Effects on Well-Being of Investing in Cleaner Air in India

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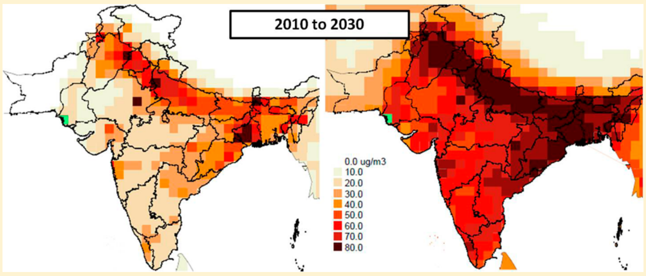

ABSTRACT: Over the past decade, India has experienced rapid economic growth along with increases in levels of air pollution. Our goal is to examine how alternative policies for air pollution abatement affect well-being there. In particular, we estimate the effects of policies to reduce the levels of ambient fine particulates ($PM_{2.5}$), which are especially harmful to human health, on well-being, quantified using the United Nations' human development index (HDI). Two of the three dimensions of this index are based on gross domestic product (GDP) per capita and life expectancy. Our approach allows reductions in $PM_{2.5}$ to affect both of them. In particular, economic growth is affected negatively through the costs of the additional pollution control measures and positively through the increased productivity of the population. We consider three scenarios of $PM_{2.5}$ abatement, corresponding to no further control, current Indian legislation, and current European legislation. The overall effect in both control scenarios is that growth in GDP is virtually unaffected relative to the case of no further controls, life expectancy is higher, and well-being, as measured by the HDI, is improved. In India, air pollution abatement investments clearly improve well-being.

INTRODUCTION

Costs of environmental measures, such as those of reducing levels of air pollution, are often seen as an impediment to economic development. This common perception emerges from a narrow focus on the direct costs of mitigation measures. Because these expenditures do not contribute to the value of newly produced goods and services that are traded in markets, they are not counted in the gross domestic product (GDP) per capita, which is often used as a surrogate for development and even well-being.

However, this perspective ignores the fact that investments in cleaner air also have indirect impacts on economic performance. Lower morbidity due to better air quality will reduce the number of sick days experienced by the working population and thereby increase productivity.[1] Lower mortality will extend life expectancy, and people who expect to live longer will, in general, accumulate more assets in their working years, thereby increasing capital formation for productive investments.[2−5] Once such indirect effects of investments in cleaner air are taken into account, it is no longer obvious how spending to reduce air pollution will affect GDP.

Moreover, GDP per capita fails to capture other important aspects of well-being, such as life expectancy. We develop a more comprehensive perspective to assess the consequences of investments in cleaner air on the economic development and human well-being. In particular, we quantify the impacts of such investments on the United Nations' human development index (HDI),[6] a widely used metric that combines GDP per capita, longevity, and education as three important dimensions of human development. We note that while the HDI improves upon narrow measures of well-being, it still does not tell the whole story. For example, surveys suggest that cleaner air is considered an improvement in the quality of life,[7−9] a source of improvement in well-being not considered here.

Our case study focuses on measures to reduce the negative effects on longevity of exposure to fine particulate matter ($PM_{2.5}$) in India. $PM_{2.5}$ comprises particles with an aerodynamic diameter of <2.5 μm, which travel far down into the lungs and contribute to a wide variety of ailments, including cardiovascular diseases, vascular inflammation, asthma, lung cancer, atherosclerosis, and COPD (including emphysema and chronic bronchitis).[10,11] A wide body of studies demonstrates that these health effects are significant in both industrialized and developing countries.[12−14] For example, approximately one-third of the increase in life expectancy in cities in the United States between 1980 and 2000 has been attributed to a decline in $PM_{2.5}$ levels.[12] Globally, outdoor air pollution resulted in an estimated 2.7 million premature deaths in 2005.[15]

We focus on India because of its high and rapidly increasing levels of $PM_{2.5}$ pollution[16,17] and the large population at risk. According to earlier GAINS model results,[18] the annual average concentration of $PM_{2.5}$ in 2005 exceeded the World Health Organization (WHO) guideline of 10 $\mu g/m^3$ by a factor of more than 2 throughout most of India. It typically reaches 50–100 $\mu g/m^3$ in the Ganges valley, a level above which significant effects on survival are observed.[11,13] These estimated overall concentrations are in agreement with the latest measurements.[19] If the level of consumption of energy in India grows as expected, without additional air pollution control measures, the concentrations of anthropogenic $PM_{2.5}$ in many parts of India will more than double by 2030. There would also certainly be significant increases in $PM_{2.5}$-induced mortality and morbidity.

Another reason to focus on India is that the costs of air pollution abatement could be perceived as being large in relation to the low income per capita. In this respect, a more comprehensive understanding of the true costs and benefits involved would include implications for human well-being and long-term macroeconomic indicators. The goals of this paper are therefore to quantify the likely effects of various policies to reduce ambient $PM_{2.5}$ concentrations resulting from anthropogenic sources and to assess the overall contribution of these policies to well-being. Rapid economic growth and the associated rapid increase in the level of damaging ambient $PM_{2.5}$ make this determination especially germane at present.

METHODOLOGY

The linkage of two models that address key aspects of development and human well-being is central to our approach. We employ the Greenhouse Gas–Air Pollution Interactions and Synergies (GAINS) model for Asia[20−22] to estimate current and future emissions of air pollutants in India and their impacts on ambient $PM_{2.5}$ concentrations, as well as the costs of different emission control scenarios. This information is then used in a simple economic demographic interaction model (hereafter termed SEDIM)[23,24] to estimate the macroeconomic impacts of these investments and to specify how they affect the components of the HDI.

2.1. GAINS Model. Our assessment of future levels of precursor emissions of $PM_{2.5}$, abatement costs, and ambient $PM_{2.5}$ concentrations is derived from the GAINS model. In general, GAINS estimates current and future emissions based on projections of fuel use and industrial production (in this case, the World Energy Outlook 2009[16] was used). It takes into account emissions of primary $PM_{2.5}$, SO_2, NO_x, and NH_3 as relevant precursors for ambient atmospheric $PM_{2.5}$, as well as a number of possible emission abatement measures. For example, for large-scale power stations, the possible emission abatement measures include coal cleaning, limestone injection, and various kinds of flue gas desulfurization. In the particular case of India, GAINS does not currently consider changes in NH_3. It is therefore not included in the table of results. Instead, in the calculations presented here, the level of NH_3 is assumed to be constant at the level reported in ref 25. Major differences in emission characteristics of specific sectors and fuels are reflected in GAINS through source-specific emission factors. The results obtained for India have been extensively verified together with national experts from The Energy and Resources Institute (TERI), and the emissions model reproduces nationally reported emissions accurately.[19] (For a comparative overview, see section S7 of the Supporting Information.)

On the basis of the detailed sectoral emission inventory described in the previous paragraph, GAINS estimates ambient concentrations of $PM_{2.5}$ across India with the help of source–receptor relationships derived from the global chemistry transport model TM5.[26] The TM5 model works on a 1 × 1 degree grid resolution, taking into account the spatial allocation of emissions, weather conditions, and the chemical transformation of precursors. It calculates ambient concentrations of $PM_{2.5}$, which result from (i) primary particulate matter released from anthropogenic sources, (ii) secondary inorganic aerosols formed from anthropogenic emissions of SO_2, NO_x, and NH_3, and (iii) particulate matter from natural sources (soil dust, sea salt, and biogenic sources).

The mitigation potential for the precursor emissions assessed in this analysis refers to the application of technologies that are currently commercially available on the world market. For each emission control measure, investments and operating costs are estimated. International data on technology costs are adjusted to represent Indian conditions, taking into account local costs for labor, energy, water, and other byproducts.[27−29]

In this paper, we limit our analysis to technical end-of-pipe measures and exclude nontechnical mitigation options that involve changes in human behavior and preferences (e.g., using a bus instead of a car). Improvements with regard to energy efficiency of biomass stoves and cement and brick kilns, which produce ~80% of the primary $PM_{2.5}$ emissions, also have a cost saving potential for which GAINS does not fully account. We also assume the uniform application of additional emission control measures throughout India and thereby ignore the cost-saving potential from spatially optimized emission control strategies, which could achieve the same environmental benefits at substantially lower costs.[21] Our assumptions, then, are likely to produce a substantial overestimate of the abatement costs. We show below that the effects on GDP of increased expenditures on abatement are trivially small, even with overestimated costs.

2.2. SEDIM Model. For our economic analysis, we use SEDIM, a relatively simple single-sector macroeconomic model that distinguishes three proximate sources of economic growth: growth of the labor force, adjusted for age and educational composition (L_t); growth of the capital stock (K_t); and growth of productivity (A_t). All other factors that influence economic growth, including the impacts of air pollution controls and their related costs, must do so through their effects on one of these.

Reductions in levels of $PM_{2.5}$ affect L_t by affecting mortality. To assess the size of the effect, our model needs to explicitly consider the age and educational structure of the aggregate and working-age populations. In addition to that, reductions in the level of exposure of the population to $PM_{2.5}$ also reduce the number of sick days, thus increasing labor productivity. The impact of variation in exposure to ambient $PM_{2.5}$ on K_t results from its effect on life expectancy. Policies aiming at reducing the level $PM_{2.5}$ change remaining life expectancies and thus affect saving behavior. Finally, reductions of ambient $PM_{2.5}$ levels indirectly affect A_t, because of changes in the education distribution of the population.

2.3. Interface between GAINS and SEDIM. The GAINS model allows for the application of different levels of emission controls and calculation of resultant emissions, $PM_{2.5}$ concentrations, and costs. Using this information as an input, the corresponding macroeconomic effects can be calculated in SEDIM.

Table 1. Primary Emissions of SO_2, NO_x, and $PM_{2.5}$ (kiloton per year) from 2010 to 2030 under the Baseline Scenario (NFC) and Two Control Scenarios

	NFC			ICL			ECL		
year	SO_2	NO_x	$PM_{2.5}$	SO_2	NO_x	$PM_{2.5}$	SO_2	NO_x	$PM_{2.5}$
2010	6755	4374	5119	6755	4374	5119	6755	4374	5119
2015	8658	5304	7467	8468	4971	5270	6927	4576	4960
2020	10500	6536	10024	10116	6022	5446	1591	2842	3585
2030	15541	10660	16545	14515	9483	5736	2218	3619	3420

2.3.1. Mortality and $PM_{2.5}$. We follow the American Cancer Society's cohort study[13] and reanalysis[12] and specify that the age-specific risk of dying for adults is related to the level of $PM_{2.5}$ as follows:

$$\mathrm{dr}^{\mathrm{scen}} = \mathrm{dr}^{\mathrm{base}}(1 + \gamma \mathrm{PM}_{2.5}^{\mathrm{scen}})$$

where $\mathrm{dr}^{\mathrm{scen}}$ is the death rate in one of our scenarios, $\mathrm{dr}^{\mathrm{base}}$ refers to the baseline death rate, and γ is the sensitivity of the death rate to future changes in the level of $PM_{2.5}$. In the baseline, we employ the United Nations' death rates forecasted for India.

In developed countries, where both mortality in general and ambient $PM_{2.5}$ levels are much lower than in India, a 10 $\mu g/m^3$ increase in the concentration of this pollutant has been found to increase the relative risk (RR) of mortality in adults by 4–6%.[13] For our central case, we adopt the lower (conservative) figure, which is well within the range employed by the recent "Global Burden of Disease" study.[30] However, there is evidence, based on cause-specific mortality, that $PM_{2.5}$ has an even stronger effect in India than, for example, in the United States because of the difference in age structures. While peak effects were observed among people ≥65 years of age in Philadelphia,[31] in Delhi these were reported in people 15–44 years of age. This implies more life years lost as a result of a death associated with air pollution in India.[32,33] To assess the sensitivity of our results, we also calculated an example using the higher relative risk (see section S5 of the Supporting Information).

The equation given above is applied, by single-year age groups, to the population >30 years of age because there are no data for the effects of $PM_{2.5}$ on people <30 years of age. Many children in India are exposed to high levels of indoor air pollution from cooking stoves. Were we able to take this into account, there would be more lives saved because of pollution abatement than we calculate.

2.3.2. Morbidity and $PM_{2.5}$. Low air quality affects L_t in a number of ways, not all of which can be quantified in their effect on productivity, let alone human well-being. In our analysis, we concentrate on lost working days. We follow Hurley et al.,[1] assuming 0.0046 lost working day for every 1 $\mu g/m^3$ increase in the ambient level of $PM_{2.5}$. While this number is based on evidence from the United States that might not be transferable to the case of India, we guard against the possibility of overemphasizing the effect by ignoring restricted-activity days. As these are considerably more frequent than work-loss days, we systematically underestimate productivity gains from a lower level of $PM_{2.5}$ exposure.

SCENARIOS OF FUTURE EMISSIONS AND AIR QUALITY IN INDIA

3.1. Scenarios. To parametrize the GAINS and SEDIM models and construct future scenarios, we reproduce the World Energy Outlook (WEO) 2009 reference projection for India (see section S3 of the Supporting Information), which assumes the continuation of current trends and practices.[16] In particular, GDP is assumed to increase by a factor of 3.4 between 2010 and 2030, accompanied by a doubling in the total level of consumption of energy. This corresponds to an increase in the level of coal use by a factor of 2.4, while the level of biomass use, another important source of precursor emissions of $PM_{2.5}$, increases only marginally (by ~9%).

Given this reference projection, we explore three air pollution control scenarios: (1) a baseline stipulating that no additional emission control measures are introduced after 2010 [no further controls (NFC)], (2) a scenario assuming the implementation of measures currently specified in Indian air pollution legislation [Indian current legislation (ICL)], and (3) a scenario simulating the application, in India, of the advanced emission control measures of the European Union [European current legislation (ECL)]. ICL includes controls on dust emissions from the power sector and industry complying with national emission limit values. ICL also incorporates controls on the sulfur content of liquid fuels for the residential, commercial, and transport sectors, as well as gradual introduction of improved cooking stoves and emission limits for road transport according to European legislation.[18] Emissions of sulfur from the power sector and industry remain uncontrolled. ECL follows the Proposal for the Industrial Emissions Directive[34] in controlling stationary sources in the power sector and industry. For transport sources, ECL means the phasing-in of EU legislation up to Euro 6 for road transport and up to stage 4 for nonroad sources. For industrial and small combustion sources, German legislation is applied if stricter than the EU-wide legislation. Note that with regard to cooking stoves, ECL uses the same assumptions as the ICL. The energy scenario underlying all policy interventions includes a general trend to cleaner fuels, leading to a reduction in the share of biomass from 66.6% in 2010 to 48.9% in 2030 (for details, see ref 35). In both scenarios, we assume that new control measures are gradually phased in between 2010 and 2020, and that beginning in 2021, all new emission sources comply with these more stringent standards. Using this approach, we are able to capture the two phases of policy implementation, i.e., buildup and maintenance.

3.2. Emissions and Emission Control Costs. Under the baseline scenario, the growth in the level of consumption of energy increases emissions of SO_2, NO_x, and primary $PM_{2.5}$ by factors of 2.3, 2.4, and 3.2, respectively, between 2010 and 2030 (Table 1). As stated before, emissions of NH_3 are kept constant in this exercise. Successful implementation of current Indian legislation would lead to smaller increases for all three controlled pollutants, but especially $PM_{2.5}$, of 2.1, 2.2, and 1.1 times current emissions, respectively. Under the more stringent ECL scenario, emissions would be reduced, by 67% for SO_2, 17% for NO_x, and 33% for $PM_{2.5}$.

Implementation of additional emission control measures costs money. We assume that costs are socialized and consumers ultimately pay for pollution control through higher taxes. In addition to the cost of pollution abatement investments, we also take into account the costs of operating and maintaining the equipment. We assume annual operating costs of 10% of the value of the abatement capital in place and a mean lifetime of the equipment of 20 years. Inside GAINS, lifetimes and operating costs do of course differ by technology.

Table 2 displays additional air pollution control costs (i.e., investment and operating costs) over those in the baseline scenario as a percentage of GDP. Costs decline in comparison to GDP, largely because of rapid economic growth in India. In the Indian legislation scenario, building up the stock of $PM_{2.5}$ abatement capital costs approximately 7.5 billion 2000 international U.S. dollars (US$), corresponding to one- to two-tenths of a percent of GDP, per year from 2010 to 2020. Implementing advanced emission controls is more than 3 times as expensive, at around 26 billion 2000 international US$ or half a percent of GDP per year. In 2030, operating, maintaining, and ensuring that new capital meets legislative requirements costs roughly three-tenths of a percent of GDP per year under the ECL scenario, versus just more than one-tenth under ICL.

Table 2. Additional Air Pollution Control Costs over the NFC Scenario as a Percentage of GDP for Two Emission Control Scenarios

year	NFC	ICL	ECL
2010	0.000%	0.151%	0.537%
2015	0.000%	0.154%	0.546%
2020	0.000%	0.153%	0.426%
2030	0.000%	0.116%	0.292%

One way to put these pollution abatement policies into perspective is to compare them with other important national priorities. In 2005, India spent ∼3.8% of GDP on health and 3.2% on education (Table 3). Hence, over the first few years of implementation, the ECL would cost ∼4% of what is being spent on education and ∼5% of what is being spent on health.

Table 3. Expenditures on Health and Education as a Percentage of GDP in India from 2000 to 2006[a]

	2000	2001	2002	2003	2004	2005	2006
health expenditure, total (% of GDP)	–	–	4.5	4.2	4.0	3.8	3.6
education expenditure, total (% of GDP)	4.4	–	–	3.7	3.4	3.2	–

[a] from World Development Indicators, World Bank, 2009.

The forecasted increase in economic activity without corresponding emission controls would more than double exposure in India from anthropogenic sources by 2030 (Table 4), increasing the population-weighted mean concentration of anthropogenic $PM_{2.5}$ from 46 $\mu g/m^3$ in 2010 to 116 $\mu g/m^3$ in 2030. Full implementation of current Indian emission control legislation would limit the increase to ∼50% above current levels, while application of advanced emission standards would actually reduce population exposure by approximately one-third. While the reduction in long-term $PM_{2.5}$ concentrations under ICL is significant in comparison with the baseline scenario, the trend is still upward, and ICL is far from achieving the reductions seen under ECL. Note that the observed level of ambient $PM_{2.5}$ from anthropogenic sources in 2010 is already well above the WHO guideline of 10 $\mu g/m^3$, even without accounting for natural sources.

Table 4. $PM_{2.5}$ Concentrations (micrograms per cubic meter) for Three Emission Control Scenarios

year	NFC	ICL	ECL
2010	46	46	46
2015	60	52	38
2020	74	57	30
2030	116	72	31

IMPACT OF EMISSION CONTROL EFFORTS ON ECONOMIC GROWTH AND HUMAN WELL-BEING

To evaluate the broad consequences of air pollution abatement policies, we consider not only the macroeconomic effects on GDP but also the changes in the HDI. The HDI is a composite indicator developed by the United Nations to provide a more comprehensive measure of well-being than GDP alone. It is derived as the geometric mean of normalized indices of life expectancy at birth, education (educational attainment and school enrollment), and income per capita. In the following, we discuss the components of the HDI individually and then the composite indicator as a whole.

4.1. GDP. Table 5 displays the effects of air pollution control scenarios on GDP per capita, GDP per worker, and total GDP, relative to the baseline scenario. GDP growth in the baseline scenario, as discussed above, is given in the WEO.[16] Total GDP is expected to be >3 times higher in 2030 than in 2010 for all scenarios, corresponding to an average annual growth rate of ∼6%.

Table 5. GDP per Capita, GDP per Worker, and Total GDP under Three Scenarios in India in 2010, 2015, 2020, and 2030[a]

	year	NFC	ICL	ECL
GDP per capita	2010	4073	1.000	1.000
	2015	5514	1.000	1.001
	2020	7200	0.999	1.000
	2030	11135	0.996	0.995
GDP per worker	2010	6713	1.000	1.000
	2015	8849	1.000	1.001
	2020	11392	0.999	1.001
	2030	17308	0.999	1.002
total GDP (billions of 2000 international US$)	2010	4.96	1.000	1.000
	2015	7.16	1.000	1.001
	2020	9.90	1.000	1.003
	2030	16.79	1.001	1.007

[a] NFC in 2000 international US$. For ICL and ECL, figures represent the ratio relative to the baseline (NFC) scenario.

The investment in air quality improvements causes trivial changes in GDP per capita, GDP per person of working age, and overall growth of GDP. For example, GDP per capita grows at an average annual rate of 5.16% in the baseline scenario, whereas in the control scenarios, growth averages ∼5.14%. Essentially, the air pollution investments envisioned here have no discernible effect on economic growth. These changes in GDP growth in our scenarios incorporate increases in individual productivity resulting from a lower frequency of lost work days. The productivity changes themselves make a relatively small contribution to GDP growth. Had we included productivity effects from restricted-activity days as well, the forecasted decreases in GDP per capita would have been even smaller.

Macroeconomic effects of air pollution control policies can also be evaluated with respect to their impacts on consumption. Private consumption, as normally defined in economic models, is shown in Table 6. In per capita terms in 2030, it is 0.5% less in the ICL scenario than without new pollution abatement policies. The corresponding average annual rate of growth of private consumption is 5.66% in the baseline case and 5.63% in ICL. In the ECL scenario, the changes are slightly larger. In 2030, for example, individuals give up ~0.8% of their consumption to enjoy cleaner air.

Table 6. Forecasted Consumption per Capita in Three Scenarios in India in 2010, 2015, 2020, and 2030[a]

	year	NFC	ICL	ECL
consumption per capita	2010	3065	1.000	1.000
	2015	4291	0.998	0.993
	2020	5702	0.997	0.993
	2030	9213	0.995	0.992

[a] Consumption per capita in NFC in 2000 international US$. Figures for consumption in the control scenarios represent the ratio relative to the baseline (NFC) scenario.

There is also a second kind of consumption, namely, unavoidable consumption of (exposure to) $PM_{2.5}$ (as shown in Table 4 above). In the absence of more stringent emissions control regulations, nobody will be able to avoid "consuming" a much larger amount of particulate matter than if either control scenario is put in place.

4.2. Longevity. The second component of HDI is longevity. While exposure to pollutants in air will cause substantial premature mortality, life expectancy in India is nevertheless expected to increase, from 70.5 to 74.9 years by 2030, as a consequence of other factors related to economic development, such as improved nutrition, better health care, and access to clean water, among others. This is reflected in the results for the NFC scenario. Even so, life expectancy at birth is more than one year higher in 2030 in the ICL scenario than in the NFC scenario (Table 7). Under ECL, life expectancy in 2030 is 2.8 years higher than in the baseline.

Table 7. Life Expectancy at Birth and Lives Saved per Year for Three Different Scenarios in India in 2010, 2015, 2020, and 2030

	year	NFC	ICL	ECL
life expectancy at birth	2010	70.5	70.5	70.5
	2015	71.8	72.0	72.5
	2020	72.9	73.5	74.4
	2030	74.9	76.2	77.7
lives saved (in thousands), $\text{deaths}^{\text{base}} - \text{deaths}^{\text{scen}}$	2010	0	0	0
	2015	0	179	462
	2020	0	423	1106
	2030	0	1212	2528

The number of lives saved per year is calculated as the number of deaths that would have occurred in the baseline scenario [roughly 13 million (compare to ref 36)] minus those that would take place under a particular control scenario. For example, under the ICL scenario, more than 1.2 million fewer people would be expected to die in 2030 than if no $PM_{2.5}$ abatement program had been undertaken. In the ECL scenario, this number more than doubles.

While there is no unique and commonly accepted method for expressing the value of human life in monetary terms, one way to integrate the number of lives saved with the economic cost of air pollution abatement policies is to compute consumption forgone per life saved (Table 8). In 2030, for example, under the ICL scenario, each life saved by reducing $PM_{2.5}$ concentrations results in a decrease in overall private consumption of around $9400. Measured on a per capita basis then, saving an additional life comes at almost no cost (the 40 millionths part of a dollar or equivalently 4 billionths of per capita private consumption). In the ECL scenario, overall private consumption is more than $12000 higher per life saved than in the baseline case, although consumption per capita is slightly lower than baseline. (This occurs because in this scenario a larger population produces a larger aggregate GDP, but a smaller GDP per capita than in the NFC scenario.) In both control scenarios, the reduction of mortality by providing cleaner air carries costs, but the burden of those costs spread over a large population is quite modest.

Table 8. Consumption Forgone To Save a Life—Overall, per Capita, and as a Proportion of Total Consumption in Three Different Scenarios in India in 2010, 2015, 2020, and 2030[a]

	year	ICL	ECL
annual consumption forgone to save a life (in 2000 international US$), $(\text{cons}^{\text{base}} - \text{cons}^{\text{scen}})/(\text{pop}^{\text{scen}} - \text{pop}^{\text{base}})$	2010	0	0
	2015	63205	74759
	2020	34199	29410
	2030	9426	−12427
annual consumption forgone per capita to save a life (millionths of 2000 international US$)	2010	0	0
	2015	54	63
	2020	39	35
	2030	40	29
proportion of annual consumption each person would have to forego to save a life (billionths)	2010	0	0
	2015	13	15
	2020	7	6
	2030	4	3

[a] All prices in 2000 international US$.

4.3. Education. Because older cohorts tend, on average, to be less educated, the higher the survival rates of elderly individuals in a given scenario, the lower the aggregate educational attainment. This is true despite the fact that the level of education in younger cohorts is increasing in all scenarios. If we were to ignore this "negative" effect of increases in longevity, increases in HDI would even be larger than observed. Table 9 summarizes the effect of $PM_{2.5}$ on mean years of schooling. In the NFC scenario, the ongoing expansion of the educational sector in India will lead to a mean increase of roughly 18 months of schooling per capita from 2010 to 2030.

4.4. Summary of Effects on the HDI. Well-being, as measured by HDI, is clearly higher when actions are taken to reduce $PM_{2.5}$ concentrations. To achieve equivalent effects on

Table 9. Mean Years of Schooling in Three Scenarios in India in 2010, 2015, 2020, and 2030[a]

	year	NFC	ICL	ECL
mean years of schooling	2010	6.88	1.000	1.000
	2015	7.27	1.000	1.000
	2020	7.65	0.999	0.998
	2030	8.36	0.998	0.995

[a]Mean years of schooling in ICL and ECL scenarios are ratios relative to baseline (NFC) levels. Source of baseline education data: IIASA/VID.[37]

HDI in the absence of additional pollution controls (i.e., as in the NFC scenario), GDP would have to be increased by 29% in 2030.

Table 10. Contributions of Individual Indices to the Change in the HDI in 2030 under Two Control Scenarios

	ICL compared to NFC	ECL compared to NFC
GDP per capita index	−3.5%	−1.8%
life expectancy index	109.%	107.6%
education index	−5.5%	−5.9%
total change in HDI	100.0%	100.0%

DISCUSSION

In this study, we investigate the costs and benefits of air pollution policies in India over the next two decades. We find that implementing such policies would improve well-being, as measured by the HDI, because increases in life expectancy outweigh the extremely small economic costs. In our two scenarios, which roughly represent current air pollution legislation in India and Europe, improvements in ambient $PM_{2.5}$ levels (which save more than 1 million lives per year) reduce the average annual rate of GDP growth per capita between 2010 and 2030 by around two one-hundredths of one percentage point (0.02%). Furthermore, much of this reduction is due to the fact that lower $PM_{2.5}$ concentrations keep older nonworking adults alive longer.

Assessing the costs and benefits of a cleaner environment is an empirical matter. Costs and benefits depend on the type(s) of pollution for which actions are being considered and the place and time period of interest. Here, we focus on $PM_{2.5}$ and on India, a country with high current $PM_{2.5}$ levels and high expected rates of growth of $PM_{2.5}$ emissions. Our conclusions might well be different had we considered other pollutants in other places and times.

This paper draws on the disciplines of energy systems modeling, atmospheric dynamics, economics, and demography; the integration of all four in a systems framework is prerequisite to constructing a plausibly realistic picture of the situation in India in the coming years.

The combination of the GAINS and SEDIM models requires a large number of simplifications to make the problem tractable. The costs of $PM_{2.5}$ abatement are calculated on the assumption that emitters do not modify their behavior in response to the new policies. If emitters were to reallocate resources toward less-polluting technologies, for example, the cost of reductions in $PM_{2.5}$ levels would be smaller than that computed here. We did not include the cost of medical care. Additional medical expenditures induced by $PM_{2.5}$ pollution act as a kind of tax, reducing both consumption of other goods and savings. Savings reductions, in turn, decrease the rate of capital formation. Had we included the cost of medical care, GDP growth in the ICL and ECL scenarios would have been slightly larger compared with growth under the NFC. We also did not include any demand-side effects. If investments in abatement caused the deployment of unemployed or underemployed resources, then the economic cost would be even smaller than we have computed. However, this response is not guaranteed. It is possible that some of the resources needed for abatement investments are in short supply and that abatement investments would increase the prices of those inputs, leading to a reduction in their use in other sectors. Such considerations are far beyond the scope of this study.

Because technologies included in the analysis are commercially available and well-developed, significant improvements are not expected over the next two decades. Hence, the model assumes that there will be no technological development and, thus, mitigation effectiveness and costs will remain constant over the analyzed period. This assumption, together with the inclusion of only well-developed technologies, makes the assessment of mitigation potential conservative rather than optimistic.

The results of this work indicate that implementing policies to reduce levels of $PM_{2.5}$ pollution in India would improve well-being, save lives, and increase life expectancy, with inconsequential effects on the growth rate of GDP and GDP per capita. Our conclusions strongly indicate that the reduction of levels of $PM_{2.5}$ in India should be high on the priority list of decision makers.

● Supporting Information

Details of the SEDIM model, parametrization for India from 1971 to 2001 and from 2002 to 2030, data sources, derivation of the HDI, sensitivity analysis, comparison of GAINS estimates with other emission measures, and future biomass usage in India. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes

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