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Combating Acid Deposition and Climate Change: Priorities for Asia

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Combating Acid Deposition and Climate Change: Priorities for Asia

BY ALAN McDONALD

When a town manager is faced with the need both to repair the town's sewers and to resurface its roads, it would only be logical that he or she do the former first. Otherwise the roads will essentially have to be done twice—and at no small expense to the town. It may happen, however, that for the present only the resurfacing project has enough popular support to be carried out. In that case, the town manager must seek the next best solution, i.e., the one that will minimize the cost of repairing the sewers at some future time. This can be done, for instance, by starting on the roads that will be least affected by sewer repairs later; by selecting less expensive surfacing materials, such as those that are designed to last 10 years instead of 30; and by avoiding new surfaces that will make it harder than it already is to get to the sewers.

What is true for roads and sewers is also true for policies to address global warming and acid rain. That is, policy prescriptions directed at one problem can make the other easier or more difficult to solve. At the third and fourth Conferences of the Parties to the United Nations Framework Convention on Climate Change (held in Kyoto in December 1997 and Buenos Aires in November 1998), the world's attention focused on greenhouse gases stemming from the combustion of fossil fuels, particularly carbon dioxide.[1] But the same fuels also produce sulfur dioxide, the principal cause of acid rain. At present, no one has a firm grip on the potential interactive effects of carbon dioxide and sulfur dioxide or on the policies—both implemented and proposed—attempting to limit each of these substances separately.

To address these issues, researchers at the International Institute for Applied Systems Analysis (IIASA), a private research institute located in Laxenburg, Austria, recently carried out a set of modeling exercises focusing on interactive effects. Although these exercises were conducted for all regions of the world, this article focuses on Asia, where populations are large and growing; living standards (and thus energy use) are low for most individuals but aspirations are high; and most of the fossil fuels currently being used are dirty. The resulting scenarios yield some surprises about the interactive effects between the two types of emissions and policies to control them. They also offer important insights into how policymakers might exercise long-term foresight while remaining responsive to the current political realities.

Fossil Fuel Emissions and Pollution in Asia

In terms of total suspended particulates, Asia is home to all 15 of the most polluted cities in the world, as well as to 19 of the 20 most polluted cities. In terms of sulfur dioxide, Asia hosts the world's four worst cities and 15 of its worst 19.[2] Moreover, Asia's situation is likely to get even worse because there are no international agreements to limit air pollution comparable to those initiated in Europe and North America 20 years ago. Indeed, national control efforts are only now beginning to spread beyond Japan to fast-growing, highly polluting countries like China.

Europe and North America adopted the Convention on Long-Range Transboundary Air Pollution (LRTAP) in 1979. This instrument led to four subsequent protocols limiting emissions of various sorts: sulfur dioxide (1985), nitrogen oxides (1988), volatile organic compounds (1991), and sulfur dioxide even further (1994). As a result, sulfur dioxide emissions in Europe (including European areas of the former Soviet Union) decreased 32 percent from 1980 to 1990 (from 52 million tons to 36 million tons). In North America, these protocols and the Clean Air Act Amendments enacted by the United States in 1990 reduced sulfur dioxide emissions 31 percent from 1980 to 1995 (from 28 million tons to 20 million tons).[3]

Historical data for Asia are more problematic, but the trends are clearly in the other direction. The data indicate a roughly 60 percent increase in sulfur dioxide emissions from 1980 to 1990, from about 11 million tons to 18 million tons.[4] And without specific policies and agreements to limit such emissions, all projections point to even greater increases in the future. The two main reasons for this are the region's rapid economic growth and its high dependence on coal. Once Asia recovers from the financial crisis that hit at the end of 1997, its growth is expected to again be the fastest in the world. Owing to increases in energy efficiency, the region's energy requirements will not rise as rapidly as its economic output, but the rise will still be substantial. For China and India in particular, this is likely to mean using a lot more coal—and thus producing a lot more air pollution. Kilowatt for kilowatt, a typical coal-fired power plant in China emits about 100 times the sulfur dioxide released by a plant using natural gas (though the exact amount depends on the type of coal used). Compared to nuclear or hydroelectric power, which emit no sulfur dioxide, coal is "infinitely dirty."

Without new control policies, sulfur emissions in Asia (excluding the Middle East and Asian areas of the former Soviet Union) are estimated to grow another 160 percent between 1990 and 2020, from 18 million tons to 48 million tons. Projections like these, combined with the already low air quality in many Asian cities, have begun to prompt policy actions in some countries. In China, for example, environmental efforts are picking up speed at both the local and national levels. Last December, Beijing adopted 19 emergency measures to improve its air quality, including a ban on burning coal in the city center. Beijing is also in the midst of a program to introduce 15,000 natural gas vehicles and 100 natural gas stations in the city. In the city of Guangzhou, 430,000 motorcycle owners will have had to add devices to clean their exhaust by 1 March 1999. Shenyang has banned high-sulfur coal and leaded gasoline. Shanghai has new exhaust regulations slated for 1 December 1999 and is almost midway through a program to convert 7,000 taxis to liquid petroleum gas (LPG) or natural gas within the next four years. Chengdu will require all city businesses to switch to clean sources of energy before July 2000.

Nationally, gasoline producers are to stop making leaded gasoline by the end of 1999 and suppliers are to stop selling it by July 2000. Import tariffs on particulate removal equipment have been reduced, and last year China established sulfur dioxide emission limits on industry—along with emissions fees—in two special control zones in south and central China. Although these zones comprise only 11.4 percent of China's total area, they account for 60 percent of the country's sulfur emissions. In addition to the restrictions on emissions, no new coal mines may be

Table 1. Population, 1990–2100 (millions)

Region	1990	2020	2050	2100
Sub-Saharan Africa	488	1,080	1,690	1,922
Centrally planned Asia[1]	1,242	1,654	1,815	1,778
Central and Eastern Europe	124	123	116	97
Former Soviet Union	289	311	330	350
Latin America and the Caribbean	434	698	920	1,085
Middle East and North Africa	270	585	985	1,424
North America	281	358	403	460
Pacific OECD	144	155	146	122
Other Pacific Asia	428	625	783	805
South Asia	1,128	1,858	2,405	2,325
Western Europe	434	475	461	394
World	5,262	7,922	10,055	10,761

[1]Includes China, Hong Kong, Laos, Viet Nam, Cambodia, North Korea, and Mongolia.
NOTE: Detail may not sum to totals due to rounding.
SOURCE: IIASA Population Project.

opened in these zones if the coal to be extracted has a sulfur content of more than 3 percent, and production from existing mines is restricted. Finally, no new coal-fired power plants can be built near the major cities in these zones, and existing plants using coal with more than 1 percent sulfur content must install desulfurization technology.[5]

Tip O'Neill, a former speaker of the U.S. House of Representatives, once observed that "all politics is local." It is therefore no surprise that China is willing to limit its sulfur emissions—whose impacts on its own citizens are relatively immediate and clear—while (like India) staunchly resisting pressure to limit its carbon emissions. This is much the same road traveled by the Organisation for Economic Cooperation and Development (OECD) countries, who were (and still are) much more willing to spend money on local and regional pollution problems than on global problems such as climate change.

Given this reality, how does one design policies that are responsive to current political pressures to reduce sulfur emissions without impeding subsequent efforts to limit carbon emissions? To answer this question, one must project how alternative policies—for both sulfur and carbon emissions—would affect each other in terms of two sets of interactions: those among the incentives each creates and those among the remaining pollutants that each produces.

Major Assumptions

The IIASA researchers began by establishing a baseline, that is, by asking what would happen if policymakers in Asia and the rest of the world were to introduce no control measures beyond those already in place for carbon and sulfur emissions. Of course, to derive a valid baseline, it was necessary to make a number of other assumptions as well, particularly with respect to population growth, economic growth, and technological advances. The assumed rates of population growth are shown in Table 1; these are the middle-of-the-road projections prepared by IIASA's Population Project. The good news here is that worldwide population growth is expected to

Table 2. Economic growth rates, 1950-2100 (percent per year)

Region	1950–1990	1990–2020	2020–2050	2050–2100
Sub-Saharan Africa	2.7	4.3	5.2	4.2
Centrally planned Asia[1]	6.1	8.4	3.8	2.2
Central and Eastern Europe	3.9	1.8	5.0	2.0
Former Soviet Union	5.2	0.4	5.4	2.8
Latin America and the Caribbean	4.2	3.7	3.8	2.7
Middle East and North Africa	4.6	4.8	3.6	3.6
North America	3.3	2.3	1.9	1.6
Pacific OECD	6.2	1.8	1.2	0.9
Other Pacific Asia	9.8	6.1	4.3	2.2
South Asia	4.5	3.8	5.2	4.2
Western Europe	3.7	2.0	1.4	1.0
All Asia[2]	6.0	4.2	3.5	2.4
World	4.0	2.9	2.9	2.4

[1]Includes China, Hong Kong, Laos, Viet Nam, Cambodia, North Korea, and Mongolia.
[2]Includes centrally planned Asia, Pacific OECD, other Pacific Asia, and South Asia.
SOURCE: IIASA Environmentally Compatible Energy Strategies Project.

slow: Instead of the 40 years required to achieve the most recent doubling of population, the next doubling will take about 90 years. The bad news is that this will still add 5.3 billion people, so that by 2100 global population will reach 10.8 billion.

Table 2 shows the assumptions about economic growth. To account for important regional differences, separate figures are given for the 11 regions into which the IIASA analysts divided the world, along with a subtotal for the four regions that comprise Asia. The basic pattern is that "the poor get richer while the rich slow down." According to these projections, there will be substantial social and economic development, particularly in the South. For the next several decades, Asia will average annual economic growth of about 4 percent, compared with 6 percent between 1950 and 1990. The world as a whole will experience economic growth of about 3 percent, compared with 4 percent between 1950 and 1990. This is a future that is assumed to be free of major wars and other catastrophes. It is a prosperous but realistic future characterized by large productivity increases and free and unconstrained trade among all regions.

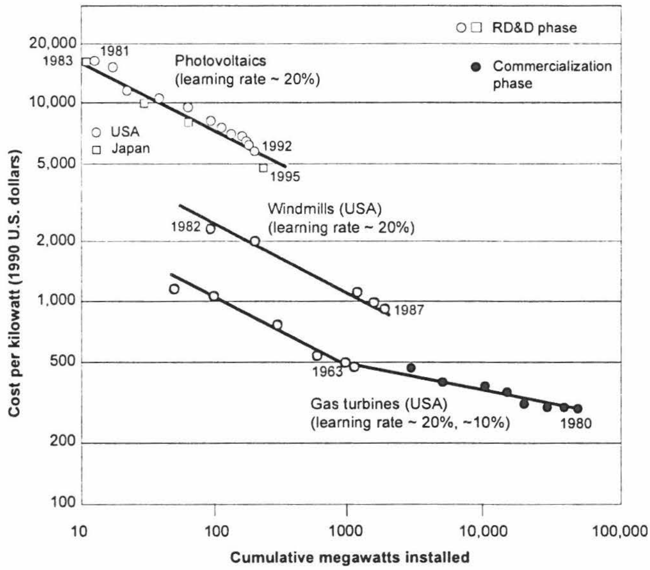
The next set of crucial assumptions has to do with technology. The assumption of no new policies to limit sulfur and carbon emissions does not mean that technology stops improving. Technology has never been static. It has consistently advanced since the beginning of the Industrial Revolution—regardless of the particular policies in place—and there is no reason to expect the process to suddenly grind to a halt. As a starting point, therefore, the IIASA researchers assumed that historical patterns of technological improvement will continue, both at the level of individual technologies and at the broader level of national economies. The distinction between these two levels deserves further comment because, as will be seen below, patterns of technological improvement are crucial to environmental impacts and depend greatly on the policies adopted and the investments made in the relatively short term. In other words, technology is a factor that we can do something about now that will make a big difference to the environment in the long term.

With respect to individual technologies, the researchers assumed that each such technology will benefit from learning-curve effects that are consistent with previous history. Learning curves reflect the fact that as society gains experience with new technologies, they become more efficient and their costs come down. The improvements are usually rapid at first and then gradually taper off. Figure 1 shows historical examples related to energy. Such improvements pertain not only to renewable sources, like windmills and photovoltaics, but also to the processes used to explore for, develop, and produce fossil fuels. These have historically improved at a rate of about 1 percent per year, and this trend was assumed to continue. Given the substantial fossil fuel resources that are still available, this means that oil, gas, and particularly coal will probably be major inexpensive sources of energy far into the future. This is good for the world's pocketbook, of course, but it may well be bad for the environment.

At the level of regional economies, both technological development and economic shifts (from agriculture to industry and then to services) are captured by an indicator referred to as primary energy intensity. This measures the amount of primary energy (tons of coal, barrels of oil, cubic meters of natural gas, and so forth) needed to produce a dollar of gross domestic product (GDP). Historically, energy intensity has decreased as economies developed, and this pattern was assumed to continue. Thus, the richer a country becomes (in terms of GDP per person), the more energy efficient its economy should be. And the faster it grows, the more quickly one would expect to see its energy intensity decline.

What these assumptions imply for energy use is shown in Figure 2. Of particular significance is the expansion of coal use worldwide and Asia's increased importance as an energy consumer. Even though global primary energy use rises at an average rate of only 1.4 percent per year—less than two-thirds the historical average since 1860 and less than projected economic growth—absolute energy consumption is 68 percent higher in 2020 than in 1990, 173 percent higher in 2050, and 350 percent higher in 2100. Coal use also increases rapidly. By 2020, it surpasses oil as the single largest source of primary energy, and its

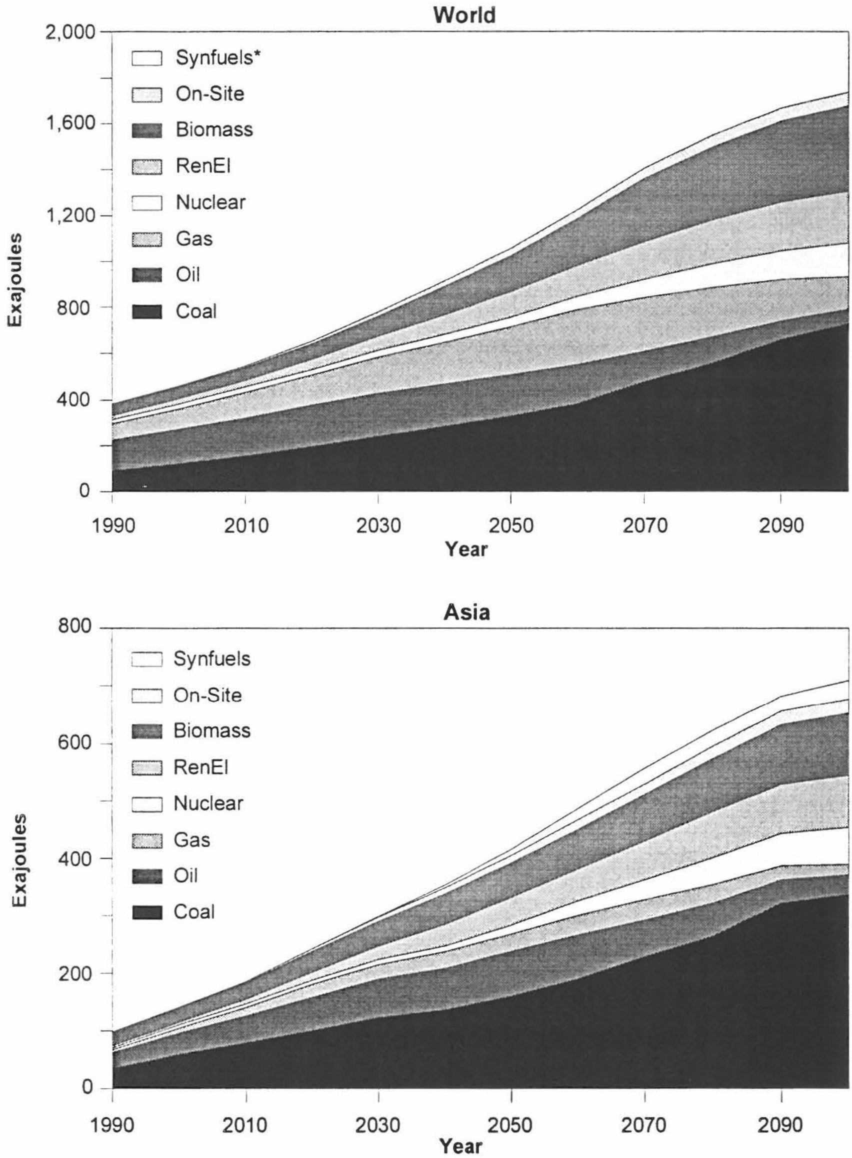
Figure 1. Technology learning curves, electricity generation



NOTES: Scales are logarithmic. RD&D stands for "research, development, and demonstration."

SOURCES: Adapted from P.R. MacGregor, C.E. Maslak, and H.G. Stoll, *The Market Outlook for Integrated Gasification Combined Cycle Technology* (New York: General Electric Company, 1991); L. Christiansson, *Diffusion and Learning Curves of Renewable Energy Technologies*, WP-95-126 (Laxenburg, Austria: International Institute for Applied Systems Analysis, 1995); and N. Nakićenović, A. Grübler, and A. McDonald, eds., *Global Energy Perspectives* (Cambridge, U.K.: Cambridge University Press, 1998).

Figure 2. Primary energy supply by source, 1990–2100

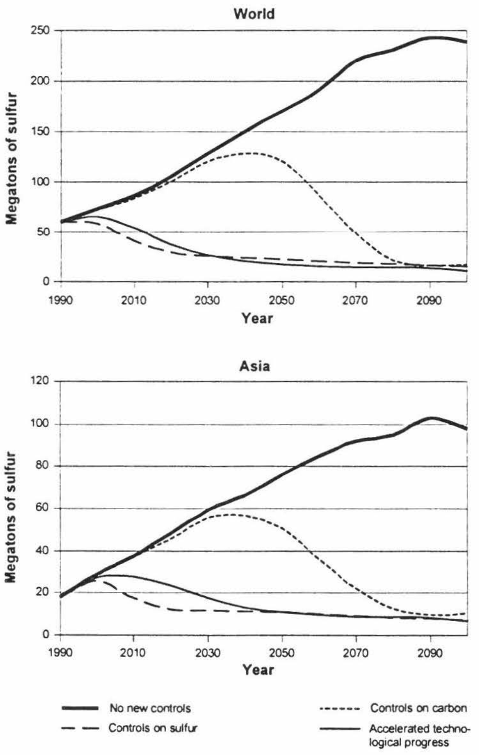


*Too small to be represented in this figure.
NOTES: 1 exajoule = 10^{18} joules. The patterns shown are based on the assumption that there are no new efforts to curb sulfur and carbon emissions.
RenEl stands for centralized electricity generation from renewable sources other than biomass (e.g., hydropower, geothermal, wind, solar thermal, and photovoltaic sources). On-site energy is from photovoltaic and solar thermal panels on roofs.
SOURCE: IIASA Environmentally Compatible Energy Strategies Project.

dominance increases steadily right through 2100. Although less and less coal is used directly (for example, to heat homes), coal is king in electricity generation and after 2050 it becomes an important source of synthetic liquid and gaseous fuels. Coal use doubles between 1990 and 2020, more than triples by 2050, and rises to eight times its 1990 level by 2100. At the same time, more and more of the world's energy is consumed in Asia; that region's share of primary energy use increases from 26 percent in 1990 to more than 41 percent in 2100. Putting the two trends together results in a tripling of Asia's coal use between 1990 and 2020, a quintupling by 2050, and a 10-fold increase by 2100.

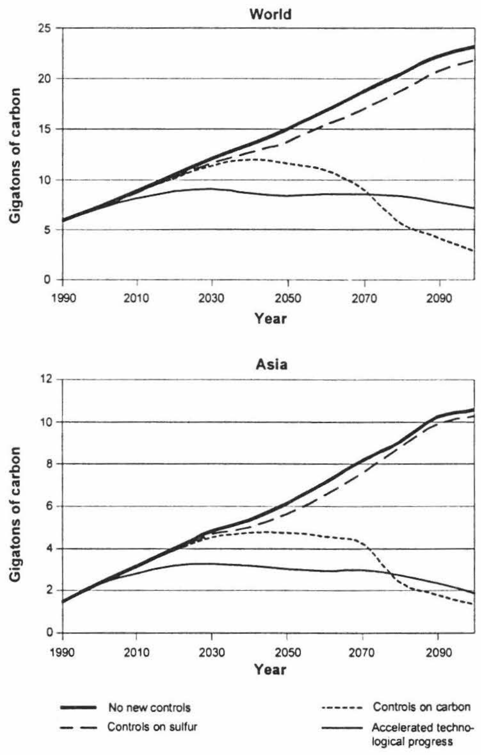
The heavy solid lines in Figures 3 and 4 show the implications for sulfur and carbon emissions. By 2030, Asia alone will emit more sulfur dioxide than the entire world did in 1990. By 2050, the same will be true for carbon dioxide. And by 2100, world carbon dioxide emissions will be 23 gigatons (1 gigaton equals 10^9 tons), more than four times the 1990 level. Thus, a future with no new policies to limit sulfur and carbon emissions promises to result in very high emissions indeed.

Figure 3. Emissions of sulfur dioxide, 1990–2100



NOTE: 1 megaton = 10^6 tons.
SOURCE: IIASA Environmentally Compatible Energy Strategies Project.

Figure 4. Emissions of carbon dioxide, 1990–2100



NOTE: 1 gigaton = 10^9 tons.
SOURCE: IIASA Environmentally Compatible Energy Strategies Project.

Table 3. Changes in agricultural output in the baseline case, 2050 (percent change)

Region	Crop Production	Agricultural GDP
North America	1.3	0.8
Western Europe	-0.2	1.5
Eastern and Central Europe, plus former Soviet Union	9.2	8.3
Pacific OECD	7.2	2.5
Other Pacific Asia	2.8	2.5
Sub-Saharan Africa	3.4	3.7
Latin American and the Caribbean	0.5	0.1
Middle East and North Africa	1.4	1.2
Centrally planned Asia[1]	-9.9	-8.2
South Asia	2.2	2.0
Developed countries	4.9	3.7
Developing countries	-0.8	-0.3
World	0.5	0.7

[1]Includes China, Hong Kong, Laos, Viet Nam, Cambodia, North Korea, and Mongolia.
NOTE: This table shows the percentage changes in crop production (measured in bushels) and agricultural GDP (measured in dollars) that would occur by 2050 as a result of changes in climate and acidification relative to a hypothetical future based on the baseline assumptions, including no new efforts to curb sulfur and carbon emissions.
SOURCE: IIASA Modeling Land-Use and Land-Cover Changes in Europe and Northern Asia Project.

Agricultural Impacts

Emissions in and of themselves are not the principal concern, however. What matters is what they lead to in terms of warmer weather; more extreme weather; rises in sea level; loss of coastal lands and displacement of people; the spread of diseases; the disruption of ecosystems and agriculture; and the possible disruption of natural phenomena such as the North Atlantic current that keeps northern Europe relatively warm. Assessment of all these potential impacts is beyond the scope of this article. Instead, it will focus on one set of impacts—those on agriculture—that demonstrate how sulfur and carbon emissions can interact and how different the results can be for different regions of the world.

Agriculture is particularly relevant to Asia because it is a large part of the region's developing economies. Such economies, of course, are much more vulnerable to climate change than are the manufacturing and service industries that dominate more developed economies.

Using models developed at IIASA and elsewhere, the IIASA researchers estimated the impacts on agriculture in 2050 of the baseline values for sulfur and carbon emissions. The results are shown in Tables 3 and 4. It should be emphasized that these results assume that farmers are "smart." This means that the models take into account farmers' reactions to the changes in crop prices that will inevitably result from climate-induced changes in agricultural yields. If yields for a particular crop decrease as a result of climate change, then the price at which that crop can be sold will increase, other things being equal. Rational farmers will weigh both the changing price signals (how much money they will earn per bushel) and the changing yields (how many bushels of each crop each acre will produce), planting those crops in those amounts that will maximize their incomes. Moreover, such adjustments will be made little by little as the climate gradually changes. The results given in the two tables are thus an improvement over those of earlier "dumb farmer" models that calculated how yields would change if the climate changed overnight, with no adaptation by farmers.

For the world as a whole, the results shown in Tables 3 and 4 are positive: Production (the number of bushels produced) and agricultural GDP (the amount of income earned) both increase while prices drop. To be sure, there are regional differences, with developed countries benefiting more than developing countries. But overall, the initial picture is surprisingly benign. One reason for this is the assumption of smart farmers in the models. By responding to the price signals transmitted through international agricultural markets, they both minimize any potential adverse impacts on agricultural production and take advantage of any opportunities created by climate change. A second reason is that a higher concentration of carbon dioxide would have positive as well as negative effects on agriculture. The negative effect, of course, would come from global warming, which would reduce the yields of crops adapted to today's climate (though not all areas would experience negative impacts, nor to the same degree). The positive effect would be what is known as carbon dioxide fertilization. Because plants utilize carbon dioxide from the atmosphere in photosynthesis, the greater the concentration of carbon dioxide, the greater the yield.

There is a third reason for the generally positive results shown in Tables 3 and 4, which has to do with the increase in emissions of sulfur in the baseline projection. Sulfur emitted into the atmosphere contributes to the formation of sulfate aerosols. These particles reflect sunlight and remain in the atmosphere long enough to have a significant cooling effect that partially offsets the greenhouse effect from more carbon dioxide.[6] In the results shown, sulfur emissions largely offset the warming effect of increased carbon dioxide—but not its fertilization effects. In this scenario, therefore, crops are substantially protected from the negative effects of high carbon dioxide concentrations while benefiting from the positive effects.

If all one cared about were global agricultural GDP, Tables 3 and 4 would certainly not provide support for new policies to restrict sulfur and carbon. Indeed, they suggest just the opposite. There are at least four problems with such an interpretation, however. First, the aggregate agricultural benefit shown in these tables comes at the expense of the developing countries. Agriculture in the region including China and centrally planned Asia is particularly hard hit by acidification from sulfur. Second, there is significant uncertainty surrounding the carbon dioxide fertilization effects. Tables 3 and 4 are based on optimistic assumptions; less optimistic assumptions produce less favorable results. Third, global warming is a long-term phenomenon, and by 2100 the slightly positive balance in Table 3 will become a slightly negative balance. And fourth, the tables address only macroeconomic agricultural impacts, not the full range of effects noted at the beginning of this section. Despite their importance, particularly to developing countries, these impacts constitute only one of the many pieces of information needed to fully evaluate alternative policies.

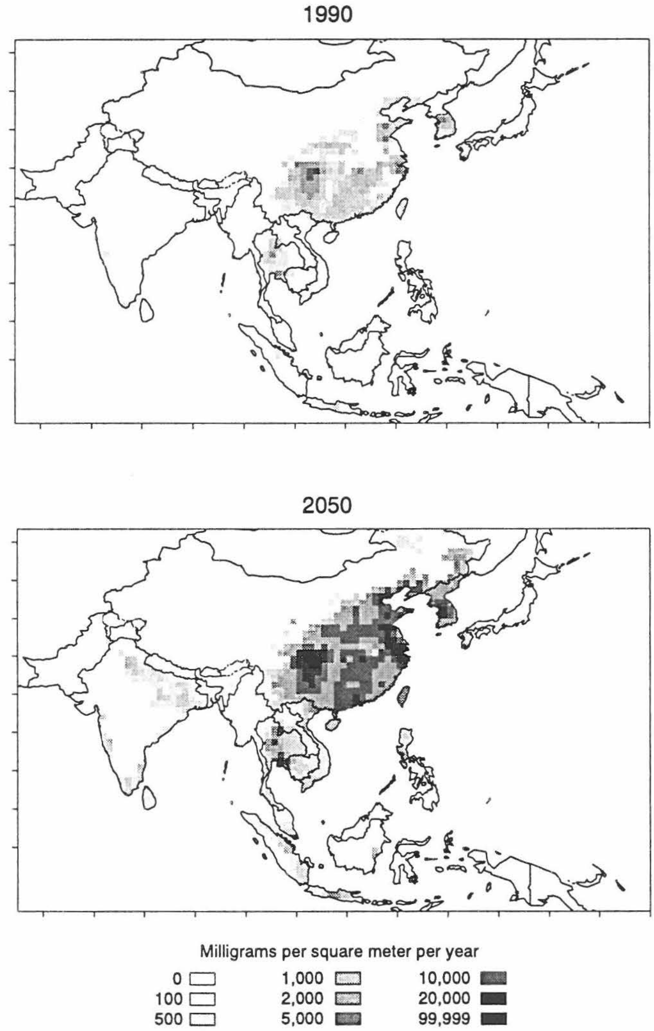
Table 4. Changes in agricultural prices in the baseline case, 2050

Product	Percent Change
Cereals	-9.0
Other crops	-12.0
All crops	-11.0
All agricultural products	-9.0

NOTE: This table shows the percentage changes in agricultural prices that would occur by 2050 as a result of climate change and acidification relative to a hypothetical future based on the baseline assumptions.
SOURCE: See Table 3.

To become familiar with both the analytical framework and the complexities of the issues involved, let us look at the first issue—acidification—and consider a strategy that focuses on that problem exclusively, i.e., one that aims to reduce sulfur emissions before attempting to deal with carbon emissions.

Figure 5. Excess depositions of sulfur in Asia, 1990 and 2050



NOTES: Excess depositions are those that exceed critical loads (the maximum loads that can occur without damage to the environment). The pattern projected for 2050 is based on the assumption that there are no new efforts to curb sulfur and carbon emissions.
SOURCE: IIASA Transboundary Air Pollution Project.

Sulfur Limits First

Figure 5 shows the impact that the baseline emissions of sulfur dioxide would likely have on ecosystems in Asia. It compares the projected depositions of sulfur with the so-called critical loads, i.e., the maximum long-term deposition levels that can be tolerated with minimal environmental damage. The top part of the figure shows the situation in 1990. At that time, there were excess depositions higher than 1 gram per square meter per year in southern and eastern China, Korea, and southern Japan, with isolated "hot spots" around large emission sources in Thailand. However, in most of Asia depositions were at relatively low levels, so that acidification was not a widespread problem.

The situation is projected to be much worse by 2050, however, as shown in the bottom part of the figure. In that year, large parts of China, Thailand, and both Koreas would experience depositions higher than critical loads, with isolated hot spots in Indonesia and Japan. Vast areas would suffer excess deposition higher than 5 grams per square meter per year, and in China excess deposition above 20 grams per square meter per year would affect some 200,000 square kilometers of territory. Such levels are much higher than those observed in the heavily polluted "Black Triangle" of Central Europe in the 1980s. Significantly lower pollution levels are known to have caused ecological disasters in Europe, such as large-scale forest dieback. The projection for 2050 thus poses a real threat to economically important ecosystems, particularly rice fields in southern China.

Without a doubt, the acidification projected in Figure 5 would cause ecological disaster in much of Asia. The damage to unmanaged ecosystems would likely be much greater than the harm done to agriculture, which would be substantial. In a nutshell, environmentally sustainable, coal-intensive development in Asia without emission controls on sulfur is simply not possible.

Most countries in Asia are aware of this constraint on their growth. As mentioned earlier, China in particular has already adopted some policies to limit sulfur emissions, and such efforts are likely to be expanded and strengthened in the future. At the same time, however, China, India, and most other developing countries in Asia continue to resist any limits on their carbon emissions. If this pattern of "sulfur limits first" were to continue, what implications would it have for Asia and the world? And are there any positive spinoffs in terms of global warming, that is, would attempting to limit sulfur emissions entail limiting carbon emissions as well?

To address these questions, the IIASA researchers repeated the analyses described above assuming limits on sulfur emissions consistent with a reasonably high level of ecosystem protection. The results are shown by the dashed lines in Figures 3 and 4. By 2050, Asia's emissions of sulfur would be only 14 percent of those that would occur if no new reduction policies were introduced. Unfortunately, these reductions would have little effect on carbon emissions. As indicated by the dashed lines in Figure 4, world carbon emissions in 2100 would be only 6 percent lower than in the baseline case, and Asian emissions would be only 3 percent lower. Worse, the loss of cooling sulfate aerosols in the sulfur-limits-first strategy implies that temperatures would be significantly higher. Whereas the global mean temperature would increase 1.2° C by 2050 (relative to 1990) in the baseline case, it would increase 1.7° C in the case of sulfur limits first. The gap would be even wider in 2100, 3.5° C as opposed to 2.6° C.

Table 5 shows that although global agricultural production would increase slightly in the case of sulfur limits first, agricultural GDP would be the same

Table 5. Changes in agricultural output with sulfur controls only, 2050 (percent change)

Region	Crop Production	Agricultural GDP
North America	4.1	3.4
Western Europe	-2.7	0.6
Eastern and Central Europe, plus former Soviet Union	8.9	8.2
Pacific OECD	5.9	1.9
Other Pacific Asia	-2.0	-1.5
Sub-Saharan Africa	-0.4	0.4
Latin America and the Caribbean	-3.7	-3.2
Middle East and North Africa	-2.0	-1.5
Centrally planned Asia[1]	3.1	2.2
South Asia	-2.0	-1.3
Developed countries	5.3	4.5
Developing countries	-0.8	-0.5
World	0.7	0.7

[1]Includes China, Hong Kong, Laos, Viet Nam, Cambodia, North Korea, and Mongolia.

NOTE: This table shows the percentage changes in crop production (measured in bushels) and agricultural GDP (measured in dollars) that would occur by 2050 as a result of changes in climate and acidification relative to a hypothetical future based on the baseline assumptions but with new efforts to curb sulfur emissions.

SOURCE: IIASA Modeling Land-Use and Land-Cover in Europe and Northern Asia Project.

as in the baseline case. What does change—and rather significantly—is the regional pattern of gains and losses. The centrally planned countries in Asia gain tremendously, but largely at the expense of other developing regions. North American countries also gain at those countries' expense. However, North America's gain is due less to changes in climate at home than it is to less favorable production conditions—and consequent increases in imports—in the more vulnerable developing countries.

Carbon Limits First

What would happen if policymakers were to pursue a strategy of limiting carbon emissions first? Would such a policy have positive spinoffs in terms of reducing acid rain? The short answer is yes, but only in the long term. The dotted lines in Figures 3 and 4 show both carbon and sulfur emissions when the carbon concentration in the atmosphere is stabilized at 550 parts per million. Through about 2030, sulfur emissions follow pretty much the same path as in the baseline case, after which they decline sharply. This is a bit of a surprise—one might well have expected limits on carbon to lead to early reductions in the use of coal with its high emissions of sulfur. The reason for the delay is that the stabilization of the carbon concentration can be accomplished equally well by early or late reductions in carbon emissions. That is, timing is not terribly important in meeting the environmental objective. It does affect costs, however—the more society can delay these reductions (by, for instance, waiting until existing facilities are due for replacement or low-carbon technologies become more efficient), the less those reductions will cost.

The impact of a carbon-limits-first strategy on global warming is clear. As indicated by the dotted lines in Figure 4, global carbon emissions in 2050 would be 23 percent lower than in the baseline case. By 2100, carbon emissions would be only 2.8 gigatons, less than half their level in 1990. Because of the huge inertia in the global climate system, however, the effect on global temperatures would lag behind the reduction in emissions. The mean global temperature in 2050 would still be 1.2° C higher than in 1990; in 2100, it would be 2.4° C higher. But the most important outcome in terms of global warming is the stabilization of atmospheric carbon dioxide at 550 parts per million.

Table 6 shows the impact of such carbon reductions and the lagged sulfur reductions on agriculture. Both the world as a whole and developing countries as a group are better off than in either the baseline or sulfur-limits-first cases. But again, the result is due entirely to the good fortune of North America and the centrally planned economies in Asia. Every other region does worse than if there were no new policies at all.

Accelerated Technology: An Alternative

If a sulfur-limits-first strategy does not prevent global warming for free, and a carbon-limits-first strategy does not solve the acidification problem for free, what about starting with sulfur reductions (the more immediate concern) and later shifting to carbon reductions (the longer term concern)? The danger here is one of technological lock-in. As an example, consider the QWERTY keyboard—the standard keyboard layout in which the first six letters on the top row are Q, W, E, R, T, and Y. This is certainly not the only possible arrangement of the keys, and inventors have come up with alternatives that may be ergonomically superior. Yet the QWERTY keyboard is as pervasive as ever. At least two arguments are given for its success. First, when the QWERTY keyboard was introduced, the mechanical hammers that actually struck the typewriter ribbon and paper were less likely to jam together than was the case with other layouts. Second, as its popularity grew, the QWERTY keyboard became transformed into a standard. Typing courses used these typewriters, businesses purchased them and expected employees to be proficient on them, suppliers featured them, and manufacturers produced them. Now, particularly in computer applications, hammer-lock is hardly an issue. But we are firmly locked in to the QWERTY layout.

In addition to technological advantages and the preference for a standard technology, there are at least two other reasons for technological lock-in. The most important is technological learning—as we gain experience with any given technology, the cost of production generally goes down and performance, quality, and efficiency of the product go up. This makes it increasingly difficult for alternatives that appear later to catch up. The second reason is government regulation. If, for instance, the government requires a catalytic converter on every new car, this removes the incentive to come up with alternative solutions as well as dramatically increasing the speed with which the cost of such converters falls and their performance improves. Even if the government were later to replace the requirement to use catalytic converters with flexible emissions limits, the converter technology would still be the de facto standard—and would have intimidating cost and performance advantages over potential competitors with less experience.

Table 6. Changes in agricultural output with carbon controls only, 2050 (percent change)

Region	Crop Production	Agricultural GDP
North America	2.2	1.7
Western Europe	-2.0	0.8
Eastern and Central Europe, plus former Soviet Union	8.8	8.1
Pacific OECD	5.2	1.9
Other Pacific Asia	1.3	1.4
Sub-Saharan Africa	1.0	1.8
Latin America and the Caribbean	-1.2	-1.1
Middle East and North Africa	0.1	0.2
Centrally planned Asia[1]	-2.8	-2.3
South Asia	0.8	1.0
Developed countries	4.5	3.7
Developing countries	-0.4	0.0
World	0.8	0.9

[1]Includes China, Hong Kong, Laos, Viet Nam, Cambodia, North Korea, and Mongolia.

NOTE: This table shows the percentage changes in crop production (measured in bushels) and agricultural GDP (measured in dollars) that would occur by 2050 as a result of changes in climate and acidification relative to a hypothetical future based on the baseline assumptions but with new efforts to curb carbon emissions.

SOURCE: IIASA Modeling Land-Use and Land-Cover in Europe and Northern Asia Project.

This is the risk of a strategy that attempts to limit sulfur emissions first and only later turns to limiting carbon emissions. To see this, note that there are five principal ways to curb emissions of sulfur: scrubbing (which accounts for more than 70 percent of the reductions achieved by the sulfur-limits-first strategy in the short term); cleaning the coal prior to combustion to remove sulfur; switching from "dirty" to "clean" coal technologies, such as integrated gasification combined cycle technologies, fluidized bed technologies, and coal-sourced fuel cells[7] (these are expected to account for 40 percent of sulfur reductions achieved by the sulfur-limits-first strategy by 2050); converting the coal to synthetic fuels prior to combustion; and switching from coal to less sulfurous fuels.

The final item on this list is the exception that proves the rule. The other strategies strive to make burning coal cleaner (at least in terms of sulfur emissions), not to advance noncoal technologies. But of all fossil fuels, indeed of all fuels, coal emits the most carbon per unit of useful energy. Making coal cleaner in terms of sulfur emissions makes very little difference in terms of carbon emissions, but it will have the important effect of locking in coal technologies. This will further entrench coal's position in the world's energy mix, making it increasingly difficult to switch to a low-coal strategy later. This point becomes very clear when one considers the dramatically different amounts of coal that would be burned under the sulfur-limits-first strategy and the carbon-limits-first strategy. Under the former, coal would make up 41 percent of the primary energy used in 2100, only one percentage point lower than in the baseline case. In contrast, coal would comprise only 15 percent of primary energy use under the carbon-limits-first strategy.

How then might we design a strategy that accomplishes the short-term objective of reducing sulfur emissions without locking ourselves into technologies that will only make it harder to reduce carbon emissions? The solution appears to lie in "going outside the box," i.e., focusing on the broader patterns of technological change rather than on specific emission limits and the relatively narrow set of technologies that such limits affect directly. To that end, let us consider what might happen under a policy that is designed to accelerate technological progress across the board.

The sulfur and carbon emission levels that result from one plausible set of assumptions about general technological progress are shown by the thin solid lines in Figures 3 and 4, and they are impressive. Under these assumptions, sulfur emissions would effectively match the low levels of the sulfur-limits-first strategy and carbon emissions would match the low levels of the carbon-limits-first strategy, despite the absence of explicit targets for sulfur and carbon emissions. The assumptions underlying these results are ambitious but not unrealistic. In formulating them, the IIASA researchers considered three distinct categories of technologies: static, incremental, and radical. The static category included mature technologies where most of the potential improvements have already been achieved through years of experience; for these no further cost and performance improvements were assumed. At the other end of the spectrum were the radical new technologies with lots of untapped potential; for these, it was assumed that the costs would decrease 30 percent each time the extent of their use doubled. In the middle were the incremental technologies where additional experience should lead to less rapid—but still significant—cost reductions of 15 percent for each doubling in use. Lest these figures seem overly optimistic, one should note that between 1930 and 1950, the cost of electricity in the United States declined 29 percent each time the market doubled.

All the analyses described here reflect the widespread (and growing) global preference for cleaner, more flexible, and more convenient end-use fuels such as electricity. Given this, (the assumed) acceleration of technological progress would lead to rapid adoption of cleaner technologies, which would lead to rapidly declining costs and thus to even more rapid adoption of these technologies, and so on in a virtuous circle. The final result would be the very low sulfur and carbon emissions shown by the thin solid lines in Figures 3 and 4.

The most important question that this analysis leaves open is how to design policies to accelerate technological progress across the board. Part of the solution is increased public and private investments in energy research, development, and demonstration (RD&D). Such crucial investments generally declined during the 1980s and 1990s. In 1997, for example, the U.S. Department of Energy spent only $1.28 billion on applied energy technology, down from $2.18 billion in 1992 and $6.15 billion in 1978 (all figures are in 1997 dollars). Private sector investment in electricity RD&D declined by nearly one-third from 1992 to 1997. At the very least, accelerating technological progress will require much more investment, but it will also require that this be done creatively and efficiently. That will require judgment and analysis that is beyond the scope of this article.

Conclusion

This article is about two types of interactions that are relevant to efforts to limit both acid rain and global warming. The first are the interactions between sulfur and carbon emissions in producing the impacts that ultimately matter, such as the impacts on agriculture in Asia. The second are behavioral interactions, i.e., the rational responses to policies targeting one problem that make the other more difficult to solve. Here the article focused on incentives to limit sulfur emissions in Asia in the near term, which might well create incentives making it harder to limit carbon emissions.

The initial calculation of what would happen with no new policies to limit sulfur and carbon emissions suggested that the interactions between sulfur and carbon emissions might work to the world's advantage. That is, the cooling effect of sulfate aerosols would offset global warming from carbon dioxide, while carbon dioxide fertilization would more than offset crop losses due to acidification. The net result for the world as a whole in 2050 would be slight increases in agricultural production and GDP and a slight decrease in prices—hardly a reason to limit sulfur and carbon emissions.

While this result is illuminating in terms of the possible interactions between different chemical substances, there are two things wrong with it as a basis for policy. First, it is a tenuous result: Reasonable changes in the assumptions about carbon dioxide fertilization plus the inclusion of agricultural impacts after 2050 tip the balance in the other direction, although hardly by enough to compel urgent action now. Second, it ignores the realities of regional differences and politics. It is highly unlikely that the centrally planned countries of Asia would tolerate the damage they would suffer under this scenario, even if the rest of the world benefited by more than just the few percentage points shown in Table 3. Indeed, China has already started to take action to reduce sulfur emissions. And while that is good for China, it removes much of the potential sulfate aerosol shade that would otherwise tend to limit global warming. Even worse, a strategy of sulfur limits first does almost nothing to reduce carbon emissions and even entrenches the importance of coal. An alternative policy of carbon limits first creates incentives with the spinoff benefit of reducing sulfur emissions, but only in the long run. The incentives are to delay if the focus is carbon, and delay does nothing to reduce the acidification and agricultural damage that matter in the near term.

But it is possible to imagine developments that would accomplish both the near-term objective of reducing sulfur emissions and the longer term objective of reducing carbon emissions. The example outlined above focused not on one side or the other of the carbon-sulfur equation but on the technologies that are common to both. Ultimately, in a world where population and living standards are expected to grow for a long time yet, technology may be the best route to reducing environmental damage from energy use. That means that the faster we can improve technology the better. And the broad message appears to be that we should figuratively "let a thousand flowers bloom" so that many millions can bloom literally. Too narrow a focus risks creating perverse incentives destined to haunt us for a long time.

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NOTES

1. On the Kyoto conference, see the November 1997 issue of *Environment* as well as H. E. Ott, "The Kyoto Protocol: Unfinished Business," *Environment*, July/August 1998, 16. On the Buenos Aires conference, see J. Lanchbery, "Expectations for the Climate Talks in Buenos Aires," *Environment*, October 1998, 16.

2. World Resources Institute, United Nations Environment Programme, United Nations Development Programme, and World Bank, *1998–99 World Resources: A Guide to the Global Environment* (New York: Oxford University Press, 1998), 264–65.

3. Executive body for the Convention on Long-Range Transboundary Air Pollution, 16th session, December 1998, item 3, table 1.

4. N. Kato, "Analysis of Structure of Energy Consumption and Dynamics of Emission of Atmospheric Species Related to the Global Environmental Change (SO_x, NO_x, and CO_2) in Asia," *Atmospheric Environment* 30, no. 5 (1996): 757; and N. Nakićenović, A. Grübler, and A. McDonald, eds., *Global Energy Perspectives* (Cambridge, U.K.: Cambridge University Press, 1998).

5. For more on China's efforts to curb pollution, see R. A. Bohm, C. Ge, M. Russell, J. Wang, and J. Yang, "Environmental Taxes: China's Bold Initiative," *Environment*, September 1998, 10.

6. The importance of sulfate aerosols gained increased visibility through the Second Assessment Report of the Intergovernmental Panel on Climate Change (IPCC). Previously, models of atmospheric change were predicting more warming than had actually occurred, and this seriously undermined their credibility. With the cooling effect of sulfate aerosols (among other factors) taken into account, the models' estimates of past temperature increases were more accurate. The match was sufficiently good that IPCC concluded for the first time that "the balance of evidence suggests a discernable human influence on the climate system." See J. T. Houghton et al., eds., *Climate Change 1995: The Science of Climate Change*, Contribution of Working Group I to the Second Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge, U.K.: Cambridge University Press, 1996). For a review of that report, see W. C. Clark and J. Jäger, "Climate Change 1995: The Science of Climate Change," *Environment*, November 1997, 23.

7. Combined cycle power plants burn gas fuels such as natural gas. The resulting combustion gases, which are under high pressure, spin a turbine that generates electricity. This is the "top" cycle of the combined cycle process. After passing through the turbine, the hot gases are used to boil water in a steam generator. High-pressure steam then spins another electricity-generating turbine in the "bottom" cycle of the process. In an integrated gasification combined cycle (IGCC) power plant, the fuel is produced by gasifying coal, which removes almost all of the sulfur from the resulting gas. As a result, sulfur emissions from such a plant are very low.

In fluidized bed technologies, pulverized coal is mixed with pulverized limestone or dolomite and ash pebbles and suspended by jets of air during combustion. (The suspended mixture, or "bed," behaves much like a liquid, hence its name.) The pulverized coal burns much more efficiently than in a standard coal-fired power plant. Because it burns at a lower temperature, fewer nitrogen oxides are produced. In addition, the limestone or dolomite absorbs nearly all of the sulfur dioxide produced during combustion.

Fuel cells, like batteries, convert chemical energy to electricity directly, without combustion. As a result, they produce no sulfur emissions. Although fuel cells powered directly by coal are probably more than a few decades away, those utilizing gasified coal are available now.

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