon the study reliability and reduce uncertainty. Moreover, future work could improve upon this study by simulating resulting $PM_{2.5}$ concentration in Hanoi due to rice residue burning.

Overall our study compiled and combined emissions factors from previous rice residue burning experiments representative of the two common practices of rice straw burning, found especially in Southeast Asia and Vietnam: 1) wet and smoldering conditions found in pile burning generally associated with hand-harvested fields; and 2) drier and flaming conditions found in non-pile burning associated with machine-harvested fields. We then used these burning practice-specific factors to estimate emissions for Vietnam, and compared emissions based on the general agriculture emission factor relied upon in global or regional studies. Our results showed a 32% difference in emissions between the two different burning practices (pile burning, versus non-pile burning), suggesting burning practice is a major factor for studies to account for in the $PM_{2.5}$ emissions equation. We also inferred that when using the global emission factors, $PM_{2.5}$ emissions are underestimated by 44%–77% compared to when using management specific emission factors. We found seasonal differences in rice residue emissions transport into Hanoi; thus we believe the emissions impact could be reduced with focused mitigation efforts. Further, we infer that mechanization of agriculture could lead to reduced $PM_{2.5}$ emissions from rice residue burning. We also stress on the need to follow crop residue best management practices and alternatives to burning. Overall, our study novelty demonstrates the importance of burning practices on resulting emissions estimates, and that burning practice is generally not considered in many existing biomass burning studies.

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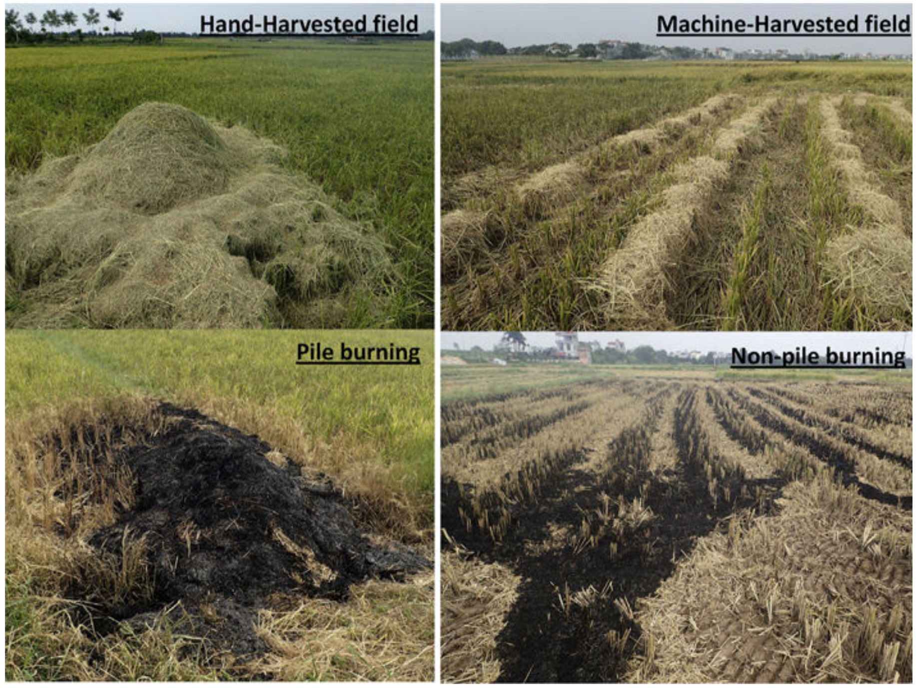

Fig. 1.
Harvested rice fields representative of the two dominant burning practices in Southeast Asia and Vietnam. Pictures taken by the author in Hanoi Province during June or October 2016.

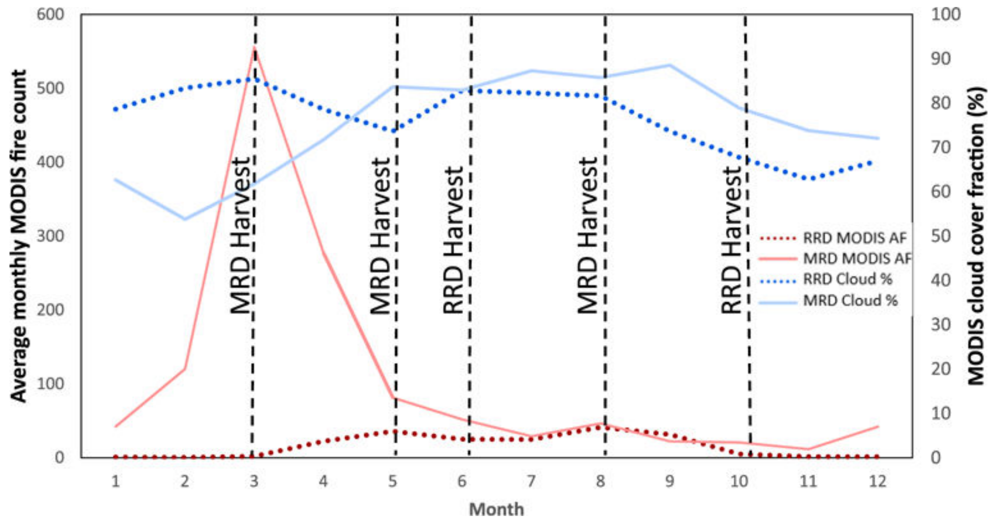

Fig. 2.

MODIS collection 6 Active Fire (AF) counts for the Red River Delta (RRD) and Mekong River Delta (MRD) averaged with 2003–2015 data. Cloud fraction is over 20% higher during main dry season harvest in RRD (June) compared with main harvest in MRD (February/March). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

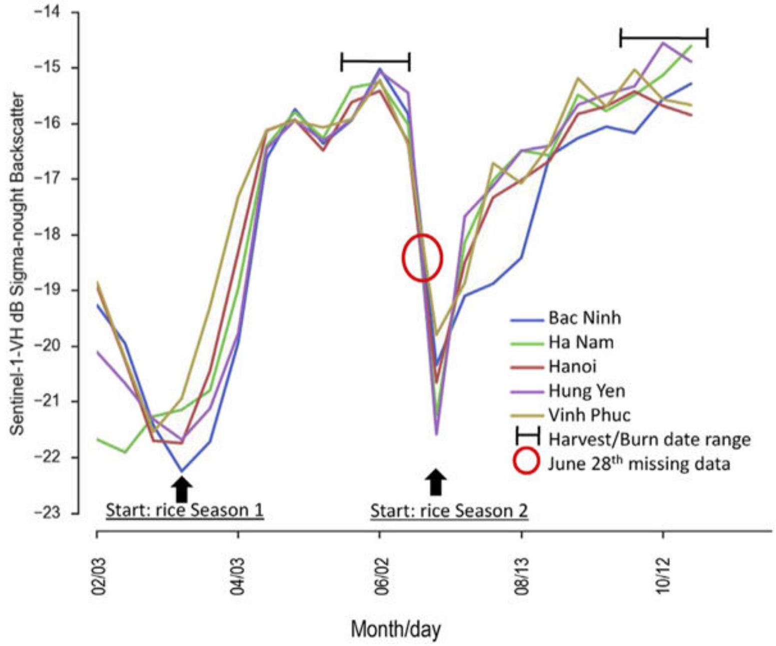

Fig. 3.

Sentinel-1 VH backscatter averaged for each province. For each rice season, the date where backscatter values reach a maximum (i.e. June 2nd and October 12th) coincides with the rice harvest; then, the burning is assumed to occur within 3 days of harvest based on our field experience. Note: data was unavailable for June 28th (circled in red) due to image corruption. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

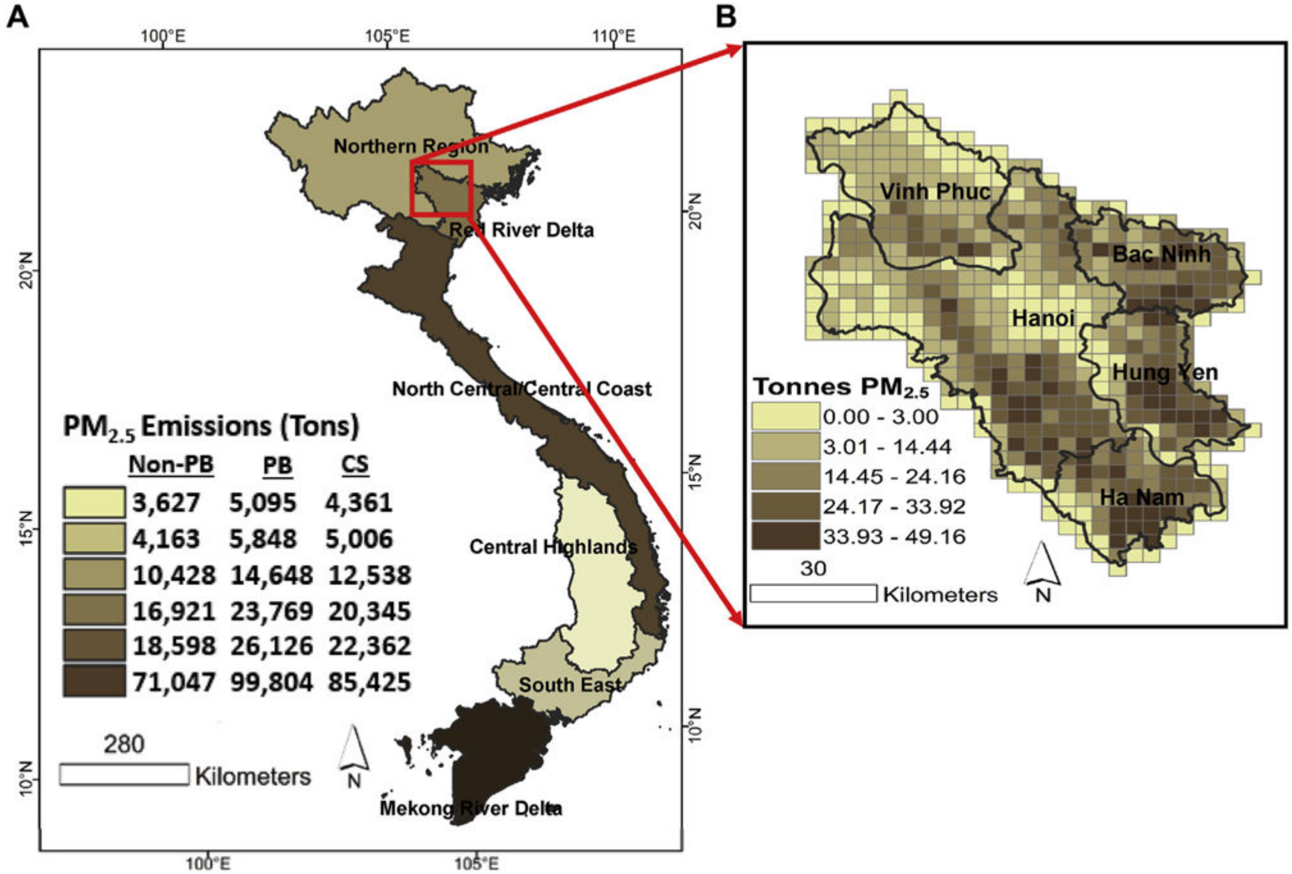

Fig. 4.

a)PM2.5 emissions in tons for Vietnam comparing values that would result from non-Pile Burning (Non-PB), Pile burning (PB), and most-likely Current Situation (CS) which assumes 50% PB and 50% Non-PB based on a report from Vietnam Office of Statistics. 4b)Most-likely (CS) PM2.5 emissions per 4 km gridcell based on the SAR rice map available for Hanoi. This scenario assumes 50% PB and 50% non-PB based on a Vietnam Office of Statistics, 2017 report.

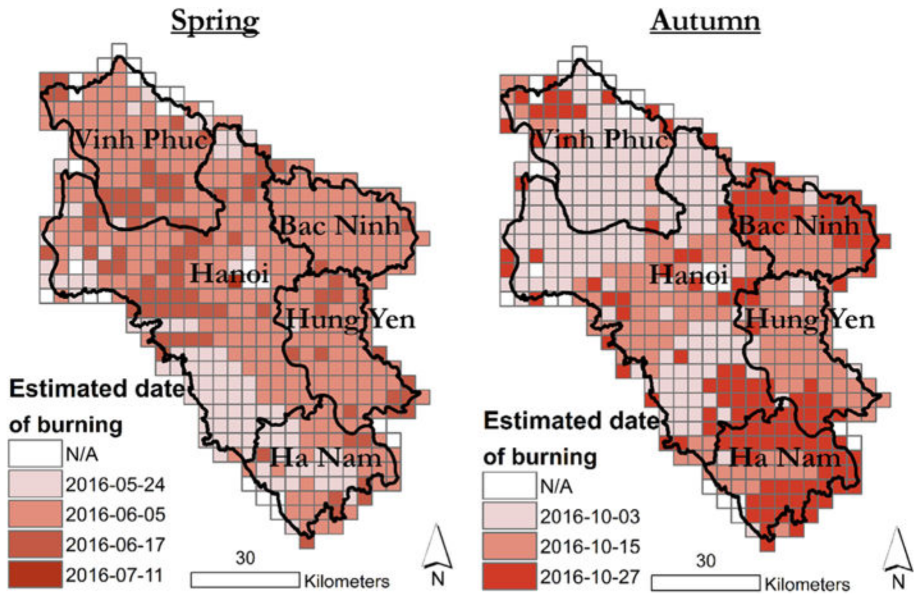

Fig. 5.

Estimated dates of burning based on Sentinel-1 SAR maximum backscatter value for each 4 km gridcell for Spring and Autumn residue burning seasons.

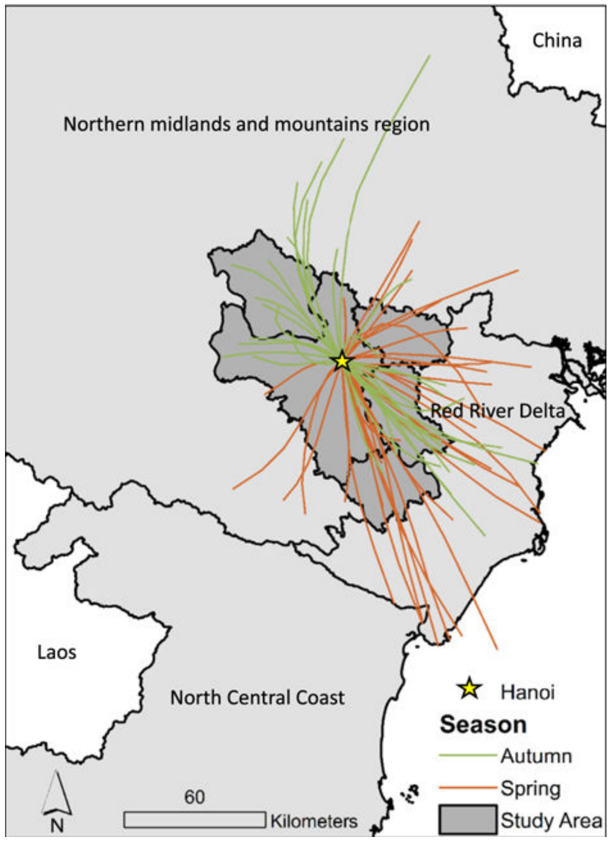

Fig. 6.

NOAA HYSPLIT back-trajectories stratified by the two different burning seasons of Spring (May/June) and Autumn (Oct). Trajectory patterns suggested relatively more polluted air parcels moving into Hanoi City originate from the North, while more originate from the South during Spring.

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Table 1

List of fine-particulate matter measurements from rice residue burning studies, and their associated burning practice type deduced from interpretation of their study design, or as listed in the study. The amount burned per trial indicates the residue amount burned in each individual test. We also report each studies emission factor and associated error/uncertainty.

Study	EF (g/kg)	Uncertainty (g/kg)	Burn type	Amount burned per trial	Description
Cao et al., 2008	6.28	1.59	Non-Piled (machine-harvest)	0.5–1 5kg	Air dried residues burned in lab
Oanh et al., 2011	8.3	2.70	Non-Piled (machine-harvest)	entire fields	in situ measurements on machine-harvested fields
Zhang et al., 2013	12.1	4.4	Non-Piled (machine-harvest)	0.3–0.99kg	air dried residues burned in lab; flaming phase EF used
Sanchis et al., 2014	8.66	2.29	Non-Piled (machine-harvest)	3kg	lab measurements with 10% moisture content
Ni et al., 2015	8.5	6.7	Non-Piled (machine-harvest)	0.1–0.2kg	low density, spread fires burned in lab
Christian et al., 2003	4.2	–	Piled (Hand-harvest)	Small piles in field	Spot measurements in selected fields. "They Noted the measurements are likely to be low. Thus, not included in our study
Hays et al., 2005	12.95	2.56	Piled (Hand-harvest)	0.75kg	Piled residues burned in lab
Kanokkanjana et al., 2010	19.21	15.76	Piled (Hand-harvest)	piles in field	Field and outdoor laboratory experiment
Zhang et al., 2013	18.3	13.5	Piled (Hand-harvest)	0.3–0.99kg	Air dried residues burned in lab; smoldering EF used
Sanchis et al., 2014	20.67	3.88	Piled (Hand-harvest)	3kg	Lab measurement with 20% moisture content
Zhang et al., 2015	9.6	4.3	Piled (Hand-harvest)	piles in field	In situ measurements on rice residue piles; CO based EF
Zhang et al., 2015	20.3	1.5	Piled (Hand-harvest)	piles in field	In situ measurements on rice residue piles; $C0_2$ based EF
Akagi et al., 2011	6.26	2.36	General agriculture	–	Exhaustive compilation and averaging of global emission factors
Andreae and Merlet, 2001	3.9	–	General agriculture	–	Exhaustive compilation and averaging of global emission factors
Li et al., 2017	14.73	2.42	Unknown	0.01kg	Rice straw burned in small chamber.
Yu et al., 2012	6.28	–	Unknown	N/A (residual mass method) EF for rice straw PM_{10} based on empirical calculation.	
Sillapapiromsuk et al., 2013	0.69	–	Unknown	500g	EF for rice straw PM_{10} in laboratory chamber experiments

Table 2

Emission factors (EFs) and Combustion Factors (CFs) used in this study. Factors were obtained from the literature in Table 1 and placed into non-pile or pile burning category based on moisture content or study design. The EFs and CFs were averaged to obtain burning practice-specific factors.

Factor	Average and Standard Deviation	EFs/CFs averaged from literature	Notes
Combustion Completeness Factor (non-pile burning)	0.89 (±0.08)	Aalde et al., 2006; Sanchis et al., 2014; Romasanta et al., 2017	Sanchis et al. (2014) includes ash and burned straw from 10% moisture test
Combustion Completeness Factor (Pile burning)	0.67 (±0.07)	Sanchis et al., 2014	Factor includes ash and burned straw from 20% moisture test
PM2.5 emission factor (g/kg) (non-pile burning)	8.8 (±1.9)	Oanh et al., 2011; Zhang et al., 2013; Cao et al., 2008; Sanchis et al., 2014; Ni et al., 2015	
PM2.5 emission factor (g/kg) (Pile burning)	16.9 (±4.1)	Hays et al., 2005; Zhang et al., 2013, 2015; Sanchis et al., 2014	
PM2.5 emission factor (g/kg) General agriculture/IPCC	5.1 (±1.2)	Andreae and Merlet 2001; Akagi et al., 2011	General crop residue burning factors employed by many global studies

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Table 3

PM2.5 emissions reported in metric tons for the Hanoi Capital Region (HCR) and Vietnam based on the different rice residue burning scenarios. Residue amounts are in terragrams. Note the emissions estimates are shown to 2 significant digits. Error rates are shown in parentheses for the emission estimates. The last column shows the total percentage of rice residue burning emissions.

Rice area dataset	Region	Rice residue amount produced (Tg)	PM2.5 using general EF/CF	100% pile burning PM2.5	100% non-pile burning PM2.5	Most-likely scenario (50/50) PM2.5	Percent of emissions for entire Vietnam
SAR map	HCR	3.762	3400	9400 (±7,800)	6600 (±4,700)	8000 (±6,200)	5%
Govt. stats	Red River Delta	9.771	11000	24000 (±20,000)	17000 (±15,000)	21000 (±18,000)	14%
Govt. stats	Mekong River Delta	31.58	46000	100000 (±88,000)	72000 (±63,000)	86000 (±76,000)	58%
Govt. stats	Entire Vietnam	62.61	80000	180000 (±150,000)	130000 (±110,000)	150000 (±130,000)	100%