Environmental Pollution 236 (2018) 795–806

Contents lists available at ScienceDirect

Environmental Pollution

journal homepage: www.elsevier.com/locate/envpol

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

Kristofer Lasko*, Krishna Vadrevu

NASA Marshall Space Flight Center, Huntsville, AL, USA

A R T I C L E I N F O

Article history:
Received 28 November 2017
Received in revised form
18 January 2018
Accepted 29 January 2018

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

A B S T R A C T

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.

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

☆ This paper has been recommended for acceptance by Dr. Yong Sik Ok.

* Corresponding author. University of Maryland, College Park, MD, USA.
E-mail addresses: klasko@umd.edu (K. Lasko), krishna.p.vadrevu@nasa.gov (K. Vadrevu).

https://doi.org/10.1016/j.envpol.2018.01.098
0269-7491/

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