Population and Pollution in the United States

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To a large extent the growing concern over environmental degradation has revolved around the attempt to find a culprit. Some find it in population growth. Others, pointing to congestion and pollution in Australia's major cities pin the problem on the spatial distribution of the population. Still others, pointing mainly to the relatively low levels of air pollution of densely populated but low-income cultures, assert that the culprit in "advanced" countries is our high standard of living: for this group, zero economic growth rather than zero population should be the watchword. Less frequently mentioned is the possibility that recent changes in the composition rather than in the rate of growth in the output and standard of living has caused most of our current problems. The preference of consumers for a style of life that includes suburban living, throwaway bottles, high compression automobiles, processed foods, and frivolous uses of electricity are cases in point. Closely related is the assertion that the principal culprit is the technology we have chosen to use: the substitution of chemical fertilizers for manure, pesticides for biological means of pest control, detergents and petrochemicals for biodegradable materials, internal for external combustion engines, new raw materials for used or reclaimed resources, and so on. Finally, there is the economist's pet peeve, a pricing system that does not properly charge for the use of common property resources, with the consequence that there is insufficient incentive to limit the consumption of those items that are heavy users of raw materials and the environment, or to develop the technologies necessary for the conservation of these increasingly scarce items. This particular culprit is not of course on a par with the others: it differs in that it provides a partial explanation for the absence of recycling, for the type of technologies in use, and for the patterns of consumption.

The importance of these various factors depends in part on the time perspective one has in mind. If our concern is with the ultimate disposition of the human race on a finite planet, factors other than population growth are of little consequence; at best they simply postpone the evil day. The laws of physics and biology cannot be repealed by technological innovations let alone by changes in consumer preferences or prices. This "ultimate" time frame must be what Ehrlich and Holdren have in mind when they say that "improved technology can postpone the onset of diminishing returns but cannot avert it" (*1*).

If our concern is with environmental quality during the next 5 to 10 years—the longest period in use for most policy planning purposes—it is most appropriate to focus on fiscal and legislative measures that will ration the use of inherently scarce environmental resources. In this time frame an effective mass transit system plus a rule that forebade the use of private automobiles within a certain radius of the central business district would do more to reduce automobile exhaust than would measures aimed at altering the birthrate. This, of course, is the outer limits of the time frame within which government agencies such as the Environmental Protection Agency normally operate.

On the other hand, if our concern is with a 30- to 50-year time horizon—the shorter end of the appropriate period in which to analyze the effects of population policy and the longer end of a period in which we can have any modicum of confidence in our ability to predict even the broadest of trends—then all the above factors play a role. Certainly we cannot assume that within this period consumer tastes, the capital stock, or the technology in use will remain constant, as we might if the time period investigated were shorter; nor can we assume in advance of careful empirical analysis that induced changes in tastes and technology are incapable of handling the environmental problems likely to arise in the next 30 to 50 years.

This time frame, then, I take to be the most interesting and relevant one for analyzing the effects of population growth on environmental quality. Within this period, what is the nature of the relations between population and environmental quality? To put this question more concretely, compare the U.S. Bureau of the Census projections B and E during the next 30 to 50 years (*2*). By the year 2000, projection B indicates a population of 440.3 million; in contrast projection E would result in a population of 299.2 million, some 17 percent less in that year. By the year 2020, the divergence is even greater, E being 21 percent less than B. As Fig. 1 suggests, it is convenient to break this question into two parts: (i) if path B occurs, what environmental pollution problems are likely to arise in the year 2000 (or 2020); and (ii) what difference would it make in that year if, instead, path E were to occur?

It is impossible to answer these questions in principle (except, of course, to say the obvious, that environmental problems would be somewhat less pressing under E than under B). In this time frame, how far will pollution controls and regulation carry us; to what extent can changes in the geographic distribution of population and economic activities offset increasing emission levels; to what extent will technological changes reduce emissions and offset tendencies toward diminishing returns and diseconomies of scale that might otherwise emerge? Adequate answers cannot be given without quantitative and qualitative information on probable developments in a wide variety of fields (*3*). Nevertheless, there is some value in presenting a general analytical framework and using it as a backdrop to discuss a number of issues that have cropped up in recent debates. In doing so in this article, I limit myself to discussing the pollution problem

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proper: questions of resource adequacy and issues arising from broader definitions of the environment will be mentioned only peripherally.

The Basic Relationships

It is convenient to begin by building a few pieces of analytical machinery. To keep the analysis simple, each variable and parameter will be spoken of as if it has only one dimension, although it is useful to keep in mind that each is really a vector of many elements. For example, I will speak of wastes generated per unit of output, knowing full well that there are many different kinds of wastes, outputs, and relations between them. This simplification should not affect the conclusions, particularly after the qualifications of the next section are added. In addition, most relationships are assumed to be linear within at least limited ranges; this assumption will also be modified in the next section which discusses how the parameters of such relationships might change over time.

Perhaps the most significant fact about man-made pollution is that it arises as a consequence of flows of materials such as metals, fuels, and foodstuffs through the economy. While there may be substantial time lags in such flows because the use-value of many commodities may not be exhausted within 1 year (the time period that most economic flows refer to), what goes in must ultimately come out in the form of waste products.

All economic processes and activities create residuals, some of which may be recycled. If that portion which is not recycled is referred to as wastes, W, and if the proportion of residuals recycled is held constant (ignoring the fact that the waste products generated in a given year come from different sources, each with its own pecularities), we can say, as a crude approximation, that such wastes are proportional to the level of economic activity

$$W = AQ \qquad (1a)$$

where Q is total output [or, as an approximation, the gross national product (GNP)] and A is a positive constant (*4*). To emphasize the role of population, total output is divided into population, N, and per capita output, q

$$W = A\,(qN) \qquad (1b)$$

These waste products can be emitted into the environment in more or less noxious forms. Carbon monoxide can be converted to carbon dioxide before emission into the atmosphere; biological degradation of wastes can be speeded up so that their ultimate emission into bodies of water requires less oxygen; particulates from combustion can be captured and along with burnable solids disposed of in landfills. When one shifts the concern for wastes generated to a concern for pollution levels and damages, the form in which the waste is emitted becomes important. In this article I concentrate on just that portion of the wastes which causes pollution. Suppose this portion is designated as B, a coefficient whose magnitude depends on the amount of capital invested in treatment facilities and the manner in which these facilities are operated. Then the pollutants, P, emitted during a period are represented by

$$P = BW \qquad (2)$$

where B is some positive fraction.

In this formulation, pollution is measured in pounds emitted per year. To move from this to what is normally meant by pollution levels or the environmental quality, these emissions must be compared with the volume, V, of the medium in which they are placed: we want a measure of concentration in, for example, parts per million. To obtain this we must take account of the fact that the environment tends to cleanse itself over time. Particulates settle out of the atmosphere at certain rates, biodegradable waste products are reduced to their inorganic components, and so on. At the end of a given time period, t, such a measure, C, depends upon the concentration at the beginning of the period, C_0, the rate, r, at which the environment cleanses itself, and the amount of pollutants, P, added to the environment during the period

$$C = C_0 - rC_0 + \frac{P}{V} = (1 - r)C_0 + \frac{P}{V} \qquad (3)$$

This formulation overstates the concentration at the end of the period because some of the pollutants are also eliminated during the period, but it is adequate for present purposes (*5*).

Finally, the damages caused by this concentration should be considered. They tend to be of three kinds. First, there are damages to economically valuable goods and services: fish killed because of DDT poisoning, lowered labor productivity because of higher morbidity rates, and so on. This class

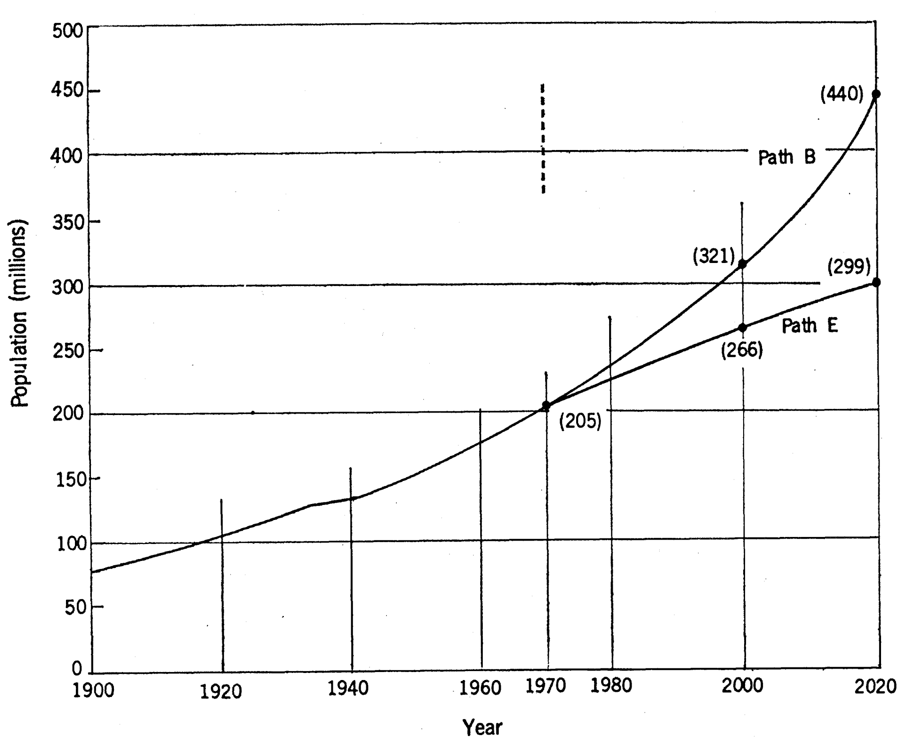

Fig. 1. Projections B and E from the U.S. Bureau of the Census showing the population in the United States for the years 1900 to 2020 (*2*).

of damages can be symbolized as a certain rate of damage to total output, Q, or qN, where the rate of damage is a function of the concentration. Second, there is evidence that human mortality is affected by pollution even within concentrations recently experienced. This fact can be symbolized by a certain rate which again is a function of concentration. Third, there are a wide variety of losses resulting from physical changes in the environment which do not enter into normal economic calculus through production and exchange but which are nevertheless considered detrimental given our current set of values. The loss of wilderness areas, increased mortality of noncommercial plants and animals, obstruction of views of snow-capped mountains, overcrowding, and noise all fit into this category. This category, then, is a catchall covering all those detrimental effects that do not fit easily into the other two classifications. These too can be thought of in terms of damage rates associated with various concentrations of pollutants.

The first and second types of damages should be entered into our models through feedback loops that result in different rates of increase in output and in population, and hence labor force, than we would otherwise have. The last type of loss should then be entered into a per capita welfare function as one of its arguments, along with other elements such as per capita output (or income) and death rate. But the main point can be made by taking sufficient liberties with reality to assert, simply, that the per capita damage, d, is a function of concentration C.

Very little is known about the form of such functions. For some pollutants and the damage they cause the relationship appears to be proportional, at least within the range for which observations have been made. For others there is reason to suspect that the relationship is indirect, the amount of damage increasing more rapidly after some threshold is reached. Some writers have suggested that synergisms may be present—that is, that the relationship may depend on what other pollutants are present at the same time; but practically nothing of an empirical nature is known about such possibilities. It is perhaps best to assume that after some point is reached, the rate at which damages occur increases with the concentration. For simplicity, we will represent the situation by a proportionality constant, δ, which itself is an increasing function (f) of the level of concentration

$$d = \delta C \qquad (4a)$$

where $\delta = f(C)$ and $f' > 0$. Total damages, D, of course, can be represented by

$$D = \delta CN \qquad (4b)$$

Substituting from Eqs. 1b, 2, and 3, the per capita damage function (*6*) becomes

$$d = (\delta \frac{1}{V} A B)\, qN + \delta(1-r)C_0 \qquad (5a)$$

and the total damage function is

$$D = (\delta \frac{1}{V} A B)\, qN^2 + \delta(1-r)C_0 N \qquad (5b)$$

If all the parameters of these equations were constant, they would describe a very simple relationship between pollution and damages on the one side and population changes on the other. They would show, simply, that pollution increases in proportion to increases in total output. If per capita output is held constant, this is equivalent to saying that pollution is proportional to population. But if population were constant, pollution could just as well increase in proportion to increases in per capita output. In this formulation, then, population and per capita output are equally important in causing pollution. The same conclusions follow for per capita damages (if δ is held constant for the moment).

If, however, we are concerned with total damages, the picture is somewhat different. While the effect of an increase in total output on concentration is the same when it occurs because of a rise in output per capita or a rise in population, if population increases (with or without an increase in per capita output) the number of victims as well as the amount of pollution increases, so that the total damages increase much more rapidly than the population.

Finally, the relative importance of per capita output and population growth is not changed by making the damage parameter, δ, an increasing function of pollution, though, of course, damages increase at a faster rate than they would otherwise.

Subject to the rather severe limitations of this analysis, this discussion answers the first of the two questions posed at the outset: pollution increases proportionately with population, if everything else, including per capita output, is held constant; per capita damages will increase somewhat faster depending on the exact form of this function, and total damages will increase at an even faster rate.

To answer the second question, which refers to a shift downward in the rate of growth of the population, a few words must be added about the relationships between output, population, and labor force. So long as population is assumed to grow at a steady rate over time, these relationships can be assumed to be stable. But if the growth rate of population were to slow down—if there were a shift from population projection path B to E, which, as noted, might make a 20 percent difference in the size of the population in the year 2020—there are several reasons for believing that total output would be significantly less than 20 percent less in that year. First, a larger proportion of the total population would be in the age group constituting the labor force which would, therefore, not be 20 percent smaller. Second, if all other inputs, including technology, were the same in the two cases, the marginal productivity of labor would rise with the fall in the labor force. Third, per capita incomes and hence savings should be greater, suggesting that the capital stock would be likely to grow more rapidly. And, finally, there should be greater availabilities of raw materials of a given quality under projection E. Since pollution is linked to total output, we can conclude that pollution and hence per capita damages would be less than 20 percent less in the year 2020 (*7*). The situation would improve but not by as much as a first glance might suggest.

Changes in Parameters

But it is important to add that all these conclusions are highly abstract and unrealistic. The whole discussion so far has proceeded on the assumption that the parameters of the relationships outlined above remain constant. During the 50-year period under consideration it is just as certain that these parameters will change as it is that population growth will occur. Indeed, if past history is any guide, some of them will change at a faster rate than population; and, of course, many of them can be made to change by changes in government policies. To complete this analysis, therefore, it is necessary to consider the major factors that could cause significant changes in these parameters.

Changes in the geographic distribution of the population. During the last century we have witnessed what Philip Hauser has called a population implosion, a flight from farms to cities which has increased the urban portion of the U.S. population from 40 to 70 percent during the course of this century. Along with this concentration of population has come, of course, a clustering of economic activities.

This movement has had two main consequences that influence the parameters of the analytical framework outlined above. First, it has permitted a massive increase in output without a commensurate increase in transportation costs. If the United States tried to produce today's output with the labor force and production units as scattered as they were in 1900, the transportation component of total output would have to be immensely larger (and the production of other goods and services that much smaller). Since transportation is a heavy user of resources and the environment, the waste load generated by our current level of output as well as the pollution resulting from these wastes would have been much greater. In other words, the parameters A and B of Eqs. 1 to 3 have been decreasing over time as a result of urbanization (I ignore other influences on these coefficients for the present) (*8*).

The second consequence of this implosion has worked in the opposite direction so far as environmental quality is concerned: it has meant a reduction in the effective size of the environment into which most wastes are poured (a reduction in V in Eq. 4). While we often think of the size or volume of the environment as fixed for a country, what is important in terms of pollution is the magnitude of the environment into which we dump the bulk of our pollutants relative to where the population resides. Thus, while this concentration of economic activities and people has reduced transportation costs and total emission throughout the country (over the amount by which they would have been reduced with the same level of output but with less urbanization), it has also increased the concentration of pollution and hence the damages experienced by the bulk of the population.

Partly because the period of rapid urbanization is now behind us, but also because of the relatively new trend toward suburbanization, supported by the availability of a cheap and convenient means of private transportation, these effects on the parameters of our analytical framework are undoubtedly petering out. But they could become important again depending on what happens to government policies with respect to zoning, location of economic activities, mass transit, and the like.

Changes in the amount and composition of consumption. Even if total output remained the same, a fall in consumption as a fraction of output would affect emissions. Such a shift could occur as a result of increase in capital per unit of output which, in effect, would mean an increase in the time that materials remain in the economic stream. It could occur as a consequence of increased investment in waste treatment and handling facilities, a particular form of capital deepening. It could also occur as a consequence of demographic changes associated with a change in the birthrate.

This last point needs some expansion. If population growth followed path E instead of B, not only the labor force but the number of households in the population in the year 2020 will be less than 20 percent less. Again this is a consequence of the changing age pattern, which reduces the number of children per family unit. In addition, there are rather sizable economies of scale involved in household purchases. Certainly expenditures on housing and other consumer durables would not fall in proportion to the fall in household size. Taking both factors together leads us to suspect that consumption as a fraction of disposable income would be likely to rise if there were a sustained fall in the birthrate. Unless the government offsets this effect by changing fiscal policy, this would mean a rise in consumption as a fraction of total output.

But suppose the net effect of these various forces was to reduce consumption as a fraction of total output. This would be reflected in Eq. 2 by a fall in parameter A (*9*). Unless the additional investment were specifically devoted to waste treatment facilities (in which case B would also fall), it is probable that the net effects of such a change would not be great, first because the movements in the components of parameter A are partly offsetting [as explained in (*9*)] and second because, historically, consumption as a fraction of output has been rather insensitive to policy changes when account is taken of effects due to business cycles.

Of far greater importance are changes in the composition of consumption. Historically, such changes have been sizable; and future changes in tastes, per capita incomes, income distribution, and household size and age structure, as well as the introduction of new goods, can be expected to continue to affect consumption patterns in significant ways.

A shift in the composition of consumption can alter the time path of waste generation quite substantially. When a consumer uses a dollar's worth of electricity, he directly and indirectly generates nearly twice as much particulate matter and more than 15 times as much sulfates as he does when he purchases a dollar's worth of breakfast cereal or bread. When he takes his car to work instead of a bus, he generates at least 20 times as much hydrocarbon exhausts. If he scraps his car after 6 years instead of after 3 years, he reduces his contribution to this source of scrap by close to half.

But it is difficult to say much about the pattern of consumption that is likely to emerge in the future, unless, of course, policies intervene to induce changes. To illustrate the difficulties of such an assessment, consider two future situations. In both situations, the total output is the same; but in the first situation per capita output is 10 percent higher (population being commensurately smaller) than in the second. Which situation will give rise to less pollution? If there were no change in the composition of output, it would not make any difference, as concluded in the previous section of this article. But when the composition of output is permitted to change the result is unclear. There is some evidence to support the contention that the income elasticity of demand (percent change in demand resulting from a 1 percentage point change in income) is greater for services than it is for commodities; by itself this should mean that the situation with higher income per capita is preferable. But there is also evidence to suggest that the demand for secondhand commodities will decline with an increase in per capita income. This effect could reduce the effective economic life of consumer durables, increasing wastes generated per unit of output quite substantially.

Research in progress should shed more light on this issue. For the present we can only conclude that the composition of consumption—indeed, of output in general—is a very important factor for the threefold reason that it has a strong bearing on the waste and pollution loads generated, that it is likely to change significantly over time, and that it can be influenced appreciably by changes in government policy.

Technological changes. Little needs to be said to prove the importance of technological and managerial innovations in altering practically all the parameters of the analytical framework presented above. Had it not been for these innovations this country would not have the kind of environmental problems it has today; nor would it have the same size population or standard of living. But it is of interest to consider whether the changes wrought by such innovations have worsened or improved the situation with respect to pollution, and how the situation might change in the future.

Before these changes are discussed, however, a comment on Ehrlich and Holdren's use of the law of diminishing returns should be injected. Their argument appears to be that technological advance and discoveries of new resources will not proceed fast enough to offset the operation of this law and that with diminishing returns will come ever greater environmental deterioration. Since the time of Malthus, those who have been making similar arguments have been proved wrong by the next wave of technical advance and discovery. Will they continue to be wrong in the future?

In some ultimate sense, the "finiteness" of the earth will undoubtedly catch up with us. But the question posed here is whether it will do so during the next 30 to 50 years, and whether population projection E rather than B will make much difference. On this score, there is no way even to begin finding an answer without considering item by item the individual changes that might come about. At a minimum, four different types of technological and managerial changes must be discussed: first, changes in materials used per unit of output; second, changes in the generation of residuals per unit of output (or per unit of materials input); third, changes in the emission of wastes per unit of residuals generated; and fourth, changes in pollution per unit of wastes (*10*).

1) So far as materials used per unit of output are concerned, a distinction must be made between materials embodied in the final product, materials embodied in capital goods that produce the final product, and energy used in producing the commodity. In general the first category, the input of materials per unit of final product, has fallen over time. Twenty years ago a cannery was able to produce 40 cases of peaches from each ton of peaches delivered to it; today it produces 55 cases per ton of input. In this case the improvement resulted from a combination of better raw materials, better equipment, and a change in product mix. In other cases, the principal ingredient has been better organization and process control. But there have been considerable substitutions of capital and energy for human labor, which work in the opposite direction. In addition, of course, the composition of materials has changed dramatically, energy and cheaper materials being substituted for higher cost minerals, chemical fertilizers and pesticides being substituted for land and natural manures.

The overall effect of these changes on wastes generated is difficult to estimate. They are less to the extent that the materials embodied in final products are less and to the extent that the materials stay in the economic system longer (as they do when embodied in capital goods). But the increase in energy per unit of output works in the opposite direction; and nothing of an overall nature can be said about the effects of changes in the composition of materials.

2) Apart from the above effects, wastes generated per unit of output have often been changing for the better. In 1928 cows produced 4.3 tons of manure for each ton of milk produced; in 1968 they produced only 2.6 tons per ton of milk. In 1943 the production of container board generated 0.45 ton of waste per ton of final product whereas by 1963 this figure had dropped to 0.21. Once again, however, the introduction of new products, processes, and materials makes generalizations difficult.

3) Changes in the emission of wastes per unit of residuals has to do with the extent of recovery and recycling. Once again the picture is mixed: since the end of World War II, recycled paper as a percentage of total pulp used has dropped significantly; but so far as copper, aluminum, and possibly iron are concerned the trend has been upward. The principal factor influencing these trends appears to be relative prices, which are, of course, subject to influence by government action.

4) There is some evidence that wastes are being emittted in forms that are more damaging than they were in the past. The substitution of synthetic for natural fibers is a case in point. But counter examples are easy to find. The substitution of natural gas for coal, for example, has clearly been beneficial on environmental grounds. On net, I suspect that the situation has worsened, simply because of the great increase in the number of products obtained from compounds not found in nature and, therefore, to which human beings have not had time to adapt. In terms of the parameters of the model, the effects of this trend may be twofold: an increase in at least some dimensions of δ damages per unit of pollution emitted and —because many new products are less degradable—a reduction in the r, the fraction of the concentration eliminated per year by natural cleansing actions of the environment.

But investment in treatment and control facilities and improvement in treatment technology have been increasing rapidly during the past 50 years. The net effect has probably been to make the situation worse so far as exotic metals and chemical compounds are concerned, but better with respect to biological wastes, solids, and particulates.

If any generalizations at all can be drawn from this multifaceted pitcure of past trends, it is that relative prices appear to drive the system. Efforts have been made to develop means of substituting capital and energy for labor because of the relatively high cost of labor. Efforts have been made to reduce the material content of output, to substitute cheaper materials and fuels for more expensive ones, and to reduce inplant wastes because costs of production can thereby be lowered. Means are found to recycle materials when it is profitable to do so; when it is not profitable to do so these means are set aside. Since relative prices change for many reasons having little to do with environmental quality, it is no wonder that the effects of past technological changes on the environment are so mixed.

If this generalization about the driving force in the system is correct, government policy can have an appreciable effect on the direction of technological changes in the future. Until recently there has been little incentive to develop "clean" technologies. We can therefore be reasonably confident that unexploited possibilities are present to reduce wastes per unit of output and pollutants per unit of wastes, if only the proper incentives to do so are provided. Of course, whether these parameters can be induced to fall rapidly enough to offset the factors working in the opposite direction is an open question requiring detailed sectoral studies.

Institutional changes. As population increases, institutions and attitudes evolved during earlier periods of lower population densities become obsolete and, under pressure from groups whose status and power have been enhanced by such developments, eventually adapt to the new circumstances. The time lags, however, may be very long. In the United States, many attitudes and institutions are still adjusting to the closing of the western frontier.

One such institution which so far has failed to adjust adequately is the price system. It works reasonably well so far as privately owned resources are concerned; but since common property resources in general are not priced at all, this particular institution becomes more and more anomalous as the scarcity value of these resources increases. Similarly our legal system, particularly as it relates to private property rights and third party damages, is not well adjusted to the presence of pervasive externalities. Once again, numerous possibilities are present for improvements through appropriate adjustments in these institutions. But whether these possibilities will be sufficient to solve our problems within the next 50 years is still an open question.

Conclusions

I have presented a simple model describing the principal links between environmental pollution on the one side and population and per capita incomes on the other. My review of factors that could cause changes in the parameters of that model has of necessity been cursory. But enough has been said to make the two principal points of this article: that no single cause is sufficient to explain this country's environmental problems, and that there is little about the pollution problems the United States is likely to face during the next 50 years that is inevitable.

It would not be difficult to devise government policies that would alter the composition of consumption and induce technological developments that could have significant positive effects on the parameters. It is not impossible to bring about some beneficial changes in the distribution of the population and in our institutions. And it is not impossible that improvements arising from these changes during the next 50 years could offset the effects of population growth, per capita incomes, and other factors working in the opposite direction.

But massive changes in attitudes and behavior patterns that have become accepted as part of the American way of life are likely to prove necessary. And here, then, is the principal effect that a slowdown in the rate of population growth would have, an effect that does not appear in any system of equations. Such a change would provide us with more time: time for vestiges of attitudes and institutions developed in frontier days to die off, time for the power struggle between vested interest groups to be played out, time to devise and to implement solutions.

References and Notes

1. P. R. Erhlich and J. P. Holdren, *Science* **171**, 1212 (1971).
2. U.S. Bureau of the Census, *Current Population Reports*, series P-25, No. 448 (Government Printing Office, Washington, D.C., 1970).
3. An attempt to provide such answers was made in *Population, Resources, and the Environment* (R. G. Ridker, Ed.), a report by Resources for the Future to the President's Commission on Population Growth and the American Future, to be published in the early summer of 1972.
4. In a more complete but complex formulation described in the next section, it is recognized that wastes are generated mainly from three sources, consumer products whose use-value has been exhausted, waste products associated with the production of these commodities, and depreciation of the capital stock. If we assume that the materials embodied in all consumer goods lose their economic value in the year of purchase we can link waste arising from this source to the dollar expenditures on such items. Similarly we can imagine a certain number of pounds of waste arising per dollar of total output and per dollar of depreciated capital stock. Assuming for simplicity that depreciation is proportional to the magnitude of total output rather than to the size of the capital stock, we can specify the following relationship

$$\underset{\text{(waste generated)}}{W} = \underset{\text{(from consumption)}}{\alpha(cN)} + \underset{\text{(from production)}}{\beta(qN)} + \underset{\text{(from depreciation)}}{\gamma(qN)} \qquad \text{(1c)}$$

where consumption, c, and production, q, have been specified in per capita terms and then multiplied by population, N, to derive their respective totals. If we also assume that per capita consumption is a constant proportion, a, of per capita income, and that per capita income, y, is proportional to per capita output ($y = bq$) we can express our waste generation formula in the following manner

$$W = (\alpha ab + \beta + \gamma)\, qN \qquad \text{(1d)}$$

where all the coefficients are positive and both a and b are less than 1. This is simply a more explicit form of Eq. 2 where $A = (\alpha ab + \beta + \gamma)$. As indicated in the text we are using the term wastes to stand for residuals less recycled materials. If then recycling increased α, and β or γ (or both) would decrease.
5. A more correct formulation starts with rate of change in concentrations, which is the sum of what is added to the environment during a period and what is subtracted because of the cleansing action—that is, $(dC/dt) = (P/V) - rC$. By integrating and setting the integration constant at C_0, we obtain

$$C = \frac{P}{Vr}(1 - e^{-rt}) + C_0 e^{-rt}$$

6. More correctly, the function for per capita damage is

$$d = [\delta \frac{1}{Vr} AB]\ qN(1 - e^{-rt}) + C_0 e^{-rt}$$

where $A = (\alpha ab + \beta + \gamma)$.
7. Once again, total damages behave in an anomalous fashion, falling more rapidly because there are fewer victims as well as because concentrations are lower. In addition there could be a change in the composition of output, investment becoming a smaller fraction of total output. First, unless government policies offset the effect, investment is likely to drop more than proportionately to output and consumption, the accelerator working in reverse; and second, as discussed in the next section, per capita consumption expenditures as a fraction of per capita disposable income are likely to increase with a fall in family size. These changes could result in an increase in waste emissions per unit of output since a smaller fraction of total output would remain tied up within the economic system in the form of capital goods.
8. More specifically, the components α, β, and γ of parameter A, as well as parameter B, have been falling over time as a consequence of changes in geographic distribution. See (*4*).
9. By referring to (*4*) this can be stated more specifically as a fall in parameters a and b, two components of A. In addition, after some time lapse, γ is likely to rise somewhat, but not enough to offset the other effects.
10. Another reason for a reduction in r for some pollutants may be increasing concentrations of pollutants themselves. Manure, for example, decomposes more rapidly when concentrations are low than when they are high. But in other cases, for example particulates, r is essentially unaffected by concentrations of particulates; and investment in waste treatment and control facilities can substantially increase the capacity of the environment to "cleanse" itself.