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Abstract

Over two-thirds of Indians use solid fuels to meet daily cooking energy needs, with associated negative environmental, social, and health impacts. Major national initiatives implemented by the Indian government over the last few decades have included subsidies for cleaner burning fuels like liquid petroleum gas (LPG) and kerosene to encourage a transition to these. However, the extent to which these programs have affected net emissions from the use of these improved fuels has not been adequately studied. Here, we estimate the amount of fuelwood displaced and its net emissions impact due to improved access to LPG for cooking in India between 2001 and 2011 using nationally representative household expenditure surveys and census datasets. We account for a suite of climate-relevant emissions (Kyoto gases and other short-lived climate pollutants) and biomass renewability scenarios (a fully renewable and a conservative non-renewable case). We estimate that the national fuelwood displaced due to increased LPG access between 2001 and 2011 was approximately 7.2 million tons. On aggregate, we estimate a net emissions reduction of 6.73 $MtCO_2e$ due to the fuelwood displaced from increased access to LPG, when both Kyoto and non-Kyoto climate-active emissions are accounted for and assuming 0.3 as the fraction of non-renewable biomass (fNRB) harvested. However, if only Kyoto gases are considered, we estimate a smaller net emissions decrease of 0.03 $MtCO_2e$ (assuming fully renewable biomass harvesting), or 3.05 $MtCO_2e$ (assuming 0.3 as the fNRB). We conclude that the transition to LPG cooking in India reduced pressures on forests and achieved modest climate benefits, though uncertainties regarding the extent of non-renewable biomass harvesting and suite of climate-active emissions included in such an estimation can significantly influence results in any given year and should be considered carefully in any analysis and policy-making.

1. Introduction

Almost 40% of the world's population or 3 billion individuals (World Bank, IEA 2017) depend on solid fuels (including traditional biomass such as wood, crop residue, and dung) to meet their daily household cooking energy requirements (Arnold *et al* 2003, International Energy Agency 2016, World Bank, IEA 2017). About a quarter of the global population dependent on traditional biomass or about 800 million individuals live in India alone, and this burning of biomass contributes to about 26.60% of total final energy consumption in India. Inefficient combustion of biomass in traditional stoves has both local as well as global

environmental impacts. Unsustainable harvesting of fuelwood, especially in densely populated areas, leads to deforestation (Arnold *et al* 2003, Foley *et al* 2007, Hosier 1993, McGranahan 1991), accelerated degradation (DeFries and Pandey 2010, Ghilardi *et al* 2007, 2009, Heltberg *et al* 2000), and depletion of local resources (Masera *et al* 2006). How biomass is harvested (sustainably or not) can also have an impact on the contribution to climate change from the carbon dioxide (CO_2) released (Edwards *et al* 2004, Hutton and Rehfuess 2006, Smith *et al* 2000). Additionally, burning of biomass contributes to the emissions of products of incomplete combustion such as black carbon (Kar *et al* 2012, Ramanathan and Carmichael

2008). The resultant household air pollution from inefficient use of solid fuels is one of the top environmental health risks in developing countries, contributing to over 4 million deaths globally (WHO 2016). Furthermore, about 25%−30% of ambient fine particulate pollution ($PM_{2.5}$) in South Asia is attributable to household solid fuel combustion (Chafe *et al* 2014), making it a leading contributor to the burden of disease in the region (Balakrishnan *et al* 2014, Rehman *et al* 2011, Smith *et al* 2014). Research has shown that the use of improved cooking technologies and fuels can significantly improve household air quality and human health from reduced smoke (Dutta *et al* 2007, WHO 2016, Singh *et al* 2014), as well as have other social benefits such as time saved from reduced fuelwood collection (Brooks *et al* 2016, Hutton and Rehfuess 2006).

Due to the multiple benefits of improved cooking technologies and clean fuels, numerous programs in India to encourage their use have been implemented since the 1970s. These programs include LPG interventions, price subsidies, public awareness campaigns, and improved distribution/delivery mechanisms. The Indian government in recent years has accelerated efforts through multiple new programs to increase liquefied petroleum gas (LPG) access to another 50 million below poverty line households by 2019 (Ministry of Petroleum and Natural Gas 2016). However, to what extent past and current policies have enabled a transition away from fuelwood to cleaner-burning fuels like LPG, and what the net emissions impacts of this has been has not been adequately studied.

Transitioning to improved stoves and cleaner modern fuels (such as LPG) can, in theory, positively influence forest resources, global climate, local air quality, and human health and well-being. Modern fuels, such as LPG, natural gas and electricity, are viewed as being the most beneficial from the perspective of human health as they significantly reduce emissions of household air pollutants (WHO 2014). However, households might be transitioning from what could be a renewable fuel (biomass—depending on how it is harvested) to a fossil fuel. This raises the question of the net climate change impact of such a switch. There has been limited work assessing this potential trade-off to date. Existing studies include calculations based on hypothetical stove switch-outs or modeling of future emissions based on projected stove adoption (Cameron *et al* 2016, Freeman and Zerriffi 2012, Ghilardi *et al* 2009, Pachauri *et al* 2013). A recent KfW report provides an overview of the evidence base on the impact of LPG use on the climate and forests (Bruce *et al* 2017). One gap in the existing knowledge base, highlighted by this and other studies, is the lack of estimations of net climate relevant emissions impacts from historic data on household fuel switching that reflect actual conditions of stove use and stacking. This paper addresses this gap specifically by examining the climate effect of the switch from fuelwood to LPG cooking in India over the decade from 2001–2011. Our analysis includes the estimation of net impacts considering a suite of various climate-active emissions (Kyoto gases and other short-lived climate pollutants) and biomass renewability scenarios (a fully renewable and a 0.3 fraction of non-renewable biomass case). We assess the aggregate change in fuel consumption and resulting changes in emissions that occurred as a result of both the suite of policies put in place as well as the supply-side and demand-side decisions that were made by companies and households over this period. However, we are unable to estimate the effect of specific policies in place between 2001 and 2011 in transitioning people to the use of LPG as policy-specific data is unavailable to us.

2. Materials and methods

We assess the net impact on emissions from increased access to LPG for cooking in Indian households over the decade from 2001−2011. In what follows, we describe our main data sources and methods. A more complete description of the methods, including data tables, is presented in the supplementary information (SI) available at stacks.iop.org/ERL/12/115003/mmedia. We define fuelwood displaced as the amount of fuelwood not used (i.e. saved) due to the use of LPG. We focus our research on India, as it has the largest solid fuel using population globally, and over two-thirds of Indian households still depend on these fuels (Government of India 2016, Ki-Moon 2011, World Bank, IEA 2017). Also, the country has seen a huge governmental push towards transitioning people to the use of cleaner fuels and stoves for over three decades.

Two key national sources of data on LPG and fuelwood access and consumption were utilized in this analysis.

- Bottom-up estimates of household LPG and fuelwood consumption are derived from the large nationally representative socio-economic surveys conducted by the National Sample Survey (NSS) organization (MOSPI 1999, 2011).
- Data on the total number of households using wood vs. LPG as their primary fuel are taken from the Indian national censuses and are used to scale the bottom-up survey estimates to national aggregates.

Using the data from the two representative national surveys, NSS rounds 55 (year 1999−2000) and 68 (year 2011−2012), we identified primary users of LPG and fuelwood (those households who identified it is their main cooking fuel), and secondary users of LPG and fuelwood (those households who did not identify it as their main cooking fuel yet consumed some amount of fuelwood or LPG). In 2011, there were about 70 million primary users of LPG, and 29 million secondary users of the fuel (table 1). Both primary and secondary users

are accounted for in our analysis so that the emissions impact of stove stacking is included.

Our methodology in this study consists of three key steps. First, we applied statistical matching techniques to create a synthetic dataset of matched households considering the subset of households that gained access to LPG between 2001 and 2011. In a second step, we used this synthetic dataset to estimate the amount of fuelwood displaced due to increased LPG access in 2011. Finally, we used our estimates of fuelwood displaced and LPG use in 2011 to estimate the net emissions impacts of this cooking fuel transition considering a suite of climate-active emissions and biomass renewability assumptions.

For the statistical matching, we utilized a mixed method based on D'Orazio (2006), which was implemented using the R StatMatch package (R Core Team 2013). The method was applied to create a synthetic dataset of over 100 000 matched households to examine changes in household fuel consumption over the decade in the absence of longitudinal panel data by matching similar households from the two NSS rounds 55 and 68 based on State, sector (urban/rural), and caste. Further details regarding the statistical matching techniques applied are presented in the supplementary information.

This synthetic dataset was then used in the analysis that followed. A filter was applied such that only those households having no access to LPG in 2000 were included in the analysis, regardless of access to or level of LPG consumption in 2011. To estimate the amount of fuelwood displaced due to LPG access in 2011, we used a three step Tobit model, based on the technique in Greene (2003). Our R-code for this analysis was based on the gamma hurdle biological model by Anderson (2014), which is the same as the Tobit model used in econometrics. We tested the model using a range of explanatory variables (urban/rural, LPG quantity, household size, income, caste, employment, and religion), and the best model was selected based on the Akaike information criterion (AIC) and log likelihood (logLik). AIC estimates the quality of a model relative to other models, while logLik compares the fit of different coefficients to maximize optimal values. By these criteria, the model we selected to predict firewood use in 2011 included the quantity of LPG consumed, household size and urban/rural as independent variables.

Coefficients of the estimated Tobit model were then used to predict the amount of annual fuelwood displaced by an average sized household that gained access to LPG in 2011. Estimates were made for average sized urban households and rural households separately. Using the census enumeration of number of households that gained access to LPG between 2001 and 2011, we then estimated the total fuelwood displaced in 2011. These estimates on household LPG consumption and fuelwood displaced were then ultimately utilized to calculate the net emissions impact (in million metric tons of carbon dioxide equivalent or $MtCO_2e$) from increased LPG access. Net emissions were calculated utilizing the emissions factors and hundred year global warming potentials (GWP_{100}) from Freeman and Zerriffi (2014) for a traditional open fire and an LPG stove. This includes the uncertainty associated with estimates of the emission factor based on reported stove testing results.

If fuelwood is sustainably procured (i.e. renewable), the CO_2 emission from wood is zero, as it is presumed to be reabsorbed into the ecosystem cycle during tree growth. However, it is known from literature that not all fuelwood harvested is renewable (Bailis *et al* 2015), and in fact, the fraction of non-renewable biomass (fNRB) extracted can vary by huge margins (0%−90%) globally. A higher fNRB would ascribe correspondingly higher emissions to biomass fuels and a greater benefit of a switch to LPG. In this work, we consider two cases of fuelwood renewability: an unrealistic case of fully renewable biomass (fNRB = 0), and a more realistic but globally conservative case where we use an estimate of 0.3 as the fNRB. Cookstove carbon markets tend to use high values hovering at 80% or more, however, Bailis *et al* (2015) estimated the national fNRB for India to be around 24 percent. Thus, we assume a conservative 30% as the fNRB to illustrate the impact of fNRB on emissions accounting.

The difference between emissions from fuelwood displaced and increased LPG use determined our estimates of the net emissions impact from the transition to LPG cooking in 2011. Net emissions were estimated under the alternate assumptions of renewability of biomass extraction as mentioned above, for a restricted case considering only Kyoto gases (CO_2 and CH_4), and a more complete case including also emissions of other important climate-active emissions (CO, non-methane hydrocarbons, organic carbon, black carbon (BC), and SO_2).

3. Results

Basic statistical analysis indicates that the proportion of Indian households primarily using fuelwood for cooking decreased by 3.5% even though the total number of households using fuelwood increased by almost 20 million over the decade 2001 to 2011 (table 1). This was due to the rapid growth of the Indian population from approximately 1.02 billion in 2001 to 1.22 billion in 2011 (Government of India 2016).
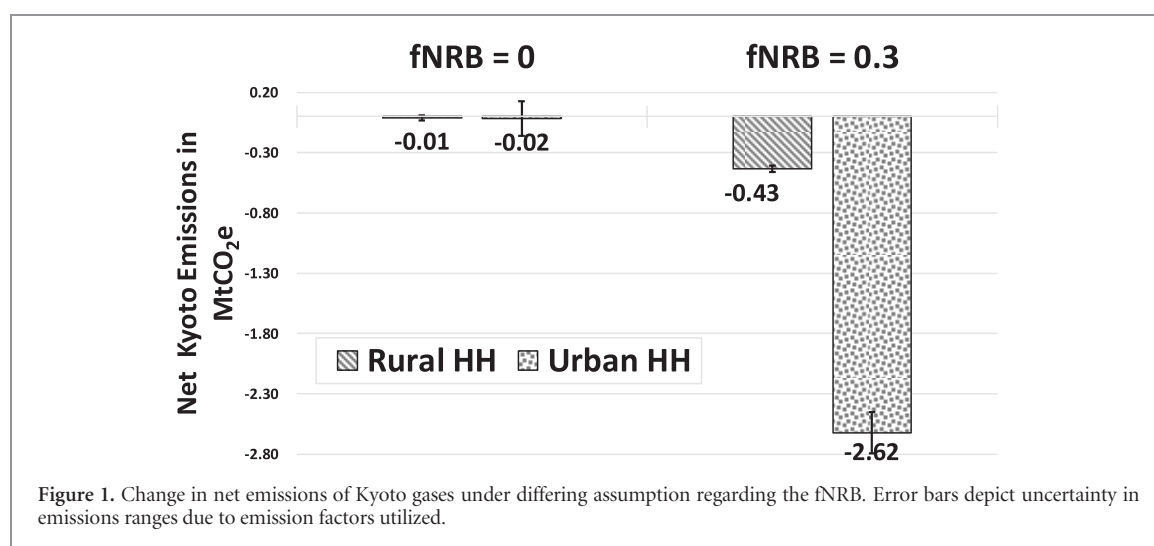
At the same time, households using LPG increased both in number and in percentage over this decade indicating a national trend towards increased use of LPG as a primary household fuel. However, the proportion of secondary users of fuelwood also increased (by 9%) suggesting that households tend to initially stack fuels before moving primarily to the use of LPG. As we do not have yearly numbers for LPG access and use over

Table 1. Descriptive statistics of NSS and Census datasets for 2001 and 2011 (HH = households).

	2001		2011		
Descriptive statistics	# of HH	Percent (%)	# of HH	Percent (%)	Source
# of HH	191 963 935		246 740 228		Census
# Urban HH	138 271 559	72.03%	167 874 291	68.04%	Census
# Rural HH	53 692 376	27.97%	78 865 937	31.96%	Census
Primary LPG HH	33 596 798	17.50%	70 425 518	28.54%	Census
Secondary LPG HH	5 050 475	2.63%	29 071 487	11.78%	NSS
Primary fuelwood HH	100 842 651	52.53%	120 878 598	48.99%	Census
Secondary fuelwood HH	5 050 475	2.63%	29 071 487	11.78%	NSS

Table 2. Average LPG consumption and fuelwood displaced by households (HH) in 2011.

	Rural	Urban	Source
Average HH size in 2011	5.11	4.34	Matched data
KG fuelwood displaced per HH yr^{-1}	−88.32	−242.52	Calculated
# HH gaining access to LPG 2001–2011	11 294 825	25 533 895	Census
Fuelwood (metric tons) displaced yr^{-1}	−997 524	−6 192 501	Calculated
LPG (metric tons) used in 2011	27 691	189 315	Matched data
Average LPG KG used per HH yr^{-1}	29.42	88.97	Matched data
# HH using LPG in 2011	19 137 351	51 285 532	Census

Figure 1. Change in net emissions of Kyoto gases under differing assumption regarding the fNRB. Error bars depict uncertainty in emissions ranges due to emission factors utilized.
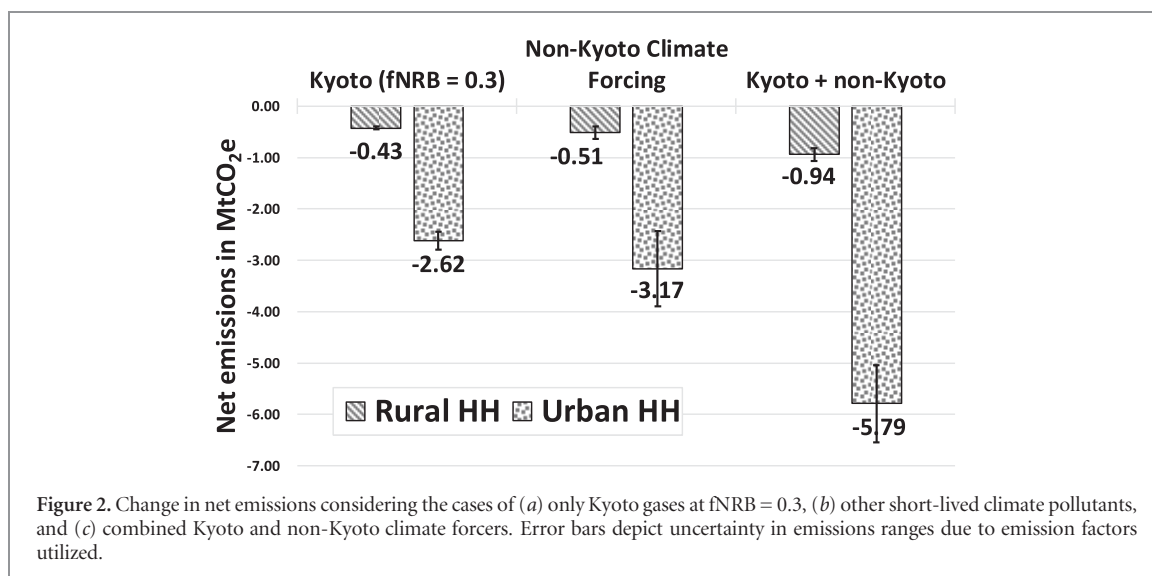
the decade, we cannot estimate the population moving from fuelwood and obtaining LPG as a primary fuel, or using it as a secondary fuel at any point during the decade.

Results of the Tobit model indicate that the total fuelwood displaced per year, assuming average sized households, due to increased LPG access in 2011 was 6.19 million tons in urban regions, and 0.99 million tons in rural regions (table 2). At a national level, this amounted to a displacement of 7.2 million tons of fuelwood in 2011. At the same time, the LPG consumption increase due to household gaining access amounted to approximately 0.028 million tons and 0.189 million tons in rural and urban households respectively.

In estimating the emissions of Kyoto gases alone due to the displacement of fuelwood between 2001 and 2011, the assumption regarding fNRB extraction, makes a substantial difference. When all fuelwood used is assumed to be renewably sourced (fNRB = 0) we estimate a slight net emissions decrease in rural regions of 0.01 MtCO$_2$e, and in urban regions of 0.02 MtCO$_2$e in 2011. However, if we conservatively assume a positive fNRB of 0.3, we estimate a net emissions reduction of 0.43 MtCO$_2$e in rural, and of 2.62 MtCO$_2$e in urban regions (figure 1). The larger net emissions decrease estimated for urban households is due to the more rapid gain in access to LPG and the higher per household consumption of it in urban regions. Furthermore, the higher net emissions reductions estimated when assuming a positive fNRB is because the increase in emissions from LPG use is offset by the reduction in positive CO$_2$ emissions from avoided burning of non-renewable biomass. The uncertainty in net emissions ranges are due to emission factors utilized from Freeman and Zerriffi (2014).

When we also consider a suite of non-Kyoto climate pollutants, in addition to a positive fNRB, our estimate of net emissions reductions is even higher at 0.94 MtCO$_2$e in rural and 5.79 MtCO$_2$e in urban

Figure 2. Change in net emissions considering the cases of (*a*) only Kyoto gases at fNRB = 0.3, (*b*) other short-lived climate pollutants, and (*c*) combined Kyoto and non-Kyoto climate forcers. Error bars depict uncertainty in emissions ranges due to emission factors utilized.

regions (figure 2). This is due to the much higher non-Kyoto climate forcing emissions associated with the use of traditional biomass stoves as compared to LPG stoves. Given that there is no well-accepted protocol for calculating fNRB globally or agreement on the suite of emissions to account for, there can be large variances in the net emissions calculated for the same quantity of fuel consumed. Regardless of these associated uncertainties, however, we still estimate a large reduction in climate forcing emissions due to the observed transition from traditional biomass stoves to LPG stoves in India between 2001 and 2011.

4. Discussion and conclusion

In recent years, there has been a strong revival in global policy circles to promote a transition to cleaner cooking given the increasing evidence of the huge environmental, social and health externalities of solid fuel use. India has a long history of providing subsidies for cleaner-burning fuels, specially kerosene and LPG. Recently, the LPG subsidy burden for the government has been estimated at about US$6 billion per year (Shenoy 2010). Government initiatives in recent years, such as PAHAL, Give it UP and Ujjwala, could further accelerate the rate of LPG access. Ujjwala in particular is targeting an additional 50 million poor families by 2019, with an allocated budget of US$300 million in 2016−2017 (Ministry of Petroleum and Natural Gas 2016). The Indian government plans to meet this estimated growth in LPG demand by appointing approximately 10 000 new LPG distributors (40% of the current base) in 2016−2017. Several analyses of the household energy transition in India exist, but the emissions consequences of this remain uncertain. Our analysis provides an estimate of the net emissions impacts of the observed transition from traditional biomass cooking to LPG stoves over the decade 2001−2011 as a consequence of both policies and socio-economic developments over

this period. While our analysis is unable to attribute the net emissions impact to specific policies, it provides a first historical estimate at the national level of emissions impacts of the household cooking energy transition that accounts for actual conditions and fuel stacking.

Between 2001 and 2011, we observe a sharp increase in LPG access in urban India (by 17%), compared to rural India (by 5%). Two factors contributed to this: (1) enhanced access and stable supply of LPG in urban regions, and (2) rapid urbanization of India whereby rural regions are being converted to urban and rural populations are moving to urban areas (Kumar and Rai 2014). Both primary and secondary users of fuelwood are accounted for in our analysis to include the emissions impact of the continued use of fuelwood along with LPG. Thus, our net emissions impact is likely to be more conservative when compared to analyses that account for only primary users of LPG. As access to LPG improved, assuming all households were of average size, urban India displaced 6.19 million tons of fuelwood in 2011, while in rural India only 0.99 million tons were displaced. The variation between urban and rural regions is due to the differences in the LPG distribution networks, average incomes and price of fuelwood across these regions. Urban households tend to generally buy fuelwood (if available) and have access to better LPG distribution and after sales networks. Urban households, thus tend to make a more rapid and complete transition to improved cooking technologies and are less likely to use wood as a secondary fuel. Conversely, as fuelwood is easily accessible in rural regions and the LPG distribution networks are not reliable, stacking of fuels is more common among rural households. In addition to fuelwood, households also use crop and animal residues like dung as cooking fuels, especially in rural India, and the emissions from these fuels also have significant health and climatic impacts. However, a lack of reliable data on crop and animal residue use in the NSS surveys limits our ability to

include it in our net emissions impact estimations. Thus, we have only included emissions from fuelwood and LPG use in our analysis. A key finding of this work is that even when biomass harvesting is assumed to be fully renewable (resulting in no CO_2 impact) there is no net emissions from the switch to LPG when considering Kyoto gases only (with some uncertainty around zero, see SI). This is because of the significantly higher efficiency of LPG stoves compared to traditional fuelwood stoves and the fact that traditional stoves emit methane while LPG stoves do not (coupled with the higher GWP_{100} for methane than CO_2). Accounting for black carbon and other non-Kyoto climate forcings results in a net reduction in emissions from a switch to LPG even at fNRB = 0 (see SI for the full range of uncertainties). Considering a more realistic, but still conservative assumption of 0.3 as the fNRB results, according to our estimates, in a larger net decrease of Kyoto emissions of 3.05 $MtCO_2e$. Accounting for non-Kyoto climate-active emissions increases our estimate of net emissions reductions even further to 6.73 $MtCO_2e$ at the national level.

The estimates we provide on reduction in fuelwood consumption (and thus on reductions in emissions) are conservative for a number of reasons. First, the fraction of biomass that is non-renewably harvested is conservatively assumed to be 0.3. Some have estimated a higher fraction at the national level for India while others have estimated a slightly lower fraction (Bailis *et al* 2015, Cashman *et al* 2016). However, all estimates are highly uncertain and we consider a fraction towards the lower end of the uncertainty range to ensure avoiding over-estimation. Second, the estimates of fuelwood displaced per kg of LPG consumed were made using NSS data that included both primary and secondary users of LPG. However, in scaling these to the aggregate national level, Census data on the total number of households with access was used, which only includes primary users of the fuel. We would expect that primary users would have a higher consumption of LPG than secondary users or a mix of primary and secondary users (as is observed in the NSSO data). Thus, the estimate at the national level is likely to be a lower bound on what each primary user of LPG is consuming. Third, again due to the fact that the Census only captures primary stove use, our estimate of households gaining access over the decade is likely a lower bound as it only captures households switching from no LPG to primary use of LPG and does not include households gaining access to LPG but using it as a secondary fuel. Fourth, the GWP_{100} used for BC is a global value of 455, whereas reported values in the literature vary regionally and some estimates for India put the GWP_{100} for BC at 1110 (Grieshop *et al* 2011, Freeman and Zerriffi 2014). Finally, we acknowledge that our estimates of net emissions from increased LPG access and use do not account for upstream emissions from the supply and manufacture of LPG. However, estimates of the emissions in the production and transport stage of LPG suggest that these are less than 10% of total emissions from LPG (Cashman *et al* 2016). It should also be noted that this analysis only capture changes at the extensive margin. That is, we only account for the reduction in fuelwood consumption and increase in LPG consumption associated with households moving from no access to having LPG access. We do not account for changes at the intensive margin (i.e. increases in LPG consumption from 2001 to 2011 by households that already had LPG in 2001). This is left to future work.

Despite these limitations, our analysis can be used to inform the design of public policies and investments to support clean cooking transitions in developing countries. The calculation of net emissions impact and fuelwood displaced due to increased LPG access and use can also be estimated using other methods. However, this is a first attempt to do so for India using the statistical matching techniques as far as we know. Better data availability in the future could allow the application of alternative methods and to other national contexts as well. Availability of longitudinal data could also make possible more research on trends in fuel stacking and LPG use over time. Little work has been done on determining the extent of public benefits from reduced emissions even though there is increasing interest in quantifying the environmental and welfare benefits for public policy and to generate more funding to promote cleaner fuel/stove use. This work could also inform future analysis of the net emissions impact from increased household LPG access as a consequence of the new set of policies being implemented by the Indian government.

Even though the transition of households from wood to LPG for cooking have significant impacts on health and fuelwood quantity used, the net climate impacts continue to remain uncertain, and have significant implications for household emissions accounting. The choices regarding the fNRB and climate-active emissions accounted for are significant for the results and household emissions accounting. These should be considered carefully in any analysis and policymaking. This also has an important impact on potential revenue generation through utilization of carbon crediting methodologies to fund future clean stove and fuel interventions. The fNRB assumed is crucial in determining the feasibility of a carbon credit based interventions, as carbon credits are based on the premise that improved stove efficiency and fuel substitution reduce the use of non-renewable biomass and its associated emissions. However, no matter what the assumption regarding fNRB, our results emphasize the importance of including non-Kyoto climate-active emissions in estimating the net climate impacts of transitioning from biomass to LPG cooking.

Acknowledgments

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