Editorial note: With the publication of this article by Professor Barry Commoner, one of the world's best-known environmentalists, the Journal begins a participation in the worldwide discourse on the relationship between population growth and environmental stress. On September 15, 1990, The Lancet *(Volume 336, Number 8716) published an article by Professor Maurice King, entitled "Health Is a Sustainable State," which presents a Malthusian perspective that has created much debate. Professor Commoner's article, with its anti-Malthusian perspective, helps to broaden that debate.*

RAPID POPULATION GROWTH AND ENVIRONMENTAL STRESS

Barry Commoner

It is often suggested that rapid population growth, especially in developing countries, correspondingly intensifies environmental degradation, which must therefore be mitigated by reducing the rate of population growth. The validity of this assumption can be tested by means of an algebraic identity that relates the amount of a pollutant introduced into the environment to the product of three factors: population, "affluence" (the amount of goods produced per capita), and "technology" (the ratio of pollution generated to goods produced). For several forms of pollution that have a known origin in a specific production process (electricity production, use of motor vehicles, and consumption of inorganic nitrogen fertilizer), it is possible to compare the inferred rate of increase in pollution levels with the rate of population growth in developing countries. The results show that the rate of increase in pollution is largely determined by the technology factor, which governs the amount of pollution generated per unit of goods produced or consumed. This observation extends earlier evidence that both the increasing levels of pollution observed in developed countries and the results of efforts to reduce them support the view that the decisive factor determining environmental quality is the nature of the technology of production, rather than the size of the population.

It is useful to begin this article by considering the purpose of analyzing the relation between rapid population growth and environmental quality. One purpose is self-evident: rapid population growth is characteristic of most developing countries and, as a guide to national policy, it is important to determine whether it creates a distinctive impact on the quality of their environment. Another aspect of the issue is more general and the subject of a considerably wider range of discussion. It is concerned with

This article is adapted from a paper presented at the United Nations Expert Group Meeting on Consequences of Rapid Population Growth in Developing Countries, United Nations, New York, August 23–26, 1988, and published in the Summary Report of that meeting.

International Journal of Health Services, Volume 21, Number 2, Pages 199–227, 1991

doi: 10.2190/B8RU-HA91-JJKW-PKUR
http://baywood.com

the origin of the environmental crisis: the sharp decline in environmental quality, worldwide, in the last 40 to 50 years.

Some observers have concluded that population growth is the dominant cause of the environmental crisis. The classic statement of this position is Ehrlich's (1):

> The causal chain of the deterioration [of the environment] is easily followed to its source. Too many cars, too many factories, too much detergent, too much pesticides, multiplying contrails, inadequate sewage treatment plants, too little water, too much carbon dioxide—all can be traced easily to *too many people*.

For a more recent expression of the same position, which relates it to the principles of ecology, we can turn to Russell W. Peterson (2), the former president of the Audubon Society:

> Almost every environmental problem, almost every social and political problem as well, either stems from or is exacerbated by the growth of human population. . . . As any wildlife biologist knows, once a species reproduces itself beyond the carrying capacity of its habitat, natural checks and balances come into play. . . . The human species is governed by the same natural law. And there are signs in many parts of the world today—Ethiopia is only one of many places, a tip of the iceberg—that we *Homo sapiens* are beginning to exceed the carrying capacity of the planet.

If this proposition—that environmental degradation is chiefly a consequence of population growth—were true, the issue under discussion here could be resolved and the operational solution identified: Rapid population growth correspondingly intensifies environmental degradation, which must therefore be mitigated by reducing the rate of population growth.

Such statements are generally supported by anecdotal data about environmental changes that appear to occur distinctively in countries that have high rates of population growth. Thus, intensive urbanization in Mexico, a country with a 2.6 percent annual rate of population growth in 1980–85 (3), has been accompanied by very high levels of photochemical smog in Mexico City. Similarly, forests have been rapidly destroyed for firewood in countries such as Kenya that have high rates of population growth. However, such anecdotal data are not definitive, for they do not establish a necessary relation between environmental quality and rapid population growth. For example, despite the rapid increase in the population of Mexico City, its photochemical smog level would be much lower if the city had developed an adequate system of electrified mass transit—a well-established technology—as it grew. Similarly, deforestation in Kenya could be greatly diminished if, for example, the rural population, despite the rapid growth, were provided with cooking stoves fired by methane (perhaps produced from sewage and manure) instead of using firewood for that purpose. In both of these cases, the concurrence of rapid population growth and environmental degradation does not necessarily reflect a direct, causal connection between them. Moreover, counter-examples can readily be cited: for example, that Los Angeles or Tokyo, in countries with low rates of population growth, have experienced photochemical smog levels approximating those of Mexico City.

ANALYSIS OF THE FACTORS THAT INFLUENCE ENVIRONMENTAL IMPACT

These examples suggest that population is only one of several factors that can influence environmental quality and that the degree of its influence cannot be assessed without comparing it with the effects of the other relevant factors.

For this purpose, environmental stress is defined as the amount of pollutant that is emitted into the environment annually, where the term pollutant is in turn defined as a substance that contributes to the deterioration of environmental quality. Such an analysis has been developed for the purpose of assessing the origin of the environmental crisis in developed, industrialized countries (4). It is based on a simple algebraic identity that relates environmental impact (for example, the amount of pollutant introduced into the environment) to the three chief factors that can influence it: population; "affluence" (the amount of goods or resources consumed per capita); and "technology" (the relation between the pollutant and the production technology that generates it, expressed as pollutant generated per unit of goods produced). Thus:

$$\text{Pollutant} = \text{population} \times \frac{\text{good}}{\text{population}} \times \frac{\text{pollutant}}{\text{good}} \tag{i}$$

In this equation, "good" represents an economic good, the production of which generates the pollutant. For example, automotive travel (expressed as vehicle miles) is a good that, as it is produced, generates the pollutant, carbon monoxide. By evaluating each of the three factors we can determine the degree to which each of them contributes to environmental impact and in that way assess the relative importance of population growth. Generally this can be done in terms of rates of change over time, so that equation (i) takes the form:

$$1 + \Delta\text{pol} = 1 + \Delta\text{pop} \times \frac{1 + \Delta\text{good}}{1 + \Delta\text{pop}} \times \frac{1 + \Delta\text{pol}}{1 + \Delta\text{good}} \tag{ii}$$

where Δpop, Δgood, and Δpol are, respectively, the rate of change in the size of the population, in the amount of a given good, and in the amount of the pollutant generated when that good is produced.

When this analysis was applied to the sharp increase in pollutant emissions that occurred in the United States between 1950 and 1970, results of the type shown in Table 1 were obtained. Such results show that the dominant contribution to the sharply rising pollution levels during that period of time was the technology factor rather than increasing population or affluence. The rate of increase in the amount of pollutant generated by the production of a unit amount of goods was considerably greater than the concurrent increase in goods produced per capita or in population.

To my knowledge this type of analysis has not yet been applied to countries characterized by rapid rates of population growth—that is, developing countries. One reason is that the necessary environmental data—yearly values of pollutant levels—are generally lacking. It is possible, however, to approach the problem indirectly, based on what is now known about the operational relation between a number of pollutants and the

Table 1

Relation between the rates of change in U.S. pollutant output and the rates of change of environmental impact factors[a]

				Environmental impact factors, rate of change		
Pollutant	Good	Period	Pollutant, rate of change[b]	Population	Good / Population	Pollutant / Good
Nitrogen oxides	Vehicle-miles	1946–67	7.28	1.41	2.00	2.58
Phosphate	Detergent	1946–68	19.45	1.42	1.00	13.70
Synthetic pesticides	Crops	1950–67	3.66	1.30	1.05	2.68
Beer bottles	Beer	1950–67	6.93	1.30	1.05	5.08

[a]Source: reference 4.
[b]Rate expressed as the increment ratio over the indicated period of time—i.e., value in final year/value in initial year.

production processes that generate them. For example, it has been established that the rising levels of nitrate, a pollutant that contributes to eutrophication and to health problems in drinking water supplies, in U.S. and European surface waters is largely due to the application of nitrogen fertilizer to crops, which represent the economic good. Some of the nitrogen is not taken up by crops, but leaches into rivers and lakes, the fraction depending on the rate of application, soil conditions, and rainfall. In temperate areas, where such data have been obtained, about 20 to 25 percent of the applied nitrogen reaches surface waters (5). Hence, subject to this range of uncertainty, the amount of nitrogen fertilizer applied to crops can serve as a proxy for the resultant level of nitrate in surface waters—that is, for environmental impact. Hence, the relative effects of the population, affluence, and technology factors can be estimated if, for a given country or area, changes over time in the following parameters can be computed: population; agricultural production per capita; and nitrogen fertilizer used per unit agricultural production.

In the same way, the number of automotive vehicles (passenger cars and trucks) operating in a country can be used as an approximation of the pollutants that the vehicles emit: for example, carbon monoxide, nitrogen oxides, and, in the case of diesel engines, carcinogen-containing carbon particles. In this case, we are compelled to use a very general measure to represent the economic good produced by operating the vehicles: gross domestic product (GDP). Similarly, the amount of electricity produced can be used as an approximation of the amount of pollution generated by typical power plants. Depending on the fuel used, these pollutants may include: airborne dust, carbon monoxide, nitrogen oxides, and sulfur dioxide, as well as various toxic chemicals. Here, too, GDP must be used to represent the economic good yielded by the use of electricity.

Since equation (ii) is based on changes in the relevant values over a given period of time, the computed values of the three determinant factors can be compared among countries that differ in the absolute values of population size, GDP, number of vehicles, electricity production, or nitrogen fertilizer utilization. Naturally, the results of such computations will be affected by the influence on the pollutant level of factors not considered in equation (ii), which are likely to differ among countries. Thus, agricultural production is influenced not only by nitrogen fertilizer, but by additional factors such as pesticides. Similarly, GDP is certain to be influenced by many factors in addition to motor vehicles or electricity production. These extrinsic factors will, of course, blur the relations among the three components of the environmental impact equation. Nevertheless, as shown below, the computations do permit, at least as a first approximation, an estimate of the relationship between rapid population growth and environmental impact.

In recent years the necessary data have become available for a number of developing countries, enabling the type of computation outlined above. Such analyses have been carried out for three cases of environmental degradation: vehicular pollutants (e.g., carbon monoxide, nitrogen oxides), in which the number of motor vehicles serves as an approximation of emitted pollutants; power plant pollutants (e.g., nitrogen oxides, sulfur dioxide), in which the amount of electricity produced serves to approximate the resultant pollutants; and nitrate pollution, in which the amount of nitrogen fertilizer used serves as an approximation of the resultant concentration of nitrate in groundwater and surface waters.

The results of the first of these analyses, regarding the environmental impact of operating motor vehicles in 65 developing countries over the period 1970–80, are summarized in Table 2. The histograms shown in Figure 1 describe the variation in the values of the three factors among the different countries. The mean value of the technology factor (vehicles/GDP), 1.054, is significantly greater than that of the other factors (1.025 for population and 1.002 for GDP/capita). These data can also be used to examine quite directly the influence of variation in the rate of population growth on the inferred environmental impact. This relationship is shown in Figure 2, a plot, for the 65 developing countries, of the rate of increase in motor vehicles versus the concurrent rate of population growth. Regression analysis shows that there is no statistically significant relationship between the two parameters ($R^2 = 0.18$).

These results are in sharp contrast to the relationships expected from the view that population growth is the determinant of environmental degradation. This theory can be stated in the framework of equation (ii) in the following way: Assume that population growth *wholly* determines environmental impact, which in the preceding example is expressed as the concurrent increase in motor vehicles. This implies that in equation (ii) the product of the affluence factor ($1 + \Delta GDP/\Delta pop$) and the technology factor ($1 + \Delta vehicles/\Delta GDP$) is 1. This means that the environmental impact, as represented by a positive rate of change in the number of vehicles, is exerted only by the increase in population. Any departure from this condition means that the affluence and/or the technology factor do influence environmental impact—to a degree represented by their size relative to that of the population factor. Thus, from the mean values of the results shown in Table 2, we can conclude that the relative impacts of the three factors are given by their respective annual rates of change: population , +2.5 percent;

Table 2

Relation between the rate of change of motor vehicles used and the rates of change of environmental impact factors, 1970–80[a]

Country	Motor vehicles in use, rate of change, 1970–80	Environmental impact factors, rate of change, 1970–80		
		Population	GDP / Population	Vehicles / GDP
Algeria	1.127	1.030	1.007	1.086
Botswana	1.173	1.044	1.047	1.073
Burundi	1.050	1.016	0.995	1.039
Central African Republic	1.055	1.022	0.970	1.065
Egypt	1.130	1.023	1.031	1.071
Ethiopia	1.009	1.022	0.983	1.004
Ghana	1.055	1.021	0.955	1.082
Ivory Coast	1.084	1.042	0.988	1.052
Kenya	1.057	1.039	0.976	1.042
Libya	1.159	1.044	0.994	1.117
Madagascar	1.015	1.025	0.960	1.032
Malawi	1.036	1.030	0.987	1.019
Mauritius	1.086	1.015	0.984	1.087
Morocco	1.075	1.026	0.994	1.054
Nigeria	1.099	1.030	0.977	1.092
Rwanda	1.106	1.031	1.019	1.052
Seychelles	1.123	1.017	1.061	1.041
Sierra Leone	1.022	1.017	0.985	1.021
South Africa	1.053	1.026	0.984	1.043
Swaziland	1.132	1.028	0.992	1.110
Tanzania	1.034	1.029	0.983	1.022
Zambia	1.002	1.028	0.953	1.023
Zimbabwe	1.030	1.028	0.983	1.020
Bahrain	1.172	1.046	0.994	1.127
Bangladesh	1.076	1.027	1.005	1.042
Brunei	1.149	1.037	1.040	1.066
Burma	1.056	1.020	0.998	1.037
Cyprus	1.055	1.002	1.024	1.029
India	1.070	1.022	0.987	1.060
Indonesia	1.126	1.023	1.033	1.065
Iran	0.996	1.030	0.963	1.004
Iraq	1.133	1.034	0.963	1.138
Kuwait	1.137	1.061	0.906	1.183
Pakistan	1.029	1.026	1.000	1.003
Philippines	1.065	1.027	1.006	1.030
Singapore	1.030	1.015	1.060	0.957
South Korea	1.153	1.017	1.051	1.079
Sri Lanka	1.041	1.017	1.010	1.013
Syria	1.153	1.033	1.016	1.098
Thailand	1.045	1.024	1.019	1.002
Turkey	1.134	1.023	1.001	1.107

Table 2

(Continued)

Country	Motor vehicles in use, rate of change, 1970–80	Environmental impact factors, rate of change, 1970–80: Population	GDP/Population	Vehicles/GDP
Costa Rica	1.088	1.028	1.005	1.053
Dominican Republic	1.090	1.029	1.009	1.050
El Salvador	1.105	1.027	0.981	1.096
Guatemala	1.145	1.030	0.996	1.117
Haiti	1.098	1.017	1.011	1.068
Honduras	1.096	1.034	0.980	1.082
Mexico	1.123	1.028	1.006	1.086
Nicaragua	1.068	1.031	0.977	1.060
Panama	1.073	1.025	1.000	1.047
Saint Lucia	1.080	1.012	1.044	1.022
Saint Vincent and the Grenadines	1.057	1.011	1.024	1.021
St. Christopher and Nevis	1.061	0.996	1.127	0.946
Trinidad and Tobago	1.081	1.010	1.030	1.040
Fiji	1.095	1.019	1.015	1.059
Tonga	1.084	1.011	1.032	1.039
Argentina	1.071	1.016	0.994	1.060
Bolivia	1.056	1.024	0.994	1.038
Chile	1.074	1.017	0.992	1.064
Colombia	1.098	1.021	1.008	1.067
Ecuador	1.108	1.028	1.030	1.047
Guyana	1.056	1.006	1.008	1.041
Peru	1.034	1.027	0.977	1.030
Uruguay	1.023	1.002	1.023	0.998
Venezuela	1.113	1.035	0.971	1.107
Average	1.082	1.025	1.002	1.054

[a]Source: United Nations. *Statistical Yearbook 1983/84*. U.N., New York, 1986.

affluence, +0.2 percent; technology, +5.4 percent. In this instance, therefore, the influence of the technology factor on environmental impact is more than twice the influence of the population factor.

This conclusion is also evident in the results shown in Figure 2. If population growth were the sole source of environmental impact, the rate of increase in motor vehicles would be equal to the rate of population growth, and the points representative of the different developing countries should lie on a line with a 45 degree slope (the broken line in Figure 2; note the different scales of the axes). Figure 2 shows that this is true of only six countries. In the remaining 59 countries, the rate of increase in motor vehicles is independent of the rate of population growth, indicating that factors other than population growth contribute to the increase in motor vehicles, and by inference, to their

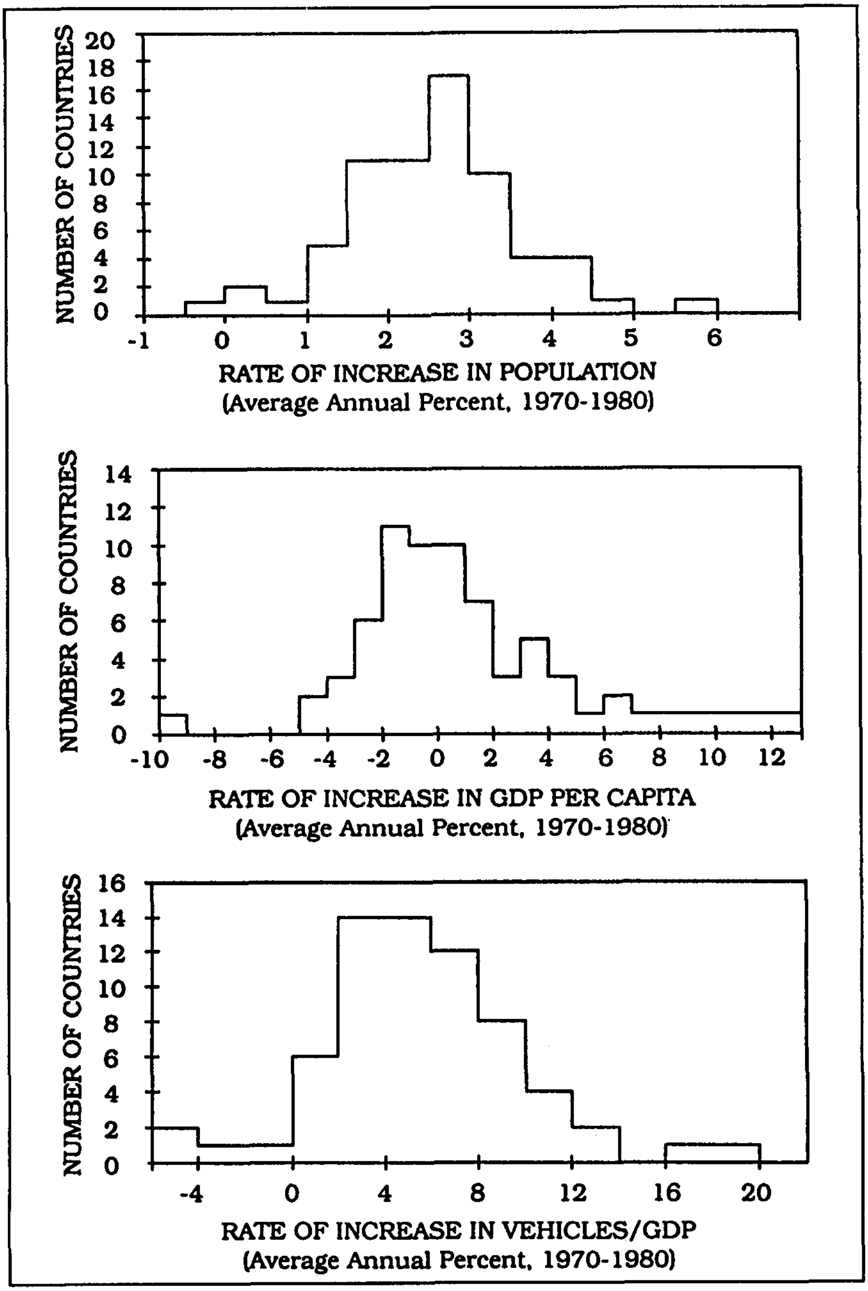

Figure 1. Increases in population, in gross domestic product (GDP) per capita, and in vehicles per GDP, 1970–80.

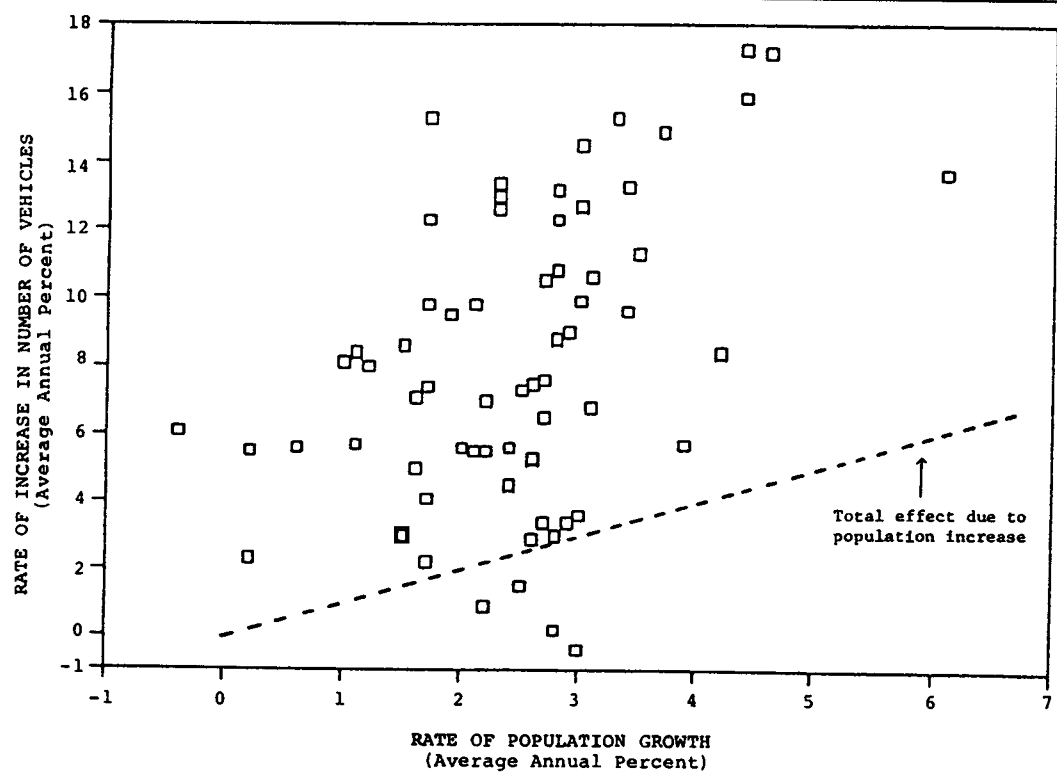

Figure 2. Relation between rate of increase in number of motor vehicles and population growth, 1970–80.

Table 3

Relation between the rate of change of electricity production and the rates of change of environmental impact factors, 1970–80[a]

Country	Electricity production, rate of change, 1970–80	Environmental impact factors, rate of change, 1970–80: Population	GDP / Population	Electricity / GDP
Algeria	1.137	1.030	1.007	1.096
Benin	0.871	1.027	0.987	0.859
Burundi	1.000	1.016	0.995	0.990
Central African Republic	1.029	1.022	0.970	1.038
Egypt	1.096	1.023	1.031	1.039
Ethiopia	1.026	1.022	0.983	1.021
Ghana	1.062	1.021	0.955	1.089
Ivory Coast	1.129	1.042	0.988	1.096
Kenya	1.098	1.039	0.976	1.082
Liberia	1.061	1.031	0.957	1.075
Libya	1.256	1.044	0.994	1.210
Madagascar	1.057	1.025	0.960	1.074
Malawi	1.114	1.030	0.987	1.095
Morocco	1.098	1.026	0.994	1.076
Nigeria	1.165	1.030	0.977	1.157
Rwanda	1.034	1.031	1.019	0.984
Senegal	1.053	1.028	0.959	1.068
Sierra Leone	1.012	1.017	0.985	1.011
Somalia	1.116	1.051	0.927	1.146
South Africa	1.059	1.026	0.984	1.049
Tanzania	1.048	1.029	0.983	1.036
Tunisia	1.334	1.024	1.031	1.263
Uganda	0.977	1.026	0.926	1.028
Zaire	1.033	1.027	0.970	1.037
Zambia	1.255	1.028	0.953	1.281
Zimbabwe	0.966	1.028	0.983	0.956
Afganistan	1.093	1.019	0.967	1.109
Bahrain	1.146	1.046	0.994	1.102
Brunei	1.131	1.037	1.040	1.049
Burma	1.095	1.020	0.998	1.075
Cyprus	1.054	1.002	1.024	1.028
India	1.069	1.022	0.987	1.059
Indonesia	1.118	1.023	1.033	1.058
Iran	1.127	1.030	0.963	1.136
Iraq	1.147	1.034	0.963	1.152
Kuwait	1.135	1.061	0.906	1.181
Malaysia	1.111	1.023	1.038	1.046
Nepal	1.124	1.023	0.976	1.126
Philippines	1.076	1.027	1.006	1.041
Saudi Arabia	1.334	1.051	0.999	1.270
Singapore	1.122	1.015	1.060	1.043
South Korea	1.154	1.017	1.051	1.080

Table 3

(Continued)

Country	Electricity production, rate of change, 1970–80	Environmental impact factors, rate of change, 1970–80: Population	GDP/Population	Electricity/GDP
Sri Lanka	1.074	1.017	1.010	1.045
Syria	1.151	1.033	1.016	1.096
Thailand	1.128	1.024	1.019	1.082
Turkey	1.104	1.023	1.001	1.078
United Arab Emirates	1.693	1.139	0.888	1.673
Antigua and Barbuda	1.058	1.004	1.012	1.041
Costa Rica	1.081	1.028	1.005	1.046
Dominican Republic	1.127	1.029	1.009	1.086
El Salvador	1.086	1.027	0.981	1.078
Guatemala	1.079	1.030	0.996	1.052
Haiti	1.100	1.017	1.011	1.070
Honduras	1.113	1.034	0.980	1.098
Jamaica	1.036	1.014	0.968	1.056
Mexico	1.088	1.028	1.006	1.052
Nicaragua	1.055	1.031	0.977	1.047
Trinidad and Tobago	1.055	1.010	1.030	1.015
Fiji	1.072	1.019	1.015	1.037
Argentina	1.062	1.016	0.994	1.052
Bolivia	1.071	1.024	0.994	1.053
Chile	1.045	1.017	0.992	1.035
Colombia	1.102	1.021	1.008	1.071
Ecuador	1.134	1.028	1.030	1.071
Paraguay	1.134	1.031	1.021	1.077
Peru	1.059	1.027	0.977	1.055
Suriname	1.018	0.995	1.071	0.955
Uruguay	1.043	1.002	1.023	1.018
Venezuela	1.110	1.035	0.971	1.014
Average	1.101	1.027	0.993	1.081

[a]Source: United Nations. *Statistical Yearbook 1983/84.* U.N., New York, 1986.

environmental impact. Since the influence of GDP/capita is very small, it is clear that most of the nearly universal departure from the total influence of population growth is due to the rapid increase in the number of motor vehicles—the technology factor.

Table 3 summarizes the results obtained from an analysis of the environmental impact represented by the production of electricity in 69 developing countries over the period 1970–80. The average annual population growth is 2.7 percent; the average annual change in GDP/capita is –0.7 percent; and the average annual increase in electricity/GDP is 8.1 percent. Thus, the impact of the technology factor is three times that of population growth.

Figure 3 is a plot of the relation between the environmental impact represented by the rate of increase in electricity production and population growth. Regression analysis shows that the relation is not statistically significant (R^2 = 0.54). Again, in only a few (five) of the countries, the rate of increase in electricity production matches the concurrent rate of population growth, indicative of an effect entirely due to population growth. In the remaining 64 countries, it is the technology factor that exerts the greatest effect on environmental impact.

Analysis of a third class of environmental impact—nitrate pollution, as represented by the amounts of nitrogen fertilizer used—for 90 developing countries, over the period of 1980–84, is summarized in Table 4. The relative effect of the different factors on the rate of change in nitrogen fertilizer utilization is expressed by the annual rate of change in population (2.5 percent), of agricultural production per capita (–0.6 percent), and of nitrogen used per unit agricultural production (6.6 percent). The influence of the technology factor is more than twice the influence of population growth. From Figure 4 it can be seen that there is no statistically significant relation between the rate of increase in nitrogen use and the rate of population growth (R^2 = 0.04). Figure 4 also shows that relatively few countries exhibit rates of increase in nitrogen use equal to the concurrent rate of population growth. Here, too, it is evident that the dominant effect on environmental impact is exerted by the technology factor. The effect of population growth on the average is less than half the effect of the technology factor, and the effect of the affluence factor is very small.

These analyses of the relative roles of the factors that are expected to influence the environmental impact represented by several pollutants in developing countries conform to the generalization reached earlier with respect to industrialized countries. The nature of the production technology has a much greater influence on environmental impact than either population growth or increased affluence. Environmental impact is not correlated with the rate of population growth. In sum, the theory that environmental degradation is largely due to population growth is not supported by the data.

THE ORIGIN OF THE ENVIRONMENTAL CRISIS

The preceding discussion has been directed toward the specific question of how rapid population growth is related to environmental impact. However, as noted earlier, this question is a subsidiary part of a more general one: the origin of the environmental crisis that for nearly 20 years has been the target of widespread remedial efforts. Indeed, as the quotations cited above (1, 2) indicate, the (erroneous) expectation that environmental degradation is largely determined by population growth derives from an effort to explain this more general issue. It is useful, therefore, to examine the broader issue, especially because a database considerably more substantial than that available for countries characterized by rapid population growth can then be applied to resolving it.

In an industrialized country such as the United States, data on environmental quality (and the factors related to it) are available that cover both 1950–70, a period of decreasing environmental quality, and a period beginning in the early 1970s, when a massive effort was made to improve environmental quality. As already indicated, analysis of the earlier period of environmental degradation led to the conclusion that the dominant causal factor was the change in the technologies of industrial and agricultural

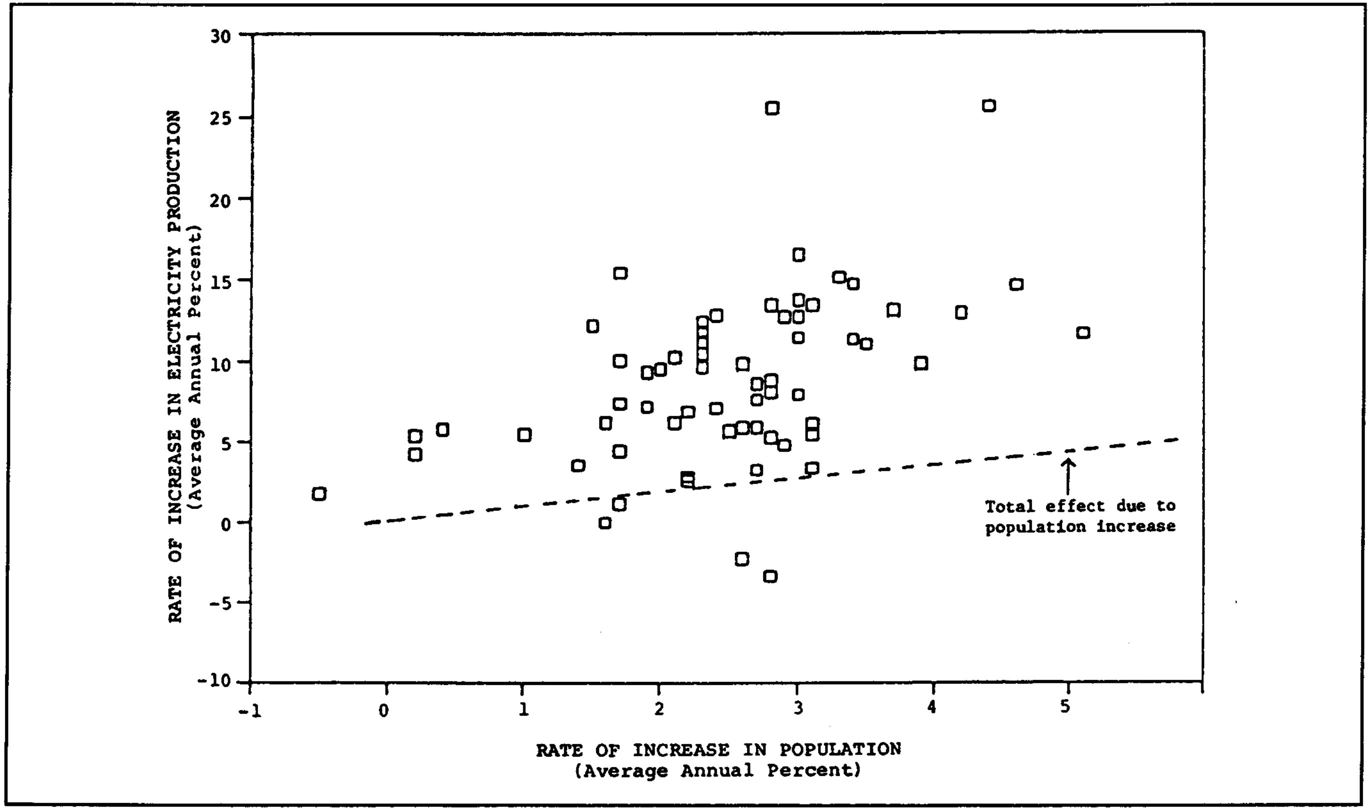

Figure 3. Relation between rate of increase in electricity production and population growth, 1970–80.

Table 4

Relation between the rate of change in nitrogen fertilizer consumption and the rates of change of environmental impact factors, 1970–80[a]

Country	Nitrogen fertilizer consumption, rate of change, 1980–84	Environmental impact factors, rate of change, 1980–84		
		Population	Agric. Prod. / Population	Nitrogen / Agric. Prod.
Algeria	0.996	1.033	0.968	0.996
Angola	0.797	1.025	0.981	0.792
Benin	1.351	1.028	1.011	1.300
Botswana	1.000	1.031	1.011	0.960
Burkina	1.197	1.024	0.979	1.195
Burundi	1.158	1.024	0.979	1.156
Cameroon	0.974	1.027	0.981	0.967
Central African Republic	1.899	1.018	0.991	1.882
Congo	1.682	1.026	0.981	1.670
Egypt	1.096	1.019	0.988	1.088
Ethiopia	1.030	1.033	0.962	1.036
Gabon	1.565	1.016	1.002	1.537
Ghana	1.070	1.031	0.991	1.047
Guinea	0.821	1.023	1.012	0.793
Guinea-Bissau	1.316	1.020	1.070	1.206
Ivory Coast	0.881	1.035	0.960	0.886
Kenya	1.114	1.041	0.984	1.088
Lesotho	1.057	1.026	0.967	1.066
Liberia	0.680	1.034	0.976	0.674
Libya	1.108	1.045	0.975	1.087
Madagascar	1.215	1.028	0.993	1.190
Malawi	1.151	1.031	0.998	1.119
Mali	1.211	1.025	0.985	1.199
Mauritius	1.022	1.014	1.023	0.986
Morocco	1.026	1.033	0.972	1.022
Mozambique	0.968	1.032	0.956	0.981
Niger	1.150	1.028	0.944	1.186
Nigeria	1.186	1.034	0.985	1.165
Rwanda	1.000	1.034	0.991	0.976
Senegal	0.953	1.027	1.032	0.899
Sierra Leone	0.964	1.018	0.971	0.976
Somalia	2.060	1.041	0.961	2.060
Sudan	1.251	1.029	0.993	1.224
Swaziland	1.282	1.043	0.988	1.243
Tanzania	0.906	1.032	0.961	0.913
The Gambia	0.925	1.012	1.036	0.883
Togo	0.931	1.029	0.970	0.933
Tunisia	1.055	1.024	0.975	1.057
Zambia	1.035	1.025	0.988	1.022
Zimbabwe	1.083	1.028	0.951	1.107
Afganistan	1.026	1.026	0.981	1.019
Bangladesh	1.072	1.022	0.990	1.059
Burma	1.133	1.028	1.028	1.072
China: Mainland	1.065	1.012	1.060	0.993
Cyprus	1.039	1.012	0.992	1.035

Table 4

(Continued)

Country	Nitrogen fertilizer consumption, rate of change, 1980–84	Environmental impact factors, rate of change, 1980–84		
		Population	Agric. Prod. / Population	Nitrogen / Agric. Prod.
Indonesia	1.140	1.022	1.013	1.101
Iran	1.260	1.032	0.990	1.233
Iraq	0.953	1.035	0.964	0.955
Israel	1.055	1.020	1.028	1.006
Jordan	1.091	1.037	0.981	1.073
Laos	1.495	1.026	1.038	1.404
Lebanon	1.030	0.998	1.000	1.032
Malaysia	1.048	1.023	1.004	1.020
Mongolia	1.263	1.027	1.013	1.214
North Korea	1.019	1.024	1.010	0.985
Pakistan	1.042	1.031	1.005	1.006
Philippines	1.015	1.026	0.982	1.007
Saudi Arabia	1.585	1.041	1.096	1.389
Singapore	1.027	1.012	0.983	1.032
South Korea	0.954	1.016	1.031	0.911
Sri Lanka	0.184	1.014	0.966	0.188
Syria	1.086	1.034	0.969	1.084
Thailand	1.124	1.021	1.018	1.082
Turkey	1.068	1.021	1.000	1.046
Vietnam	1.317	1.021	1.025	1.258
Malta	1.000	1.011	0.980	1.009
Barbados	1.041	1.003	0.961	1.080
Costa Rica	1.082	1.031	0.966	1.086
Cuba	1.000	1.007	1.042	0.953
Dominican Republic	0.924	1.029	0.992	0.905
El Salvador	1.041	1.032	0.953	1.058
Guatemala	1.012	1.024	0.953	1.037
Haiti	0.913	1.009	1.008	0.898
Honduras	1.163	1.035	0.994	1.130
Jamaica	1.086	1.015	0.992	1.078
Mexico	1.052	1.026	0.990	1.035
Nicaragua	1.239	1.037	1.001	1.194
Panama	0.981	1.022	0.991	0.968
Trinidad and Tobago	0.954	1.002	0.980	0.971
Fiji	0.887	1.015	1.024	0.854
Papua New Guinea	1.023	1.047	0.982	0.995
Argentina	1.023	1.016	1.012	0.995
Bolivia	1.170	1.028	0.973	1.170
Brazil	0.923	1.023	1.010	0.894
Chile	1.064	1.017	1.014	1.032
Ecuador	1.037	1.029	0.981	1.028
Guyana	1.102	1.020	0.998	1.083
Peru	0.880	1.026	1.016	0.845
Uruguay	0.994	1.007	1.030	0.959
Venezuela	0.936	1.029	0.974	0.934
Average	1.086	1.025	0.994	1.066

[a]Source: United Nations. *Statistical Yearbook 1983/84.* U.N., New York, 1986.

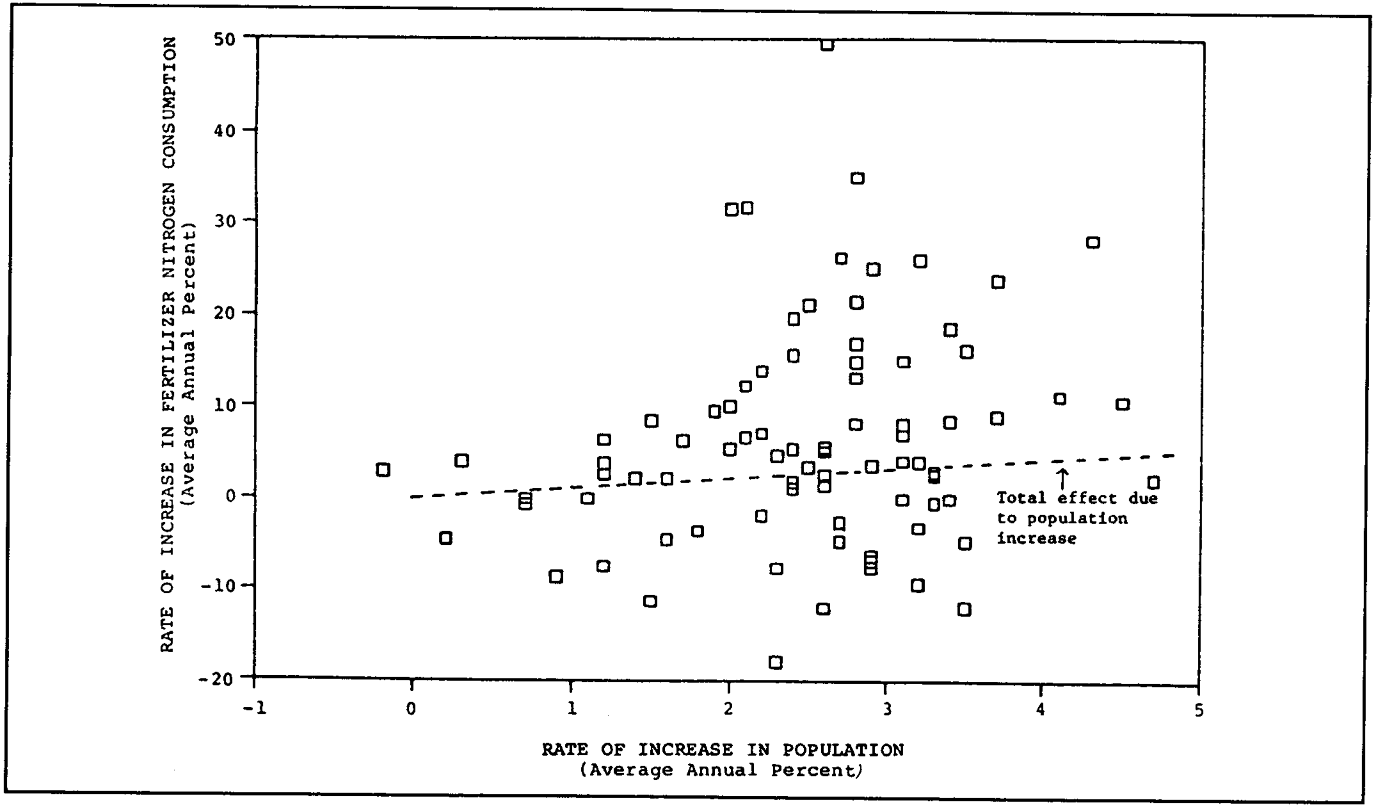

Figure 4. Relation between rate of increase in nitrogen fertilizer consumption and population growth, 1980–84.

production and transportation. (For a summary, see 6.) Thus, U.S. automobile engines produced much more nitrogen oxide per mile—and therefore smog—because they were redesigned, after World War II, to run at high compression and temperature. This caused oxygen and nitrogen in the cylinder air to react and form nitrogen oxides, which triggered the photochemical smog reaction. Similarly, the ongoing increase in nitrate levels in groundwater and surface waters can be traced to the introduction, after World War II, of increasing amounts of inorganic nitrogen fertilizer. In the same way, the sharp increase in glass trash from beer bottles resulted from the replacement of returnable bottles, which were used about 40 times before being discarded, with nonreturnable ones, which are discarded after only one trip.

These changes were part of the dramatic transformation in production technology that has occurred in every industrialized country since World War II. A series of natural products—soap, cotton, wool, wood, paper, and leather—have been displaced by synthetic petrochemical products—detergents, synthetic fibers, and plastics. In agriculture, natural fertilizers have been displaced by chemical ones, and natural methods of pest control, such as crop rotation, have been displaced by synthetic pesticides. In transportation, rail freight has been displaced by truck freight. In manufacturing, the amount of energy, especially in the form of electricity, used per unit of goods produced has increased sharply. In commerce, reusable goods have been replaced by throw-aways.

In nearly every case the new, rapidly growing production technologies have intensified environmental degradation. The toxic pollution generated by the petrochemical industry—the inevitable accompaniment of the production and use of its new synthetic products—is notorious. For the benefits that farmers gain from the heavy use of nitrogen fertilizer, we pay the price exacted by eutrophication of rivers, lakes, and estuaries and by toxic levels of nitrate in drinking water. Since truck freight uses four times more fuel than rail freight per ton-mile of freight, more fuel is burned, worsening air pollution. With the increased use of electricity comes acid rain from coal-burning plants, and radioactive hazards from nuclear plants. Throw-away goods have sharply increased the burden of trash. These technological changes far outweigh the influence of increasing population or affluence on the rising levels of pollution.

Now, with the introduction of corrective measures since the early 1970s, we have a new source of data. We can now ask: which ameliorative methods have effectively reduced pollution, and which have not? Such a comparison can help explain the failures, define the principles of success, and provide new insights into the origin of the environmental crisis.

In the United States, data are available that provide a fairly detailed picture of the trends in pollution levels since the enactment, in the 1970s, of extensive remedial legislation. Since 1975 the U.S. Environmental Protection Agency (EPA) has published consistent sets of data regarding the annual emissions and ambient concentrations of a series of standard air pollutants: particulates, sulfur dioxide, nitrogen oxides, carbon monoxide, ozone, volatile organic compounds, and lead. Data on water pollution are less comprehensive, but nevertheless describe the time trends in the concentrations of basic water pollutants such as fecal coliform bacteria, phosphate, and nitrate. From these and more scattered reports, it is possible to determine what changes in the levels of a number of environmental pollutants have been brought about by the considerable effort, in the United States, to reduce them.

Perhaps the most striking aspect of these data is their very wide range. At one extreme are a few clear-cut successes: the few pollutants that have decreased in environmental levels by 70 percent or more in the last 10 to 15 years. On the other hand, most pollutant levels have decreased by only 10 to 20 percent in that period, and some have actually increased. Given this range of effects, it is possible to relate the magnitude of changes in pollution levels to the types of corrective measures employed and thereby to identify the reasons for the successes and the failures.

The changes in air pollution (Table 5) can be summed up fairly simply. For all the standard air pollutants except lead, the average annual rate of emission has declined only moderately: by 14.1 percent between 1975 (when consistent measurements began) and 1985. In that period, the annual emission of nitrogen oxides actually *increased* by about 4 percent. This is hardly the sort of accomplishment envisioned in the environmental legislation adopted in the early 1970s, which called for a 90 percent reduction in air pollution levels by 1977. On the other hand, lead emissions have decreased by 86 percent (and the level of lead in blood declined about 40 percent) in that period, an accomplishment that does approximate the goal of solving the environmental crisis.

There is a similar situation in water pollution. A recent survey of water pollution trends at some 300 sites in U.S. rivers shows that between 1974 and 1981 there has been no improvement in water quality at 90 percent of the test locations (Table 6). Concentrations of fecal coliform bacteria, dissolved oxygen, suspended sediments, and phosphorus improved at only 13 to 17 percent of the test sites. The nitrate pollution problem has become progressively worse: nitrate concentration increased at 30 percent of the river sites and decreased at only 7 percent of them. For the five standard water pollutants, sites with improving levels averaged 13.2 percent of the tested locations; sites with deteriorating levels averaged 14.7 percent of the total; 72.1 percent were unchanged.

If a reduction of 70 percent or more in national pollution levels is taken as evidence of a qualitative solution of the problem, a search through the available data reveals that

Table 5

Changes in emissions of standard air pollutants,
United States, 1975–85[a]

	Emissions, million metric tons/year		
Pollutant	1975	1985	Change
Particulates	10.4	7.3	–29.8%
Sulfur dioxide	25.6	20.7	–19.1%
Carbon monoxide	81.2	67.5	–19.1%
Nitrogen oxides	19.2	20.0	+4.2%
Volatile organic compounds	22.8	21.3	–6.6%
Average			–14.1%
Lead	147.0	21.0	–85.7%

[a]Sources: U.S. Environmental Protection Agency. *National Air Quality and Emission Trends Report 1984* and *National Air Quality and Emissions Trends Report 1985*. Office of Air Quality Planning and Standards, Research Triangle Park, N.C., 1986 and 1987.

Table 6

Water quality trends in U.S. rivers, 1974–83[a]

	Trends in concentration, percent of sites		
Pollutant	Improving	Deteriorating	No change
Fecal coliforms	14.8	5.2	80.0
Dissolved oxygen	17.1	11.1	71.8
Nitrate	7.0	30.3	62.7
Phosphorus	13.1	11.3	75.6
Suspended sediment	14.1	14.7	71.2
Average	13.2	14.7	72.1

[a]Source: Smith, R. A., et al. Water-quality trends in the nation's rivers. *Science* 235: 1607–1615, 1987.

only a very short list of pollutants can meet this criterion; lead, DDT (and related insecticides), PCB, mercury in fresh waters, radioactive fallout from nuclear bomb tests, and, in some local situations, phosphate. Of course, in certain localities a river or a lake has been greatly improved by halting the dumping of specific pollutants into it. But as the trend data show, there has been little or no overall national improvement.

What can we learn from these observations? Table 7 lists the few environmental successes and the measures used to achieve them. There is a common theme in the successful remedial measures. In each case the pollutant was prevented from entering the environment not by recapturing it after it was produced, but by simply *stopping its production or use.* Thus, the sharp drop in lead emissions is the result of removing lead from gasoline; the environment is less polluted with lead because less of it is now being used. In the same way, the declining environmental levels of DDT have been achieved because the insecticide has been banned from U.S. agriculture; it is therefore no longer being disseminated into the environment. Similarly, the decline in environmental PCB followed legislation that banned its production and use. There has been a sharp decline in strontium 90 levels because atmospheric nuclear bomb tests, which produce it, have nearly ceased since 1963. In certain rivers, phosphate concentrations have been sharply reduced by banning the use of phosphate-containing detergents; as a result, that much less phosphate is sent down drains, into the aquatic ecosystem.

In contrast to these successes, control measures that are designed to recapture the pollutant after it is produced, rather than to halt its production or use, are relatively ineffective. The control devices that are designed to recapture or destroy air pollutants—such as the power plant scrubbers that trap sulfur dioxide or the catalytic converters that destroy carbon monoxide in automobile exhaust gases—have had little overall impact on emissions. In these instances, the basic production technology is unchanged and the control device is simply appended to it: the sulfur dioxide scrubber is attached to the power plant without changing the power-producing technology; the catalytic converter is attached to the gasoline engine's exhaust without significantly changing the engine itself.

Thus, the decade or more of efforts to improve the quality of the environment teaches us a fairly simple lesson: pollution levels can be reduced enough to at least approach the

Table 7

Significant improvements in U.S. pollution levels

Pollutant	Time period	Change	Control measure	Reference
Lead emissions[a]	1975–85	–86%	Removed from gasoline	U.S. EPA, 1986, 1987[d]
DDT in body fat[b]	1970–83	–79%	Agricultural use banned	U.S. EPA, 1984[e]
PCB in body fat[b]	1970–80	–75%[c]	Production banned	U.S. EPA, 1984[e]
Mercury in lake sediments[b]	1970–79	–80%	Replaced in chlorine production	U.S. EPA, 1984[f]
Strontium 90 in milk[b]	1964–84	–92%	Cessation of atmospheric nuclear tests	U.S. EPA, 1984[e]
Phosphate in Detroit river water[b]	1971–81	–70%	Replaced in detergent formulation	U.S. EPA, 1984[f]

[a]Measured as amount emitted per year.
[b]Measured as concentration.
[c]Change in percentage of people with PCB body fat levels greater than 3 ppm.
[d]See Table 5, footnote *a*.
[e]U.S. Environmental Protection Agency. *Environmental Quality.* The 15th Annual Report of the Council on Environmental Quality. EPA, Washington, D.C., 1984.
[f]U.S. Environmental Protection Agency. *Lake Erie Intensive Study 1978–1979.* Final report prepared by D. E. Rathke, Ohio State University, Columbus. EPA-905/4-84-001. EPA, Washington, D.C., Jaunary 1984.

goal of elimination only if the production or use of the offending substance is halted; the control device strategy is ineffective. In sum, environmental pollution is an essentially incurable disease; it can only be prevented—by replacing the production technology that generates it.

The sharply reduced level of mercury in freshwater sediments is a particularly informative example of what prevention means. This improvement came about when it was discovered that the major source of environmental mercury in the Great Lakes was manufacturing plants that produce chlorine by electrolyzing a brine solution (mercury is used to conduct the electric current). Required to give up this practice, the plant operators substituted a semipermeable diaphragm for mercury in the production process. The plants no longer dumped mercury into nearby rivers for the simple reason that they were no longer using it. The plant output, which is largely consumed by the chemical industry, is chlorine, and chlorine consumption has not decreased. On the contrary, as shown in Table 8, during the period 1970–79, when mercury pollution declined sharply, the total national production of chlorine increased by 26 percent. The pollution due to mercury was eliminated by preventing its entry into the environment; and this was achieved by *changing the means of producing chlorine*, rather than by consuming less of it.

The same pattern is evident in lead pollution. In this case, the production process is automobile travel, and what is "consumed" is passenger-miles traveled. As shown in Table 8, between 1975 and 1984, while vehicular lead emissions declined by 72 percent, passenger-miles traveled *increased* by 26 percent. Clearly, this considerable

Table 8

Changes in output of production processes with significantly reduced U.S. pollution levels

Pollutant	Relevant goods produced	Time period	Change in amount of goods produced	Reference
Lead emissions	Automobile passenger-miles	1975–85	+26%	U.S. Dept. of Commerce, 1986[a]
DDT in body fat	Cotton	1970–85	+31%	U.S. Dept. of Commerce, 1986[a]
PCB in body fat	Electrical transformers	1970–85	–12%	U.S. Dept. of Commerce, 1986[a]
Mercury in lake sediments	Chlorine	1970–79	+26%	U.S. Dept. of Commerce, 1985[b]

[a]U.S. Department of Commerce. *Statistical Abstract of the United States, 1987*, Ed. 107. Bureau of Census, Washington, D.C., 1986.
[b]U.S. Department of Commerce. *Business Statistics 1984*, Ed. 24. Bureau of Economic Analysis, Washington, D.C., 1985.

environmental improvement was not achieved by limiting consumption of the good, but, again, by changing the technological means of producing it.

DDT provides a similar example. Here the good produced for consumption is the crop that DDT protected from insects, in the United States largely cotton. Between 1970 and 1984, environmental levels of DDT decreased by 70 to 80 percent; yet the production of cotton increased by 31 percent. Again, what was changed was not the amount of goods produced or consumed, but the technological means of producing it. And certainly, none of these changes was brought about by reducing the U.S. population.

Although they are less complete, European environmental data follow the pattern evident in the United States. For example, between 1978 and 1982, sulfur dioxide emissions decreased by an average of 26 percent in European countries, while average nitrogen oxide emissions declined by only 1.7 percent (excluding a 358 percent increase in Poland). Environmental changes in the Baltic Sea closely resemble those in Lake Erie, where, because of continued phosphate and nitrate pollution, eutrophication has persisted and oxygen levels have declined. In the Baltic Sea, between 1979 and 1984 average oxygen levels decreased by 11 percent, phosphate concentrations increased by 101 percent, and nitrate concentrations increased by 37 percent. And, as in Lake Erie, for apparently the same reasons, the levels of DDT and PCB in fish improved considerably, by 80 percent and 45 percent, respectively (7).

Recent reports by Weidner (8, 9) provide data comparable to the U.S. trends of air pollutant emissions shown in Table 5. As in the United States, the data are based on annual compilations of emissions from different sources made by the relevant government agencies. As shown in Table 9, the trends in West Germany and Great Britain in emission levels since the institution of modern regulatory efforts are generally similar to those in the United States. The average change in West Germany is comparable with the

Table 9

The effect of controls on emission of standard air pollutants[a]

Pollutant	Change in emissions, 1970–82 West Germany	Great Britain
Sulfur dioxide	−17%	−30%
Nitrogen oxides	+29%	+0.3%
Carbon monoxide	−37%	+15%
Volatile organic compounds	−6%	+12%
Dust	−46%	—
Average	−15.4%	−0.75%

[a]Sources: references 8 and 9.

very modest improvement in the United States, but in Great Britain, there is almost no overall improvement.

These examples help to define the meaning of the changes that have brought about the few sharp declines in environmental pollution. Clearly, what has been changed is not population pressure or affluence (as measured by the level of consumption), but the technology of production. The improvements were not achieved by reducing the level of production or consumption of goods, nor by reducing the population, but by changing the technology of production.

In sum, analysis of three classes of data—in industrialized countries, the origin of both the sharp increase in environmental degradation in the period before the early 1970s and of the few significant improvements since then, and the less direct evidence from developing countries—leads to the same conclusion: The most powerful factor that determines environmental quality is the technology that is chosen to produce goods and services.

THE RELATION BETWEEN ECONOMIC DEVELOPMENT AND ENVIRONMENTAL QUALITY

The foregoing provides a useful link between the issue of environmental quality and the issue that, rightfully, dominates the concerns of developing countries: economic development. Clearly, production technology is a major determinant of economic development. If, as we have seen, it also largely determines environmental quality, a crucial question arises: Are technologies that are more economically productive always more hazardous to the environment? If so, developing countries must make a cruel choice between environmental quality and economic development. Or, on the contrary, are some production technologies *both* economically productive and environmentally benign, and therefore a means of solving the environment/development dilemma?

The conventional approach, which is based on the experience of industrialized countries, is that those technologies that are highly productive economically generally have a serious impact on the environment. This leads to the view that developing countries must use such technologies as the means of economic development, and that environmental quality can then be achieved, or at least approached, only by using control devices to minimize their untoward effects. It is this view that has largely governed the introduction of new production technologies in developing countries. In the absence of contrary evidence, it is assumed that the economic strength of industrialized countries is largely derived from the economic merits of their production technologies, and that these technologies will yield the same benefit when transferred to a developing country. In theory, the means of dealing with the technology's environmental impact—"controlling" emissions rather than preventing them—is imported along with the technologies themselves. In practice, however, developing countries are likely to make a much greater effort to introduce economically productive technologies than to control their environmental impact. Thus, as the recent Brundtland report points out: "The industries most heavily reliant on environmental resources and most heavily polluting are growing most rapidly in the developing world, where there is more urgency for growth and less capacity to minimize damaging side effects" (10). Unfortunately, as we have seen, the strategy of appending control devices to the polluting technologies has already failed in developed countries and therefore offers no hope of solving the problem in developing ones.

Clearly a new approach is needed, which must be based on technologies that are *both* economically productive and environmentally benign. But this appears to be a vain hope that is contradicted by the argument that the new technologies were introduced after World War II *because* they were more economically productive than the older, more environmentally benign technologies that they displaced. And given the huge economic expansion that accompanied these changes in industrialized countries and their uniformly harmful effects on the environment, it can be argued as well that the linkage between economic merit and environmental malevolence is unbreakable. On these grounds, the environmental crisis is often viewed as an inevitable consequence of the technological choices that were made in order to enhance economic development after World War II. It is this fact that often leads to the impression that economic development is necessarily accompanied by environmental pollution, and that developing countries must accept this burden as an unavoidable cost of development.

But this impression is misleading. There is reason to question both the economic merit of the postwar production technologies and the notion that all highly productive technologies are inherently polluting. Nuclear power provides a sobering example. When nuclear power—the major postwar innovation in generating electricity—was introduced, it was hailed as an economic panacea. The head of the U.S. atomic energy program declared, for example, that "nuclear power will be so cheap that no one will bother to meter it." But the reality is very different. Nearly everywhere, the initial, rapid expansion of nuclear power has slowed down, and in a number of countries has come to a halt. In the United States, for example, no new plants have been ordered in the last ten years; many orders have been cancelled; nearly completed plants have been abandoned, and even some completed ones are not allowed to operate; a power company heavily dependent on nuclear power has gone bankrupt, the first such failure since the Great Depression.

Nuclear power is an economic failure *because of its environmental faults*; the need to protect against accidents and routine radiation hazards has so severely increased the capital cost of nuclear power that it has become the most expensive large-scale source of electricity. In effect, the high costs generated by its environmental hazards have been *internalized* economically and are therefore directly reflected in its low level of economic productivity.

There are more general examples that appear to be less dramatic only because, unlike nuclear power, the technology's environmental defects, although serious, have thus far remained economic *externalities* and do not yet appear in the industry's profit-and-loss columns. The petrochemical industry is an instructive example. The enormous and increasing environmental hazards generated by this industry are only too well known. But the petrochemical industry is equally famous for its economic success, having grown in the United States, for example, to a $100 billion industry (in value of output) in less than 40 years. What is less well known, however, is that a serious effort to rectify the industry's environmental defects would severely damage its economic viability.

The U.S. petrochemical industry generates about 300 million tons of toxic waste annually, 99 percent of which is introduced into the environment—in deep-well injections, surface lagoons, or temporary storage tanks. The only way to ensure that these often long-lasting and highly dangerous substances do not accumulate and eventually threaten living things is to destroy them; but only 1 percent of the waste is now treated in this way. If the present (and still environmentally unsatisfactory) method of destruction—incineration—was applied to the active agents in the annual hazardous waste stream (about 1 percent of the total mass) the cost would be so high as to more than wipe out the industry's annual profit (11; see also 12). In sum, the petrochemical industry has been in a favorable economic position only because it has managed, thus far, to avoid paying its environmental bill. If the industry is required to meet the full cost of its environmental impact, at the least its ability to compete with the production of alternative products—for example, natural fibers, paper, glass, metal, and wood—would deteriorate.

The environmental costs of other industries are more difficult to evaluate, but many of them may also be large enough to drastically unbalance the industries' books. How viable would the power industry be if it were required to pay the costs of acid rain, not to speak of the many other pollutants that it produces? What would remain of the auto industry's already shaky profits if they were diminished by the cost of smog? And how would we reckon the net economic gain of modern industry after we confront the immeasurable cost of the flooding and climatic disruption that will ensue when the rising levels of carbon dioxide become critical, as they surely will if the numerous technologies based on fossil fuel consumption are not replaced?

Apart from these unmet costs, there are more general economic defects in the highly polluting postwar technologies. Most of them are large-scale, highly centralized capital- and energy-intensive enterprises. As a result, they are economically encumbered by low capital productivity (i.e., output per unit capital) and low energy productivity (i.e., output per unit energy). These economically burdensome factors are closely related to the harmful effects of these industries on the environment. For example, conventional power plants not only have a much lower capital productivity than cogenerators, but, since they use more fuel per unit energy output, they are also a more serious source of pollution.

Thus, it can be argued not only that the postwar technologies are faulty environmentally, but that this very failing limits their continued ability to contribute to economic development. It appears, in sum, that the developed nations have been relying on production technologies that are severely limited in their ability to support further economic development *because* they have harmful effects on the environment.

It is significant in this connection that the effort to internalize environmental costs in developed countries by enforcing controls on heavily polluting industries has been accompanied by a reduction in their relative contribution to the GDP. Thus, Janicke and colleague (13) have shown that in most industrialized countries, between 1973 and 1983 the contributions of especially polluting industries such as energy production, steel, cement, and transport to the GDP have decreased significantly. As indicated earlier, in developing countries the opposite is true—for example, with respect to motor transport. Such shifts may reflect the financial benefits to multinational corporations of moving a polluting operation from a highly regulated country to a developing country that may be willing to tolerate the environmental burden for the sake of the immediate economic benefit. This trend is probably responsible for the appearance of petrochemical plants and insecticide factories—such as the notorious one in Bhopal, India—in developing countries. And, more recently, as environmental constraints have sharply raised the costs of the disposal of toxic waste and urban trash in the United States, with increasing frequency these pollutants have been shipped to developing countries.

In sum, instead of being changed, the polluting technologies are being moved; instead of being prevented, the environmental crisis is being spread. This is the global consequence of reliance on production technologies that are inherently dangerous to the environment.

It is possible, however, to construct an approach that enhances development without intensifying environmental degradation. The basic precept can be stated quite simply, albeit negatively: Developing countries should avoid the production technologies that have characterized the postwar production system in developed countries: centralized power systems, and nuclear power in particular; transportation based on high-compression internal combustion engines; agriculture based on the intensive use of synthetic chemicals; and the petrochemical industry, almost in its entirety (excepting necessary and irreplaceable products such as medicinal drugs). Stated positively, the precept calls for the introduction in developing countries of those new technologies that correct *both* the environmental and economic defects—which, as we have seen, are closely linked—of the major production technologies that have caused so much trouble in the developed countries.

Energy production, which is such a crucial component of economic development, is a useful example of this approach. In those developing countries that have already introduced them, modern energy systems are almost entirely based on the consumption of nonrenewable fuels (chiefly, coal, oil, and natural gas); they are also highly centralized, involving, for example, large capital-intensive facilities such as power plants and refineries. These features have generated both environmental and economic difficulties that can be avoided by adopting policies that favor renewable fuels and decentralized systems.

In practice this could be accomplished by a series of linked steps. To begin with, the need for electrical power, at first necessarily based on nonrenewable fuels, could be met by decentralized power plants based on cogeneration. Such plants recover both heat and electricity from the fuel; they are therefore more economic and less polluting than conventional power plants, which waste two-thirds of the fuel's energy in the form of rejected heat. For the sake of efficiency, cogenerators must be sized according to the *local* demand, avoiding the huge investments in a central power plant and its attendant large-scale transmission network. They are therefore decentralized.

Once such a decentralized, energetically and economically efficient energy system is in place, its energy supply can be gradually shifted from nonrenewable to renewable sources. The cogenerator's conventional fuel can be replaced by solar fuels: ethanol produced from crops or vegetation, or methane produced from sewage and manure, or from marine algae. Similarly, ethanol and methane can gradually replace nonrenewable motor fuels, and photovoltaic cells can be used to produce electricity, augmented by solar collectors for heat. In each case, these technologies sharply reduce environmental impact, in comparison with the conventional ones. They also cut the cost of energy, and eventually free the economy from the self-destructive effect of the ever-increasing cost of nonrenewable fuels.

The importance of this approach to economic development in developing countries is emphasized by the consequences of perhaps the most spectacular example of its inverse—the introduction of nuclear power in a number of developing countries. As shown in a recent study (14), in developing countries nuclear power does not make the contribution to economic development that is expected of a source of electricity. Thus, Figure 5 shows that although there is a close correlation between total electric power capacity and GDP among both developed and developing countries (regression analysis shows that 90 percent of the variations in GDP are accounted for by its relation to total electric power capacity), this is not true of nuclear power. The close correlation between GDP and electric power capacity breaks down in developing countries when *nuclear* capacity is considered, although the correlation is maintained in developed countries.

The reasons can be gleaned from the disparities between nuclear technology and the technical needs of the rest of the production system in developing countries. The remaining productive uses of nuclear energy are limited to gamma-ray testing of metal structures, radiation-induced mutations of agricultural plants, radiation sterilization, and tracer experiments in research. Alternative energy sources, by contrast, have very considerable secondary implications. Production of solar collectors, for example, will enhance a country's facilities for glass, metal, and plastics fabrication; photovoltaic cell production is a point of entry into the semiconductor industry. Similarly, the production of plant material, or biomass, for energy—sugar crops, for instance, can be used to produce ethyl alcohol, an effective automotive fuel—stimulates agriculture, forestry, and marine enterprises.

From almost every point of view, then, nuclear power is a very unsuitable source of electricity for developing countries. It is uneconomical; it often requires a plant size incompatible with developing countries' small power systems; it threatens environmental hazards that developing countries are woefully unprepared to cope with; and, unlike electricity generally, it appears to make no contribution to the economic development of developing countries.

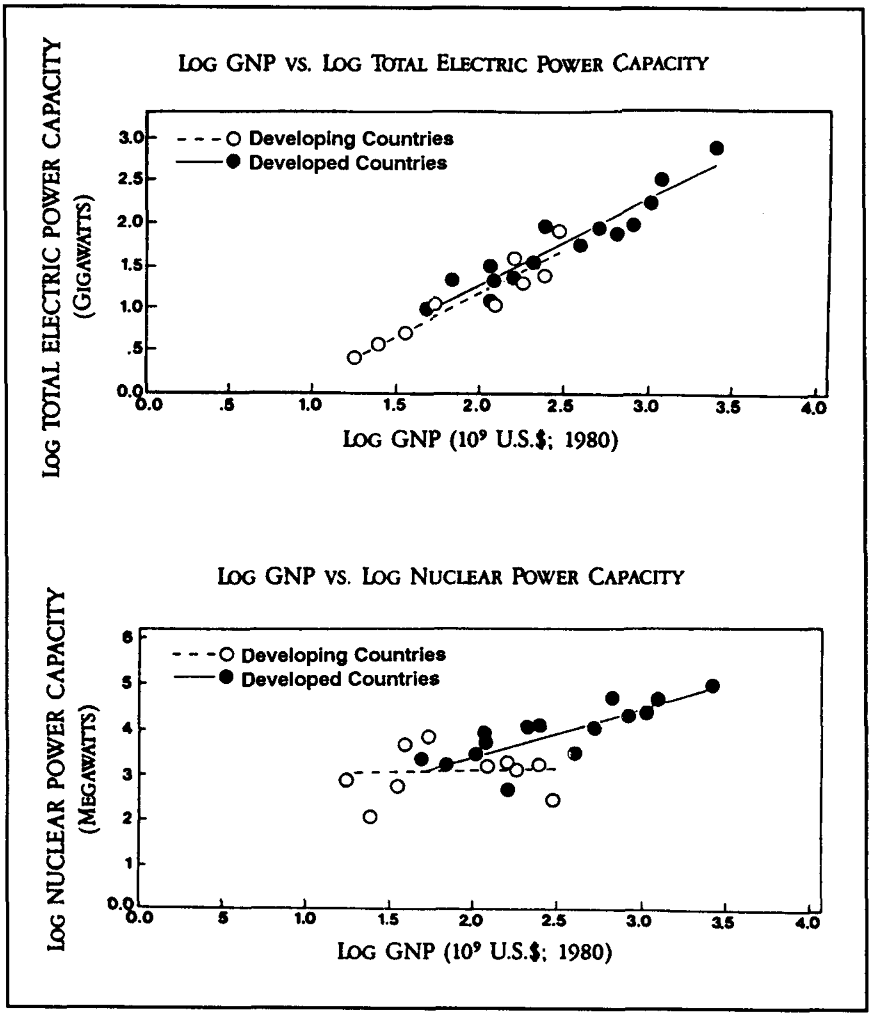

Figure 5. Relation between gross national product (GNP) and total electric power capacity (*top*) and nuclear power capacity (*bottom*), 1980. Source: reference 4.

CONCLUSION

The chief conclusion of this analysis of the relation between rapid population growth and environmental quality is that the latter is largely governed, not by population growth, but by the nature of the technologies of production. As already noted, this conclusion links environmental quality directly to the issue that quite properly dominates the concerns of developing countries: economic development. And, indeed, because of that linkage, these issues are themselves closely related to the problem of population growth.

I refer here to the analysis that offers the best explanation of historic and current population trends: the demographic transition. Briefly stated, this analysis shows that rapid population growth is the natural response to a *partial* improvement in living standards that reduces the death rate without creating the level of economic security that motivates the next stage of the demographic transition. In this second stage, the birth rate begins to fall, through social effects such as increased education and delayed marriage, and cultural effects such as the influence of reduced infant mortality on fertility. But this has occurred only where standards advance enough to encourage these effects—that is, in developed, industrialized countries. As has been pointed out in more detail elsewhere (see, for example, 15), in many developing countries rapid population growth is largely the unresolved residue of their economic exploitation during the period of colonialism. Deprived of the economic resources needed to raise living standards to levels that allow the second, population-stabilizing phase of the demographic transition, the former colonies suffer through a prolonged period in which their economic development is insufficient to reduce their high rates of population growth. In sum: "Hunger and overpopulation are not ecological manifestations; they are signs of economic and political problems that can be solved humanely, by economic and political means" (11).

Thus, the resolution of the major problems confronted by developing countries—economic development, stabilization of population growth, and environmental quality—all hinge on the proper choice of production technologies. Properly chosen production technologies can improve both economic development and environmental quality. Since by stimulating economic development such choices will enhance the demographic transition, they will also contribute to the stabilization of the population. This choice is, therefore, a supreme requirement of national policy.

The chemical disaster at Bhopal, India, is only the most dramatic evidence that many of the new industrial technologies are particularly unsuited to developing countries. The trouble arises because modern technological developments are often accepted uncritically as "objectively good," despite the fact that they have been designed with the total well-being of neither industrialized societies nor developing countries in mind. "Appropriate technology" is a concept that ought to be applied everywhere. However, developed countries have a special obligation, for the technological transformation that they must undertake for the sake of environmental quality and long-term economic development is itself well adapted to the needs of developing countries. By initiating this transformation and providing the material resources to carry it out, the industrialized countries can properly repay their debt to their former colonies.

Acknowledgments — The author thanks his colleagues, Michael Frisch and Tom Webster, for their contributions to the analyses described in this article.

REFERENCES

1. Ehrlich, P. *The Population Bomb*, pp. 66–67. Ballantine Press, New York, 1968.
2. Peterson, R. W. Our stake in global issues. *Interaction* 5(2), June 1985.

3. United Nations. *World Population Prospects. Estimates and Projections as Assessed in 1984*. United Nations, New York, 1986.
4. Commoner, B. The environmental cost of economic growth. *Chemistry in Britain* 8: 52–65, 1972.
5. Vollenweider, R. A. *Scientific Fundamentals of the Eutrophication of Lakes and Flowing Waters, with Particular Reference to Phosphorus and Nitrogen as Factors in Eutrophication*. OECD Technical Report DAS/CSI/68.27. OECD, Paris, 1968.
6. Commoner, B. *The Closing Circle*. Alfred A. Knopf, New York, 1971.
7. United Nations Economic Commission for Europe. *Environment Statistics in Europe and North America*. Conference of European Statisticians Statistical Standards and Studies, No. 39. United Nations, New York, 1987.
8. Weidner, H. *Air Pollution Control Strategies and Policies in the F. R. Germany*. Ed. Sigma Bohn, Berlin, 1986.
9. Weidner, H. *Clean Air Policy in Great Britain, Problem-shifting as Best Practicable Means*. Ed. Sigma Bohn, Berlin, 1987.
10. Brundtland, G. H., World Commission on Environment and Development. *Our Common Future*. Oxford University Press, Oxford, 1987.
11. Commoner, B. A reporter at large: The environment. *New Yorker*, June 15, 1987.
12. *Il cerchio da chiudere*, Ed. 2. Garzanti Editore, Milan, 1986.
13. Janicke, M., et al. Economic Structure and Environmental Impact. A Survey of 31 Countries. University of Berlin Research Unit Environmental Policy, 1987.
14. Commoner, B. Nuclear power for the Third World: Bane or blessing?" *World Policy J.*, Spring 1987. [A condensed version of "Environmental Impacts of Expanded Utilization of Nuclear Energy," prepared for U.N. Environment Programme, April 19, 1985.]
15. Commoner, B. How poverty breeds overpopulation. In *At Issue: Politics in the World Arena*, Ed. 2, edited by S. L. Spiegel, pp. 392–402. St. Martin's Press, New York, 1977.

Address reprint requests to:

Dr. Barry Commoner
Center for the Biology of Natural Systems
Queens College, City University of New York
Flushing, NY 11367