SAMPLING FOR RADIONUCLIDES AND OTHER TRACE SUBSTANCES^{1,2}

L. L. Eberhardt
Battelle Memorial Institute, Pacific Northwest Laboratory
Richland, Washington 99352

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1. INTRODUCTION

Much of the difficulty in determining whether a particular "environmental crisis" is real or not has to do with sampling. Until we understand the mechanisms and rates governing behavior of the chemical agents regarded as a potential threat to man and his living environment, there is no assurance that a given substance is or is not a problem. Most of the available scientific evidence indicates that past and current levels of radioactivity in the environment cannot be regarded as hazardous in the ordinary sense of the word. Intensive study of radionuclides in food chains during and since the period of worldwide fallout associated with nuclear weapons testing has provided much in the way of technology for studying other contaminants in natural systems and led to the development of the field of radioecology.

Sampling methodology for dealing with contaminants and pollutants has generally lacked the sharp focus existing in studies of natural resources. That focus is the emphasis on effective exploitation, which translates readily to questions of "how much?" or "how many?", and thus permits direct application of sample survey methods. Success in management can be appraised in terms of yield or harvest. Somewhat analogous objectives can, of course, be framed for studies of pollutants, and ultimately tested by success in reducing levels. However, other kinds of objectives may call for quite different approaches to sampling. The purpose of this lecture is to describe some of

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these objectives and comment on the available technology.

2. BACKGROUND AND NATURE OF PROBLEMS

Table 1 provides a partial list of issues involved in the recent widespread concern about our environment. This list is not claimed to be complete nor to assign a particular importance to various items. It should help to identify some of the different kinds of sampling problems likely to be involved and to suggest how objectives may vary. Table 2 supplies a categorization of man's concerns with natural environments and thus provides another basis for considering sampling and objectives.

Among the many concerns suggested by Tables 1 and 2, we will here mostly concentrate on those having to do with the distribution and redistribution of some trace substance in a natural system. For the most part we will assume that substance to be a contaminant introduced by some human activity. A pesticide, like DDT, provides a concrete example. We note that the substantial International Biological Program "Analysis of Ecosystems" effort in the study of the productivity of various biomes involves very similar kinds of investigations, but the trace substances there are largely nutrients. Contaminants can, of course, also be nutrients, as is all too evident in many of our lakes and streams.

It is convenient to consider two broad classes of contamination -- global and local. Excepting fallout radionuclides, it is only quite recently that the global aspects of pollution have begun to be appreciated. It now is becoming apparent that substances like DDT and the PCB's (polychlorinated phenyls) may be redistributed by atmospheric processes and thus be as all-pervasive as the radionuclides produced by weapons testing in the 1950's and early 1960's. DDT is now found in the biota of the Arctic and the Antarctic, and scattered instances of real damage to the biota leads to considering it as a threat to our living resources.

No sampling has yet been done on a global scale, although there are reports of what one might call "global skimming" -- heterogenous collections of analyses of assorted organisms depending mostly on opportunities provided by other investigations. Such studies may provide useful background data and suggest possible mechanisms, but are also subject to over-interpretation and serious errors. A recent report on chlorinated hydrocarbons in the marine environment (National Academy of Sciences, 1972) summarizes current knowledge of the fate of the huge quantity of DDT estimated to have been produced in the world. For the most part, it has been necessary to resort virtually to guessing to obtain some notion of the distribution and transfer rates for DDT on a global scale. Large scale surveys are clearly needed and have been repeatedly called for in panel reports published in the last decade, but are apparently not in immediate prospect.

Implementation of the National Environmental Protection Act (NEPA) has begun to focus attention on some instances of the "environmental impact" of those construction activities involving Federal agencies. So far the working basis is largely one of analyzing the impact of a single installation of some sort. One can then take a conceptual point of view built around the likely polluting effect of a single effluent stream of some sort. While this is the kind of framework essential to enforcement or any sort of legal activity, the actual effect on ecosystems depends very much on all of the other sources of "impact" in the vicinity. Since the most evident large-scale damage thus far has been apparent in lakes and streams, one can visualize the problem as one of evaluating a single source in terms of its incremental effect on those effects produced by a variety of sources upstream from the one under consideration. We thus find the local problem to be at least a regional one so that the sampling problems may not be greatly different from those on a global scale.

3. SAMPLING OBJECTIVES

A review of some objectives in sampling for contaminants will help show the need for some additional developments in sampling methodology. The following suggested objectives seem to be to be arranged roughly in order of difficulty.

3.1 Balance study

This is the situation in which the more or less standard survey sampling technology applies directly. The objective of the survey is taken to be that of determining the total amount of some substance (like DDT) in the environment. Some unnecessary complications can be avoided if we stop to consider the small mass of the biota relative to that of the rest of the environment. That is, if our objective is to estimate the total amount of DDT in our environment, then the governing considerations are those having to do with essentially "air, earth, and water". That is, the relatively small mass of the biota ensures that most of the DDT residues (which we here take to include various biologically active degradation products of the original chemical) are at any given time either in the atmosphere, suspended in water (including adsorption to non-living particulate matter), or bound up in soil, silt, etc. Although our concern may be mostly with that DDT currently associated with living organisms, this is not where the main quantity of DDT will be found, nor is the biota quantitatively important in transport or redistribution. In establishing a material balance, one may thus do relatively little sampling of biological material. Any attempt to do a balance study for a pesticide presumably would be greatly facilitated by a review of the existing experience with radionuclides -- in particular the "global" study of strontium-90 done in the last two decades.

3.2 Baselines and monitoring

Since our concern with substances like DDT has mostly to do with effects on living systems, actual sampling objectives may be more along the lines of what have been described as "baseline" surveys. Sampling objectives then have to do with measuring changes over time and, since the major concern is with concentrations in the biota, a large fraction of the sampling effort may be devoted to biological material. However, it seems foolish not to also sample with an eye to eventually predicting future changes, so we then need to incorporate measurements on the major reservoirs (air, earth, and water). Hence the situation becomes more complicated.

Once we begin to deal with the biota, the highly dynamic nature of the system begins to become evident. Many more studies of actual cases need to be accumulated to provide good definition, but the presently available evidence points to distinct seasonal cycles in concentration in the biota. This is only reasonable in a temperate zone dynamic system, in view of the marked seasonal changes in environmental conditions. At the present we simply do not know what seasonal shifts may occur in the main transport routes. For pesticides, there obviously are sharp seasonal peaks in application, and stream transport presumably might have a seasonal peak during maximal flow periods. If the stratosphere is involved in atmospheric transport, then analogy with fallout radionuclide phenomenology would indicate a spring peak in fallout of the transported material.

For the most part, not enough is known to make any definitive statements about seasonal variations, but the presumptive evidence certainly seems sufficient to require that any sampling scheme be carefully designed to reflect seasonal changes. In fact, for efficiency in sampling, we really need to either find a flat place on the seasonal curve, or fit some sort of curve to the data (over time). Otherwise, any marked seasonal change may

greatly inflate the variance, making the supposed baseline untrustworthy.

Given a baseline, there follows a need for monitoring to determine what changes occur. The chief problem with monitoring schemes is that they necessarily involve a routine, within which those responsible for operations tend to lose sight of the original objectives. By and large, it seems prudent to try to arrange to understand the system well enough to minimize the need for routine monitoring.

3.3 Human health and pollution

There are a number of recent claims of "statistically significant" evidence of long-term damage to the health of humans from various sources of pollution (largely of atmospheric origin). No attempt will be made to go into details here, but most of the claims rest on some sort of multiple regression analysis with "health" parameters as dependent variables and various presumed measures of pollution as independent variables. Some examples and references are to be found in the Proceeding of the Sixth Berkeley Symposium on Mathematical Statistics and Probability, Volume VI, "Effects of Pollution on Health" (now in press). Unfortunately this volume deviates sharply from the usual product of the Berkeley Symposia, and the the statistical aspects of the question are left unresolved.

One approach to the health problem is to require that any mechanism for damage postulated for a real life situation be one that can be substantiated in the laboratory. Such a rule leads immediately to troubles with extrapolation. One difficulty is that of extrapolating from levels that do demonstrable damage in the short term experiments usually feasible in the laboratory, down to effects that might result at much lower levels in the real world. The other aspect is that of extrapolation from test animals to man.

The relationship of low levels of chronic pollutants and human health

is obviously a complex one, and not likely to be soon resolved (unless, of course, pollution becomes very serious in the near future, whereupon we may have irrefutable evidence of damage to human health). It does seem evident that the problem is one set within a framework of dynamics of pollutants in the environment, so that the complexities of understanding effects are compounded by those already discussed.

3.4 Understanding environmental systems

We might consider this as the category concerned with the "health" of our living environment. In ecology, it is seldom feasible to consider the "health" of an individual. We are instead concerned with the well-being of populations. In assessing the effect of some pollutant on natural populations, one may thus need to study a sequence of phenomena, beginning with the kinetics of the contaminant in food-chains, progressing through the dose-response relationship exhibited by individuals, and terminating in a possible effect on the population dynamics of the species of interest.

Deaths of individuals may have little apparent effect on the success of the population.

The point of view adopted here is one of a need to understand the system under study. In consequence of the complexities of ecosystems and our limited knowledge, we are unable to justify extensive population studies in search of effects of pollutants at levels far below those causing any known consequence to individuals under experimental conditions. We can, however, try to determine the fate of such substances in natural systems, as insurance against as yet unknown conditions or hazards. Any policy that assumes no damage in the absence of lethal effects in the laboratory is obviously a dangerous one. DDT provides a prime example, in that rather high tissue

concentrations are required to evoke a toxic response in individuals. Thus proponents of the unrestricted use of DDT were able to point to laboratory data showing "non-toxicity" for many years. Now it turns out that much lower levels of a degradation product of DDT interfere with calcium metabolism in birds, causing thin eggshells and reproductive failure. Furthermore, by not knowing what happened to DDT in an ecosystem, we tended to look for trouble in the wrong species, and it was only after the decimation of a rare species actually occurred that a link with pesticides was inferred. In point of fact, we still do not have definitive studies of food chain kinetics of DDT, in spite of warnings given by some foresighted wildlife managers as early as 1945.

Objectives in sampling thus become anything but clear-cut at this level. We might characterize them as "sampling to understand the system", but any practical application will call for some way to reduce such a diffuse goal into some operational rules. One possibility -- and perhaps the only one -- is to construct some sort of a model and define the objectives for particular field studies in terms of relevant components of the overall model. That this kind of approach can lead to a variety of conceptual and philosophical difficulties is well-known; it also seems to be how many people interpret the processes labelled "systems analysis". However, our purpose here is just to try to break down a complex, but poorly defined, problem into pieces that we can work with.

4. COMPONENTS OF A STUDY OF ENVIRONMENTAL CONTAMINATION

A detailed format for the study of contaminants in a natural system has yet to be worked out. Some tentative categories are suggested in this section.

4.1 Compartment models

A very convenient symbolism for the underlying model is that provided

by the graphic "boxes and arrows" diagram showing the transfers of some substance through a system. A variety of logical and mathematical techniques can be used to describe such a system, but the essential feature here is the argument that most of the transfers observed in food-chain systems are of an input-output nature, which can conveniently be described by a compartment model. Details necessarily vary with the system under study and the aims of the study. We note that such models are in wide use in biomedical research where the compartments are associated with various organs and tissues, and perhaps the widest study of such models has been in the biomedical field (for some references, see Eberhardt (1970)). These models are also useful over a scale of activities reaching on up to geophysical studies.

Complications in use of compartment models may arise in many directions. One well-known in biomedical studies is the reality of the compartments, which often cannot be identified as specific tissues. Probably this poses less difficulty in ecological systems, but it may still be convenient to regard a plant, for example, as having two compartments -- an "exterior" (for material adsorbed to the surface) and an "interior" compartment. In the simplest case, losses are assumed proportional to the quantity of substance already present in the compartment. This may be objected to as unrealistic in a given case, and an alternative process may have to be postulated. Very often we do not know the size or mass of various compartments, and proceed in terms of measurements of concentration only. In general, though, if an input-output system exists, it appears that the compartment scheme provides a convenient framework for a model.

One feature of the discussion in Section 3.1 may be of great value in at least the initial stages of modelling. This is the argument that the small mass of the biota relative to that of its physical environment results in a very small fraction of most trace substances being found in the

biota. If such an argument holds in a given case, then it may be feasible to ignore or minimize the importance of one of the features dear to many modellers -- that of "feedback". For purposes of studying the biota, one simply regards the rest of the environment as a huge "sink" into which excreted substances go. Their reappearance in the biological system may be fairly certain, but the time-lag may be such that one can neglect such recycling for many purposes. Such a rule cannot be universally applied, of course. Some trace elements in aquatic systems may be recycled very rapidly as a consequence of their scarcity and importance in the system.

4.2 System identification

If it is accepted that a compartment model will serve to represent the system under study, there then arises the problem of actually structuring the model. In its simplest form this amounts to sketching and labelling those boxes and arrows that are considered important. To do so, one must have a good practical knowledge of the ecosystem concerned, and a clear idea of objectives for the study. The objectives will somehow have to supply a choice of species to study. In many practical cases, main concern will be with economically important species. No rules have been worked out for a general approach, but presumably such features as relative biomass of a particular species and perhaps some measure of its "function" in the ecosystem would be considered.

Many other factors need to be considered in an actual field study, and some of them very likely will only turn up when the initial study is nearly complete. Hence the best working rule is to plan a pilot study on as large a scale as is feasible. Some experience with DDT in an aquatic system (Eberhardt, Meeks, and Peterle, 1970) led to several worries: (1) An arbitrary assumption of two compartments served to represent most species reasonably well in terms of fitting the data, but suggested the need for laboratory studies to identify the compartments and their

interconnections. (2) The source of DDT (in this case application was with clay granules) required better measurements as to release rate than were available. (3) Animal uptakes could not reliably be separated into components due to direct uptake from DDT in water and that coming through the food supply. (4) Suspended mater (living and dead) in the water and periphyton on plants played an evident role in transport and retention of DDT, but the details were not apparent. (5) A similar problem occurred in regard to the effect of organic matter on the pond bottom -- presumably DDT reaching underlying silts was bound in place, but there was a suspicion of an exchange between water and organic matter (or some other component of the environment) that may have maintained a low equilibrium level of DDT in the water (below measurement capability) for a long time.

The above examples suggest some of the problems in defining the system to be studied. It seems self-evident that only experience with a variety of actual studies will serve to resolve such questions. In the absence of such experience it seems doubtful that we can reliably satisfy most of the objectives described previously.

4.3 Sampling in space and time

Once the system to be studied is somehow defined, it then becomes necessary to arrive at a sampling plan. Samplings in both time and space are necessarily involved. Sampling in time might conveniently be associated with curve-fitting problems -- for a given organism or substance, what is the best pattern of sampling over time? Since one clearly cannot hope to obtain enough samples to adequately define the multitude of relevant features of any natural system, some sort of compromise scheme has to be adopted to meet the requirements of sampling over time and those associated with spatial coverage. As a starting point, allocation over time might be dealt with in terms of the pattern and number of samples necessary to

describe a particular curve reasonably well (i.e., minimize the variances of parameter estimates).

Sampling in space is perhaps not a broad enough term, since the real need is for sampling the "system". In addition to coordinates of time and space, one must also deal with components of the biota and substrate. Choice of a species list for sampling may, as previously suggested, best be predicated on the objectives of the study. In some cases, concern with hazards to man or to certain economically or ecologically important species may lead to the selection of a reduced list of key species. Justifying a given list may, however, require a much better knowledge of ecosystem dynamics than we now have.

A promising approach to a large-scale study would be that of doing an exploratory (pilot) study with a labelled or tracer substance. One might then use a balance study as the initial objective. The ultimate goal may then be described as one of determining the fate of all of the tracer substance released in the study. With substances like DDT that are already widely distributed, this immediately puts a premium on the use of a radioactive label. Obviously considerable prior knowledge of the system is necessary for planning. It will not only be necessary to estimate the biomass of components of the system, but also to decide in advance what components will contain the main quantities of tracer substance at various points in time. Physical features of the study area, along with variation in the application method, will certainly lead to spatial variability in concentrations in a given species. Differences in size and physiological state will very likely also contribute to variability between individuals.

Retention times of many radionuclides, and very likely some pesticides, are apparently influenced by the body size (weight) of many animals. The

appraisal of concentrations in populations of animals thus may be aided by considering retention-time (or excretion rate) to be a function of the $3/4$ power of body weight. A much more interesting aspect of the matter is that this relationship may serve as the basis for a "similarity-ratio" (Eberhardt, 1969, Thomas and Eberhardt, in press) that provides a common denominator for contrasting retention time of two species of disparate sizes for a range of substances. There is thus the possibility of working towards a methodology for dealing with the very important problem of treating many species and many contaminants without a one-by-one laboratory study.

"Pooling" samples is one frequently-used method for reducing the sampling load. This technique may serve to meet the objectives of a balance study, in the sense of determining the ultimate fate of the initial quantity of tracer, but the differences between species encountered in the available field experience indicate that pooling will obscure the dynamics of the system. Very likely only a great deal more experience with sampling individual components will serve to determine when and where pooling is desirable.

As experience and background data accumulate, simulation modelling will become an increasingly useful tool in designing and conducting system studies. A reasonably good model should permit rapid testing and revision of sampling schemes. In the face of uncertainty about various components of the system, the experimenter may elect to test alternate sampling schemes against very different patterns of system behavior, and can thus obtain some notion of the "sensitivity" of various methods to deviations from the expected pattern of events. A simulation study might be very helpful in planning specific experiments to study these unresolved questions of routes and mechanisms.

It seems likely that real success in understanding both the dynamics of ecosystems, and the behavior of contaminants in ecosystems will depend

on construction of rather sophisticated models of a sizable number of systems for detailed comparative studies.

4.4 Effects on the system

The ultimate need in studies of contaminants is to appraise their effects on the biota. One thus needs to look into the problems of bioassay, including responses other than death or apparent injury (as, for example, behavioral responses). A desirable research goal is that of obtaining some general index of sensitivity as exemplified by radio-sensitivity and chromosome size. The prospect of defining similarity-ratios seems important in appraising effects in field situations, in that excretion rates clearly have a bearing on likely severity of exposure of individuals.

In natural populations, one needs to be concerned with the ability of a population to "compensate" for added mortality, so that an expected mortality as deduced from bioassay studies may have little real consequence in nature. The other side of the coin is that of interactive or "synergistic" effects of two different contaminants, whereby the compounded effect may be much more severe than expected from the sum of two independent components of mortality.

The needs for further study may thus be seen to provide a sequence, starting with physical processes determining distribution of a contaminant, its progress through a food-chain -- comprised of populations of individuals -- and the ultimate effect on the biota.

4.5 An example

We now come to the point of describing an actual example. The purpose is to illustrate some of the details that have to be encompassed in order to begin to understand even quite simple food-chains and to suggest some

objectives. The results described here have no apparent relationship to the "health" of the humans or animals involved. The radiation levels from fallout (weapons testing) radionuclides approach those of natural background radioactivity. Several decades of expensive and dedicated research have as yet failed to produce any meaningful way of extrapolating laboratory effects down to this very low level -- apart from the question of genetic effects, which digression would take too long here.

A very simple sketch will show the nature of one food-chain -- that of cesium-137 in an arctic Alaskan situation. Please note that this data concerns a population of less than 200 Eskimos in Alaska, so that what we describe here is a rather unique circumstance (but is replicated in Canada, Lapland, and in the USSR). The basic model is as follows (for details see Eberhardt and Hanson, 1969):

In the model, a source of some tracer substance (here cesium-137) enters one compartment (lichens) and is then transferred through several others (caribou and Eskimos). This particular instance can be greatly simplified, as suggested previously, by assuming that losses from the various compartments go into a "sink" (essentially the soil) and do not reenter the chain. Some peculiarities in the lichen data have recently persuaded us that we probably

must modify that assumption for lichens.

Time doesn't permit going into many of the interesting details of the system and its environment. We will instead have to settle for a sketch of the basic relationships as a way of pointing up the kinds of features generally involved in such food-chains. One way to do this is to represent the burdens in the three compartments as a system of three differential equations following the usual "input-output" model appropriate to a very simple uptake-and-retention system:

If the input to such a system is constant, and the output is a constant fraction of the current level in the compartment, then the differential equation

$$\frac{dy}{dt} = \lambda - \mu y$$

has a simple solution, $y = \frac{\lambda}{\mu} [1 - e^{-\mu t}]$. It turns out, of course, that these simple conditions do not hold in nature, and all we have done thus far in practice is to represent the situation by difference equations, and use a computer to produce curves depicting "solutions". These curves can then be compared with the actual data, giving us some idea as to the reliability of our guesses as to constants and functional relationships.

The set of equations can be written as:

LICHENS $\frac{dy_L}{dt} = \lambda(t) - \mu_L y_L$

CARIBOU $\frac{dy_C}{dt} = k_1 y_L - \mu_C y_C$

ESKIMOS $\frac{dy_E}{dt} = k_2 y_C - \mu_E y_E$

Now, what about the complications? For a first "cut" at the broad outlines of the system, we can let the loss rates remain constant. There is evidence that this isn't true, but these complications don't seem important overall as far as system behavior is concerned. The input to the system (fallout cesium-137) declines exponentially on a scale of years. However, within a given year, there is a very definite cycle associated with atmospheric phenomena. A "spring turnover" transfers a "slug" of cesium-137 from the stratosphere to the troposphere, so that $\lambda(t)$ is best represented as an exponential function with an annual cyclic function. As noted previously, we now suspect a seasonal cycle in the lichens, and since the caribou only eat the tops of lichens, we apparently need to insert another "box" in the system, wherein lichens cycle cesium up and down (perhaps to a "substrate") each year.

It turns out that the caribou change from a winter diet of almost exclusively lichens to a spring and summer diet of other plants that contain relatively little cesium-137. Thus, although the long-term retention of cesium-137 by lichens is the key to the overall situation, we cannot regard k_1 as a constant. It must instead become a variable coefficient, say $k(t)$, depending on caribou food habits. The next complication is that the caribou migrate long distances annually. The Eskimos live in a small village (Anaktuvuk Pass in the Brooks Range) and kill sizable numbers of caribou twice each year -- once in the spring when the caribou are migrating north after a winter of a "cesium-rich" diet of lichens, and again in the fall, when the south-bound caribou herds have been on a summer diet low in lichen content.

The retention time of cesium-137 in caribou is relatively short. Cesium-137 is excreted with a half-time of perhaps 15 to 30 days, while it is comparatively longer in humans, being perhaps 60 days more or less. The Eskimos

store caribou for consumption in between the two annual harvests. We thus must regard k_2 as a function of time, or at least consider it as two constants, each applying for part of the year. The end result is a seasonal cycle of cesium-137 concentration in both caribou and Eskimos (lichens, too, for that matter), with the cycles noticeably out-of-phase.

One set of data, that of cesium-137 concentration in caribou muscle, will supply some notion of how well the data fit the model. The most striking deviations seem to me likely to be related to weather conditions, possibly as an effect on caribou migration and feeding habits. At the moment, we simply do not know the cause. However, we believe that the "man-made" radionuclides (strontium-90 also needs to be considered here) are not the only radioactive substances that need to be considered here. There is a naturally occurring series (lead-210 and Polonium-210) that apparently also are important in the lichen-caribou-Eskimo system and thus should be studied in detail. Since these substances undoubtedly have been present during the entire time that this food-chain has existed, we are faced not just with assessing a model for 10 years of observational data, but also with a real need to extrapolate backwards in time for thousands of years. But that is another story -- one which may never be thoroughly documented.

5. Conclusion

The steady succession of panel reports and symposia dealing with environmental problems over the last decade have exhibited a common emphasis on ecological approaches. This sudden popularity (and an accompanying touch of prosperity) seemed for awhile to have stimulated an effort to convert an observational science into one based on an experimental technology. However, interest in "systems ecology" now seems to have taken the lead. One can hardly deny the importance of both experiment and observation as

appropriate, and we need only contemplate the successes of astronomy and meteorology to suppose that not all science can or need be experimental.

It might also be noted that some crucial technical and financial difficulties stand firmly in the way of controlled experiments in natural environments.

(replications vs. boundary effects, for example).

From the viewpoint of statistical inference, it seems that the two areas for which substantial theory and methodology are available are not very relevant to the problems of environmental quality surveys, anyhow. These are the "fixed-effects" experiment and the standard sample survey.

The "tight" experiment makes inferences for a specified set of treatments on a particular set of areas, while the usual sample survey estimates means or totals of selected variables for a given, finite population. On the other hand, we need here to deal with experiments in which only a subsample of the treatments of interest is applied to a sample of possible areas ("random-effects" model) and surveys in which average values are intercompared ("analytical" surveys). For these situations, questions of theory and inference are difficult and widely debated, but the present analytical machinery seems much the same for both experiment and survey.

The distinguishing feature between experiment and survey (in the "random-effects" class appropriate to this discussion) is obviously the matter of selection and location of treatments. However, most of the immediate and practical situations to be dealt with in terms of pollution yield little opportunity for any such deliberate manipulation -- although there have been a few such planned experiments with pesticides. Undoubtedly designed experiments are needed; but they are sufficiently expensive (both in biological and dollar costs) to require a good deal of preliminary work.

The chief difficulty in experimentation may be the complexity of food-chain passage of contaminants, combined with the requirement of sizable experimental areas to reduce "boundary effects". At least for the present it seems to me that we will have to proceed by piecemeal methods -- by a combination of experience, experiment, and observation all tied together by a framework supplied by mathematical and/or computer models.

Very clearly some general principles ("invariants", if you will) have got to be established in the face of the literally enormous number of species present in natural environments, and the easily-demonstrated hazards of "pooling" or "lumping" samples. One such principle appears to me to be the correlation between metabolic rates and size or weight. Faced with the need to estimate excretion rates for some "biologically active" substance over an entire ecosystem, one very likely can only settle for some such approximate approach, depending on experimental determinations for selected representative forms. Various other ways and means for ordering and ranking seem imperative needs.

If the discussion here seems to have wandered rather far afield from the topic of biological sampling, one explanation is that the subject matter is too complex and as yet too poorly understood for straightforward application of known technology. Another is that objectives in sampling have a considerable bearing on the methodology. If we take "understanding the system" as an objective, the standard estimation techniques may become less useful than they are in instances where "how much?" or "how many" are the questions of interest. If "understanding" is equated to "good fits" for a compartment model, then the sampling problems may have to do with estimating the parameters of a non-linear equation, and thus deviate considerably from standard survey methods. Questions of sample size and allocation have not yet received much attention in such circumstances. Nor do we know

much about the practical use of regression and covariance techniques in these cases, but it can be expected that much practical progress might be made with these tools, and that we may currently be over-emphasizing modelling.

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Table 1

A LIST OF SOME ENVIRONMENTAL PROBLEMS

This list is intended to illustrate some of the issues involved in the recent widespread concern about our environment. The list is not intended to be complete or to assign a particular importance to various items.

Atmospheric

- (1) CO₂ balance. Burning of fossil fuels and reduction in photosynthesis has resulted in a significant increase in atmospheric CO₂. Quantitative data from 1958 to 1968 show a rise from 312 ppm to perhaps 320 ppm. Both a warming and cooling effect have been postulated, with warming ("green-house" effect) mostly accepted as the likely consequence, possibly ending in melting the polar icecaps. Storage in oceans is an important aspect.
- (2) O₂ balance. Reduction in available O₂; now considered highly improbable.
- (3) Increased particulate burden. Generated by industry and through accelerated desert formation by improper agricultural activity. Net effect to reduce incoming solar radiation; suggested as a possible cause of a new ice age. Injection of particles into stratosphere one of concerns leading to abandonment of US SST.
- (4) Air pollution. Variety of industrial and automotive exhaust products. Claims of demonstrable long-term effects on human health in urban areas (Immediate effects of short-term "episodes" well-known).

Water

- (5) Eutrophication. Sewage, fertilizer, detergents, manure (feedlots), etc., contribute to accelerate "aging" of lakes, streams, and estuaries. Effect on Lake Erie well-known; threat to other Great Lakes.

(6) Thermal "pollution". Temperature increases due to discharge of heated effluents from industry and power-generating plants.

(7) Persistent pesticides and PCB's. Both run-off and atmospheric transport threaten aquatic ecosystems. Several species on road to extinction. Main immediate economic threat seems to be to estuaries (nursery grounds for fish, shellfish, crustacea, etc.). Long-term threat to oceans and man (e.g., via photosynthesis) unknown. Data on amounts produced not available for some substances (e.g. PCB's: polychlorinated biphenyls).

(8) Oil and heavy metals. Additional damage to aquatic biota. Build-up of oil pollution in oceans just beginning to be recognized.

(9) Radioactive wastes. Long-term storage problem seems most serious question.

Agriculture

(10) Source of pesticides (importance of atmospheric transport now evident), loss of topsoil, ground water depletion, salinization, tropical problems (milpa or "slash and burn", laterite soils, etc.), and so on.

Population

(11) Exponential growth of human populations regarded as root cause of many if not most environmental problems. "Affluence" exacerbates situation. "Technological fix" (Weinberg) makes it possible to delay the ultimate.

(12) Nuclear war. One possible consequence of overcrowding.

Table 2

SOME CATEGORIES OF ENVIRONMENTAL PROBLEMS

I. Pollution of Environments

- A. Baselines for future reference
- B. Concentration and rate processes
- C. Effects on biota

II. Biological Productivity of Environments

- A. Primary productivity (basic processes)
- B. Secondary productivity (population management)

III. Industrial, Residential, and Recreational Use of Environments

- A. Ecosystems as "sinks" and renovators
- B. Degradation of the environment
- C. Multiple-use of resources

IV. Engineering Modification of Environments

- A. Surface water management
- B. Modification of weather and climate

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