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Projecting the impact of air pollution on child stunting in India – synergies and trade-offs between climate change mitigation, ambient air quality control, and clean cooking access

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Abstract

Many children in India face the double burden of high exposure to ambient (AAP) and household air pollution (HAP), both of which can affect their linear growth. Although climate change mitigation is expected to decrease AAP, climate policies could increase the cost of clean cooking fuels. Here, we develop a static microsimulation model to project the air pollution-related burden of child stunting in India up to 2050 under four scenarios combining climate change mitigation (2°C target) with national policies for AAP control and subsidised access to clean cooking. We link data from a nationally representative household survey, satellite-based estimates of fine particulate matter ($PM_{2.5}$), multi-dimensional demographic projection and $PM_{2.5}$ and clean cooking access projections from an integrated assessment model. We find that the positive effects on child linear growth from reductions in AAP under the 2°C Paris Agreement target could be fully offset by the negative effects of climate change mitigation through reduced clean cooking access. Targeted AAP control or subsidised access to clean cooking could shift this trade-off to result in net benefits of 2.8 (95% uncertainty interval [UI]: 1.4, 4.2) or 6.5 (UI: 6.3, 6.9) million cumulative prevented cases of child stunting between 2020-50 compared to business-as-usual. Implementation of integrated climate, air quality, and energy access interventions has a synergistic impact, reducing cumulative number of stunted children by 12.1 (UI: 10.7, 13.7) million compared to business-as-usual, with the largest health benefits experienced by the most disadvantaged children and geographic regions. Findings underscore the importance of complementing climate change mitigation efforts with targeted air quality and energy access policies to concurrently deliver on carbon mitigation, health and air pollution and energy poverty reduction goals in India.

Key words: stunting, air pollution, India, climate change mitigation, co-benefits, projection

Abbreviation	**Definition**
AAP	Ambient air pollution
CCA	Clean cooking access
GAINS	Greenhouse-Gas Air Pollution Interaction and Synergies
HAP	Household air pollution
HAZ	Height-for-age z score
IAM	Integrated assessment model
LPG	Liquefied petroleum gas
MAD	Minimum acceptable diet
MFR	Maximum feasible reduction
NFHS	National family health survey
NPi	National policy implementation
OR	Odds ratio
PM2.5	Fine particulate matter
UI	Uncertainty interval

Introduction

The 25 million children born annually in India are exposed to some of the highest levels of ambient air pollution (AAP) in the world, several-fold greater than current WHO guidelines. With 56% of households in the country relying on highly polluting solid fuels to meet household energy needs, many children bear the double health burden of both high AAP and household air pollution (HAP) (International Institute for Population Sciences (IIPS) and ICF 2017). Air pollution (both AAP and HAP) is currently recognised as the second leading risk factor for disease burden and mortality in India, surpassed only by malnutrition (IHME 2019). A recent India Disease Burden study attributed 4.8% (95% uncertainty interval [UI] 3.6-6.0) of all under-5 deaths in the country to AAP and 4.0% (95% UI 3.0-5.1) to HAP (India State-Level Disease Burden Initiative Child Mortality Collaborators 2020). Exposure to air pollutants in-utero and early in life can be especially detrimental for children´s health because of their biological vulnerability and rapid development resulting in a range of adverse health outcomes (Perera 2017; Backes *et al* 2013). These include adverse birth outcomes, such as low birth weight and pre-term birth; respiratory diseases such as pneumonia, asthma and bronchitis; and impaired cognitive and neurological development. In addition to these well-established health outcomes, there is accumulating evidence that in-utero and early life exposure to AAP and HAP are also associated with child linear growth retardation (Zhu *et al* 2015; Yuan *et al* 2019; Bruce *et al* 2013; Pun *et al* 2021; Boamah-Kaali *et al* 2021).

Stunting, defined as being too short for one´s age, is a largely irreversible linear growth impairment that can have severe long-lasting impacts on child health and human capital formation. In childhood, stunting is associated with poor cognitive development (Poveda *et al* 2021), higher risk of mortality, and susceptibility to infectious diseases such as pneumonia and diarrhoea. Later in life stunting can lead to lower productivity and earnings and increased risk of metabolic diseases (Prendergast and Humphrey 2014). Although the biological mechanisms underlying the effects of air pollution on stunting are yet to be fully understood, it is recognised that these start during the in-utero period. Particles or their components can reach beyond the lungs of pregnant women to induce systemic inflammation or oxidative stress, leading to poor foetal growth (Backes *et al* 2013). Postnatally, environmental exposure to air pollution may compound the adverse effects of poor nutrition and pathogens on immune development and function, resulting in a cycle of recurrent disease and malnutrition (Dewey and Mayers 2011). More specifically, recurrent respiratory infections caused by air pollution may lead to suppressed appetite, impaired absorption of nutrients, increased nutrient loss, and diversion of nutrients towards immune response and away from growth (Dewey and Mayers 2011). Several observational studies from India, where child undernutrition is among the highest in the world, reported consistent associations between early-life exposure to AAP (Singh *et al* 2019; Spears *et al* 2019) and use of polluting cooking fuels (Islam *et al* 2021; Fenske *et al* 2013; Tielsch *et al* 2009) and child stunting. The epidemiological evidence linking AAP and HAP with prenatal (small for gestational age) or postnatal (low height-for-age Z-score) stunting has been summarised by several meta-analyses (Zhu *et al* 2015;Yuan *et al* 2019; Bruce *et al* 2013; Pun *et al* 2021). According to the most recent pooled estimates a 10 μg/m^3 increase in ambient PM$_{2.5}$ over the entire pregnancy increased the odds of prenatal stunting by 8% (95% CI: 3–13%), while postnatal exposure to solid versus clean cooking fuel increased the risk of postnatal stunting by 19% (95% CI: 10-29%)(Pun *et al* 2021).

Previous studies have shown that reductions in greenhouse gas emissions in line with climate change mitigation targets can bring substantial AAP improvements and health benefits in India, so-called co-benefits (West *et al* 2013; Silva *et al* 2016; Vandyck *et al* 2018 ; Markandya *et al* 2018; Sampedro *et al* 2020; Chowdhury *et al* 2018), and even more so when combined with stricter national measures for air quality control (Dimitrova *et al* 2021). However, scenario analysis from six different Integrated Assessment Models (IAMs), which quantified the interactions between climate change mitigation and energy access, suggest that stringent climate policy might significantly slow down the transition to clean cooking fuels by affecting energy prices (McCollum *et al* 2018). Thus, climate change mitigation may have opposing effects on the levels of AAP and HAP exposure and the associated health and developmental outcomes for future generations of children.

Most assessments of air pollution health co-benefits from climate change mitigation to date have focused on mortality outcomes and on adult populations. These estimates obscure the full health burden from air pollution by not including morbidity impacts. The potential lifelong consequences for future generations of children are still very poorly reflected in the literature, even though these populations will bear a disproportionate amount of the disease burden from environmental change. Furthermore, existing health co-benefit projections are based on comparative risk assessment or life table methods, which do not allow for more detailed analysis of health inequalities across different socio-demographic groups and geographical areas. Lastly, the health co-benefits literature has largely focused on single exposure pathways and rarely considered concurrent effects of multiple exposures. A few microsimulation models analysing health outcomes under air pollution control have been developed for some high-income countries (Symonds *et al* 2019, Pimpin *et al* 2018), but models focusing on health co-benefits from climate change mitigation and on Low and Middle-Income countries are lacking. We addressed these research gaps by investigating for the first time how the synergies and trade-offs between climate change mitigation, targeted ambient PM$_{2.5}$ control and energy access support policies could affect future child linear growth in India. We employed a static microsimulation with a soft link to an IAM and a multi-dimensional demographic projection, which allowed us to incorporate population-specific exposure response functions, explore differential impacts across population groups and geographical areas, and consider simultaneous effects of indoor and outdoor air pollution.

Methods

Study design

Our analysis proceeded in two stages. First, we examined the associations between early-life exposure to ambient $PM_{2.5}$ and polluting cooking fuel and stunting in a large dataset of children under-5 years in India. In the second stage, we developed a static microsimulation model of child stunting based on the following input data (1) National Family Health Survey (NFHS) data; (2) a multi-dimensional population projection; and (3) projections of ambient $PM_{2.5}$ concentrations, clean fuel use and per-capita income levels from an IAM (IIASA 2021). We projected the prevalence of child stunting at local level (district and urban/rural residence) and for distinct population groups under four scenarios combining climate change mitigation, air quality control, and policies to support clean cooking access (CCA). A detailed description of the data sources and methods is provided in the appendix.

Stage one: Epidemiological analysis

Observed population data We used nationally representative anthropometric and household data of children under-5 from India´s 2015-16 NFHS (NFHS-4, also known as the 2015–16 India Demographic Health Survey (DHS)). NFHS is a nation-wide, multi-round, two-stage stratified survey conducted in a representative sample of women of reproductive age (International Institute for Population Sciences (IIPS) and ICF 2017). Using NFHS´s child anthropometric data, we defined stunting as height-for-age z score (HAZ) two standard deviations below the median of the WHO Child Growth Standards.

Baseline ambient $PM_{2.5}$ and clean cooking access data We retrieved high resolution annual average $PM_{2.5}$ concentrations (0.01 ° x 0.01°) for the period 2009-2016 from the Atmospheric Composition Analysis Group (Hammer *et al* 2020). Each child was assigned average $PM_{2.5}$ exposure in-utero based on their date of birth, pregnancy duration and the geo-location of their household cluster.

As a proxy of exposure to HAP we used the type of primary cooking fuel of the households reported in the survey. We assumed households used the same fuel at the time of birth of the child as reported at the time of interview as previous studies have shown that cooking fuel transitions are relatively slow (Van Der Kroon *et al* 2013). We analysed the effect on child stunting of cooking with clean cooking fuels (electricity, liquefied petroleum gas (LPG), natural gas and biogas) compared to high-polluting fuels (kerosene, coal, charcoal, wood, straw, crop waste and dung).

Statistical analysis We estimated the effect of $PM_{2.5}$ exposure in-utero and type of cooking fuel using logistic regression, with a random intercept for administrative district to account for clustering. Based on the literature, we identified and adjusted for the following confounders: age and sex of the child, age, education and caste of the mother, urban-rural residence and household income category (based on the household wealth index as shown in the next section).

We included a penalized spline for child age in months and interaction terms between $PM_{2.5}$ in-utero with the child's sex, urban-rural residence, maternal education, household income category and caste, and interaction terms between clean fuel use with the child's sex and caste in order to account for differential vulnerabilities to air pollution across different socio-demographic groups. The analysis was performed with R (version 3.6.1), using the package *mgcv* (Wood 2011).

We performed a series of model specification checks by including a larger set of covariates in the model, adjusting for seasonality, estimating effects of life-course $PM_{2.5}$ exposure (i.e. in-utero and after birth). We also conducted a sensitivity analysis based on a subsample of the data to explore potential residual confounding by nutrition as operationalised by a Minimum Acceptable Diet (MAD) index (appendix 1.1).

Stage two: Projections

Scenarios We developed four hypothetical pathways for India to deliver on the Paris Agreement target and compared them to a reference scenario (Table 1). "NPi (National Policy implementation) without access policy" specifies a business-as-usual pathway of global greenhouse gasemissions based on currently announced climate policies through 2030, current AAP legislation and no additional support for CCA. We explored four mitigation pathways, which assumed the implementation of a carbon price of US$40 per ton CO_2 equivalent in the year 2020 that increased at the social discount rate through until the end of the century. These pathways were consistent with a >66% chance of limiting global mean temperature increases to 2°C relative to pre-industrial levels throughout the end of the century. The four mitigation pathways differ only with respect to the AAP control and compensatory energy access policies implemented at the national level. The 2°C scenarios assume compliance with current air pollution legislation only, while the 2°C MFR (Maximum Feasible Reduction) scenarios model implementation of additional end-of-pipe national air quality control measures in industrial, power generation, household, and agricultural sectors. The "no access" scenarios assume no counterbalancing price support policies on clean fuels and stoves, while the two "access" scenarios model a universal subsidy covering 15% of the cost of LPG cooking stoves and 75% of the cost of LPG fuel.

The AAP and CCA scenarios were developed independently in the MESSAGE-GLOBIOM global energy-economy IAM framework (IIASA 2021) based on the same national CO_2 budget constraints and projections of population growth, urbanisation and various regionalised economic activities. The AAP projections were generated within the Greenhouse-Gas Air Pollution Interaction and Synergies (GAINS) module, while the clean access transitions were modelled within the Access household fuel-choice module of MESSAGE-GLOBIOM. More details on the climate-energy modelling and the linkages of the different modules can be found elsewhere (Cameron *et al* 2016; Purohit *et al* 2019).

Scenario	**Climate Change Mitigation**	**Ambient Air Pollution Control**	**Clean Cooking Access**
NPi without access policy	National Policies for climate, energy, environment and development until 2030, no climate policy after 2030.	Current air pollution legislation	No additional clean cooking access support policy
2° C without access policy	National Policies until 2020, after which mitigation measures in line with a >66% chance of staying below 2°C throughout 21st century.		No additional clean cooking access support policy
2° C with access policy			15% LPG cooking stove & 75% LPG cost subsidies available to all households
2° C MFR without access policy		Maximum Feasible Reduction (MFR) of air pollution	No additional clean cooking access support policy
2° C MFR with access policy			15% LPG cooking stove & 75% LPG cost subsidies available to all households

***Table 1*: Scenarios description**

NPi – National Policy Implementation, MFR – Maximum Feasible Reduction

Static microsimulation For each year and scenario, we generated datasets with individuals with identical characteristics to those in the stage one dataset. We applied a reweighting procedure to reproduce the changes in the demographic characteristics of children under-5 over time (age, sex, subnational state, urban/rural place of residence, maternal education) as forecasted by a multi-dimensional demographic projection for India (Samir *et al* 2018). The population projection assumes a continuation of past demographic trends, leading to a decline in fertility and in child mortality, improvement in educational attainment and increase in urbanisation (Table S2). In each simulated dataset we altered the individual $PM_{2.5}$ exposure during pregnancy, the income category and the household primary cooking fuel based on projections from the IAM, keeping other covariates fixed.

Under each scenario for the period 2010-2050, gridded annual mean $PM_{2.5}$ concentrations from the GAINS model were matched with the simulated datasets based on the geographic coordinates of NFHS-4 clusters.

Data on changes in income levels and uptake of clean cooking fuels from the MESSAGE-Access household fuel-choice model were available for the whole of India and for four socio-economic groups based on rural-urban residence and daily per-capita expenditure threshold (Purchasing Power Parity of $2 per day in rural and $5 per day in urban areas) (Cameron *et al* 2016). We translated aggregate level projections into individual cooking fuel choices based on several assumptions. First, we assumed the same rate of change in income and uptake of cleaner cooking fuels for all regions. Second, for each future year and scenario we generated an indicator of household income level based on the household wealth index from NFHS-4 and the projected population distribution in each income category from the IAM (appendix 1.2). Third, we ranked fuel preferences following the theory of the "energy ladder" and assumed that as households´ economic status improves they tend to gradually shift to cleaner fuels (Van Der Kroon *et al* 2013) (appendix 1.2). To account for the importance of socio-demographic factors in determining household fuel choice, we conditioned transition to clean cooking on maternal educational level. We used the regression model specified in the epidemiologic analysis (Stage one) to predict the probability of stunting under the specified scenarios for each individual in the dataset. The adjusted sampling weights were then applied to estimate the stunting prevalence in the population under each scenario.

We performed posterior simulations to derive 95% uncertainty intervals (UIs) (appendix 1.3). Lack of confidence bounds in the projections of ambient $PM_{2.5}$, access to clean cooking fuels, income, and population change limited our ability to incorporate these uncertainties in our final estimates. We performed a sensitivity analysis by re-running the simulations after calibration of modelled $PM_{2.5}$ concentrations in GAINS with those from the Atmospheric Composition Analysis Group (appendix 1.4).

Results

Epidemiological analysis

We included 203,870 children from the NFHS-4 in our final sample, after removing missing observations, children that died or changed location since birth. Summary statistics for the exposure variables and other covariates by stunting status are presented in Table S1. Children were on average exposed to 73.6 μg/m^3 $PM_{2.5}$ in-utero, while 67% of them lived in households without CCA. There were large regional variations in ambient and household air pollution exposure as well as in stunting prevalence (Figure 1).

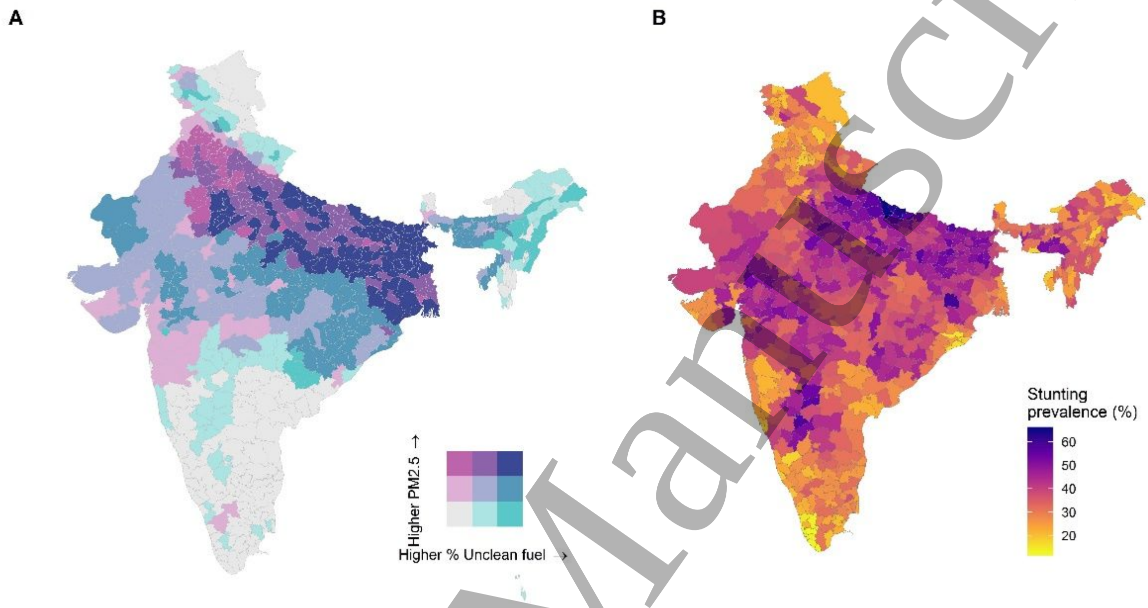

***Figure 1*: Map of India showing (a) children's district-level mean ambient $PM_{2.5}$ exposure in-utero (μg/m^3) and households using polluting cooking fuel (%) in 2015, and (b) district-level prevalence of stunting among children under-5 in 2015.**
All values are weighted using sampling weights of NFHS-4.

After adjustment for confounders, in-utero exposure to ambient $PM_{2.5}$ significantly increased the odds of child stunting (OR: 1.04, 95% CI: 1.03-1.05 per 10 μg/m^3 increase in $PM_{2.5}$), while clean compared to polluting cooking fuel decreased the odds of stunting (OR: 0.81, 95% CI: 0.79-0.84) (Table S3). We observed modification of the effect of in-utero $PM_{2.5}$ exposure on stunting by sex, residence (urban/rural), maternal education, caste, and household income (p interaction term < 0.05). The effect of CCA was modified by sex and caste (p interaction term < 0.05). In particular, female children, those living in urban areas, born to less educated mothers, belonging to more disadvantaged castes and to lower income households were more susceptible to the harmful effects of $PM_{2.5}$ on linear growth. Conversely, the beneficial effects of CCA on child stunting were more pronounced for children who were female and did not belong to socially disadvantaged castes. Similar to Spears *et al* (2019) we found no evidence of a non-linear association between $PM_{2.5}$ in-utero exposure and child stunting. Adjusting for additional covariates including month of birth to account for seasonal variation in exposures had minimal effect on the exposure effect estimates (Figure S1). Adjusting for MAD among children aged 6-23 months did not change observed associations between ambient $PM_{2.5}$ in-utero and clean cooking fuel use with child stunting (Table S4). While MAD was associated with lower odds of child stunting in models without adjustment for socio-economic status (Table S4, model 3), the association was fully attenuated after adjusting for urban residence and socio-economic status (Table S4, model 2), suggesting nutritional status is not an important confounder in models with already adjusted for socio-economic status and urban residence. As we used annual $PM_{2.5}$ data in the analysis, we could not test the effect of $PM_{2.5}$ exposure in different trimester periods on child stunting. In-utero exposure to ambient $PM_{2.5}$ was more strongly associated with child linear growth than life-course exposure (in-utero and after birth) (Figure S1).

Projections of impacts on stunting

Projected in-utero ambient $PM_{2.5}$ exposure and the share of population with CCA by residence and year are shown in Table 2. Under most scenarios average in-utero $PM_{2.5}$ exposure was projected to decrease and CCA to increase over time relative to the baseline year both for rural and urban areas. The largest reductions in ambient $PM_{2.5}$ were observed in scenarios where climate change mitigation was accompanied by end-of-pipe AAP controls, while population access to clean cooking was maximised in scenarios with additional access support policies. The projected characteristics of children under-5 were identical across all scenarios (Table S2).

Scenario	**Year**	**Average in-utero ambient $PM_{2.5}$ ($\mu g/m^3$)**		**Share of children living in households with CCA (%)**	
		Rural	**Urban**	**Rural**	**Urban**
	2015	45	58	17	73
NPi without access policy	2030	50	61	53	90
	2050	57	73	65	95
2° C without access policy	2030	48	59	36	80
	2050	49	60	49	90
2° C with access policy	2030	48	59	77	96
	2050	49	60	90	97
2° C MFR without access policy	2030	39	48	36	80
	2050	22	30	49	90
2° C MFR with access policy	2030	39	48	77	96
	2050	22	30	90	97

Table 2: **Baseline and projected exposure variables according to scenario and year**
The 2015 values for CCA are calculated based on NFHS-4 data, applying sampling weights. Ambient $PM_{2.5}$ concentrations and future CCA are based on the GAINS and MESSAGE-Access modelled data, respectively, applying adjusted sampling weights to account for changes in demographics, urbanisation and maternal education over time.

Figure 2 and Table S5 show the cumulative (2020-50) preventable number of stunted children over time under each intervention scenario compared to NPi and disaggregated by the contribution of changes in AAP and HAP. In the 2°C scenario without access policy, the increase in child stunting from higher HAP (+ 4 million) is larger than the reduction in the burden from AAP (-1.2 million), leading to an overall higher cumulative number of stunted children compared to NPi (2.9 million, UI: 2.8, 3.0). However, accompanying the 2°C mitigation efforts with additional AAP control or CCA support is projected to reduce the overall burden of child stunting from air pollution compared to NPi. Implementation of national policies for maximum feasible reduction of AAP can help prevent 2.8 (UI: 1.4, 4.2) million cases of child stunting between 2020-50, while compensatory subsidies for LPG cooking fuel and stoves can avert growth faltering in 6.5 (UI: 6.3, 6.9) million children. The joint implementation of the two policies along with mitigation efforts had synergistic effects for child growth, i.e. yielded greater health benefits than the sum of health benefits from individual implementation, and prevented linear growth impairment in 12.1 (UI: 10.7, 13.7) million children compared to NPi. Sensitivity analysis with calibrated ambient $PM_{2.5}$ data did not notably affect the final results (Table S6 and S12, S13).

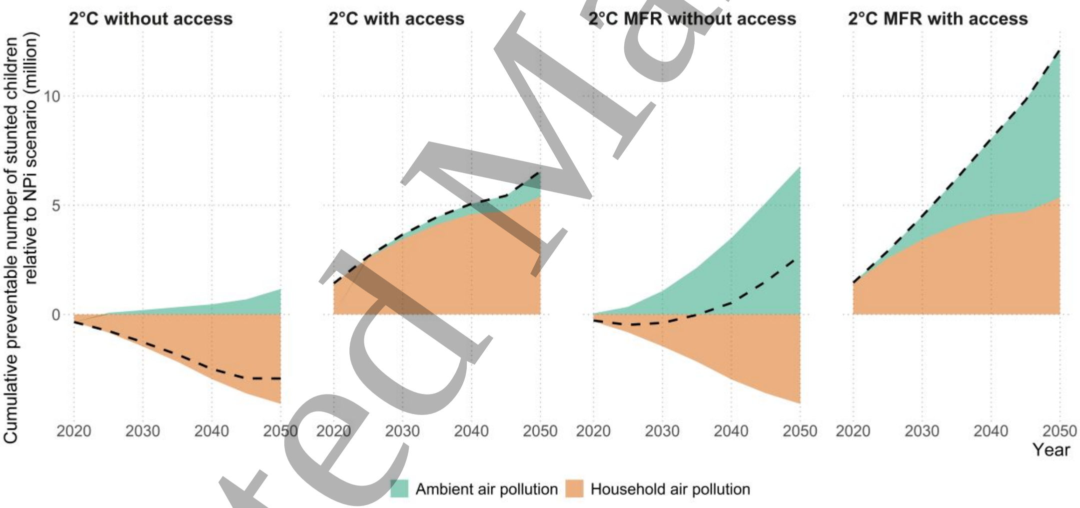

***Figure 2*: Cumulative preventable number of stunted children (in million) from changes in household air pollution (orange), ambient air pollution (green) and household and ambient air pollution combined (dashed black line) according to mitigation scenario and year relative to NPi scenario.**

The benefits of the most aspirational scenario (2°C MFR with access policy) compared to NPi differed by population groups (Figure 3 and Tables S7-S11). While all children benefited from improvements in indoor and outdoor air quality under the 2°C MFR with access policy scenario compared to NPi, child linear growth improved the most among more disadvantaged groups with the highest prevalence of stunting in 2015. Larger difference in the prevalence of child stunting in 2050 between the 2°C

MFR with access policy and the NPi were estimated for children living in poorer households (– 6.3% compared to – 2.3% for richer households), belonging to a scheduled caste or tribe (– 3.6% compared to – 1.6% for those from other castes) or having an uneducated mother (– 5.8% compared to – 2.2% for those with highest maternal education). The benefits of the 2°C MFR with access policy scenario in 2050 were similar for both sexes and for urban and rural residents, thus only marginally reducing existing disparities in child stunting among these groups.

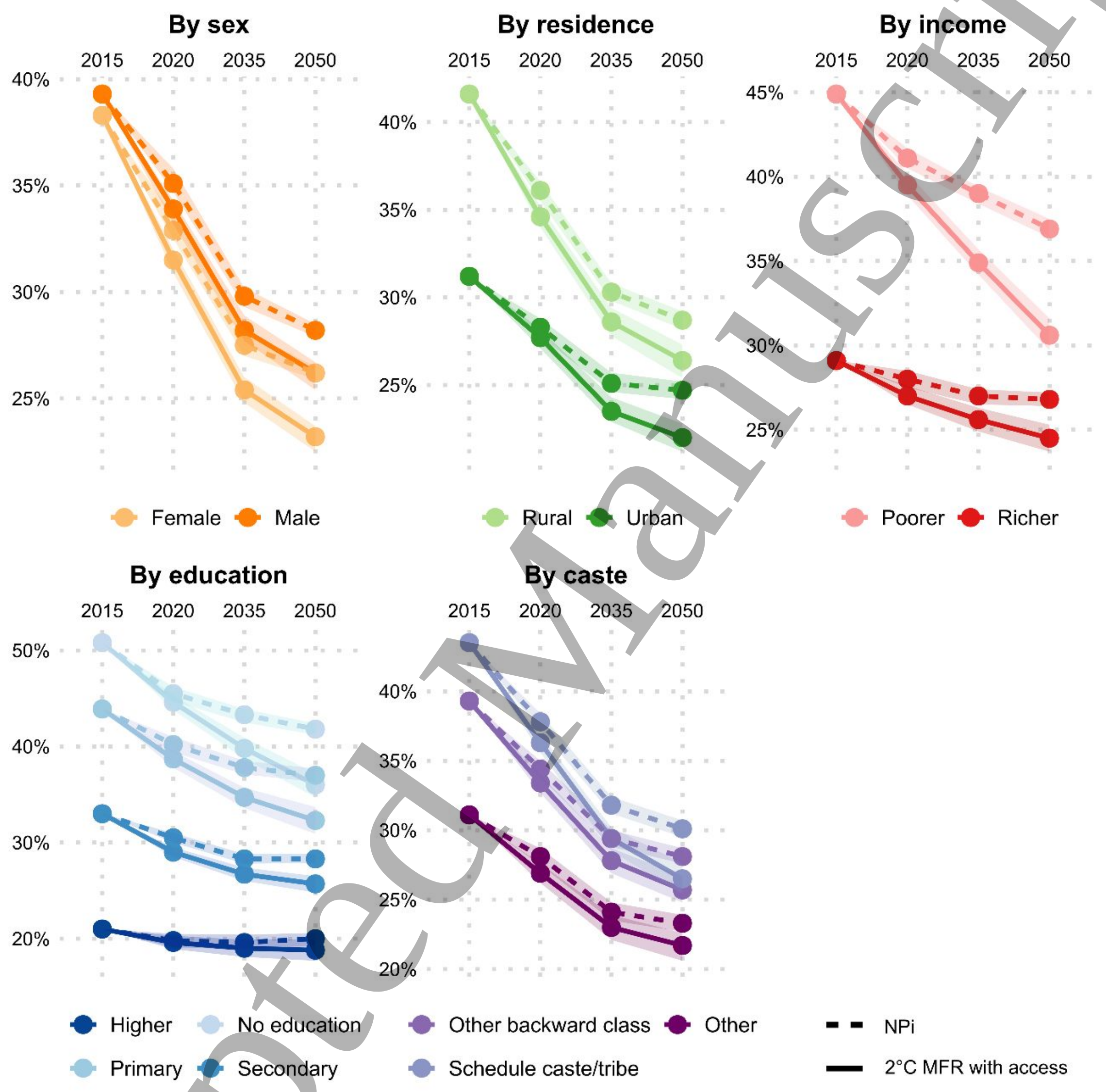

Figure 3: Projected trends in stunting prevalence (children under-5) by population sub-group under NPi and 2°C MFR with access policy scenarios

Similarly, implementation of the 2°C MFR with access policy scenario was projected to reduce stunting prevalence in the districts with the highest burden of child stunting in 2015, especially in North-eastern India and around the Indo-Gangetic Plain (Figure 4). In 2050, largest reductions in the prevalence of child stunting were recorded in the Purbi Singhbhum and Saraikela Kharsawan districts in Jharkhand (– 6%) and in districts within the National Capital Territory of Delhi (– 7%), almost three times higher than the India average (– 2.5%) (Figure 4).

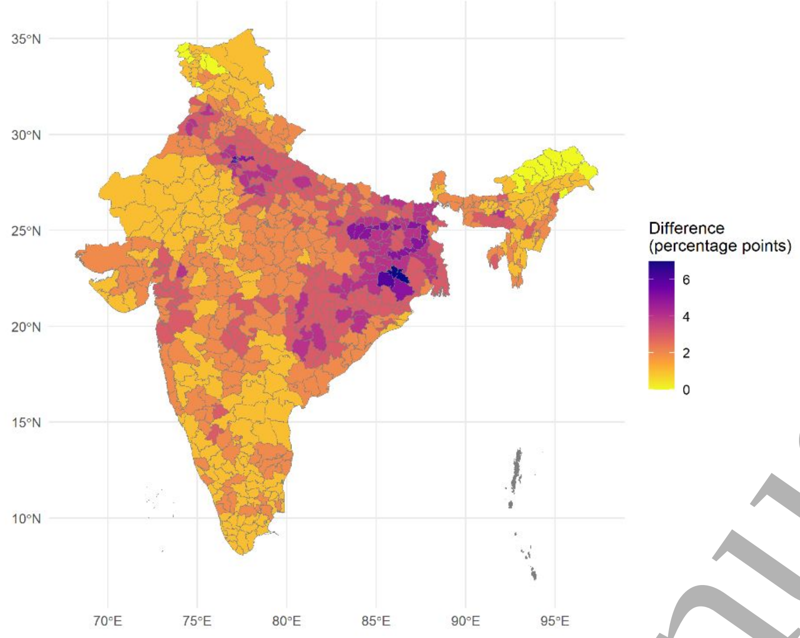

***Figure 4:* Percent difference in projected prevalence of child stunting in 2050 between the 2°C MFR with access policy and NPi scenarios according to administrative district.**

Discussion

We used a static microsimulation model to assess the potential impacts of changes in AAP and HAP on child linear growth impairment in India under four policy scenarios for delivering on the Paris Agreement climate change mitigation target. Our analysis resulted in several key findings. First, the slower transition to clean cooking fuels under climate change mitigation could fully cancel out projected benefits for child linear growth due to reduced AAP without additional policies. Second, net benefits for health could still occur if stringent climate policy were complemented by well-designed national end-of-pipe air quality control or universal clean cooking access subsidies. These policies could prevent stunting in 2.8 (UI: 1.4, 4.2) million and 6.5 (UI: 6.3, 6.9) million children between 2020-2050, respectively, compared to business-as-usual. Third, optimal results for child growth can be achieved when mitigation action is combined with both complementary policies (stunting avoided in 12.2 (UI: 10.7, 13.7) million children). This policy pathway could also provide an opportunity to reduce inequalities in health and human capital early in life by benefiting the most underprivileged children – those with lowest household income, maternal education and social status.We estimated that implementation of integrated climate, air quality and energy access policies would help reduce stunting in locations where it is currently most prevalent (e.g. Indo-Gangetic Plain, north-east). Due to the high concentrations of ambient $PM_{2.5}$ and high levels of poverty and reliance on polluting cooking fuels, children in these regions would particularly benefit from the combined ambient air pollution controls and clean cooking access policies.

We used a novel health impact modelling approach, which allowed for an in-depth assessment of complex population-environment dynamics and multiple exposure pathways on human health not captured by comparative risk assessment methods. Compared to other modelling approaches that allow for comprehensive evaluation of the distributional effects of policies including dynamic microsimulations and agent-based models, a particular advantage of static microsimulation is the more modest modelling and computational requirements. We identified a number of socio-economic effect modifiers for the two exposure variables in the first stage of the analysis. The static microsimulation approach allowed us to reflect these heterogenous individual effects in the health impact assessment without the full computational burden of a dynamic microsimulation. By using a re-weighting procedure, we accounted for changes in many important socio-demographic characteristics of the population – age, sex, urban residence, region and maternal education – without having to perform a multidimensional demographic projection. The combination of static microsimulation with integrated assessment models and demographic projections offers a flexible and efficient approach for meeting the policy demand for projections that assess long-term health impacts and differential population vulnerabilities related to climate change.

Our findings, which differentiate impacts across multiple population subgroups and regions, could inform more targeted national- or local-level efforts to improve air quality and clean cooking access. However, policy makers may also have other policy tools at their disposal for increasing clean energy access apart from universal LPG price support, such as microfinance or clean cooking subsidies targeting only the most vulnerable. The health gains of modelled policies will depend on effective enforcement and overcoming legal, financial, social, behavioural and other barriers to their sustained implementation (Peng *et al* 2020, Malakar *et al* 2018, Sharma *et al* 2020). The Indian Government provides subsidies for LPG consumption and connection through the Pratyaksh Hanstantrit Labh Yojana and Pradhan Mantri Ujjwala Yojana programmes. Despite the success of the two programmes in rapidly increasing LPG adoption, they have been less effective in ensuring sustained use, especially among low-income rural households (Kar *et al* 2019, Sharma *et al* 2021). Poor and socially marginalised households face major obstacles in accessing LPG subsidies as a result of their informal living situation, precarious income, limited access to information and physical and social isolation (Neto-Bradley *et al* 2021, Saxena and Bhattacharya 2018). Therefore, designing government support with consideration to the specific needs and constraints of different types of households will be important for realising the equity benefits of the modelled interventions.

Our analysis has a number of limitations. First, although the ambient $PM_{2.5}$ and the clean cooking access projections in our model were developed within the same IAM, they were not fully integrated. The effect of clean energy uptake on ambient $PM_{2.5}$ exposure was not considered, leading to a possible underestimation in the reductions in ambient $PM_{2.5}$. Chowdhury *et al* (2019) showed that complete mitigation of biomass emissions from cooking in 2015 would have reduced ambient $PM_{2.5}$ concentrations in India by 17.5%. The likely underestimation in our analysis would be smaller since the difference in clean cooking access in our mitigation scenarios with and without access in 2050 was 29 % rather than 100 %. Ambient $PM_{2.5}$ reductions from end-of-pipe air quality control on indoor air quality were not reflected in the MFR scenarios since we used CCA as a proxy of indoor air pollution exposure. The adoption of more efficient biomass cookstoves modelled in the MFR scenarios was also not implemented as NFHS does not include data on type of cooking stove. However, this effect is likely to be small as improved biomass cookstoves have resulted in minimal health benefits (Sambandam *et al* 2015). Second, we did not explicitly model fuel stacking due to lack of data on use of multiple fuels in NFHS-4. Fuel stacking is a well-documented behavioural response to volatile fuel supplies and prices, household incomes, or a result of cultural preferences (Van Der Kroon *et al* 2013). Accounting for fuel stacking would likely lead to somewhat smaller estimated benefits of CCA policies on child stunting given that some households might not use clean fuels exclusively. Third, projected trends in average daily per-capita income and clean fuel use were available only at aggregate level from the IAM. Differences in trends in average per-capita income and CCA across states in our model thus only reflect disparities in 2015. As higher resolution energy, population and income projections from IAMs and demographic models become available in the future, more refined geographical variations in health impacts could be assessed. Fourth, our scenarios did not explicitly consider expansion of electrification. Our analysis focused on LPG intervention scenarios due to the dominance of LPG in national policy plans for expansion of clean cooking access in India and because historically electricity has rarely been used for cooking purposes in South Asia. While this could change in the future, in the short to medium term, electricity is unlikely to become a dominant means of meeting cooking energy needs. While we do not explicitly model electricity access, the effect on indoor air quality from cooking with electricity or LPG is assumed to be identical. Fifth, our sensitivity analysis did not indicate that nutrition (measured as MAD) was a confounder of the AAP or HAP stunting associations conditional on household income and other socioeconomic variables. However, MAD was based only on feeding practices on the day or evening preceding the survey and may not fully reflect longer-term nutritional status and we cannot rule out possible residual confounding. Finally, the population, energy and income projections in our model do not reflect the catastrophic effects that COVID-19 has had on population health, the economy, and clean energy access. Although the full impacts of the crisis are still to be fully evaluated, research suggests that the pandemic might slow down the transition to clean cooking fuels and other development objectives (Ravindra *et al* 2021;

Pachauri *et al* 2021) and affect global investments in emission reductions (Reilly *et al* 2021).

Future extensions of this modelling approach could focus on incorporating dynamic feedback effects and behavioural responses such as the effects of air pollution on child survival over time or the influence of child stunting on educational attainment and adult survival later in life. In addition, an extension of this analysiscould evaluate the balance of costs between scenarios. Both the end-of-pipe air quality measures and the CCA subsidies presented here entail additional policy costs besides mitigation finance. However, previous research has shown that avoided premature mortality through climate change mitigation or MFR of ambient air pollution in India will considerably outweigh the potential implementation costs (Sanderson *et al* 2013; Markandya *et al* 2018). Additional finance to cover subsidies for universal CCA could be mobilised through effort-sharing international climate regimes (Cameron *et al* 2016). The anticipated improvements in child linear growth, both through air pollution co-benefits and through avoided impacts from climate change via income and food prices (Lloyd *et al* 2018), represent a human capital investment, which is likely to bring substantial savings through higher productivity, reduced morbidity, work absenteeism and associated health care costs. Future studies should consider other pathways through which climate change can impact child health in India. The adverse effects associated with increases in rainfall, heat stress and extreme weather events (floods/draughts) on child linear growth have been well documented (Dimitrova and Muttarak 2020, Phalkey *et al* 2015, Cooper *et al* 2019, Tusting *et al* 2020, Muttarak and Dimitrova 2019, Baker 2020, Belesova *et al* 2019). Some of these effects are mediated by altered patterns of water- and vector-borne infections, quality and quantity of crops, food prices and household income (Myers *et al* 2017, Phalkey *et al* 2015). Considering these multiple causal pathways, stringent climate change mitigation is likely to bring much larger benefits to child linear growth than those quantified in this study. Previous studies have also reported a strong social gradient for some of these effects, with the poorest and least educated being most affected (Dimitrova and Muttarak 2020). More detailed consideration of the timing, magnitude and equity implications of the multiple impacts of climate change on child health, apart from energy access and outdoor air quality, would be important for a more accurate comparison of the trade-offs and benefits of mitigation action in India.

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