Environmental Science

Challenge for the Seventies

NATIONAL SCIENCE BOARD
1971

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REPORT OF THE NATIONAL SCIENCE BOARD

NATIONAL SCIENCE BOARD
NATIONAL SCIENCE FOUNDATION
1971

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LETTER OF TRANSMITTAL

January 31, 1971

My Dear Mr. President:

It is an honor to transmit to you this Report, prepared in response to Section 4(g) of the National Science Foundation Act, as amended by Public Law 90-407, which requires the National Science Board to submit annually an appraisal of the status and health of science, as well as that of the related matters of manpower and other resources, in reports to be forwarded to the Congress. This is the third report of this series.

In choosing environmental science as the topic of this Report, the National Science Board hopes to focus attention on a critical aspect of environmental concern, one that is frequently taken for granted, whose status is popularly considered to be equivalent to that of science generally, and yet one whose contribution to human welfare will assume rapidly growing importance during the decades immediately ahead.

The National Science Board strongly supports the many recent efforts of the Executive Branch, the Congress, and other public and private organizations to deal with the bewildering array of environmental problems that confront us all. Many of these problems can be reduced in severity through the use of today's science and technology by an enlightened citizenry. This is especially true of many forms of pollution and environmental degradation resulting from overt acts of man. Ultimate solutions to these problems, however, will require decisive steps forward in our scientific understanding and predictive skills, and in our ability to develop the wisest control and management technologies.

There is in addition a much larger class of environmental phenomena with enormous impact, today and in the future, on man's personal and economic well-being. These phenomena extend from fisheries to forests. They include the natural disasters of hurricanes and tornadoes; earthquakes and volcanoes; floods, drought, and erosion. They encompass problems in the conservation of our resources of water, minerals, and wildlife. Included too are the more subtle effects of civilization on weather and climate, as well as many forms of natural pollution, such as allergens, environmental pests and diseases, and volcanic dust. Together, these phenomena share a common characteristic: they can be fully understood, predicted, and modified or controlled only by studying them in terms of the complex environmental systems of which they are a part. Such studies, however, have become possible only in recent years. Greatly expanded efforts will be required to understand the forces involved in the confrontation between man and his natural environment.

This Report is presented as a contribution to the decisions that need to be made if environmental science is to become a fully effective partner in society's efforts to ensure a viable world for the future.

Respectfully yours,

H. E. Carter

H. E. Carter
Chairman, National Science Board

The Honorable
The President of the United States

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The National Science Board wishes to express its appreciation of the generous contributions made by many individuals and organizations during the course of this study.

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Special mention should be made of a sixth consultant, the late Dr. Wilbert M. Chapman (Ralston Purina Company) who served with distinction until his final illness. The Committee was fortunate in being able to benefit from Dr. Chapman's great knowledge and experience, as well as his good humor and enthusiasm.

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In addition the Board is grateful for the help of the National Academy of Sciences — National Research Council, the American Geophysical Union, the Ecological Society of America, the 1970 summer Study of Critical Environmental Problems (SCEP) sponsored by the Massachusetts Institute of Technology, the National Oceanic and Atmospheric Administration, and many others.

Finally, important contributions to this study were prepared by approximately 150 scientists, representing a significant sample of the intellectual leadership of environmental science. These individuals are identified at the end of the report. A second report, *Patterns and Perspectives in Environmental Science,* will be based on their contributions and issued separately as a Report to the Board.

Although the Board is privileged to thank these distinguished persons and organizations for their interest, help, and cooperation, it is essential to note that the synthesis of the opinions and voluminous information received, their interpretation, and their use in arriving at the conclusions stated in this report are the responsibility of the National Science Board.

Summary and Recommendations

Modern civilization has reached the stage where, henceforth, no new use of technology, no increased demands on the environment for food, for other natural resources, for areas to be used for recreation, or for places to store the debris of civilization, can be undertaken to benefit some groups of individuals without a high risk of injury to others. No environmental involvement of man can any longer be regarded as all good or all bad. Problems can be mitigated, but absolute solutions are probably unattainable. The best that can be sought, therefore, is to optimize, to try to achieve the wisest cost-benefit decision for society for each action contemplated. Such a strategy requires a strong base of scientific knowledge and understanding of the environment, ability to predict reliably its future course, and, especially, the ability to construct models through systems analysis of the environment and of man's interaction with it on a scale never previously achieved.

It is within this perspective that the present status of Environmental Science has been examined. **Environmental Science is conceived in this report as the study of all of the systems of air, land, water, energy, and life that surround man. It includes all science directed to the system-level of understanding of the environment, drawing especially on such disciplines as meteorology, geophysics, oceanography, and ecology, and utilizing to the fullest the knowledge and techniques developed in such fields as physics, chemistry, biology, mathematics, and engineering.** Included, therefore, are such diverse matters as climate, air turbulence, the air-sea interface, estuaries, forests, epidemics, earthquakes, and groundwater. These environmental systems contain the complex processes that must be mastered in the solution of such human problems as the maintenance of renewable resources (water, timber, fish), the conservation of non-renewable resources (fuel, metals, species), reducing the effects of natural disasters (earthquakes, tornadoes, floods), alleviating chronic damage (erosion, drought, subsidence), abating pollution by man (smoke, pesticides, sewage), and coping with natural pollution (allergens, volcanic dust, electromagnetic "noise").

Environmental Science is now exceedingly vigorous, considered in relation to its development over many centuries. Notable advances are being recorded at an accelerating rate. New tools and techniques, borrowed from all of science and technology, are being brought to bear on the problems of observation, measurement, and analysis. Across all of environmental science there is a heightened awareness of the essential nature of the environment and the directions that scientific effort should take. Nevertheless — and it is the principal conclusion of this report —

> Environmental science, today, is unable to match the needs of society for definitive information, predictive capability, and the analysis of environmental systems as systems. Because existing data and current theoretical models are inadequate, environmental science remains unable in virtually all areas of application to offer more than qualitative interpretations or suggestions of environmental change that may occur in response to specific actions.

There are two primary reasons for this state of affairs. One involves the nature of environmental science itself, the other the resources available for its advancement.

(1) The natural environment is not a collection of isolated events and phenomena, but rather a vast, integral, mutually interacting system. The recent advent of new technology and technique (satellites, advanced computers, instrumentation of many types, and the methods of systems analysis) for the use of environmental science has, indeed for the first time, provided feasibility for attacking the scientific problems that this environmental system presents. The tasks ahead, however, are of unprecedented magnitude and difficulty.

(2) The trained scientific manpower available to meet this challenge is extremely limited in each of the essential aspects of environmental science. More serious is the fact that this manpower is spread exceedingly thin, both with respect to the manifold problems presented and to the institutions within

which research is conducted, new scientists are educated, and scientific results are applied to the solution of problems of the public interest. Indeed, the institutions of environmental science, as here defined, remain in an early stage of development.

This situation constitutes a crisis for the Nation. While environmental problems are so diverse and diffused that virtually every activity of civilization interacts with the environment, few persons can be aware of the full scope of challenge that lies ahead. The current mismatch between capability and need is at least comparable to any other challenge to science and technology that was encountered during this century.

To meet this situation the National Science Board offers five groups of recommendations:

1. NATIONAL PROGRAM

Several factors emphasize the urgency of establishing a national program for advancing the science of environmental systems: (a) New organizations formed at the highest level of the Federal Government, the Council on Environmental Quality and the Environmental Protection Agency, have been charged with responsibilities that include the assessment of the environmental impact of civilized man. These agencies must foresee secondary effects and compare quantitatively the multiple consequences of alternative courses of action. Such efforts are severely limited by the present level of understanding of the behavior of environmental systems. They would become progressively more feasible as advances in environmental science increase man's predictive power. (b) The use of energy and the processing of material by man are doubling every 14 years.* Correspondingly, the number and severity of environmental problems will increase, while the adequacy of *ad hoc* piecemeal expedients will decrease. (c) As population grows, and with it the artifacts of civilization, the human and economic losses due

*Both activities have shown 5% average annual growth rates for the last 20 years, as reported in *Man's Impact on the Global Environment: Assessment and Recommendations for Action,* MIT Press, Cambridge, Mass., 1970. The total consumption of fossil fuel in the United States also grows about 5% per year; the conversion of an increasing fraction of fossil energy to electrical energy leads to a higher annual growth rate in the utilities.

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to sporadic natural disasters, already great, will increase in scale. (d) At the same time, the intensification of man's needs for both renewable and non-renewable resources requires even greater manipulation and mastery of the natural and man-made systems that constitute the environment.

It is, therefore, recommended that this urgency be recognized through the early development of a comprehensive national program to expedite the progress of environmental science.

The problems with which environmental science must deal, however, do not respect local, State, or even national boundaries. It is thus further recommended that this national program explicitly provide for the essential Federal role in encouraging and supporting the work of environmental science, quite apart from the role the Federal Government is already exercising with respect to improving and protecting the environment (e.g., programs of soil conservation, sewage treatment, air and water pollution control, etc.). Both nationally and in matters of international cooperation the Federal Government must assume leadership in fostering scientific advance.

This national program should be based on three efforts:

(1) Emphasis should be given to projects, manned by coordinate teams, directed to intermediate scale or "mesoscale" problems, that is, problems on the scale of lakes and estuaries, urban areas, regional weather systems, and oceanic fisheries. Advances on this scale will provide immediate benefits to man.

(2) At the same time, the program must ensure continued effort on global problems, even though their solution may require the resolution of smaller scale issues. In the long run it is the global constraints that will shape and delimit the future development of civilization.

(3) Finally, the program should ensure the continued vigor of those aspects of disciplinary research and gradu-

ate education needed to provide the specialists and new knowledge required for environmental science.

The remaining recommendations form an important part of the total recommendation of a national program. The entire program should be established at the earliest practicable date, if progress during this decade and its culmination during the following decades are to be commensurate with the urgency now faced.

2. PRIORITIES

One of the inescapable conclusions of this report is that the number and complexity of scientific problems, both theoretical and experimental, that confront environmental science far exceed the capability of available manpower to attack all of them effectively at the same time. If these resources remain distributed as they are, scattered and fragmented, and if problems to be solved are selected largely on the basis of the perceptions of individuals or small isolated groups, progress in environmental science cannot meet the needs of expressed national goals and purposes.

Accordingly, it is recommended that early consideration be given to strengthening arrangements whereby priorities for environmental science can be set, matched to existing and required scientific and engineering manpower, and changed as circumstances warrant. In setting such priorities appropriate weight must be given to the feasibility of achieving scientific solutions in a reasonable time and to the social and economic costs and benefits that could accrue if solutions were attained.

3. ORGANIZATION FOR ENVIRONMENTAL SCIENCE

The scope encompassed by the national program, proposed above, the Federal role inherent in this broad effort, and the patent need for establishing priorities raise serious questions of the adequacy of present arrangements within the Federal Government for planning, coordinating, managing, and reviewing programs of environmental science. As for all science, environmental science today is the responsibility of many agencies, often with conflicting interest under differing agency missions and responsive to many Congressional committees. At the same time the problems to be solved are broader, more difficult, and more dependent upon the coordinated use of scientific resources than those faced in the earlier development of nuclear energy, radar, and space exploration.

For these reasons, it is strongly urged that the Federal responsibility for environmental science, and for its promotion, organization, and support, be considered as important as the corresponding but separate responsibility for environmental quality. In particular, arrangements for Federal decision-making must be especially effective for the following activities:

(1) The setting of priorities affecting all research and development in environmental science supported by the Federal Government.

(2) The determination of appropriate and feasible time schedules for the projects of the national program and ensuring that projects are managed in accordance with such schedules.

(3) The provision of full coordination of the efforts of all Federal agencies engaged in the support or performance of research in environmental science, quite apart from efforts in application or regulation.

(4) The establishment of organizational and employment incentives suitable for the types of projects that are characteristic of environmental science through the support of national centers and specialized institutes.

(5) The encouragement of State and local governments and private supporting organizations to subscribe to the national program, as it is developed, and to the pattern of priorities adopted.

With respect to the organizations where the work of environmental science is done, several considerations are of the greatest importance.

Environmental science, as defined in this report, should be viewed as a distinctive type of activity lying between the extremes of traditional, basic science, on the one hand, and the organizations established by society for the application and use of science and technology. It shares the scientific motivations of the former and the multidisciplinary and organizational complexity of the latter.

Various types of organizational structures should thus be attempted, as experiments in the management of environmental science. Two conclusions are especially important:

(a) In academic institutions, which employ two-thirds of the manpower in environmental science, the need for strong departmental structures has historically hindered the development of effective interdepartmental programs. Within the last few years, however, new capability and experience in systems management, often combined with central funding for complex problems, have given a new vitality to multidisciplinary efforts. A few research institutes and national laboratories have also begun ambitious multidisciplinary studies of environmental problems. These experiments in organization should be continued, expanded, and followed closely.

(b) Industry possesses great capability in systems analysis and systems management, but rarely offers the broad array of scientific competence needed in environmental science. Government has additional strengths, particularly in the application of environmental science to environmental management. A more effective use of these resources can be made by combining the talents of industry, government, and universities in new types of research organizations and by seeking new approaches to the management of environmental science.

4. FUNDING FOR ENVIRONMENTAL SCIENCE

If progress in environmental science is to be made at an acceptable rate it is essential that additional manpower be made available both through education and through transfer from other fields and activities. This will occur only if appropriate employment opportunities and incentives are provided. The **character** of funding is especially important to this end.

In addition to the opportunity provided by new types of organizations, as recommended above, provision should be made for continuity of funding of programs of environmental science as being one of the principal means for attracting the best talent.

It is further recommended that the funding of equipment, facilities, and logistics for environmental science be consistent with scientific needs and opportunities. The highest priority should be given to the needs of multidisciplinary teams engaged in the study of environmental systems.

5. DEVELOPMENT OF ADDITIONAL MANPOWER

While it is essential that the disciplinary strength of academic institutions be maintained and increased across all fields of science, these institutions also have a responsibility specifically with respect to the manpower of environmental science.

Although competent specialists transferring from related disciplines can constructively enter fields of environmental science through on-the-job training, the process can often be faster and more effective if retraining opportunities are available within the educational context. Hence, it is recommended that colleges and universities consider appropriate means for supplementary education in environmental science for scientific and technical personnel.

Of special importance to implementing a national program for environmental science is the existence of an informed citizenry, both as a source of future scientists and as the necessary basis for national understanding and motivation of the entire program. The colleges and universities thus have a special opportunity to contribute by the development of new curricula in which to present the perspective of environmental science, as well as of new courses and programs, especially directed to the undergraduate.

Manpower needs related to environmental science are not confined to the scientists, engineers, technicians, and others who contribute to scientific progress. As environmental science advances, there will be an increasing need for "natural resource administrators" to serve in local, State, or Federal governments. The education of these public administrators involves two types of interdisciplinary training. On the one hand, scientists and engineers must gain a better understanding of the social, economic, legal, and political environment within which practical action must be sought. On the other hand, students of public administration must gain a better perception of the scientific process and a better understanding of how scientists can contribute effectively to the practical solution of environmental problems. It is recommended that substantial and adequate funding be made available for these purposes.

Even with the implementation of these recommendations only gradual progress can be anticipated. Environmental science is too difficult, too broad in scope, and too near the beginning for an effective match with societal need to be achieved during this decade. But, correspondingly, the stakes are too high to miss the opportunity for making the 1970's the base on which a constructive future for mankind will be established.

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Introduction

This is a report on the status of a part of science. Frequent references within the report to the environment, to environmental problems, and to human welfare establish the relevance of the science, but in no sense is this a report on the status of these areas.

Many recent reports and a flood of legislation, proposed or enacted, reflect the growing national concern over the present or future state of the environment. Many reports have also been prepared to review the condition of various parts of what has been termed the "environmental sciences" and to recommend appropriate actions. It is the conclusion of the National Science Board, however, that there is yet another message related to the environment, one that has failed to date to receive the attention and discussion that it deserves, and one that is especially timely today. This message consists of two parts, a proposition and a question:

The proposition. — Although early naturalists saw nature as a whole, the natural environment has been increasingly viewed as a heterogeneous ensemble of more or less independent parts—the sky, the oceans, the dry land, . . . Inhabiting this complex array and supported by it were the living things, each following a "dust to dust" trajectory and carrying with it a sense of being separate and apart. Scientific study of these parts, abetted by the disciplinary traditions and departments of academic science, retained the separation and gradually led to many fields of inquiry, including those known by the recent expression "environmental sciences." One of the most important trends of recent years, however, and one that is shared more and more by the general public, is the developing recognition that the environment is in fact a single entity, a gigantic system. It includes the radiations and tidal influences arriving from the outside, the solid earth, the envelope of air and water, and life itself, and must be described in terms of its relationships and interactions as well as its individual components. Such an approach crosses the boundaries between disciplines, bringing to bear whatever science is available and useful in studying one aspect of the environment. Hybrid fields such as geochemistry, cloud physics, and bioclimatology have emerged. Although the traditional disciplines remain relevant and necessary to the continued study of natural processes, it is their coherence rather than their identity that is useful in the study of environmental systems. For this reason the plural term "environmental sciences" is avoided in this report. In its place it is proposed to examine the status of

> ENVIRONMENTAL SCIENCE, defined here as the study of natural processes, their interactions with each other and with man, and which together form the earth systems of air, land, water, energy, and life.

It is this emphasis on the systems and subsystems, tying together the myriad elements of the physical world, that distinguishes environmental science from science as a whole. Of those engaged in research, development, and teaching in the natural sciences, however, only six percent of the doctorates and seven percent of all scientists are working in the disciplines most central to the study of environmental systems. Another ten percent work in related supporting areas and in applications of environmental science.

The question. — In recent years the environment, and especially its quality in relation to human welfare, has become a focus of public concern that has approached climactic proportions. At Federal, State, and local levels this concern has produced a number of action programs and restrictive regulations, all designed to ameliorate a situation that many have only recently recognized. The issue is seen to be a matter of an increasing rate of deterioration resulting from man's intervention. Since science provides information and concepts, increased options, and predictability that can contribute to informed public opinion and sound action programs, the question arises:

> To what extent does environmental science today possess the basic knowledge and understanding needed to help resolve problems of the public interest, to provide an objective basis for the setting of public policy and programs, and to anticipate the effects of increasing demands of population and industry upon an irreplaceable and vulnerable resource?

This report, therefore, is addressed to the status of environmental science, without primary regard for disciplinary subdivision, and to the issues that arise, as a matter of public policy, and that relate the contribution that science can make today or in the future to this aspect of the quality of life. Correspondingly, **the concern in this report is not with the state of the environment, nor with the state of the disciplinary structure of environmental sciences, but rather with the state of Environmental Science as a whole in 1970, in its relation to this important endeavor, and with the steps that need to be taken if it is to match the challenge that confronts it.**

The Board is aware that many important problems, such as the removal of sulphur from smoke, the recycling of industrial wastes, and the protection of open space, can be solved with technology and institutional change. The exclusion of these problems here should not be misunderstood; the Board agrees with the emphasis they have received in other reports and in social and political action. The emphasis here is on a class of problems whose solutions are much more difficult to achieve, in the sense that they require advances in the science of environmental systems as well as technology and institutional change.

Essential to the important service that environmental science can provide is the determination and willingness of society to establish the priorities and support the institutions that are necessary for the translation of environmental science and technology into sound political action and public decision. Although study of the social dimension of environmental science was deemed, for practical reasons, to be beyond the scope of this report, it is fully recognized that social judgments and political decisions are implicit in any evaluation of the adequacy of scientific programs and in the assessment of policy needs and action. The social and managerial sciences have a central role in the task of building a stable, healthy, and happy environment within which man can look to a constructive future. It is thus of the greatest importance that research in the social and managerial sciences be coupled with that in the natural sciences to the end that knowledge and understanding will be used effectively and wisely.

In arriving at the conclusions contained in this report, full consideration has been given to important contributions that have been prepared by a large segment of the scientific leadership of environmental science. This voluminous material forms the basis of a second report, *Patterns and Perspectives in Environmental Science,* to be issued separately.

The Past Decade – Expanding Horizons

The period of the 1960's was unique in the history of American involvement — emotional, intellectual, and technological — with the natural environment. **It was a period of transition.** The previous era of individual opportunity to exploit continued to be replaced by one of increased public responsibility, and indeed necessity, to conserve. **It was a period of preparation.** New tools, concepts, and procedures emerged that would ultimately form a powerful supplement to methods used for generations in man's efforts to observe and understand the complex world about him. And **it was a period of promise,** for it marked a new threshold in man's capacity to view his total environment in perspective, to live with it, and to manage his interactions with it more wisely.

PUBLIC PERCEPTIONS

In the 1900's Americans were deeply aroused by dwindling forest and mineral resources, and they established large-scale conservation programs. In the 1930's they acted dramatically to halt erosion and to provide better management of their waterways. In the 1960's the citizen became acutely aware of other instances of the deterioration of his environment and of real or imagined dangers for the future, of the dirty habits of many of his fellowmen, of the loss of aesthetic values for large segments of his environment, of the finite nature of many of the resources he must depend upon, and in a general way of the potential irreversibility of much that he is doing in the name of civilization.

The citizen became cognizant, for the first time as a member of society, that the technology he had created had the potential to place him in jeopardy: the automobile, although he had experienced smog before; the power plant, although the problems of sulfur oxides are not new; the factory, although industrial wastes had long degraded the Nation's streams. He recognized the urgent need for sewage treatment plants, although eutrophication of lakes had already destroyed fisheries. The idea was new that the city was altering his weather, or that pesticides could kill hundreds of miles from the site of application. How much of this increased awareness has been due to more rapid environmental change, to deeper dissatisfaction with the state of society, or to heightened sensitivity as a byproduct of affluence is not clear.

To attempt to offset the unfortunate trends that seemed to threaten the citizen from all sides, a new effort was initiated, together with a new expression, *technology assessment,* through which the effects of technology can, in principle, be anticipated, thereby avoiding unwanted consequences. This ambitious design, however, can only succeed when environmental science, through fact and scientific understanding, can provide a sound basis for such assessments.

The concerned citizen often has parochial interest, and he demands quick action. This leads to the selective solving of environmental problems that are local and often straightforward. Many individuals lack a sense of personal involvement in large-scale problems to which they may be contributors: the growth of the world's population, the precarious balance between people and food supply, the implications of *per capita* economic growth, and the growing gap between developed and developing nations. Similarly, the public has only a vague awareness of the need for a much greater capability to predict changes in the complex systems that relate man to his environment.

SCIENTIFIC PERCEPTIONS

The outlook of the scientist, to the extent that he differs from other citizens through training and experience, has followed a somewhat different course. For years he has been conscious of interactions among many aspects of the environment, of the "subsystems of the universe." In fact, the view that many parts of the environment, especially those that affect man, are the result of gigantic confrontations involving natural forces has been held both by scientists and their early counterparts from the beginning of man's history. The 1960's, however, marked a distinctive period in three important respects.

(1) The physical extent of the environment, in the sense of including all parts of nature that interact with man, expanded to encompass the entire universe. Two extreme examples would include:

> Processes occurring in the far reaches of space, discovered through astronomy and radio astronomy but still little understood, generate cosmic radiation that in turn is continuously causing gene mutations in living things on earth, including man.
>
> In the earth's central core other processes, also poorly understood, produce the magnetic field, familiar to man for centuries as a means for navigation. Less familiar are recent findings that the effects of solar disturbances on the earth's atmosphere (and therefore man's immediate environment) may be modified and influenced by this magnetic field.

From the center of the earth to the distant galaxies the physical universe, in a most important sense, is congruent with the natural environment. The differences between environmental science and all natural science are primarily those of viewpoint and method, leading in turn to differences in the phenomena to be studied. These phenomena are illustrated in the following sections.

(2) A distinction between the environment and the universe arises from the focus on man, and has attained broad recognition only in recent years. For centuries the major efforts in science, in most of its branches, have been directed to the discovery of the building blocks of nature, to securing an understanding concerning how these building blocks behave and what they are made of, and to the generation of a theoretical structure of natural law and its validation. This effort, a continuing one to be sure, has been enormously successful. Apart from forming an essential ingredient of the intellectual heritage of mankind, this body of science has made possible the explosion of technology that has resulted in the advances in standard of living and human health enjoyed in many nations today.

In contrast, science of the environment is of a different character. An element of the environment is not a matter that can be studied successfully or completely in isolation. Neither does it represent natural laws that differ from those that science generally has sought. Indeed the emphasis in environmental science is now seen to be

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necessarily placed on the ways in which many elements relate to each other and synergistically produce the kinds of phenomena with which man must cope. The following examples are illustrative:

Weather and climate are continually varying and infinitely complex phenomena that combine radiation from the sun, heat from deep in the earth, and radiation into space, all of these altered by absorption, reflection, and scattering in the atmosphere, and including the effects of clouds and particulates; reflection to various degrees from the surfaces of water, vegetation, and land; evaporation and the transfer of heat from water and land and the similar effect of transpiration from plants; temperature differences between the tropics and the poles; the orbital movement of the earth about the sun and the effect of the earth's inclined axis; and many others.

Solid rock, made "plastic" under extreme pressure and temperature, rises from the earth's mantle in gigantic convective currents, sometimes melting and forming lava, emerges from mid-ocean ridges to form enormous "plates" that may produce mountain ranges when they collide, and that generate earthquake prone regions or deep trenches when one plate dives beneath another. The demonstration of this process of seafloor spreading and continental drift in what we now know to be a "living" dynamic earth is one of the revolutionary achievements of science during the 1960's.

The finite life of seafloors leads to the concept of geological cycling on a very large time-scale, ocean sediments eventually being returned to the continental masses or to the earth's mantle. This geological cycle interacts with the much faster ecological cycle of organic production and decay. A small portion of organic production is buried each year in the sediments, and accumulates over the millions of years that seafloors persist. Each year a small amount of organic matter is folded into the mantle or lower crust, burned, and expelled as volcanic gas. This interaction of geologic and ecologic cycles is part of the process that regulates the amounts of carbon dioxide and oxygen in the atmosphere.

Interactions of a different character produce great cyclonic storms. For example, atmospheric disturbances having an unknown origin, apparently near the east coast of Africa, traverse the Atlantic and somehow intensify into hurricanes. The hurricanes themselves simultaneously involve the interaction of large scale tropical weather systems, intermediate scale cyclonic behavior, and small scale interactions between atmosphere and ocean. The resulting hurricane forms an essential mechanism for the transfer of heat from tropical to temperate latitudes, brings needed rainfall to many areas, and causes unneeded destruction to human life and to structures that man has created.

Also complex are the interactions that result in oceanic food resources (Figure 1). They include the transport of warm water on the surface of the sea through the action of atmospheric winds, its replacement by cold bottom water with its dissolved nutrients, with the warm water cooling and sinking as it approaches the polar regions to repeat the cycle. Also involved are the growth of microscopic plants in the surface layers resulting from this process of "upwelling," with the simultaneous action of solar radiation, water, nutrients, and carbon dioxide present in the water or entering from the atmosphere, and then a complicated array of food chains as small animals prey upon the plankton, small fish prey upon these small animals, and so on until the process culminates in the fish that man habitually eats. In this process it is now recognized that the populations of the lower species of these food chains are substantially controlled from the top through predator-prey relationships, a reversal of views that were held only a decade ago. Finally, the resources contained in the bodies and wastes of all living things are eventually decomposed by bacteria and other organisms, thus releasing these resources for further use.

(3) The method of approach to investigation emphasizes another distinction between the efforts of traditional science and those of environmental science. It is in a sense analogous to systems engineering, defined by tools, techniques, and procedures which proved their power in major technological developments during and since World War II. There has been a broad effort to bring these methods to bear across almost the entire field of environmental science. This circumstance forms a distinctly new departure in the search for scientific knowledge and understanding.

NOTE TO FIGURE 1

The distribution of the world's fisheries. The four figures of this report represent four different kinds of situations in environmental science. In this case, the final output of the system is a clearly identified resource, obtained primarily from the coastal oceans. Much less clear are the future responses of this system to exploitation, and the future opportunities that may derive from a better understanding of the system. One critical factor is the *total* fish production of the oceans, which has recently been estimated to be only four times greater than the 1968 catch, for corresponding species. Another is the vital role played in estuaries and along coastlines, where pollution threatens the nurseries of many commercial species. A third is the role of upwelling, as discussed in the text. Weather is important to the success of fishing, and further improvements in local weather forecasting await a better understanding of larger scale meteorological phenomena. Altogether, the systems of air, water, and life are intimately interwoven in the production of fishery yields.

LEGEND

COASTAL AREAS—About 50% of Global Commercial Harvest

UPWELLING AREAS—About 50% of Global Commercial Harvest

Less than 1% of Global Commercial Harvest

Prepared by the National Science Foundation

Figure 1

DISTRIBUTION OF THE WORLD'S FISHERIES

TECHNOLOGY FOR ENVIRONMENTAL SCIENCE

The advances of the last decade — a maturing of concept, a shift of perspective towards the systems aspects of the environment, and a determination to attack scientific problems of a diversity and complexity that had not previously been attempted — have been directly related to the advent of significant new technology. New types of equipment for measurement and data-gathering, communication, and data analysis have marked a giant step forward in the ability of environmental scientists to handle environmental problems. Much of this equipment is well-known, as are many of its applications. Major examples include:

A variety of instruments developed in other fields have enormously expanded our sensitivity to the environment, enabling us to identify, trace, and otherwise evaluate an extraordinary array of phenomena. Included here are mass spectrometers, gas analyzers, X-ray diffraction apparatus, electron and ion microprobes, radioactivity counters, particle counters, amino-acid analyzers, chromatographs, and scanning electron microscopes.

A variety of satellites, including those for the study of the solar surface and the space between the sun and the earth, the series of operational meteorological satellites and those developed especially for atmospheric research, the planned satellite for the study of the earth's resources, communications satellites to contribute to global data handling, and "stationary" satellites operating at synchronous altitude, taken together, have provided an enormous and expanding capability for observations on a global scale, a capability that is entirely new in the history of man's attempts to understand his environment.

Automatic data-handling equipment provides central filing or display from sensors of all kinds located, for instance, on mountain tops, lake bottoms, trees, bears, whales, birds, or airplanes. Remote sensing includes the use of Doppler and other ultra-sensitive radars, acoustic "radars," and the first application of laser "radars" in meteorology and seismology, and the expanded use of infra-red and multi-spectral sensors in studies of vegetation, land, atmosphere, and water surfaces. Data gathering has been coupled with data processing, and in one major international study of marine upwelling the entire complex has gone to sea.

Special mention should be made of the development of new types of deep sea drilling techniques and their use on the unique, prototype vessel, *Glomar Challenger*. This facility has brought to light in only a few years information that has literally revolutionized man's understanding of physical processes occurring in the earth's crust.

The rapidly increasing volume of data about the environment has brought with it the opportunity to study for the first time the systems aspects of many features of the environment. This effort is being made through the use of mathematical modeling and simulation techniques and their attempted application to the solution of environmental questions. The development of this technology is essential if satisfactory answers to many of the problems of current public concern are to be found.

This technology implies another, for the enormous computational complexity represented by environmental systems has required the increasing use of larger, faster, and more powerful computers. Of special significance may be the development of the parallel processor computer to replace sequential operations by simultaneous operations on vast amounts of diverse input data.

The exploitation of new technology in environmental science is just beginning. It forecasts an era of unprecedented productivity.

III

The Present Day—A Problem of Timing

Although recent years have witnessed a tremendous increase in awareness, on the part of scientists and non-scientists alike, of the nature, complexity, and extent of the natural environment, the mutual interactions of its parts, and its interactions with man, while powerful new tools for the study of the environment have been introduced with outstanding initial successes in the exploitation of prototypes, there should be no misunderstanding concerning the status that has so far been achieved. Simply stated, environmental science today is rarely able to provide the quantitative information, interpretations, and predictions needed to match the needs of society. The current situation can best be viewed in two ways.

MULTIPLICATION OF PROBLEMS

Environmental science is perhaps the oldest of man's scientific activities. The most ancient records of mankind contain evidence of careful observations of many types of natural phenomena, efforts to predict or forecast coming events that would affect his activities or well-being, or efforts to control or at least to modify the course of natural events. These efforts were usually made, however, within a framework of simple beliefs. The complexity of the natural environment, on the other hand, is such that, although observations and measurements have continued to be made to the present day, observational data of immediate concern to man remains sporadic, incomplete, and inadequate to serve as a basis for sound scientific investigation. For example and with respect to general understanding across the entire field of environmental science, one need only recall the comment of the late Professor John von Neumann to the effect that the atmosphere represents the second most difficult challenge to scientific understanding, man and society presumably occupying first place. Environmental science has become in many respects more difficult as more has been learned. The following examples serve to illustrate this situation.

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The earlier presumption that exchange of carbon dioxide between the atmosphere and the oceans could account for the fate of carbon dioxide produced by burning fossil fuel has proven false. About as much of the carbon dioxide produced has gone into the vegetation as into the oceans, and the interaction in both cases is more complicated than anticipated.

The discovery of several systems of counter currents in the deep ocean has demonstrated that oceanic circulations are considerably more complex than they had previously been thought to be.

Measurements of the exchange of heat and water vapor between the ocean and the atmosphere, important to understanding the behavior of both, indicate considerably greater complexity than had previously been thought. Results from the "Barbados Oceanographic and Meteorological Experiment" (BOMEX) will require fundamental revisions of theoretical formulations.

Ecology texts show bacteria and fungi in water and soil acting as decomposers of organic material, distinct from the animals (consumers) and the green plants (producers). It is now known that decomposition is often accomplished through the combined, and often interdependent, action of microflora and small animals. Furthermore, many green plants live in intimate physical bonding of their roots with fungi, the latter serving as the major means for removing water and nutrients from the soil. These complex relations cannot be unravelled adequately today because the many species of fungi and small animals are poorly known.

Eddy currents have long been known to be important to circulations in both oceans and lakes, and atmospheric turbulence, including the special case of clear air turbulence, is now seen to play a most significant role in atmospheric energy exchange. Both types of phenomena, however, are exceedingly difficult to measure and to fit into a general circulation theory.

Observations from the Applications Technology Satellite (ATS-III) have uncovered types of cloud structures and clusters of such structures that are new and for the present remain unexplained.

The very achievements of environmental science in recent years thus render the solution of major scientific questions both more remote and more urgent.

STATUS OF UNDERSTANDING

Conversely, there exists a significant body of knowledge and understanding across environmental science that is daily being brought to the service of mankind. The weather is in fact being forecast, however well or poorly these forecasts are regarded. In certain instances, notably in the California Current, the tuna catch is being successfully predicted. The ionosphere, in spite of its great variability, is being used for reliable long-range radio communication through the use of adaptive techniques. The characteristics of mineral-bearing structures are known and this information is being used for exploration. Much is known and understood about such diverse topics as forest-watershed management, the controlled use of forest fire, environmental disease, and the physiological effects of high altitude.

The fundamental scientific laws of the universe are necessarily identical to those operating in the environment. Yet the environment is so diverse and so complex that in many instances it has not yet been possible to enunciate general principles of practical utility. Nevertheless significant progress has been made in the identification and interpretation of the phenomena, processes, and inhabitants of the natural environment. Large and complex problems can be partitioned and simplified, and partial solutions and understanding can come from the study of these smaller portions of the whole. Ultimately, however, the larger systems must be understood, since it is at such scales that many problems of interest to human welfare are found. At present, scientific understanding of such systems is almost entirely qualitative. Several examples illustrate this aspect of the state of knowledge:

> It is not possible to predict in any definitive manner in many situations the transport of pesticides, pollens, airborne radioactive particles, mercury, lead, or other materials, nor are the mechanisms of concentration of these substances in the food web well understood. Neither are the detailed nor the long-term chronic effects of low level concentrations of pollutants

on man, other animals, or plants adequately known; and the resulting changes in the relative balance among species in a natural landscape are virtually unexplored.

It is not possible today to predict earthquakes or volcanic eruptions. The mechanisms whereby hurricanes and tornadoes are generated cannot be explained, nor can their movement be predicted except in terms of extrapolation from historical statistics. Nor is there any appreciable understanding today about why or how electric charge separates in clouds and forms lightning.

There is inadequate theory today for assessing with confidence the long-term climatic effects of carbon dioxide, heat, or particulate matter introduced into the atmosphere by today's technology, or the possible effects of aircraft contrails, or the consequences of jet exhaust at stratospheric altitude.

The currents in lakes and oceans cannot be described in detail, nor can the transport or ultimate destination of wastes or other materials introduced into these bodies of water be adequately appraised.

It has been demonstrated that the ability of a landscape to retain its nutrient elements is related to its plant and animal species; shifts in the latter may alter the nutrient balance in the system, yet the relationship is poorly understood. Indeed it is usually not possible to predict or assess quantitatively the effects of external influences on any ecosystem.

Although a great deal has been learned about the nature of emissions from the solar surface, it is not yet possible on the basis of fundamental physical principles to predict solar flares, nor their intensity, nor all of their effects on the earth's environment.

There is today little understanding of why the earth has a magnetic field, how the earth's core generates such a field, nor why the field reverses polarity from time to time. In connection with the last, it is known from studies of the magnetism of ancient rocks (Figure 2) that the earth's field has reversed at least 40 times in the past 10 million years. The next reversal, which will occur at an unknown time, at an unknown rate, and with unknown consequences, is believed to be overdue.

Although great progress has been made and accretions to man's understanding of his environment are being made daily, important questions of all types remain unanswered. Details concerning these and many other items relating to the status of environmental science will be presented in a separate report, *Patterns and Perspectives in Environmental Science.*

ENVIRONMENTAL PREDICTION

The maturity of a science can often be judged by the precision with which successful predictions can be formulated and computed. Given the appropriate initial conditions, how will a given system under study evolve or develop with time? The path of Apollo 12 or the orbits of the planets can be predicted with great precision, using only Newton's laws and the universal law of gravitation. But prediction in this sense is not possible in every science, either for practical reasons, related to complexity, or because of the inherently statistical or random nature of the phenomena being studied. It is precisely in this area that a major scientific controversy exists with respect to environmental science. A great deal of effort is currently being placed on approaches to prediction of environmental regimes. Because of the many contributing factors involved, these efforts generally take the form of systems modeling or simulation, based on established physical laws, and the use of these mathematical models to project the state of the environmental regime at some time in the future.

A problem, however, has been encountered in efforts to predict the state of the atmosphere, that is, weather forecasting. Much publicity has been given to the prospects for "accurate" forecasts (and this term is generally not defined) at least one to two weeks in advance, on a global scale. Major programs have been undertaken to achieve this end. Some scientists, however, question the innate predictability of the atmosphere, except on a long-term, statistical, climatic basis. To these scientists the upper limit is perhaps five days. While it can be predicted with fair confidence that thunderstorms, tornadoes, or other severe storms will occur over a general area, little can be said about where individual storms will form, for they appear to be governed by causes of a statistical nature.

NOTE TO FIGURE 2

Reversal in polarity of the earth's magnetic field. These data derive from measurements of the direction (N-S) of magnetism frozen into lava as it hardens, and the dates of many lava flows. The same phenomenon has recently been confirmed in the spreading seafloor. This figure is an example of a phenomenon of global extent that is known to occur, but has never been witnessed. The effects of reversal are unknown. There is possibly a transient weakening of the shield that protects the earth from a part of cosmic and solar flare radiation. A shortening of life span as well as an increased mutation rate would be possible effects on life.

LEGEND

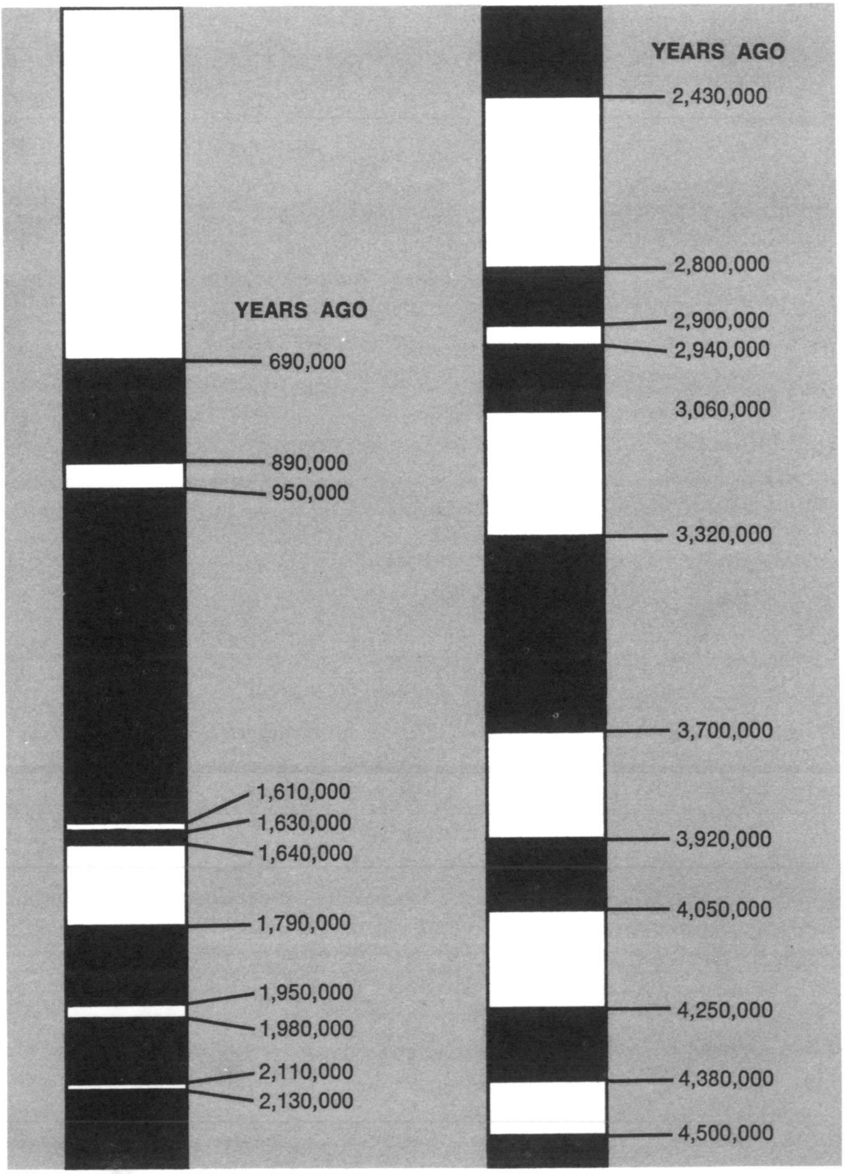
☐ Field as at Present

■ Field Reversed

Prepared from data provided by Professor Allan Cox, Stanford University

Figure 2

CHRONOLOGY OF EARTH'S MAGNETIC FIELD REVERSALS



At the same time, there has been a relative neglect of efforts to improve short-term, local or regional forecasting. Efforts to achieve successful long-range forecasting should certainly continue because of the large potential benefits that could result. However, it should be recognized that large economic benefit and advantages to the lives of human beings would accrue from the ability to predict more precisely atmospheric conditions for periods ranging from about an hour to several days in advance. **Far greater effort should be placed on research leading to this end than has hitherto been the case.**

The capability to predict is not balanced across all parts of the environment. While the situation described above exists with respect to the atmosphere, the status of oceanic prediction is even less satisfactory. Although intensive efforts are being made to develop models of life-centered systems or ecosystems for purposes of prediction, no complete model of any ecosystem yet exists (Figure 3). For the solid earth or for the solar-terrestrial region reliable prediction is still a matter for the future. In this important subject of scientific prediction environmental science remains a young science.

THE BASIC ISSUE

A central problem thus exists with respect to environmental science, one that can best be illustrated by comparing the situation today with the circumstances that prevailed at the time of Sputnik. A decade ago the state of relevant science and technology — physics, chemistry, propellants, control systems engineering, mechanical design, communications, manufacturing capability — was such that an immediate effort could be mounted to meet a perceived challenge, and technological goals could be stated for the decade ahead. **Today again there is a perceived challenge, more serious and more generally shared than the one a decade ago, and one that science, environmental science, cannot provide the tools to meet.** This is a matter of the utmost importance — both for the United States and for the world as a whole.

> There is a clear and urgent need for the establishment of a national program to develop environmental science to the point where it can contribute decisively and authori-

tatively the information, the interpretations, and the predictions that are needed for wise public decision on all matters relating to the environment within which man is constrained to live and to look forward to a constructive future. At the same time, there is a corresponding need for vigorous and expanded programs of research on the social, behavorial, economic, political, and administrative arrangements and institutions that are essential, if the results of environmental science are to be effectively applied and if the crucial physical and biological issues are to be recognized.

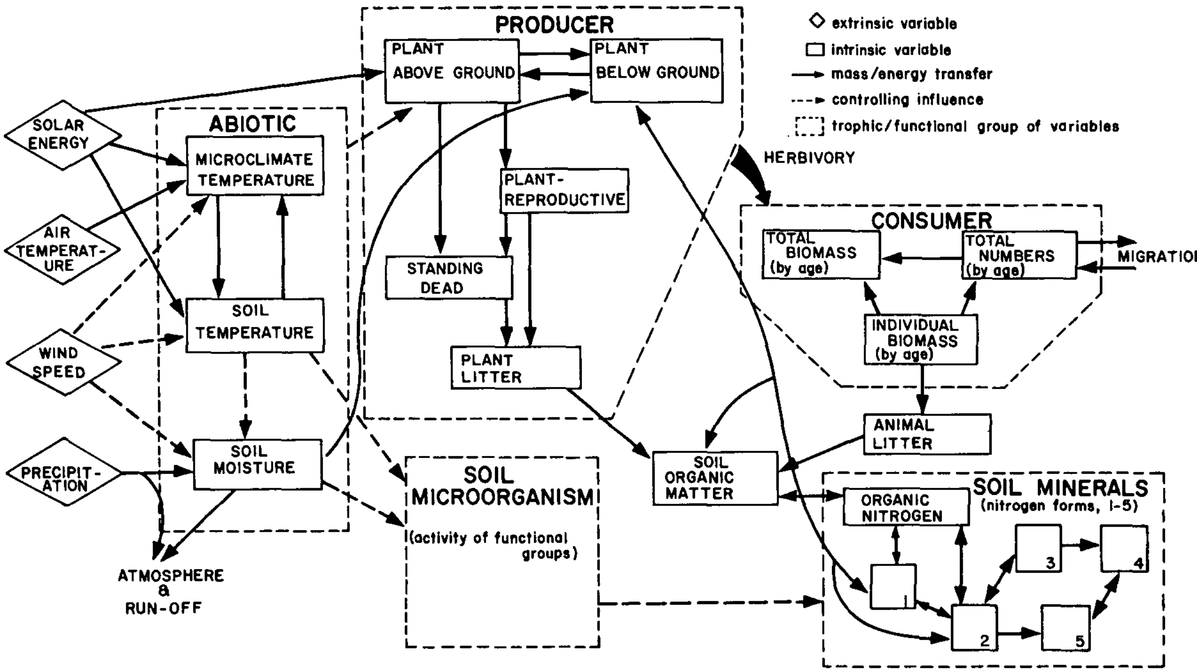
On the other hand, it must not be inferred that all actions to improve or protect the environment should be deferred until everything is understood. Enough is known today for many things to be done. Even though it is not known what concentrations of sulfur oxides are produced by what levels of emission under various meteorological conditions, it is known that lower emission at the source will improve the situation. Sulfur oxide concentrations can be measured and correlated empirically, even without the ability to explain them, to a degree sufficient to permit the objective enforcement of certain control measures.

NOTE TO FIGURE 3

A systems model for a grassland ecosystem. This diagram represents a giant step forward in the conceptual approach to the study of an ecosystem, and has proven invaluable in the design of research, team organization, and analysis of data. Nonetheless, the level of sophistication shown here is well below that needed for application in practical problems. The complexities arising from the several hundred species and several thousand relationships are still overly simplified, as are the interactions of the system with human intervention. This figure represents very well the general level of adequacy that exists in all subfields of environmental science, and demonstrates the youth of the field.

Figure 3

A SYSTEMS MODEL FOR A GRASSLAND ECOSYSTEM



Courtesy of the Grasslands Biome Project, International Biological Program.

IV

The Future — Three Levels for Action

Efforts to advance environmental science during the coming years will necessarily follow three directions, each essential to the public purpose. These directions concern efforts to solve global problems; corresponding efforts related to local, regional, or "mesoscale" phenomena; and basic scientific investigation to solve many of the elementary questions that underlie much of environmental science. The second of these is probably essential for success in the first; the third is essential for the first two. All three share a common scientific purpose: to obtain the information, understanding, predictive capability, and basis for developing appropriate control technology or management techniques that will serve the needs of society. The three differ substantially in required magnitude of effort and, consequently, in cost.

> It is of the most fundamental importance, therefore, that major attention be given to the priorities that will determine the distribution of available resources across these three efforts, and that continuing concern for priorities be maintained for the foreseeable future. Mechanisms for this purpose should be centralized among all agencies and organizations that support research in environmental science.

The stakes involving environmental science are so high that its progress on many fronts should not be entrusted to the initiative of individual private investigators, one unrelated to another, nor to major programs where the scientific objectives have not been clearly defined.

DISCIPLINARY SCIENCE — A CONTINUING NEED

While environmental science is fundamentally **science** addressed to the interactions among complex processes in complex systems, it should not be inferred that only investigations of systems and subsystems are involved. Indeed there are innumerable problems that need to be solved before needed information can be obtained for the systems work, whether the systems are addressed to prediction, to potential environmental modification or control, or to gaining understanding, three alternatives that are intimately connected. Examples of such basic research extend from solar physics to the geochemistry and geophysics of the solid earth, from biological studies of countless species still unknown in tropical forests or the ocean bottoms to the chemical environment of ozone in the upper atmosphere, or from the fundamental nature of water, still a mysterious substance, to the detailed mechanisms that determine the growth of hailstones or the way in which cloud seeding agents operate. **These are problems of discipline-oriented research. They need to be vigorously supported — as basic research — if environmental science is ultimately to achieve the position of a fully effective partner in man's efforts to live securely and successfully with his environment.**

INTERMEDIATE SCALE SYSTEMS

It is in the area of regional or local environmental systems that the major efforts of environmental science will be made. There are two reasons. First, the kinds of scientific knowledge and understanding that are necessary for a sound approach to the elucidation of global systems must come from thorough investigation of the subsystems which, taken together, form the global environment. Secondly, the subsystems of the environment are those with which man is most immediately concerned both for his economic and personal well-being. From severe storms to the natural or man-made ecosystems that sustain mankind, from fisheries to the condition of lakes and estuaries, from volcanoes to rainfall and water supplies the subsystems of the environment present a catalogue of major scientific challenges that will require heavy efforts and heavy expenditures by many nations and for many years to come.

It is of the greatest importance, however, if the most effective progress is to be made, that these problems be in fact treated as systems problems. Major examples include: the biome studies and ecosystem modeling efforts of the International Biological Program

(IBP); the Barbados Oceanographic and Meteorological Experiment (BOMEX), noted previously, of the Global Atmospheric Research Program (GARP); and the proposed Geochemical Sections Program (GEOSECS), to be undertaken as part of the International Decade of Ocean Exploration (IDOE) and to be addressed to sampling as many chemical substances as possible, from the surface of the ocean to the bottom, in the major ocean basins of the world. The magnitude that studies of this kind will frequently attain is well illustrated by BOMEX (Figure 4) which involved nearly 100 experiments performed by 1,500 scientists, technicians, sailors, and airmen, using 28 aircraft, 12 ships, operational meteorological satellites, two research satellites, buoys, and land-based facilities on the Barbados. This effort was primarily addressed to gaining a deeper understanding of air-sea interactions, an important determinant of the condition of the world's weather and oceans. **Many efforts of this type will need to be undertaken, if environmental science is to achieve the status required to match societal need. These efforts should be fully and enthusiastically supported.**

GLOBAL SYSTEMS

Approached at very general levels to include such characteristics as average carbon dioxide levels, total plant productivity, and total emissions of particulates, models of global systems can be relatively simple and still useful for determining overall constraints to human activity. **More detailed models of greater predictive power must await the development of better syntheses at the intermediate scale, even though global models are needed now to answer questions on the future effects of human action.** In the meantime, a number of global programs to improve the information base are already useful. Three major examples will serve to illustrate the value of such information, both in public service and in the advancement of science.

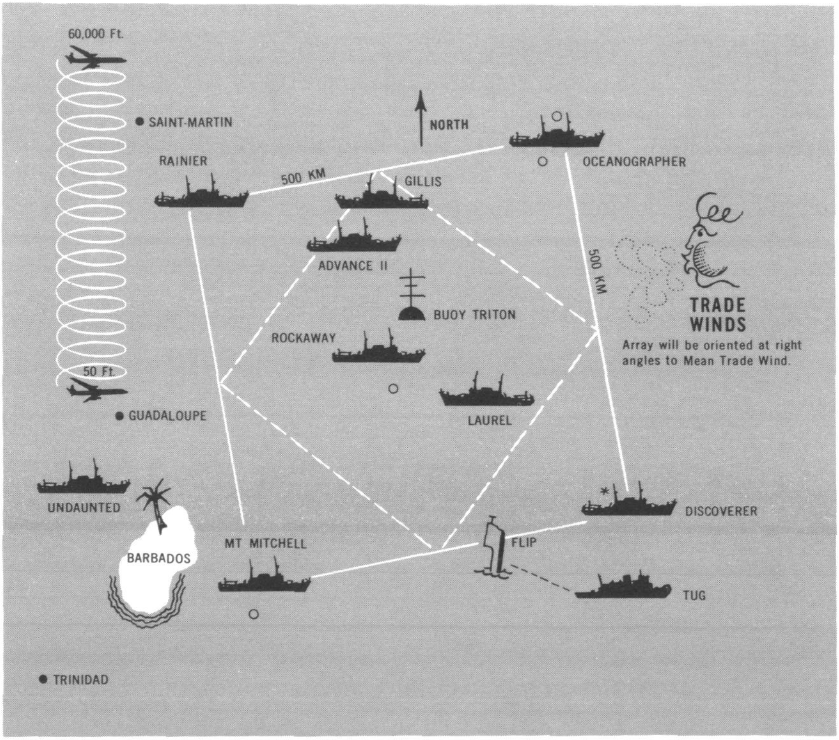
A highly successful international undertaking, under the direction of the World Meteorological Organization, is known as the World Weather Watch (WWW). This program is designed to pool the world's weather data and to make available to all nations the best weather forecasts that the present state-of-the-art can provide. It is a public service program, based on the applications of environmental science. This program will be improved as new scientific

NOTE TO FIGURE 4

Deployment for the 1969 BOMEX project. This figure represents the consequence of designing a group of experiments of sufficient scope and precision to test hypotheses and obtain useful new data from an intermediate scale system. The event is unique in human history. Of the four situations in environmental science represented by the four figures of this report, this one is the most "mature." This experiment was participated in by the Departments of Commerce, Defense, Interior, State, and Transportation, the National Aeronautics and Space Administration, Atomic Energy Commission, the National Science Foundation, the National Center for Atmospheric Research, and more than 10 universities.

Figure 4

INITIAL ARRAY FOR BARBADOS OCEANOGRAPHIC AND METEOROLOGICAL EXPERIMENT (BOMEX)



● Land Based Station
○ Current Stations
* Thermistor Array Moorings

Courtesy of the National Oceanic and Atmospheric Administration.

results become available, especially from GARP with which it is associated under the World Weather Program, and can be incorporated within it. It is not clear today that the types of weather observations that provide the input to this system are the best ones. There is reason to believe, for example, that certain types of data obtained by satellite may be more reliable, provide better coverage, and lead to a better scientific basis for global forecasts. When this and many other questions are resolved, WWW will be correspondingly strengthened.

A second program, one that appears to be exceedingly promising, is known in the United States as the Global Network for Environmental Monitoring (GNEM). Planning for this program is being conducted jointly by the United States, Sweden, and the Soviet Union, under the coordination of the International Council of Scientific Unions (ICSU). The program is based on the recognition that there is literally no long-term base-line information that can be used to assess changes in the world's climate, the state of the oceans, or the condition of life systems throughout the world. It is being proposed, therefore, to establish a limited number of monitoring stations throughout the world and to begin to collect the kinds of data that will help to resolve questions concerning the effects of man's intervention. This program is, in a sense, intermediate, between one designed to provide a public service and one of aid in environmental science. It should be strongly supported by the United States.

A third program, also international in participation, is that of deep sea drilling, already mentioned, under the general oversight of the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES). In addition to providing full confirmation of the theory of continental drift and seafloor spreading, this program has been extremely fruitful in uncovering information concerning deep seabottom sediments and minerals, including oil and gas in the Gulf of Mexico. It is a major source of information in environmental science.

As understanding of the environment and predictive capability increase, while at the same time population growth and associated demands and effects on the environment multiply, there will be constantly increasing pressures to manage the environment to the benefit of man, to modify or control elements of the environment (e.g., through weather modification, reduction of earthquake severity, etc.), and to mitigate many of the more subtle effects of man's interference (e.g., the effects of urbanization, other than pollution, on local or regional weather patterns, associated ecosystems, etc.). The corresponding technologies, planning approaches, and management techniques are ultimately dependent upon advances in environmental science. Simultaneously, however, they introduce a host of social, legal, economic, and political problems of the greatest difficulty. While three scales of future activity in environmental science have been noted above, it is also essential that major efforts be devoted to gaining needed insights into the structure, behavior, and needs of related social systems and institutions through increased emphasis across the social sciences.

V

Resources for Environmental Science

The fact that environmental science today is generally unable to match the needs of society for definitive interpretations or quantitative answers to pressing problems must ultimately reflect the priorities that society has placed in the past on the various activities of environmental science. These priorities can be judged from a review of present resources.

MANPOWER — THE CRITICAL RESOURCE

Information concerning scientists in the United States who are engaged primarily in research and development, the administration of research and development, or teaching in the natural sciences is available from recent surveys of the National Register of Scientific and Technical Personnel of the National Science Foundation. Thus in 1968 a total of 153,068 scientists could be identified with these activities **in all of the natural sciences.** They were working in 780 primary employment specialties of science. This same source contains a corresponding total of 68,032 scientists holding a doctorate. These totals were analyzed and divided into three groups: 87 specialties of Environmental Science, corresponding generally to the systems emphasis adopted for this report; 86 Applied and Supporting Specialties of Environmental Science; and 607 specialties of Other Natural Sciences. The definitions that generally form the basis for these three groups, together with the results of the analysis, are shown in Table 1.

Of special importance in Table 1 is the average number of doctorates per specialty, obtained by dividing the number of doctorates by the number of specialties for each of the three groups. Thus for Environmental Science, as interpreted in this report, the value is 46, smaller by a factor of 2 than the corresponding ratio for non-environmental "Other Natural Sciences." **The thinness with which**

NOTES TO TABLE 1

(1) Includes the Solar-Terrestrial System (aeronomy, ionosphere, aurora and airglow, solar physics, etc.), Climatology, Atmospheric Science (atmospheric dynamics, mesometeorology, micrometeorology, atmospheric electricity, etc.), Air-Sea Interactions, Oceanography, Biological Oceanography, Marine Geology (including ocean-bottom processes and shore and near shore processes), Solid-Earth Geophysics, Solid-Earth Geochemistry, Petrology, Sedimentology, Geomorphology (including glacial geology), Hydrology (including erosion and sedimentation; evaporation and transpiration; snow, ice, and permafrost; soil moisture; etc.), Ecology, Renewable Resources (including fish and wildlife, forestry, and range management), and Geography (excluding cultural geography, historical geography, military geography, and political geography).

(2) Includes many agricultural sciences, meteorological applications (including weather analysis and forecasting), exploration and extraction geology and geophysics, pollution sciences, mineralogy, paleontology, geodesy, instrumentation, etc.

(3) Includes, following the classification of the National Register, Chemistry, Earth and Marine Sciences, Atmospheric and Space Sciences, Physics, Mathematics, Computer Sciences, Agricultural Sciences, and Biological Sciences.

Table 1

SPECIALTIES OF ENVIRONMENTAL SCIENCE AND ASSOCIATED SCIENTISTS ENGAGED IN RESEARCH AND DEVELOPMENT, ITS ADMINISTRATION, OR TEACHING—1968

	Number of Specialties	Number of Scientists		Average Number of Ph.D.'s per Specialty
		Total	Ph.D.	
Environmental Science (1)	87	10,506	4,044	46
Applied and Supporting Specialties of Environmental Science (2)	86	12,516	6,185	72
Other Natural Sciences	607	130,046	57,803	95
Total Natural Sciences (3)	780	153,068	68,032	

Source: National Register of Scientific and Technical Personnel, National Science Foundation, 1968 survey.

this specialized manpower is spread across the activities of environmental science is further emphasized by the fact that the MEDIAN number of doctorates is 20 for the 87 specialties considered.

The number of doctorates has been given special attention, in spite of significant and extensive contributions made by those with lesser degrees, since the doctorate generally represents, by virtue of the nature of the educational process during its terminal years, the intellectual leadership in generating scientific advance. This is especially true today, because of the level of knowledge and understanding that has been attained in all of the basic contributing disciplines that necessarily form the underpinning for such advance. The number of doctorates has thus been chosen as an important index of resource status.

Two-thirds of the 4,044 doctorates reported in environmental science were employed in colleges and universities. The distribution is the following:

	Percent of doctorates
Colleges and Universities	68
Governments	20
Other (largely industry)	12

In spite of this heavy preponderance in academic institutions, there are significant concentrations in some specialties within government (especially renewable resources, geophysics and geochemistry, atmospheric science, and the solar-terrestrial system) and within industry (particularly geophysics and geochemistry, and the solar-terrestrial system).

Another dimension of this distribution among types of employers, probably the most significant aspect of the manpower situation in environmental science, is demonstrated in Table 2. Adopting the generally held view that a high quality organization in research and development generally requires a "critical size" or minimum number of scientists, communicating with each other, and arbitrarily choosing 7 as this number, the **maximum possible number** of such groups of doctorates has been determined for each of the 87 specialties included in environmental science for the three principal employer types. **Thus in 19 specialties no group of "critical size" could have been formed in 1968 in colleges and universities,**

while for 63 specialties this situation existed in government and industry respectively. However, these results are optimum, since in the situation actually prevailing the scientists in these 87 specialties were distributed among many universities, many government agencies, and many industrial corporations and research organizations. The distribution shown in Table 2 clearly confirms the existence of a severe manpower shortage in environmental science and a scattering of resources throughout the Nation, a circumstance that strongly reflects employment opportunity and hence public priorities.

That the situation described above is beginning to correct itself is suggested by comparing the 1968 and 1970 surveys for specialties that retained their identity. Apart from the solid-earth sciences, where a change of structure and nomenclature precludes the comparison, it was possible to examine changes between 1968 and 1970 for 66 of the 87 specialties of environmental science:

	Percent Change
All scientists	+11
Doctorates	+18

These changes, noted for a two-year period, are the result of several causes. First, they reflect growing numbers of persons completing their academic training, especially doctoral, in aspects of environmental science. Secondly, they result from significant numbers of scientists who changed their fields of work and entered environmental science as the employment situation deteriorated in their original occupations. Thirdly, the indicated growth may be overstated because of the choice of a different name of employment specialty by a respondent to conform to the growing popularity of certain areas of environmental science, while no change occurs in the nature of the work performed. This is especially true for many biologists, biological oceanographers, and others who choose Ecology as the generic expression to describe their work.

It is noteworthy, however, that the number of doctorates in environmental science appears to be increasing more rapidly than the total number of scientists. This trend has been especially strong for a number of specialties that only recently have begun to receive substantial support, notably those related to the atmosphere and the oceans.

NOTES TO TABLE 2

(1) This tabulation is based on the proposition that in general a research group of high quality will contain at least seven members as a "critical size" (See the report *Graduate Education—Parameters for Public Policy,* NSB 69-2, issued by the National Science Board in 1969).

(2) Obtained by dividing the number of *doctorates* in a specialty by 7. Thus, for example, of the 87 specialties identified with environmental science, there were in 1968 sufficient doctorates, engaged in research and development or teaching in colleges and universities, in 29 specialties to form only *one* group of critical size each, provided that the scientists associated with a single specialty were located in one place. In fact, however, these scientists were scattered among a number of colleges and universities.

Table 2

MAXIMUM POTENTIAL NUMBER OF GROUPS OF CRITICAL SIZE ENGAGED IN RESEARCH AND DEVELOPMENT, ITS ADMINISTRATION, OR TEACHING IN ENVIRONMENTAL SCIENCE—DOCTORATES DISTRIBUTED BY TYPE OF EMPLOYER—1968 (1)

Maximum No. of Groups of Critical Size (2)	Number of Specialties		
	College or University	Government	Other
0	19	63	63
1	29	12	16
2	12	7	5
3	7	2	2
4	3	0	0
5	3	0	0
6	3	0	0
7	2	0	0
8	0	0	0
9	1	0	0
10 or more	8	3	1
	87	87	87

Source: Based on information from the National Register of Scientific and Technical Personnel, National Science Foundation, 1968 survey.

Manpower shortage is not confined to those needed to provide the science base, to conduct environmental research, and to generate systems understanding. As the science base is established, the need for technicians, engineers, and administrators to implement policy and programs also becomes greater. **The function of government, in relation to questions of environmental management, is largely to legislate policy and to administer the application of controls. Such an administrative role for government requires knowledgeable scientist-administrators.** They must be sufficiently trained in science to be perceptive of the characteristics of theory and data base resulting from research. They must be perceptive too of the political and sociological environment within government. They should have formal education in the social sciences, law, and administration, as well as in science. A specifically trained "science-natural resource" administrator is thus needed. This should be a person who would operate at the final implementation level of mission agency policy regarding the environment. The education of these persons can be accomplished in two ways: by adding the natural sciences and science policy to the curricula of schools of public administration, and by expanding the programs of engineering schools to include the social sciences and elements of public administration.

FUNDING FOR ENVIRONMENTAL SCIENCE

With the present situation regarding scientific manpower in environmental science, where essentially all manpower appears to be gainfully employed, funding specifically to cover the costs of personnel in environmental science has generally matched the need. The total manpower, however, is increasing. Whether the influx of this additional, needed manpower occurs through education or through transfer from other activities, it creates new opportunities for the funding of environmental science.

Many of the scientists who contributed to this study, however, expressed the judgment that it is more difficult than it should be to obtain adequate funding for facilities and specific items of major equipment and for the logistics necessarily associated with their use. This observation applies particularly to such matters as oceanographic ships, specifically designed for the purpose, radars of several types, surveillance aircraft and associated instrumentation, expeditions, surveys and monitoring arrangements, and many others. One of the major achievements of recent years has been the advent of new and powerful instrumentation that should be brought to bear as quickly as possible on pressing measurement needs of environmental science. **It is a poor economy to encourage highly trained and qualified personnel to enter this field of work without ensuring the essential tools that can help to expedite progress.**

THE ORGANIZATION OF ENVIRONMENTAL SCIENCE

The large number of specialties among the contributing sciences, the small number of scientists in many of these, and the wide dispersion of individuals among the universities, agencies of government, and industry raise formidable problems whenever and wherever "critical size" is required for work on environmental systems. Research programs such as those of the IBP and GARP require extraordinarily complex institutional arrangements among many universities, agencies, and industries.

Types of Arrangements

Within universities the interdepartmental nature of environmental science ensures an awkward relationship with discipline-oriented research. Neither the institution nor the individuals can tolerate excessive crossing of boundaries, and interdepartmental arrangements usually fail to incorporate the mix that is needed for study of environmental systems. One possible benefit on a national scale is that different schools achieve different mixes. On the whole, however, the total number of strong programs in environmental science is indeed small. Although the Nation has approximately 200 universities awarding doctorates in science and engineering, none of the following areas is well developed in more than 20: meteorology, oceanography, system-level ecology, geophysics, geochemistry, and hydrology.

Scientists in government are divided among State and Federal agencies. At both levels many excellent research teams are found that work in soil science, geology, forestry, and fisheries and wildlife. It is fair to state, however, that most of these teams are fully occupied with the problems of resource development, long-term maintenance, and protection of the public interest. Their concern is with environmental management, and the needs are so intense that little effort can be devoted to environmental science. Fortunately, these particular areas are also well developed at many universities, where more basic aspects of environmental problems can be pursued.

Scientists in industry, as noted previously, have flourished where their interests are needed. Most of the Nation's research in petroleum geology, fertilizer processing, and pesticides takes place in industry. More recently industry has taken the lead in the employment of scientists in the specialties of air and water pollution. Research teams in industry can be tightly organized to work on well-defined problems. Their major concern, of course, is with the health of industry, and with the technological means for reducing the societal costs to which the public and government object.

In summary, although most environmental scientists are in universities, they are divided among many schools and many departments where problems of organization are severe. Although such problems may be less difficult in government and industry, each has a "critical size" of competence in only a few areas.

> The end result is that ENVIRONMENTAL SCIENCE is poorly organized. On the campus it is difficult to maintain any organization at all. Among the Federal agencies a duplication of effort in environmental science tends to develop as each agency pursues its statutory mission. In industry the emphasis is usually on traditional science and technology. Even in companies strong in systems research the fight for survival generally means contracts and industrially-oriented research, rather than the long-term, large-scale view of natural systems.

Poor organization has led to several penalties in environmental science. Standards of performance vary from organization to organization and from field to field. Duplication of effort tends to occur, even in different departments on the same campus, but more seriously in different departments or agencies of State and Federal governments. Finally, information systems, such as mapping surveys and monitoring programs, often fail to collect the most useful kinds of information. Indeed many information systems are finally designed with little input from potential users.

If environmental scientists were twice as numerous, and if the total level of support were correspondingly greater, more rapid progress could be anticipated in the solution of environmental problems. For the 1970's, however, neither the manpower nor the levels of support can confidently be expected to increase by this large a factor. Thus, better organization emerges as the primary means by which significant progress in environmental science can be made within a decade.

How the organization of environmental science should be improved depends strongly upon the nature of the scientific problem itself. Here again the differences among environmental problems must be stressed. For all of them, however, some degree of disciplinary science, applied science, technology, and institutional change are necessary. If this is all that were involved, the recommended organization would be one that is strongly problem-oriented, with teams embracing each of the above aspects, combined in many ways in many places, and each with a well-defined environmental problem to solve. Indeed, many such efforts are already underway as a part of the effort to improve the human environment.

There remains, however, an extensive set of problems whose solutions require major advances in environmental science, namely, the SCIENCE OF ENVIRONMENTAL SYSTEMS, as defined in this report. Furthermore, any serious program in technology assessment, environmental protection, or environmental forecasting requires the strength that can be developed only from the advancement of such environmental science. For all of these needs the science itself is relatively universal, in the sense of being common to many types of problems. It is THIS kind of science that is so woefully inadequate for present societal needs, so difficult to organize, and so likely to remain undone. An immediate and intensive effort must be made to foster management organizations for research in environmental science that facilitate teamwork, concentrate on thinly-spread manpower, and promote the conceptualization of environmental systems.

Governments at the local, State, and national level have responded rapidly to the sense of environmental crisis, creating a variety of new institutions. Most of these are oriented to problems arising from pollution, or to those associated with resource allocation. They are directed more to the applications of science than to its development, and more to the solution of well-defined individual problems than to broad-scale advances in the basic scientific capability for solving such problems. **These immediate efforts are important and necessary developments if man is to improve relations with his environment, but they are not sufficient to ensure long-term or permanent gains.**

A Federal mechanism is also urgently needed specifically to provide for the promotion and support of environmental science as a whole. Such a mechanism should be responsible for ensuring that the knowledge, understanding, and predictive power concerning environmental systems be developed in accordance with perceived needs to solve environmental problems and to improve human welfare. Such an activity would supplement, not duplicate, those of organizations concerned with the managerial aspects of the environment or with the forecasting of environmental events. By being responsive to their priorities, however, such a mechanism would speed the development of the scientific tools that these institutions require.

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