Supporting Online Material for:

The Effects on Well-being of Investing in Cleaner Air in India

Warren Sanderson, Erich Striessnig, Wolfgang Schöpp, and Markus Amann*

*Corresponding author.

E-mail: Sanderson.Warren@stonybrook.edu

Pages: 12

Figures: 3

Tables: 3

Contents

S1 – Model Description

In our analysis, we use the Simple Economic Demographic Interaction Model (SEDIM), a single-sector model of economic growth designed for the study of out-of-equilibrium dynamics, with a specific focus on demographic components. This model responds to the growing literature stressing the important role of population dynamics in economic growth. [1] The most practical feature of SEDIM is its general applicability—it can easily be parameterized for different countries without a need for *ad hoc* assumptions. Conceptually simple, it does not require too broad a range of assumptions.

SEDIM is based on a Cobb-Douglas production function. Gross domestic product, GDP_t, is generated as a function of capital K_t, which is paid its share $(1-\alpha)$ of output, effective labor L_t, which is rewarded by its share (α), and a third term, A_t, that represents total factor productivity. The subscript t refers to a particular year.

$$GDP_t = A_t \cdot L_t^{\alpha} \cdot K_t^{1-\alpha} \qquad (1)$$

Accordingly, in SEDIM, there are three proximate sources of economic growth: growth of the labor force, adjusted for age and educational composition; growth of the capital stock; and the growth rate of productivity. All other factors that influence economic growth must do so through their effects on one of these.

SEDIM makes the traditional economic assumption that the factors of production—labor and capital—are paid according to their productivities. This allows the value of output to be divided among all the participants in the economy. Consumers receive two types of income: labor income, which depends on their efficiency; and income from interest, which depends on how much capital they hold. There are taxes on income from both labor and capital, which are used to pay for the support of the elderly and for education. As formulated for this study, SEDIM incorporatesthe cost of regulations to reduce $PM_{2.5}$ as an additional tax. Working life-cycle savers also make intergenerational transfers to older life-cycle savers.

Effective Labor: $L_{(t)}$

While SEDIM does not consider the age at which capital is taken out of service, the age structure of the labor force is explicitly taken into account, as are full educational details of the work force. Labor market entry and exit and the productivity of individual workers are all education-specific.

$$L_t = \sum_{a=alfe}^{alfx} EU_{a,t} \cdot POP_{a,t} \qquad (2)$$

$EU_{a,t}$ is the age- and education-specific number of efficiency units embodied in each worker of age *a* in year *t*. $POP_{a,t}$ is the population at age *a* in year *t* and *alfe* and *alfx* are the youngest possible ages of labor market entry and exit, respectively.

Capital: $K_{(t)}$

Equation (3) describes the way capital, K_t, is accumulated in SEDIM, that is, the way gross investments (IG_t) are determined.

$$K_t = K_t - \delta * K_t + IG_t \qquad (3)$$

SEDIM includes two different kinds of capital holders. Whereas the first group—corporate non-lifecycle savers—is not directly affected in its behavior by changes in life expectancy, for the second group—private lifecycle savers—such a change alters the length of their savings horizon. People's saving behavior in SEDIM is forward looking and adaptive, but suffers from imperfect foresight. In each year, individuals consider their asset holdings and expected future incomes, including public pensions and intergenerational transfers. In doing so, they make use of some limited common information about how wages evolved in the past five years, as well as a general understanding of how their productivity will evolve as they grow older. Aiming at spending all of their wealth before dying (they do not plan on leaving behind any wealth for bequests) consumers decide on a pattern of expected savings and consumption that smooths their consumption levels over their entire lifetime. An increase in life expectancy will therefore be met with a higher savings rate by those still active in the labor market, which in turn also influences the saving decisions of non-lifecycle savers by changing the return to capital.

It is important to note that changes in people's saving horizons are a feature of SEDIM. Even without changes in environmental policies that affect life expectancy, people adapt their saving behavior from year to year as their circumstances change. In SEDIM, we assume that in making their saving decisions, consumers know the current mean and standard deviation of the age distribution of deaths from senescent mortality and have a planning horizon (*ph)* that depends on that distribution. For example, let *ph* be 10 percent and let *prob(a*)* be the probability that the person survives to age *a** or beyond, given the current mean and standard deviation of the distribution of age at death. The end of the planning horizon for the person then is that value of *a** such that *prob(a*)* is equal to 10 percent. The planning horizon changes because life expectancy changes over time, but also because the person did not die in the past year and therefore is repeatedly facing a different conditional age distribution of dying than in the previous year.

This produces a feedback loop. People behave based on what they expect the future to be like. They might save a little more because they expect to live longer. But as everybody increases savings, capital stock increases, and so do productivity and wages. Ultimately, consumers might not have to sacrifice much consumption since they will be wealthier in the future. It is unclear whether people will save more because they expect to live longer or less because they expect to be richer.

Total Factor Productivity: $A_{(t)}$

The last way for demographic changes to affect output in the Cobb-Douglas framework is total factor productivity. This has been discussed previously in great detail [2], therefore, we restrict ourselves to a short description of those drivers of technological progress in SEDIM that would also be affected by envisioned policy reforms.

Being a model of conditional convergence, SEDIM distinguishes between two different kinds of productivity growth. The level of productivity in one region compared to the rest of the world can be described by its conditional frontier, that is, the maximum level the regional economy could reach, given its particular characteristics, as well as a global technological frontier, which corresponds to the highest level that productivity could possibly reach in each year. Growth in $A_{(t)}$ could therefore imply either an approach to the conditional frontier, or a convergence of that frontier towards the global best-practice level of technology.

In SEDIM, demographic changes can affect productivity in both of these ways, since the determinants of both the conditional frontier and of the speed of the approach to this frontier include demographic factors. Without going into great detail, it can be said that changes in the age-structure of the labor force affect its absorptive potential with respect to technological innovations. A younger labor force tends to increase the rate at which an economy approaches the conditional frontier. An older labor force, on the other hand, shifts the level of the conditional frontier upward. When age-specific probabilities of dying change this also changes the average level of education of the labor force. Per SEDIM, the age-structure of education matters, and it is better to have education concentrated among the young rather than the old.

Finally, SEDIM is designed for studying out-of-equilibrium dynamics. The specification of savings in the model is designed so that neither equilibrium nor a transition path to one is required. Savings behavior is assumed to be motivated by a desire to smooth consumption over the life cycle. Therefore, it is influenced by expectations of future wage growth, longevity, tax rates, interest rates, and resources provided by public pensions or family support in old age. These expectations are based on observations of the recent past and lead people to change their behavior as economic conditions change. The model does not assume perfect foresight, although under stationary conditions people's expectations of the future will be realized. The most practical feature of the model is its simplicity, which allows it to be easily parameterized for different countries and regions. The parameterization of SEDIM for Indian data from 1971 to 2001 is discussed in the next section.

S2 – Parameterization for India from 1971 to 2001

The labor force $L_{(t)}$ in SEDIM is endogenous. It is influenced by birth and death rates and age-structure dynamics. Changes in $PM_{2.5}$ concentrations affect death rates. $A_{(t)}$ is parameterized in [2] using data on total factor productivity from 1971 to 2001 for nine world regions, including South Asia. Adjusting the region-specific parameters to fit the Indian—rather than the South Asian—data, we obtained a parameterization of $A_{(t)}$ for India, leaving only capital stock to be parameterized. The growth rate of capital stock depends mainly on the saving behavior of people and companies. This, in turn, depends on tax rates and the extent of intergenerational transfers to the elderly. We also allow for direct foreign investment.

Direct data on saving behavior by age are generally lacking. We chose plausible constant parameters so as to replicate as closely as possible the dynamics of growth of the capital stock. These, in turn, depend in complex ways on the age and education structure of the population and the interaction of private and corporate savings.

Error! Reference source not found. Figure S1 shows the observed capital stock in India and the capital stock generated in SEDIM. The difference between the predicted and the actual capital stock at the end of the period is likely due to policy changes in India that are not captured in the model. We provide for these changes after 2001, when we parameterize the model to match the WEO/GAINS baseline scenario for the period to 2030 (see Section 3 in the main article). Figure S2 shows observed and predicted GDP.

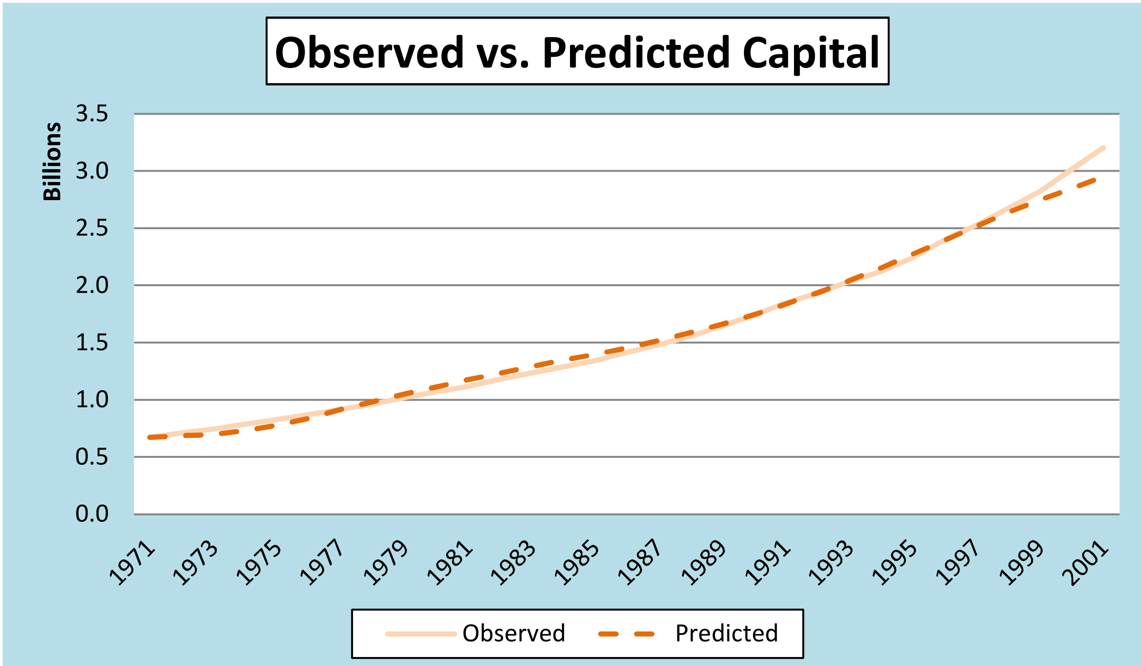

Figure S1. Observed and predicted capital stock in billions of 2000 international US$, India, 1971-2001. Source: Penn World Tables and authors' calculations

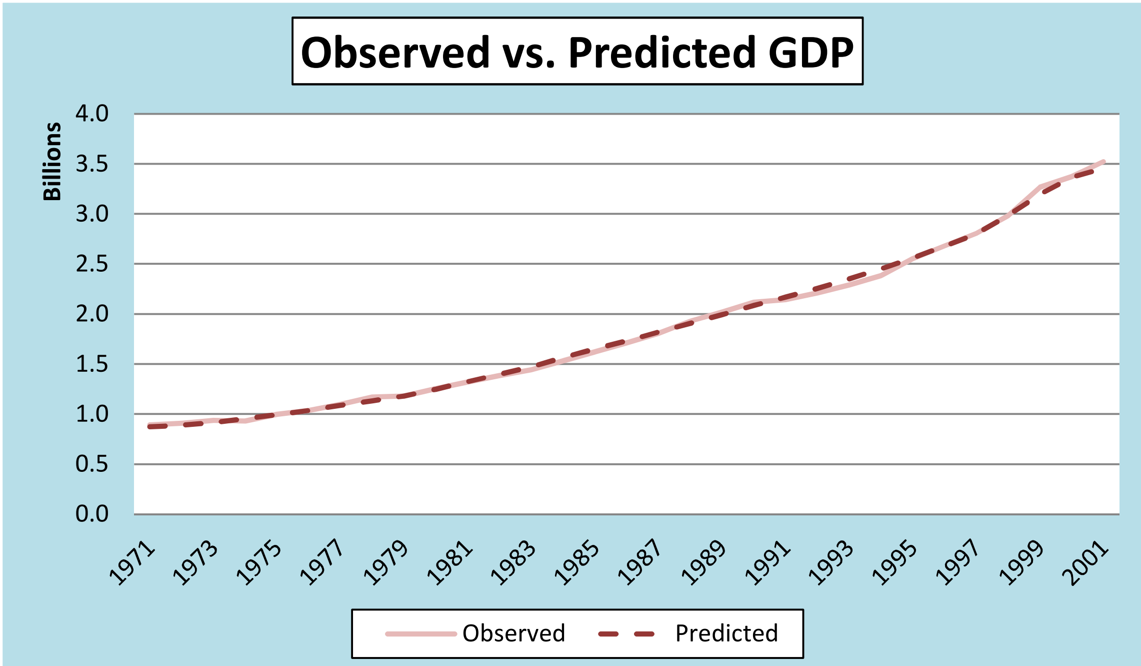

Figure S2. Observed and predicted GDP in billions of 2000 international US$, India, 1971-2001. Source: Penn World Tables and authors' calculations.

S3 – Fitting the energy future

In order to match our forecast of economic growth in India with the slightly faster growth pattern that underlies the WEO/GAINS baseline scenario, we only had to make a few minor and realistic assumptions. Total factor productivity in SEDIM is influenced by a few institutional quality variables. These are factors that we quantified for our nine world regions for 1971-2001 [2]. Among other things, these are correlated with pro-growth economic policies. In order to reflect the policy changes in India, we assumed some modest improvements with respect to these institutional factors and these affect economic growth positively. As shown in Figure this is enough to reproduce the baseline WEO/GAINS growth pattern.

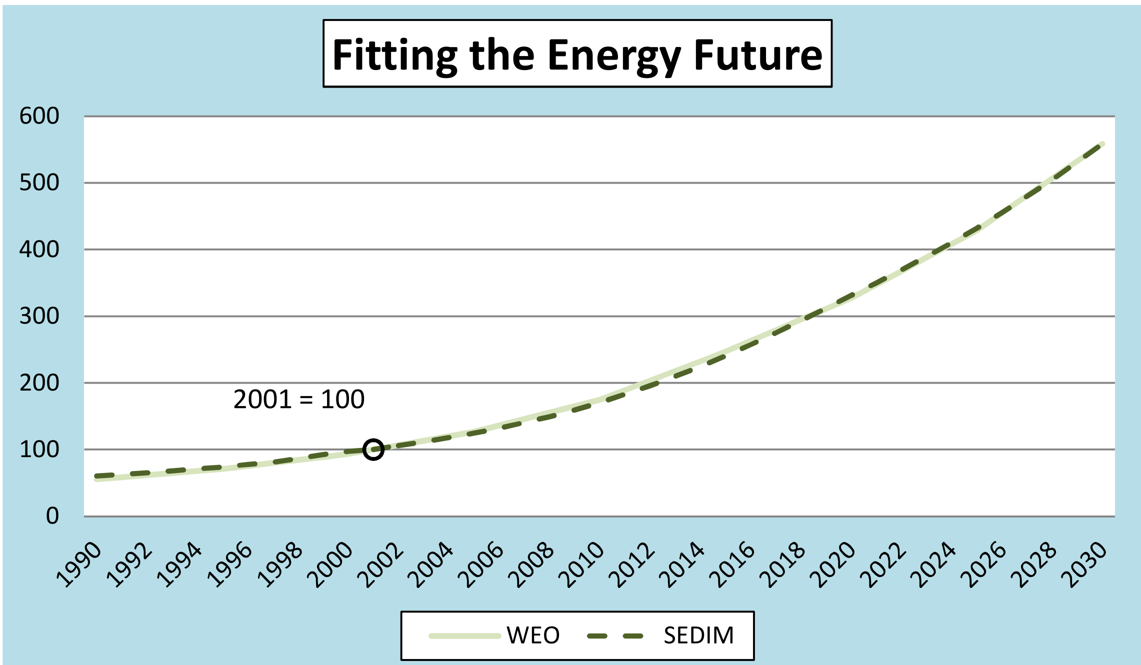

Figure S3. WEO and SEDIM estimates and forecasts of GDP, India, 1990-2030 (2001 = 100). Source: WEO 2009 and authors' calculations

S4 – Data

Table S1 summarizes our main sources of data.

Data	Source
Real GDP (PPP)	*Penn World Tables* [3]
Populations by age	*UN World Population Prospects* [4]
Mean Years of Schooling by age	*IIASA-VID education data set* [5]
Real Investment (PPP)	*Penn World Tables*
Productivity by age and education	*Skirbekk (2008)* [6]
Mortality rates by age	*UN World Population Prospects*

Table S1. Main sources of data

Capital stock is computed using the perpetual inventory method based on real investment data for India from the *Penn World Tables*.

S5 – HDIs

The Human Development Index (HDI) combines indicators of life expectancy, educational attainment and income. The official version of the HDI, provided by UNDP [7], calculates an educational component using mean of years of schooling for adults aged 25 years and over and expected years of schooling for children of school entering age. While the policy interventions influence educational attainment of the population of working ages, school enrollment is not affected in SEDIM. We therefore calculate our version of the HDI based only on the first of the UNDP criteria. For a comparison with the UNDP-version, see Figure S3 below, which illustrates that the trend in HDI since 1980 is still captured.

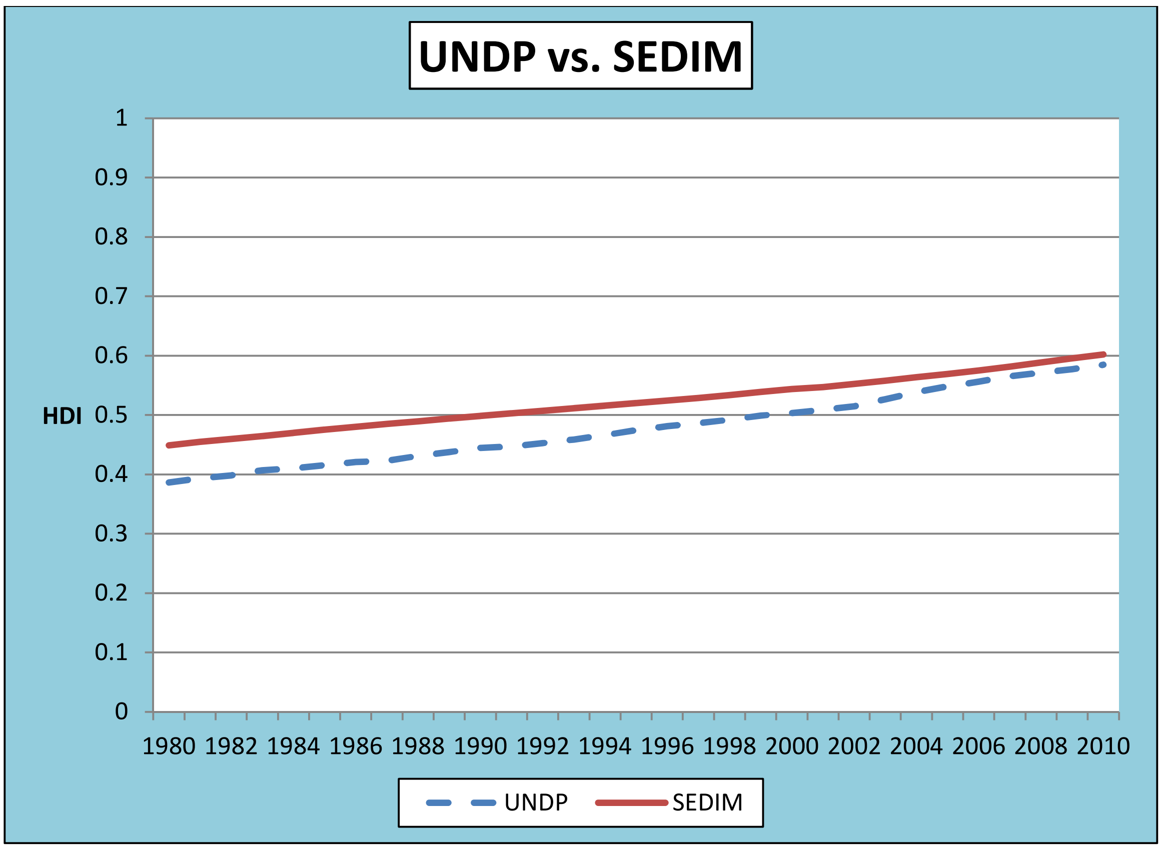

Figure S3. Human Development Index (HDI) as provided by UNEP and HDI calculated within SEDIM, 1980-2010.

S6 – Sensitivity

In this section, we show the sensitivity of our results to changes in the assumptions about a) the relationship between sick days and $PM_{2.5}$ concentrations, b) the impact of $PM_{2.5}$ on mortality rates, and c) the nature of financing of the direct costs of $PM_{2.5}$ reductions.

In order to test our results against modified assumptions on the impact of $PM_{2.5}$ on morbidity, we halved the additional work days lost or gained due to changes in $PM_{2.5}$. We did this because the information from Hurley *et. al.* [8] is based on European data and impacts on morbidity and work days lost may be less in South Asia. Results are shown in **Error! Reference source not found.**, but are not significantly different from those in Section 4 of the main article. Our conclusions are thus insensitive to changes in our assumption about the relationship between changes in lost work days and changes in $PM_{2.5}$ concentrations.

We also investigate the consequences of assuming a higher sensitivity of mortality rates to changes in $PM_{2.5}$. In Section 4, we assumed that the relative risk of mortality increased by 0.004 for each 1 $\mu g/m^3$ increase in $PM_{2.5}$ concentration. This was not quite in line with findings from developed countries, which suggest that relative risk factor might be as high as 0.006 for a 1 $\mu g/m^3$ increase.[9] In **Error! Reference source not found.**, we show how our results would change if we adopt this higher figure for India. Standard economic indicators such as GDP per person of working age, GDP per capita, and consumption per capita are marginally lower with this assumption, because $PM_{2.5}$

reductions save more lives and there are more old, non-working people in the population. Changes in life expectancy are, of course, larger under the control scenarios when $PM_{2.5}$ sensitivity is higher. Table S3 shows that in 2030 under ICL, the higher $PM_{2.5}$ sensitivity assumptions lead to a life expectancy at birth that is 0.5 years more than in Section 4 of the main article. This translates, as well, to more lives saved through reducing $PM_{2.5}$. The Human Development Index in the ICL scenario in 2030 is slightly higher, too, because higher life expectancy outweighs the slightly worse economic performance. The effects of increasing the sensitivity of mortality to $PM_{2.5}$ are generally very small and none of the conclusions in Section 4 would be changed under the modified assumptions.

Finally, we investigated the effects of financing the expansion of the stock of pollution abatement capital by sharing the burden of taxation between consumers and corporations. Our baseline assumption is that consumers pay for the air pollution improvements. This does not mean that they pay directly, only that eventually, through higher prices or other means, the burden is shifted entirely to consumers. Here, we assume that one-quarter of the costs cannot be shifted to consumers and are thus paid by corporations. The economic results, in this case, are slightly worse, with marginally lower GDP and consumption per capita. This arises because the taxation of corporations results in less capital formation. Nevertheless, the results are sufficiently similar to those in Section 4 that we can conclude that our findings are not sensitive to assumptions about how reductions in $PM_{2.5}$ concentrations are financed. It is interesting to note that, while consumers are initially taxed less when the tax burden is shared with the corporate sector, they eventually forgo a greater fraction of their consumption in that situation. These kinds of tax shifts are common in models like SEDIM, where a variety of indirect effects and feedbacks are taken into account.

Reducing $PM_{2.5}$ concentrations in South Asia saves lives, reduces sick days and has virtually no effect on economic growth. It improves well-being as measured by the Human Development Index. In this section, we have shown that these results are not sensitive to three important assumptions on which those conclusions are based.

		BASELINE		75% PRIVATE, 25% CORPORATE		PM2.5 IMPACT 0.006		HALF THE REDUCTION IN SICK DAYS	
	YEAR	ICL	ECL	ICL	ECL	ICL	ECL	ICL	ECL
Total GDP (in Billions of US$)	2010	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	2015	1.000	1.001	1.000	1.001	1.000	1.001	1.000	1.001
	2020	1.000	1.003	1.000	1.002	1.000	1.003	1.000	1.002
	2030	1.001	1.007	1.000	1.005	1.001	1.007	1.001	1.004
GDP per Worker	2010	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	2015	1.000	1.001	1.000	1.000	1.000	1.001	1.000	1.000
	2020	0.999	1.001	0.999	1.000	0.999	1.001	0.999	1.000
	2030	0.999	1.002	0.998	1.000	0.998	1.001	0.999	0.999
GDP per Capita	2010	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	2015	1.000	1.001	1.000	1.000	1.000	1.000	1.000	1.000
	2020	0.999	1.000	0.999	0.998	0.998	0.999	0.999	0.998
	2030	0.996	0.995	0.995	0.994	0.995	0.992	0.996	0.993
Consumption per Capita	2010	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	2015	0.998	0.993	0.998	0.993	0.998	0.993	0.998	0.993
	2020	0.997	0.993	0.997	0.992	0.997	0.993	0.997	0.992
	2030	0.995	0.992	0.994	0.991	0.994	0.989	0.995	0.990
HDI	2010	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	2015	1.002	1.006	1.002	1.006	1.003	1.008	1.002	1.006
	2020	1.004	1.012	1.004	1.012	1.006	1.017	1.004	1.012
	2030	1.009	1.020	1.009	1.020	1.012	1.027	1.009	1.020
Consumption Foregone to Save a Life (US$)	2010	0	0	0	0	0	0	0	0
	2015	63205	74759	69351	83232	43883	53376	63205	81736
	2020	34199	29410	40283	37708	23538	19691	34199	38430
	2030	9426	-12427	14661	-4736	4210	-12697	9426	518
Consumption Foregone per Capita to Save a Life (Millionths of US$)	2010	0	0	0	0	0	0	0	0
	2015	54	63	59	70	39	46	54	68
	2020	39	35	44	41	31	28	39	42
	2030	40	29	43	34	37	29	40	37
Proportion of Consumption each Person Would Have to Forego (in Billionths)	2010	0	0	0	0	0	0	0	0
	2015	13	15	14	16	9	11	13	16
	2020	7	6	8	7	6	5	7	7
	2030	4	3	5	4	4	3	4	4

Table S2. **Sensitivity analysis.**

Notes: All prices in 2000 international US$

		BASELINE: PM2.5 IMPACT 0.004		SENSITIVITY: PM2.5 IMPACT 0.006	
	YEAR	ICL	ECL	ICL	ECL
Lives Saved in 1000s	2010	0	0	0	0
	2015	179	462	246	636
	2020	423	1106	574	1508
	2030	1212	2527	1597	3388
Life Expectancy at Birth	2010	70.5	70.5	70.5	70.5
	2015	72.0	72.5	72.1	72.7
	2020	73.5	74.4	73.7	75.0
	2030	76.2	77.7	76.7	78.7
Total Population (in Billions)	2010	1.000	1.000	1.000	1.000
	2015	1.000	1.001	1.000	1.001
	2020	1.001	1.003	1.002	1.004
	2030	1.005	1.011	1.007	1.015

Table S3. Sensitivity of lives saved, life expectancy at birth, and total population to $PM_{2.5}$ impact factor for three scenarios. India, 2010, 2015, 2020, 2030.

The costs of funding air pollution abatement programs could be distorting, potentially having some (probably small) effect on the incentive to work. This is a complex issue, because the changes in life expectancy that emerge from the SEDIM model could also slightly change these incentives. Modeling such factors was not plausible in the current study. We allowed PM2.5 to affect survival rates and health only for adults because data for children is largely unavailable, although PM2.5 almost certainly affects the health and survival of children. SEDIM takes into account the costs of educating children. More children imply higher education costs and a greater proportion of the population not of working age, both of which would reduce GDP per capita growth. But expenditures on education are an investment. In the short time span considered here, we would expect mainly to observe the costs of this investment and not the returns. As well, there may be a synergy between better health of children and better educational outcomes. Over the period of forecasting implemented in this study, we expect that the aforementioned considerations would have relatively minor effects that would not affect our overall conclusions.

S7 – Emission estimates of air pollutants in India

Table S4: Emission estimates of air pollutants in India

1990	1995	2000	2005	2010	REFERENCES
SO2 EMISSIONS (KT)					
3106	4253	5128	6413	8597	GAINS/IIASA_CLE (2008)
3106	4253	5128	6413	6987	GAINS/IIASA_ALT (2008)
3668			6699		IEA/OECD (2007)
2850	3660	4260	4800		Garg et al. (2006)
		7920			EDGAR
		6141			REAS ver.1.1
	4330				Reddy and Venkataraman (2002)
NOX EMISSIONS (KT)					
2630	3516	4135	5065	6134	GAINS/IIASA_CLE (2008)
2630	3516	4135	5065	5423	GAINS/IIASA_ALT (2008)
2791	4109	5165		8528	IEA/OECD (2007)
2640	3460	4310	5020		Garg et al. (2006)
		6579			EDGAR
VOC EMISSIONS (KT)					
9396	10253	11295	12953	13646	GAINS/IIASA_CLE (2008)
9396	10253	11295	12953	13591	GAINS/IIASA_ALT (2008)
7369	8124	9372			WRI
			2800#		Parashar et al. (2005)
PM2.5 EMISSIONS (KT)					
4272	4745	5022	5803	6120	GAINS/IIASA_CLE (2008)
4272	4745	5022	5803	5989	GAINS/IIASA_ALT (2008)
4206	4681	4469	4192		IEA/OECD (2007)
	4040##				Reddy and Venkataraman (2002)
NH3 EMISSIONS (KT)					
5535	6032	6268	6638	7021	GAINS/IIASA_CLE (2008)
5535	6032	6268	6638	7020	GAINS/IIASA_ALT (2008)
	6764				REA ver.1.1

*High coal use scenario

**Low coal and renewable dominant scenario

#OC+BC

##50% control scenario for 1996-97

Literature Cited

1. Crespo Cuaresma, J., Lutz, W. & Sanderson, W. Age Structure, Education and Economic Growth. *IIASA Interim Report* **IR-12-11,** (2012).
2. Sanderson, W. & Striessnig, E. *Demography, Education, and the Future of Total Factor Productivity Growth*. (International Institute for Applied Systems Analysis, 2009). at <http://www.iiasa.ac.at/Admin/PUB/Documents/IR-09-002.pdf>
3. Heston, A., Summers, R. & Aten, B. *Penn World Table Version 6.3*. (Center for International Comparisons of Production, Income and Prices, 2009).
4. United Nations. *World Population Prospects: The 2008 Revision*. (Department of Economic and Social Affairs, Population Division, 2009).
5. Lutz, W., Goujon, A., KC, S. & Sanderson, W. Reconstruction of populations by age, sex and level of educational attainment for 120 countries for 1970-2000. *Vienna yearbook of population research* 193–235 (2007).
6. Skirbekk, V. Age and productivity capacity: descriptions, causes and policy options. *Ageing Horizons* **8,** 4–12 (2008).
7. *The Real Wealth of Nations: Pathways to Human Development*. (United Nations Development Programme, 2010).
8. Hurley, F. *et al. Methodology for the Cost-Benefit analysis for CAFE: Volume 2: Health Impact Assessment.* at <http://www.cafe-cba.org/assets/volume_2_methodology_overview_02-05.pdf>

9. Pope III, C. A. *et al.* Lung Cancer, Cardiopulmonary Mortality, and Long-term Exposure to Fine Particulate Air Pollution. *JAMA* **287,** 1132–1141 (2002).