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**Terrestrial Perturbation
Experiments as an Environmental
Assessment Tool**

G. W. Suter II

ENVIRONMENTAL SCIENCES DIVISION
Publication No. 1528

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ENVIRONMENTAL ASSESSMENT TOOL

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ABSTRACT

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The National Environmental Policy Act of 1969 (NEPA) was initially interpreted as requiring full disclosure of the environmental impacts of a federal action. Because of the limitations of time, money, and manpower, this requirement that all impacts be considered has led to superficial analysis of many important impacts. Data collection has largely been limited to the enumeration of species because this information can be applied to the analysis of any problem. The President's Council on Environmental Quality (CEQ) has provided a solution to this problem by reinterpreting NEPA as requiring analysis of those impacts which have significant bearing on decision making. Because assessment resources can now be concentrated on a few critical issues, it should be possible to perform field perturbation experiments to provide direct evidence of the effects of a specific mixture of pollutants or physical disturbances on the specific receiving ecosystem. Techniques are described for field simulation of gaseous and particulate air pollution, soil pollutants, disturbance of the earth's surface, and disturbance of wildlife. These techniques are discussed in terms of their realism, cost, and the restrictions which they place on the measurement of ecological parameters. Development and use of these field perturbation techniques should greatly improve the accuracy of predictive assessments and further our understanding of ecosystem processes.

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INTRODUCTION

The terrestrial ecological information contained in environmental impact statements and assessments has largely been limited to species lists, irregularly supplemented by indications of distribution and relative abundance. This information contributes little to analysis of terrestrial ecological impacts because the responses of natural species to any specific anthropogenic stress are extremely limited.

Extrapolation from studies of other species are difficult because taxonomic similarity does not imply similar sensitivity. This difficulty is compounded by variation in sensitivity due to a variety of environmental factors including soil, climate and population parameters. In addition, toxicants, noise, and other perturbations occur as mixtures which may produce synergistic and antagonistic responses. The number of combinations of species, environmental conditions and toxicant mixtures is so large as to overwhelm the resources of traditional laboratory toxicology. Because these problems prevent assessment of impacts at the level of the individual organism, assessment of population and community and ecosystem level (higher level) effects from species lists are also precluded.

This dismal situation cannot be remedied by simply collecting more and better data concerning population- and community-level properties of the proposed receiving systems. Theories predicting population, community and ecosystem level responses to perturbations such as the diversity-stability hypothesis are either currently discounted or are too vague or poorly supported to serve as assessment tools. Ecosystem

simulation models provide tools for extrapolating proximate responses but cannot predict those responses.

The result of this incapacity is that genuinely predictive assessment of terrestrial ecological effects has been limited to actual acts of destruction. These include complete destruction of natural systems as in right-of-way management and destruction of individual organisms, in hunting, or in selective timber harvesting. Even these assessments are typically limited to the level of ecological organization directly affected. Assessments of hunting generally do not consider community-level effects. Assessments of right-of-way management and other community manipulations do not consider ecosystem-level effects such as energy and nutrient transfers between the managed and unmanaged communities. Assessments of construction projects seldom look beyond the local ecosystem destroyed to effects on hydrology or radiation balance.

Anthropogenic perturbations such as emissions of toxicants, water vapor, noise and behavioral disturbance affect the rates of ecological processes. These effects are acknowledged in impact assessments but are seldom quantified. In the absence of information which permits even rough quantification of effects, assessors typically assume that there will be no significant effects if all legal requirements are met. This strategy often fails because the primary regulatory emphasis is on protection of human health. This regulatory bent is demonstrated by the recent increase in the secondary ambient air quality standard for ozone to levels at which significant phytotoxic effects occur (Heagle et al. 1979b).

The logical and direct solution to the problem of assessing secondary effects and non-lethal primary effects is to perform experimental perturbations of the proposed receiving system. These would consist of either simulations of proposed perturbations such as the various field fumigation techniques or imposition of the actual perturbation on a small scale. This option has been largely precluded in the past by the judicial mandate to make impact statements "full disclosure documents." Only a species list can give the appearance of having considered all ecological components thereby satisfying the requirement that all effects be disclosed.

The full disclosure problem is eliminated by the new National Environmental Policy Act regulations (Council on Environmental Quality 1978) which have the goal of "distinguishing the important from the trivial." This goal is to be accomplished through scoping, "an early and open process for determining the scope of issues to be addressed and for identifying the significant issues related to a proposed action." This emphasis on analysis of a limited number of highly important issues should permit resources to be concentrated on a few site-specific field experiments. This document will review a variety of field experimental techniques which are available, their relevance to energy technologies and to the NEPA process, and their cost.

EXPERIMENTAL TECHNIQUES

This section considers techniques for the simulation of the major classes of terrestrial perturbation resulting from the development and conversion of energy resources. Techniques are considered in terms of

their realism and adaptability for use in a wide range of ecosystem types.

GASEOUS AIR POLLUTANTS

All of the early field fumigation systems were closed chambers resembling small green houses into which filtered or contaminated air was pumped. Closed chambers are poor simulators of natural conditions because they drastically alter radiation balance, temperature, humidity, precipitation and access by insects and pathogens. Closed chambers are, however, still potentially useful for the short fumigations. Small portable chambers can be placed over plants in the field and fumigated for a few hours using mobile equipment (Cocking 1973, Treshow and Stewart 1973, Hill et al. 1974). The plants or plots are marked and later examined for signs of response. Miller and Yoshiyama (1973) developed small closed chambers which are self-ventilating due to convection through 2.4-m stacks. Because they are portable and self-operating, these chambers are suited to studies of ambient pollution at remote sites and could be adapted to delivery of air polluted by compressed gases. With some ingenuity, a closed chamber can be devised for almost any vegetation, including epiphytic lichens on tree trunks and branches (Anderson 1976).

Examination of chronic pollutant effects requires the use of more elaborate systems to avoid serious alteration of the plant's environment. There are two general types of systems currently available, open-top chambers and tube arrays. The most popular form of open-top chamber is the one developed by a cooperative program of the

U.S. Environmental Protection Agency, U.S. Department of Agriculture, and North Carolina State University, referred to as the EPA-type chamber (Heagle et al. 1973). It consists of a cylindrical frame 2.4 m high and 3 m in diameter, covered with a clear flexible plastic film. The lower portion of the chamber is double walled and perforated on the inner wall, forming a plenum to dispense filtered, polluted or ambient air. This air is delivered by a duct and fan from any of a variety of air treatment devices. A similar chamber was developed independently by the Boyce Thompson Institute for Plant Research (Mandl et al. 1973). The Boyce Thompson chamber consists of 2.74 m diameter rigid fiberglass hoops stacked 1.22 m high. The air delivery plenum, which consists of perforated plastic tubing fastened around the chamber wall, can be raised as the canopy grows.

The first tube-type system was the zonal air pollution system (ZAPS) developed by the Corvallis Environmental Research Laboratory for the study of SO_2 effects on rangelands (Lee and Lewis 1978). ZAPS consists of a half hectare array of perforated rigid plastic tubes suspended above the vegetation surface receiving compressed SO_2 contaminated air. A 61-m buffer is provided between arrays to reduce cross contamination. Miller et al. (1977) have developed smaller versions of ZAPS which include a number of refinements including the ability to be raised along with canopy growth.

The ZAPS system is not capable of delivering filtered air to exclude ambient pollutants so they can be used to study the effect of air pollution increments but not background pollution. The Tennessee Valley Authority has developed an air-exclusion system to study effects

of power plant emissions on crops (Jones et al. 1977). The TVA system consists of perforated flexible plastic tubes which are laid on the ground between rows of crops and inflated with charcoal-filtered air when ambient SO_2 concentrations reach a predetermined level. The inflated tubes fill the space between the rows saturating the foliage with purified air and then subside to the soil surface at the end of the pollution episode. This type of system could also be used to deliver polluted air.

A hybrid tube and chamber system was developed at the Lawrence Livermore Laboratory which consists of rows of flexible plastic tubes like the TVA system surrounded by a low, rectangular, clear fiberglass wall (0.6 m x 7.5 m x 3 m) (Shinn et al. 1977). This system combines the even delivery of tube arrays with some reduction by the walls in interference from wind.

Each of these field fumigation systems has peculiar advantages and disadvantages. Closed chambers are highly flexible in terms of the range of conditions to which they can be applied and are typically simple to build and easy to install and operate. Because they are closed, control of air quality is nearly absolute. Their major disadvantage is the large effect of the chamber on the physical characteristics of the test environment (chamber effect) which can significantly alter the susceptibility of the test organisms to stress. This characteristic limits their utility to studies of responses to brief, infrequent episodes of fumigation such as result from impact of a poorly dispersed plume with the ground.

Opening the top of fumigation chambers greatly diminishes chamber effect while retaining a large measure of control over the test atmosphere. Heagle et al. (1979a) performed extensive measurements on an EPA-type chamber which indicated that chamber effects were smaller than are believed necessary to affect pollutant sensitivity (0.56-0.86°C higher temperatures, 88% light transmission, 1.47-3.07 km/hr air speed and no measurable change in relative humidity).

Reported performance of the original Boyce Thompson chamber is comparable (Mandl et al. 1973), but Kats et al. (1976) found light intensities of only 45-75% of ambient in a Boyce Thompson type chamber. Heagle et al. (1979a) summarize seven years of experience with EPA-type chambers as indicating that chamber effect causes a slight but significant increase in plant height but "rarely" affected yield. Howell et al. (1976), however, found significant reductions in soybean yield due to chamber effect. The major factor is probably the "rainshadow" created by the chamber walls, but this problem requires further study. A second technical problem with open-top chambers is the ingress of ambient air, particularly into filtered air chambers. This problem may be reduced by adding a simple baffle to the top of the chamber (Kats et al. 1976), but results have been inconsistent.

The ZAPS-type systems provide the least interference with natural conditions and the least control of dose. Because these systems are open, concentrations of the pollutant vary widely depending on wind speed, relative humidity, solar radiation, and temperature stability class (Lee et al. 1979). Coefficients of variation in SO₂ concentrations at a central monitoring point averaged over entire

seasons of continuous fumigation ranged from a low of 0.33 on a high fumigation rate plot up to 2.00 on a low rate plot (calculated from Lee et al. 1979). Although the geometric means of SO_2 concentrations on the control plots are low (0.2-1.6 pphm), occasional high concentrations have resulted from winds carrying SO_2 from the treatment plots. These problems are considerably reduced by fumigating only when the predominant wind direction is approximately perpendicular to the line of plots (Miller et al. 1977). While the variation in dose associated with ZAPS-type systems is probably too high for purposes of standards setting, it is not large relative to the variation in dose delivered by a real plume. The variation in response to climate factors may in fact make ZAPS a better simulator of plume effects than chambers which are either on at a relatively constant dose or off. Miller et al. (1979) found that variation in SO_2 concentration in their system during individual fumigation episodes was similar to variation observed during measurements near real point sources.

The TVA and LLL systems have a number of advantages for the study of low-growing row crops in terms of control of air delivery and little interference with natural conditions. However, because the delivery tubes lie on the ground, they can not be adapted to natural vegetation, with the possible exception of desert shrublands.

Many questions concerning the relative performance of these field fumigation systems can only be resolved by side-by-side comparisons. Such comparisons are planned by the EPA for the upcoming National Crop Loss Assessment Program. Meanwhile, numerous modifications of the basic chamber and tube designs can be made to improve their performance

or adapt them to particular situations. Movable open-top chambers could be used like closed chambers for intermittent fumigations in order to minimize interference with natural conditions during, as well as between, fumigations. Low walls could be used with ZAPS-type systems to obtain the air control advantages of the LLL system in studies of natural systems. Chambers have been used to fumigate small individual trees or portions of trees, but the responses of a forest to fumigation have not been investigated. Howard Odum's (1970) forest respirometer demonstrated that even plots from a mature tropical forest can be enclosed in an open top chamber. ZAPS-type systems could be built in tiers to fumigate forest plots. It should be remembered that the variance associated with all of these fumigation systems is not large relative to the variance of most field ecological measurements, and the combined variance of perturbation and measured response is small relative to the uncertainty of any assessment of gaseous emissions not based on a field fumigation.

The discussion above suggests the importance of the temporal pattern of exposure to pollutants in designing an experimental fumigation system. Experiments must rely on atmospheric dispersion modeling to indicate realistic temporal and spatial patterns of pollutant concentration. This information must then be combined with knowledge of the biotic communities potentially exposed, in order to determine which conditions must be simulated. More than one system type or mode of operation may be used if both near- and far-field effects are thought to be important or if structurally different plant communities must be tested.

PRECIPITATION

Precipitation scavenges pollutants from the atmosphere including gases, aerosols, and particulates. Contaminated rainfall has been simulated in the field using a variety of sprayer nozzles, irrigation sprinklers and watering cans. A portable sprinkler system developed by Shriner et al. (1977) delivers realistic droplet size and intensity with uniform, reproducible rates of application to a 5.76 m^2 area. Through the use of roofs which slide over the plots when a switch is wetted by rain, plots can be exposed to only artificial rain without modifying the physical environment.

Rain simulators have been used in combination with a ZAPS-type fumigation system (Irving and Miller 1977) and are being used with open-top chambers at Oak Ridge National Laboratory and the Boyce Thompson Institute in order to study the combined effects of acid rain and gaseous pollutants. Real rain could be collected and dispensed in order to generate three treatments equivalent to the filtered, ambient, and polluted air treatments. While acidity is the primary concern in rain experiments, it may be important to consider other rain contaminants including rain entrained particles (Whitford 1968).

ATMOSPHERIC PARTICLES

Atmospheric particles and aerosols are difficult to realistically generate, dispense or control in experimental systems. Filtered open-top chambers exclude most particles, but the unnatural upward air movement in these chambers must result in unrealistic rates and

patterns of deposition. Chamber effects make comparisons of filtered chambers with open plots questionable.

Particles larger than 5 μm aerodynamic (resistance) diameter (D_a) settle relatively rapidly and may be expected to settle approximately below the point of release in reasonably still conditions. Simulated fallout particles consisting of 44 to 88 μm particles were uniformly spread by a modified and motorized fertilizer spreader which ran on raised tracks (Dahlman et al. 1969, Witherspoon and Taylor 1970). Particles smaller than 5 μm D_a behave as aerosols and therefore travel farther from the point of release, whether a stack or a field dispenser. Laboratory systems for dispensing fine particles utilize the Wright dust feed mechanism (Wright 1950) which can be combined with cyclone separators to produce a stream of fine particles free from large, secondary agglomerations (Raabe et al. 1979). Such systems should be adaptable to field chambers. An alternate mechanism for dispensing aerosol particles in the field was recently developed by Battelle Columbus Laboratories (Van Voris and Toole 1979).

For preoperation experiments, sources of ash and similar particles other than dust must be pilot plants or plants similar to the one being assessed and using a similar fuel. Stack-emitted particles are best represented by particles collected from the stack. A system has been developed to collect kilogram quantities of size-fractionated particles from stacks (McFarland et al. 1977). An alternate strategy is to use material collected in electrostatic precipitators or bag houses. This material must be sorted because the fine particles which escape such systems have higher concentrations of organic and metallic compounds

than the average of those that are retained. Raabe et al. (1979) describe a size classification system developed for this purpose. Particles may be modified to simulate the emissions from a new technology by adsorbing substances onto the particle surface (Miguel et al. 1979). Completely synthetic aerosols can be generated from solutions fed through a vibrating orifice (Wedding and Stukel 1974). This approach is particularly useful for studies of sulfate aerosols and other aerosols which form from droplets in the atmosphere.

SOIL POLLUTION

Energy development may result in the contamination of soil by a variety of non-airborne pollutants. These include spilled natural and synthetic fuels, pesticides and herbicides used on rights-of-way or biomass plantations, "land-formed" wastes, and leachates from wastes or stored solid fuels. All of these may be simulated by applying the contaminant directly to the soil-vegetation surface, but experimental designs are considerably complicated by considerations of dose, frequency and collateral treatments such as tillage, fertilization and revegetation.

Oil spills on land have received considerably less attention than spills on water. Most terrestrial oil spill research has been carried out in connection with Alaskan and Canadian oil pipelines (Deneke et al. 1975, Miller et al. 1977). These experiments have included the spraying and flooding of taiga and tundra vegetation and soil with relevant crude oils. Similar experiments concerning the fate and

effects of various liquid fuels in other ecosystem types would aid assessment of technology and the development of clean-up protocols.

Most pesticide and herbicide studies have consisted of laboratory toxicity and degradation studies or the monitoring of actual commercial applications. Examples of controlled field experiments are described in the following references: Barrett 1968, Shure 1971, Robel et al. 1972, and Graf et al. 1976. These studies, like the oil spill studies, provide few technical problems for simulation of real perturbations. Grow et al. (1973) developed a truck-mounted sprayer which delivers accurate pesticide doses for field experiments.

Landfarming is the disposal of solid organic wastes by incorporation into the soil. Most of the waste which is suitable for such disposal is municipal sewage sludge or animal wastes, and most of the relevant field research has considered these materials (e.g., Loehr 1977, Kelling et al. 1977, Koterba et al. 1979, Sidle and Kardos 1977). Land farming is also used for the disposal of sludges, filter cakes, waste oils, and other organic wastes derived from energy industries. Experiments to investigate the effects of waste oil disposal with tilling and fertilization have been conducted by Kincannon (1972) and Watts et al. (1978). The wide range of responses reported in the relatively voluminous literature on land disposal of fecal materials clearly demonstrates the need for site-specific and waste-specific experiments.

Nearly all studies of the leaching of solid wastes and the fate and effects of leachates have consisted of laboratory leaching experiments which provide material for laboratory studies of toxicity

or simply monitor existing landfills. The need for preoperational experiments which are more realistic than laboratory leaching is becoming more widely recognized. Boegly (1979), and Skogerboe et al. (1979) are conducting leaching experiments in field lysimeters consisting of large containers which are loaded with waste and soil. A more direct approach is the filling of small trenches or single landfill cells with waste and the monitoring of leachate collected in wells or tension lysimeters. This small-scale demonstration approach is appropriate for site-specific studies in which case realism is more important than experimental flexibility. Ecological effects should be studied in the biotic communities established on the fill material, and in downslope communities which may be exposed to leachate.

Heat may be added to soils by a variety of energy-related technologies. The effects of a hot, buried, oil pipeline on arctic soil and vegetation were investigated at the University of Alaska's heated-pipe test facility (Scarborough and Flanagan 1973, McCown 1973). The feasibility and effects of using soil as a sink for power-plant waste heat and thereby decreasing water use and aquatic ecological perturbations while possibly increasing crop yields have been studied by Boersma et al. (1974), Allred et al. (1975), and Stanley et al. (1978). The use of buried high-voltage electrical transmission lines will also involve considerable soil heating or, in the case of superconductors, soil cooling. Soil heating can have significant effects on vegetation and the soil biota due to changes in evapotranspiration rates, growing season, soil freeze-thaw cycles and the rates of microbial processes occurring in the soil.

SURFACE DISTURBANCE

Because of the large body of theory and experience concerning terrestrial ecological succession, the effects of most surface disturbance are broadly predictable on the basis of a description of the preexisting community. However, disturbances which drastically alter the character of the substrate such as disposal of mine, mill or dredge spoils and tailings can unpredictably alter the course of succession. Such novel substrates may require considerable management in order to establish a self-maintaining community and prevent excessive erosion.

Reclamation experiments present no great conceptual difficulties and the technical difficulties have to do with obtaining substrate to test early in the decision-making process. Most reclamation experiments are simply attempts to establish vegetation on material which has proved resistant to standard revegetation techniques. As soon as sufficient disturbed substrate becomes available, proposed and alternate revegetation techniques should be compared for the stability of the vegetation produced and its ability to support wildlife or livestock. Such experiments may be modeled on standard agronomic field trial designs. The literature in reclamation research is too voluminous to summarize here except to recommend four symposium volumes (Shaller and Sutton 1978, Thames 1977, Wright 1978, and Vories 1976) and two bibliographies (Goodman and Bray 1975; and Bituminous Coal Research, Inc. 1975).

Less drastic disturbances may require investigation when the source of disturbance is novel such as air-cushioned vehicles or the system affected is poorly understood such as tundra or desert. The best examples of studies of this type are the experiments conducted in connection with oil and gas development in the arctic. Investigations of the response of tundra vegetation to varying intensities of disturbance by different types of vehicles revealed responses ranging from promotion of plant growth to long-term scarring of the surface (Rickard and Brown 1974, and Challinor and Gersper 1975).

WILDLIFE DISTURBANCE

Disturbance of wildlife can result in habitat abandonment, reproductive failure, or physiological stress due to arousal and flight. The severity of the responses to a particular activity depend on the importance of the habitat involved and the sensitivity of the particular organisms. Sensitivity varies greatly between populations of a species due to differences in their history of human contact (Geist 1971). Disturbance simulations may simply consist of observations of the distance at which animals flee from an approaching human (Stalmaster and Newman 1978). Animals may be experimentally exposed to noisy equipment (Freddy et al. 1977), or noise-making devices may be utilized to simulate particular development activities (White and Thurow 1979). While flight distance is the parameter which is most easily obtained and interpreted, much more complete knowledge of effect can be obtained by observing physiological parameters such as heart rate or population parameters such as reproduction rate.

Physiological responses can be monitored by radio-telemetry (Freddy et al. 1977, Ward et al. 1976).

RELATION TO OTHER ACTIVITIES

Field experiments must be coordinated with other assessment activities. Before experiments can be planned, a preliminary field and literature survey must characterize the receiving system; review of the project plans must identify potential sources of perturbation and the scoping process must identify the important issues.

Results of field experiments must be available for the NEPA assessment. The time available prior to the assessment depends to a large extent on the policies of the federal and state agencies involved; the Nuclear Regulatory Commission, U.S. Department of Energy, and predecessor agencies have traditionally required a minimum of one year of field data. Some federal agencies have required two or more years of field data for specific projects or classes of projects in order to estimate year-to-year variance. The CEQ regulations (CEQ 1978) encourage the setting of time limits on the NEPA process and include in the list of considerations the "state of the art in analytical techniques" and the "degree to which relevant information is known and if not known the time required for obtaining it." They require that any time limits be "consistent with the purposes of NEPA." Thus, field experiments should be planned to run for at least one year prior to the first assessment and should run longer if necessary to support choices between alternate designs or actions.

Field experiments should typically continue beyond this first assessment in order to elucidate chronic effects as early as possible in the course of development. Slips in development schedules are the rule rather than the exception, and they may permit considerable time for data collection before disturbances begin. Federal agencies are required to prepare supplements to environmental impact statements if "there are significant new circumstances or information relevant to environmental concerns and bearing on the proposed action or its impacts" (CEQ 1978). This requirement implies an obligation on the part of federal agencies to continue to obtain relevant information after issuance of an impact statement if the information could be reasonably expected to affect the outcome of the assessment.

Field experiments may continue during project operation as a supplement to field effects monitoring. While field measurements of responses to an operating facility are more realistic than similar measurements in perturbation experiments, they may not demonstrate ongoing effects. Uncontrolled variation in environmental factors and in project operation frequently mask stress-induced ecological responses, resulting in false conclusions of no effect. Field experiments may better control extraneous operational and environmental variation while becoming progressively more realistic by coupling the characteristics of the experimental perturbation to in-plant and ambient monitoring.

PARAMETER SELECTION

Selection of response parameters for field experiments is limited by time availability, by the amount of space which reasonably can be perturbed and by interference from the perturbation devices. Experimental results often must be available after the first year of data collection. However, population and community level responses of multicellular organisms to sublethal stress do not appear until at least the second year when perturbation effects are reflected in reproductive success. It is necessary, therefore, to monitor the proximate responses which will later be reflected in population- and community-level (ultimate) responses. Proximate responses include toxicant uptake and accumulation, leaf chlorosis, gas exchange rates, blood chemistry, and behavior. In addition, soil microbes and some invertebrates reproduce with sufficient frequency to show population or community responses in the first year. For example, the most rapid and clearest responses measured on the ZAPS SO₂ fumigation plots has been sulfur content of leaves, followed by activity of hydrogen oxidizing bacteria, plasmolysis in lichens, early leaf necrosis, seed viability, mycorrhizal infection, and leaf chemistry of grasses (Preston and Gullett 1979). After two or three years of fumigation (ZAPS II and I, respectively) the population and community responses that would be directly reflected in range production are only beginning to be apparent.

Population-, community-, and ecosystem-level ultimate responses must be monitored in the first year along with the proximate response

in order to detect acute responses such as mortality. In cases where acute responses do not predominate, ultimate responses should be monitored for from three to five years in order to quantify chronic effects. Although proximate responses can indicate that a system component is being affected, the corpus of empirical and theoretical ecology is not sufficient to allow confident extrapolation from proximate to ultimate responses. The ultimate response parameters for experiments are selected using the same criteria of importance and sensitivity as apply to monitoring (Suter, in press; Sanders and Suter, in press).

The size of the area experimentally perturbed can limit the range of parameters monitored due to minimal area requirements for display of the phenomena of interest and the requirements of sampling. For example, existing open-top chamber designs are marginally large enough (approximately 7 m²) to display plant and small insect population- and community-level responses in grasslands but could support little destructive sampling. Population and community parameters of most grasslands and shrublands including those of animals at least as abundant as common small mammals can be studied on half hectare plots. Communities with low diversities and moderately high productivity such as marshes and planted pastures would require somewhat smaller plots, but very low productivity or high diversity and high patchiness would require larger plots. Large, long-lived species such as forest trees can only be studied in terms of individual-level responses; and large, highly mobile species, unless restrained, can only be studied in terms of behavior.

The area requirements of ecosystem level studies are quite variable. The current standard for experimental ecosystem studies is the whole watershed study which allows integration of all processes within natural boundaries (Bormann and Likens 1979, Best and Monk 1975, Corbett et al. 1978). However, many ecosystem parameters such as movement of minerals between litter, mineral soil and plants can be measured in a few square meters.

Some constraints are placed on parameter selection by the equipment used to induce the perturbation. The ZAPS fumigation pipes, for example, prevent the study of livestock grazing on the SO₂ exposed plots. A more general problem is the effect of plot enclosures. The effects of walls on physical parameters have already been discussed, but they may also affect the response of mobile organisms. Walls have been used to restrict the movement of small mammals and produce a uniformly stressed study population (Barrett 1968, Johnson and Barrett 1975). Enclosure has been shown, however, to drastically affect the population dynamics of small rodents in 0.8-ha plots (Krebs et al. 1973). Mandl et al. (1973) intended that their open-top chamber would permit free passage of insects and pathogens. It seems likely, however, that a 2.44-m wall around a 2.16-m plot with filtered, upward moving air would have significant effects on movement of insects and pathogens. For studies of natural systems, walls used to limit air movement should be kept as low as possible and should be raised just above ground level to permit movement of animals. The problem of monitoring stress effects on animals moving to and from plots can be handled by separate accounting of resident and transient

individuals (Chilgren 1979). Alternately, when enclosure or chamber effects are not expected to be significant, use of both unwalled and walled controls can establish the absence of effects. When this double control demonstrates effects of enclosure on the stress responses, as in Howell et al. (1976), it is impossible to quantify the stress response.

COST

The CEQ has required that "if the information relative to adverse impacts is essential to a reasoned choice among alternatives and is not known and the overall costs of obtaining it are not exorbitant, the agency shall include the information in the environmental impact statement" (CEQ 1978). The clarity and force of this requirement is mitigated only by the qualifier concerning costs. The cost of constructing and emplacing fumigation systems and a rain simulator are listed in Table 1. Because the costs of equipment or supplies for most ecological sampling are minimal, the primary additional cost is the salary for one full-time technician to maintain and operate the system and to perform the sampling. Costs of the other types of perturbation experiments will be more variable but should be lower because special equipment is not necessary to simulate the perturbation. These costs are low relative to the \$750,000 to \$1,500,000 that is typically spent to gather data into an environmental report for a power plant or strip-mine lease.

Table 1. Costs of perturbation equipment in 1979 dollars

Item	Costs in dollars x 10 ³	Source
ZAPS-type fumigation systems	40-50 per set of 4 plots ^a	E. M. Preston Corvallis Environmental Research Lab. and J. E. Miller Argonne National Lab.
Open-top chambers	1.2-2 per chamber	Heagle et al. (1979) and D. S. Shriner Oak Ridge National Lab.
Rain simulator	0.15-0.2 per 2.4 x 2.4 m plot plus 0.8 per water delivery system	Bob Philbeck North Carolina State U.
Movable rain-exclusion roof	3 per roof	J. M. Kelly Tennessee Valley Authority

^aIncludes the pollutant gas monitoring system.

CONCLUSION

The scoping process required by the new NEPA regulations provides a procedural context which encourages an experimental approach to assessment. Given the low predictive power of contemporary ecology, the regulatory requirement that information be obtained which permits a reasoned choice between alternatives amounts to a mandate for an experimental approach to assessment. Techniques are available to simulate most energy-related perturbations at reasonable cost. While none of these field simulations is perfect, the gain in realism obtained by perturbing the actual receiving system more than compensates for the loss of control associated with leaving the laboratory. Even a seriously flawed experiment is more easily interpreted than unaccompanied lists of species, and moderate competence in the design and execution of experiments would result in a quantum advance in impact assessment.

Widespread use of field perturbation experiments would also greatly contribute to the advancement of pure ecology. The best way to gain an understanding of any dynamic system is to observe its response to displacement from equilibrium. The field experiments of Joseph Connell, Robert Paine, and Charles Krebs have an importance to ecology far exceeding the resources expended. A large body of such experimental results should prove invaluable.

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