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Author(s): BARRY COMMONER

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Substitution of synthetic
for natural products
has hastened pollution
of the water, the air,
and the soil

Economic growth and ecology—a biologist's view

BARRY COMMONER

ENVIRONMENTAL COST of economic growth in the United States is a complex issue which has appeared rather suddenly on the horizon. It therefore suffers somewhat from a high ratio of concern to fact. In addition, the issue is one which does not coincide with any established academic discipline. Environmental costs have been, until recently, so far removed from the concerns of orthodox economics as to have been nearly banished under the term "externalities." For its part, the discipline of ecology has, also until very recently, maintained a position of lofty disdain for such mundane matters as the price of ecological purity.

To evaluate the cost of economic growth in terms of environmental deterioration, it is necessary to define both terms, if possible, quantitatively to permit a description of their relationship. The common definition of economic growth would appear to be applicable here: the increase in goods generated by economic activity. Environmental deterioration is a more elusive concept. It may be defined as changes which degrade the ecosystems which are the habitat of all life on the planet. The problem is, then, to describe such ecological changes in terms that can be related, quantitatively if possible, to the processes of economic growth.

To begin with, we note the self-governing nature of the ecosystem. It is this property which ensures its stability and continued activity. This basic property helps to define both the process of ecological degradation and the nature of the agencies that can induce it. We can define ecological, or environmental, degradation as a process which places such stresses on an ecosystem as to reduce its capability for self-adjustment, and which, therefore, if continued can impose an irreversible stress on the system and cause it to collapse.

An agency which is capable of exerting such an effect on an ecosystem must arise from *outside* that system. This results from the cyclical nature of the ecosystem, which brings about, automatically, the system's readjustment to any internal change in the number or activity of any of its normal biological constituents. For what characterizes the behavior of a constituent of an ecological cycle is that it both influences and is influenced by the remainder of the cycle. For example, organic waste produced by fish in a closed aquatic ecosystem, such as a balanced aquarium, cannot degrade the system because the waste is converted to algal nutrients, and simply moves through the ecological cycle back to the fish. In contrast, if organic waste intrudes upon this same ecosystem from without, it is certain to speed up the cycle's turnover rate and, if sufficiently intense, to consume all of the available oxygen and bring the cycle to a halt.

The internal changes in an ecosystem which occur in response to an external stress are complex, nonlinear processes and not readily reduced to simple quantitative indices. One of the relatively few instances in which this goal can, to some degree, be approached is the aquatic ecosystem, since oxygen tension is a sensitive internal indicator of the system's approach to instability. However, in most cases such internal measures of the state of an ecosystem have not yet been elucidated. Hence, as a practical, but, it is to be hoped, temporary expedient we need to fall back on a measure of the *impact* on the ecosystem of external degradative agents as an index of environmental quality.

Thus the environmental impact of a given economic process will be represented by the amount by which an agent external to the ecosystem intrudes upon it and tends to degrade the system's capacity for self-adjustment.

We now turn to the possible environmental im-

Barry Commoner is director of the Center for the Biology of Natural Systems, Washington University. An earlier version of this paper was presented at a Forum on Energy, Economic Growth, and the Environment, sponsored by Resources For the Future, Washington, D.C.

pacts that may result from *human* activity. In one sense, human beings are simply another animal in the earth's ecosystem, consuming oxygen and organic food stuff and producing carbon dioxide, organic wastes, heat, and more people. In this role, the human being is a constituent part of an ecosystem and therefore exerts no environmental impact on it. However, a human population has zero environmental impact only as long as it is in fact part of an ecosystem; for example, when food is acquired from soil which receives the population's organic waste. If a population is separated from this cycle, for example, by settling in a city, its wastes, with or without treatment, enter surface waters. Now the population is no longer part of the soil ecosystem, and its wastes are *external* to the *aquatic* system into which they intrude. Here an environmental impact is generated, leading to water pollution.

Environmental impacts are generated not by human biological activities, but by human productive activities, and are therefore governed by economic processes. Such impacts may be generated in several different ways:

1. Certain economic gains can be derived from an ecosystem by exploiting its biological productivity. In these cases, a constituent of the ecosystem which has economic value—for example, an agricultural crop, timber, or fish—is withdrawn from the ecosystem.

2. Environmental stress may also arise when the amount of some component of the ecosystem is augmented from outside that system. This may be done either for the purpose of disposing of waste or in order to accelerate the system's rate of turnover and thus increase its yield. Examples of these effects are the intrusion of sewage into surface water and the intensive use of fertilizer nitrogen in agriculture.

3. Apart from these stresses, environmental impact may be due to the intrusion into an ecosystem of a substance wholly foreign to it. Thus, DDT has a powerful environmental impact in part because it readily upsets the naturally balanced ecological relations among insects, pests, plants, and insects which, in turn, prey on the pests.

We turn now to the practical problem of evaluating the environmental cost of economic growth. The theoretical aspect of this problem has already been alluded to. Given that the global ecosystem is closed, and that its integrity is essential to the continued operation of any conceivable economic system, it is evident that there must be an upper limit to the growth of productive activities on the earth although, at this point we cannot say what that limit is.

Nonetheless, it would seem useful to make the problem more concrete by examining the relationship between economic growth and environmental impact in the real world.

Exploration of environmental impact

What follows represents the results of an initial effort to describe the origins of environmental impacts in the United States.[1] Most United States pollution problems are of relatively recent orgin. The beginning of the postwar period, 1945–46, is a convenient benchmark for a number of pollutants—manmade radioisotopes, detergents, plastics, pesticides, and herbicides began to be widely used at that time. The statistical data available for this period in the United States provide an opportunity to compare changes in the levels of various pollutants with the concurrent activities of the United States productive system that might be related to their environmental effects.

Although we lack sufficiently comprehensive data on the actual environmental levels of most pollutants in the United States, some estimates of historical changes can be made from intermittent observations and from computed data on emissions of pollutants. Some of the available data are summarized in table 1, which indicates that, since 1946, emissions of pollutants have increased within a range of 200–2,000 percent. In the case of phosphate, which is a pollutant of surface waters and enters mainly from municipal sewage, data on the longterm trends are available.[2] Between 1910 and 1940, phosphorus output from municipal sewage increased gradually from about 17 million pounds a year to about 40 million pounds a year. Thereafter the rate of output rose rapidly, so that between 1940 and 1970 phosphorus output increased to about 300 million pounds a year.

These data deal with the computed *emission* of pollutants. This is not necessarily descriptive of their actual concentration in the environment or of their

Table 1. Postwar increases in selected items which contribute to environmental pollution, various periods

Period	Item	Percent increase over period
1949–68	Inorganic nitrogen fertilizer	648
1950–67	Synthetic organic pesticides	267
1946–68	Detergent phosphorus	1,845
1946–67	Tetraethyl lead (automotive)	415
1946–67	Nitrogen oxides (automotive)	630
1950–67	Beer bottles	595

ultimate effects on the ecosystems or on human health. Numerous, complex, and interrelated processes intervene between the entry of a pollutant into the ecosystem and the expression of its biological effect. Moreover, two or more pollutants may interact synergistically to intensify their separate effects. Most of these processes are still too poorly understood to enable us to convert the amount of a pollutant entering an ecosystem to a quantitative estimate of its degradative effects. Nevertheless, it is self-evident that these effects (such as the incidence of respiratory disease due to air pollutants, or of algal overgrowth due to phosphate and nitrate) have increased sharply, along with the rapid rise of pollutant levels, since 1946.

If we define the amount of a given pollutant introduced annually into the environment as the *environmental impact* (I), it then becomes possible to relate this value to the effects of three major factors that might influence the value of I by means of the following identity:

$$I = \text{Population} \bullet \frac{\text{Economic Good}}{\text{Population}} \bullet \frac{\text{Pollutant}}{\text{Economic Good}}$$

Here *Population* refers to the size of the United States population in a given year, *Economic Good* refers to the amount of a designated good produced (or where appropriate, consumed) during the given year, and *Pollutant* refers to the amount of a specific pollutant (as defined) released into the environment as a result of the production (or consumption) of the designated good, during the given year. This relationship permits estimation of the contribution of three factors to the total environmental impact: (a) the size of the population; (b) production (or consumption) per capita, "affluence;" and (c) the environmental impact (that is, amount of pollutant) generated per unit of production (or consumption).

Since we are concerned with identifying some of the sources of the sharp increases in the environmental impacts experienced in the United States since 1946, it becomes of interest to examine the concurrent changes in the nation's productive activities. In 1946–68, the population increased at a rate of about 42 percent overall; GNP (1958 dollars) increased exponentially by about 126 percent; GNP per capita also increased approximately exponentially by about 59 percent.[3]

The contribution of population growth to the overall values of the environmental impacts generated since 1946 is about 40 percent. In most cases, this represents a relatively small contribution to the total environmental impact, since, as indicated in table 1, these values increased by 200–2,000 percent in that period.

In order to evaluate the effects of the remaining factors, it is useful to examine the growth rates of different sectors of the productive economy.[4]

1. Production and consumption of certain goods have increased at an annual rate about equal to the annual rate of increase of the population, so that *per capita* production remains essentially unchanged.

Short course in ecology

1. The environment is defined as a system comprising the earth's living things and the thin global skin of air, water, and soil which is their habitat.

2. This system, the ecosphere, is the product of the joint evolution of living things and of the physical and chemical constituents of the earth's surface. On the time scale of human life the evolutionary development of the ecosphere has been very slow and irreversible. The ecosphere is irreplaceable; if destroyed, it could never be reconstituted or replaced.

3. The basic functional element of the ecosphere is the ecological cycle, in which each separate element influences the behavior of the rest of the cycle and is in turn itself influenced by it. For example, in surface waters fish excrete organic waste, which is converted by bacteria to inorganic products; in turn, the latter are nutrients for algal growth; the algae are eaten by the fish, and the cycle is complete. Such a cyclical process accomplishes the self-purification of the environmental system, in that wastes produced in one step in the cycle become the necessary raw materials for the next step. Such cycles are cybernetically self-governed, dynamically maintaining a steady state condition of indefinite duration. However, if sufficiently stressed by an external agency, a cycle may exceed the limits of its self-governing processes and eventually collapse. Thus, if the water cycle is overloaded with organic animal waste, the amount of oxygen needed to support waste decomposition by the bacteria of decay may be greater than the oxygen available in the water. Lacking the needed oxygen, the bacteria die and this phase of the cycle stops, halting the cycle as a whole. It becomes evident, then, that there is an inherent limit to the turnover rate of local ecosystems and of the global ecosystem as a whole.

4. Human beings are dependent on the ecosphere not only for their biological requirements (oxygen, water, food) but also for resources which are essential to all their productive activities. These resources, together with underground minerals, are the irreplaceable and essential foundation of all human activities.

These include food, fabric and clothing, major household appliances, and certain basic metals and building materials, including steel, copper, and brick.

2. The annual production of certain goods has decreased since 1946, or has increased at a slower pace than population. Horsepower produced by work animals is an extreme example; it declined at an annual rate of about 10 percent. Other items in this category are saponifiable fat, cotton fiber, wool fiber, lumber, milk, railroad horsepower, and railroad freight.

3. Other productive activities have increased faster than population:

(a) Certain of these represent technological displacement of an older process by a newer one, the sum of goods produced remaining essentially constant (per capita) or increasing slightly. These include (1) natural fibers (cotton and wool) by synthetic fibers; (2) lumber by plastics; (3) soap by detergents; (4) steel by aluminum and cement; (5) railroad freight by truck freight; (6) harvested acreage by fertilizer; (7) returnable by nonreturnable bottles.

(b) Certain of these activities are secondary consequences of displacement processes. Thus the displacement of natural products by synthetic ones involves the use of increased amounts of synthetic organic chemicals. Moreover, since many organic syntheses require chlorine as a reagent, the rate of chlorine production has also increased rapidly. Finally, because chlorine is efficiently produced in a mercury electrolytic cell, the use of mercury for this purpose has also increased.

(c) Finally, among rapidly growing productive activities some are true increments in per capita availability of goods. An example, is consumer electronics—radios, television sets, sound equipment. Such items represent true increases in "affluence."

In sum, the pattern of growth in the United States economy in 1946–68 may be generalized as follows. Basic life necessities, representing perhaps one-third of the Gross National Product, have grown in annual production at about the pace of population growth, so that no significant overall change in *per capita* production has taken place in this period. However, within these general categories of goods—food, fiber, and clothing, freight haulage, household necessities—there has been a pronounced displacement of natural products by synthetic ones, of power-conserving products by relatively power-consuming ones, of reusable containers by "disposable" ones.

Environmental impact of growth

Given the foregoing conclusions we can now rephrase the original question as follows: What are the relative costs, in intensity of environmental impact, of the several distinctive features of the growth of the United States economy from 1946 to the present? Reasonably complete quantitative answers to this question are, unfortunately, well beyond the present state of knowledge. At present, it is possible in most cases to provide only an informal, qualitative, description of the changes in environmental impact induced by the postwar transformation of the United States economy. In some cases it is also possible to produce a quantitative evaluation in the form of an Environmental Impact Index. In a few cases, a partial Environmental Impact Inventory can be constructed. As will be shown, such evidence leads to general conclusion that in most of the technological displacements which have accompanied the growth of the United States economy since 1946, the new technology has had an appreciably greater environmental impact than the technology which it has displaced, and that the postwar technological transformation of productive activities is an important reason for the present environmental concern.

Agricultural production. As measured by the U.S. Department of Agriculture Crop Index, agricultural production in the United States has increased at about the same rate as the population since 1946. However, the technological methods of production have changed significantly. Although agricultural production per capita has increased only slightly, harvested acreage has decreased and the use of inorganic nitrogen fertilizer has risen sharply.

In 1946, the crop index was 80; by 1968, it rose to 120. At the same time, harvested acreage dropped from 350 million acres to less than 300 million. The implied rise in yield per acre was facilitated by an increase in the use of nitrogen fertilizers from 1 million tons in 1946 to 7 million in 1968.[5] This displacement process—fertilizer for land—leads to a considerably increased environmental impact.

Briefly stated, the relevant ecological situation is the following.[6] Nitrogen, an essential constituent of all living things, is available to plants from organic nitrogen stored in the soil in the form of humus. Humus is broken down by bacteria to release inorganic forms of nitrogen, eventually as nitrate. The latter is taken up by plant roots and reconverted to organic matter, such as the plant's protein. Finally the plant may be eaten by a grazing animal, which returns the nitrogen not retained in the growth of its own body to the soil as bodily wastes.

Agriculture imposes a drain on this cycle. Nitrogen is removed from the system in the form of plant crops or of livestock. In ecologically sound husbandry all of the organic nitrogen produced by the soil system, other than the food itself—plant residues, manure, garbage—is returned to the soil, where it is converted by complex microbial processes to humus and thus helps to restore the soil's organic nitrogen content. The deficit, if it is not too large, can be made up by the process of nitrogen fixation—in which bacteria, usually in close association with the roots of certain plants, take nitrogen gas from the air and convert it into organic form. If the nitrogen cycle is not in balance, agriculture "mines" the soil nitrogen, progressively depleting it. This process does more than reduce the store of organic nitrogen available to support plant growth, for humus is not only a nutrient store. Due to its polymeric structure, humus is also responsible for the porosity of the soil to air. And air is essential to the soil, not only as a source of nitrogen for fixation, but also because its oxygen is essential to the root's metabolic activity. In the United States, for example, in Corn Belt soils, about one-half of the original soil organic nitrogen has been lost since 1880. Naturally, other things being equal, such soil is relatively infertile and produces relatively poor crop yields. However, beginning after World War II a technological solution was intensively applied to this problem: sharply increasing amounts of inorganic nitrogen were applied to the soil in the form of fertilizer. Annual nitrogen fertilizer usage in the United States increased over seven-fold between 1946–68.

With the intensive use of fertilizer, each acre of soil annually produces more food than before. The economic benefits of this new agricultural technology are appreciable; however, this advantage may be counterbalanced by the increased impact on the environment. This arises because, given the reduced humus content of the soil, plants' roots do not efficiently absorb the added fertilizer. An appreciable part leaches from the soil as nitrate and enters surface waters where it becomes a serious pollutant. Nitrate may encourage overgrowth of algae, which on their inevitable death and decay tend to break down the self-purifying aquatic cycle.

Table 2. Increase in the production of fertilizer nitrogen, 1949–68

Item	Number		Ratio: 1968 to 1949	Percent increase
	1949	1968		
Population (thousands)	149,304	199,846	1.34	34
Crop production (units per capita)	[1] 5.43	[1] 6.00	1.11	11
Fertilizer nitrogen per crop production unit (in tons)	11,284	57,008	5.05	405
Nitrogen fertilizer (thousands of tons)	914	6,841	7.48	648

[1] Actual numbers are .000000543 and .000000600. Numbers shown result of multiplying by 10^7.

Excess nitrate from fertilizer drainage leads to another environmental impact, which may affect human health. While nitrate in food and drinking water appears to be relatively innocuous, *nitrite* is not, for it combines with hemoglobin in the blood, converting it to methemoglobin—which cannot carry oxygen. Unfortunately nitrate can be converted to nitrite by the action of bacteria in the intestinal tract, especially in infants, causing asphyxiation and even death. On these grounds, the United States Public Health Service has established 10 parts per millimeter of nitrate nitrogen as the acceptable limit of nitrate in drinking water.[7]

Table 2 shows that between 1949 and 1968, the total annual use of fertilizer nitrogen, the total environmental impact, increased 648 percent. Population size increased 34 percent; crop production per capita ("affluence"), 11 percent; change in fertilizer technology, 405 percent. Clearly the last factor dominates the large increase in the total environmental impact of fertilizer nitrogen.

A similar situation exists for pesticides. Between 1950 and 1967, there was a 168 percent increase in the amount of pesticides used per unit of crop production nationally. (See table 3.) By killing off natural insect predators and parasites of the target

Table 3. Increase in the production of synthetic organic pesticides, 1950–67

Item	Number		Ratio: 1967 to 1950	Percent increase
	1950	1967		
Population (thousands)	151,868	197,859	1.30	30
Crop production (units per capita)	[1] 5.66	[1] 5.96	1.05	5
Pesticide consumption (thousand pounds per production unit)	3,326	8,898	2.68	168
Synthetic organic pesticides (millions of pounds)	286	1,050	3.67	267

[1] Actual numbers are .000000566 and .000000596. Numbers shown result of multiplying by 10^7.

pest (while the latter often becomes resistant to insecticides), the use of modern synthetic insecticides tends to exacerbate the pest problems they were designed to control. As a result, *increasing* amounts of insecticides must be used to maintain agricultural productivity.

Another technological displacement in agriculture is the increased use of feedlots for the production of livestock in preference to range feeding. Range-fed cattle are integrated into the soil ecosystem; they graze the soil's grass crop and restore nutrient to the soil as manure. When the cattle are maintained instead in huge pens, where they are fed on corn and deposit their wastes intensively in the feedlot itself, the wastes do not return to the soil. Instead the waste drains into surface waters, where it adds to the stresses due to fertilizer nitrogen and detergent phosphate. At the present time the organic waste produced in feedlots is more than the organic waste produced by all the cities of the United States.

Textiles. There have been significant changes in textile production since 1946. While total fiber production per capita has remained constant, natural fibers (cotton and wool) have been significantly displaced by synthetic ones. Between 1948 and 1968, cotton and wool consumption declined from over 5 billion pounds a year to about 4 billion while consumption of noncellulosic synthetic fibers increased from almost nothing to close to 3.5 billion pounds a year.[8] This technological change considerably increases the environmental impact due to fiber production and use.

One reason is that the energy required for the synthesis of the final product is greater for the synthetic material. Although quantitative data are not yet available, this is evident from the comparison of the two productive processes. Nylon production involves as many as 10 steps of chemical synthesis, each requiring considerable energy in the form of heat and electric power. In contrast, energy required for the synthesis of cotton is derived from sunlight and is transferred without combustion and resultant air pollution. Moreover, the raw material for cellulose synthesis is carbon dioxide and water, both freely available renewable resources, while the raw material for nylon synthesis is petroleum or a similar hydrocarbon—nonrenewable resources. It would appear that the environmental stress due to the *production* of an artificial fiber is probably well in excess of that due to the production of an equal weight of cotton.

A synthetic fiber, such as nylon, also has a greater impact on the environment as a waste material. The natural polymers in cotton and wool (cellulose and keratin) are important constituents of the soil ecosystem. Through the action of molds and decay bacteria they contribute to the formation of humus, a substance essential to the natural fertility of the soil. Hence, they cannot accumulate.

The contrast with synthetic fibers is striking. The structure of nylon and similar synthetic polymers does not occur in natural living things. Ecologically, synthetic polymers are literally indestructible. Hence, every synthetic fiber or polymer that has been produced on the earth is either destroyed by burning—thus polluting the air—or accumulates as rubbish. One result, according to a recent report, is that microscopic fragments of plastic fibers, often red, blue or orange, have now become common in certain marine waters.[9]

Detergents. Synthetic detergents have largely replaced soap in the United States as domestic and industrial cleaners, with the total production of cleaners per capita remaining essentially unchanged. In 1946, over 3 billion pounds of soap were produced compared with 1 billion pounds in 1968. This decrease was offset by a rise in detergent production from nearly zero in 1946 to almost 2 billion pounds in 1968.[10]

Soap is based on a natural organic substance, fat, which is reacted with alkali. Being natural, fat is extracted from an ecosystem and when released into an aquatic ecosystem after use is readily degraded by bacteria. Since most municipal wastes in the United States are subjected to treatment which degrades organic waste to its inorganic products, in actual practice the fatty residue of soap wastes is degraded by bacterial action within the confines of a sewage treatment plant. What is then emitted to surface waters is only carbon dioxide and water. Hence, there is little or no impact on the aquatic ecosystem due to biological oxygen demand (which accompanies bacterial degradation of organic wastes) arising from soap wastes. Nor is the product of soap degradation, carbon dioxide, usually an important ecological intrusion since it is in plentiful supply from other environmental sources, and in any case is an essential nutrient for photosynthetic algae.

In contrast, even the newer detergents, which are regarded as degradable because the paraffin chain of the molecule can be broken down by bacterial

Table 4. Increase in output of phosphorus in detergents, 1946–68

Item	Number		Ratio: 1968 to 1946	Percent increase
	1946	1968		
Population (thousands)	140,686	199,846	1.42	42
Cleaner [1] use per capita (pounds)	22.66	[2] 15.99	[2] 1.00	0
Phosphorus in cleaners (pounds per ton)	6.90	137.34	[2] 13.70	[2] 1,270
Detergent phosphorus [3] (Millions of pounds)	11	214	19.45	1,845

[1] Assumed 35 percent of detergent weight is active agent.

[2] Because of uncertainties regarding the content of active agent in detergents, the apparent reduction in per capita use of cleaners is not regarded as significant. Numbers shown based on assumption that usage does not change significantly. (If the reduction is assumed to be true, 1.00 would be 0.69, 13.70 would be 19.90, and 1,270 would be 1,890).

[3] Based on assumption average phosphorus content of detergents is 4 percent.

action, nevertheless leave a residue of phenol which may not be degraded and may accumulate in surface waters. Phenol is a rather toxic substance, being foreign to the aquatic ecosystem.

Unlike soap, detergents are compounded with considerable amounts of phosphate to enhance their action as cleansers and water softeners. Phosphate may readily induce water pollution by stimulating heavy overgrowths of algae, which on dying release organic matter and thus overburden the aqueous ecosystem. Nearly all of the increase in sewage phosphorus in the United States can be accounted for by the phosphorus content of detergents. Since soap is quite free of phosphate, the environmental impact due to phosphate is clearly a consequence of the technological change in cleaner production. The change in the environmental impact of phosphate in cleaners between 1946 and 1968 is shown in table 4.

Secondary effects of technological displacements. Increased production of synthetic organic chemicals leads to intensified environmental impacts in several ways. This segment of industry has heavy power requirements; in contributing to increased power production the industry adds as well to the rising levels of air pollutants that are emitted by power plants. In addition, organic synthesis releases into the environment a wide variety of reagents and intermediates, which are foreign to natural ecosystems and often toxic, thus generating important, often poorly understood, environmental impacts. Common examples are massive fish kills and plant damage resulting from release of organic wastes, insecticides, and herbicides into surface waters or the air.

Perhaps the most serious environmental impact attributable to the increased production of synthetic organic chemicals is the intrusion of mercury into surface waters. This effect results from growing production. A considerable proportion of chlorine production is carried out in electrolytic mercury cells; until recent control measures were imposed on the industry, about one-fifth to one-half pound of mercury was released into the environment per ton of chlorine manufactured in mercury electrolytic cells. From 1946 to 1968, production of synthetic organic chemicals increased from 10 billion pounds to 110 billion pounds. Simultaneously, chlorine production rose from 5 million to over 12 million tons and mercury consumption for chloralkali production rose from less than 1 to 18,000 75-pound flasks per year.[11] This means, for example, that substitution of nylon for cotton has generated an intensified environmental impact due to mercury, for nylon production involves the use of chlorinated intermediates.

Similarly, the displacement of steel and lumber by aluminum adds to the burden of air pollutants, for aluminum production consumes great amounts of power. Each pound of aluminum produced requires about 29,860 BTU's of power compared with 4,615 BTU's per pound of steel produced. Cement, which tends to displace steel in construction, also uses greater amounts of power. The production of chemicals, aluminum, and cement account for about 28 percent of the total industrial use of electricity in the United States.

Packaging. The displacement of older forms of packaging by "disposable" containers, such as nonreturnable bottles, is another example of intensified environment impact due to the postwar pattern of U.S. economic growth. This is illustrated in table 5. There has been a very striking increase in environmental impact due to beer bottles, which are not assimilated by ecological systems and in their manufacture use a lot of power. The major factor in this intensified

Table 5. Increase in the production of beer bottles, 1950–67

Item	Number		Ratio: 1967 to 1950	Percent increase
	1950	1967		
Population (thousands)	151,868	197,859	1.30	30
Beer consumption (gallons per person)	24.99	26.27	1.05	5
Beer bottles relative to gallons beer consumed	.25	1.26	5.08	408
Beer bottles (thousand gross)	6,540	45,476	6.95	595

environmental impact is new technology—the use of nonreturnable beer bottles—rather than "affluence" with respect to per capita consumption of beer or increased population. At the same time, a recent study shows that the total expenditure of energy (for bottle manufacture, processing, shipping, and so forth) required to deliver equal amounts of fluid in nonreturnable bottles is 4.7 times that for returnable ones.[12]

Automotive vehicles. Finally, there is the problem of assessing the environmental impact of changes in patterns of passenger travel and freight traffic since 1946. Particularly important has been the increased use of automobiles, buses, and trucks.

The environmental impact of the internal combustion engine is due to the emission of nitrogen oxides, carbon monoxide, waste fuel, and lead. The intensities of these impacts, as measured by the levels of these pollutants in the environment, is a function not only of the vehicle-miles traveled, but also of the nature of the engine itself.

Technological changes in automotive engines since World War II have worsened environmental impact. For passenger automobiles, overall mileage per gallon of fuel declined from 14.97 in 1949 to 14.08 in 1967, largely because average horsepower increased from 100 to 240. Another important technological change was in average compression ratio, which increased from about 5.9 to 9.5 during 1946–68.[13] This engineering change has had two important effects. First, increasing amounts of tetraethyl lead are needed as a gasoline additive to suppress the engine knock that occurs at high compression ratios. Annual use of tetraethyl lead has increased significantly in 1946–68. Lead consumption for gasoline additives rose from about 50,000 tons in 1946 to nearly 275,000 tons in 1968. This amounted to an increase of lead per 100,000 gallons of fuel from about 350 pounds in 1946 to about 600 pounds in 1968; and of lead per 1 million vehicle miles of approximately 300 pounds in 1946 to approximately 500 pounds in 1968.[14] Essentially all of this lead is emitted from the engine exhaust and is disseminated into the environment. Since lead is not a functional element in any biological organism, and is in fact toxic, it represents an external intrusion on the ecosystem.

Table 6. Increase in emission of nitrogen oxide by passenger vehicles, 1946–67

Item	Number		Ratio: 1967 to 1946	Percent increase
	1946	1967		
Population (thousands)	140,686	197,859	1.41	41
Vehicle miles driven per person	1,982	3,962	2.00	100
Nitrogen oxides [1] emitted per vehicle mile	33.5	86.4	2.58	158
Nitrogen oxide emissions [1]	10.6	77.5	7.30	630

[1] Emissions estimated based on nitrogen oxide (parts per milimeter) multiplied times gasoline consumption in millions of gallons. Parts per milimeter (PPM) are determined from emissions of average engine in 1946 (average compression ratio of 5.9) and in 1967 (compression ratio of 9.5), under running conditions at 15 inches manifold pressure. PPM in 1946 were 500 and 1,200 in 1967.

Table 7. Increase in emission of tetraethyl lead by passenger vehicles, 1946–67

Item	Number		Ratio: 1967 to 1946	Percent increase
	1946	1967		
Population (thousands)	140,686	197,859	1.41	41
Vehicle miles driven per person	1,982	3,962	2.00	100
Tetraethyl lead (in pounds) [1] emitted per million vehicle miles	300	630	1.83	83
Tetraethyl lead (thousands of tons)[1]	48	247	5.15	415

[1] Refers only to weight of lead content of emissions.

A second consequence of the increase in engine compression ratio has been a rise in the concentration of nitrogen oxides emitted in engine exhaust. This has occurred because the engine temperature increases with compression ratio. The combination of nitrogen and oxygen to form nitrogen oxides is enhanced at elevated temperatures. Nitrogen oxide is the key ingredient in the formation of photochemical smog. Through a series of light-activated reactions involving waste fuel, nitrogen oxides induce the formation of peroxyacetyl nitrate, the noxious ingredient of photochemical smog. Smog of this type was first detected in Los Angeles in 1942–3; it was not generally recognized in most other United States cities until the late 1950's and 1960's, but is now a nearly universal urban pollutant. Peroxyacetyl nitrate is a toxic agent to man, agricultural crops, and trees. Introduction of this agent has probably increased sharply during 1946–68. The increased environmental impact of nitrogen axides and lead are shown in tables 6 and 7 respectively.

A similar situation obtains with respect to overland shipments of intercity freight. Here truck freight has tended to displace railroad freight. And again the displacing technology has a more severe environmental impact than does the displaced technology. This is evident from the energy required to transport freight by rail and truck: 624 BTU per ton-mile by rail and 3,462 BTU per ton-mile by truck. Also, the steel and cement required to produce equal lengths of railroad and expressway differ in the amount of power required in the ratio 1 to 3.6.

An environmental impact inventory

Our analysis represents only small fragments of a complex whole. What is required is a full inventory of the various environmental impact indices associated with a productive enterprise and the identification of the origins of the impacts within the production process and of the ecosystems on which they intrude. As an exploratory exercise, an Environmental Impact Inventory is constructed with reference to the production of chlorine and alkali by establishments employing mercury electrolytic cells.

The needed data include: (a) the Environmental Impact Indices associated with the input goods, chiefly, electric power, salt, and mercury; (b) the Environmental Impact Indices representative of the process' wastes and the properties of the ecological systems which are affected by them; (c) the Environmental Impact Indices representative of the ecologically significant wastes associated with the process' output goods (chlorine and alkali) and the environmental fate of this material. Thus, the production of one megawatt of electricity by fossil-fuel burning plants results in the release of 34.20 pounds of sulfur oxides into the atmosphere. Since 4,300 kwh is consumed by a mercury cell chlor-alkali establishment per ton of chlorine produced, 147 pounds of sulfur oxides are released to the environment per ton of chlorine produced. In this way the corresponding values for other power-plant pollutants (for example, nitrogen oxides, dust) can be computed as well. Table 8 shows the Environmental Impact Inventory for chlorine production when mercury cells are used.

Some observations

The data presented reveal a functional connection between economic growth in the United States since 1946 and environmental impact. It is significant that the range of increase in the computed environmental impacts agrees fairly well with the independent measure of the actual levels of pollutants occurring in the environment. Thus, the increase in environmental impact index for tetraethyl lead computed from gasoline consumption data for 1946–67 is about 400 percent; a similar increase in environmental lead levels has been recorded from analyses of layered ice in glaciers.[15] Similarly, the 648 percent increase in the 19-year period 1949–68 in the environmental impact index computed for nitrogen fertilizer is in keeping with the few available large-scale field measurements.[16]

The conclusion that the computations in the environmental impact index provide a useful approximation to the changes in environmental impact associated with certain features of economic growth of the United States economy since 1946 is supported by actual field data. In particular, we can place some reliance on the subdivision of the total impact index into several factors: population size, per capita production or consumption, and the technology of production and use.

It is of interest to make a direct comparison of the relative contributions of increases in population size, in "affluence" and of changes in the technology of production to increases in total environmental pollution which have occurred since 1946. The ratio of the most recent total index value to the value of the 1946 index (or to the value for the earliest year for which the necessary data are available) is indicative of the change in the total impact over this period. The relative contributions of the several factors to

Table 8. A partial inventory of the environmental impact of chloralkali production through the use of mercury electrolytic cells

Goods or step [1]	Production process: input, treatment, or output	Ecological system affected [2]	Environmental impact (per ton of chlorine produced)	
			Item	Amount
Input good	Electric power (4,300 kilowatt hours per ton of chlorine.)	Air	Oxides of sulfur	147.1 pounds
			Oxides of nitrogen	29.4 pounds
			Particulates	5.9 pounds
			Mercury	.004 grams
			Heat	5.5 million BTU's
		Surface waters	Heat	16.56 million BTU's
Step in production process	Hydrogen (H_2) gas ventilation	Air	Mercury	17–35 grams
	Hydrogen (H_2) condensate, wash water	Surface waters (via settling pond or drainage system.	Mercury	35–121 grams
	Brine sludge removal Anode sweepings removal	Surface waters Soil (via landfill)	Mercury	6–97 grams
Output goods	Selected alkali-using goods (soap, lye, cleansers, pulp, and paper).	Air Surface waters	Mercury	1–5 grams

[1] Only a few of the actual items are shown for purposes of illustration.

[2] In an actual index, reference would be made to a standarized description of each of the relevant ecological systems.

the total change is then given by the ratios of their respective partial indices. Our analysis shows that the population factor contributes between 12 and 20 percent of the total changes in environmental impact for the six environmental pollutants—nitrogen fertilizer, detergent phosphate, synthetic pesticides, one-way beer bottles, and passenger vehicle emissions of nitrogen oxide and tetraethyl lead—examined. For all but the automotive pollutants, the "affluence" factor makes a rather small contribution—no more than 5 percent. However, this factor accounts for about 40 percent of the total increase in automotive pollutants, reflecting the considerable increase in the number of vehicle-miles traveled per capita since 1946. The technological changes in the processes which generate the various economic goods contribute from 40–90 percent of the total increases in environmental impact.

During the period from 1946 to the present, pollution levels in the United States have increased sharply. It seems evident from the data presented that most of this increase is due to the technology of production and that both population growth and increase in "affluence" exert a much smaller influence. Thus the chief reason for the sharp increase in environmental stress in the United States is the sweeping transformation in production technology in the postwar period. *Productive activities with intense environmentual impacts have displaced activities with less serious environmental impacts: the growth pattern has been counter-ecological.*

This foregoing conclusion could be easily misconstrued to mean that technology is, *per se,* ecologically harmful. But this interpretation is unwarranted, as can be seen from the following example.

Consider the following simple transformation of the present, ecologically-faulty, relationship among soil, agricultural crops, the human population, and sewage. Suppose that sewage, instead of being introduced into surface waters as it is now, whether directly or following treatment, is instead transported from urban collection systems by pipeline to agricultural areas, where—after appropriate sterilization procedures—it is incorporated into the soil. Such a pipeline would literally reincorporate the urban population into the soil's ecological cycle, restoring the integrity of that cycle and incidentally removing the need for inorganic nitrogen fertilizer. Since the urban population is then no longer external to the soil cycle, it is incapable either of generating negative biological stresses upon the soil or exerting a positive ecological stress on the waters. But this state of zero environmental impact is not achieved by a return to "primitive" conditions, but by an actual technological advance, the construction of a sewage pipeline system.

It would appear possible to reduce the environmental impact of human activities by developing alternatives to ecologically-faulty activities. This can be accomplished, not by abandoning technology and the economic goods which it can yield, but by developing *new* technologies which incorporate not only the knowledge of the physical sciences but ecological wisdom as well.

If we are to survive economically as well as biologically, much of the technological transformation of the United States economy since 1946 will need to be altered to bring the nation's productive technology much more closely into harmony with the inescapable demands of the environment. This will require the development of massive new technologies including: systems to return sewage and garbage directly to the soil; the replacement of synthetic materials by natural ones; reversal of the present trend to retire soil from agriculture and to elevate the yield per acre; the development of land transport that operates with maximum fuel efficiency at low combustion temperatures; the sharp curtailment of the use of biologically active synthetic organic agents. In effect what is required is a new period of technological transformation of the economy, which reverses the negative ecological trends developed since 1946. The cost of the new transformation, like the cost of the former one, must represent a capital investment in the range of hundreds of billions of dollars. To this must be added, of course, the cost of repairing the ecological damage which has already been incurred, such as the suffocation of Lake Erie, again a bill to be reckoned in the hundreds of billions.

The enormous size of these costs raises a final question: Is there some functional connection between the tendency of a given productive activity to inflict an intense impact on the environment and the role of this activity in economic growth? A cursory comparison of the productive activities which have rapidly expanded in the United States economy since 1946 with the activities they displaced shows replacing activities are also considerably more profitable than the displaced ones. The correlation between profitability and rapid growth is one that is presumably accountable by economics. Is the additional linkage to intense environmental impact also functional, or only accidental?

Environmental pollution represents a long-unpaid debt to nature. Is it possible that the United States economy has grown since 1946 by deriving much of its new wealth through the enlargement of that debt? If this should turn out to be the case, what strains will develop in the economy if, for the sake of the survival of our society, that debt should now be called? How will these strains affect our ability to pay the debt—to survive? □

FOOTNOTES

[1] This study has been carried out as part of the program of the American Association for the Advancement of Science Committee on Environmental Alterations in collaboration with Michael Corr and Paul J. Stamler. For a preliminary report of this work, see Barry Commoner, Michael Corr and Paul J. Stamler, *Environment 13:3,* 2 (1971).

[2] L. W. Weinberger, et al., *The Adequacy of Technology for Pollution Abatement,* Hearings before the Subcommittee on Science, Research, and Development, House Committee on Science and Astronautics, 1970, p. 756.

[3] *Statistical Abstract of the United States* 1970 (U.S. Department of Commerce), p. 5; and *The National Income and Priduct Accounts of the United States,* 1929–65 (U.S. Department of Commerce, 1966) pp. 4–5.

[4] *Statistical Abstract,* volumes for 1948 to 1970.

[5] *Agricultural Statistics* (U.S. Department of Agriculture, 1967), pp. 531–544, 583; and *Agricultural Statistics* (1970) pp. 444, 454, 481.

[6] L. W. Weinberger, D. G. Stephan, and F. M. Middleton, *Annals New York Academy of Sciences,* 136, p. 131–154 (1966).

[7] Barry Commoner, "Threats to the Integrity of the Nitrogen Cycle: Nitrogen Compounds in Soil, Water, Atmosphere, and Precipitation," *Global Effects of Environmental Pollution,* Symposium organized by American Association for the Advancement of Science, Dallas, Tex., December 1968, edited by S. Fred Singer (Dordrecht-Holland, Reidel, 1970).

[8] *Statistical Abstracts* (1962), p. 198; (1966), p. 789; and (1970), p. 713.

[9] See note in *Marine Pollution Bulletin 2,* February 1971, p. 23.

[10] *Agricultural Statistics* (1970), p. 149. Detergent data represent actual cintent of surface active agent which is estimated at about 37.5 percent of total weight of marketed detergent.

[11] *Current Industrial Reports: Inorganic Chemicals and Gases,* Series M–28A (U.S. Bureau of the Census); and *Statistical Abstract* 1970.

[12] Bruce Hannon (University of Illinois, Urbana), Personal communication.

[13] Gasoline consumption data from *Statistical Abstract* 1970. Brake, horsepower, and compression ratio data are from 1951 to 1970 issues of Ethyl Corp., *Brief Passenger Car Data.*

[14] *Mineral Yearbook* 1947–68 (U.S. Department of Commerce); and *Statistical Abstract* 1970.

[15] C. C. Patterson, *Environment 10* (1967), p. 72.

[16] See reference in footnote 7.

The use of pricing to protect against pollution

Pollution is the entering of new elements of the universe into the realm of scarcity. As clean air and pure water become scarce, the same problems arise as when labor became scarce with the expulsion from Eden and land became scarce as man became fruitful and multiplied and filled the earth. The resulting pains were alleviated by the use of *prices,* wages of labor and rent of land, to keep these resources from being used for less urgent purposes that could not pay the prices offered by the more urgent uses. But the application of pricing to the newly scarce elements calls for the adaptation of the price mechanism to deal with *public* goods where there is no proprietor to demand a price from those who consume (that is, destroy) them.

—ABBA P. LERNER,
"The 1971 Report of the President's Council of Economic Advisers: Priorities and Efficiency,"
American Economic Review, September 1971.