J. ENVIRON. SYS., Vol. 4(2), Summer, 1974

ENVIRONMENTAL IMPACT: PART 1– Development of a Semi-quantitative Parameter and its Implications

DR. PETER NEWMAN
Environmental and Life Sciences
Murdoch University
Western Australia

ABSTRACT

A model is presented in which the multiple causes of damage to the environment by human activities are reduced into one easily calculated semi-quantitative parameter. This is achieved by understanding an ecosystem disturbance in terms of its energy and material flows and super-imposing on it the activities of man due to imported or exotic energy (food and fuel). Environmental Impact (I) is defined as Exotic energy use (E)/Area of environment (A); this is developed to show that $I = E/P \times P/A$, where P = population, in order to show the two fundamental interrelated components of environmental damage as exotic energy use per capita and population density. Broad implications of the model are discussed including misconceptions about the value of energy-intensive pollution technology and alternative energy sources, and the meaning of energy conservation based on this model is developed. Calculations using the model are presented in a second paper.

Introduction

Man is becoming increasingly aware of his impact on the natural environment, however only a few attempts have been made to model and quantify this impact. Ehrlich and Holdren [1] have developed a parameter (Environmental Impact = Population × Impact per person) to illustrate the effect of population growth on the environment but did not attempt to quantify the impact; Commoner [2] has taken this formula further (Environmental Impact = Population × Consumption of Goods per person × Environmental impact of goods) in order to show quantitatively the change in environmental impact produced by a specific change in technology but made no attempt to model total environmental damage; Herzog [3] has developed a computer model based on

doi: 10.2190/RDV0-UP1K-68XD-AH85
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economic input-output to minimize environmental impact from different technological alternatives but total impact was seen only as a sum of fourteen specific pre-determined pollutants and so the model does not begin to cover the many possible ways in which man damages the environment.

It is the purpose of this paper to describe a model in which simple calculations can be made in order to give a general picture of how much environmental damage is caused by different levels of man's activities. A parameter will be developed essentially for assessing environmental impact in different nations and the second paper in this series presents some calculations for twelve selected countries, however the size of the environment is not limiting and the principles upon which the parameter is based could equally well be used for a national park, a metropolitan area or the whole biosphere.

Bringing together into one environmental impact parameter all the factors which cause damage to the environment (e.g., physical, chemical, and thermal pollution of air, soil, and water, clearing of forests, over-grazing, etc.) is a very difficult task, as even assuming the factors could all be isolated, it would be impossible to measure the numerous interactions between them. However underlying these, there are more basic factors and it is suggested that energy, population, and area can be used to give a parameter that represents the generalized level of damage caused by man's activities and an essentially accurate tool for predicting further damage. To develop this parameter, ecosystem theory will be used to describe what is meant by a damaged environment, man's energy flow through an environment will be used to explain the activities which cause this damage, then energy flow will be analyzed into two components which involve population and area as the other basic factors in the environmental impact model, and finally some of the inherent implications in this model will be examined.

As this general approach entails factors that are quite abstract, it is necessary to give detailed examples in the description of this parameter, to show how the factors used relate to the more obvious patterns of environmental damage.

Environmental Impact as Ecosystem Disturbances

An ecosystem is defined as a group of living organisms that take part in a common flow of energy and materials. In a natural ecosystem the flow of energy is from the sun via photosynthesis into chemical energy which is used to order dispersed chemical materials into the components of a viable biological system. This ecosystem tends to adjust itself until a stable self-regulating state is reached; the processes involved have been labelled "ecological succession" [4] and the states of development as "young" and "mature ecosystems" [5]. The characteristics of succession can be generalized as an increase in community structure, species diversity, biochemical diversity, spatial diversity, and material inventory; in terms of energy and material flows there is an increased efficiency in energy use due mainly to an increase in the number of alternative paths through which energy and materials can flow [6].

If a mature ecosystem is disturbed by climatic changes, by natural disasters like a fire, by mechanical clearing or by a sudden pulse of nutrients, it is forced back to a younger stage. A sudden pulse of nutrient materials into an ecosystem forces it into a less mature state by encouraging high productive low efficiency processes—use of this is made in agriculture by application of artificial fertilizers which favor one or two productive species useful to man. Woodwell [7] has described the effects of pollution on ecosystems and concluded that they are the same as those found in these disturbed ecosystems forced into less mature conditions. In the same way one of the prime characteristics used in water quality management to describe polluted water is a low diversity index [8]. Therefore a disturbed or damaged ecosystem is one that has been forced into a less mature state, with a lowered overall energy efficiency, a reduced number of alternative paths through which energy and materials can flow. Environmental impact is thus defined as man's damage to ecosystems by which he is responsible directly or indirectly for a decrease in the alternative patterns for energy and material flow; this concept will be further expanded to show how man's use of energy causes environmental disruption, but in this definition there is essentially no difference between man's effect on the environment and that of more "natural" effects like a fire or a volcano.

There does not appear to be any stage in man's history where he was not involved in some kind of ecosystem-disrupting activities, however Paleolithic and early Neolithic Man's level of disruption was certainly minimal. Hunting and food gathering Paleolithic Man was essentially integrated into the energy and material flows of his ecosystem; food was virtually his sole energy source and any waste materials produced were rapidly and easily recycled. Another energy source available was fire and it now appears quite possible that the extinction of some large prehistoric mammals was largely due to man's misuse of this energy [9]. However these activities of man were certainly no greater than natural ecosystem disruptions, so that looking at the ecosystem overall, man did not influence successional trends to any appreciable extent. Even though agriculture reverts succession in an ecosystem, early Neolithic Man's simple incipient agriculture was also essentially integrated into the energy and material flows of his environment as can be seen in similar societies today [6]. This steady state relationship was altered when man began to use exotic energy sources in addition to the ecosystem's natural energy flow.

Ecosystem Damage Through Exotic Energy Flow

With the advent of commerce, agricultural goods could be produced in one ecosystem and consumed in another. The resulting concentration of energy flow in one area meant that more people could live in any one place, cities could grow, more land could be cleared, more intensive agriculture was fostered, more waste products were produced—man's environmental impact was no longer minimal. It was further increased as man brought other exotic energy sources such as fossil fuels into his environment. The effect of this man-produced exotic energy flow on an ecosystem can be viewed from two different perspectives: first, in terms of the process of dissipation which must accompany energy use and second, from an overall thermodynamic viewpoint.

The energy in food and fossil fuels is stored in energy-rich chemical bonds and is released when the compounds are oxidized, the energy eventually ending up as waste heat which is radiated out into space. Waste heat can cause isolated thermal pollution problems and its effect on global weather patterns is considered the ultimate limit to man's growth in energy use [10], however the major environmental problems from energy use stem more from the materials which become involved in energy dispersion processes rather than waste heat itself. Materials such as CO_2, H_2O, PO_4^{3-}, and NO_3^- are brought into use in an ecosystem by solar photosynthetic energy and are transformed and dispersed slowly through the food chains and biogeochemical cycles of the ecosystem until totally dispersed again. Energy in wind and water movement assist in this dispersion and each ecosystem is adapted to utilize these energies, so that in mature ecosystems there is a steady state whereby material input equals material output. The material dispersion process is as important to the life of the ecosystem as the material ordering process.

The steady state situation, which can include man, no longer holds when exotic energy sources are used in an environment by man, as the energy must be dissipated and the dispersion of materials which is associated, overloads the natural dispersion processes so that material input and output are no longer balanced. For example, the dissipation of food energy involves the dispersion of sewage through the natural material cycles of an ecosystem, but if food energy is imported above that extracted from the natural environment, then there is an increased concentration of people and of sewage thus causing that material cycle to be overloaded. In the associated catchment area, energy and material flows are disrupted as eutrophication occurs from the extra pulse of nutrients, diversity is decreased, the aquatic ecosystem is disturbed. The dissipation of fossil fuel energy involves a similar dispersion of materials to the environment—products such as oxides of carbon, nitrogen, and sulphur, water vapor, hydrocarbons and other trace products that together are the fundamental cause of air pollution with its associated damage to ecosystems.

The waste materials mentioned so far are direct dispersion products from exotic energy use, but man goes further by using the energy gained from food and fossil fuels to produce vast quantities of many different materials, from automobiles to synthetic chemicals. Eventually all these materials must also be dispersed in the environment causing the same type of problems as they disturb the steady state material and energy flows. The innumerable secondary effects of modern technology on the world's ecosystems (e.g., those listed in *The Careless Technology* [11]) can all be traced in some way to man's exotic energy use. Thus the process of using net imported food energy and fossil fuel energy can be seen to cause direct and indirect dispersion products which interfere with the environment. Figure 1 summarizes this dissipation of energy.

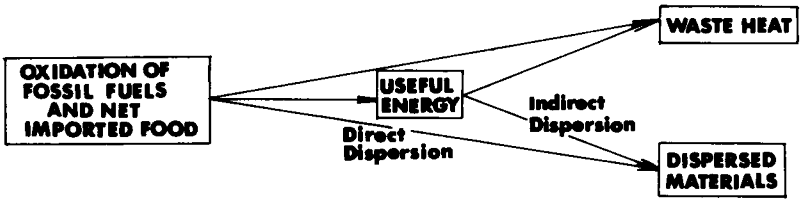

Figure 1. The dissipation of man's exotic energy by direct and indirect dispersion processes.

Physical, Chemical, and Thermal Pollution From Exotic Energy Dissipation

An understanding of how the dissipation of exotic energy causes damage to biological systems can be gained from dividing pollution into three forms—thermal, chemical, and physical [12]. Each of these forms of pollution disrupt natural ecosystem energy and material flows because they are in man-produced high energy states that interact with biological processes in a random way. Thermal pollution is a pulse of waste heat that is of higher energy than the environment in which it is being dispersed. Its effect is to create a new set of optimum survival conditions in aquatic ecosystems disrupting those organisms adapted to the previous energy flow; a new succession can be generated only if random heat changes are prevented, i.e., if thermal equilibrium is attained [13].

Chemical pollution arises from dispersing synthetic chemicals, heavy metals, etc, end products of industrial society, which have high energy states due to their bonds (synthetics) or their concentration (heavy metals). On contact with the energy and material flows of an ecosystem they block biochemical pathways until their energy is fully dissipated by microbial or chemical action.

This occurs even with chemicals designed to have a beneficial effect on the environment, e.g., fertilizers which produce unnaturally high concentrations of PO_4^{3-} and NO_3^- in surface waters, leading to eutrophication and loss of species diversity. Those chemicals which are concentrated in food chains, decrease diversity by selectively poisoning specialist species at the top of the food chain.

Physical pollution is from energetic particulate matter that is caused by man's energy use, e.g., when a forest is cleared, some of the energy used is transferred to soil particles which are no longer sheltered from rain and wind by vegetation but instead are swept away causing erosion and silting up of dams and estuaries. Man-created dust storms have a similar basis. Both chemical and physical pollutants are in higher energy states than their environment because they are only semi-dispersed relative to the natural environment in which they are found. In the same way radioactive wastes are a problem as long as they are above background levels (fully dispersed) and airborne particulates are semi-dispersed energetic particles that interfere with atmospheric weather processes indirectly disturbing ecosystems [14]. Noise pollution also fits into this system as it is obviously dependent on exotic energy use and it disrupts natural ecosystems by driving away sensitive animals and birds.

Thus exotic energy flow is a common denominator to all these environmentally damaging processes. There are, of course, differences in environmental effects between pollutants that have similar energy content, but the differences are often anthropocentric and to find an overall ecosystem effect the exotic energy flow gives the best first approximation. Figure 2 compares the natural ecosystem energy and material flows (a), with that due to man's imposed exotic energy flow (b), which produces semi-dispersed materials and high energy waste heat, then eventually fully dispersed materials and completely degraded waste heat as background levels are reached. The cycle from dispersed to ordered materials is incomplete as man takes raw materials that are already ordered to a considerable extent, e.g., metal ores and oil, then transforms them before they

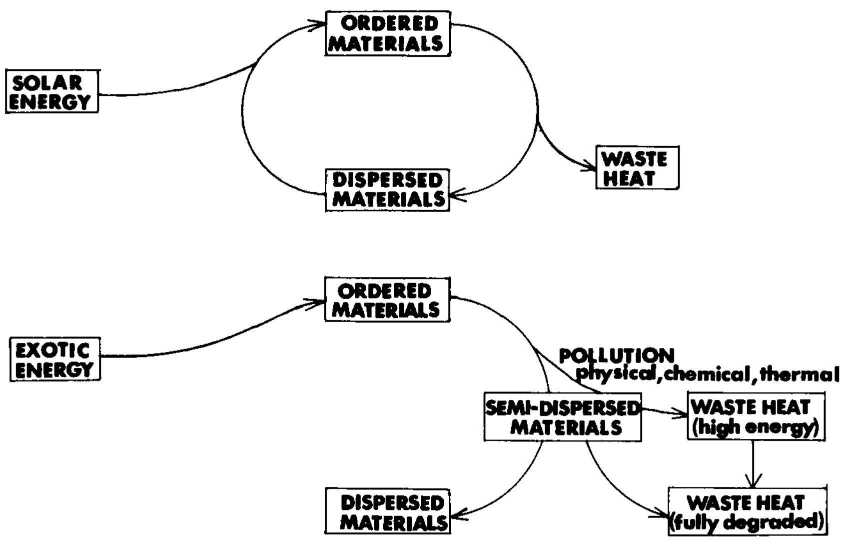

Figure 2. Comparison of natural ecosystem energy and material flows (a), with that due to man's use of exotic energy (b). The two flows should be super-imposed to show how man disrupts the natural cycle.

are released and dispersed, unlike the complete cycle of natural ecosystems. This also graphically shows why the superposition of dispersing materials from man's exotic energy use onto a natural ecosystem, disturbs the steady state material balance of nature.

Thermodynamic Perspective on Ecosystem Damage

From a different perspective, the interaction between man's use of exotic energy and the state of an ecosystem can be seen thermodynamically. The concept of entropy is used today in physical sciences (disorder) [15], statistical mechanics (low probability) [16], and information theory (information = negative entropy) [17] with mathematical links between each definition. Natural sciences are increasingly using entropy, based on the theory of irreversible or non-equilibrium thermodynamics [18] to understand the chemical and biological order or information in life processes, including human affairs [19].

In this framework, man's use of exotic energy sources can be seen to have an associated increase in entropy due to the spontaneous processes of waste heat generation and chemical dissolution (entropy of mixing) from both direct and indirect dispersal of materials. On an ecosystem level the disruption of a mature ecosystem back into a younger state with its decrease in diversity, smaller inventory of nutrients, decreased efficiency in energy use and loss of structure, can also be described as an increase in entropy [4]. So the physico-chemical processes of man's exotic energy use when superimposed on an ecosystem's natural energy flow cause an increase in entropy which is observable as a loss in biological complexity or information, i.e., the ecosystem is damaged. Exotic energy can be used in isolated applications to decrease entropy but the total effect of its use in an environment is to increase entropy.

Environmental Impact Parameter

Environmental impact therefore involves on the most basic level a damaging flow of energy from exotic sources through that ecosystem. Inherent in the discussion so far has been the idea that the level of damage depends on the concentration of exotic energy flow, i.e., on the area over which this energy is dissipated—if spread over a large area that ecosystem can more easily absorb the effects. Woodwell [7] indicates a clear pollutant concentration effect on ecosystems. Environmental impact is thus defined in the following way:

$$\text{ENVIRONMENTAL IMPACT (I)} = \frac{\text{EXOTIC ENERGY USE (E)}}{\text{AREA OF ENVIRONMENT (A)}}$$

This formula can be expanded into two components which further help to delineate the causes of environmental impact. As it is the use of exotic energy by human populations that is under consideration, the relation $I = \frac{E}{A}$ can be split up into the following:

$$I = \frac{E}{P} \times \frac{P}{A}, \text{ where } P = \text{population.}$$

i.e.,

ENVIRONMENTAL IMPACT = EXOTIC ENERGY USE PER CAPITA X POPULATION DENSITY.

A model of environmental impact based on these two factors and their interrelationship gives a further picture of the mechanism by which the environment is degraded by man's energy-using activities.

Energy Use and Population

A man whose energy source comes entirely from food, grown in his own environment, has no problems with waste dispersion and is severely limited in his abilities to damage (or control) his environment. As other sources of energy become available to him the effects of his activities and waste dispersion become more and more damaging to the environment. An increase in exotic energy use per capita produces an increase in environmental impact, but whatever the level of exotic energy use, each extra person in an environment (increase in P/A) also increases the total ecosystem damage, as every human being has an energy flow which must be dissipated through the area in which his activities are concentrated. The problem of population is not as simple as this though, for a synergistic relationship between energy use and population exists.

Deevey [20] has shown that man's population density has increased throughout history whenever he has developed a new ability to make energy available, identifying the three major stages as toolmaking, the agricultural revolution, and the industrial revolution. But Ehrlich and Holdren [1] have shown that increasing population also increases the energy per capita required to provide the same facilities and goods for the new total population, i.e., the environmental impact due to a population increase is greater than just increasing the population density in E/P X P/A with E/P constant. The reasons for this are manifold: an increased pressure for more living space and more intensive land use causes more land to be cleared which today is invariably of poorer quality and is thus more easily damaged, it causes over-grazing of pastures, filling in of estuaries, intensive use of pesticides and fertilizers to maximize food yields, it causes water and soil quality deterioration as they do not have time to recover before they are re-used and it causes the development of mineral and energy resources that are more and more difficult to exploit. All of these things require an increased use of energy per capita as the population density increases, thus compounding the environmental impact. The effects can be avoided for some time with careful land and water management but they are inevitable if the population density continues to increase.

Data on exotic energy use, population, and area can be readily obtained, thus making it possible to calculate estimated levels of environmental impact; the second paper in this series compares some calculations for twelve selected nations. But not only does the model allow some calculations, it also suggests some implications for our approach to energy use.

Implications

If impact is taken to mean the same as exotic energy use, then the formulae of Ehrlich and Holdren [1] and Commoner [2] bear resemblance to the one derived in this paper, with the exception of area as a further parameter involved. The Ehrlich-Holdren and Commoner formulae are designed to show the global impact of man's activities and so have an implicit area in their expressions–that of global area. To include area means the broad principles outlined by these authors in preserving the biosphere can be narrowed down to an environment of any size, including a nation or a national park. These principles have been distilled in this paper into two fundamental interwoven components necessary for controlling man's environmental impact, i.e., exotic energy use per capita and population density. Some further implications stem from these fundamentals.

1. Technological answers to pollution invariably involve an energy-intensive technique which may increase the overall environmental impact not decrease it. For example, cleaning SO_2 from stack gases with limewater involves the substitution of one volume of CO_2 for SO_2, the release of residuals when limewater is made from lime, the environmental costs of mining limestone and disposing of $CaSO_4$ and the direct dispersion effects resulting from electricity production necessary for the whole process. Pollution devices for auto emissions require an elaborate energy-intensive production technique which produces a machine that replaces CO, hydrocarbons and nitrogen oxides with CO_2 and new quantities of SO_2 and particulate platinum [21]. Such processes may be judged socially convenient but unless there is an overall reduction in energy use the total effect on the environment is not diminished but in many cases may be increased, the effects merely being shifted either in character or to another geographical area. The alternatives may be more socially acceptable but they cannot automatically be seen as diminishing man's impact on the environment. The same can be said for recycling which definitely saves resources but except in the obvious case of aluminium, may not save energy. Entropy considerations led Georgescu-Roegen [19] to conclude: "There is no free recycling just as there is no wasteless industry."

2. Non-energy intensive methods of controlling pollution center essentially around the techniques of applied microbiology. By this means a semi-dispersed pollutant can be used as an energy source by a specific microbe under controlled conditions so that dispersion of the substance is not a random, damaging process which the environment must take, but is directed so that the self purifying mechanisms of nature are utilized to our advantage [22]. Nevertheless such methods still require some energy to set up, are only applicable for liquid wastes and often pose problems with the final disposal of the product.
3. Alternative energy sources like solar and geothermal power have been highly rated as non-polluting. This is true as far as direct dispersion products are concerned, as the only problem is waste heat which does not affect the overall heat balance but may cause significant effects if concentrated in a local environment [23]. These sources are therefore preferable to fossil fuels, however they are not non-polluting–indirect dispersion products from these energy sources are just as damaging to the environment as from other sources, e.g., automobiles and synthetic chemicals produced from this energy must be used and dissipated in the environment. *The Careless Technology* [11] is not altered by a different source of energy. Also as these sources are developed on a large scale, other environmental factors will become more obvious, such as problems in making available the necessary water and other resources for power generation. Using microbiological techniques to produce energy in the form of methane or hydrogen from organic wastes appears to be the most environmentally sound of the alternative energy sources under discussion at present [24]. Instead of disrupting the material and energy flows in an environment, energy in the waste material is organized by microbes into a useful form for man. Again there must be final dispersal of materials but in this case the dissipation process has been controlled so that the energy content of semi-dispersed materials is minimized.
4. The only sure way to protect the environment is by energy conservation. This must include at least three things–population control, personal consumption changes, and technological energy conservation. The environmental impact formula clearly shows that population control is part of energy conservation as each person is an energy flow; if a nation does not attempt to control exploding population growth, then all other conserved energy will inevitably be replaced just through the sheer weight of people. Personal consumption patterns in industrial societies are essentially created and maintained by advertising, not by anything that is a real need or which promotes quality of life [25]. Such lifestyles and social organization can only end up destroying themselves unless a more realistic approach to the number and type of goods consumed is made. Technological energy conservation can be achieved by a movement to less energy intensive technologies such as mass transit rather

than the private auto [26], through the removal of planned obsolescence [27], and by increased technological efficiency. Many authors have shown the gross inefficiencies in most of our technological processes [28], including modern agriculture [29], and it is hoped that considerable energy conservation and thus less environmental impact will be achieved in future technology. The three factors of energy conservation can be included in the environmental impact formula by introducing the parameter of goods (G) in the following way:

$$I = \frac{E}{G} \times \frac{G}{P} \times \frac{P}{A}$$

Impact is thus reduced by lowering the energy used per goods (technological efficiency), the consumption of goods per person, and the population density. Calculations can be made using this formula but there are far too many goods of different types to make an assessment for the total environmental impact of a large ecosystem like a nation—this is done in Part II using the formula derived earlier.

Man can use his exotic energy sources to increase the productivity and even the beauty of his environment but as far as the total natural ecosystem is concerned, this energy is the cause of disruption to its diverse patterns of energy and material flows. Each ecosystem should be assessed to see whether this disruption is a necessary evil or an unnecessary result of irresponsible energy use.

REFERENCES

1. P. R. Ehrlich, and J. P. Holdren, *Science*, 171: 1212, 1971.
2. B. Commoner, "The Environmental Cost of Economic Growth," in *Energy, Economic Growth and the Environment*, Resources for the Future, Johns Hopkins Press, 1972.
3. H. W. Herzog, *Technological Forecasting and Social Change*, 5: 75, 1973.
4. E. P. Odum, *Science*, 164: 262, 1969.
5. R. Margalef, *The American Naturalist*, 897: 357, 1963.
6. R. A. Rappaport, *Scientific American*, 225: 117, 1971.
7. G. M. Woodwell, *Science*, 178: 429, 1970.
8. J. L. Wilhm, and T. C. Dorris, *Bioscience*, 18: 477, 1968.
9. P. S. Martin, *Natural History*, 76: 32, 1967.
10. J. P. Holdren, "Global Thermal Pollution," in *Global Ecology*, J. P. Holdren and P. R. Ehrlich (Eds.), Harcourt, Brace and Jovanovich, N.Y., 1971.
11. M. T. Farvar, and J. P. Milton, (Eds.), *The Careless Technology*, The Natural History Press, New York, 1972.
12. R. F. Mueller, *Thermodynamics of Environmental Degradation*, Goddard Space Flight Centre, Publication Number X-644-71-121, March 1971.
13. J. R. Clark, *Scientific American*, March 1969.

14. MIT Report, *Man's Impact on the Global Environment*, The MIT Press, Cambridge, Massachusetts, 1970.
15. E. A. Guggenheim, *Thermodynamics*, Ed. 5, North-Holland, Amsterdam, 1967.
16. T. L. Hill, *Introduction to Statistical Thermodynamics*, Addison-Wesley, Reading, Massachusetts, 1960.
17. L. Brillouin, *Science and Information Theory*, Academic Press, New York, 1962.
18. I. Prigogine, *Introduction to the Thermodynamics of Irreversible Processes*, Wiley, New York, 1965.
19. H. J. Morowitz, *Entropy For Biologists*, Academic Press, New York, 1970; R. T. Blackburn, *Science*, 181: 1141, 1973; N. Georgescu-Roegen, *Ecologist*, 2: 13, 1972.
20. E. S. Deevey, *Scientific American*, September 1960.
21. D. Shapley, *Science*, 182: 368, 1973.
22. D. Hughes, *New Scientist*, 10 January 1974.
23. J. P. Holdren and P. Herrera, *Energy*, Sierra Club Battle Book, San Francisco, 1971.
24. L. L. Anderson, *Energy Potential from Organic Wastes*, Bureau of Mines Information Circular 8549, 1972.
25. J. Ellul, *The Technological Society*, Ch. 5, "Human Techniques," Vintage Books, New York, 1964.
26. E. Hirst, *Bulletin of the Atomic Scientist*, 29: 36, 1973.
27. V. Packard, *The Wastemakers*, Penguin, Middlesex, 1960.
28. R. S. Berry and M. F. Fels, *Bulletin of the Atomic Scientist*, December 1973; M. Tribus and E. C. McIrvine, *Scientific American*, 225: 179, 1971.
29. J. H. Lawton, "The Energy Cost of Food Gathering," in *Resources and Population*, B. Benjamin (Ed.), Academic Press, London, 1973.