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Emissions from residential combustion considering end-uses and spatial constraints: Part II, emission reduction scenarios

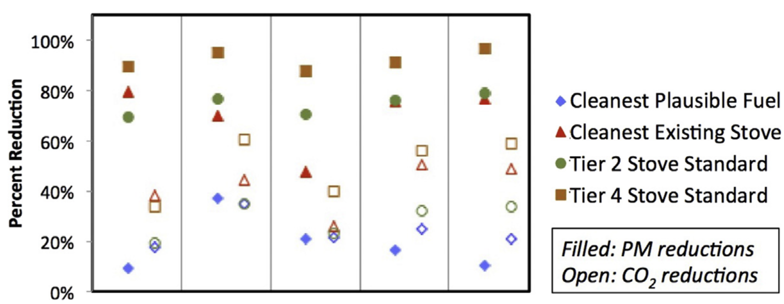
Ekbordin Winijkul, Tami C. Bond*

Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

HIGHLIGHTS

- Residential emission scenarios based on spatial distribution and end-use.
- Clean-fuel scenario reduces emissions by 18–25%, depending on pollutant.
- Stove improvements with existing technology reduce emissions by 25–82%.
- If stoves meet tightest performance standards, particulate matter is reduced by 95%.

GRAPHICAL ABSTRACT



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ABSTRACT

Cooking, heating, and other activities in the residential sector are major sources of indoor and outdoor air pollution, especially when solid fuels are used to provide energy. Because of their deleterious effects on the atmosphere and human health, multinational strategies to reduce emissions have been proposed. This study examines the effects of some possible policies, considering realistic factors that constrain mitigation: end-uses, spatial constraints involving proximity to forest or electricity, existing technology, and assumptions about user behavior. Reduction scenarios are applied to a year-2010, spatially distributed baseline of emissions of particulate matter, black carbon, organic carbon, nitrogen oxides, methane, non-methane hydrocarbons, carbon monoxide, and carbon dioxide. Scenarios explored are: (1) cleanest current stove, where we assume that existing technology in each land type is applied to burn existing fuels; (2) stove standards, where we assume that stoves are designed to meet performance standards; and (3) clean fuels, where users adopt the cleanest fuels plausible in each land type. We assume that people living in forest access areas continue to use wood regardless of available fuels, so the clean-fuels scenario leads to a reduction in emissions of 18–25%, depending on the pollutant, across the study region. Cleaner stoves preferentially affect land types with forest access, where about half of the fuel is used; emission reductions range from 25 to 82%, depending on the pollutant. If stove performance standards can be met, particulate matter emissions are reduced by 62% for the loosest standards and 95% for the tightest standards, and carbon monoxide is reduced by 40% and 62% for the loosest and tightest standards. Reductions in specific regions and countries depend on the existing fuel mixture and the population division among land types, and are explored for Latin America, Africa, East Asia, South Asia, and Southeast Asia.

* Corresponding author.
E-mail address: yark@illinois.edu (T.C. Bond).

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1. Introduction

Cooking, heating, and other activities in the residential sector are major sources of indoor and outdoor air pollution, especially when solid fuels are used to provide energy (Ezzati and Kammen, 2002; Mehta and Shahpar, 2004; Jetter and Kariher, 2009; Kim et al., 2011). In rural areas and resource-constrained countries, solid fuel can provide a large fraction of the household energy budget (Pandey, 2002; Tabuti et al., 2003; Bhatt and Sachan, 2004; Sumati, 2006). WHO (2006) estimated that more than three billion people depend on solid fuels (coal, charcoal, fuelwood, agricultural waste, and dung) to fulfill their basic household energy needs. High emissions from solid fuel combustion create indoor air pollution (Ezzati et al., 2000; Albalak et al., 2001), climate change and regional haze (Bond et al., 2004; Edwards et al., 2004; MacCarty et al., 2008; Ramanathan and Carmichael, 2008; Ramanathan et al., 2008). Deforestation by fuelwood collection is another pressing environmental problem in many regions (Bhatt and Sachan, 2004; Dovie et al., 2004).

Although the impacts may be severe, users at subsistence level are not expected to ameliorate them on their own. Thus, there has been attention from organizations that provide support to reduce negative impacts. Examples of current initiatives include the Global Alliance for Clean Cookstoves (UN foundation, 2013), which has set a goal of using clean and efficient stoves and fuels in an additional 100 million homes by 2020, and The World Bank (2013), which provides about $8 billion a year in financing to boost access to electricity, clean fuels, renewable energy, and energy efficiency.

Two basic approaches to achieving improvement are better stoves and cleaner fuels (Goldemberg et al., 2004; Bazilian et al., 2011; Foell et al., 2011; Lewis and Pattanayak, 2012; Pachauri et al., 2013). Since the 1980s, more efficient stoves have been introduced in China, India, and other parts of the world (Lu, 1993; Edwards et al., 2004; Kumar et al., 2013). The primary goal of early programs was to reduce deforestation, while improving health was a focus in later years (Boy et al., 2000; Edwards et al., 2004; Smith et al., 2007; Romieu et al., 2009). One of the most successful stove programs has been the Chinese National Improved Stove program, which introduced approximately 129 million improved biomass cookstoves into rural areas during 1982–1992, of which more than 100 million are still in use (Smith et al., 1993; Kumar et al. 2013).

Another approach to reduce the negative impacts of household energy is making cleaner, higher-efficiency fuels more accessible through subsidies or reduced fuel price. The factors that affect fuel switching are not fully understood. Even when liquefied petroleum gas (LPG) is subsidized, it usually does not replace fuelwood completely (Masera et al., 2000). Fuelwood is still used to cook some foods for both practical and cultural reasons. Fuel switching is triggered by a range of changes associated with development, urbanization, electrification, and education to some extent (Heltberg, 2004). Fuel choice and consumption decisions are also sensitive to fuel access and energy prices (Barnes et al., 2005).

Several studies estimate atmospheric or health impacts of residential fuel consumption, and some evaluate the benefits of changing fuels or stoves. Bhattacharya and Salam (2002) estimated that switching to biofuel, biogas, and gasifier stoves could provide 38–61% reductions in greenhouse gas emissions compared with traditional stoves used in Asian countries. GAINS (2012) estimates country-level emissions for present day until 2030. Grieshop et al. (2011) found that replacing traditional stoves with kerosene, LPG stoves, and improved stoves with fans could provide benefits to indoor health and global climate. UNEP (2011), relying on *GAINS* emission inventories, estimated that reducing black carbon through improved biomass stoves or switching to cleaner-burning fuels would deliver the greatest health and near-term climate benefits, compared with improving transportation, banning open burning of agricultural waste, or providing modern brick kilns and coke ovens. IEA (2010) estimated energy consumption reduction in a scenario called "Universal Modern Energy Access", in which universal access to cleaner fuels occurred by 2030. The Global Energy Assessment (Riahi et al., 2011) also suggested that final energy consumption would be significantly reduced with a shift from biomass to LPG, while greenhouse gas emissions would either remain constant or increase.

IEA (2010) and the Global Energy Assessment (Riahi et al., 2011) estimated that investment between $17 and $38 billion per year would be required, beyond IEA's reference scenario, in order to provide 100% universal access to clean cooking facilities, including electricity, LPG stoves, biogas systems or advanced biomass cookstoves in 2030 (Foell et al., 2011). To achieve the same target, Pachauri et al. (2013) estimated a requirement of $65–86 billion per year until 2030 and dedicated policies.

All of the studies discussed above infer emissions by combining measured emission factors and efficiencies with fuel consumption. Although the benefits of cleaner stoves, emission reduction policies, and fuel switching have been widely reported, other considerations related to feasibility have been neglected. Estimates of emissions and mitigation potential often rely on national aggregate data, not considering factors that vary between nations or within the nation. This paper is the second in a series that explores potential changes in emissions with constraints on plausibility guided by the spatial distribution of users and resources. It considers the appropriateness of cleaner stoves for the wide variety of residential end-uses, and the likelihood of adopting better fuels based on users' proximity to free fuels. This paper relies on the method for spatially allocating current fuel use and emissions among land types developed in a companion paper (Winijkul et al., 2015). Here, we examine the effects of hypothetical programs that could reduce current emissions, considering end-uses, current technology, and plausible assumptions about user behavior. We estimate emissions that have both local and global impacts: particulate matter (PM), black carbon (BC), and organic carbon (OC), carbon monoxide (CO), carbon dioxide (CO_2), nitrogen oxides (NOx), methane (CH_4), and non-methane hydrocarbons (NMHC).

2. Methodology

2.1. Overview of fuel allocation and emission calculation method

The detailed methodology describing spatial distribution of fuel consumption in the residential sector is discussed in a companion paper (Winijkul et al., 2015). Briefly, our distribution method hybridizes top–down calculations using national residential fuel consumption data from International Energy Agency (IEA, 2012a, b) and Fernandes et al. (2007), and bottom–up calculations of energy requirements for major end-uses in households. In each country, we classify five land types using population, forest, and nighlight data: Urban, Non-Forest access (URB); Electrified Rural with Forest Access (ERFA); Electrified Rural, Non-Forest access (ERNF); Non-electrified Rural with Forest Access (NRFA); and Non-electrified Rural, Non-Forest access (NRNF).

We calculate energy consumption for cooking, heating, and lighting end-uses, as well as a miscellaneous category called "Other." We then estimate the types and quantity of fuels used for each end-use. Next, we distribute fuels among land types and end-uses. In ERFA and NRFA, fuelwood is free and we assume it is preferentially used there. The highest efficiency fuels go to urban areas. In ERNF, without easy access to forest and with available electricity, we assumed that the next most efficient fuels are used, including fuelwood, but all of these fuels are purchased. Fuel consumption estimates in each country differ, but typical energy carriers in this land type include LPG, natural gas, and fuelwood. Finally, the least efficient fuels are distributed to NRNF, and tend to include coal, fuelwood, agricultural waste, and dung. A major assumption is that useful energy (energy that heats the pot or household) is consistent throughout the country for each end-use.

Finally, we calculate emissions using fuel-based emission factors (Equation (1)). The principle of our approach is that emissions in any location are the sum of emissions from a number of end-uses (j), each of which is supplied with a number (k) of different fuels. Thus,

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

where Em is emissions in grams, P is the population, $f_{j,k}$ is the fraction of population for whom fuel k is used for end-use j, UE_j is the per-capita useful energy in MJ required for end-use j, $\eta_{j,k}$ is the thermal efficiency of the device used, and LHV_k is the lower heating value of fuel k in MJ (kg fuel)$^{-1}$. $EF_{j,k}$ are emission factors measured in grams of pollutant per kilogram of fuel burned. The values $\eta_{j,k}$ and $EF_{j,k}$ are specific to the combustion device chosen for end-use j and fuel k (see Section 2.2). Population (P), devices chosen, per-capita useful energy for each end-use, and fuel fractions (f) also depend on location.

Many studies have reported emission factors from residential fuels and stoves. Choices of emission factors for traditional stoves in this study are summarized by Winijkul et al. (2015, Supporting information). Emission factors chosen for improved stoves are given in Table S1 (Supporting Information of this paper), while a brief history of measured emission factors for improved stoves is summarized here. The first large database of emission factors was developed by Zhang et al. (2000) for China and Smith et al. (2000a, b) for India. Bhattacharya and Salam (2002) measured improved biofuel, biogas, and gasifier stoves as well as traditional stoves. Emissions from fuels specific to China, including coal and agricultural waste, have been provided by Cao et al. (2008); Zhi et al. (2008); Shen et al. (2010); and Shen et al. (2013). More recent studies have measured a large number of stoves, with the purpose of choosing the best interventions (MacCarty et al., 2010; Jetter et al., 2012). With few exceptions, tests have been conducted in controlled laboratory settings. Because of more carefully controlled user operation and fuel quality, emission factors measured in laboratories are typically lower than those from field studies (Johnson et al., 2008; Roden et al., 2009), and there is presently insufficient evidence to conclude that percentage reductions observed in laboratory settings are representative of actual practice. When possible, emission factors are drawn from in-field measurements.

2.2. Emission reduction scenarios

We consider two general types of interventions: cleaner stoves and cleaner fuels. Serious mitigation efforts would rely on a combination of the two, so this division is exaggerated. We investigate these extremes to demonstrate where and how benefits are likely to occur from each type of mitigation. Emission scenarios are summarized in Table 1 and discussed in the following sections. In each scenario, we assume that the spatial distribution of energy required for each end-use remains the same, but stove efficiencies, emission factors, or fuels may change.

In the improved stove scenarios, we assume that the type of fuels consumed in each land type remains the same, and evaluate emission reductions from replacement of stoves that burn the same fuel with higher efficiency and, sometimes, lower emissions. These updated stoves have been broadly termed “improved stoves.” In the clean-fuels scenario, we evaluate emission reductions by providing cleaner fuels to some land types.

2.2.1. Improved stoves: cleanest current stove

In the “cleanest current stove” scenario, we alter the stoves in the baseline scenario to the cleanest existing stoves that are compatible with each land type, summarized in Table 2. Emission factors and efficiencies for the stoves chosen are summarized in Supporting Information (Table S1). Clean stoves may be used as interventions when people cannot or will not switch to cleaner fuels due to financial limitations, adherence to traditional cooking practices, or persistent availability of a competing fuel (Wijayatunga and Attalage, 2003; Barnes et al., 2005; Schlag and Zuzarte, 2008).

The criteria for inclusion is that stoves are commercially available and have broad acceptability demonstrated in at least one location. The highest efficiency stove for fuelwood is the improved stove with a fan, which can currently be used where electricity is available. This type of stove uses a small fan to introduce air either below or above the combustion chamber. The increased turbulence causes mixing and improves combustion, decreasing emissions (Witt, 2005; Philips, 2006; MacCarty et al., 2010; Raman et al., 2013). For land types without electricity, the cleanest current cookstove is one with a chimney. Chimneys remove exhaust from the home, although not from the ambient environment; they also improve combustion by inducing draft through the combustion chamber. Cookstoves improved by insulating the combustion chamber, but not adding a chimney or fan, have shown only modest improvements in field-based emissions or indoor air quality (Roden et al., 2009; Kar et al., 2012). Field-measured emission factors of improved coal stoves showed no significant difference from those of traditional stoves, so the same emission factors are used. For lighting, we assume a switch to hurricane lamps, which have lower emissions than kerosene wick lamps (Lam et al., 2012). Some stoves termed “improved” may increase combustion efficiency but yield higher emission per fuel burned (Smith et al., 2000b; Jetter and Kariher, 2009). Even so, total emission may decrease if fuel savings offset emission increases.

New technologies not considered here include photovoltaic and thermoelectric stoves that can generate electricity from the sun or the heat of combustion, respectively, operating fans without grid electricity (Champier et al., 2010; Champier et al., 2011; Kumar et al., 2013; O'Shaughnessy et al., 2013). These fan-assisted stoves could be used in both electrified and non-electrified land types. Another novel technology is the semi-gasifying stove, in which release of volatile matter from fuelwood is spatially separated from combustion (MacCarty et al., 2010; Varunkumar et al., 2012; Kumar et al., 2013). Although these promising stoves can have low emissions and high efficiency, the persistence of use has not yet been demonstrated in large programs.

2.2.2. Improved stoves: stove standards

To promote good stove performance and guide international replacement programs, there have been efforts to set standards for efficiency and emission (ISO, 2012), summarized in Supporting Information (Table S2). One current rating system is known as the International Workshop Agreement (IWA), produced through a process led by the International Organization for Standardization (ISO), hereafter ISO-IWA. It provides ratings in four Tiers. Similar to automobile standards, the higher the Tier, the lower the emission and the higher the efficiency. The Tiers were set by considering performance relative to a three-stone fire, and by estimating room concentrations relative to the World Health Organization

Table 1
Emission Reduction Scenarios Explored in this Work.

Scenario	Major assumptions
Improved Stoves: cleanest current stove	Cleanest existing stoves in each land type and fuel for all end-uses
Improved stoves: stove standards	Stoves that meet performance standards for cooking, water heating, and heating end-uses
Clean fuels: fuel switching	Switching to electricity in electrified areas and LPG in non-electrified areas, except when free fuels are available[a]

[a] Free fuels refer to fuelwood in forest access areas, and agricultural waste and dung in rural areas.

Table 2
Improved stove technologies assumed for the "Cleanest Current Stove" scenario. The same technology is used in electrified and non-electrified land types unless stated. Emission factors and efficiencies, whose values are given in Table S1, are based on laboratory measurements unless indicated. Tier values (Tx/Ty) refer to standards that the stoves would meet for efficiency (Tx = Tier x) and PM emissions (Ty = Tier y), as discussed in Section 2.2.2.

Fuel	Improved stove technology
End-use: *cooking and other*	
Fuelwood: electrified land types	Ceramic composition materials for inner wall of combustion chamber and fan to provide primary and secondary air[a] (Tier 3/3), with flue
Fuelwood: non-electrified land types	Insulated combustion chamber to increase combustion efficiency; stove with flue[b] (in-field emission factors, Tier 2/0)
Natural gas	Infrared head (circular device to convert heat to radiation), without flue[c]
LPG	Infrared head (see above), without flue[c]
Coal	Galvanized flue pipe and ceramic chamber with cast iron ring[d] (laboratory emission factors with ignition period included, Tier 2/0)
Charcoal	Insulated combustion chamber, slanted pot rests and equally distributed holes on a grate[e] (Tier 2/2)
Agricultural waste	Metal with equally distributed holes on a grate without flue[f] (Tier 1/0)
Dung	Stove made with metal with equally distributed hole on a grate without flue[g] (Tier 2/0)
All others, including kerosene	No change in technology
End-use: *space heating*	
Fuelwood	USEPA certified catalytic fireplace woodstove[h] (Tier 4/4)
All others, including coal	No change in technology
End-use: *lighting*	
All fuels: electrified land types	Electricity
All fuels: non-electrified land types	Kerosene Hurricane Lamp[i]

[a] Philips (2006) and MacCarty et al. (2008).
[b] Johnson et al., (2008) and Roden et al., (2009).
[c] Zhang et al. (2000).
[d] Zhi et al., (2008); Zhi et al. (2009).
[e] Bhattacharya et al. (2002).
[f] Joshi et al. (1989) and Smith et al. (2000b).
[g] Joshi et al. (1989) and Venkataraman and Rao (2001).
[h] Houck and Tiegs (1998), McDonald et al. (2000), and USEPA (2013).
[i] Lam et al. (2012).

guidelines (World Health Organization, 2010). The highest Tiers are aspirational rather than demonstrated, as many improved stoves in wide use do not achieve the goals set by the standards.

In this work, we explore the implications of achieving each Tier for cooking stoves. These standards affect efficiencies and emissions only for solid-fuel stoves, because other fuels are cleaner and more efficient than Tier 4 standards.

We applied the ISO-IWA standards to stoves for cooking and other end-uses for efficiency and for emissions of CO and CO_2, and PM. These standards are independent of fuel, and other pollutants are not specified by the standards. The ISO-IWA standards do not address heating stoves, so we applied standards existing in China that govern heating end-uses of biomass and coal. These standards regulate stove efficiency and PM, NO_X, and CO emissions. To approximate Tier 1 and Tier 2 standards, we apply Chinese national standards (People's Republic of China (2012)), and to match Tier 3 and Tier 4 standards, we apply the tighter standards applied by the City of Beijing (2008). Values of emission and efficiency standards for both cooking stoves (ISO-IWA) and for heating stoves (Chinese standards) are listed in the Supporting Information (Tables S2 and S3, respectively). The treatment here assumes that stoves used for heating are separate from those supplying cooking. In practice, both needs may be supplied with the same stove.

The stove-standard scenarios differ from the cleanest-current-stove scenarios in two general ways. First, when a standard for a particular stove is cleaner than present technology, choosing that scenario implies a forcing of technology that does not yet exist or is not yet widely accepted. Second, when emission or efficiency standards are poorer than those of existing devices, policies relying on standards allow higher emissions than those that specify technology. There is some overlap between the cleanest-current-stove scenario and the stove-standard scenarios, yet these scenarios represent different approaches to policy, similar to the "Best Available Control Technology" and emission-standard approaches employed in the United States.

2.2.3. *Clean fuels: fuel switching*

The Fuel Switching scenario illustrates the assumption that the cleanest plausible fuels are made available to users, and that the plausibility of adoption differs by land type. This scenario assumes either that users can already afford these clean fuels or that a policy mechanism makes them financially accessible, and that distribution and supply are developed to ensure availability. Because emphasis is on providing clean fuels rather than improving stove quality, traditional stoves are still used for the new fuels, with efficiency and emission factors as discussed in the companion paper (Winijkul et al., 2015, Table S1).

A major assumption is that fuelwood in forest access areas, dung, and agricultural waste are free, disregarding the value of the users' time in collecting them, so that users do not switch even to clean fuels whose price is reduced. For cooking, heating, and other end-uses, we assume that users of kerosene, coal, firewood or charcoal switch to electricity if it is accessible (electrified land types), or *LPG if it is not*. Electricity and kerosene are used for lighting in electrified and non-electrified areas, respectively, as reported by Zhou et al. (2009), Miah et al. (2010), and Gwavuya et al. (2012). Specific assumptions are summarized in Table S4.

3. Results and discussion

In this section, we compare emissions under each reduction scenario. Emission changes by land type are discussed in Section 3.1. Section 3.2 discusses emissions grouped into five world regions: Africa, Latin America, East Asia, South Asia, and Southeast Asia. National emission reductions are discussed in Section 3.3. Information needed for improving emission estimates is discussed in Section 3.4.

CO_2 emissions are affected only by efficiency. A similarity between reduction levels for CO_2 and for another pollutant indicates that the main improvement is caused by lower fuel use; if the reduction levels are very different, improved combustion has also played a role. When improved combustion reduces products of incomplete combustion, many pollutant reductions are similar to PM. NOx behaves differently; emission per unit fuel burned may increase with stove efficiency and hotter combustion. Therefore, we discuss mainly CO_2, PM, and NOx reductions here, with other pollutants summarized in the Supplemental Information (Figs. S1–S15). However, the residential sector produces just 4% of global NOx emissions (IIASA, 2012; EDGAR, 2012), so reductions of that pollutant are discussed in less depth.

3.1. Overall emission reduction

Fig. 1 summarizes overall emission reductions for fuel-switching and cleanest-current-stove scenarios for the study region, as well as stove standard scenarios. Each figure shows emissions of PM in five land types in a cumulative manner; that is, the level of emissions shown for each land type is equal to emissions in that land type plus all land types to the left. Total emissions under each scenario are the emission values at the farthest right. The change in emissions in a particular land type can be determined by comparing the size of the steps between the scenario and the baseline. A comparison of reductions in pollutants over all land types also appears in each figure.

The upper panel in Fig. 1 compares global emissions of PM in three scenarios: baseline, cleanest-current-stoves ("Stoves"), and fuel-switching ("Fuels"). Baseline emissions and reduction of PM in urban areas (URB) are low in absolute magnitude because of the efficient fuels already used there. Relative reductions in the Fuels and Stoves scenarios are large, 99% and 91%, respectively, because the cleanest fuels and stoves can be introduced there.

Cleaner fuels cause a 24% PM reduction overall. Much of this change can be attributed to a shift toward greater efficiency, rather than an improvement in combustion. CO_2 emissions change by almost the same amount (26% overall) and other products of incomplete combustion have similar shifts, with a 32% overall reduction in CO and a 20% reduction in NMHC. These measures have the greatest effect in areas where fuel switching is assumed, outside of land types with forest access. More than 75% of the 3669 Gg reduction in PM occurs in ERNF and NRNF, and for all other pollutants except NOx, 69–82% of the reduction occurs in those two land types.

Cleaner stoves, in contrast, preferentially affect land types with forest access, where about half of the fuel is used and fuel switching is assumed to be ineffective. The cleanest-current-stove scenario gives an overall PM reduction of 72%. Other pollutants except for NO_x are reduced by 39–76%. Efficiency improvements are largely responsible for these changes, as CO_2 emissions decrease by 39%. Products of incomplete combustion decrease by more than CO_2 because of better combustion with lower emission factors.

Unlike products of incomplete combustion, NOx emissions might increase as combustion improves because it is produced, in part, by hotter combustion. However, in the cleaner-fuels and cleanest-current-stove scenarios, NOx emissions decrease by 16% and 28%, respectively, largely driven by the decrease in fuel consumption without a large increase in NOx emission factor. NOx emissions increase in only one land type (NRNF) under the fuels scenario, caused by switching to LPG, which has a higher NOx emission factor.

The lower panel of Fig. 1 summarizes emission changes under the stove-standard scenarios. Only PM, CO, and CO_2 are discussed here because there are no standards for the other pollutants. Tier I stoves, the lowest level of improvement, are not as good as the cleanest current stoves. Tier I stoves result in PM reductions of 64%, CO reductions of 40%, and CO_2 reductions of only 5%. Tier II stoves are much better than Tier I stoves in terms of efficiency, resulting in large emission reductions of all pollutants, and an overall reduction greater than the cleanest-current-stove scenario. Compared with Tier II, Tier III and Tier IV stoves also make efficiency advances; the CO_2 reductions are 29%, 43%, and 51%, respectively. The higher Tiers make aggressive PM reductions of 81%, 91% and 94% for Tiers II, III and IV. However, for CO, comparative decreases beyond Tier II are lower than CO_2 percentage reductions. CO emissions for cooking stoves are specified as emissions per liter of water boiled, rather than per amount of fuel burned. Efficiency decreases are more than sufficient to satisfy the CO emission standards.

For the stove standard scenarios, 62% of PM emission reductions occur in NRFA and NRNF land types, where most of the solid fuel is used. In ERFA, improved stoves with fans reduce emissions relatively more than the stove alternatives in land types without electricity. In contrast, when cookstove standards are assumed to be achievable regardless of current technology, a noticeable efficiency increase and emission reduction occurs in all Tiers. Greater emission reduction in cookstove standard scenario is found in the two non-electrified land types (NRFA and NRNF) where solid fuels are most prevalent.

In all regions included in this study, cooking standards provide the highest emission reduction because they account for energy consumption and emission in both cooking and other end-uses. The overall PM emission is reduced by 77% and 3% by applying Tier 2 cooking and heating stove standards, respectively. With Tier 4 standards, PM emission reduction of 88% in cooking and 5% in heating can be achieved. For lighting, only 1% of PM emission reduction is caused by switching simple wick lamps to hurricane lamps.

3.2. Regional emission reductions

World regions differ in the types of fuels used, the availability of forests and electricity, and the prevalence of each land type. In this section, we discuss the effectiveness of each scenario in five major world regions. Fig. 2 summarizes PM and CO_2 emission reductions in four scenarios for PM (filled symbols) and CO_2 (open symbols). The "total" graph (upper right in Fig. 2) covers the entire study region and corresponds to the data in Fig. 1. The figures show the fuel-switching scenario and the cleanest-current-stove scenario. They also include Tier II stove standards, which achieve significant reductions (Fig. 1), and the aspirational Tier IV stove standards. Tier I standards, which gave little reduction, and the intermediate Tier III standards are excluded to avoid clutter. For context, Fig. 2 also indicates the absolute magnitude of baseline emissions (first and third rows). A combination of high emissions and large reductions

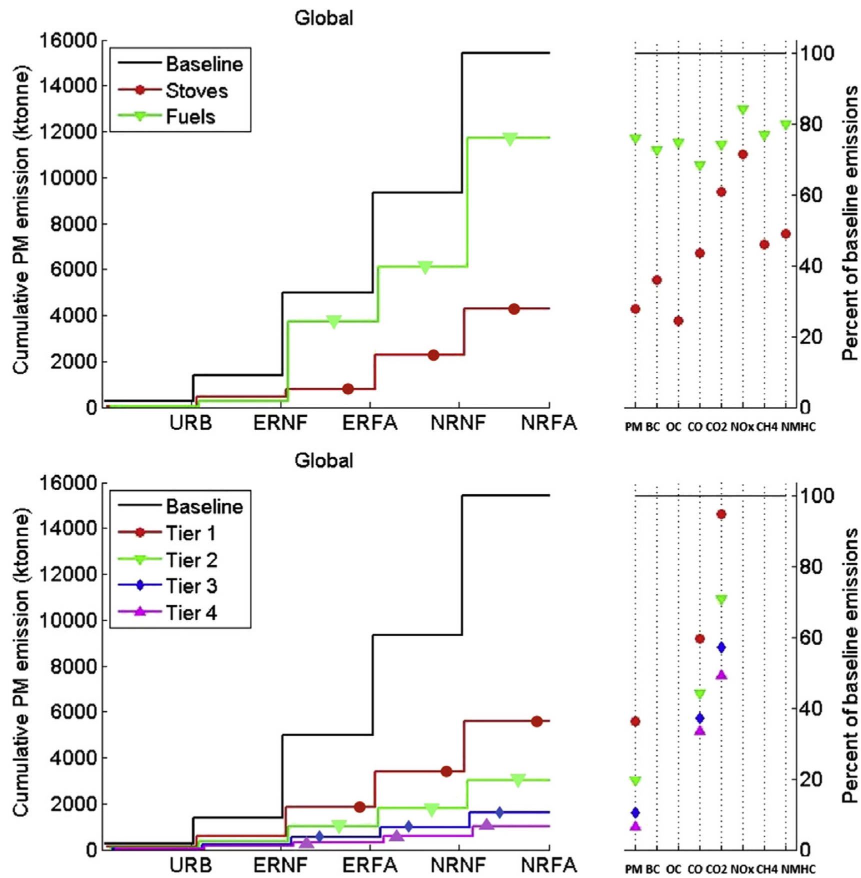

Fig. 1. Emission reductions in the entire study region for fuel-switching and cleanest-current stove scenarios (top) and stove standard scenarios (bottom). Each figure shows cumulative emissions over five land types; that is, the level of emissions shown for each land type is equal to emissions in that land type plus all land types to the left. Right panels show the total percent of baseline emissions for eight pollutants (top) and for the four pollutants affected by stove standard scenarios (bottom).

indicates a greater mitigation potential.

Latin America: In Latin America, modern fuels are already widespread, especially in urban land types. The largest fuel consumption and remaining emissions are in forest access areas, where we assume that fuel switching has little effect. Fuel switching reduces PM emission by more than 69% in NRNF with a switch from fuelwood to LPG.

With clean stove scenarios, large CO_2 and PM emission reductions occur in ERFA and NRFA. There is a greater reduction when fan-assisted improved stoves can be used (ERFA compared with NRFA). In this region, some land types (URB, ERNF, and NRNF) have higher reductions in the cleanest-current-stove scenario than in the Tier 4 scenario. The reason is that present-day advanced fuels, like LPG, already meet Tier 4 standards without requiring improvement in combustion devices. In all cases, PM is reduced much more than CO_2. If the assumptions used in these scenarios are correct, clean-stove interventions will do more to reduce emissions and energy consumption throughout Latin America than will fuel-switching.

Africa: In Africa, most energy consumption and emission occur in non-electrified rural areas (NRNF, NRFA). Fuelwood is a primary energy source, accounting for 75% of consumption in this region. Fuel switching greatly reduces CO_2 and PM in areas without forest access; reductions are nearly 100% in URB and ERNF, and 57–76% in NRNF for CO_2 and PM.

Fuelwood use persists in areas with forest access, ERFA and NRFA. Clean-stove scenarios produce large reductions in PM (98% and 97%, respectively, for Tier 4) and also reduce energy consumption. Although most pollutants are reduced, NOx emission sometimes increases with combustion efficiency. In Africa, a mix of fuel-switching and clean stoves will be required to reduce emissions, depending on the land type.

East Asia: East Asia has high total energy consumption because of its population. Primary energy sources are fuelwood, agricultural waste, and coal. Heating end-use has a relatively higher share compared with other regions. The largest fuel consumption occurs in forest access areas, where Tier 4 scenarios have the greatest effect (86% and 91% in ERFA and NRFA, respectively). Clean fuels reduce PM emissions by 58% in ERNF, where coal and agricultural waste are switched to electricity. They have less effect than clean stoves in other areas, including NRNF, where the majority of the fuel is agricultural waste and no switching occurs. The cleanest-current-stove scenario also reduces PM emissions in NRNF by 42%, while CO_2 reduction ranges from 11 to 41% in all land types. Overall, clean stoves—especially Tier 4 stoves—provide the greatest emission reduction. Not considered in the clean-fuels scenario, however, is the use of coal briquettes that are prevalent throughout China.

South Asia: Most PM emissions in South Asia come from biomass: fuelwood, agricultural waste, and dung. Unlike most other regions, fuel consumption and emissions are about evenly spread among the four rural land types. Clean fuels are effective where they can be distributed, reducing 97% of the PM emission in ERNF. Fuel switching provides little or no reduction in the other land types because of persistent solid-fuel use. In forest-access land types, fuelwood consumption provides 98% of energy, and in NRNF,

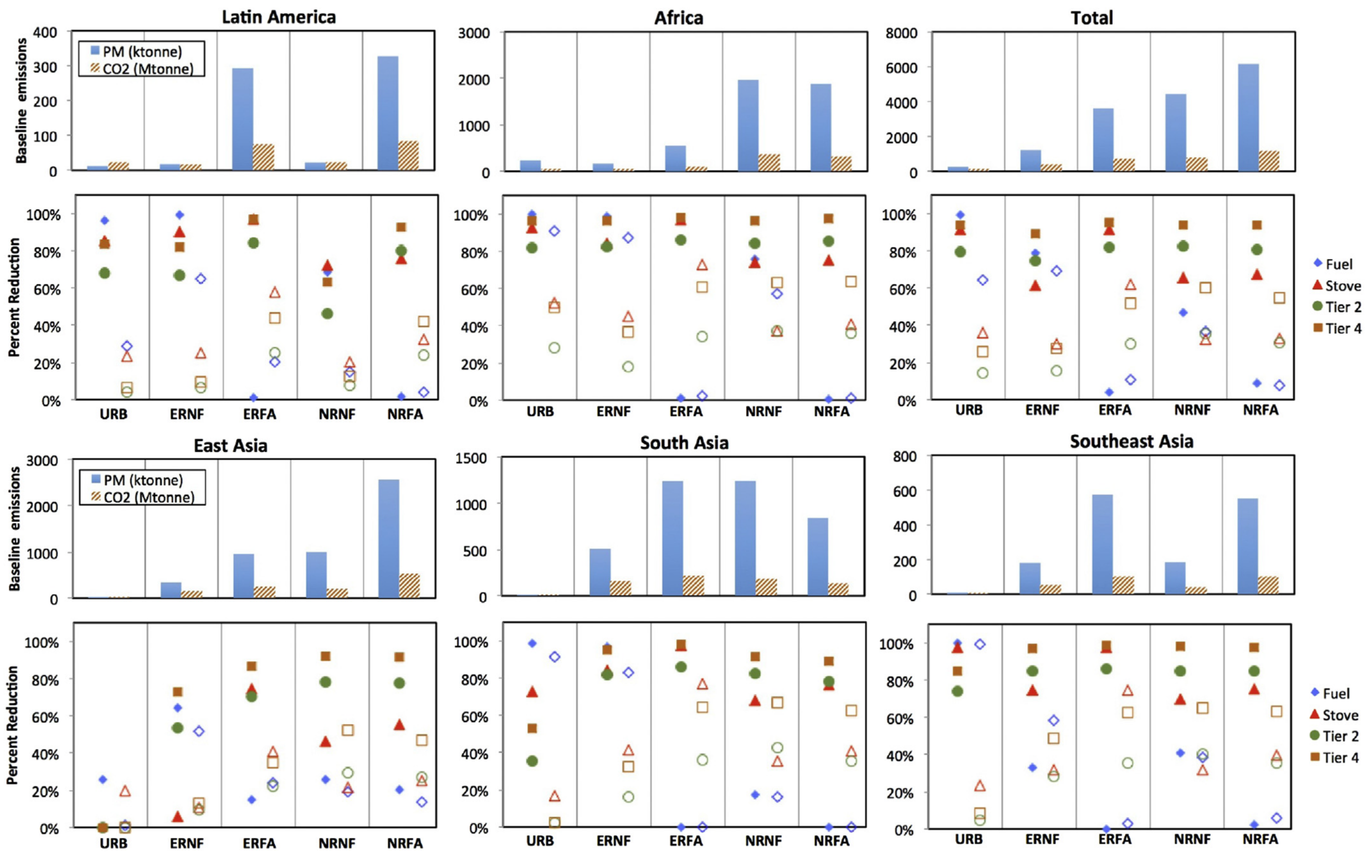

Fig. 2. Mitigation potential for PM and CO_2 in each land type under four scenarios: fuel switching (Fuel), cleanest-current-stove (Stove), and Tier 2 and Tier 4 stove standards. First and third rows: Baseline emissions of PM and CO_2, indicating locations of greatest emission requiring reductions. Second and fourth rows: Percentage reductions of PM (filled symbols) and CO_2 (open symbols) for each region. CO_2 emissions may be considered a proxy for energy consumption. Land types are Urban (URB); Electrified Rural with Forest Access (ERFA); Electrified Rural, Non-Forest access (ERNF); Non-electrified Rural with Forest Access (NRFA); and Non-electrified Rural, Non-Forest access (NRNF).

agricultural waste and dung use accounts for 76%. In the cleanest-current-stove scenario, PM emissions are reduced by 98%, 68%, and 77% in ERFA, NRNF, and NRFA respectively; these improvements are much more than the decrease in CO_2 emission, so that PM reductions can be attributed to both efficiency and emission improvements. Tier 4 stoves achieve 89–98% PM reductions in all rural land types.

Southeast Asia: In Southeast Asia, the main energy sources are fuelwood and agricultural waste. Emissions and fuel consumption are higher in forest access areas, with 68% of the total emissions in ERFA and NRFA. In forest access land types, fuelwood supplies more than 88% of total consumption. In ERNF and NRNF, agricultural waste is the major fuel. For this reason, clean stove scenarios make a greater difference in total emissions. For PM, 98% reductions are achieved in both ERFA and NRFA in the Tier 4 scenario. Fuel switching is most effective in NRNF where the reduction is around 40%. For CO_2, the fuel-switching scenario produces a higher reduction than any stove scenario in URB and ERNF.

3.2.1. *Summary of regional emission reductions*

Fig. 3 summarizes current baseline emissions and emission reductions in each region across all land types. Because of the large number of people, and hence emissions, in forest access areas, our assumptions lead to the finding that cleaner stoves are more likely to yield major reductions in particulate matter emissions than cleaner fuels. Tier 2 stove standards generally perform better than the cleanest current stoves; even this modest reduction would produce emission benefits. Tier 4 stove standards yield the maximum benefit among all scenarios. These devices, however, are not yet proven with real users.

In the cleanest-current-stove scenario, improved stove efficiency decreases LPG and fuelwood consumption in all regions. East

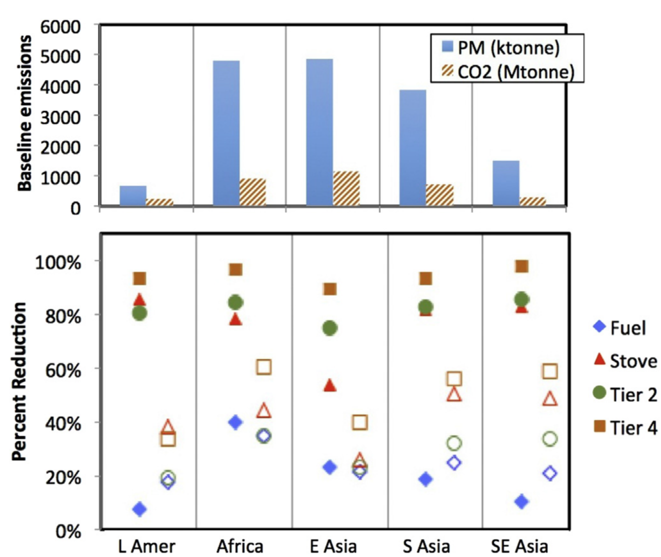

Fig. 3. Mitigation potential for regional emissions under four scenarios. Top: Baseline emissions of PM and CO_2 in five regions, for context. Bottom: Reductions of PM (filled symbols) and CO_2 (open symbols) for each region under four scenarios: fuel-switching (Fuel), cleanest-current-stove (Stove), and Tier 2 and Tier 4 stove standards.

Asia has a lower energy reduction compared with other regions, because heating stoves have a greater contribution in that region and efficiency improvements have a lower impact. For Africa, the energy reduction is lower because more fuelwood is used in non-electrified land types, where more efficient stoves with fans cannot be used.

Table 3 summarizes the changes in use of the main energy carriers under each scenario. In the fuel switching scenario, electricity consumption increases (28–112%) and fuelwood consumption decreases (0–44%) in all regions. In Africa and East Asia, LPG consumption increases to fulfill demand in non-electrified areas. In Latin America, South Asia, and Southeast Asia, the provision of electricity in electrified areas frees LPG for distribution to outlying areas, and existing LPG consumption is sufficient to provide energy to users in the remaining non-electrified land types.

3.3. National emission reductions

The preceding discussion emphasized emission improvements in broad geographical areas. However, because of differences in current fuel availability and use, benefits vary among nations. Particulate matter emission reductions in each country are summarized in Fig. 4 for three scenarios: cleanest current stove, Tier 2 stove standard, and fuel switching. Also shown in the figure is the fraction of remaining PM emissions from the highest emitting fuels: coal, charcoal, fuelwood, agricultural waste, and dung. This division demonstrates that for all scenarios and regions, emissions from the residential sector are still largely driven by solid-fuel combustion. The division also provides additional insight into the differences among regions.

In the cleanest-current-stove scenario, regional variation among countries can be seen in Asia where most countries achieve more than 60% PM emission reduction, except for countries in East Asia. Because high biomass consumption occurs in most of Asia, cleaner stoves reduce emissions. However, the lower emission reduction in East Asia occurs because heating consumes a large portion of energy, and this scenario does not include improved heating stoves. In the Tier 2 scenario, the effect of stove standards upon heating stoves becomes apparent in China and Mongolia.

In the fuel switching scenario, high variation among country emission reductions is found in Africa. Low emission reduction (less than 20%) occurs in countries whose baseline consumption of clean fuels like LPG is already high. Countries with high consumption of both fuelwood and agricultural waste also have low reductions, since fuelwood fills needs in areas with forest access, and agricultural waste fills needs when forests are distant. The highest reduction, more than 80%, is found in countries where fuelwood is a dominant source and there is little to no consumption of other solid biomass.

Table 3
Changes in consumption of fuels in two mitigation scenarios, compared with the baseline scenario.

Region	Percentage change[a] in fuel consumption				
	Cleanest current stove		Fuel switching		
	LPG	Fuelwood	Electricity	LPG	Fuelwood
Latin America	−15	−52	+28	−38	−6
Africa	−15	−49	+79	+197	−44
South Asia	−15	−55	+112	−73	−24
East Asia	−12	−49	+41	+36	0
Southeast Asia	−15	−54	+47	−48	−11

[a] Positive change means increase in energy consumption from the baseline scenario.

A combination of cleaner stoves and cleaner fuels is necessary to reduce emission in most countries. Pie charts in each of the scenarios demonstrate the fuels that have residual emissions after the scenario is implemented. Fuel switching provides large emission reduction from fuels that are not free, such as coal and charcoal, while cleaner stoves provide higher emission reduction when free fuels are used.

4. Summary and outlook

This study examined residential emissions and the potential for reduction when end-uses and surrounding resources were considered both in placing the initial emissions and in determining plausible mitigation strategies. Three emission reduction scenarios were studied: cleanest current stove, stove standard, and fuel switching. In the cleanest-current-stove scenario, we altered the stoves in the baseline scenario to the cleanest existing stoves compatible with each land type. In the stove standard scenario, we assumed that heating stoves and cooking stoves met existing performance standards. In the fuel-switching scenario, we assumed that users adopt the cleanest plausible fuels governed by land type.

In forest access areas (ERFA and NRFA), our assumption that fuelwood is free and its use is persistent leads to the finding that cleaner-stove scenarios are required to reduce energy consumption and emissions. On the other hand, when fuelwood is not free (URB and ERNF), the fuel-switching scenario reduces energy consumption and emissions more than clean-stove scenarios. In all regions, clean stove scenarios yield larger emission reductions than fuel switching scenarios. This finding is a result of the assumptions that wood fuel is used in forest access areas, and that people in these areas will not switch to cleaner fuels even if they are available. In NRNF, with the most diverse assumed fuel mix, the change in energy consumption varies among scenarios.

If the assumptions given here are broadly correct, then a combination of cleaner stove and fuel switching scenarios is required to achieve maximum reduction across all land types. Variations among nations are found within the same region, depending on the fuel mix and location of the largest population. These dissimilarities point to the need to consider national and sub-national circumstances when estimating causes of and reduction measures for emissions and energy consumption in the residential sector.

This work provides a preliminary framework to estimate emission reductions from the residential sector, considering resources and end-uses. Despite the importance of this sector for pollutant emissions on a global scale, data on household energy use are limited, leading to uncertainties in these mitigation estimates. Here, we summarize needs for information that could support studies like this one.

Success of improved stove programs. For the study year of 2010, we assume that all current stoves are traditional. Many improved stove programs are in place (Urmee and Guamfi, 2014), for example in China (Smith et al., 1993; Kumar et al., 2013), India (Venkataraman et al., 2010; Kumar et al., 2013), Zimbabwe, and Haiti. In previous decades, replacement cookstoves were designed with chimneys to remove smoke from the home, but emissions and efficiency were not markedly improved, and thus these programs had little effect on baseline emissions. With recent focus on stove technology development and an increase in large programs, emissions and efficiency of updated stoves will alter the baseline calculation in the coming years. Measurements of sustained adoption beyond the program lifetime, and evaluation of in-use emission and efficiency of these improved stoves, will be required to estimate the actual impact of these programs.

Fuel type. For consistency with other studies, we used national biomass consumption data given by *IEA* (2012a, b). These data are

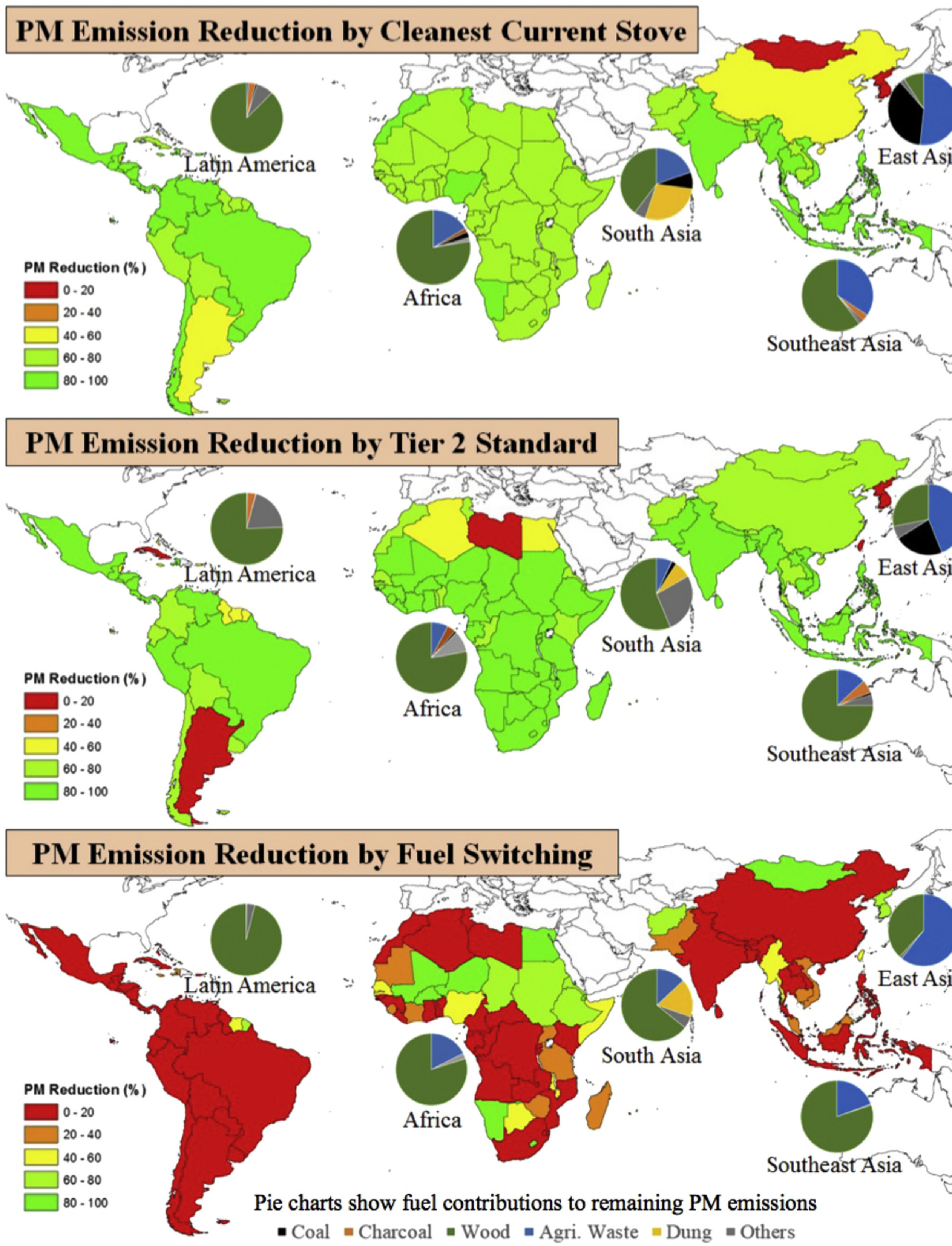

Fig. 4. PM emission reductions by country for three scenarios. Pie charts indicate fraction of emission from different fuel types remaining in each region after the emission reductions.

given only as total biomass, and we allocated them among fuelwood, agricultural waste, and dung by using data from other studies (Winijkul et al., 2015). Each of these fuels requires different stove designs to improve combustion and reduce emissions. Data on consumption by fuel type, as well as stoves designed to improve emissions and efficiency of mixed fuels, would inform both the baseline and mitigation estimates.

End use. There is very little information on energy required for household end-uses, and the division provided here was based on only a few observations. The large fraction allocated to "Other" uses in some regions indicates that household use is not well understood. This lack of knowledge implies that interventions targeting cooking or heating alone may not provide sufficient services to displace household uses completely.

Realistic emission factors and stove efficiencies. We used average stove efficiencies and emission factors for each stove and fuel. Reported emission factors may vary by factors of three or more, and stove performance is not understood well enough to determine whether this range reflects variability between homes or between regions. Emission factors are greater when measured in household settings than in laboratories, and in-field emission measurements are available only for wood and coal. Neither are in-field efficiency and emission measurements for advanced technologies such as fan stoves.

Inclusion of advanced technologies. Development of cooking and heating stoves is now occurring rapidly given increased attention and funding. Existing measurement datasets do not include the latest coal heating stoves in China or biomass cookstoves with gasification, among others.

Causes of fuel and stove switching. We have assumed that programs can achieve full replacement of fuels or stoves, governed only by availability, which in turn is affected by land type. Household decisions about energy consider many factors, including income, tradition, and other benefits of the fuels or technologies chosen. Greater understanding of these decision factors will lead to more realism in estimating mitigation potential.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at http://dx.doi.org/10.1016/j.atmosenv.2015.10.011.

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