Science of the Total Environment 627 (2018) 523–533

Contents lists available at ScienceDirect

Science of the Total Environment

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

Modeling crop residue burning experiments to evaluate smoke emissions and plume transport

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HIGHLIGHTS

- Detailed evaluation of fuel loading and emission factors of $PM_{2.5}$ and CO for bluegrass and winter wheat fuel types.
- 30% to 200% underestimation in buoyancy heat flux with default field information underestimate plume height up to 80.
- Improved plume structure modeling for crop residual burning with field measurements based buoyancy heat flux estimation.

GRAPHICAL ABSTRACT

ARTICLE INFO

Article history:
Received 9 November 2017
Received in revised form 24 January 2018
Accepted 24 January 2018
Available online xxxx

Editor: Jianmin Chen

Keywords:
Air quality modeling
Biomass burning
Emissions
Smoke plume
CMAQ

ABSTRACT

Crop residue burning is a common land management practice that results in emissions of a variety of pollutants with negative health impacts. Modeling systems are used to estimate air quality impacts of crop residue burning to support retrospective regulatory assessments and also for forecasting purposes. Ground and airborne measurements from a recent field experiment in the Pacific Northwest focused on cropland residue burning was used to evaluate model performance in capturing surface and aloft impacts from the burning events. The Community Multiscale Air Quality (CMAQ) model was used to simulate multiple crop residue burns with 2 km grid spacing using field-specific information and also more general assumptions traditionally used to support National Emission Inventory based assessments. Field study specific information, which includes area burned, fuel consumption, and combustion completeness, resulted in increased biomass consumption by 123 tons (60% increase) on average compared to consumption estimated with default methods in the National Emission Inventory (NEI) process. Buoyancy heat flux, a key parameter for model predicted fire plume rise, estimated from fuel loading obtained from field measurements can be 30% to 200% more than when estimated using default field information. The increased buoyancy heat flux resulted in higher plume rise by 30% to 80%. This evaluation indicates that the regulatory air quality modeling system can replicate intensity and transport (horizontal and vertical) features for crop residue burning in this region when region-specific information is used to inform emissions and plume rise calculations. Further, previous vertical emissions allocation treatment of putting all cropland

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https://doi.org/10.1016/j.scitotenv.2018.01.237

residue burning in the surface layer does not compare well with measured plume structure and these types of burns should be modeled more similarly to prescribed fires such that plume rise is based on an estimate of buoyancy.

1. Introduction

Crop residue burning is commonly used in agricultural land management to dispose of crop residue and provide other benefits such as pest control and ash generation for fertilization (McCarty, 2011). However, pollution from open biomass burning has been linked to negative human health impacts (Liu et al., 2016; Reid et al., 2016; Liu et al., 2015; Rappold et al., 2011). In addition, particles emitted from fires have direct radiative effects and contribute cloud condensation nuclei which have indirect effects (Yu et al., 2016; Forster et al., 2007). Nationally, approximately 1.2 million ha of croplands are burned annually on average, which is equivalent to 43% of the annual average area of wild fires in the U.S. (McCarty et al., 2009). The Pacific Northwest is a region of major agricultural burning, with cropland burning of nearly 200,000 ha per year (McCarty et al., 2009). Photochemical transport models have been used to support scientific and regulatory assessments that quantify the impact of wildland fires and cropland burning on O_3 and $PM_{2.5}$ (Baker et al., 2016; Fann et al., 2013; Jain et al., 2007). In those studies, differences between model predictions and ambient measurements were partially explained by uncertainty in meteorological input fields and fire emissions (Garcia-Menendez et al., 2013; Seaman, 2000; USDA Forest Service, 1998; Urbanski et al., 2011). Numerous laboratory experiments have been conducted to quantify biomass burning emission factors, but the accuracy of applying these emission factors for open biomass burning is still uncertain (Holder et al., 2017; Aurell and Gullett, 2013; Aurell et al., 2015; Dhammapala et al., 2006). In addition to the magnitude of emission rates, the spatial and temporal allocation of emissions is critical to sufficiently describing the fire smoke impacts (Larkin et al., 2012; Garcia-Menendez et al., 2014). In particular, plume rise height is important in terms of how fire emissions are transported and chemically transformed which impacts total residence time in the atmosphere and ambient pollutant levels (Paugam et al., 2016).

The relative composition and magnitude of emissions from fires varies due to meteorology, fuel type, combustion efficiency, and fire size (Urbanski et al., 2011; Wiedinmyer and Hurteau, 2010). Field data from specific and well characterized fires is critically important to improve emission estimation approaches for fires and plume transport in photochemical transport models. Field measurements have been made downwind of cropland burning, but rarely include information about the type of fuel burned, amount of fuel burned, and the area burned (Liu et al., 2016). In other studies, fuels are well characterized but lack downwind plume characterization (Washington State University, 2004; U.S. EPA, 2003). A field study in eastern Washington and northern Idaho in August 2013 consisted of multiple burns of well characterized fuels with nearby surface and aerial measurements including trace species concentrations, plume rise height and boundary layer structure (Holder et al., 2017). The ground-based, airborne and remote sensing data from this campaign provides a unique opportunity to assess how well a regulatory modeling system quantifies the air quality impacts of cropland residue fires by characterizing emissions and subsequent vertical plume transport.

Here, surface and aerial measurements taken during the August 2013 field study in eastern Washington and northern Idaho (Holder et al., 2017) are used to evaluate the cropland burning emission estimation approach (Pouliot et al., 2017) used to support regulatory air quality modeling. Field specific data were used in place of typical assumptions for regulatory modeling to evaluate how well plume rise and near-fire transport are characterized for cropland burning in the Pacific Northwest using the Community Multiscale Air Quality (CMAQ) model. The sensitivity of modeled plume rise is explored using CMAQ by varying input assumptions and using actual field data where possible. Analysis is focused on ground-based ($PM_{2.5}$ and CO) and downwind (CO) field measurements since information is available at the emission factor scale (ground level in-plume) and grid scale (aircraft downwind in-plume). Improved emissions and model approaches for cropland plume transport can help improve regulatory modeling (e.g., State Implementation Plans), forecasting systems (e.g., AIRPACT), and smoke management programs.

2. Materials and methods

2.1. Observations

All observation data used in this study were obtained from the crop residue burning field experiment in the Pacific Northwest (Holder et al., 2017). Fig. 1 shows the location of the Nez Perce and Walla Walla instrumented burns along with nearby wildland (wild and prescribed) fires. The Nez Perce burns were at higher elevation and closer to more complex terrain compared to the Walla Walla burns. Specific fields burned and nearby surface and aerostat measurements are shown for both Nez Perce in Fig. 2 and Walla Walla in Fig. 3. Four fields of Kentucky bluegrass and one field of winter wheat were burned in Nez Perce, Idaho during 19–20 August 2013 and three fields of winter wheat were burned in Walla Walla, Washington during 24–25 August 2013. Fields at Nez Perce were squares and similar in area. Burns happened in both the late morning and afternoon on August 19 and 20 at Nez Perce. The fields at Walla Walla were irregularly shaped and follow natural terrain features with roads used as fire breaks. The location, duration, field size, fuel type, and fuel load for each burn are listed in Table 1 with additional details in Table S1. Burn 7 was not sampled by the aircraft and not included as part of this analysis.

Aerial (aerostat and airplane) sampling was employed to measure $PM_{2.5}$ and gases including CO and carbon dioxide (CO_2) during the burning. Ground-based measurements of $PM_{2.5}$ were provided by multiple Environmental Beta Attenuation Monitors (EBAMs, Met One Inc., Grants Pass, OR) arrayed downwind of each burn measuring at 10-min and hourly average intervals. Remote sensing instruments were deployed to detect boundary layer height (ceilometer) and smoke plume top (lidar) (Kovalev et al., 2015). The location of ground monitors, aerostat, and remote sensing instruments are indicated in Figs. 2 and 3 and colored to match the field burned. The Modified Combustion Efficiency (MCE) was calculated as $\Delta CO_2 / (\Delta CO_2 + \Delta CO)$, where ΔCO_2 and ΔCO are the mixing ratio enhancements of these gases above background. MCE was used as a metric to subjectively describe fire as flaming (MCE > 0.95) or smoldering (MCE < 0.90). A detailed description of the field experiment including surface, aerostat, and aircraft observation data are provided in Holder et al. (2017).

2.2. Model configuration and inputs

The CMAQ model version 5.2 (Byun and Schere, 2006; Foley et al., 2010) was applied from August 18 to 28, 2013 to match the period of instrumented crop residue fires set in southeast Washington state and northern Idaho. The model simulated emissions, transport, and physical/chemical transformation of primary and secondary pollutants (e.g. O_3, $PM_{2.5}$) from all sources. Anthropogenic emissions (e.g. point, area, and mobile sources) were based on the 2011 version 2 National