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Section 6

IMPACTS OF REGIONAL CHANGES ON CLIMATE AND AQUATIC SYSTEMS

Charles Cooper, Team Leader

Pedro J. Depetris
James Ehleringer
Richard Fisher
Stuart Hurlbert
Stephen Schneider
Jay Zieman

I. Introduction

Man lives on a finite earth. Neither the full range of opportunities and alternatives nor the ultimate limits to his use of that earth are yet known. It is increasingly clear, however, that land, water, and atmosphere are intimately linked through complex biological and geophysical processes without respect to national political boundaries or even to continental limits. "Action at a distance" is indeed an accurate metaphor to describe the interregional and international impacts of one major ecosystem upon another.

Better understanding of regional ecosystem interactions can be of substantial help in private and governmental planning to maximize the contribution of natural resources to human welfare. For example, multidisciplinary studies of Lake Maracaibo, Venezuela, and its environs (Rodriguez, 1973) have shown that this highly industrialized tropical water body can be managed to maintain its biological productivity despite the perturbations of the oil and petrochemical industries. The oil industry in the Maracaibo basin yields a present economic return some 180 times that of the lake's fishery, yet the latter supports a significant number of people from lower income groups. The problems stem not just from oil pollution but also from complex changes in inflow and outflow patterns of lake water due to dam construction on its tributary streams and to navigation control structures at its meeting with the sea.

Rodriguez and his associates have shown how ecological analysis can suggest relatively minor changes in the operation of the dominant industry and its associated engineering works that will improve the fishery at relatively low cost. These changes involve not only the obvious actions to reduce the size and frequency of oil spills (their total elimination is virtually impossible in a lake producing more than three million barrels of oil daily), but also revision in placement and operation of water control dikes. Minor alterations in the plans for these dikes, yet to be built and intended chiefly to aid navigation, can result in current and salinity patterns benefiting rather than harming the fishery. Multidisciplinary ecological research can aid in reconciling industrial development and biological productivity.

Applied ecology in a regional setting involves four principal steps: (a) to identify the ecological perturbation and its cause, (b) to determine how to predict the long- and short-term consequences of the perturbation, (c) to apply the prediction to the formulation of regional plans, and (d) to define government action to enforce the regional plan and regulations.

Our concern here is with the first two of these steps. We have endeavored to identify major geophysical processes on a regional or continental scale which have significant biological implications. We have also attempted to define important actions of man likely to have a substantial ecological effect, beneficial or detrimental, on other regions or nations.

We first consider some of the major biogeochemical relationships in tropical freshwater, estuarine, and coastal ecosystems. Particularly important is the dependence of coastal and estuarine ecology upon terrestrial processes. Man's industrial and agricultural activities often upset natural relationships. The results are usually categorized under the broad headings of pollution and overexploitation. We give particular attention to problems of pollution in the near-shore marine environment. Questions of overexploitation of coastal fisheries, important though they are, have been treated extensively elsewhere (e.g., Rothschild, 1972) and will not be further considered here.

In reality, many widespread human diseases are ecological problems where regional land-water interactions are paramount. A case in point is schistosomiasis, which despite its importance in many tropical regions is uncommon in the Amazon Basin because of the local ecological context. Changes associated with accelerated development could, however, drastically alter the present favorable situation.

The worldwide circulation of the atmosphere rapidly carries material to distant regions. Little is known about prospects for alteration of tropical vegetation and soil through man-induced changes in atmospheric chemistry. Deliberate weather modification through cloud seeding may enable man to influence tropical precipitation amounts and hurricane intensities. This could have substantial ecological consequences. Of far greater long-term importance, however, is the possibility of global climatic change.

The region between 30° North and 30° South receives more than half of the incoming solar radiation driving the earth's climate. The possibility needs to be evaluated that man's activities, e.g., changing the turbidity of the atmosphere, altering regional evaporation patterns, modifying surface reflectivity, may generate large-scale and possibly irreversible changes in global climate.

Finally, advances in remote sensing and in computer simulation offer prospects for a major advance in our capability to predict, from regional climatic and soils data, the ecological capabilities of relatively remote regions, their resistance to stress, and their suitability for intensive human exploitation.

Perhaps most important of all regional ecological interactions, however, are those involving the flows of money, raw materials, finished products, people, and information between the tropics and the temperate zones. These problems have not been treated here, but the need for their study is acknowledged.

II. Recommendations for Research

1. Land and water are intimately linked through complex biological, geological, and geophysical processes. Interdisciplinary research is urgently needed to determine more fully the nature of these processes and the magnitude of their effects: (a) Expanded studies of the biogeochemistry of major tropical drainage basins are required to establish the initial physical, chemical, and biotic characteristics of their streams and associated estuaries. This information is needed as a basis for assessing the direction and magnitude of change under man's influence. Experimentation, inc'uding model building, should be undertaken to improve knowledge of the relative importance of environmental factors controlling the ecology and geochemistry of tropical rivers. Comparative studies of this sort should be started in relatively small watersheds, and then extended into larger tropical drainage basins. Hydrological, geochemical, and sedimentological studies should be carefully integrated with ecological research in the planning of such investigations. (b) Tropical estuaries have extremely low concentrations of nutrients and extremely rapid and conservative recycling mechanisms. The effects of added nutrients on these systems should be studied in more detail as the effects are apt to be different than in temperate estuaries. (c) The relative roles of various energy sources such as mangroves, algae, and river-borne detritus in tropical estuaries should be established, with particular emphasis on the effect of perturbation of these sources on food webs and fish yields. Similarly, there is a need to determine the detailed effects of alterations in fluvial regimes on the productivity of rivers, lakes, marshes, deltas, and estuaries. Such alterations may result

either from dam construction or other forms of river regulation, or from natural or man-induced climatic fluctuation. (d) Marshes, other wetlands, and running-water ecosystems in tropical regions are important to the ecology and food resources of distant lands as well as to the local area. Field studies should be undertaken to determine the quantitative importance of such systems for production and support of pelagic fishes and of waterfowl and other birds that migrate between continents and as habitat for resident birds and mammals.

2. Many currently recognized ecological problems are the consequence of large-scale human perturbations whose effects are felt at a distance. Among these are the transport of agricultural and industrial chemicals to distant estuaries, and engineering structures altering natural water flow patterns. (a) Additional research should be directed toward more fully establishing the acute and chronic limits of aquatic and estuarine organisms toward pollutants (e.g. pesticides, heavy metals), temperature, and wide fluctuations in ambient conditions, such as the effects of recurring droughts. Since it appears that many tropical aquatic and estuarine organisms normally exist closer to their tolerance limits than do most temperate counterparts, special attention should be given to rates of acclimatization of tropical organisms to changed conditions. (b) Hypotheses should be tested concerning the differential rates of food consumption, pesticide storage, excretion, and enzymatic degradation and the food chain concentration of pesticides in temperate and tropical organisms. The results will permit more valid extrapolation of existing temperate zone knowledge of pesticide-ecosystem relations to the tropics. (c) Expanded investigations should be made of tissue concentrations of organochlorine insecticides, PCBs, and selected heavy metals in carnivorous birds (pelicans, cormorants, hawks, owls, vultures) and of commercially important tropical fish species (both freshwater and marine). In regions where body loads of these pollutants are high, investigation of the possibility of declining reproductive success of these animal populations should be immediately initiated. (d) The influence of thermal and mixing regimes characteristic of tropical lakes and reservoirs on the circulation and biological effects of pollutants should be studied so that information that has been obtained in the temperate zone may help solve tropical problems. A similar comparison should be made of the nature of eutrophication in tropical versus temperate waters, fresh and marine. (e) Governments should require pesticide importers, distributors, manufacturers, growers, and international agencies to regularly submit exact information on importation, sales, uses, and use rates on a compound-by-compound basis. These data should be made public and published in conveniently accessible documents. Similarly, it is highly important that data on water quality be made readily available to the international scientific community. Where political or institutional barriers to the dissemination of the relevant

data are evident, scientists in the nations concerned should endeavor to point out the advantages of free exchange. (f) Before major modifications of shoreline physical conditions or of river flow regimes are undertaken, careful study be given to their probable effect on longshore current patterns, littoral drift, and sediment accumulation or erosion.

3. An intergovernmental committee should be established to explore the desirability, feasibility, and structure of a monitoring program designed to determine the sources and distribution of (a) organochlorine insecticides, (b) PCBs, and (c) selected heavy metals in a limited number of species widely distributed along the Pacific and Atlantic coasts of tropical Americas. Possible organisms might be (a) the sand crab *Emerita* sp. whose residue levels can serve as an excellent indicator of local pollution problems (see Burnett, 1971); (b) the mullet *Mugil* sp., which utilize estuaries and lagoons as nursery and feeding areas (they also move up and down coasts and their residues therefore might indicate pollution problems significant on a regional scale); and (d) the anchovy *Anchoa* sp. whose residues might serve as an index of pollution levels further off the coast. Such a monitoring program should be coordinated with any worldwide program that may be instituted under United Nations or other auspices.

4. Each coastal nation undertake a program to classify its estuarine resources on the basis of sound management and ecological considerations. Such a classification should delineate areas that should be reserved for heavy industrial development, those that are suitable for multiple use and those to be maintained as scientific preserves.

5. Many widespread human diseases can be dealt with most effectively as regional ecological systems in which land-water interactions are paramount and in which social, economic, demographic, political, agricultural, industrial, chemical, geological, and climatic factors all have strong influences. These disease systems should lend themselves well to a modeling approach. (a) Analysis of these disease systems should focus on large-scale regional aspects and particularly on how changes in regional demographic and land-use patterns affect aquatic ecosystems to the benefit or detriment of the aquatic vectors and hosts of disease organisms. (b) A critical review should be undertaken of the possibility that man will inadvertantly raise water pH, increase aquatic vegetation, and reduce populations of fish and other natural enemies of snails, accelerating the spread of schistosomiasis in the Amazon basin. Studies should be undertaken on water chemistry and dietary requirements of host snails, on their dispersal and migratory behavior, and on the role of natural enemies in controlling their populations. Information on these topics is prerequisite to realistic modeling efforts. (c) In many tropical regions, coordinated surveys should be taken of the present status of water-related public health problems, of aquatic populations (especially vertebrates), of river and lake hydrology, and of the physical-chemical characteristics of

the water in drainage basins presently being or soon to be subject to significant alteration by man. Such surveys can anticipate the kinds and magnitudes of problems that may develop and provide standards to measure and keep track of man's influence, favorable and unfavorable.

6. Increasing industrialization in tropical countries may well bring increased air pollution, particularly if high-sulfur fuels should predominate. Likewise, deliberate modification of weather for human benefit may eventually become feasible in the tropics. Both of these possibilities present important research problems: (a) An assessment of potential ecological consequences based on explicit consideration of local climate, plants and animals, land use, and patterns of human activity in the area of application should be made before initiating cloud-seeding programs to increase or decrease precipitation or to reduce hurricane intensity. (b) Additional research is needed to define the effects on native and introduced plant species of air pollutants generated by accelerated industrialization in tropical regions. (c) Additional research should be undertaken on the effects of large additions of sulfate on the chemistry of tropical soils and on the chemistry of heavy metals, both natural and as contaminants, in tropical soils.

7. Tropical ecosystems play a significant role in global climate, but the quantitative aspects of atmosphere-ecosystem interactions are largely unknown. Smoke and other particulate matter from tropical vegetation affect the turbidity of the atmosphere. Tropical ecosystems, particularly forests, help to regulate atmospheric carbon dioxide. Changes in vegetation cover may alter the global heat balance. Expanded collaborative research should be undertaken by ecologists and atmospheric scientists to obtain better quantitative data on ecological processes that influence climate: (a) Field research and simulation modeling are needed to determine more accurately the annual and seasonal evaporation and transpiration rates from extensive areas of various types of vegetation, natural and man-modified, in tropical lowlands. Only on the basis of such information can the magnitude and direction of any possible impact of major land-use changes on the global energy balance, and the resulting climate, be estimated with reliability. (b) Improved estimates of production rates, size distribution, and mean residence times of particles entering the atmosphere from burning of agricultural and forest wastes, including site preparation in shifting cultivation, should be made. Remote sensing at both thermal infrared and visible wavelengths is likely to prove useful in this respect. (c) Regular monitoring of the total biomass, and hence carbon storage of tropical forests, grasslands, and agricultural crops is needed. Multispectral remote-sensing methods are in prospect by which earth-resource satellite observations can be used to map the spatial distribution of biomass, chlorophyll, and leaf water.

8. The geographic scale and the large number of data points required for studies of ecosystem-atmosphere interactions virtually compel extensive use of numerical simulation and related mathematical methods. Ecologists should become more aware of current developments and applications in synthetic climatology and climatic modeling. Communication should be improved between ecological and atmospheric modelers. Many atmospheric scientists have little understanding of the problems inherent in situations lacking close relationships to physics, whereas biological scientists often feel that the parameters necessarily used by atmospheric scientists result in excessive oversimplification. Specifically, (a) Atmospheric scientists should be encouraged to continue efforts toward development of a spectrum of climatic models, including those that incorporate biological variables. Such models will permit more quantitative estimation of the possible impact on local and global climate of perturbations of the energy balance by modification of tropical ecosystems. (b) Atmospheric modelers and tropical ecologists should cooperate to devise a series of simulation experiments that can be performed with existing global climatic models. (c) Improved models of local and regional energy balance in the tropics should be designed to yield time-dependent estimates of potential and actual transpiration, soil moisture, transpiration deficit, and other ecologically significant variables. It may be desirable to base the models on synthetic as well as measured climatic data. Research should be undertaken to relate the resulting climatic estimates to observable characteristics of tropical ecosystems, using multivariate and other mathematical methods. This will result in improved procedures for expressing the environmental factors governing ecosystem structure and function, and for relating these factors to the observed properties of natural and man-modified ecosystems.

9. Modeling and prediction of ecosystem-atmosphere interactions will impose requirements for both climatic and ecological data on a greatly expanded scale Therefore: (a) Cooperation should be improved between ecologists and atmospheric scientists concerned with global climatic measurements. Specifically, operations planners for the forthcoming Global Atmospheric Research Program (GARP) should be encouraged to incorporate ecologically important data into their program without jeopardizing the primary GARP objectives. For example, climatic measurements taken at a terrestrial location of interest to ecologists could be incorporated into the data net for the First GARP Global Experiment (FGGE), planned for about 1978. Interdisciplinary cooperation of this type implies establishment of an ecological advisory committee to GARP. (b) Designers of meteorological and climatological satellites should be encouraged to accelerate the development of methods for improved acquisition and retrieval of ecologically important climatic data by remote-sensing methods.

III. Ecological Impact of Technology on Aquatic Ecosystems

A. Biogeochemical Relationships

Rivers are the major pathways for transferring dissolved and suspended materials from the continents to the oceans. The introduction of these phases into the marine environment has sizeable impacts on the chemical composition of estuarine and coastal waters, and upon the concentrations of particulate matter in the sea and the mineral composition of sea-floor sediments. Clearly, the magnitude of the effect on the near-shore environment is a function of the fresh-water volume introduced by any particular drainage system. River influences have been observed hundreds of kilometers from the coast (Griffin et al., 1968; Goldberg and Griffin, 1970). Since tropical rivers are the largest source of fresh water entering the ocean (the Amazon River alone supplies 20 percent of all the river water discharged into the oceans) their impact on the marine environment is by far the most important.

The ecological characteristics of rivers are a function of the diverse interdependent environmental factors of their drainage basins, such as climate, biota, geology, relief, and soil types. Some of these factors are under variable stress induced by man's activities. Little is known about the role played by each variable in controlling biological and geochemical characteristics of tropical rivers.

Processes in rivers have their corresponding response in estuarine and coastal zones. In tropical regions, for instance, rivers transport large amounts of organic matter, such as floating vegetation and detritus. Most of this material moves during seasonal floods, when the plants are flushed from their natural environment, viz., ponds and marshes, into streams and rivers. This organic debris is largely responsible for the high productivity of estuaries.

Odum (1970) identified five important characteristics of the estuarine environment: (a) the nutrient-trap effect, (b) the unique structure of estuarine webs, (c) the harsh nature of the physical conditions and the resultant vulnerability of the estuarine organisms, (d) sedimentary control of estuarine waters, and (e) the key role of fresh-water inflow.

The nutrient-trap effect is due to a series of factors. The minerals carried into the estuary are usually deposited as the river widens and velocity decreases. In tropical estuaries the typical sedimentary discharges are clay-sized particles. The circulation of the estuary carries many of these particles out on the ebbtide and returns them on the flood. These clay particles have a high capacity to adsorb chemicals, including nutrients. Unfortunately this great sorptive capacity allows the estuary to act as a pollution trap, since pesticides and heavy metals are also adsorbed. At certain salinity levels, the electrical charges on the particles change and the nutrients—or pollutants—are released.

Tropical estuaries are usually biologically more diverse than their temperate counterparts, but they have very short food chains, which are primarily detritus-based as opposed to grazer-based. The organic detritus comes from river input from the bordering mangrove swamps and the input from tropical sea grasses, such as turtle grass *(Thalassia testudinum)*. The history of this plant illustrates the consequences of overexploitation and near extinction of a formerly abundant grazer and the conversion of a grazing food chain to a detrital system. Formerly, the vast turtle grass beds of the tropics were grazed by large herds of green sea turtles. Since the demise of these large herbivores, most of the production of this plant is not grazed and goes into the detritus food chain (Wood et.al., 1969).

The estuary is an extremely harsh environment for most organisms. It is an ecotone, a border community between the river (and land) and the sea, and is usually more productive than the river or sea. It has many of the properties of both neighboring systems as well as its own unique characteristics. It is a stressed environment, where physical parameters vary rapidly over short time spans and the organism must be adapted to handle these changes. It is, in the classification of Sanders (1969), a "physical-dominated" community, where the physical parameters and their variation are far more important in determining the communities present than classical biotic competition. These are important points since in the tropics biota live much closer to their lethal points than their temperate counterparts, with the result that small physical disturbances have a far greater proportional effect than in the temperate zone (see Moore, 1972).

The relative shallowness of many estuaries and the proximity of the sediments to the entire water column is partly responsible for high estuarine productivity. Bacteria in the sediments drive rapid regenerative mechanisms for the turnover of nutrients, such as compounds of nitrogen and phosphorus.

The fresh-water input sustains the salinity gradient defining the estuary. The middle zones of tropical estuaries are vital nurseries of many important animal species. Comparatively few organisms can survive in this section of the estuary, where conditions vary the most rapidly. Therefore, those organisms that can survive here, such as juvenile shrimp and mullet, face less competition for survival and less predation.

This brief review of the essentials of estuarine ecology, with emphasis on points of particular importance in the tropics, has shown that some mechanisms are quite susceptible to external alteration. Environmental changes often take place in concert, such as simultaneous changes in salinity and temperature regimes. Stressing an organism by modifying one parameter often lowers its tolerance for perturbations of all other parameters. This should be remembered in considering specific perturbations of the tropical estuarine environment.

B. Effects of Altered Water Regimes

1. Changes in flow

Seasonal flow patterns of rivers are mainly changed by the construction of dams and channels for irrigation and power generation. Significant changes in the watershed vegetative cover also have profound influences on the hydrologic behavior of streams and rivers.

The results of these man-induced changes are usually either a reduction or a sharp increase in the supply of silt and nutrients to downstream environments or a change in river dynamics. Both effects have profound impacts on biological activity in rivers, marshes, deltas, and other aquatic environments. Large areas in tropical river flood valleys, such as wetlands and ox-bow lakes, where highly productive ecosystems are located, are normally subject to an annual flood period. The amplitude and regularity of flooding is of the utmost importance in these "fluctuating water level ecosystems" (Odum, 1969), where communities are adjusted to the pulse of seasonal variations in water levels. Decreased water flow can also cause several pollutants, such as excess heat, particulate matter, industrial and domestic wastes, etc., to reach undesirable levels. Although we understand these specific effects, the rearrangement of hydrological patterns, such as the proposed creation of a series of man-made lakes that would interconnect the Orinoco, Amazon, and Rio de la Plata Basin in South America (Panero, 1967), will result in such large-scale changes that the ecological consequences cannot be predicted from current information.

The normal estuarine salinity distribution is a function of many factors, including tidal volume, circulation pattern, morphology, and fresh-water input. The variation of the fresh-water input to an estuary can produce profound changes on the biota. Reduction of fresh-water influx will cause the estuary to become more saline, advancing estuarine organisms into the formerly fresh-water zone. Effects on biota can be direct or indirect. When the fresh-water flow to the Everglades National Park was reduced, salinity increased in the estuary, and the area covered by mangroves increased 70 percent in less than 20 years. At the same time, the shrimp fishery in Florida Bay was damaged because juvenile shrimp were not able to detect the greatly diminished streams of low-salinity water emanating from the lower estuary. The young shrimp were therefore unable to find their optimal nursery grounds.

Changing the fresh-water inflow can also have profound effects by changing the stratification regime of an estuary. Reducing the fresh-water flow can allow more tidal mixing, whereas the increase of river-flow rates will tend to produce a more stratified, two-layered system. Obviously, a shift to a fresh-water regime will favor certain biota over others, reducing the ability of a community to withstand a "normal" drought (Heald, 1970). A less obvious change involving the true estuarine organism is that those inhabiting intermediate salinity water where rapid salinity change happens with each tide, will also shift distribution.

2. Changes in salinity

Changes in river flow can sometimes increase the salinity of river systems by concentration of natural dissolved loads by evaporation during the process of water recycling, or by raising the contribution of highly saline tributaries in the total flow of certain tropical drainage systems.

Salinity effects can also be subtle and cumulative. Lake Maracaibo was a fresh-water lake with a productive fishery. The opening of the navigation canal allowed the gradual accumulation of a layer of higher salinity at the bottom of the lake causing displacement of the normal fresh-water biota and the decline of the fresh-water fisheries. As noted in the introduction to this section, a number of engineering solutions to alleviate this situation and reduce the maintenance requirements of the navigation system are being considered.

Salinity changes of only a few parts per thousand usually have less effect on estuarine organisms than other variables (e.g., temperature) since variations in salinity are a part of the daily tidal fluctuation of the estuarine environments. Pronounced changes can be traumatic, however. Induced salinity changes are often accompanied by other undesirable environmental modifications, such as the effluents of a desalination plant, which are usually hypersaline (40 to 60 percent) and hot. Their increased density causes them to remain on the floor of the estuary with a large potential for ecological damage to the sessile organisms. In addition, the effluent may contain high concentrations of heavy metals. Sea-salt refineries introduce extremely hypersaline water (> 100 percent). Cintrón, Maddux, and Burkholder (1970) recorded stagnation, severe anoxia and accumulation of H_2S resulting from the effluent of a "salina" in Bahia Fosforescente, Puerto Rico. This caused extensive mortality of fish and estuarine invertebrates.

3. Thermal loading

Severe potential damage to the tropical coastal marine ecosystems is caused by increased thermal loading from the cooling effluent of electrical generating stations and certain industries. This is a particular problem in the tropics since tropical estuarine biota live much closer to their thermal maxima than their temperate counterparts (Moore, 1972). Biebl (1964) has shown that the thermal death point of marine algae in Puerto Rico is only 4 to 6°C above the average summer maximum whereas on the north coast of France the upper thermal limit is 10.5 to 13.5°C above the average summer maximum. Recent studies demonstrate that raising the temperature of tropical estuaries only 1 to 2°C can have a strong impact on the normal communities and the raising of the ambient only 3°C can destroy most of the biota of a subtropical estuary (Zieman and Wood, in press). Evidence is emerging that the optimal water temperature, even in tropic regions, is 30°C or below.

Increases in water temperature decrease the solubility of oxygen and therefore its concentration in water. At the same time the respiration of most biota is increased. This combination adds an additional stress to the system. In temperate regions, if temperatures are raised and the normal biota displaced, there is the possibility of replacement by more heat-tolerant forms from lower latitudes. In tropical estuaries there is no further source of higher heat-tolerant organisms tolerant to still higher temperatures. When the normal biota are destroyed by heat, they are usually replaced by heat-tolerant blue-green algae, which are sometimes directly toxic, or which may lead to ciguatera, an extremely severe poison concentrated in the higher trophic levels in marine tropical areas (de Sylva and Hine, 1970).

The vast columes of cooling waters of nuclear-power plants have reached the point where the circulation induced by the pumping of cooling water can overpower the normal estuarine circulation in areas where the tidal prism is small (Zieman and Wood, in press). This is not yet known to have happened in tropical estuaries, but may well occur as nuclear-power generation becomes more widespread. Because tropical marine forms are already near their thermal limits, there appears to be far less potential than in temperate regions for making constructive use of waste heat in mariculture or other schemes to increase biological productivity.

The discussion above has centered on marine and estuarine forms, as there is no information available on tropical fresh-water biota and their heat tolerance. It is to be expected however, that they will show the same problems of upper temperature lim'ts as their marine and estuarine counterparts.

4. Suspended material

The increase of sediment load of rivers and estuaries is one of the major impacts of development. It has a variety of causes, and the effects of this increased sediment load on the biota of aquatic environments are many and varied. As development of the tropical river and coastal areas proceed, sedimentation will increase.

Suspended sediment concentrations on some major tropical rivers seems to be mainly controlled by relief. Gibbs (1967) showed that 82 percent of the total suspended sediments removed from the Amazon Basin was supplied by the Andean portion of the drainage. Rivers such as the Negro, Tapajos, or Xingu, with basins developed wholly within Amazonia lowlands, have very low suspended-solids concentrations and, hence, very low erosion rates—10.0, 3.8, 2.8×10^6 g km^{-2} yr^{-1} respectively, Nevertheless, given the tropical climatic conditions (including abundant and intense rains), certain man-induced changes in tropical ecosystems, such as deforestation, road construction, dredging and filling operations, and open pit mining, can significantly increase the suspended-solids concentrations of rivers even in the tropical lowlands where the controlling effect of relief is minimized.

Increased solid-phase concentration in river waters has marked biological and physical effects. Particulate matter or colored dissolved compounds such as humic acids, normally accompanying siltation, can diminish light penetration and hence the depth of the photic zone. This will bring nearer the surface the so-called compensation point, the point where production exceeds respiration. The decreased light levels may eliminate the highly productive macrophytes, such as the estuarine turtle grass *(Thalassia testudinum)* and also many species of macroalgae that require light intensities that do not normally occur below 10 m in tropical coastal zones. The net effect is a reduction in primary productivity and in food available for passage to higher trophic levels.

A marked decrease in the suspended-solids content of rivers resulting from impoundments can cause a reduction of the supply of silt and particulate organic matter responsible for the great productivity of deltas and estuaries.

Increased siltation modifies the geomorphological features of floodplains and rivers, adding sizeable amounts of sediments that must be removed by dredging to keep channels clear for river craft.

The biotic effects of the increased siltation in estuaries are often serious. Very high inputs of sediment kill biota by simply covering them. Corals can sweep away small amounts of silt, but are killed when they can no longer clear themselves. *Thalassia* and other sea grasses can recover from burial in moderate amounts (10 to 30 cm) of sediment by relying on stored starch reserves until they can photosynthesize again. Burial coupled with deteriorating water conditions causes the long-term destruction of the beds. Mangroves are also susceptible to sedimentary death. They possess aerial roots or pneumatophores which have air ducts leading to the deeper roots. When these ducts are clogged with sediment, the plants die within a few weeks.

The darker surfaces produced by turbidity also affect the heat distribution in water bodies with consequent effects on biological activity. When sediments are resuspended due to dredging or wind action they often release noxious gases, such as H_2S, and fine organic particles which have a high biological oxygen demand, noticeably reducing the dissolved oxygen content of the waters.

The effects of heavy-metal pollution will be discussed below. However, it should be kept in mind that metals are often complexed with silting particles. This has a variety of implications. In a sense it is a cleansing mechanism since the pollutants are removed from the water column. But even if the source of the pollution is stopped, the pollutant may be resuspended by the stirring of the sediments.

Littoral drift is responsible for the transportation of large volumes of sediments along the coastal zones. The interactions of this process with biological activity in coastal regions is insufficiently known. Nevertheless, sand transport along beaches can be substantially altered by man, either by a reduction of sand input caused by river damming or by physical modifications along the coasts (e.g., harbors, piers, coastal development, etc.). Ecologists working on coastal zones are often not fully aware of this phenomenon. Additional research is needed to foster sound advice on beach management and to alleviate existing problems.

5. Naturally occurring compounds

a. Dissolved solids. On a regional scale, atmospheric precipitation is the major mechanism controlling the chemical composition of low-salinity tropical waters, where the dilution by rainfall is high and the rate of supply of dissolved salts to the system is low. Tropical marine water may have natural nutrient concentrations lower than their temperate counterparts, but possess exceedingly rapid recycling mechanisms.

Gibbs (1970) has shown that the chemical composition and concentration of 16 tropical Amazon tributaries is close to that of the rainfall over the basin, and, with the exception of some rock-derived elements (such as silicon and potassium), it is also similar in composition to seawater. This clearly suggests the sea as the main source of salts transported into the precipitation cycle through wind systems.

All land-use practices that increase erosion rates in tropical river basins will accelerate the introduction of salts and nutrients into rivers, altering the river-water quality and eventually altering estuarine and coastal zones. Several agricultural practices linked with irrigation procedures, such as the fluctuating water level of wide use in rice crops, introduce varying amounts of salts through redox reactions, salts that would otherwise have remained in an insoluble state.

b. Nutrient enrichment—eutrophication. Construction of large reservoirs risks natural eutrophication of the lake and sometimes unpredictable and far-reaching consequences downstream, such as the impairment of the estuarine mechanisms controlling aquatic production. The growing use of fertilizers, which may be introduced into riverine systems by overland flow, accelerates river and lake eutrophication.

Eutrophicating compounds can be put into three general classes. The simplest are the fertilizers, which contribute only nutrients into the waters and simulate excess plant growth resulting in eutrophication. Certain industrial wastes such as those from sugar cane and copra processing plants in the tropics add nutrients, but also add organic solids, which immediately add to the Biological Oxygen Demand (BOD) load. These markedly decrease light penetration and oxygen concentration in water. The third group is sewage waste. This material has the properties mentioned above plus the added problem of adding potential pathogens into the water ranging from those that cause minor gastrointestinal discomfort to serious epidemic diseases.

Added nutrients, from whatever source, cause excess production leading to excess respiration at night. The resulting oxygen depletion may cause the destruction of some species. In addition, the communities favored by high nutrient levels are usually not composed of the same species as the natural community and may be noxious or even toxic. The vast quantities of excess organic material produced falls to the bottom. There, it combines with industrial and sewage wastes creating an anaerobic condition and blanketing the benthic communities. This is a serious form of pollution occurring in most harbors in the tropics. It presents one of the most immediate threats to man and his environment. Notable examples are Kingston Harbor in Jamaica (Wade, Antonio and Mahon, 1972), Hong Kong Harbor (Trott and Fune, 1973), and Guanabara Bay in Brazil (Castello, 1970).

6. Alien Pollutants

a. Heavy metals. Pollution from heavy metals comes from a variety of sources and is brought about by the release into the water of metals at a concentration from several times to several orders of magnitude above normal background levels. The sources are as varied as the metals themselves and include municipal sewage, agriculture, industrial wastes, and desalinization plants. Highly toxic metals include mercury, lead, cadmium, copper, nickel, chromium, and zinc. They present severe hazards because they may be cumulative in biota and are passed up food chains to higher trophic levels. They are also concentrated on particles and sediments up to 10^4 to 10^5 times their free-water concentrations and are not decomposed as some chemical pollutants are, but may be resuspended and liberated upon disturbance.

Mercury was the first heavy metal pollutant to which attention was drawn and is probably still the most important. In the tropics, mercury and other metals associated with biocides are apt to prove the most troublesome. Lead concentrations in estuarine waters of the Everglades due to agricultural runoff are the highest concentrations recorded in coastal waters (up to 200 μg/l).

Desalination-plant effluents release several tons of copper per year. This is entrapped in the stable dense effluent and absorbed into the benthic communities and the sediments causing severe problems.

With the increasing use of accurate and simple analytic techniques for the measurement of heavy-metal levels, such as atomic absortion techniques, the pervasiveness of a variety of metals is being discovered.

b. Oil. Minor oil spills are frequent in rivers with active traffic of river-going craft. Such spills can either occur during the transportation of oil and derivatives or during the cleaning process of bilges. Contrary to popular thought, the vast majority of oil released into aquatic systems comes from these normal industrial and transportation operations and not from the spectacular major spills.

Short-term acute effects (major spills) cause widespread destruction in the intertidal zone where the floating oil contacts the biota. Birds attract much attention because they are especially susceptible to damage from oil. Tropical mangroves also would appear to be very susceptible to damage by oil pollution. Rutzler and Sterrer (1970) observed that following an oil spill at Galeta Island, Canal Zone, seedlings of *Rhizophora* and *Avicennia* were killed when oil prohibited root respiration. A recent spill of aviation fuel, diesel oil, and bunker oil at the harbor entrance of Wake Island contaminated the coastline and killed over 2,500 kg of reef fishes and uncounted invertebrates (Gooding, 1971).

Compared with the severe acute spill, little is known of the effects of small quantities of long-term releases, or of the effects of the dissolving of certain soluble compounds from the oil into the water column. Oil at low concentrations has been shown to be deleterious to phytoplankton and marine invertebrate larvae. In addition to direct effects, oil is capable of being incorporated in the sediments and continues to be available for redispersal for indefinite time periods.

c. Pesticides. Tropical ecosystems are subject to the same effects of pollution by pesticides as are the temperate ecosystems from which most of our present information on these topics has been derived. Numerous reviews of this information have been made [see Study of Critical Environmental Problems (SCEP), 1970, and The Institute of Ecology, 1972 (MILE report), for global perspectives and summaries], and there is no need to repeat the generalities here. There are, however, certain specific features of the tropics, especially higher temperatures and greater predation, that directly influence the movements and effects of pollutants in tropical drainage systems. More research has been done on DDT than on any other major contaminant in the tropics. Therefore, despite indications that this compound is gradually being replaced by others of lesser persistence, attention in this discussion will be centered on DDT. Many of the principles developed are applicable, in either a general or specific manner, to circulation and effects of other pollutants in tropical drainage systems.

The ecology of DDT and related compounds has been extensively reviewed (Miller and Berg, 1968; Gillett, 1970; Study of Critical Environmental Problems, 1970; The Institute of Ecology, 1972), and significant additional studies have been published recently or are in progress. The severe effects of low concentrations of DDT on survival and reproduction of crustaceans, carnivorous fish, and carnivorous birds have been proven experimentally and are extensively confirmed by field studies. Data from field studies are less easily interpreted as our knowledge increases, however. There is now evidence that thin egg shells of carnivorous birds, for example, result not only from DDT, but also from other organochlorine insecticides, from PCBs, and from heavy metals such as lead (Witt and Gillett, 1970), and the levels of these various pollutants in the environment are often correlated.

Major uses of DDT in the tropics are in malaria control programs where it is applied to the interior of houses, in oncocerciasis control programs where it is appled directly to streams and rivers inhabited by blackflies *(Simulium)*, and in control of agricultural pests, especially in cotton. The claim that DDT applied to the interior walls of houses contributes negligibly to environmental contamination (Brown, 1970) seems reasonable but has been neither supported nor negated by empirical studies. The use of DDT for *Simulium* control is claimed to not cause fish mortality (Brown, 1970; Kershaw, 1966) but substantiating data are weak. Possible effects on fish reproduction have not been researched, and it is almost certain that deleterious effects are occurring on populations of fish-eating birds downriver from the treated localities.

Use of DDT in tropical cotton plantations bordering on lowland waterways and estuaries is frequently heavy, facilitating transfer of DDT from the agricultural to the aquatic systems. On the Pacific coast, "cotton plantations border approximately two thirds of the Guatemalan estuary system" and receive more than 100 pounds of insecticides per acre during the growing season (Keiser et al., in press). DDT is one of the principal pesticides employed, but toxaphene, heptachlor, parathion, and methyl parathion are also used, and most applications are pesticide mixtures (1964 data). Mean DDT residues of 36 to 45 ppm (whole-body basis) have been reported for two fish, *Mugil* sp. and *Poecilia sphenops*, which are eaten by the coastal human populations. It is suggested that DDT and other residues have decreased the estuarine nursery areas of the white shrimp *(Penaeus)*, on which another fishery is based. In some areas the local human population has been observed to eat fish apparently killed by dieldrin (S. Herman, personal communication). Studies of effects on tropical carnivorous birds are almost nonexistent, but Guatemalan cattle egrets are now producing extremely thin-shelled eggs (S. Herman, personal communication) and reproductive failures and thin egg shells have been reported for double crested cormorants on islands off off northwestern Mexico (Gress et al., in press). Shell thickness of these cormorants showed significant negative correlations with both DDT and PCB residues levels. No data are available on these problems in tropical raptors.

At the regional level perhaps the two major classes of ecological disruptions likely to be caused by DDT and similar substances are (a) destruction of fisheries, especially in the estuaries, but also in lakes and reservoirs, and (b) destruction of predator populations, both fish and birds, which may play crucial roles in regulating the structure and function of their ecosystems.

Crustaceans are extremely sensitive to DDT and many commercially exploited species live in estuaries or utilize them as nursery areas. In the tropics, fisheries also exist for fresh-water crustaceans such as *Macrobrachium*. Fish are less sensitive to DDT, but generally occur higher up the food chain and in this case may have higher DDT residues than their food. Well-documented cases of regional fisheries destroyed by pesticide pollution are rare even in the temperate zone, and nonexistent in the tropics. Declines in the speckled sea trout populations on the Texas coast and Dungeness crabs on the California coast are associated with the high DDT residues in eggs or larvae [Study of Critical Environmental Problems (SCEP), 1970]. Massive mortality in 1967 of the fry of the coho salmon from Lake Michigan was associated with high-residue levels in the parent fish (Johnson and Ball, 1972) and suggests that this new fishery may collapse as rapidly as it had developed.

In any region, lakes, reservoirs, and estuaries serve as DDT traps, greatly slowing the downstream movement of the pesticide. As discussed earlier, DDT entering one of these systems will be mostly adsorbed on particulate matter, much of which will either settle out as a result of slowed currents or will be incorporated into the food chains of reservoir organisms feeding on plankton or on particulate detritus. The creation of a reservoir on a river system contaminated by DDT can be expected to reduce the influx of DDT to downriver systems, including estuaries. Populations developing in the reservoir will, however, be subjected to higher DDT levels than were the populations in the former freeflowing river.

Tropical lakes and reservoirs, but probably not estuaries, show less frequent mixing of surface and bottom waters (turnover), higher rates of decomposition of organic matter, and longer periods of anaerobic conditions in the sediments and lower water column, than do similar systems in temperate zones. Major differences in the circulation patterns and degradation rates of DDT in temperate and tropical aquatic systems are expected. However, even for temperate systems hard data on these processes are scarce or nonexistent. Some attention has been given to degradation of DDT under anaerobic conditions (Fries, 1972), but the data are inconclusive for a comparison of anaerobic and aerobic breakdown rates.

The lower oxygen concentrations in tropical reservoirs also greatly prolong the time required for decomposition of the woody tissues of inundated vegetation, since the principal decomposers of lignin are aerobic fungi (Ruttner, 1963). Failure to clear forest in a developing reservoir basin may greatly hinder and delay the development of gill net fisheries on the reservoir, in which case concern over fish mortality or fish-residue levels become very academic matters from a fisheries point of view.

The rate at which individuals concentrate DDT residues in their bodies and therefore the rate at which DDT concentrations are magnified from one trophic level to another may be greater in the tropics than in temperate zones if respiration rates and food consumption rates are higher in the tropics. However, comparative data do not exist. If carnivorous species are more abundant in the tropics, if food chains are longer, and if second- and higher order carnivores occur more frequently, then not only is the number of species likely to suffer severely from DDT contamination much greater in the tropics, but also the "average" tropical carnivore will receive more residues and be more severely affected than will the "average" temperate zone carnivore.

Reduction of any single carnivore population in the tropics would usually have less effect than similar reduction of a co. responding temperate carnivore population because there may be a greater probability in the tropical system that other carnivores can increase to occupy the niche of the declining species. On the other hand, carnivory (or predation) appears to be a more important regulator in tropical than in temperate ecosystems, so a 10 percent reduction of carnivory (or of the pool of carnivorous species) might occasion a greater disruption of a tropical system than of a temperate one. As suggested in the previous paragraph, a given level of DDT pollution might be expected to cause the percent reduction of carnivory to be greater in a tropical than in a temperate system.

Principal disruptions to be expected from reduction of carnivore populations include increased amplitudes in the fluctuations of prey populations (and of any populations functionally linked to them), increased amplitudes in fluctuations of physical-chemical variables subject to biological influence (e.g., pH, turbidity, O_2 levels), minor to large shifts in mean values for population densities and for physical and chemical variables throughout the system, competitive exclusion or elimination in lower trophic levels by some species of other species with inferior competitive abilities but superior antipredator defenses (biochemical, morphological, behavioral). These types of disruption and species impoverishment will result not only from DDT but from any factor reducing carnivore populations. Nevertheless, with industrial and agricultural growth in tropical regions, the rate of environmental contamination by DDT, other organochlorine insecticides, and PCBs is likely to increase more rapidly than are the rates of other processes that deleteriously affect carnivores.

PCBs are chemically similar to many of the chlorinated hydrocarbon pesticides. They are found in many types of industrial effluents, and are highly toxic and pervasive. It seems that they are concentrated and transferred in similar ways to the pesticides, and like pesticides they are found in high concentrations in pelagic North Atlantic seabirds far from the sources of these compounds (Bourne and Bogan, 1972). No information is currently available about their distribution or impact in the tropics.

IV. Tropical Diseases as Ecological Systems

Many tropical diseases are ecological phenomena in which the interaction of terrestrial with aquatic ecosystems on a regional and local scale are of paramount importance. These include malaria, schistosomiasis (discussed earlier in Section 5), oncocercariasis, various forms of encephalitis, and other diseases where aquatic vectors or intermediate hosts are critical to the life cycle of the disease organism. As an example, consider the status of schistosomiasis (bilharziasis) in the Amazon basin and the likelihood of its further spread there. This example treats the largest river system in the world and the most widespread human disease caused by a metazoan parasite, clearly illustrating how man's use of the land can affect aquatic systems in a manner directly deleterious to himself.

At present, schistosomiasis is surprisingly uncommon in the Amazon Basin. The reasons appear to be the environmental requirements (especially pH and aquatic vegetation) of the *Biomphalaria* snails, which are obligate intermediate hosts for the schistosome *(Schistosoma mansoni)*, as well as certain cultural and demographic properties of the Amazonian human population. However, properties of the basin's aquatic environment and human population are changing rapidly as man develops the economic resources of the basin, and most of the anticipated changes are likely to favor an increased incidence and spread of schistosomiasis.

Where the *Biomphalaria* snails are absent, there is no risk of schistosomiasis, and snails appear to be absent in most Amazonian springs, creeks, and streams. These are rather acid (pH 5.5) and would tend to dissolve the calcium carbonate shells of any snails that did attempt to colonize them (Sioli, 1953). There are several ways in which man's activities may increase pH and remove this limitation. Lime applied to render the very acid soils of the Amazon region more suitable for agriculture could be leached into creeks and rivers, raising their pH. Although little lime presently is used in the Amazon Basin, its use is a prerequisite to agricultural development and will be increased as soon as limestone-crushing plants are established in the few good limestone deposits in the basin (Alvim and Araujo, 1952; Pinheiro, 1973).

Influx of nutrients in runoff from fertilized agricultural land or in human and animal wastes dumped into lakes, creeks, or rivers favors increased phytoplankton and macrophyte populations, which may raise pH values by photosynthetic uptake of CO_2. Brazilian agriculture so far makes very little use of commercial fertilizers, but its use doubled from 1962/64 to 1968 (Schuh, 1970). Impoundment of water in reservoirs also favors the development of phytoplankton and macrophyte populations, which might give a reservoir a higher pH than the water has flowing into it, once the inundated organic matter in the basin has been decomposed. Sioli (1967) reports pH values as high as 10 in naturally impounded flood-plain lakes of the Amazon.

Increased pH values in streams and rivers can also result from increased insolation of soils in altered terrestrial environments, e.g., as where natural forest is replaced by agriculture. Resultant higher soil temperatures foster accelerated decomposition of soil organic matter and reduction in numbers of soil microorganisms (possibly after a brief increase). Water percolating through such modified soil picks up smaller quantities of organic acids and smaller quantities of carbon dioxide (from microorganism respiration) than formerly, and the pH of the receiving streams will increase accordingly. In the Congo River Basin in Africa, Marlier (1972) has noted that streams flowing from denuded areas have higher pH (and higher salt concentrations) than do streams from areas of more intact vegetation, presumably as a result of the mechanism outlined above.

Snail distribution is also limited by availability of appropriate food, such as algae and aquatic vascular plants. These in turn, are limited by the extreme nutrient poverty of most Amazon waters and by forest canopies which overarch the streams to such an extent that even at midday less then one percent of the solar radiation reaches the water surface (Fittkau, 1964; Sioli, 1956). The significance of shade is seen at Fordlandia, an inoperative plantation established in 1928 when the natural forest was cleared right to the stream banks. Following this clearance, increased aquatic vegetation has confined to a good food supply for the *Biomphalaria* populations that subsequently established themselves in the more-or-less neutral water streams of the area. For at least the past two decades Fordlandia has served as the principal focus of schistosomiasis in the Amazon Basin (Sioli, 1956). Ordinances forbidding clearing of forests on banks of watercourses, such as those established by the Dutch in Indonesia as a siltation-preventive measure (Pelzer, 1961) might have a new and additional value in the Amazon system.

If agricultural and other activities of man tend to raise pH, increase dissolved nutrients, and increase the exposure to sunlight of presently snail-free streams, it is also true that the best soils for agriculture on the Amazonian "terra firme" are undoubtedly to be found in some parts of the Carboniferous bands along the Lower Amazon Valley," where the mostly neutral water creeks are already populated with *Biomphalaria*. This reflects the rough correlation of soil pH and the water pH and the fact that agriculture, like snails, fares poorly in a highly acid environment. It is thus conceivable that colonization and local population growth rates in the Amazon Basin will be greatest in just those areas where the possibility of schistosomiasis is greatest.

Other possibilities that merit attention are the reduction of fish, turtle, and other molluscivore populations by man, either inadvertantly by water pollution or as a result of his exploitation of these natural control agents for food. The introduction of the old world *Schistosoma haematobium* and *S. japonicum* by infected immigrants and the acceptability to these schistosomes of either native Amazonian or introduced snail hosts should be recognized as a very unlikely but also very dangerous possibility. After all, *S. mansoni* itself apparently is not native to the Americas but was introduced as a result of the African slave trade (Cheng, 1964).

Biomphalaria snails occur among the floating shore vegetation in flood-plain lakes and along the banks of several of the larger rivers (Solimões, Amazon, Madeira, etc.) in the basin. Although most of the basin's human population also lives along the banks of these same rivers, schistosomiasis has not become established in these areas. Sioli (1953) suggested as a partial explanation the facts that (a) the "Amazonian population does not have the custom of defecating in the water," (b) they avoid bathing in vegetated areas, and (c) a very high-dilution factor minimizes the probability of a schistosome miracidium encountering a snail. Central sewage systems emptying into watercourses and higher population densities might have unfavorable effects, if these explanations are valid. More information on human behavior and on snail population ecology along these larger rivers is clearly necessary before an understanding of the present situation and reasonable consideration of future prospects are possible.

V. Impact of Technology on Climate

A. Interregional Atmospheric Processes

Interactions between the atmosphere and the sea largely determine the chemical composition of precipitation. As already discussed, this strongly influences the ionic composition of tropical rivers. Pollution of the atmosphere by man may also become more important as industrialization progresses.

Smoke and haze from agricultural and forest burning already result in intense air pollution [see table 8.1 in Study of Man's Impact on Climate (SMIC), 1971] in tropical areas. Although such pollution may influence local and even regional climate, it has little direct effect on vegetation or soils. As tropical areas develop and industrialize, particulate matter in the atmosphere may be reduced because of decreased forest burning. But, many compounds that are now only trace components of the tropical atmosphere will be introduced in large quantities by industrialization.

Observations in temperate regions indicate that such emissions as sulphur dioxide, carbon monoxide, fluoride, ozone, lead and other heavy metals, and oxides of nitrogen become important and troublesome constituents of the atmosphere in industrialized areas. There is a highly developed symptomology for air pollutant effects on temperate vegetation and reasonable understanding of the susceptibility of many temperate plant species to various pollutants. Unfortunately, the effects of atmospheric pollutants on the survival and growth of tropical vegetation is virtually unknown. In addition, there seems to be no strong correlations between plant characteristics and susceptibility to air pollution which would allow us to predict the susceptibility of tropical species from temperate experience.

Large areas of vegetation in the vicinity of smelters and other heavy industries have been destroyed by air pollution in the temperate zone. This denudation has led to massive soil erosion, river and lake siltation, and the production of an altered environment that probably will never return to normal. If we are to avoid similar situations in the tropics we must not only use advanced methods to control industrial emissions but we also need to determine the susceptibility of tropical plant species to damage from atmospheric chemicals.

Another and somewhat more predictable effect of air pollutants is that of sulfur dioxide on soils. Low-cost high-sulphur-content fuels common in the early stages of industrialization lead to the production of large amounts of sulfur dioxide that reach the soil during rain storms as sulphuric acids.

The soils of the neotropics are quite diverse. They include very ancient soils developed on the Brazilian and Guayanan shields, somewhat younger soils of the Andean range, and very young soils of recent volcanic origin. As a result there is a wide diversity of nutrient status and a considerable range in pH (Beck and Bramao, 1968). Because the pH, buffering capacity, nutrient status, and content of weatherable minerals in the very old soils are already low, they would be much more easily damaged by additions of sulphuric acid than most temperate soils. One might expect the young volcanic soils to respond somewhat like their temperate counterparts. However, due to the accelerated rate of weathering in the tropics these soils might also be altered by acidic conditions.

Whereas the primary effects of sulphuric acid rains is to lower soil pH, there also are many secondary effects on soil chemistry. The solubility of most elements in the soil is quite dependent upon pH. In general, the availability of plant nutrients decreases with decreasing pH, whereas the solubility of many metallic elements increases. These changes could lead to great changes in leaching losses of elements from the soil. A change in the soils input of nutrient elements or metallic compounds to river systems could influence the aquatic biotic component.

Changes in soil pH might result in changes in surface and ground water quality, but this has not been conclusively demonstrated.

Although most tropical plants are adapted to grow under low pH and nutrient conditions, the extreme acidity and low nutrient status created by large inputs of sulphuric acids may lead to severe reductions in vigor and even death.

We have long considered that sulfur dioxide was the prime agent in this phenomenon; however, many sources of SO_2 also produce considerable quantities of heavy metals and these are often quite toxic to plants. Metallic elements remain in the soils long after the source of pollution has been removed and thus may have long-lasting deleterious effects.

B. Deliberate Weather Modification

Man may soon be able to exert a degree of deliberate control over local weather in the tropics. Artificial seeding of tropical cumulus clouds may increase or decrease precipitation over target areas by 20 percent or more. The ability to moderate the peak wind velocities of hurricanes, although probably not to steer them, may be achieved within a few years [National Advisory Committee on Oceans and Atmosphere (NACOA), 1972]. The low direct cost of weather modification technology, coupled with its apparent attractiveness for alleviating economic loss due to weather, ensures that there will be strong pressures for early application should weather modification become fully practical. Before this new technology is widely adopted, however, potential social, environmental, and economic costs as well as benefits should be addressed.

Several such assessments are under way in North America, Israel, and elsewhere, but their results will not necessarily be applicable to the American tropics. The only way to determine the ecological consequences of weather modification is to relate the specific way in which the weather regime will be altered to the existing climate vegetation, soil, land use, and patterns of human activity.

Deliberate weather modification largely depends upon introduction of artificial nucleating agents into properly selected cloud systems. Silver iodide is the most common nucleating agent, although several organic compounds may be more widely used in the future. There is a need for adequate evaluation of the long-term consequences of injecting potentially toxic materials into the atmosphere, but these materials are the same in temperate regions as in the tropics. Enough research on this topic is currently being done elsewhere so that research programs directed specifically toward determining the ecological effects of cloud seeding agents in the tropics are not warranted. In any event, preliminary evaluations indicate that silver contamination is not likely to be a serious problem, at least during the current exploratory stage in the development of weather modification technology (Cooper and Jolly, 1970).

There is considerable dispute about possible downwind effects, but the consensus among meteorologists is that if weather modification technology should prove capable of increasing or decreasing precipitation over a target area by as much as 20 percent, this will not result in a one-for-one change anywhere else. The precipitation scavenging process in the natural atmosphere is sufficiently inefficient such that artificial extraction of a little more moisture from a cloud system does not greatly change the amount available for precipitation downwind. Artificial cloud seeding on the scale now contemplated is not expected to alter cloudiness extensively, or to otherwise affect the factors influencing surface temperature (except to the limited extent that latent heat of evaporation of added or diminished rainfall affects local temperature). This would not necessarily be the case if worldwide modification schemes were mounted at a greatly expanded level.

This decision to initiate a rainfall-modification program will generally be motivated by the expected effect of the changed precipitation regime on agriculture or hydroelectric power. Since there is no way that the modification program can be confined to sharply delimited boundaries of land ownership or even national jurisdiction, an adequate assessment of its costs and benefits should include consideration of the potential effect on nontarget plants, animals, and people. This assessment will not be made easier by the fact that precise control over the amount of precipitation change cannot be achieved. It may be possible to determine statistically that precipitation over a season or a year has been increased or decreased by a given amount, within some probability range. Such a prediction cannot be made for an individual storm, however.

Decision makers may choose to alter precipitation throughout the year or only at certain seasons. Efforts may be concentrated on low rainfall years, when water shortages may be critical but few seedable air masses are around, or emphasis may be put on years with many suitable storms, when the same investment may yield a greater return of water but the water is less urgently needed. Innumerable combinations are conceivable. The ecological consequences of altering normal rainfall variability or its seasonal pattern may be more significant than those of altering the amount (Cooper, 1973). (But note in Section 5 the poor level of knowledge of normal rainfall.)

Research now in progress may lead to some degree of hurricane control. Hurricanes are among the most destructive of natural phenomena but also have some beneficial effects, particularly on the marine environment. They significantly affect the temperature of the ocean surface, and there is evidence of upwelling from a depth of 200 feet or more near the storm track. This can bring significant quantities of nutrient-rich water to the surface, thereby stimulating marine growth. Increase in phytoplankton standing crop near the surface to about double prehurricane values has been measured after a severe hurricane in the Gulf of Mexico. Whereas biological productivity at lower depths was reduced on account of turbidity restricting light penetration, the integrated effect was a substantial increase in the biological productivity of the water column (Franceschini and El-Sayed, 1968).

C. Global Climatic Change

Of greater significance for mankind than deliberate cloud seeding to alter rainfall is the possibility of altering global climate. The climate of the earth is maintained by a balance between the incoming solar radiation absorbed by the earth-atmosphere system within the outgoing planetary infrared radiation emitted to space by the earth's surface, the atmospheric gases and particles, and the clouds. The possibility of climate modification by *direct* human interference with the motions of the earth-atmosphere system is less likely than the chance of man's activities modifying the climate *indirectly*, by altering the energy balance or cloud nucleation processes. However, by diversion of rivers or ocean currents or by changes in the character of the land surface on a large scale, or by injection of carbon dioxide or particulate matter into the atmosphere, man might trigger mechanisms that affect the energy balance of the atmosphere—which could ultimately have an impact on climate.

1. Factors affecting the climate

The earth's atmosphere is a closed system, where at any particular time and place its state is related to and influenced by the atmospheric conditions at every other place on earth. The nonuniform latitudinal distribution of solar radiation reaching the globe and the heterogenous nature of the earth's surface combine to assure that the earth-atmosphere system is heated heterogeneously. Thus, each part of the system affects each other part because the *geographical differences* in heating drive the atmospheric heat engine.

The amount of solar radiation absorbed in the earth-atmosphere system must be equal over a sufficiently long time to the outgoing infrared or planetary radiation for the earth as a whole. However, this is not necessarily true locally. For example, the input of solar radiation in the equatorial latitudes exceeds the outgoing infrared radiation flux. This condition is referred to as a "positive" radiation balance. In middle latitudes, the incoming and outgoing radiant energies are about equal, whereas at the polar latitudes the outgoing infrared flux exceeds the absorption of incoming solar radiation by a large margin. The latter results from both the relatively small values of average incoming solar energy at the poles and the relatively high values of albedo (reflectivity) of the polar ice caps. This unequal or differential solar heating of the globe occurs primarily in zones (latitudinal belts). When coupled with the rotation of the earth, the unequal heating drives the motion we recognize as winds and ocean currents. These motions, both horizontal and vertical, regulate the distribution of temperature, cloudiness (which also requires the presence of suitable particles, called cloud nuclei), and precipitation over the globe, i.e., the major climatic variables.

The radiation balance of the earth-atmosphere system depends upon the concentration of optically active gases and particles in the atmosphere, the amount, kind, and thickness of the clouds, and the optical character of the earth's surface (especially the albedo or reflectivity of the surface to incoming solar radiation). Any alteration to these constituents persisting for a sufficient length of time (roughly 10 or more years), will alter the radiative heating of the earth-atmosphere system, and affect the thermal forcing of the atmosphere controlling the atmospheric motions.

The motions of the system result in a transport of heat from areas of positive radiation balance (the equatorial regions) to areas of negative radiation balance (the polar regions). In this process, the jetstreams, trade winds, eastward winds of the midlatitudes, westward winds of the polar latitudes, and migratory large-scale weather systems or eddies are all generated in the atmosphere. These variables, of course, estentially define the state of the climate. When the north-south temperature gradient is increased, the circulation becomes more vigorous in order to ameliorate the large temperature gradient. Eventually, the zonal nature of the east-west winds breaks down, generating large-scale transient eddies (storm systems) that transport additional heat and moisture poleward, reducing some of the equator-to-pole temperature difference. This situation is more characteristic of the winter hemisphere.

Thus, the temperature, winds, and precipitation in temperate latitudes are very much related to the same variables in the tropical latitudes. As an example, Namias (1972) has compiled statistical records showing a possible teleconnection between the highly variable year-to-year rainfall over northeast Brazil and the degree of cyclonic activity in the Newfoundland-Greenland area during the northern hemisphere's winter and spring.

The atmosphere carries heat in two forms—sensible and latent. For example, when warm air is directly transported to a cold region, it is a transport of "sensible" heat. Water vapor, evaporated or transpired at the earth's surface, can also be transported by the atmosphere. When it undergoes cooling in the presence of suitable nuclei (particles), the water vapor may condense into drops, releasing the "latent heat" needed originally to change it from liquid water to water vapor. Thus, any process that affects the evapotranspiration rate at the earth's surface or the concentration or character of the suspended atmospheric condensation nuclei that govern cloudiness and the release of latent heat will alter the energy balance of the earth's atmosphere system.

The process of evaporation, transport of water vapor, condensation, precipitation, and re-evaporation, which is called the "hydrological cycle," is responsible for about one-third of the net heat transported poleward across the 30° north and south latitude circles. Sensible heat transport by the atmosphere accounts for another third of the total heat transported, and oceanic currents such as the Gulf Stream carry the remaining third of the total heat flowing poleward. The ocean surface temperatures, controlled by turbulent mixing processes in the upper hundred meters or so of the oceans, play an important role in the exchange of sensible and latent heat with the atmosphere. Unfortunately, our knowledge of these processes is till inadequate to permit satisfatory quantitative determination of the oceans's role in the global heat budget.

2. Man's activities in the tropics that might affect climate

Human activities that might affect climate can be classified as modifications to the earth's surface, to the troposphere (i.e., lower atmosphere), or to the stratosphere (i.e., upper atmosphere). A detailed discussion of the entire subject of inadvertent climate modification can be found in the SMIC Report [Study of Man's Impact on Climate (SMIC), 1971]. SMIC concentrated heavily on the possible effects of industrial activities in the temperate latitudes, whereas usé practices in tropical regions were given less attention. The general discussion in SMIC concerning the potential inadvertent consequences to the global climate from industrial activities in nontropical latitudes generally can be extrapolated to apply to industrial activities that are anticipated and current in tropical latitudes. However, since the region between 30° north and south latitude comprises half the earth's surface and receives considerably more than half of the incoming solar radiation absorbed in the earth-atmosphere system, it is apparent that large-scale modifications to either the land surface or atmospheric composition in tropical latitudes is likely to be more significant for global climate change than comparable changes in temperate latitudes. However, the climate in polar regions is probably the most sensitive to slight changes in the energy balance. Yet, it has been argued with the aid of simplified semiempirical mathematical models that the extent of the polar ice cover could be very sensitive to the radiation balance of the equatorial latitudes (Schneider and Gal-Chen, 1973).

Proposed tropical land-use projects, such as extensive alteration of the Amazon forests, would affect the physical character of a large and important fraction of the earth's surface. As we have stressed, these tropical regions are essential factors in governing the global energy balance and therefore large-scale modification projects might not have an effect limited to the local or regional climate, but might influence atmospheric processes thousands of miles away as well.

Change in either the albedo or moistness of the land surface could affect the local surface temperature. If the albedo of the surface were to be increased, leaving the moisture of the surface unchanged, then less heat would be absorbed at the surface, and the temperature would be decreased locally (assuming no local change in cloudiness resulting from the diminished surface heating). On the other hand, if the surface albedo were to remain unaltered while at the same time the moistness of the surface were changed, then there would be no change in the amount of solar energy absorbed by the surface, but there would be some change in the proportions of absorbed energy used to evaporate water, to that absorbed energy directly added to the local environment as sensible heat. If the surface moistness is increased while the albedo is unchanged, then more liquid water is evaporated at the surface and less sensible heat energy is available to warm the local region, and then the climate is cooled near the surface. At the same time, the evaporated water vapor is carried upward into the atmosphere and is transported downstream until it eventually condenses back into droplets in the clouds, releasing the latent heat energy needed originally to evaporate the liquid water at the surface and convert it to water vapor. Thus, there is a net energy loss at the original evaporation site (the surface) and an equal net energy gain at the condensation site (the atmosphere). Of course, the overall global energy input is unaltered since the albedo was unchanged.

If very large artificial bodies of water were to be constructed, they would likely warm the global climate and moderate the local climate, since it is probable that an artificial body of water will both decrease the surface albedo and increase the surface moistness. Deforestation, as explained below, is likely to do just the opposite. To examine this further, let us look at the geographic distribution and composition of diabatic heating of the atmosphere (bearing in mind that this heating drives the atmospheric "heat engine" or climate machine, as explained

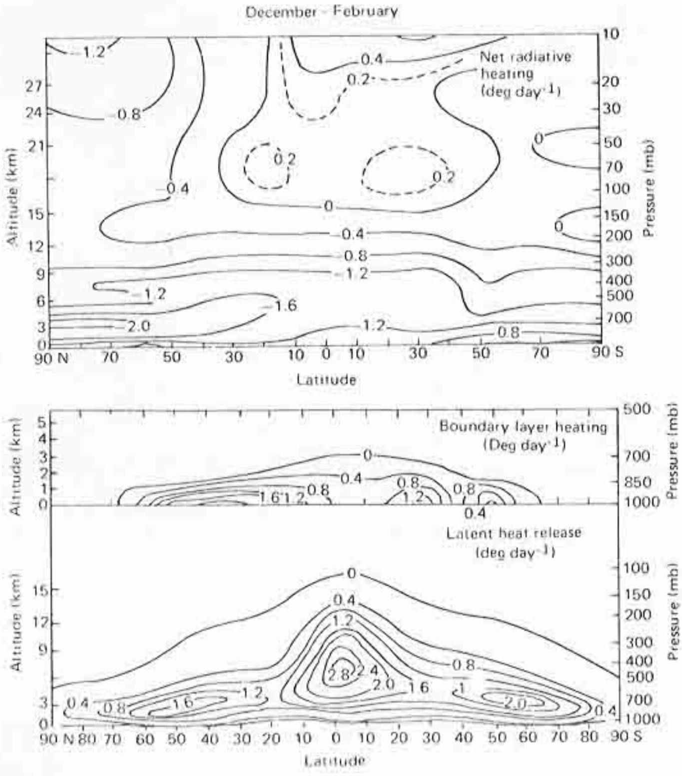

FIG. 6.1. Composition of diabetic heating for the atmosphere for December-February. From Newell et al. (1970.)

above). Figure 6.1 (from Newell et al., 1970) shows the heating of the atmosphere. Note the dominance of the latent release terms, especially in tropical latitudes.

Newell (1971) asks the question: "What will happen to the large-scale atmospheric general circulation if the tropical forests are removed over Brazil and Indonesia and perhaps over Central Africa? I think that the answer . . . is that we do not know, but we can speculate on the kind of influence it will have." Newell (1971) then speculates on the possible effects of deforestation: "Reduction of the water cycling between the forests and the air, which provides the latent heat high in the column, would clearly alter the pattern of the latent heat forcing function." If one examines the heat balance at say 500 mb and 5° south, one finds that the latent heat term is almost exactly offset by radiation and adiabatic cooling by rising motion (the magnitude of this is not shown in Figure 6.1, but must be about the same as the radiative cooling term). If a change occurs in the latent heat term one would expect changes in other terms also to maintain a balanced budget. It is difficult to even guess what they might be without a proper dynamical model. Boundary layer heating would obviously change due to the change in the surface albedo and conductivity as the forests are destroyed, although it should be borne in mind that the total longitude span over which the change of land surface occurs is small. Most of the contribution to the latent heat term comes from South America, Africa, and the Maritime Continent at this season, so that changing the tropical forests would interfere in a major way with this term. The radiational term would also change on account of less cloudiness.

Water vapor transport patterns, horizontal heat and momentum transport, and the convergence-divergence patterns of all these transports would also be expected to change. The amount of regular upper air information over the tropical continents is so small that we cannot yet establish the normal values of these transports properly.

Furthermore, as Newell points out, at low latitudes most of the latent heating is provided to the air in the regions of mean rising motion centered over South America, Africa, and the Indonesian region associated with summer season monsoonal circulations. Over the oceans between these land masses, mean sinking motions occur. Thus, the land areas (although comprising a smaller fraction of the total area of the earth's surface in tropical latitudes than the oceanic areas) are of more consequence in the heating of the global atmosphere than their relative surface area might suggest.

As an example of how strongly deforestation affects both evapotranspiration and runoff, we can consider the estimates from Sellers (1965, his Fig. 43) given here in Fig. 6.2. Although these data are for a middle latitude station (North Carolina) and may not be valid for tropical regions, deforestation can have a significant effect in decreasing evapotranspiration and increasing runoff as Newell has suspected. The extent to which similar differences would be observed in tropical regions would depend largely on the relative amounts of water available over the year to the root systems of native forests and to the crops that replace them. Field research and simulation modeling should be undertaken to determine the annual and seasonal evapotranspiration values from extensive areas of various types of vegetation

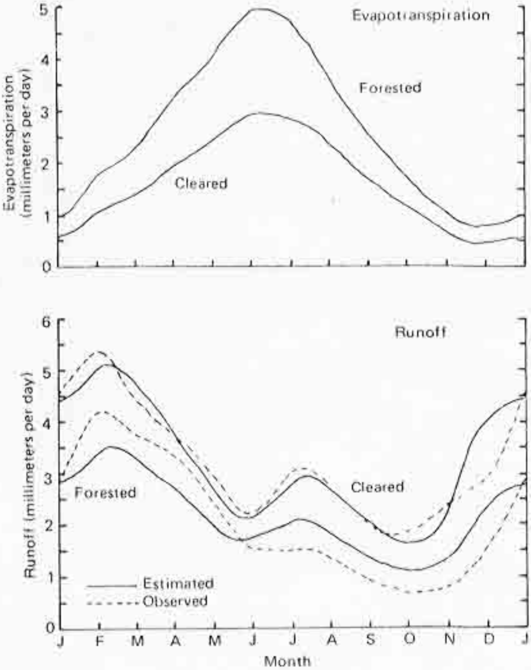

FIG. 6.2. Estimated evapotranspiration (top) and estimated and observed runoff (bottom) from cleared and forested watersheds near Coweeta, North Carolina. (From Sellers 1965.)

in tropical lowlands. Only on the basis of such information can the magnitude of any possible impact on the energy balance from tropical deforestation or other l· ıd-use schemes be quantitatively estimated with any degree of reliability. It is indeed not improbable that, at least in regions of heavy rainfall uniformly disturbed throughout the year, there would be little difference in transpiration between forests and cultivated crops.

Finally, it is essential to emphasize that while it is quite possible that land-use p. actices in tropical regions could significantly affect the local climate, the degree to which such climatic changes might be felt elsewhere is still entirely uncertain.

Although Newell (1971) has argued that tropical changes could affect the global energy budget, he has also recognized that predictions of any such possible effects must be approached with extreme caution. Newell states: "I should emphasize here that the linkages between the various parts of the general circulation are not well understood, even diagnostically. The extent to which latitude displacements of heat sources force changes in the tropics, and vice-versa, is particularly uncertain."

Thus, although we cannot "predict" precisely what climatic changes would result from large-scale changes in usage, we can say that a modification to the energy balance much larger than a few tenths of 1 percent would be expected to cause climatic changes both locally and in other parts of the world (Budyko, 1972). Thus, it is important to estimate the magnitude of the effects on the energy balance of agricultural development on the scale proposed. It is necessary to determine how such a perturbation to the energy balance might affect the climate. This exercise presupposses the existence of a quantitative theory of climate, expressible in the form of mathematical models of the earth atmosphere system. Such models must be complete enough to include all important climatic feedback mechanisms (such as changes in cloudiness or polar ice that might be associated with the change in energy balance which could "feed back" and either ameliorate or accentuate the initial effect on the climate of the change in the tropical energy balance that followed the deforestation). Although current climate modeling efforts are still insufficient to determine confidently the ultimate effect of tropical land-development schemes on the climate, several existing models include many of the important atmospheric feedback mechanisms, and should be applied to this question in order to produce a first estimate of the possible effect.

For a more complete description of climatic modeling and feedback mechanisms see Chapter 6 of the SMIC Report or the survey article by Schneider and Kellogg (1973).

Slash and burn agricultural practices, resulting in the injection of a considerable amount of dust and smoke into the atmosphere, is another example of a human activity in tropical ecosystems that could also have inadvertent climatic consequences. As stated earlier, particles in the atmosphere can affect the energy balance of the earth-atmosphere system by two processes: (a) by directly altering the radiation field by scattering and absorbing radiation, and (b) by providing condensation nuclei that can affect the cloud forming processes, with possible consequences on precipitation, latent heat release and albedo (reflectivity) of individual clouds. (This subject is treated in considerable depth in Chapter 8 of the SMIC Report.)

The atmospheric particle loading is a result of both natural and man-made processes. Windblown soil and rock debris, evaporated sea water that leaves sea salt particles in the air, organic exudation from plants that forms particules, and sulfate or nitrate particles (which are originally in the form of oxide gases of sulfur or nitrogen that are subsequently photochemically converted to particles) are all examples of naturally produced particle "pollution." Of course, deforestation or desertification resulting from man's activities will substantially increase the amount of windblown soil and rock debris, and it is fair to question whether such a particle source is really "natural."

Man-made particle sources result primarily from the photochemical conversion to sulfate particles of sulfur dioxide gas associated with the burning of fossil fuels. Also, there is a measurable direct injection of man-made particles into the atmosphere. However, the most important source of man-made particles could be those that result from forest fires and slash and burn agricultural practices. Unfortunately, estimates of this source range from 3×10^6 all the way up to 150×10^6 metric tons per year (see Table 8.1 of the SMIC Report), a spread in uncertainty which is highly unsatisfactory for determining the possible influence of vegetation fires on the global energy balance. SMIC shows that our present knowledge of the sources and sinks of atmospheric particles is such that we can only estimate at present that the man-made fraction of the total particulate loading is from 5 to 50 percent. Clearly, improvement of these estimates should be an important research priority.

Remote sensing at both thermal and infrared wavelengths may be useful in such improvement. Thermal imagery from earth resource satellites can quite easily display the number and area of clearance fires burning at any one time. Spectral analysis should make it possible to differentiate such fires from other heat sources. Imagery at optical wavelengths can be used to determine the relative area of burned vegetation and the extent of smoke plumes. These data can, in turn, be used to estimate the total input into the atmosphere as a function of time.

Remote sensing also seems likely to permit mapping of the spatial distribution of biomass, chlorophyll, and leaf water in tropical and other regions. Techniques have been developed for determining the biomass of large areas (ca. 1.9 ha) of grassland vegetation from multispectral scanner data. Correlations of 0.8 to 0.9 between estimated biomass values from multispectral data and from clipped plots have been obtained (Pearson and Miller, 1972). It appears likely that these techniques can be extended to forest and shrub vegetation. If so, the way would be open to more accurate estimation of the role of tropical vegetation in regulating the global carbon dioxide balance, as well as to a variety of other ecological analyses.

In summary, a plausible argument can be made to the effect that alteration of tropical ecosystems by land development or increase in slash and burn practices can alter the energy balance of the earth-atmosphere system enough to cause more than local changes in the climate. While it is difficult at present to be very precise about what kind of changes might occur and where, a continued program of development of mathematical models of climate change will undoubtedly help our understanding of any possible consequences to the climate arising from use practices. At the same time, the magnitude of environmental stress from such practices needs to be estimated with far more precision than has been done at present.

There is considerable evidence (see SMIC Report, Chapter 6) that if changes to the global climate are allowed to proceed, they could then become irreversible. It is essential that more definitive answers to the questions posed about inadvertent climate modification resulting from man's activities be found before the changes are likely to occur. We now have a unique opportunity to evaluate the possible impact of large-scale technological efforts before the projects are completed. In view of the negligibly small expenditures that this sort of research effort will cost in relation to the vast sums to be spent on the large-scale projects, a continous effort at understanding the consequences of modifications to terrestrial ecosystems seems truly essential.

3. Atmospheric oxygen: a nonproblem

It is a usual question to ask what might happen to the concentration of life-sustaining atmospheric oxygen should there be a reduction in photosynthetic organisms, either through herbicide destruction or by direct deforestation practices. However, recent measurements and calculations (see SCEP Report, p. 74-75) show that there would be virtually no change in the concentration of oxygen for tens of thousands of years, even if, for example, all the known recoverable fossil fuels were burned. Of course, the carbon dioxide released by such an action would be of considerable importance to the global climate, but atmospheric oxygen is essentially a nonproblem.

D. Synthetic Climatic Statistics As Ecological Predictors

New possibilities have opened in recent years for more productive research on the regulatory role of climate in ecosystem structure and function. Advances in remote sensing and in computer simulation models of global atmospheric circulation promise that greatly improved representations of ecologically important climatic variables can be determined for tropical regions. This in turn would lead to a major advance in our capacity to predict the ecological capabilities of relatively remote and unknown regions, their resistance to stress, and their suitability for various kinds of human exploitation.

If the promise of the new technological methods is fulfilled through research, it should be possible to present, for any desired terrestrial location, synthetic arrays of climatic variables that preserve the statistical structure, although not the instantaneous values, of the actual climatic conditions. This would mean that simulated regimes of temperature, solar radiation, atmospheric humidity, wind velocity, and eventually perhaps precipation, can be produced for places lacking adequate long-term weather records. These simulated regimes would have seasonal patterns, means, variances, and other statistical properties similar to those of the real world climate, even though they were not derived from ground level measurements of the weather at the location being considered.

Much effort has been devoted to estimating unmeasured characteristics of tropical physical environments from observed physiognomic and structural characteristics of the vegetation. Such indirect estimation has been necessary because of the paucity of adequate environmental measurements. Examples are the vegetation classification scheme developed by Webb (1968) in Australia, and the Holdridge Life Zone System, widely used in Latin America. The possibility now exists that this traditional approach to environmental analysis may be entirely reversed. Instead of attempting to infer the nature of the environment from its vegetation, it may soon be feasible to specify the physical environment almost completely. This specification can then be used to better explain and predict the characteristics of a region's native ecological communities.

Contemporary satellite systems permit statistical studies of cloud cover. Near-earth polar satellites provide a nearly global picture of cloud cover twice every day. There are plans for advanced instruments to be flown in the 1970s which will make it possible to determine a coarse vertical profile of total water vapor in the atmosphere with an accuracy of about 20 percent. Instruments capable of determining the surface temperatures to better than 1°C absolute with about 0.25°C precision are planned for forthcoming meteorological satellites. A combination of available and projected satellite techniques is expected to permit estimation of net radiation at the surface. There are, however, at this time no satellite developments that might provide satisfactory observing techniques for local rainfall [Committee on Space Research (COSPAR), 1972]. A range of possible statistical and other estimating methods may be usable for this purpose by the time required climatological satellites are fully operational, however (Follansbee, 1973).

Concurrent with development of satellite observational techniques, work has progressed on the design of large computer simulation models of the global circulation of the atmosphere, particularly at the National Center for Atmospheric Research (NCAR) and at the National Oceanographic and Atmospheric Administration (NOAA) Fluid Dynamics Laboratory of the United States Department of Commerce. These models are becoming increasingly effective in mimicking the annual patterns of significant climatic variables everywhere. They can be operated to simulate a year's climate of the whole earth, at a scale of resolution of 5° or less of latitude and longitude, in a small fraction of a day. Repeated simulation runs of the global circulation models can be used to build up statistical distributions of climatic variables of interest, in effect extending in time the short period of record obtainable from satellites. There is now close collaboration between researchers concerned with obtaining and improving satellite observations and those developing atmospheric circulation models.

Synthetic climatic data will permit computation of regional energy balance and evapotranspiration values. The Penman method for determination of potential transpiration, as modified by van Bavel (1966) and others, provides a starting point for this investigation. Given regional values of net radiation, temperature, humidity, daily wind movement, and moisture holding characteristics of the soil, relatively simple computer programs can be written to estimate potential transpiration, actual transpiration, transpiration deficit, and soil-moisture storage. These variables can be summed over convenient periods, say half-months, and displayed as vectors representing the annual march of climatic phenomena. Associated with each vector element can be a measure of its variance from year to year. This sort of multidimensional representation of the climatic variables that drive ecosystem processes should logically yield more reproducible and interpretable results than would simple correlations of vegetation structure and function with annual rainfall and temperature alone. There will, of course, be a need for a number of carefully chosen calibration and validation sites, to test the methods in the field and to provide data for "tuning" the models.

Multivariate methods now exist for relating vectors such as transpiration and soil-moisture sequences to observable characteristics of biological systems. The eventual goal should be a scheme for arranging ecosystems in relation to one another on a hypersurface built around a biological model of responses to amounts, time distributions, and variances of soil moisture, temperature, solar radiation, and other pertinent environmental variables.

Development of satellite sensors capable of making the relevant observations has largely been motivated by a desire to understand and predict large-scale processes and events in the atmosphere itself. The prospective capability to make surface measurements of the type needed by ecologists is an almost accidental consequence of atmospheric scientists' needs for the same kinds of data. There is a need for greatly improved cooperation between ecologists and those atmospheric scientists concerned with global climatic measurements. Specifically, designers of meteorological and climatological satellites should be encouraged to accelerate the development of methods for improved acquisition and retrieval of data likely to be of value to ecologists as well as to atmospheric scientists.

There is a danger here that must be clearly faced, however. For the foreseeable future, meteorological and earth resource satellites will be operated in any numbers only by the U.S. and the U.S.S.R. As the Swedish ecologist Bengt Lundholm (1972) points out, relative to remote sensing we are in a situation where the technical development is much more advanced than the political tools with which to handle this development. He states

> A certain sensitivity, to use an understatement, may be felt by nations overflown by satellites that make inventorial surveys for economic reasons. Information concerning the agricultural aspects of natural resources might be used against the overflown country, especially if this type of information is not available to everyone. According to the USA's plans for earth-surveying satellites, all information is to be open and free. In spite of this there is a real danger that this new technology will increase the gap between the developed and the less developed countries.

There have already been objections from certain nations to the open dissemination of information discovered by satellite that may indicate previously unknown mineral deposits in their national territory. Considerable attention will be required to ensure that proper institutional arrangements are made for effective use of remote-sensing information in the general interest.

Somewhat similar conditions exist in instances where only a few nations possess the powerful computing systems that are required for truly large-scale atmospheric, geophysical, and ecological models. Institutional mechanisms should be developed to ensure that scientists from the countries or regions concerned are closely involved in the planning and conduct of computer simulation experiments involving ecological relationships in their countries.

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