ECOLOGICAL AND ENVIRONMENTAL PROBLEMS IN THE APPLICATION OF BIOMATHEMATICS

BURTON E. VAUGHAN
BATTELLE MEMORIAL INSTITUTE
PACIFIC NORTHWEST LABORATORIES
RICHLAND

1. Introduction

In view of the purpose of this symposium, I thought it appropriate to delineate some ecological aspects of pollution—aspects which require fairly sophisticated biomathematical approaches. If we are to have a plan to estimate health effects for any one of several suspected pollutants, be it DDT, a heavy metal, or a radionuclide, a good deal of descriptive information must be consolidated, quantized, and assigned priority. In some cases, the descriptive information still remains to be established, and in any event, we need a "road map" for the consolidation, quantizing, and assignment of priorities. We also need to be clear about objectives in such handling of the data, and I will have more to say on this at a later point.

During the past several days, considerable discussion about nuclear materials has taken place. It may be useful to take a brief look at the nuclear industry as regards other pollution problems. Let me say simply that the nuclear industry provides us with one of the few examples of a comprehensively planned technology. Operationally, it provided for the building of nuclear plants, their regulation, environmental monitoring, the setting of radiation exposure standards, and the support of studies on ecological and health problems. As a result, the assessment of risk to man and the underlying ecological pathways affected by discharge of radioactive wastes are probably more completely understood than any other kind of industrial risk. We have been taken by surprise with environmental deterioration (the poisoning of birds and fish by DDT) and with serious toxicity effects (the contamination of fish by mercury). Yet, the dissemination of many such pollutants, particularly persistent chlorinated hydrocarbon compounds, is analogous to the radiation situation. The attendant phenomena of dispersal, biological concentration, and concentration in feed webs were predictable.

2. Environmental deterioration as a concern

Let's examine our ecological objectives more closely. Emphasis, during the past few days, has been placed on narrow aspects of health—mortality, long term toxicity, and potential mutagenicity. I hope we can also agree that a good natural environment is a determinant of one's general well being. Environmental quality is much less well defined, at this point in time, than is physical health in the sense of one's freedom from disease. Yet, its over-riding importance has been clearly indicated by creation of the first Presidential Commission on Environmental Quality, by the report of that Commission [6], and by the creation of the Environmental Protection Agency, itself.

Most authorities agree that widespread environmental effects affecting our health could potentially overtake us, and rapidly, as a direct consequence of our very large technological growth rate (for example [6], [14]). This growth rate is typified by the projection of total energy demand in the United States shown in Figure 1. The growth rate shown is only about four per cent per year,

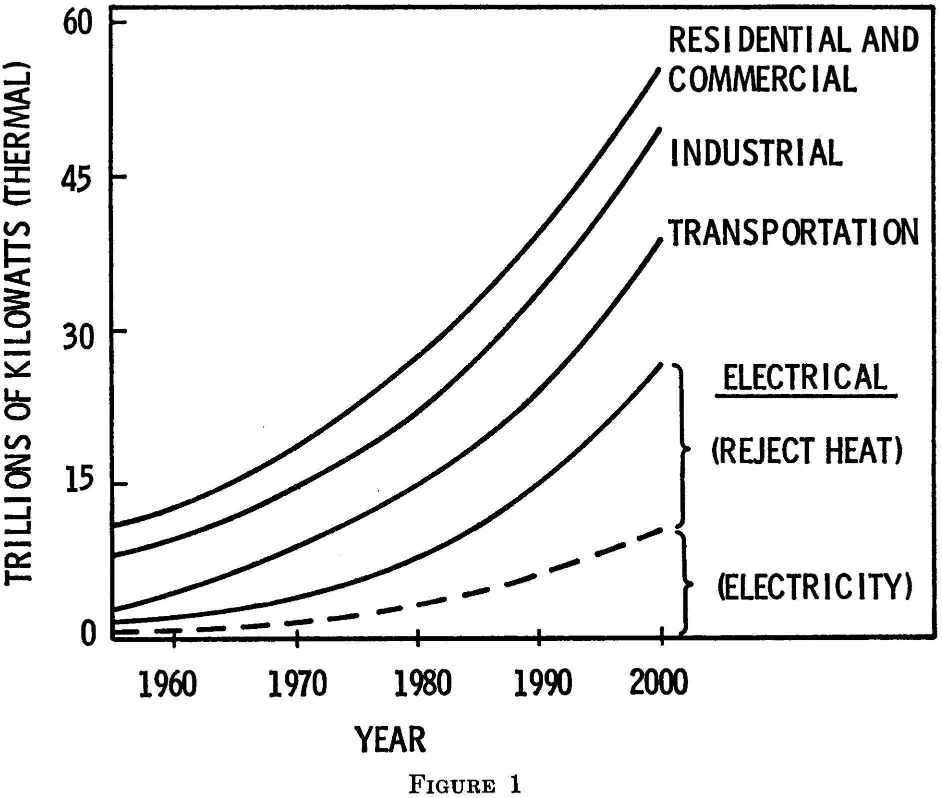

FIGURE 1

Total energy, projected demand to year 2000. Waste heat consequent on electrical generation in year 2000 will exceed present total electrical generation.

but the utilities companies frequently use larger rates for planning purposes. Note that waste heat ("reject" in Figure 1) will, in year 2000, exceed total electrical generation as of 1955. The problem of heavy pollution consequences—in this case waste heat—exists in a situation where there is little land reserve. Worldwide, land reserves amount to about ⅓ of global land surface and are principally in forest holdings [14]. The U.S. Picture is much tighter, with less than five per cent in any sense to be considered reserve [6].

How does pollution affect environmental quality? Are there important values other than personal esthetic values? These questions, in fact, have been answered well in several recent publications [5], [13], [14], so I will take time only to indicate one peculiarly ecological problem which the SCEP work group termed "pesticide addition" [14]. In this situation, regular use increases the need for and frequency of application of pesticide. Continued use creates new and sometimes resistant pests. Also, new herbivorous insects find shelter among crops where their predator enemies cannot survive. To stop pesticide use in this situation invites catastrophic crop damage. The problem shows another aspect. In Table I, if we compare crop yield with pesticide use, we see that a 10-fold increase in pesticide application led to a crop yield which increased only threefold. Thus, we find ourselves locked into a new technology with highly polluting consequences and, perhaps, at an irreversible point.

TABLE I

PESTICIDE USE COMPARED TO AGRICULTURAL YIELDS, IN SELECTED WORLD AREAS

Source: FAO, *Production Yearbook*, 1963.

Area or nation	Pesticide use (grams per hectare)	Yield (kilograms per hectare)
Japan	10,790	5,480
Europe	1,870	3,430
United States	1,490	2,600
Latin America	220	1,970
India	149	820
Africa	127	1,210

3. The environmental approach to pollution effects

With a broader definition of health and pollution in mind, let us now approach the problem of planning an epidemiological study of pollution effects. To be systematic, we need to keep in mind several types of effort which, in fact, constitute determinants of any pollution process. Several of these factors have already been well recognized in nuclear energy development. They are:

(1) Environmental pathways; identifying the geographic distribution, of sources and magnitudes of pathways.

(2) Ecosystem structure; description of biotic systems likely to be affected: (a) food webs, food chains, and trophic levels; (b) physical factors, their interaction with different biota (climatic, meteorological, edaphic, and hydrological factors).

(3) Indicator species; monitoring their activity. Involves measurement of uptake, concentration, population levels, and loss for (a) organisms important to the functional integrity of ecosystems, and (b) organisms which are critical for certain food chain links.

(4) Biological effects and retention; measuring (a) toxicity data for extrapolation to man, and (b) most sensitive species for assessing ecological perturbation; for example, loss of eagles, insect predators, and fish.

(5) "Ultimate reservoir"; assessing potential size and possibilities for reentrainment of pollutant (may be air, organisms, soil, or water).

4. What pollutants need study?

A serious difficulty remains, in any of this work. For any pollutant of concern, we have, simultaneously, insufficient data in certain categories mentioned above and an overwhelming amount of secondary data in the other categories. In such a situation, we do well to start with as accurate as possible a case history for individual pollutants, then ask what kind of biomathematics is desirable and necessary to further a solution. Pesticides like DDT, petroleum, phosphorous, lead, and mercury, can be selected as good case studies. They are not necessarily the most important pollutants, but they differ significantly in their target, their effects, their sources, and their routes into living organisms. Considered together, they represent a broad spectrum of the considerations necessary to assess global pollution and its effects directly and indirectly on health.

Biocides used for the control of weeds have increased substantially during the past 20 years, particularly the organochlorine compounds. In 1964, 184 million pounds of herbicides were sold in the United States, and 97 million acres of agricultural land were treated with them [2]. In a major study [1], many substances were considered from an operational point of view. Such an analysis had to be ultimately limited to lead and to DDT, because of the scarcity of data regarding the environmental effects of the other biocides. DDT and lead were, of course, in widespread use, longer than any other material, and they had demonstrated wide interaction with all of the potential ecological and other transport pathways for man-made chemicals in the environment.

The relatively short time allotted this morning will not permit comprehensive discussion of lead, or the other pollutants mentioned above, so we will, this morning, confine our attention to a single case study, DDT. Partial information on the other pollutants can be found in the literature [1], [2], [14]. Basically, we approached each of these problems with the five-step approach, indicated above.

5. DDT case study

5.1. *Environmental pathways.* Figure 2 is based on comprehensive studies of sources, production levels, and various reported concentrations in the environment [1], [16]. Geographic locations of DDT producers are less well known, however. One may note, also, that an operational analysis of this kind includes data from many workers, based on non-standardized technics. Thus, many of the reported water concentrations are too high, 10 or 1000-fold higher than the solubility limit of DDT. Undoubtedly, these samplings included microscopic organisms in which DDT was concentrated. It is of interest that of the DDT produced annually, about ¼ ends up in the ocean. This estimate is based on measured concentrations in rainfall [20] and estimated total oceanic precipitation [14]. There are, however, about 25-fold differences among some of the DDT samplings measured [14], [16], [17], and the discrepancies show a need for comprehensive world-wide monitoring. Since DDT binds to the surface of the soil clay particle, runoff concentrations as we have reported them here are

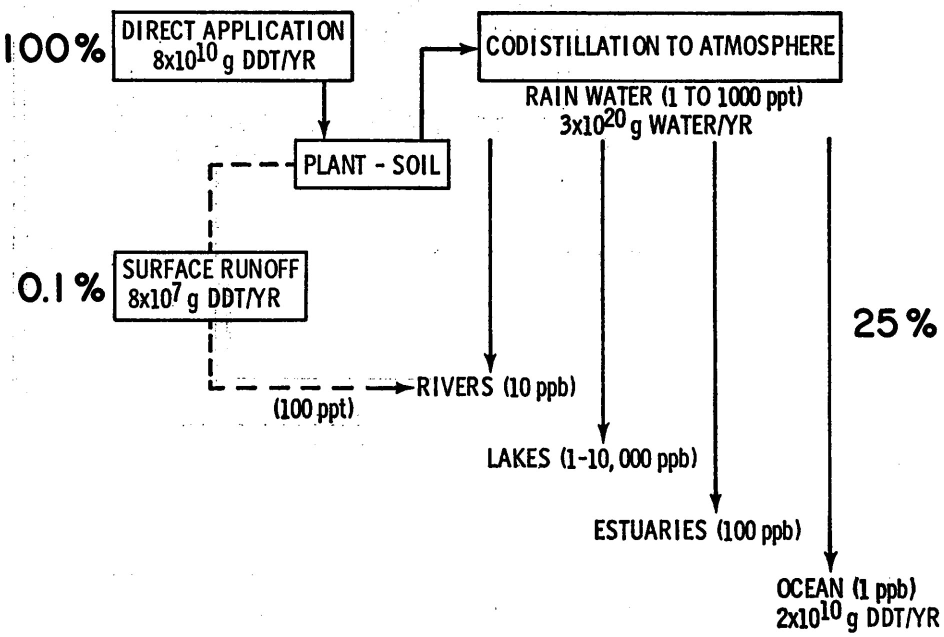

FIGURE 2

Environmental pathways for DDT, showing ranges of reported concentrations and estimated magnitudes of transport. Water concentrations except ocean probably represent mixed activity (see text).

probably overestimated for average conditions. Most of DDT finding its way into the oceans appears to be disseminated atmospherically after redistillation with water from the soil and water surfaces [14], [16]. An alternative explanation may be that soil particles carrying DDT are aerosolized by winds, since our (unpublished) data on co-distillation seem low in comparison to present estimates.

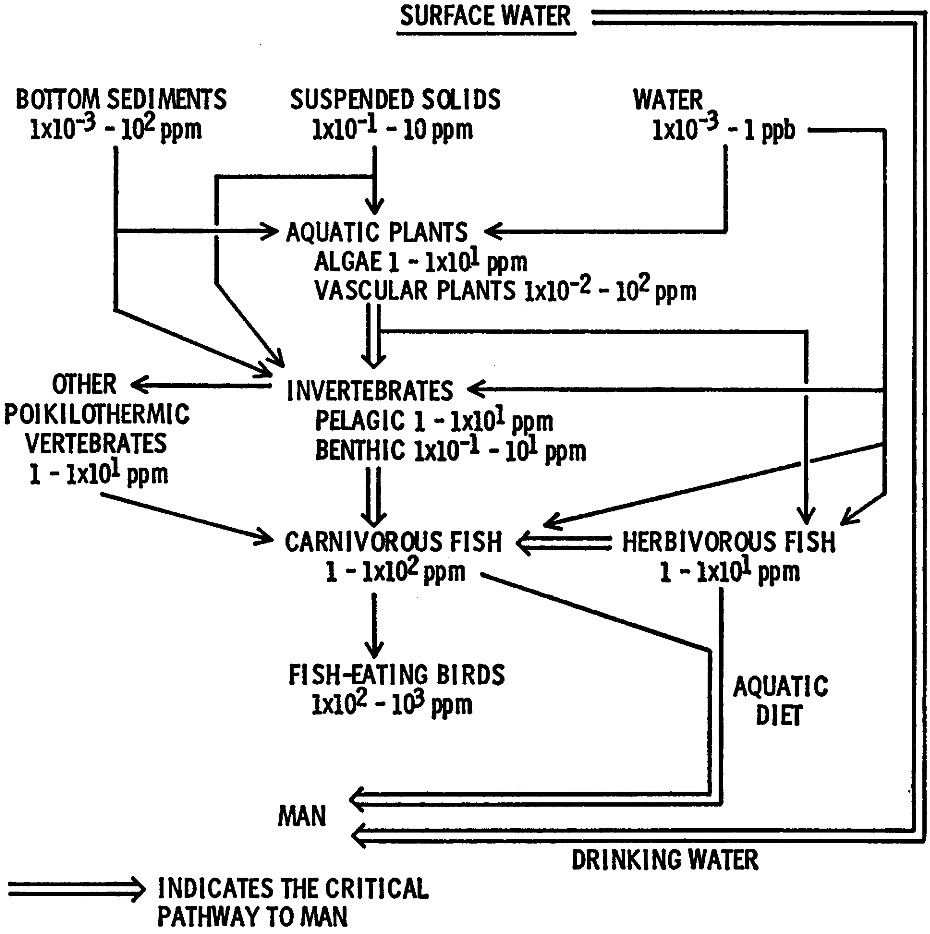

FIGURE 3

Ecological pathways for DDT in aquatic ecosystem, showing also critical pathways to man. This is only one of six subsystems indicated in the preceding figure.

5.2. *Ecosystem structure.* In Figure 3, we have summarized the ecological structure of a marine aquatic system, showing both typical classes of organisms according to their trophic (feeding) levels and their measured concentrations of DDT. The significant features here are (1) the 1000-fold concentration of DDT in aquatic plants as compared to water (shown in the preceding slide) and (2) another 1000-fold increase in concentration in the tissues of fish eating birds. At worst, a 10^6-fold concentration has taken place from water to bird. This representation is generalized, it also shows the set of pathways for DDT entering man through fish. I'll have more to say about man at a later point. Here we will temporarily ignore man and examine the rest of the ecological system from the standpoint of deterioration in environmental quality. The DDT levels shown represent approximately steady state magnitudes where world-wide concentrations are only slowly increasing. There are, however undoubtedly wide regional differences.

Comparable magnitudes also have been measured in experimental situations where radioactively labelled DDT was administered in a single aerial spraying. In such a study of a freshwater marsh [8], [9], we attempted to model a restricted aquatic ecosystem, in order to predict transfer rates between trophic levels. As shown in Figure 4, the maxima for tissue accumulation of DDT, for various organisms, were attained in about 30 days, with multiexponential loss curves thereafter. Some of difficulties of sampling are indicated in this study, in which, for example, had we rigidly adhered to a fixed time sampling program (desirable for reasons of economy) we would have missed important features about DDT turnover in sediments, tadpoles, and pondweeds.

The ecosystem shown in Figure 4 is in a dynamic state, with organisms in higher trophic levels dependent on next preceding organisms. With more complete data, one might be able to quantitatively estimate standing populations and energy transfer rates between trophic levels. However, most of the populations are changing rapidly with time, and in location, so that the model portrayed is not presently adequate as a quantitatively predictive model for system behavior. One may see how productivity of the whole system would be impaired if aquatic plants were to disappear. As it stands presently, this model is useful for revising sampling strategy, assessing organisms for their utility as biological concentrators of DDT, and for estimating transfer rates between trophic levels.

In the two preceding figures, we showed a marine and a marsh aquatic ecosystem. There are also several important terrestrial ecosystems to consider for DDT. Information on terrestrial food-webs is much more sparse, primarily as a consequence of the greater difficulty in sampling and monitoring (see [21]). We do not have adequate information about deterioration of terrestrial environments, although warning signs are up.

5.3. *Indicator species and biological effects.* Both of these pollution parameters are now fairly well established. Fish-eating birds, for example, petrel and pelican, are extremely sensitive because of their high concentrating capacity. Both the causative mechanism and the correlation between reproductive success and DDT levels are established for these birds and also for carnivorous fish, especially sea trout [16]. Robert Risebrough, earlier this week, documented the near extinction of the brown pelican as a consequence of DDT interference

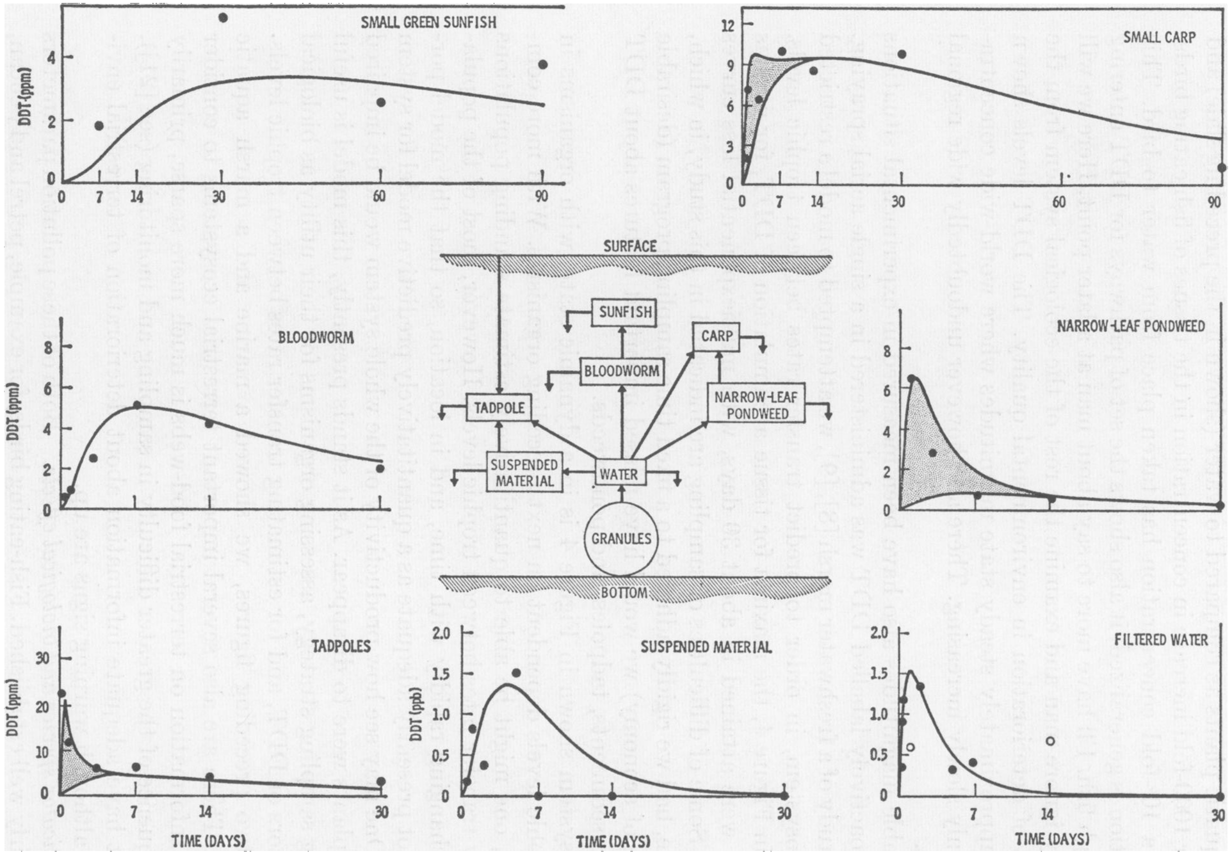

FIGURE 4

Spraying of a freshwater marsh with Cl 36 labelled DDT, showing simulation and observed data (superimposed points) (based on [8], [9], reprinted with the permission of the author and the editors of *Nature*).

with normal hatching. Laboratory toxicity determinations now show that *at least some marine organisms at every trophic level are exposed to lethal concentrations,* for DDT at the higher levels reported in Figure 3. This includes fish larvae, crab, shrimp, oysters, molluscs and other species [16]. Certain phylplankton are extremely sensitive to DDT, in the parts per billion range [15], [22]. There are, of course, myriad planktonic organisms, and it is not clear that the depth or range of species concerned are equally affected by water concentrations as presently measured. DDT and the polychlorinated biphenyls (PCB) seem to distribute together, and they have similar biological effects in birds [24]. It is not clear at present to what extent effects attributed to DDT are consequent on PCB. Analytic differentiation of the compounds is difficult, but it should be better established.

5.4. *Ultimate reservoir.* As to reservoir, we have only sketchy information, not readily quantifiable. Soil degradation rates are quite slow [12]. We know little about the long term cumulative effects on soil micro-organisms. The quantitative estimates I described earlier for codistillation suggest that the ocean is the ultimate accumulation site. However, we have little or no information on rainout patterns in relation to aquatic breeding sites—in estuaries and on continental shelves, as in Figure 5—nor do we know about depth distribution

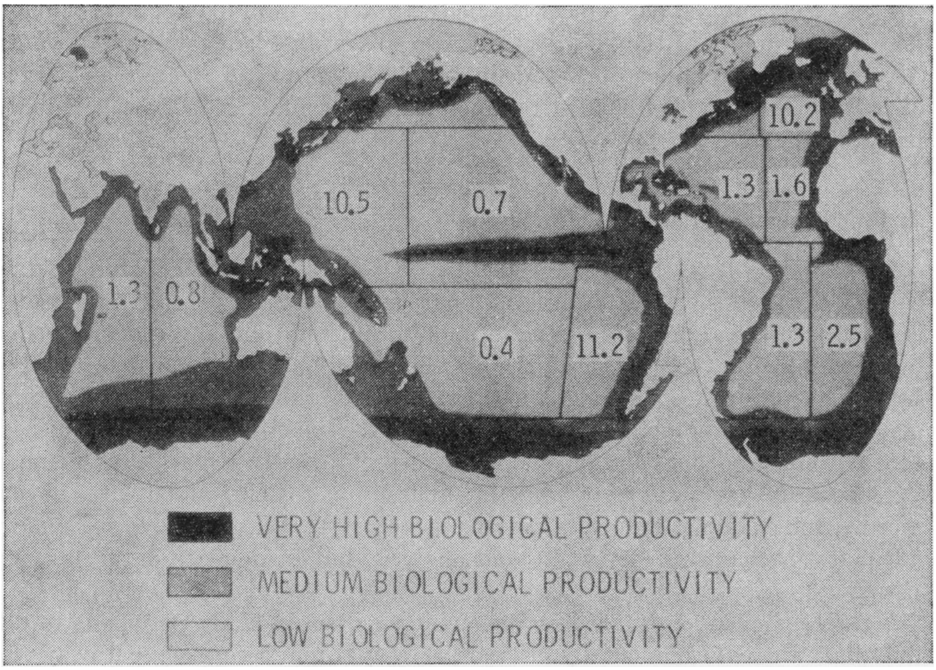

FIGURE 5

Productivity of marine fisheries in millions of metric tons (copied from [16]).

profile important to the behavior of organisms. DDT and other organochlorine residues are probably concentrated in the surface water by activity of the microorganisms present [16].

6. Environmental factors affecting body burden of DDT in man

Study of environmental pathways is not only important from the standpoint of environmental deterioration. There are also less obvious routes by which man is affected, apart from ingesting food.

Human exposures can be divided into direct and indirect pathways [1]. The direct pathway deals with the uptake from primary sources, during manufacture and applications where human exposure is primarily by inhalation. Dermal uptake as well as ingestion are features of the direct pathway. The indirect pathway involves human exposure by translocation through the air, water, or food. Of these, the critical pathway to man is through the aquatic food chain, particularly fish. One should note, however, that conflicts exist in the data, as to indirect pathway. Worldwide, persistent pesticide content in man is remarkably constant. Within the United States there are, however, significant racial and geographical differences. Such differences are difficult to explain if food is the major transport pathway to man. Indirect evidence, from residues in animals, suggests that only 50 per cent of the body burden is from food. The remainder may come from inhalation of insecticide aerosols or dust laden with insecticides. Assuming the correctness of this deduction, then control of the human burden of pesticides by control of food residues, as is now practiced, is, at best, only partially effective.

7. Biomathematical aspects of pollution

The real problem, at this point in time, as exemplified by DDT, but holding equally for the other pollutants—oil, phosphate, mercury, 2-4-5-T, and lead—is the need for an adequate system of monitoring and sampling. This is needed in order to definitively establish the dissemination pathways and patterns. For DDT, operational considerations point to atmospheric dissemination and codistillation as key factors. We already know the sensitive species, with respect to environmental degradation and with respect to critical pathways to man. We probably have adequate work in progress on toxicity and related mechanisms; for example, inducible enzyme systems [4]. We also have reasonably adequate mechanisms for operational analysis, but inadequate data, in many cases.

7.1. *Monitoring needs.* Adequate monitoring would likely permit us to differentiate the environmentally critical pathways from secondary pathways for dissemination of DDT. For example, a synoptic series of maps, like Figure 5, is needed, showing DDT levels of water or biota in relation to precipitation patterns. An analogous series should be prepared showing DDT levels in relation to ocean currents. Such maps should also show locations and magnitude of manufacturing source and density of effluent. Similar analysis has already been done, with the necessary curve-fitting technics, for certain air pollutants, as Joseph Behar showed earlier this week. It is only in this way that operational analysis achieves its full potential as a useful tool.

7.2. *Sampling strategy.* Monitoring is, however, costly, and optimum sampling strategy cannot usually be specified *a priori* without a good understanding of the descriptive aspects of the system.

The sampling problem has held our attention for several years [7] through [11]. We have generally assumed that the principles of first order kinetics provide a reasonable mathematical model of the actual processes governing pollutant movement through food chains. Our procedure generally involves (1) establishing "case histories," (2) constructing computer simulation models for individual case histories, (3) investigating linear least squares methods as tools for fitting models to data, (4) attempting to elucidate some general principles that may be appropriate for predicting rate constants for substances and species that have not been directly studied, and (5) formulating questions about efficient sampling procedures. At present, it seems necessary to limit an approach via simulation to some rather simple situations, inasmuch as there are a number of unresolved questions about descriptive aspects of the systems of concern. In Figure 6, and in Figure 4 shown earlier, we can examine two simulated ecosystems with a view toward optimizing sampling strategy. Basically, there are three elements to consider [8]: (1) sampling in time, (2) sampling the system, and (3) sampling the space.

Of these elements, sampling in time is basically a curve fitting process. Seasonal cycles in concentration are usual, and they will affect measurement levels. Also, an optimum sampling spacing for one species may be very inefficient for another.

Sampling the system involves assessing the potential pathways of accumulation for a pollutant. If we have extensive data available in the literature, the problem is simplified, but considerable experience and judgment are still required. Such judgment is evidently not yet generally available for efficient "systems analysis." If the pollutant is, in fact, doing serious damage to some species population, there is evidently need to bring in whole new areas of study, for example, population dynamics and dose response models. Field study of the effects of pollutants on natural populations is something that we see very much in prospect, but I do not at the moment perceive much more than that we somehow have to establish connections between "food chain kinetics" and population dynamics as the relevant fields of inquiry.

Sampling in space is complicated by seasonal cycles and by feedback effects. Of these two problems, potential recycling (re-entrainment) constitutes a formidable problem. Usually, only a small fraction of material is found in aggregate mass of biota compared to the "reservoir" locations. For this reason, a balance study must usually be coupled to the dynamic study. In this connection one

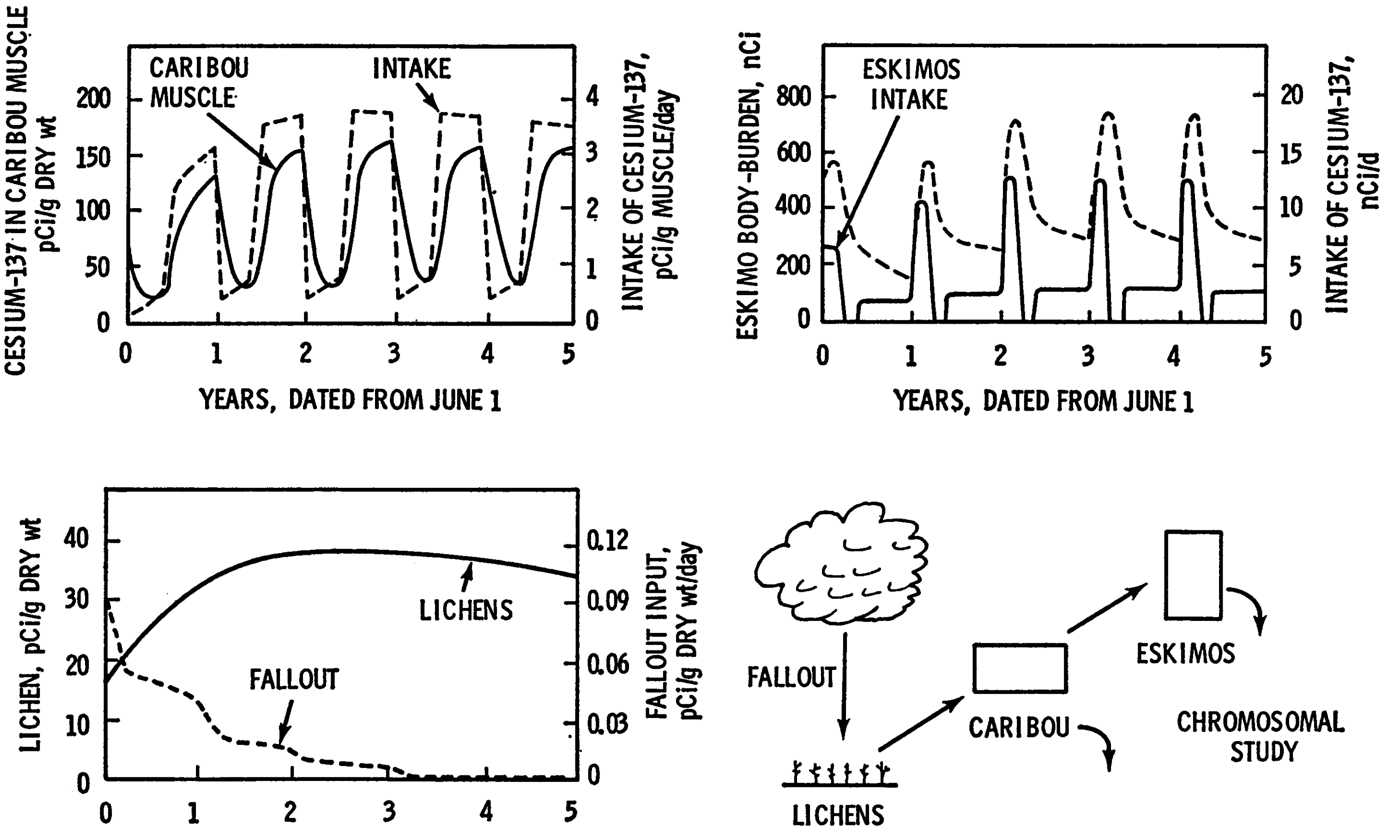

FIGURE 6

Simulation model of arctic ecosystem; showing effect of caribou feeding pattern on man's body burden of Cs 137. The model is based on extensive observational data (points omitted for clarity), see Figure 7.

should note the 1000-sample ocean baseline sampling program proposed in the SCEP report [14].

The Arctic ecosystem shown in Figure 6 lends itself particularly well to ecological modelling because the pathways are comparatively simple and because a very extensive body of data was accumulated on all aspects of the system. A remarkable feature of the system is how faithfully the seasonal increase in body burden of Cs 137, in those Eskimos following native ways, reflects the seasonal variation in Cs 137 in the caribou. The variation in caribou is a consequence of their winter dependence on lichens for forage (seasonal migration to feed on lichens). Lichens are good accumulators of Cs 137 from fallout. The Eskimo's body burden is related to that of the caribou herd and to its movement, thus, a complex consideration exists as to modelling parameters. In Figure 7, we can judge better the simulation in relation to observed data points for Cs 137 in muscle. The parameters here include time of the migration and the amount of lichen eaten, which then apply to the entire six season run of data. The

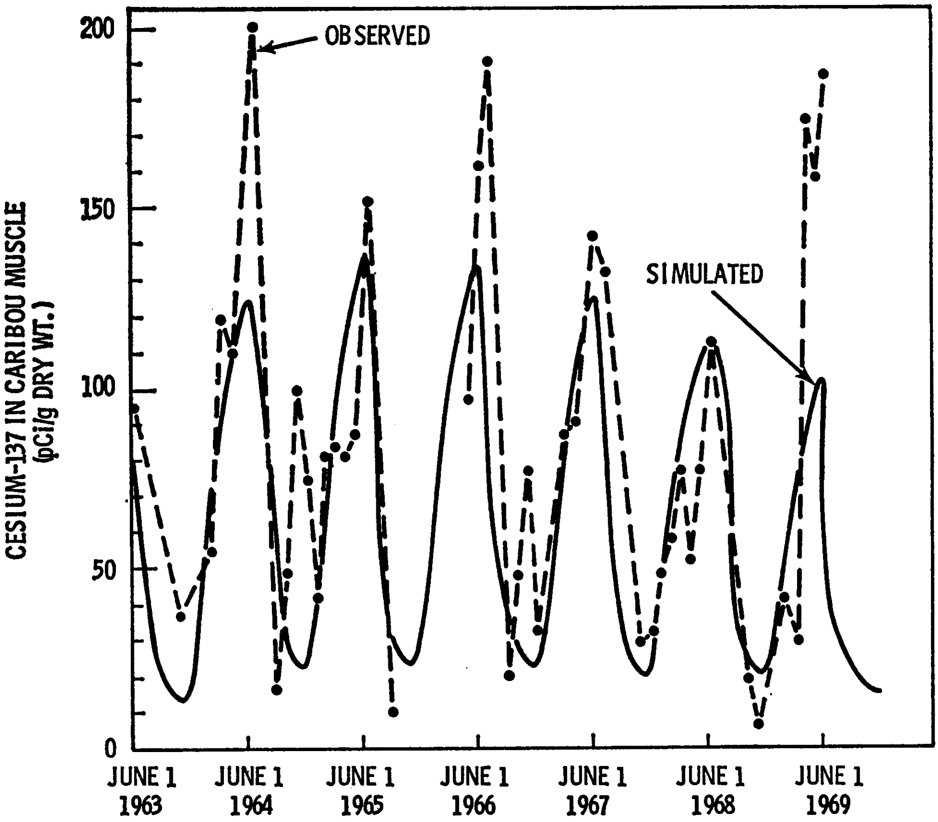

FIGURE 7

Comparison of simulation and observed points; Cs 137 in caribou muscle.

simulation is rather accurate in time phasing, but of note are the several high peaks, which we cannot yet model from *a priori* considerations.

Sample survey methods are a well established and essential feature of natural resource biometry. Since the ecosystems studied are dynamic, the problems encountered have many features in common with population studies. If objectives of a given study are taken to be the estimation of total quantities of a contaminant, it becomes necessary also to estimate the biomass of the species considered. So far, most studies have dealt with concentration rather than quantities, and interest in the immediate future appears likely to center around supplying parameter estimates for kinetic models expressed as concentrations. Beyond the evident difficulties of dealing with mobile forms of life (in the consumer and higher trophic levels) lie the prospects that concentrations may change rapidly in time. Perhaps the major departure from standard sample theory is that surveys are largely "analytic" in nature. That is, objectives are usually not so much to estimate totals as to discover and measure differences in time, space, and species. Brief treatments of analytic survey methods are available [3], [18], [23].

8. Conclusion

I have not attempted to describe in any detail our biostatistical procedures, but rather to delineate the broad range of ecological and environmental problems. Each problem has intensive biomathematical need. The needs encompass systematized operational analysis, statistical estimation, and, in a few cases, deterministic models of the ecological system.

I would like to thank my colleagues at Battelle Memorial Institute. My comments here have drawn freely on their studies.

REFERENCES

[1] BATTELLE MEMORIAL INSTITUTE, *Technical Intelligence and Project Information System for the Environmental Health Service*, Columbus, Battelle Memorial Institute, Vol. 3; see also, *ibid.* 29 June 1970, Vol. 4, pp. 20–38.

[2] BATTELLE MEMORIAL INSTITUTE, *Environmental Pollution* (background paper for the Atlantic Council and BMI conference on Goals & Strategy to Environmental Quality Improvement in the Seventies), Columbus, Battelle Memorial Institute, 1 December 1970, pp. 6–8.

[3] W. G. COCHRAN, *Sampling Techniques*, New York, Wiley, 1963 (2nd ed.).

[4] A. H. CONNEY, "Pharmacological implications of microsomal enzyme induction," *Pharmacol. Rev.*, Vol. 19 (1967), pp. 317–366.

[5] J. CONSTABLE and M. MESELSON, "The ecological impact of large-scale defoliation in Viet Nam," *Sierra Club Bull.*, Vol. 56 (1971), pp. 4–9.

[6] COUNCIL ON ENVIRONMENTAL QUALITY, *Environmental Quality* (first annual report of the President's council transmitted to Congress), Washington, D.C., U.S. Government Printing Office, 10 February 1970.

[7] L. L. EBERHARDT, "Modelling radionuclides and pesticides in food chains," *Proceedings*

of Third National Symposium on Radioecology, Washington, D.C., USAEC, 12 May 1971, in press.

[8] L. L. Eberhardt, R. L. Meeks, and T. J. Peterle, "DDT in a freshwater marsh—a simulation study" (Document No. BNWL-1297), Richland, Battelle Memorial Institute, Pacific Northwest Laboratories, 1970.

[9] ———, "Food chain model for DDT kinetics in a freshwater marsh," *Nature*, Vol. 230 (1970), pp. 60–62.

[10] L. L. Eberhardt and R. E. Nakatani, "Modelling the behavior of radionuclides in some natural systems," *Symposium on Radioecology* (edited by D. J. Nelson and F. C. Evans), CONF-670503, Springfield, N.T.I.S., 1969.

[11] L. L. Eberhardt and W. C. Hanson, "A simulation model for an arctic food chain," *Health Phys.*, Vol. 17 (1969), pp. 793–806.

[12] C. A. Edwards, "Insecticide residues in soils," *Residue Rev.*, Vol. 13 (1966), pp. 83–132.

[13] D. W. Ehrenfeld, *Biological Conservation*, New York, Holt, Rinehart & Winston, 1970.

[14] Massachusetts Institute of Technology, *Man's Impact on the Global Environment, The Study on Critical Environmental Problems* (SCEP Report), Cambridge, MIT Press, 1971.

[15] D. W. Menzel, J. Anderson, and A. Randthe, "Marine phytoplankton vary in their response to chlorinated hydrocarbons," *Science*, Vol. 1967 (1970), pp. 1724–1726.

[16] National Academy of Sciences, *Chlorinated Hydrocarbons in the Marine Environment* (Report of panel on monitoring persistent pesticides in the marine environment, Committee on Oceanography), Washington, D.C., National Academy of Science, 1971.

[17] T. J. Peterle, "DDT in Antarctic snow," *Nature*, Vol. 224 (1969), p. 620.

[18] J. Sedransk, "An application of sequential sampling to analytic surveys," *Biometrika*, Vol. 53 (1966), pp. 85–97.

[19] H. V. Sverdrup, M. W. Johnson, and R. H. Fleming, *The Oceans*, New York, Prentice-Hall, 1942, p. 120.

[20] K. B. Tarrant and J. Tatton, "Organopesticides in rainwater in the British Isles," *Nature*, Vol. 219 (1968), pp. 725–727.

[21] U.S. Department of Agriculture, *Wastes in Relation to Agriculture and Forestry* (Miscellaneous publication no. 1065), Washington, D.C., U.S. Government Printing Office, March 1968.

[22] C. F. Wurster, "DDT reduces photosynthesis by marine phytoplankton," *Science*, Vol. 159 (1968), pp. 1474–1475.

[23] F. Yates, *Sampling Methods for Censuses and Surveys*, New York, Hafner, 1960.

[24] R. W. Risebrough, S. G. Herman, D. B. Peakall, and M. N. Kirven, "Polychlorinated biphenyls in the global ecosystem," *Nature*, Vol. 220 (1968), pp. 1098–1102.

Discussion

Question: E. L. Scott, Department of Statistics, University of California, Berkeley

The fit of the models shown by Dr. Vaughan is very impressive. From the slide alone, I do not know whether the deviations are important. They raise the question of the possible effects, with interactions, of other pollutants. In the Eskimo study might there not be, say, DDT from the atmosphere as well as cesium entering the food chain? Are there data towards questions like this and have they been considered?

Reply: B. E. Vaughan

Referring to the Arctic lichen-caribou-Eskimo food chain, the deviations from simulation curves, as shown for Cs 137 in caribou (Figure 7), are certainly important. We do not know why occasional groups of samples peak at higher than predicted values. I doubt that these peculiarities in the data represent interactions with other pollutants, because we measured Cs 137 specifically and because the concentrations measured are known to be without significant physiological consequences. It is much more probable that the early peak and unusually high values represent some as yet undescribed phenomena concerning the growth cycle of the lichens, or the migrating habits of the caribou, or both.

On the question of DDT as well as Cs 137 and other pollutants entering such food chains via the atmosphere or water, we try to get simultaneous data where possible for monitoring purposes. But analysis costs can be quite expensive. More importantly, there remain problems about suitable sampling strategy. Such data as we have are very few and not indicative of unexpected phenomena. It will be a very long time in the future before the question of possible synergistic effects can be considered experimentally.

Question: R. W. Gill, Department of Biology, University of California, Riverside

Would you comment on the relative importance of the different biological and physical factors as possible vectors for the transportation of DDT from ecosystem to ecosystem throughout the world?

Reply: B. E. Vaughan

Vectors in the sense of the carrier for DDT? Well, certainly atmospheric precipitation seems to be a prime factor in disseminating DDT worldwide, and it is governed chiefly by physical processes. This matter is not proven to rigorous standards, however, so we should beware of some of the discrepancies in the data.

Biological vectors seem to be unimportant. Bacteria and planktonic organisms, in surface water, which concentrate DDT thousands of times over its water solubility cannot really be considered a vector in the epidemiological sense of the term. They are ubiquitous and don't move far. Neither should carnivorous fish and sea birds be considered important as vectors, even though their feeding habits and the biochemical properties of DDT lead to high concentrations. Fish and birds are accumulators, not disseminators, and they are ultimately killed by DDT.

Question: Joel Swartz, Biophysics, University of California Berkeley

Is it feasible to obtain a lot more data points for the systems described? It seems that there are insufficient data to distinguish between models.

Reply: B. E. Vaughan

It is feasible but expensive. Fifteen years of effort and at least two people were involved in the Arctic food chain study. There is also nothing intrinsically more real about one or another mathematical model of the Arctic ecosystem. More than one approach can be designed; the important consideration is whether or not a given model allows a better evaluation of sampling or dynamical problems.