Transient climate and ambient health impacts due to national solid fuel cookstove emissions

Forrest G. Lacey[a,1], Daven K. Henze[a], Colin J. Lee[b], Aaron van Donkelaar[b], and Randall V. Martin[b]

[a]Department of Mechanical Engineering, University of Colorado, Boulder, CO 80309-0427; and [b]Department of Physics and Atmospheric Science, Dalhousie University, Halifax, NS, Canada B3H 4R2

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Residential solid fuel use contributes to degraded indoor and ambient air quality and may affect global surface temperature. However, the potential for national-scale cookstove intervention programs to mitigate the latter issues is not yet well known, owing to the spatial heterogeneity of aerosol emissions and impacts, along with coemitted species. Here we use a combination of atmospheric modeling, remote sensing, and adjoint sensitivity analysis to individually evaluate consequences of a 20-y linear phase-out of cookstove emissions in each country with greater than 5% of the population using solid fuel for cooking. Emissions reductions in China, India, and Ethiopia contribute to the largest global surface temperature change in 2050 [combined impact of −37 mK (11 mK to −85 mK)], whereas interventions in countries less commonly targeted for cookstove mitigation such as Azerbaijan, Ukraine, and Kazakhstan have the largest per cookstove climate benefits. Abatement in China, India, and Bangladesh contributes to the largest reduction of premature deaths from ambient air pollution, preventing 198,000 (102,000–204,000) of the 260,000 (137,000–268,000) global annual avoided deaths in 2050, whereas again emissions in Ukraine and Azerbaijan have the largest per cookstove impacts, along with Romania. Global cookstove emissions abatement results in an average surface temperature cooling of −77 mK (20 mK to −278 mK) in 2050, which increases to −118 mK (−11 mK to −335 mK) by 2100 due to delayed CO_2 response. Health impacts owing to changes in ambient particulate matter with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$) amount to ∼22.5 million premature deaths prevented between 2000 and 2100.

aerosols | climate | human health | cookstoves | atmospheric modeling

Globally over 3 billion people presently use solid fuel for meal preparation (1). The extent of this activity and the associated air quality pollutant emissions have led to numerous cookstove intervention studies and programs, such as the Global Alliance for Clean Cookstoves work to implement 60 million clean cookstoves by 2017 (cleancookstoves.org/about/news/11-20-2014-market-enabling-roadmap-phase-2-2015-2017.html). A primary goal of these efforts is to improve indoor air quality, estimated to cause ∼4.3 million premature deaths annually, along with enhancing livelihood of woman and children via reprieval from fuel collection and other solid fuel cooking-related tasks (2).

The magnitude of the emissions of aerosols, aerosol precursors, and greenhouse gases from solid fuel use has also motivated studies of the impact of these emissions on climate and ambient air quality. An estimated 370,000–500,000 global premature deaths in adults occur annually owing to ambient exposure to fine particulate matter associated with residential cookstoves (3–5), and there are as many as 1.0 million global annual premature deaths of adults and children under the age of 5 y from combined residential and commercial energy generation (which includes solid fuel use for cooking) (6). This is a significant fraction of the ∼2.9 million premature deaths owing to degraded ambient air quality from all sources (5). These emissions' climate impacts have also been quantified to some extent; for example, Bailis et al. (7) estimate that 1.9–2.3% of the global CO_2 emissions are from wood fuel, enough to cause a radiative forcing (RF) of 25–47 mW m^{-2} (8), whereas the aerosol RF ranges from −20 mW·m^{-2} to 80 mW·m^{-2} (9, 10). The large range of uncertainty in the aerosol climate impact of cookstoves stems from uncertainties regarding fuel characterization given coemissions of absorbing or reflective species, compounded by uncertainties in the interactions of aerosols with clouds (11, 12).

Although these previous studies have highlighted the potential cobenefits of reducing cookstove emissions globally, such findings are limited in terms of their relevance for evaluating domestic-scale mitigation efforts. First, the impacts of aerosols on climate and ambient air quality are highly spatially variable owing to several factors, and thus global-scale assessments may not well represent the consequences of national-scale action plans. Unlike long-lived greenhouse gases, which are well mixed in the atmosphere and have a constant impact per ton of emission globally, aerosols have atmospheric residences times on the order of 1 wk; their spatial distributions thus contain sharp gradients that lead to order of magnitude regional variances in their health and climate impacts per ton of emission, depending on factors such as their proximity to populated areas (e.g., ref. 13), their impact on RF in different regions (14), and the regional climate sensitivity to forcing (15). Second, integrated assessment of cookstove interventions must account for both greenhouse gas (GHG) and aerosols, which is a challenge owing to the disparate timescale of the climate impacts of aerosols (decades) compared with that of long-lived GHGs (centuries). Finally, modeling

Significance

Widespread use of solid fuels for cooking results in a significant source of anthropogenic emissions. Of foremost concern for indoor air quality, reductions to these emissions could also impact both climate and ambient air quality. These potential cobenefits are appealing to efforts aimed at reducing cookstove emissions on national to urban scales, but have yet to be comprehensively evaluated at these scales. We thus estimate the per cookstove impacts on ambient air quality and global mean surface temperature for every individual country with significant cookstove use, considering reductions to both aerosols and long-lived greenhouse gases over the next century. This estimation provides information for policy makers evaluating climate and ambient air quality cobenefits of cookstove intervention programs worldwide.

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[1]To whom correspondence should be addressed. Email: forrest.lacey@colorado.edu.

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studies of aerosol health impacts are often detailed yet limited to a single region or are global yet suffer from errors in exposure estimation at coarse model scales (16).

To address these limitations, here we estimate the transient (present day to 2100) climate and ambient health impacts of national-scale coemissions of aerosols, aerosol precursors, and GHGs resulting from a 20-y phase-out of cookstove emissions in each country with greater than 5% of the population using solid fuels for cooking (101 countries in total). Attribution of these impacts to emissions from individual countries and species is made possible through the use of adjoint sensitivity analysis, building on our earlier work evaluating climate impacts of carbonaceous aerosols (11) and of source attribution of exposure to ambient particulate matter with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$) resolved throughout the globe using remote sensing observations (13).

Methods

Transient climate and health impacts are calculated for a scenario in which emissions of aerosols, aerosol precursors, and GHGs from solid fuel cooking are linearly eliminated over a 20-y horizon. Details of the emissions, models, and methods summarized here are provided in *Supporting Information*.

Transient climate impacts are estimated as follows. Adjoint model calculations (14) are used to calculate the sensitivities of regional RF in four different latitude bands with respect to grid-scale emissions of aerosols and aerosol precursors. Regional RF values are combined with absolute regional temperature potentials (15, 17) to estimate surface temperature response. This approach, introduced in Lacey and Henze (11), is expanded here by including GHGs and transient temperature responses. GHG emissions are modeled using transient functions for species-specific radiative impacts (18, 19), which relate the timescale of emissions to the resulting transient RF impacts (Tables S1 and S2) . These GHG RF impacts are then combined with the aerosol RF to estimate the total RF as a transient function. This net RF is multiplied by the transient global mean sensitivities and integrated for all prior years to estimate the temperature response of an emissions perturbation as a function of time. To account for uncertainties in RF, ranges of radiative efficiencies of short-lived climate pollutants (SLCPs) from multimodel ensemble estimates (8, 20, 21) are applied (Table S3). Whereas the climate responses to these ranges of RF estimates are calculated using absolute regional temperature potentials (ARTPs) derived from a single climate model [Goddard Institute for Space Studies (GISS)], other studies have found consistency between ARTP-based projections and mean surface temperature responses across models (*SI Methods, Temperature Response*). Further uncertainties in climate impacts are derived from ranges of emissions factors based on fuel characterizations (22, 23). The uncertainties in climate impacts from GHGs are estimated as $\pm 10\%$ of their total impact and are combined with the species-specific SLCP errors in quadrature.

We also estimate global premature mortality due to chronic exposure to ambient concentrations of $PM_{2.5}$. To mitigate uncertainties in exposure estimates owing to model resolution (e.g., ref. 16), satellite-derived $PM_{2.5}$ concentrations (24) are used to redistribute GEOS-Chem $PM_{2.5}$ concentrations from the $2^\circ \times 2.5^\circ$ to the $0.1^\circ \times 0.1^\circ$ scale following Lee et al. (13). Population-weighted $PM_{2.5}$ exposure is calculated using population estimates at the same resolution (25), which have been rescaled to 2050 national-scale population based on 2010 United Nations World Population Prospects (https://esa.un.org/unpd/wpp/).

The modeled exposure estimates are combined with disease-specific relative risk (RR) parameters for disease-specific integrated exposure responses (IER) (26) for all people over the age of 30 y and country-level baseline mortality rates (27) to estimate premature deaths from exposure to ambient $PM_{2.5}$. The causes of premature mortality considered are ischemic heart disease, chronic obstructive pulmonary disorder, cerebro-vascular disease, and lung cancer. The adjoint model is used to calculate the sensitivities of global premature deaths with respect to grid-scale speciated emissions perturbations (13). Transient health impacts are estimated by linear interpolation of sensitivities calculated for the present day and the year 2050 [using Representative Concentration Pathway (RCP) 4.5 emissions] and are assumed to increase post-2050 following the same rate of change as 2020–2050 to approximate sustained changes in population. Uncertainties in the health response are calculated following Lee et al. (13), in which the model was run with perturbed IER responses and baseline mortality rates corresponding to ± 1 SD for each impact. These are combined with a comparison of results obtained using different satellite-derived $PM_{2.5}$ surfaces (24, 28) to estimate the range of annual premature deaths attributed to ambient $PM_{2.5}$ exposure from solid fuel cookstove use; our central estimate uses the Global Burden of Disease 2013 exposure dataset (24) for consistency with other health impacts studies.

Results

Climate. Transient global climate impacts for removal of cookstove emissions, from each emitted species, are shown in Fig. 1. For aerosols, we present impacts of emissions of sulfur dioxide (SO_2), primary black carbon (BC), and primary organic carbon (OC), as well as additional secondary organic aerosol (SOA) formed from volatile organic carbon emissions. Fig. 1*A* shows these contributions to the net transient temperature response. SLCP impacts dominate the response for the first half of the century, whereas the GHG impacts, particularly CO_2, become increasingly important by 2100, consistent with previous studies of other types of mitigation (29–31). Cooling caused by removal of the absorptive species (BC, CO_2, and CH_4) outweighs the warming from removal of reflective aerosols (OC and sulfate, the latter from coal), with BC contributing the most to the surface temperature impact.

The use of adjoint sensitivities allows us to identify the contribution of each country's emissions to global climate

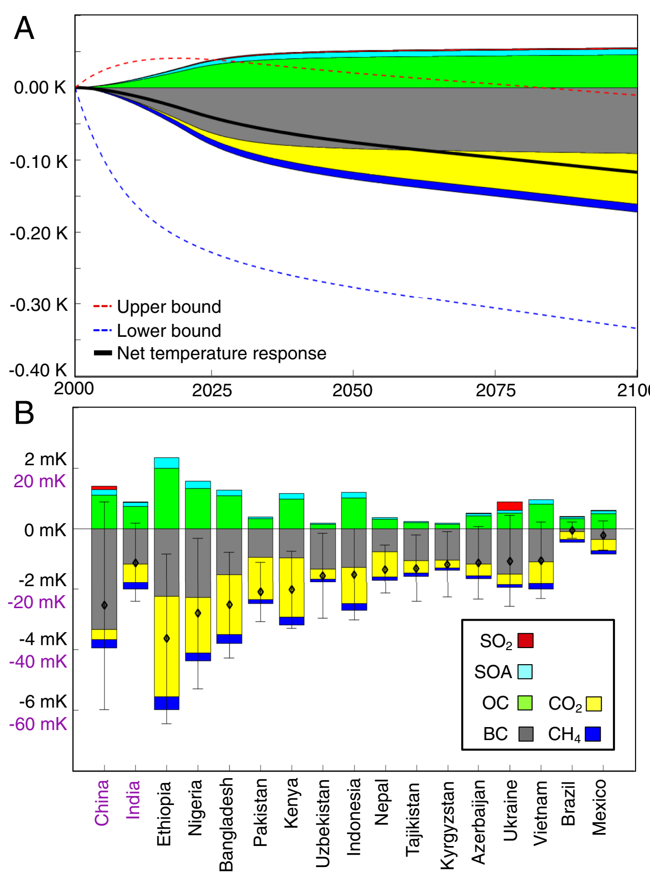

Fig. 1. The global transient surface temperature response to a phasing out of solid fuel cookstove emissions by 2020. Individual colors represent each emitted species' contribution to the global response. (*A*) The global mean surface temperature response (net impact shown as solid black line). (*B*) National contributions to global surface temperature response in 2050 for the countries with the largest contribution, along with Brazil and Mexico for comparison. China's and India's contributions are shown in purple on the *y* axis.

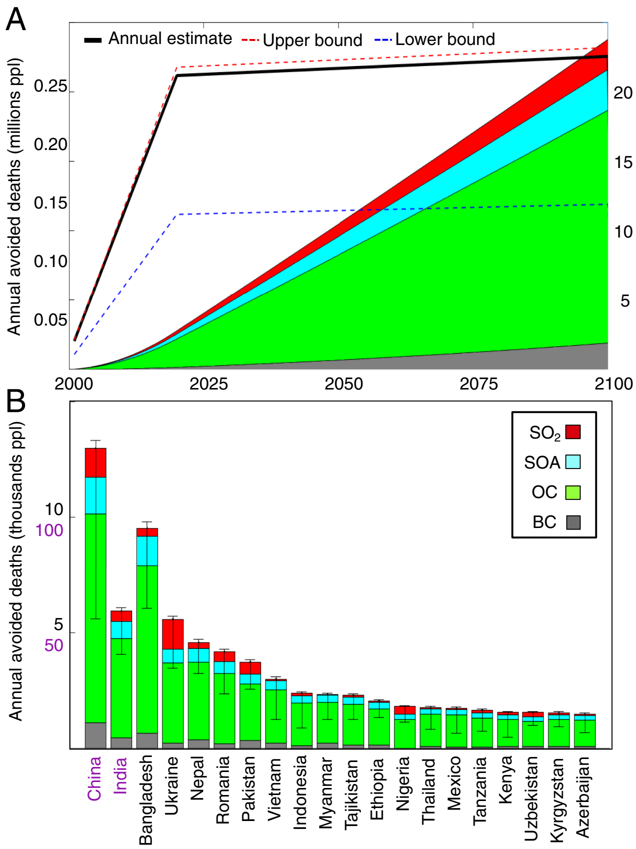

Fig. 2. The global transient premature deaths avoided due to changes in ambient $PM_{2.5}$ from a phased removal of solid fuel cookstove emissions by 2020. Colors show the species' contributions to the global response. (*A*) The annual (solid black line) and speciated cumulative health impact response (colored wedges). (*B*) National contributions to annual avoided premature deaths in 2050 from changes in ambient $PM_{2.5}$. China's and India's impacts are shown in purple on the *y* axis.

change. Fig. 1*B* shows countries with the largest contributions of national-scale emissions to the global average surface temperature response in 2050, with the breakdown of each species' contribution to that impact, along with Brazil and Mexico for comparison. Note that countries with large GHG contributions will have relatively larger overall impacts in later decades than are shown in Fig. 1*B*, as GHG effects increase, consistent with global-scale trends shown in Fig. 1*A*; the tabulated transient national-scale contributions for all countries with larger than 5% solid fuel use can be found in Dataset S1. Considering only carbonaceous aerosols, Lacey and Henze (11) highlighted the value of mitigating BC emissions in high-latitude countries, which incur the largest-magnitude cooling response per kilogram of abated BC emission, whereas the removal of coemitted OC in many countries (e.g., Central and South America and parts of Africa) leads to a net warming. Accounting for coemitted GHGs, here we find that in regions wherein residential solid fuel emissions have a large OC component, the climate impact from CO_2 and CH_4 counteracts the cooling impact of these reflective aerosols. This occurs in African countries that use large amounts of nonrenewable solid fuels (7), as shown by the larger percentage of contribution of CO_2 to the net temperature impact in countries such as Ethiopia and Kenya. Fig. 1*B* also shows the uncertainties in the net global surface temperature response. For several countries (e.g., Ethiopia, Bangladesh, Kenya), the range of temperature impacts spans zero, meaning that removal of these countries' emissions may have a net warming.

Health. Fig. 2*A* shows each species' contribution to cumulative and annual global premature deaths avoided due to changes in ambient $PM_{2.5}$ from the removal of cookstove emissions. The large increase in annual avoided deaths from 2000 to 2020 is due to the phased emissions reduction. The change in annual avoided premature death from 2020 to 2100 is due to increases in population and changes in the formation of sulfate aerosol caused by shifts in anthropogenic emissions.

The health impacts in Fig. 2*B* show that OC is the largest contributor to ambient $PM_{2.5}$ exposure from cookstove emissions throughout all countries. This plot also highlights the importance of SO_2 emissions in countries that use a combination of traditional wood and herbaceous fuels along with coal. The countries with the largest contribution to global premature deaths from exposure to ambient $PM_{2.5}$ from cookstoves are not necessarily the countries with the highest solid fuel use or number of cookstoves (i.e., Ethiopia, Nigeria, and Kenya). Large ambient health impacts from emissions in countries such as Nepal, Pakistan, and Vietnam are due to transport of $PM_{2.5}$ over populated regions. In contrast, emissions in countries such as Ukraine and Romania contribute to a large percentage of the global health impact owing to high baseline mortality rates (13).

Cobenefits. To directly compare climate and ambient air quality impacts, we have calculated each country's percentage of contribution to global climate and health impacts and plotted these in Fig. 3 on the x and y axes, respectively. Other studies have compared health and air quality impacts by monetizing both climate and health (e.g., ref. 32). To avoid confounding the estimated transient global impacts with the changing social costs of emissions and statistical values of life, we present both as separate objectives and recognize that country-specific impacts could be monetized in future studies. To illustrate, the impacts plotted here are calculated for 2050, but values for each decade between 2000 and 2050 for 101 countries are provided in Dataset S2. Countries are color coded by continent to highlight differences between regions in terms of the net coimpacts that they exhibit

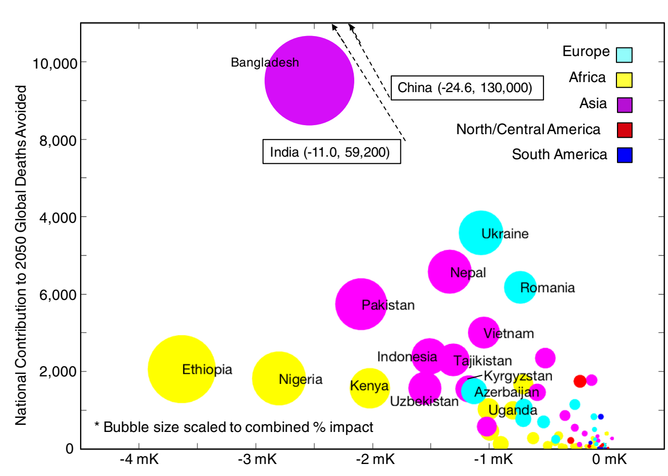

Fig. 3. National-scale contributions to total global climate and health impacts in 2050 for complete phase-out of cookstove emissions by 2020. The *x* axis shows the change in global surface temperature (relative to 2050 following RCP 4.5). The *y* axis shows the number of premature deaths from the change in ambient $PM_{2.5}$ concentrations attributed to a country's individual emission reduction. The bubble size of each country is scaled to the combined percentage of contribution of health and climate impacts for that country.

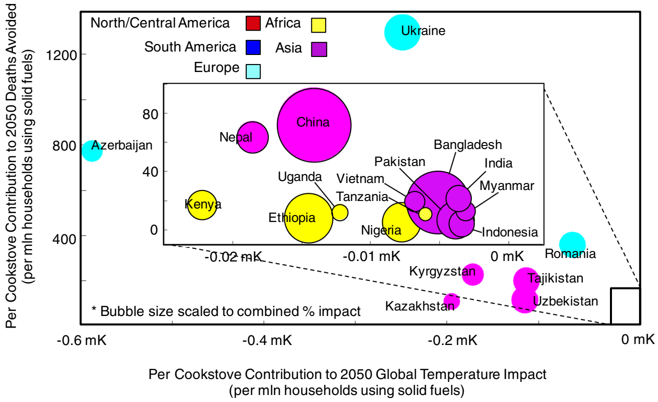

Fig. 4. National-scale per cookstove contributions to climate and health impacts. *Inset* shows the countries at the lower end of the scale. Individual bubble sizes are colored by continent and scaled to the combined percentage of contribution of net health and climate impacts (China and India bubble size scaled by 1/10 due to the overall magnitude of their impacts).

as a response to the phased removal of cookstove emissions. In general, African countries tend to contribute to a larger temperature response due to large amounts of cookstove use and the cooling potential from the removal of the associated GHG emissions. In contrast, the ambient health impacts of emissions from African countries are smaller than in other regions due to the lower population densities. Countries in Southeast Asia tend to contribute to more balanced climate and ambient health impacts in part due to higher population densities and transport of primary aerosol emissions over populated areas, as well as significant solid fuel use and high aerosol radiative efficiencies. The large ambient health impacts from Eastern European emissions reductions are a function of higher baseline mortality rates (13). Also note that impacts of emissions from China and India lie outside the plot axes.

Whereas the overall magnitude of the impacts is important in understanding the drivers of global climate and ambient air quality, of more value with regard to policy, specifically cookstove interventions, are the impacts on a per cookstove basis. We thus next consider (Fig. 4) the national-scale contributions to global climate and air quality impacts divided by the national-scale number of cookstoves, which is estimated using the number of people using solid fuels in 2010 (1) and the household size from the Global Burden of Disease Institute for Health Metrics and Evaluation. Per cookstove (i.e., marginal) impacts are largest for cookstoves in certain regions not typically targeted for cookstove interventions (30), such as those in Central Asia and Eastern Europe, with emissions from Azerbaijan ranking the highest in terms of climate and second highest in terms of health.

Discussion and Conclusions

The results presented here show that for the year 2050, the impacts from the phased removal of global solid fuel cookstove emissions are a global average surface temperature cooling of 77 mK (ranging from a 20-mK warming to a 278-mK cooling) and an avoidance of 260,000 (137,00–268,000) annual premature deaths due to ambient $PM_{2.5}$ exposure, cumulatively avoiding 10.5 (5.55–10.80) million premature deaths from 2000 to 2050. Aerosols contribute 41% to the central estimate of net global cookstove climate impacts by 2050 and alone may be cooling or warming with large uncertainties based on fuel type and aerosol's climate impacts. However, net climate impacts of cookstove emissions reductions are likely cooling, when considering benefits of curbed GHG emissions, which become increasingly prominent on longer time horizons. National-scale contributions of cookstove emissions to global premature deaths due to ambient $PM_{2.5}$ exposure are driven by primary organic carbonaceous aerosol.

Emissions from cookstoves in China and India are the largest, and they contribute the most to ambient air quality and climate impacts; however, the role of other countries does not in general always correspond to the magnitude of their emissions. Fig. 5 depicts how ambient air quality and climate benefits of cookstove interventions are modulated by the role of transport of aerosols over populated regions, the combined impacts of absorbing and reflective components of aerosols, the ratio of GHG to aerosol emissions as a function of fuel type, and the magnitude of semi- and indirect climate effects of opposite sign. Several countries (Azerbaijan, Kyrgyzstan, Uzbekistan, and Ukraine) rank in the top 20 in terms of their coimpacts without being ranked highly in terms of total population using solid fuels. Despite a smaller amount of cookstove use, intervention programs in these countries are estimated to result in the highest cobenefit per cookstove replaced owing to increased climate impacts of BC due to transport to the Arctic and over snow and the increased number of premature deaths due to high baseline mortality rate in these regions.

Although this study uses state-of-the-art modeling techniques to estimate climate and health impacts, several assumptions must be made to allow for efficient model calculations. We consider a range of emissions factors for BC to OC, but our estimates do not explicitly consider uncertainties in total carbonaceous emissions (although marginal impacts, to first order, are less sensitive to this type of uncertainty). We attempt to account for this when estimating health impacts by considering a range of satellite-derived $PM_{2.5}$ datasets (24, 28), but additional assessment of cookstove emissions inventories and resulting $PM_{2.5}$ concentrations would be valuable (33). Our work only crudely treats SOA formation and is sensitive to uncertainties in emission factors of nonmethane organic compounds (34, 35). New understandings

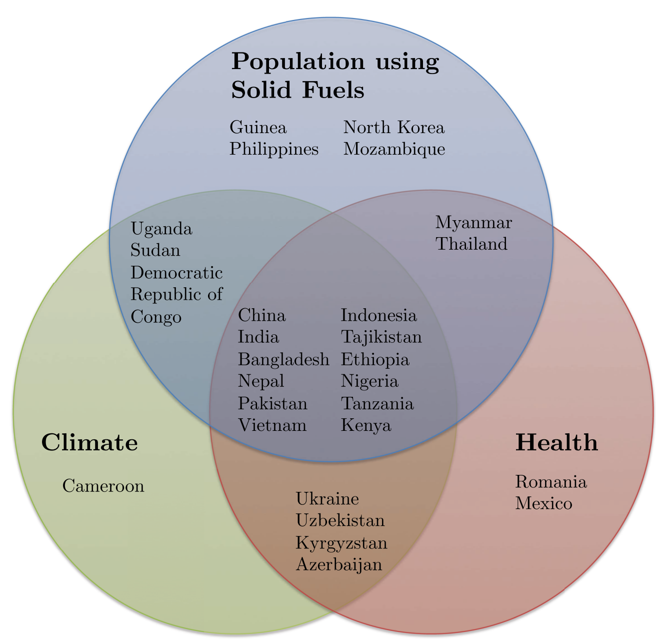

Fig. 5. The top 20 countries ranked in terms of three variables: population using solid fuels for cooking (blue), total net contribution to the global surface temperature change from the emissions from cookstove solid fuel emissions (green), and the total net contribution to global premature deaths from exposure to ambient $PM_{2.5}$ from cookstove solid fuel emissions (red).

in the roles of SO_2 and NO_x emissions on SOA formation (e.g., ref. 36) may indicate our SOA estimates are lower bounds. Our methods also use global estimates of aerosol semi- and indirect climate impacts (37) and assume a central BC radiative forcing from Bond et al. (38) that has been suggested to be 27% too large (39). Our adjoint sensitivities were calculated using a single year of meteorology (2009) that may not reflect a climatological mean, although error bounds of our radiative forcing estimates do draw from comparisons of multiyear modeling studies. Future work may be able to extend the source attribution techniques used in our study for direct RF to indirect effects and account for future changes in meteorology. For the health impacts, our assumption that present-day mortality rates persist throughout the scenarios may lead to overestimates, as recent work predicts that baseline mortality rates in the top countries impacted by changes in solid fuel use may decrease by 30% in 2050 (40). Finally, we have focused on the impact of cookstove emissions under an illustrative yet simplistic phase-out scenario. If instead cookstoves were replaced with tier 1 or tier 2 solid-fuel cookstoves, we would expect a 28% and 56% reduction, respectively, in health and climate impacts from this replacement, given the emissions factors for these stoves (41). Tier 3 and tier 4 stoves require access to different fuel sources and a more comprehensive integrated assessment of life-cycle impacts. Nonetheless, despite the stated uncertainties and assumptions, this work provides information to decision makers to evaluate climate and ambient health impacts of current and ongoing cookstove interventions (cleancookstoves.org/about/news/11-20-2014-market-enabling-roadmap-phase-2-2015-2017.html).

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