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Emissions from residential combustion considering end-uses and spatial constraints: Part I, methods and spatial distribution

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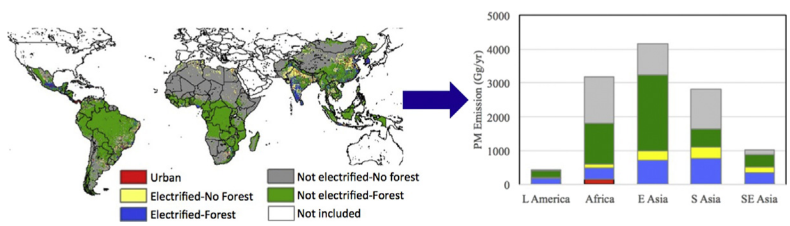
HIGHLIGHTS

- New method to distribute fuel consumption and emissions from household energy.
- Population density, forest boundaries, and nightlights used to classify land types.
- Cooking accounts for over half of fuel consumption.
- Method predicts higher emissions in areas near forests and without electricity.

GRAPHICAL ABSTRACT



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ABSTRACT

This study describes a framework to attribute national-level atmospheric emissions in the year 2010 from the residential sector, one of the largest energy-related sources of aerosol emissions. We place special emphasis on end-uses, dividing usage into cooking, heating, lighting, and others. This study covers regions where solid biomass fuel provides more than 50% of total residential energy: Latin America, Africa, and Asia (5.2 billion people in 2010). Using nightlight data and population density, we classify five land types: urban, electrified rural with forest access, electrified rural without forest access, non-electrified rural with forest access, and non-electrified rural without forest access. We then apportion national-level residential fuel consumption among all land-types and end-uses, and assign end-use technologies to each combination. The resulting calculation gives spatially-distributed emissions of particulate matter, black carbon, organic carbon, nitrogen oxides, methane, non-methane hydrocarbons, carbon monoxide, and carbon dioxide. Within this study region, about 13% of the energy is consumed in urban areas, and 45% in non-urban land near forests. About half the energy is consumed in land without access to electricity. Cooking accounts for 54% of the consumption, heating for 9%, and lighting only 2%, with unidentified uses making up the remainder. Because biofuel use is assumed to occur preferentially where wood is accessible and electricity is not, our method shifts emissions to land types without electrification, compared with previous methods. The framework developed here is an important first step in acknowledging the role of household needs and local constraints in choosing energy provision. Although data and relationships described here need further development, this structure offers a more physically-based understanding of residential energy choices and, ultimately, opportunities for emission reduction.

1. Introduction

Emission inventories, or tabulations of the amount of pollutants emitted to the atmosphere (USEPA, 2012), are required inputs

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to models of atmospheric chemistry and chemical composition (Dentener et al., 2006; NARSTO, 2005; Cofala et al., 2007; EMEP/EEA, 2009). As such, both present-day and future emission inventories of air pollutants are needed to study expected pollutant concentrations, impacts of emissions in one region on concentrations in another (Berge et al., 1999; Jacob et al., 1999; ApSimon et al., 2001), and climate change due to short-lived and long-lived pollutants (Mickley et al., 2004; Quinn et al., 2008; Shindell et al., 2009). These inventories also form baselines for studying policies or mitigation options that will be implemented to reduce air pollution or climate impacts.

Some illustrative studies have shown that introducing cleaner technology to reduce atmospheric carbonaceous aerosol and tropospheric ozone can benefit human health, air quality and climate (Anenberg et al., 2012; Shindell et al., 2012). In these studies, emissions were calculated at national level based on fuel consumption data, or, for larger countries, fuel consumption data at sub-national level. They assume that all polluting devices could be simply replaced. While these studies have demonstrated large potential benefits, a more mechanistic treatment of the factors underlying high emissions is needed to evaluate the plausibility of the proposed measures and to demonstrate the path to achieving them.

This study describes a framework to estimate emissions and mitigation potential from the residential sector. This sector is one of the largest energy-related sources of carbonaceous aerosol emissions (Bond et al., 2004a; Klimont et al., 2009, greater than the industrial, transportation, and power sectors. High emissions of air pollutants are primarily caused by incomplete combustion of solid fuel including wood, agricultural waste, dung, and coal (Bond et al., 2004b; EDGAR, 2012; GAINS, 2012). We therefore focus on regions where solid biomass fuel provides more than 50% of total residential energy— Latin America, Africa, and Asia—according to data from the International Energy Agency (2012a, 2012b). These regions account for 92% of global consumption of biomass in the residential sector and include most of the locations where the selection of residential fuels is driven by necessity rather than preference.

We place special emphasis on two factors that affect fuel and technology choice in the residential sector: end-uses (cooking, heating, and lighting) and spatial constraints. To give two simple examples of the importance of these factors, households that are distant from electrical service cannot meet their needs with electricity; and the availability of clean cooking stoves would not affect users who also need home heating.

In this work, we present a method to apportion the national-level fuel consumption used in large-scale emission inventories and projections among end-uses and locations with different resources. Household emissions can be calculated by estimating energy needed for end-uses as functions of physical drivers, as done by Daioglou et al. (2012) for carbon dioxide. The method presented here employs the national statistics used in most global emission inventories but adds a description of end-use and location of use. The calculation framework we describe is driven by the need to develop a method that is applicable in all countries, even those with sparse data. We therefore incorporate geographic information system (GIS) data on population, forest, and electrification to guide fuel and technology choice used in different locations within a country. The resulting framework gives a spatial distribution of fuel usage that allows exploration of feasible emission changes, and a spatial distribution of emissions to benefit models of atmospheric transport. This paper describes the methodology, and a companion paper (Winijkul et al., 2015) describes potential emission reductions. The results described here are limited by availability of data; we hope that by identifying major knowledge gaps in the present work, the framework we present can be updated and improved in the future.

Exposure to smoke from residential use of solid fuels contributes to chronic illnesses and acute health impacts such as early childhood pneumonia, emphysema, cataracts, lung cancer, bronchitis, cardiovascular disease, and low birth weight (Naeher et al., 2007; Zhang and Smith, 2007; Pope et al., 2015). The 2.1 million premature deaths annually (Rao et al., 2012) are concentrated among women and children in poorer households and rural populations, and have recently put preventive measures high on the agenda of international development and public health organizations (Baumgartner et al., 2011; Yu, 2011; Oguntoke et al., 2013). Although this work emphasizes emissions for atmospheric modeling, the framework developed here can also be useful for studies of health impacts by providing emission and reduction potentials of current available fuel and stove technologies in different parts of countries (Ezzati and Kammen, 2002; Mehta and Shahpar, 2004).

Emissions calculated are fine primary particulate matter with diameters smaller than 2.5 microns ($PM_{2.5}$), including its subcomponents black and organic carbon (BC and OC). Gaseous pollutants are also calculated: carbon monoxide (CO), carbon dioxide (CO_2), oxides of nitrogen (NOx), methane (CH_4), and non-methane hydrocarbons (NMHC) that are directly emitted from combustion sources. Several of these pollutants change together. Improving combustion tends to decrease all products of incomplete combustion (PM, EC, OC, CO, CH_4, and NMHC), although emission rates are not perfectly correlated and EC sometimes increases with better combustion. Products of incomplete combustion pollutants tend to be anti-correlated with NOx, which increases in better, hotter combustion. PM and NOx emissions are summarized in the main body of the paper, and other pollutants are discussed in Supplemental Information.

2. Methodology

2.1. Overview

The principle of our approach is that emissions in any location (x) are the sum of emissions from a number of end-uses (j), each of which is supplied with a number (k) of different fuels. We assume that a single device d, which may depend on location, is used for a given combination of fuel and end-use in each location. Emissions are calculated as:

$$Em(x) = \sum_j \sum_k P(x) \cdot f_{j,k}(x) \cdot \left(\frac{UE_j}{\eta_{j,k}(d(x))LHV_k} \right) EF_{j,k}(d(x)) \qquad (1)$$

where Em is emission in grams, P is the population, $f_{j,k}$ is the fraction of population for whom fuel k supplies end-use j, UE_j is the per-capita useful energy in MJ required for end-use j, $\eta_{\mathrm{j,k}}$ is the thermal efficiency of the device used, and LHV_k is the lower heating value of fuel k in MJ (kg fuel)$^{-1}$. The term in brackets gives the mass of fuel k used by one person for end-use j, required because most emission factors ($EF_{j,k}$) are measured in grams of pollutant per kilogram of fuel burned. Emissions (Em), population (P), and fuel fractions (f) depend on location. The values of $\eta_{\mathrm{j,k}}$ and $EF_{j,k}$ are specific to the combustion device d chosen for end-use j and fuel k, which in turn also depends on location. Emission factors and efficiencies for each fuel–stove combination are summarized in Table S1 and discussed further in Section 2.6.

The baseline analysis year is 2010, a common year for energy data and global geographic information system (GIS) databases, although projections from year 2000 were used for some data. The GIS maps used in this study will be discussed in Section 2.4.