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A COMMON FRAMEWORK FOR INTEGRATING THE ECONOMIC AND ECOLOGIC DIMENSIONS OF HUMAN ECOSYSTEMS. II: PROCESSES AND PROBLEM CHAINS WITHIN THE NATURAL STRATUM

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PREFACE

The interactions between agriculture and the environment have emerged as important factors linking the concerns of the agriculturist, the economist, the ecologist, and the systems analyst. Recognition of their importance has led to the establishment of a task at IIASA to study the environmental problems of agriculture. This task will look at environmental problems at the field level and at the regional and national levels, and it will attempt to provide a framework which can allow insights made at one level to become meaningful at the other as well.

This paper is the second in a series designed to examine the interrelationships between the economic and ecological aspects of human ecosystems and to create a framework within which they can be included in analyses of environmental problems of agriculture. It concentrates on the natural aspects of the system and develops a way of focusing an analysis onto the most important issues and deriving feasible models for their analysis.

ABSTRACT

A human ecosystem (e.g. agriculture) is a managed environment. It may be maintained in a state very different from that of a natural ecosystem. But the basic laws of the natural system (here termed the natural stratum of the human ecosystem) still hold. The interactions of the processes governed by these laws can be seen as a highly branched chain of issue areas which are influenced and observed by society at certain key places. The overall ecosystem is not highly controllable. So an analysis of problems in a human ecosystem must consider the chain of issue areas connecting them with the points of control as well as those aspects of the system actually monitored by society. The linkage of ecosystem processes into problem chains provides a straightforward way of organizing a detailed analysis of the dynamics of the natural stratum of a human ecosystem. At its simplest, this analysis may be relatively qualitative, but the problem chain approach also simplifies the organization of quantitative analyses based on mathematical models.

A Common Framework for Integrating the Economic and Ecologic Dimensions of Human Ecosystems. II. Processes And Problem Chains Within the Natural Stratum

Modeling the interactions between the economic and ecologic portions of human ecosystems for management and policy design is an extremely new and important area of study. Because of its newness, there are no clear principles for identifying the boundaries of the system to be considered. We have discussed the specifications for a common analytical framework for economic and ecologic dimensions of such systems in the first paper in this series (Clapham and Pestel, 1978a). In that paper, as this one, agriculture was taken as the example of a human ecosystem. Such systems are effectively viewed as multilevel hierarchical systems in which the economic and political considerations of the farmer and society are considered as middle strata and basic natural and ecological phenomena are considered as the bottom, or natural stratum (Figure 1). This implies that we must both deal adequately with the problems of each stratum and with communication between strata.

In the previous paper, we have concentrated on the problems of interstratal communication. The problems and mechanisms for dealing with the middle strata will be discussed in the third paper in this series. We shall concentrate here on the processes and problems within the natural stratum. Numerically-oriented ecologists, soil scientists, and other workers have been dealing with this stratum for a long time, but seldom in a way that has emphasized the kind of coordination between disciplines which would be necessary for linkage with the economic and political considerations for a multistratum approach. There are exceptions, notably within the International Biological Programme (IBP) Biome projects, but they have represented extremely large projects mounted with some difficulty. Fortunately for the analyst, most studies are oriented toward specific problems rather than the

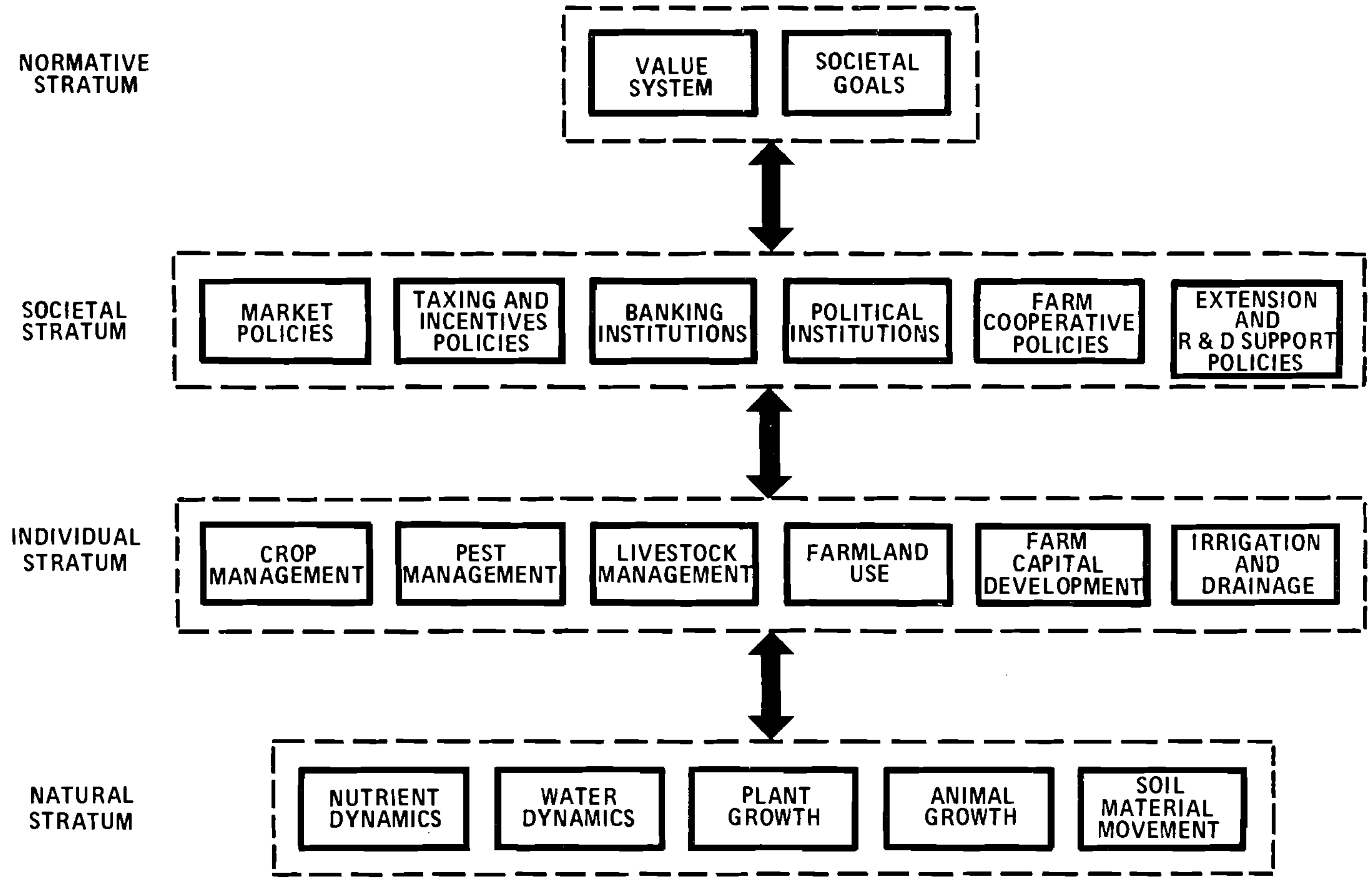

Figure 1. Agriculture as a multilevel hierarchical system. Only those parts of the society directly involved with agriculture are shown. All processes or phenomena within a stratum are assumed to affect each other.

global understanding sought by IBP, and not all of the system needs to be understood and modeled in detail. But a satisfactory interstratal management or policy model of an agricultural system does require more than either routine ecological or economic models. In this paper, we shall discuss the natural stratum from a problem-oriented viewpoint and suggest some basic approaches for treating it comprehensively and adequately.

The basic conceptual problem in modeling the natural stratum is to organize it in a comprehensible way and to identify meaningful boundaries for it. Once this has been done, then the various subsystems can be considered in a more straightforward (although perhaps rather complex) manner. Many positions can be taken on organizing and setting limits on a study of the natural stratum. The most extreme is that it includes "everything". This would suggest that an adequate analysis must consider all aspects of the dynamics of soil, nutrients, and water, all plant and animal populations, and so forth. This is the logic of Barry Commoner's so-called First Law of Ecology (Commoner, 1971), in which "everything is related to everything else". In its gross interpretation, of course, the "first law of ecology" is true. And it is nowhere more true than in the natural stratum of a human ecosystem. Soil conditions do affect pests which do affect crop production and so forth. As a qualitative paradigm, it is extremely useful. But as a basis for a practical analysis, it is so inclusive that any attempt to implement it would be infeasible.

Almost equally extreme is the more usual breakdown along disciplinary or taxonomic lines. This treats the system as biotic vs. abiotic, agronomic vs. entomologic, and so forth. Such decompositions are almost always easier for individual researchers, as they allow them to retain a conceptual grasp of all of the elements within the boundaries of the analysis. But in some ways, this is almost as global as the "everything" view, since disciplinary breakdowns are inherently likely to include subsystems which might otherwise be disregarded because their linkages to the subsystems of main interest are quite weak, while disregarding subsystems whose linkages are very strong.

From a systems viewpoint, it makes the most sense to think in terms of two complementary decompositions. The first is into the basic phenomena such as those indicated in Table 1. These phenomena are entirely general and occur in all agricultural systems. The second is a topical decomposition into a series of problems or interest areas, such as those listed in Table 2. While general in the sense that each problem or interest area applies to conditions in several regions or countries, most are geographically restricted to at least some degree.

This dual decomposition is useful from our viewpoint because it captures those aspects of the actual system which are most robustly described (i.e., the basic phenomena) as well as those which are of greatest practical interest (i.e., the problems and issue areas). In addition, there is generally a straightforward mapping from interest areas to processes. That is, a description of an interest area will typically include at least a listing and perhaps a more detailed description of the relevant basic phenomena and their interactions. Even if this listing is not complete in some sense, the notion of the interest area provides a simple heuristic device for completing it as the need arises.

Issue areas tend to be rather narrowly defined, so that even related problems are often considered separately. As a concrete example, soil erosion and stream siltation are two problems that are often considered separately. Nevertheless, the one is commonly the precursor to the other, and stream siltation is virtually never a problem without soil erosion. In a less obvious way, eutrophication of surface waters is closely related to soil erosion. The eutrophication process in most watercourses is controlled by phosphorus. But very little phosphorus is delivered to surface waters in soluble form. Most enters either as organic phosphate or adsorbed onto soil particles. In both cases, the mechanism whereby the nutrient is delivered to the water is soil erosion.

Table 1. Basic phenomena found on the natural stratum of human ecosystems.

Chemical phenomena: reactions, ion exchange, colloidal properties, characterizations and dynamics of mixtures.

Water-related phenomena: reactions, movement, cycling.

Biological growth: plants and animals, desirable and undesirable, in the context of very simple or relatively complex community.

Mass balance and movement phenomena: soil states and movement.

Genetic phenomena at all levels.

Land and related phenomena.

Table 2. Problems and issue areas to consider for a human ecosystem, arranged by type.

Soil Processes

Soil fertility
Wind soil erosion
Fluviatile soil erosion
Soil oxidation
Soil compaction
Waterlogging & Salinization
Soil structure
Soil water status

Ecosystem Processes

Land conversion
Vegetation cover
Natural habitat
Changes in natural genetic resources
Climate

Water Processes

Water quality
Eutrophication
Waterborne disease
Flooding
Buffer capacity of system

Soil-Water Processes

Siltation
Agricultural Chemical Runoff

Crop Processes

Crop productivity
Crop genetic base

Pest Processes

Pesticide resistance
Pest and weed attack

Air-related Processes

Air pollution
Air quality

In this very simple example, soil erosion represents, in some sense, a basic process. But as shown in Figure 2, it is basic not in the sense of control, but rather of contingency. The other two interest areas are not controlled by soil erosion, they simply tend not to happen unless it happens first. At the same time, the precise information content required of an issue area depends on the issue areas to which it is related. That is, the description of the soil erosion problem must include information about adsorbed and organic nutrients if we wish to relate it to eutrophication, whereas it need not if the contingent issue area is stream siltation.

ROLE OF TOPICAL SUBSYSTEM DECOMPOSITION IN A MULTILEVEL HIERARCHY

The topical decomposition of the human ecosystem comprises a set of aggregates of the basic phenomena. Both the topics and the basic phenomena comprise the greater part of the natural stratum within a multilevel hierarchical view of a human ecosystem. Neither is entirely comprehensive, and they both give quite different perspectives of the stratum. As a general rule, the basic phenomena provide a better orientation to modeling; the topics are preferable for system organization and specification. The two are closely related, however, and one can always translate topics into basic phenomena: we must simply specify the mapping between the two.

It does not affect our perception of information flow between strata whether the natural stratum is treated with respect to topics or to basic phenomena. The patterns of feedback within and across strata are the same in either case.

One of the basic tenets of multilevel hierarchical systems theory is that the information flow across strata is asymmetric. Downward flow usually represents control of some sort. For an agricultural system, the communication from the individual to the natural stratum comprises the factors involved in managing the soil, water, crops, livestock, and/or pests. The farmer and

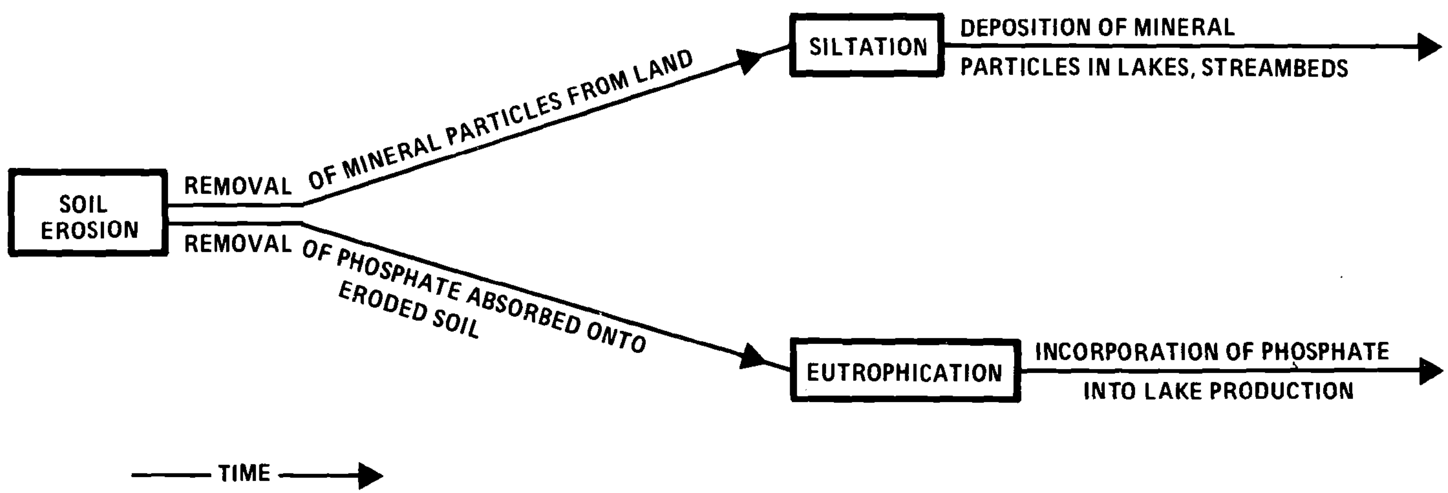

Figure 2. Relationship between soil erosion and siltation and eutrophication. The last two are contingent on the first in different ways.

the economic institutions occupying the middle strata perform certain actions which are intended to manipulate the variables (animals and plants, soil and water) on the natural stratum. The natural stratum is not completely controllable, but it is clear that the controlling efforts of man on middle strata are very different from any kind of control analogue which would be conceivable in the other direction. The information flow from a lower stratum to a higher stratum is process information. In the case of the agricultural system, the processes under observation are the growth and development of the crop or livestock herds. The kinds of control implemented by the middle strata are limited by the technological, organizational, and managerial capability of the society in question, but they change and adapt to conditions as perceived by the managers. Thus, feedback across strata is a relatively sluggish phenomenon (Clapham and Pestel, 1978a).

This can be contrasted with the more usual notion of feedback which obtains within a stratum. Here a signal impacts on a subsystem which may respond quickly. This response may result in a rapid change in the behavior of the first signal. Feedback within a stratum may also be somewhat slow, but the point is that it need not be. We may say in general that feedback loops which cross strata and which involve the responses of managers to changes in the natural stratum are always longer than the fastest feedbacks within the natural stratum. For modeling or analytical purposes, the former can be characterized as "slow" and the latter as "fast". The decomposition of the system into "slow" and "fast" variables has been used very effectively in engineering design of complex technological systems such as nuclear reactors. For analyses with discrete iterations the "slow" feedbacks crossing strata are invariably of one or more iterations in length. This type of discretization is quite realistic in the couplings between economic and political subsystems on one hand and field-level systems on the other hand, as the point of contact between the two tends to be the market. And the market has an annual rhythm (at least if we wish to limit our discussion to a temperate-zone agricultural society, although the assumption is not too bad for tropical countries either). All of the adaptations of the managerial strata are then responses to the integral of the past year's performance of the natural strata as realized in the crop which is brought to market.

Because of the different types of feedback between and across strata, the couplings between strata tend to be relatively weak most of the time and consist of relatively few indicators of process performance. But in order to capture the essential control-response-adaptation nature of the management process, it is necessary to consider the entire information path through the natural stratum, including the points at which information enters and leaves it. This is often extraordinarily difficult, as the information flow within the natural stratum may be extremely complex and involve a large number of subsystems. This implies that we must consider chains of topical subsystems as such. These chains map the information flow throughout the natural stratum. In addition, the chain must connect information flow channels between strata such that a given chain can include all of the instruments of control which are available to the society, as well as the observation points used to monitor the progress of the system. This is shown diagramatically in Figure 3, with some features that are not entirely obvious. As an example, it is easy to visualize a simple chain of subsystems as shown in Figure 4. The points of control are the normal agricultural inputs of fertilizer, pesticides, machinery, labor, land, irrigation, and so forth. One obvious monitoring point is the growth of the crop. But in addition, the chain includes the larger dynamics of the soil-water-plant system. We know something about the nutrient status of water which percolates through the soil and which may lead into the groundwater system. Insofar as this is used as drinking water, then this too is a monitoring point of society, and failure to consider this monitoring point either in analysis or in the real world can lead to relatively serious consequences.

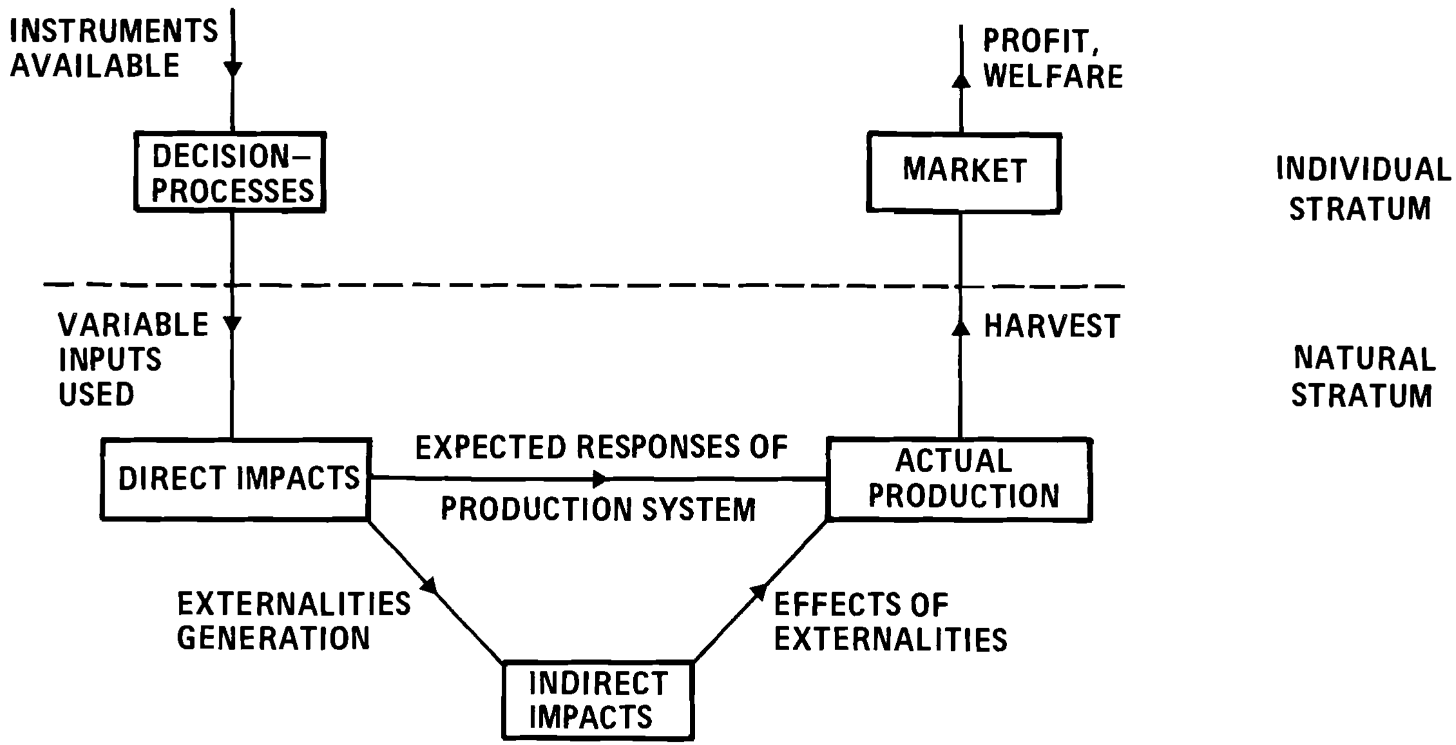

Figure 3. Schematic representation of a problem chain in the natural stratum with inputs and monitoring parts shown. No instruments are available to the farmer on the natural stratum, and responses of the natural stratum depend not only on the direct expectations but also on the externalities imposed between the inputs and production.

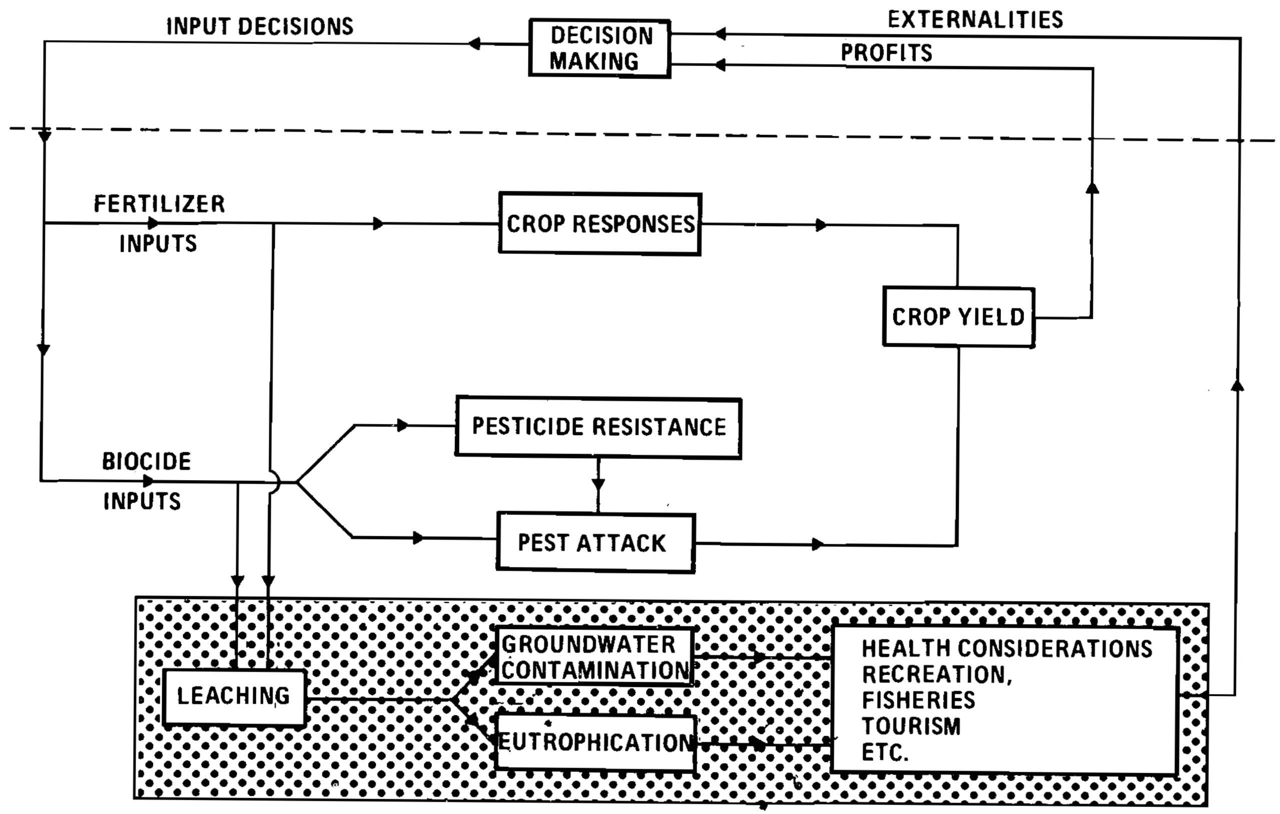

Figure 4. Example of a relatively simple problem chain. The shaded section is often not considered in decision-making models or analysis of specific problems, but it can be. Contingency relationships are indicated with arrows.

A VIEW OF THE NATURAL STRATUM

We can now present a general view of the natural stratum which can serve as a basis for analysis of the agricultural system. It consists of a large number of topical subsystems with certain interactions specified between them. It is a very general view which is meant to be representative of the important kinds of interactions rather than as any detailed statement of what things ought to be considered in any specific case. It is probably not complete for certain instances, and it may be over-complete for others (Figure 5). It is derived from a set of problems enumerated by a task force on Environmental Sustainability and Improvement of Agrosystems held at the International Institute for Applied Systems Analysis in April, 1977, and it was adapted and completed by the authors. Any other list of problems could have been used, and the picture presented here could easily be adapted for other purposes. As such, it can serve as an adequate heuristic device for most situations. The natural stratum is represented by 26 subsystems representing problems or interest areas which are monitored in 3 points by higher strata and controlled by them through 9 activities.

The diagram has two dashed vertical lines, one to the left and one to the right. These represent the places in which information crosses strata. Those activities to the left of the left-hand shaded line represent activities of the managerial strata which impart control information to subsystems on the natural stratum. Those activities to the right of the right-hand shaded line represent monitoring points within the managerial stratum in which the state of the natural stratum is observed, and with respect to which adaptive changes can be made. Subsystems between the two shaded lines represent problems or issue areas on the natural stratum which interact with each other. For simplicity in diagramming, no distinction is made in Figure 5 of the types of information involved in the flow, but we shall shortly specify them in much greater detail.

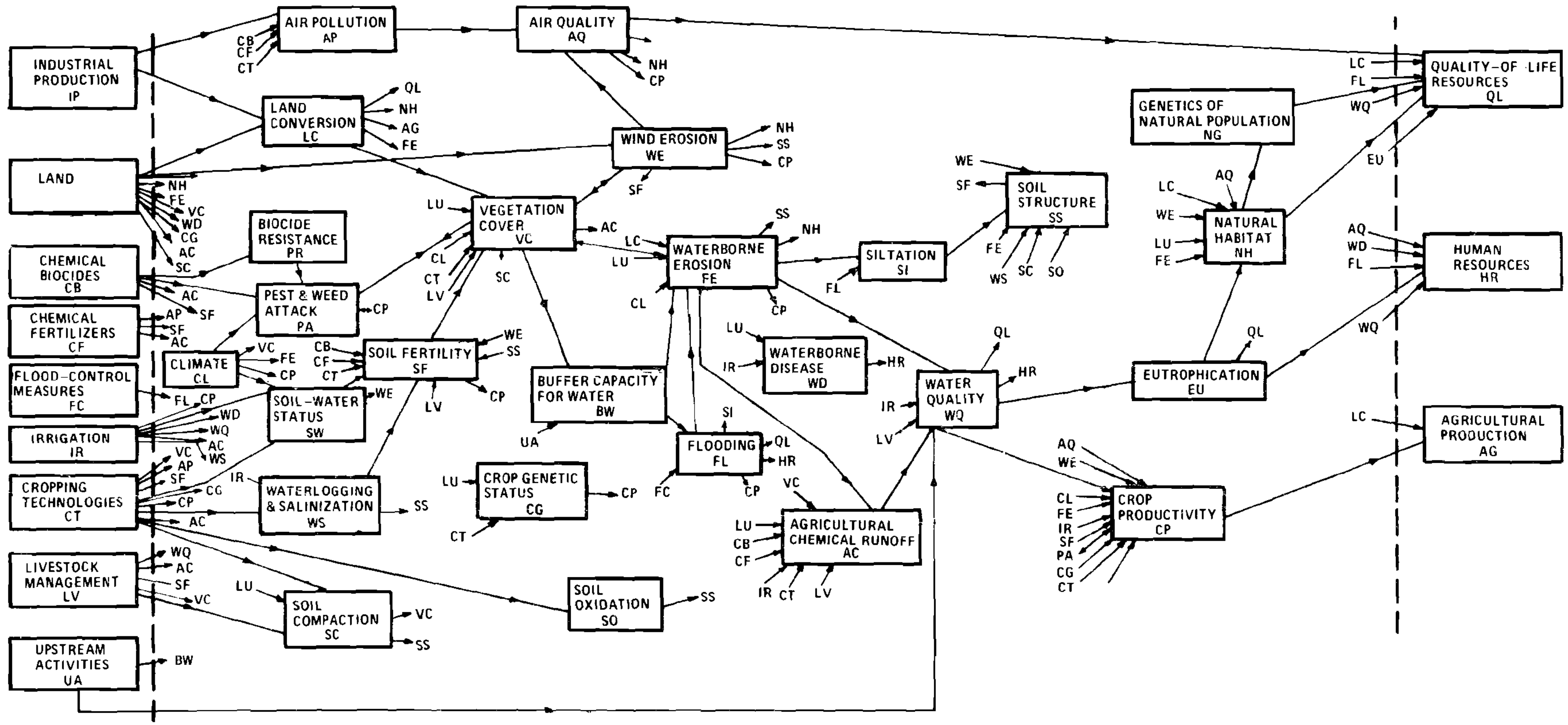

Figure 5. Schematic diagram showing interrelationships between problems and issue areas on the natural stratum, with inputs and monitoring in formation indicated.

Inputs to the Natural Stratum

We recognize two kinds of inputs to the natural stratum. The first is downward flowing information from the individual stratum termed "control inputs"; the second is events such as climatic disturbance or change. The control inputs represent conscious control by man. The events are outside of human regulation, and they can be regarded as *sui generis* phenomena which affect other issue areas on the stratum. See Pestel, Helmer, Clapham, and Fischer (1978) for a more detailed description of the nature of events.

The nine control inputs are, for the most part, quite straightforward. The first is *industrial production.* This includes all industry, both heavy and light, and it is mainly important as a factor in air pollution generation and land conversion. The *land use* policies and practices of a society constitute an extremely important factor in agricultural production, since land is one of the essential basic inputs of agriculture. These include the management techniques and controls placed on the land area under the control of the society in question.

Chemical biocide use patterns include not only the amounts of pesticides, but also the types and ways in which they are used. A level of technology is implicit in this notion. *Chemical fertilizer* use patterns are entirely parallel to those of chemical biocides, except that they refer to plant nutrients. *Flood control* works have a relatively minor role in the agricultural system except insofar as they affect flood-stage water level management. Because of the catastrophic nature of flooding, on the other hand, agricultural-related water management in flood-prone areas should consider the monitoring implications of flooding. *Irrigation* patterns, as with pesticide and fertilizer uses, refer to the amounts, technologies and ways in which water is used directly in the agricultural system.

The *cropping patterns* characterizing the system include a number of very important factors. For example, the number of crops realized per year, the specific crops and rotation schemes, and the use of other variable inputs such as machinery and labor are all considered here, along with information about the technology of cropping which is being used in the area of study. In the same way, *livestock management* provides information about the livestock patterns of the society or area in question.

Finally, there are *upstream activities* which produce effluent water that is used in one of several ways by agriculture. It may be used deliberately for irrigation, or it may affect soil fertility and/or structural characteristics through one of several mechanisms.

Monitoring Information

The three types of information monitored by the higher strata are also quite straightforward. *Agricultural production* refers both to amount of agricultural produce and its specific mix and quality. The *human resources* of a society include health, sociological stability, and several attitudes which can become very important to the decision-making process. This is a very large and vague category, and those aspects of it which are most significant in the human ecosystem will become clear in the description of the effects of changes within the natural stratum on human resources. Finally, there are what might be called *quality-of-life resources*. This is another vague term which can mean many things to many people. As used here it indicates those resources of society which do not necessarily play an important role in basic production for the society but which may be very important for people's feelings of well-being. These are things like clean air, clean water, lakes for fishing, boating, natural beauty, tourist attractions, and so forth. This is a more restricted view of quality of life than most usages of the term, as it does not include economic or material well-being. Some of these aspects are embodied in the other types of monitoring information, but some are ignored in this analysis. Nevertheless the notion is a useful one, bearing in mind that it refers to marginal quality of life considering only natural or quasi-natural environmental resources.

Subsystems of the Natural Strata

The twenty-six problems or issue areas can be grouped approximately into seven basic types (Table 2). We shall describe each issue area briefly, by type.

Air-related Processes: The air-related subsystems concern air pollution generation and air quality. These are the simplest subsystems as far as agriculture is concerned, and they are really important in only a few areas. The first represents the process of *air pollution* formation. Air pollutants are generated mainly by industrial production (including electric power generation), with some pollutant generation within agriculture by mechanical tilling of soil as well as chemical biocides and fertilizers. In the latter two cases, there are several mechanisms by which these are taken into the air. These include bacterial action, the way in which the chemical is spread onto the land, and blowing by wind.

Air quality includes much more than the concentrations of air pollutants derived from industry and agriculture. Many air pollutants are secondarily produced in the atmosphere through photochemical and other chemical reactions. This is especially true for oxidizing air pollution such as photochemical (Los Angeles-type) smog, but it is also true, to a degree, of reducing (London-type) smog. Air pollution can affect human society in several ways. There are several documented instances of air pollution damaging agricultural productivity, even substantially. It has even destroyed certain agricultural industries such as the truck farms of southern California. Photochemical smog has virtually eliminated this area as a producer of leafy green vegetables. Air quality may also have a substantial affect on human mortality and morbidity, as well as labor effectiveness and sickness. Adverse air quality may also affect quality-of-life resources. Perhaps one of the most interesting effects of air processes is its potential effect on climate. The freons from aerosol sprays and the nitrous oxides from nitrogen fertilizers have both been implicated in destruction of the atmosphere's ozone layer. If these implications are correct, then regional or global climate may also be affected strongly by air quality at least under some circumstances.

Ecosystem Processes: The so-called ecosystem processes are a diverse group of issue areas, some of which occupy key roles in agricultural systems. One of the most basic of these is *land conversion.* This refers to all of the changes, both intentional and unintentional, which accompany conversion of land from one use or management type to another. These can affect the biological, physical, and chemical properties of the area, and land conversion can have consequent effects on several other subsystems. It is a function of industrial production, which affects the demand for land outside of agriculture (including urbanization), as well as changing styles of agricultural land use.

Land conversion has a direct impact on quality-of-life resources such as forests, parks, and farmland as it most commonly represents the conversion of an amenity resource to a more economically productive sort. Land conversion within agriculture likewise has a direct effect on agricultural production. Land conversion can remove natural habitat. There are many parallels between this and the impact on quality-of-life resources, but there are some substantial differences as well. The concern with quality-of-life resources is as they are used by man. The habitat effect refers to the way the same land resources are used by natural populations of animals and plants. In a similar way, land conversion alters vegetation patterns and the tendency for areas to erode. Many forms are accompanied by construction, plowing, planting, removal of plants, and similar direct influences on factors controlling soil erosion.

One of the key processes in any human ecosystem is that which defines the type and extent of *vegetation cover.* Indeed, it is impossible to describe the dynamics of most of the factors comprising the ecosystem without explicit consideration of the vegetation cover. It is affected by land conversion, as well as many others which may be even more important. For example, agricultural land use practices may determine much or all of the vegetation cover. The types of rotations used in an area, as well as the farmer's assessment of the trade-offs between perennial crops, annual crops, and livestock forage, all change the vegetation cover. So can specific cropping technologies, livestock-use patterns, and changes in soil fertility. Vegetation can be damaged or killed by excessive erosion. Climatic change and soil phenomena such as compaction may also change it substantially. Vegetation cover, especially of crop plants, is also affected by pest attack.

It affects other subsystems throughout the natural stratum. For example, air and water erosion of soil are very much related to the plant cover and root volume. The buffer capacity of the soil for water control depends on vegetation both for the amount of water transpired through it and for the degree to which the mechanical effects of the presence of the vegetation moderates and even determines runoff patterns and rainfall/runoff ratios. In the same way, it is also a key factor in agricultural chemical runoff patterns. The abundance of suitable target plants is also correlated with the intensity of plant pest and disease attacks.

The *natural habitat* is affected by a great many forces. One of these is land use techniques and land conversions which remove natural habitats for more economically productive uses or allow them to deteriorate from neglect or mismanagement. The impact of the removal of a given piece of natural habitat on the natural ecosystem is very much related to the specific geographic and ecological situation, and it is impossible to generalize about the effect of any given change. Soil erosion by wind or water can also modify or even destroy natural habitats very quickly. Eutrophication is probably the most potent force for the loss of natural habitat in lakes and streams.

The impact of habitat destruction on human ecosystems is perhaps felt most strongly on the quality-of-life resources. Natural habitats tend as a rule not to be terribly important for economic activities except for fisheries, wildlife, and tourism. This does not mean that they are not critically important; it simply means that it is very difficult or impossible to measure their worth satisfactorily by placing a price on them. In some ways, however, there is a more subversive impact. The size of populations which can be maintained in an area is closely dependent on the habitat for those populations. If the habitat is damaged, altered, or destroyed, then associated populations will suffer accordingly. Damage may not be very great before vulnerable populations show substantial negative population growth. Such cases lead to *genetic erosion*, which in turn leads either to simplification of the genome or even to extinction of the population. The list of endangered species is large and growing rapidly, and the list of species which have been lost to the biosphere through extinction is also large,and growing daily. For some of these species, the pressure has been a result of over-active hunting. But most have succumbed to erosion of their genetic base, generally caused by habitat destruction. This genetic erosion and the consequent losses of natural diversity have direct and palpable consequences on quality-of-life resources, and they may also have wider impact as well.

The patterns of temperature and precipitation fluctuations comprise the *climate*. This issue area is one of the most complex in the ecosystem, as well as one of the least subject to human control. The effects of ozone layer destruction discussed above have been cited as probable mechanisms for climatic change, as have the albedo changes from massive deforestation, and the absorption/radiation balance changes from the addition of both CO_2 and aerosols into the atmosphere. But the complexities of climate are so great that their relationships remain uncertain. Climate is one of the most important considerations in any ecosystem, and climatic change is felt on many other issue areas. All biological subsystems, including pest and weed attack, crop productivity, and vegetation cover, respond to changes in both temperature and precipitation. This is also true of soil water status and waterborne erosion. Despite the lack of control by man, this is probably one of the key issue areas in the system, as it is failure of rainfall which are the most important trigger for the most serious, irreversible episodes of desertification.

Crop Processes: Natural populations are not the only ones who are subject to *erosion of their genetic base.* It occurs in domesticated crops, and it can be argued that this is an even more significant problem than that of natural populations. The genetic base of a crop population is a function of the breeding techniques underlying the cropping technologies used and the land-use patterns through which these technologies are spread. The impact of genetic change in crops is on productivity, and this impact may be positive or negative, depending on environmental circumstances. Yields commonly rise as the result of genetic selection, but so does vulnerability to environmental fluctuation. Under certain circumstances, the losses to pests or disease may be very high. A detailed discussion of the problems of genetic vulnerability of crops is given by Horsfall et al. (1972).

Crop productivity is a function of soil fertility, cropping types and technologies, losses to erosion, floods, attacks by pests and weeds, irrigation intensity and water quality, air quality, climate, and crop genetics. The dependence of crop productivity on these factors is perhaps the most recognizably significant of interactions in the entire natural stratum, as it embodies most of a crop production function. Soil fertility is the result of numerous variable inputs from the managerial stratum. Cropping technology comprises those inputs often represented as "capital" or "technological change", and the genetics of a crop stand results from the particular seed breeding program used. Irrigation water quality can affect many of the physiological responses of the crop plants, and pest and weed attacks embody the crop equivalents of the predator-prey and competitive interactions found among organisms in all ecosystems. Erosion and deterioration in air quality can lead to death or lowered productivity. The luxuriance of the crop population is sometimes a factor in its attractiveness to pests, and hence to the intensity of pest attacks. But the main importance of crop productivity is its contribution to total crop production.

Pest Processes: Pests can destroy substantial shares of agricultural production, making pest management a serious issue. Chemical biocides have become the most important factor in pest management, and they will unquestionably have a prominent role for a long time to come. But the application of chemical biocides (and presumably other kinds of pest management tools as well) has several effects, not all of them desirable. It may blunt the attack of pests but may also impose a chemical selection process on the pest populations which inevitably leads to *genetic resistance* against the biocide. It also affects non-target populations in ways which may be more damaging to the long-term interest of the farmer than the pest itself. Both affect the actual attack patterns of pests on the crop population.

The incidence and severity of *pest and weed attack* on crops depend on climate, the degree of resistance in the population, the biocide use patterns, the diversity of the vegetation, and the luxuriance of the crop. Its effects on vegetation may be qualitative or quantitative, and there may be a substantial effect on crop productivity, especially if vulnerable varieties predominate in the crop.

Soil Processes: The soil processes comprise a number of different phenomena occurring within the soil. Some are quite closely tied with other processes. Perhaps the most important is *soil fertility*. This can be defined roughly as the available-nutrient status of the soil, considering the vegetation and its nutrition requirements as well as the soil's tilth and structure. It is thus an abstract and aggregated concept and is affected by most of the rest of the ecosystem. Soil fertility can be controlled to a degree by biocides and fertilizer use. In general, chemical fertilizers increase fertility, while an influx of chemical biocides decreases it. But neither of these statements is absolute. If the use of chemical fertilizer allows the farmer to maintain his yield at the expense of the organic content (and hence cation exchange capacity) of his soil, then it has contributed to a long-run decrease in fertility rather than an increase.

Likewise, if biocide use allows the maintenance of higher plant biomasses which result in larger root-derived detritus contributions to the soil, then it leads to long-run increases in fertility. Mechanical tillage can affect the oxygen and water dynamics within the furrow slice, and both are important both biologically and chemically. Erosion and irrigation-related problems such as waterlogging and salinization reduce soil fertility.

The effects of soil fertility changes are reflected in the vegetation and the productivity of the crop. Major changes in fertility can be felt quite rapidly in both of these areas.

Several factors contribute to *wind erosion* of the soil. The most important is decline in vegetation cover, which reduces the soil-holding capacity of the roots and the particle-trapping ability of the above-ground vegetation. Vegetation changes also bring about significant changes in the microenvironment. Almost as important is the water content of the upper soil layer. A soil close to field capacity is much less likely to erode than one which is much drier. Soil erosion also arises from plowing practices, construction, and other activities related to land-use. It can contribute to the destruction of natural habitat and can reduce crop productivity on both the short and longer time scale. In the short range, soil erosion by wind can cover plants or obscure the sun, hence lowering actual crop yield. The long-term effects of the soil losses through erosion are felt through deterioration in the soil structure, and the loss of nutrients in topsoil can directly affect soil fertility.

Waterborne soil erosion stems from similar sorts of causes and has similar impacts. Land conversion creates surfaces which are amenable to soil erosion, and it also may alter nonagricultural water-use patterns so that soil erosion is increased. Changes in land-use patterns may have similar effects, as can any kind of change in the climate or the vegetation cover. One of the more interesting issue areas is the ability of the soil to buffer water throughput. As this buffer capacity is reduced, the rate of water runoff increases, and so does soil erosion.

Finally, floods may vastly increase the amount of soil erosion in one area just as they may increase soil deposition and siltation in another.

Waterborne soil erosion may lead to the destruction of natural habitats, as well as a deterioration in water quality of receiving watercourses. Erosion in one place generally leads to siltation in another, and soil structure in both areas is altered in the process. This is often detrimental, but it is sometimes beneficial: alluvial soils are typically the most fertile soils of tropical areas. Vegetation can be impaired by erosion, and fluviatile soil erosion is the chief mechanism for the runoff of particulate or adsorbed agricultural chemicals.

Soil oxidation is a geographically restricted problem which can be of considerable local importance. It is the oxidation of acid sulfate soils due to excessive drainage. As such, it can be regarded as the result of cropping types and crop technologies. Its result is irreversible changes in the soil structure which lead indirectly to deterioration in crop yield.

Soil compaction results from overgrazing and the physical action of too many animals, crop tillage practices involving extensive use of heavy machines, and land use practices which are detrimental to overall soil structure. Its main impact on the production side is a deterioration in soil structure.

Waterlogging and salinization of soils refers to increases in the salt or water content of soils as the result of irrigation and watershed-management practices. The degree to which waterlogging and salinization are important is a function of the environment in which the practices are being carried out, and most cases can be arrested or improved with improved management. The result is a long-term deterioration in the soil fertility, as well as the soil structure which can lead to destruction of the soil as a productive entity.

Soil structure is an index of the overall status of the soil. Almost all phenomena which affect agricultural production in the long-term do so via soil structure. These include waterlogging and salinization, compaction, oxidation, siltation, wind and water erosion, and desertification. Soil structure is a very complex phenomenon with biological, physical, and chemical components. Its impact on agriculture is probably best understood in its role as a key factor in long-term soil fertility.

The *water status* of a soil refers to the amount of water that exists in the furrow slice with respect to fixed capacity and related measures of soil water capacity as well as its clay mineralogy, organic content, and basic composition. It is a function of irrigation inputs of water as well as climate and the management techniques which retain water or increase evapotranspiration ratio. It is an important aspect of soil fertility, and the role of hydrogen bonding between water molecules and soil particles gives this phenomenon a key role in wind erosion.

Soil-water Systems: The soil-water systems are those which are very closely linked to both soil and water. These are siltation and runoff of agricultural chemicals. *Siltation* is a relatively simple phenomenon which comes about as a result of waterborne soil erosion. Soil which has been eroded from upstream areas is deposited downstream, generally in places such as reservoirs where it is not wanted. It is especially important at times and places of flooding. Siltation is a major contributor to those aspects of flooding which make it a severe problem. Removal of the silt deposited in built-up areas following a flood may be almost as traumatic as the catastrophic destruction of the flood itself. Silt deposited in fields, on the other hand, may be beneficial or detrimental, depending on local conditions.

Of more importance is the dynamics, balance, and *runoff of agricultural chemicals*, i.e. biocides and fertilizers. The factors controlling agricultural chemical runoff include the land use distributions that determine rainfall runoff patterns, the uses of chemical biocides and fertilizers, irrigation works and the runoff patterns induced by them, cropping and livestock management patterns, etc. Vegetation cover and waterborne erosion are actors in the geochemical dynamics of the soil and so have a major impact on nutrient and biocide status, leaching, and related factors. The main effect of chemical runoff is on water quality.

Water Systems: The water systems include those issue areas which describe the state of water in the overall ecosystem. *Water quality* is affected by upstream water uses, waterborne erosion, irrigation return-water, livestock, and agricultural chemical runoff. Water quality has several effects. It represents the main input of nutrients to the eutrophication process. It also has a direct influence on human health, as water quality--especially drinking water--may have a substantial effect on health. It affects crop yields since water used for irrigation may comprise most of the water reaching the plant roots. Finally, water quality is a basic factor in quality-of-life resources over and above questions of eutrophication.

Eutrophication is the process by which surface waters increase their nutrient content and become progressively more productive biologically but less useful for most purposes. The eutrophication process is driven directly by the nutrient component of water quality. It affects natural habitat, quality-of-life resources, and human health. Of these, the most direct is the natural aquatic habitat. There are many organisms whose habitats are dependent on oligotrophic aquatic conditions and which simply cannot live under eutrophic conditions. The process of eutrophication is almost always a uni-directional one. That is, it is relatively easy for a body of water (that is a lake or stream) to become eutrophic, but rather difficult for it to become oligotrophic. This process also has an impact on quality-of-life resources, notably bodies of water used for various recreational purposes. Oligotrophic water bodies are generally more useful for fishing and swimming than are eutrophic bodies. Finally, the conditions of eutrophic water are more likely to be detrimental to health than those of oligotrophic bodies of water.

Some processes are very closely related to irrigation technologies. Of these, the most important are the *waterborne diseases* such as schistosomiasis, or snail fever. It has been estimated that of all diseases, schistosomiasis is the leading cause of human debilitation in the world today. The incidence of such diseases are closely related to irrigation techniques and associated patterns of land use.

The most catastrophic of the water problems is *flooding*. Its effects can be altered by flood control projects, whose effectiveness is related both to their technological sophistication and to specific environmental conditions. The degree to which an environment is prone to flooding can also be related to the so-called water-buffer capacity of the environment. The impacts of floods are widespread, and they may be quite devastating. There is a direct impact on agricultural production through the destruction of fields or stocks, human resources may be destroyed through mortality or destruction of a population's livelihood or psyche, and quality-of-life resources may be completely destroyed. In addition, waterborne soil erosion and siltation may be strongly increased by floods.

The final issue area is the *buffer capacity for water* of the ecosystem. This is the inherent ability of the system to control the flow and throughput of water. If conditions in the overall system allow for high degrees of control so that water moves relatively slowly and smoothly through the system, then it can be said to have a high buffer capacity. If, on the other hand, water arrives quickly and flows through quickly and destructively, then the system has a low buffer capacity. It is a function jointly of upstream practices such as forestry and agriculture (both of which affect the rates of delivery of water to the area in question) and the vegetation cover within the region itself. The buffer capacity has a pronounced effect on erosion by water, and it may also be a significant component of flooding.

MANAGEABLE PROBLEMS

The view of the natural stratum presented graphically in Figure 5 provides a general picture of the interactions of the main interest areas on the stratum. As will shortly be shown, it also provides a way of building a model which is both identifiable and computable, at least in principle. But the view is obviously too complex to provide a feasible structure for most practical instances. We are more generally interested in particular parts of the system which appear to be points of stress or points of generation for significant problems. It is seldom (if ever) necessary or even desirable to consider the entire natural stratum every time we construct a model of an agricultural system. The practical question is how much must be considered in order to retain its structural dynamics and to deal with a given problem in a realistic and straightforward way. As shown in Figure 5, even a problem-oriented topical view of the natural stratum shows a massively interconnected system which must be decoupled and decreased significantly in order to gain a sufficient degree of simplication. Ideally, one could take the simplification sufficiently far that one would consider only areas of primary interest and subsystems having significant effects on those areas.

The only reasonable way to determine the degree of necessary complexity is with respect to the information flow through the entire system, centering on the problems of primary interest. In some cases, it may make sense to consider a fairly restricted subsystem by itself, with inputs treated as exogenous variables and the outputs as indicators. But this should be less common than analyses that treat individual problems in terms of their relationships with other issue areas, and especially those parts of the total agricultural system which determine the behavior of the issue areas. This type of analysis must consider all related subsystems which have a significant role in the behavior of those issue areas and the information network connecting them. Furthermore, since the entire system is under societal control, special attention must be paid to the points at which control inputs from and information monitored by higher strata cross stratum boundaries. This view is implicit in Figure 5, but must be simplified before it becomes useful. Whatever simplifications are made, however, should have minimal effect on the accuracy of the consideration of issue areas within the natural stratum and the amount or richness of information crossing between strata. To realize this, we might have to consider subsystems that we might otherwise prefer to ignore because they provide important input to the area of interest, or because they translate the behavior of systems of interest into information of interest to monitoring points not usually considered in analyses of agricultural systems. In short, the problem is to complete the information chains (Clapham and Pestel, 1978a) connecting all subsystems of interest.

Most of the subsystems shown in Figure 5 have inputs from and/or outputs to several other subsystems. Nevertheless, it is generally fairly easy to identify what might be considered the primary information chain. This is the information chain linking the direct or most obvious controlling inputs with the problem of interest and then to the most obvious monitoring points. But identifying the most important side branches and removing those that are not significant may be a considerable problem. Some issue areas are not important in some locations and can be ignored immediately. For example, schistosomiasis and soil oxidation are not problems in Sweden. But choosing whether a given subsystem should or should not be included in a study when it cannot be rejected immediately requires a detailed preanalysis that has different rules for input and output information branches.

The input branches are conceptually simpler, but they are also more troublesome in some ways, since they cannot be ignored even as a first-order approximation. The behavior of any subsystem is obviously dependent on its inputs, and all significant inputs must be specified. Only if an input is so consistent that its role can be embodied in the parameter estimation process or if it is constant under the feasible range of conditions under which the model is used can an inputting subsystem be ignored. So the preanalysis step must include a sensitivity analysis (Pestel, Helmer, Clapham, and Fischer, 1978) to estimate the potential volatility of all inputs and the potential sensitivity of all subsystems of interest to inputs from prior issue areas. When an input is volatile or the subsystem's response is sensitive, the subsystem producing the input should be included explicitly in the model. Otherwise, inputs can generally be entered exogenously or embodied in the parameter estimation process. It should be noted that any input entered exogenously represents a "handle" whereby the subsystem producing that input can later be modeled explicitly, if that turns out to be desirable. Exogenous variable inputs generally represent a safe course to follow if there is any doubt as to the usefulness--or feasibility--of modeling a given subsystem and the decision is made not to model it for the time being.

An important case of exogenous inputs is the events which may occur either within the natural stratum or on higher strata. We can often not be sure that something will occur in a given area, but we can estimate its probability of occurrence. The best example on the natural stratum is climatic disturbance; the best examples on higher strata are related to technological change. There are several methods for generating scenarios for changes in such key variables which are much more reasonable than strict scenario specification. These are discussed in some detail by Pestel, Helmer, Clapham, and Fischer (1978).

Output branches are conceptually more difficult because the first-order approximation would be that they could be ignored if they do not affect the monitoring points of greatest interest. But monitoring points which are not on the primary information chain can often be significant, and the system as a whole may be quite sensitive to feedback information generated through them. For example, the use of agricultural chemicals to increase crop production is a widespread practice (Figure 4). From the farmer's viewpoint, the decision of the appropriate levels of chemical use would be based on expected profit. But the use of agricultural chemicals also has significant impact on water resources through leaching into groundwater systems or runoff into surface waters. The attendant problems of eutrophication have led in many countries to a powerful decision-making structure to reduce agriculture-related (among others) contributions to eutrophication. Only if the information required by the separate decision-making processes of the farmer and the appropriate environmental protection board are included in the analysis can a realistic analytical scope be obtained. And if the various subsystems related to both problems are not modeled, the only recourse of the environmental protection board is to constrain the use of agricultural chemicals at relatively arbitrary levels. This is more likely to be too restrictive or too lax than to be a really good constraint level.

There is an important corollary to this argument: the output-side branches can be included meaningfully in an analysis only if the decision-making implications of the corresponding monitoring points are also included in the analysis. The problems of carrying this out will be addressed in the third paper in this series (Clapham and Pestel, 1978b)

These considerations allow a protocol for building up chains of subsystems to be considered in constructing interstratal models of complex systems and for including or neglecting subsystems that are part of the system in the real world. We must first choose the subsystems of greatest interest. These can be located in a framework such as Figure 5. The inputs to those systems can be assessed to see whether they are significant. If so, inputs to those systems from still prior subsystems can be assessed, and so on until all significant inputs to the subsystems of interest have been included. The input problem chain will then connect the issue areas from the problem of greatest interest back to the stratum boundary where all significant control inputs cross into the natural stratum. A similar strategy is followed on the output side. In general, it is not possible to deal with simply a small number of subsystems. But at least a preanalysis such as this one insures that one has a thorough grip on the framework of the analysis.

Throughout the actual construction of a problem chain the level of system definition and also the capacity of the information chains linking them need to be adequate both for analysis and for the requirements of the subsystems themselves. This is not always a trivial matter, and it is one of the more difficult factors which must be addressed when constructing an interstratal model of a complex system. These problems have been considered in the first paper in this series (Clapham and Pestel, 1978a).

Also, few analyses of environmental problems of human ecosystems can be treated adequately considering only the natural stratum. The ways in which observations are translated into control must also be considered. These processes have also been considered in the third paper in this series (Clapham and Pestel, 1978b).

Typical Problem Chains

At this point, let us identify some typical chains of environmental problems of agriculture. We shall identify the issue areas of greatest interest and follow the protocol defined above within the framework outlined in Figure 5. This yields a chain of subsystems which would need to be considered if we really wanted to look at the environmental impacts of the control measures being generated by a society in the context of an agricultural system, and if we wanted to visualize the feedback of those impacts on the society and on its capacity for control.

Let us first take an extremely simple problem chain, such as the one related to air quality shown in Figure 6. The focus issue areas are air pollution and air quality, and the primary monitoring points are quality-of-life resources such as clean air and urban property values, as well as the health aspects of

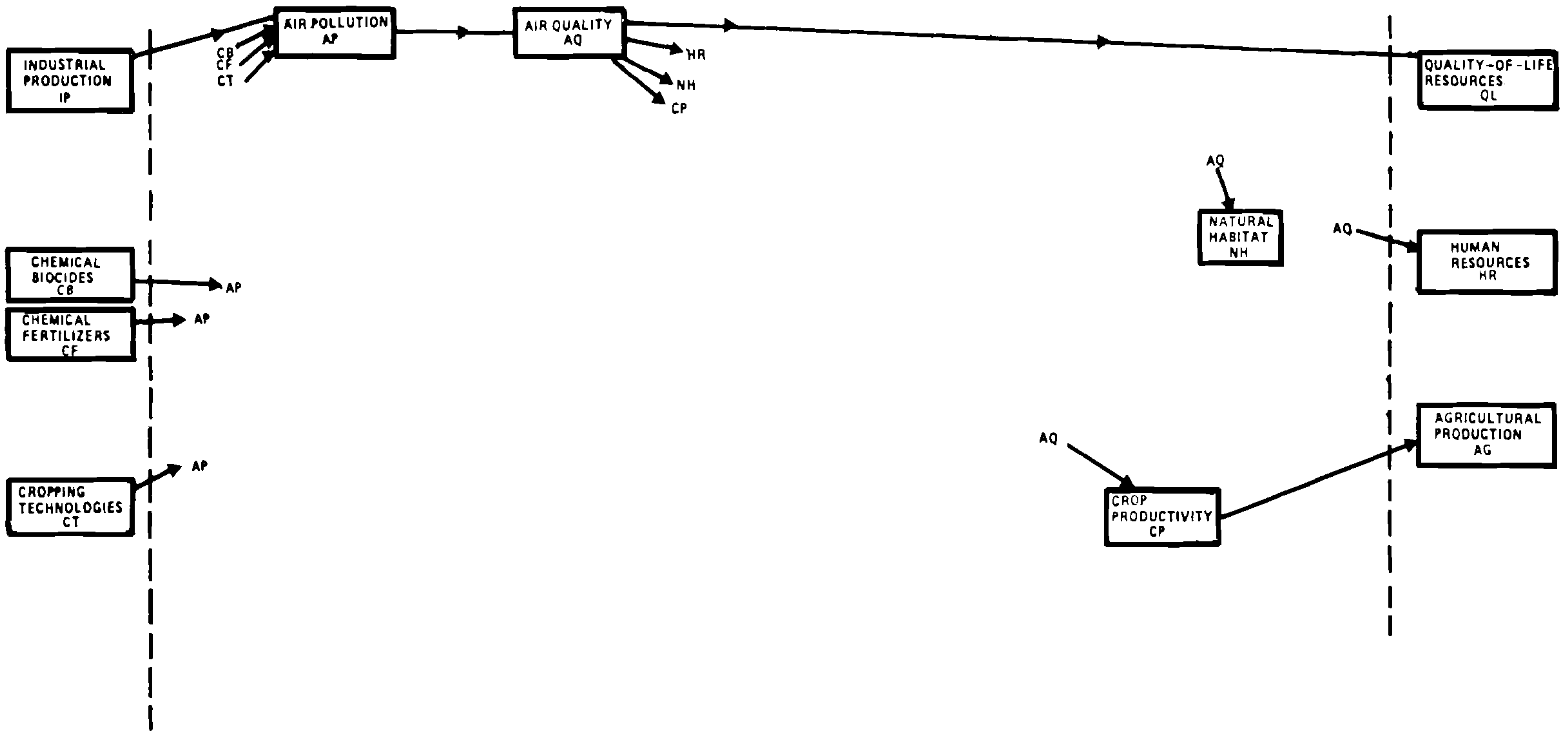

Figure 6. Construction of problem chain centering around agricultural effects of air pollution and air quality. The figure is derived from figure 5, as described in the text.

human resources. The sources of air pollution are industrial pollution and the agricultural pollution generated from agricultural chemicals and mechanical tilling. For this simple example, let us assume that wind erosion except for that directly related to mechanical tillage can be ignored. There may be substantial local impact on agricultural productivity such as in the leafy-green vegetable industry of Southern California. These are monitored by society via the market in the form of agricultural production. Deterioration in air quality affects the first three subsystems directly. The effect on agricultural production is indirect. In most places, it is highly unlikely that the strictly agricultural effects of air quality deterioration lead to the kinds of feedback which would change the situation in any way. The exceptions are in places such as Southern California, where a poor showing in the market can lead to major changes in land use as farmers go out of business or as regulations are introduced to retain the amenities represented by farms or at least to use the losses in farmland amenities as one of the excuses of imposing restrictions on the main problem.

This example is an extremely simple one, and it is presented mainly as a way of illustrating a specific problem chain. A less straightforward and more significant example is represented by agriculture-related water pollution, as shown in Figure 7. This is a major problem in many localities. It focuses on water quality and eutrophication, and the primary monitoring points are the quality-of-life resources and human resources. Other direct impacts are on natural habitat and crop productivity. The main primary contributors to the problem are obviously irrigation, waterborne erosion, agricultural chemical runoff, livestock patterns, and upstream activities affecting water quality. On the output side, changes in natural habitat also affect the genetic resources of natural populations, changing quality-of-life resources in a different way. Crop productivity changes are felt by agricultural production. These indirect effects are not unexpected, and they would cause no conceptual problem in any

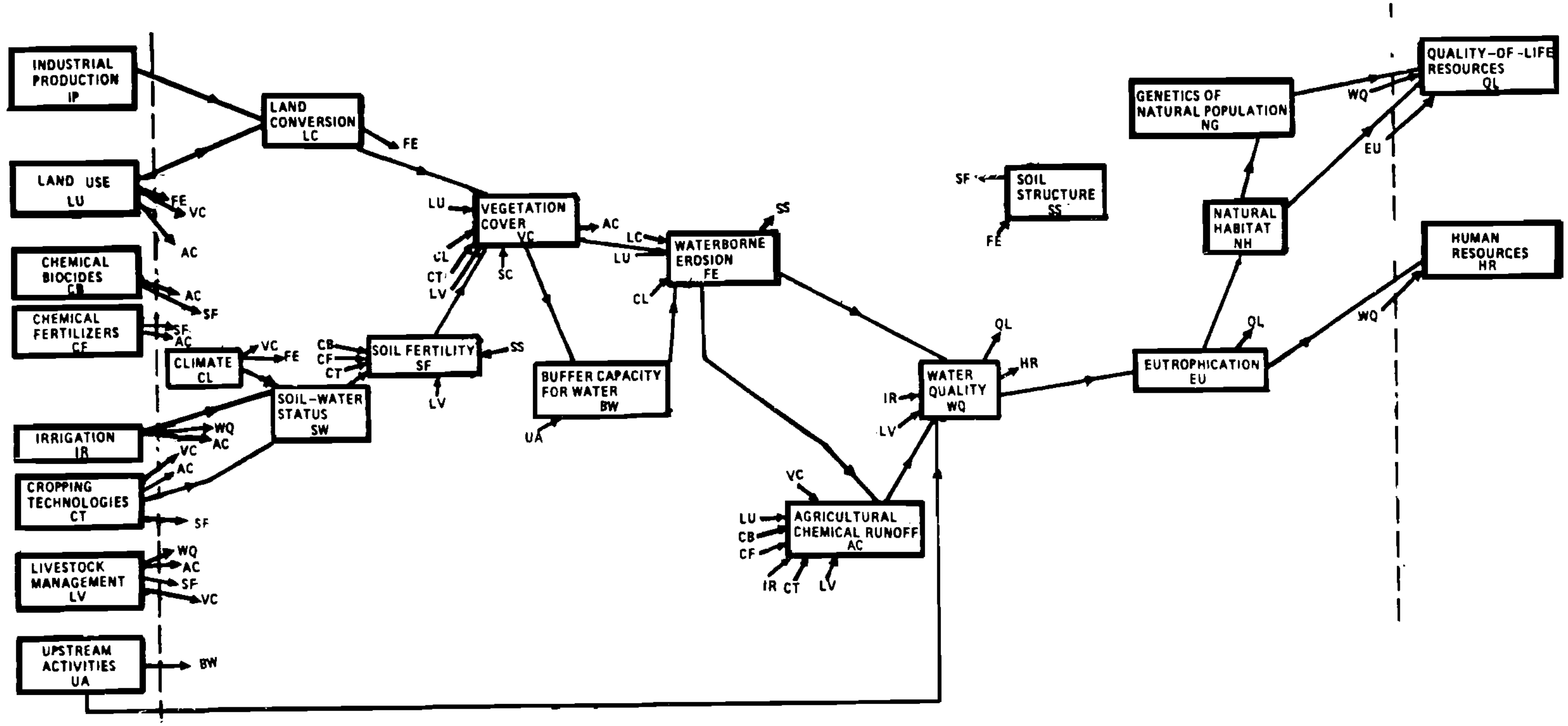

Figure 7. Construction of problem chains centering around agricultural water pollution. The focus is water quality and eutrophication, and the figure is derived from figure 5 using the method described in the text. The number associated with each box denotes the order in which subsystems enter the chain.

analysis. However, the agricultural chemical runoff and water-borne erosion must also be explained. In order to do this, the indirect inputs shown in Figure 7 must also be considered. These include land use and land conversion patterns, chemical biocides and fertilizers, cropping patterns, water buffer capacity, and vegetation cover. Vegetation cover must then be described: this requires considering soil fertility and pest and weed attack. This may be quite easy if the only vegetation is the crop, but this is seldom the case. Adequate control of agricultural pollution is generally facilitated by planting strips of vegetation which are not the primary crop, so even if "vegetation" means "crop" at the beginning of an analysis, it is unlikely to mean so at the end. Pest and weed attack requires the consideration of biocide resistance, and industrial production must also be studied in order to include land conversion.

In short, the problem chain needed to deal with agriculture-related water pollution requires the consideration of most of the issue areas in the scheme. This is a much more complicated set of subsystems than simply eutrophication, water quality, and agricultural chemical runoff. And yet all are essential parts of the system in the real world.

A realistic analysis of any agricultural ecosystem would probably not consider all of these subsystems. But starting with the problem chain would force the analyst to consider the complexity of the system in a straightforward way and to justify the omission of areas by demonstration that their role is not important. This is a much more powerful approach than a "from-scratch" assessment of what things ought to be considered in a specific analysis. For example, it might not be obvious that a consideration of agricultural water quality had to consider vegetation cover. But as can be seen from Figure 7, this is probably one of the key elements of the system as a whole. However, it might be possible to ignore some other subsystems if their effects were not significant.

PROBLEM CHAINS IN ANALYSES OF AGRICULTURAL SYSTEMS

Let us simplify Figure 7 in a way which is probably realistic for most temperate-zone agricultural situations. The effects of eutrophication on irrigation water quality can be neglected, as can the effects of siltation on soil structure. Changes in water quality can be regarded as sufficiently independent of flooding, wind erosion, and pest and weed attack that the latter can be treated as events or embodied in parameter estimation. Let us further assume that waterlogging and salinization, soil compaction, and soil oxidation are not important. This leaves us with Figure 8, which is much simpler than Figure 7. This is not to say that it is simple, but the real-world system is not simple either.

But before we can use a picture such as Figure 8 to organize an analysis of any specific ecosystem, we must first return to the basic phenomena found in agricultural ecosystems listed in Table 1 and deal explicitly with the mapping from interest areas to basic phenomena. The problem chains by themselves can clarify the contingencies and assist in forming priorities. But they do not contain enough information to complete a meaningful analysis. The basic phenomena do, and the relationship between them and the interest areas allows a relatively simple conversion from a problem chain to basic phenomena.

Table 3 characterizes the 26 interest areas in terms of the 6 basic phenomena summarized in Table 1. The characterization suggests the mapping from the issue area to the basic phenomena. But once a complete problem chain is identified, then the entire chain can also be mapped. The contingency relationships pose no analytical problems because they are set by the direction of the problem chains. The latter also provide a consistency check on the analysis by providing a qualitative notion of what should be the linkages among problems against which any quantitative results can be compared. If there is disagreement, it may be due to inadequacies in the basic scheme, which can then be rectified by suitable changes. In such cases it may be necessary to

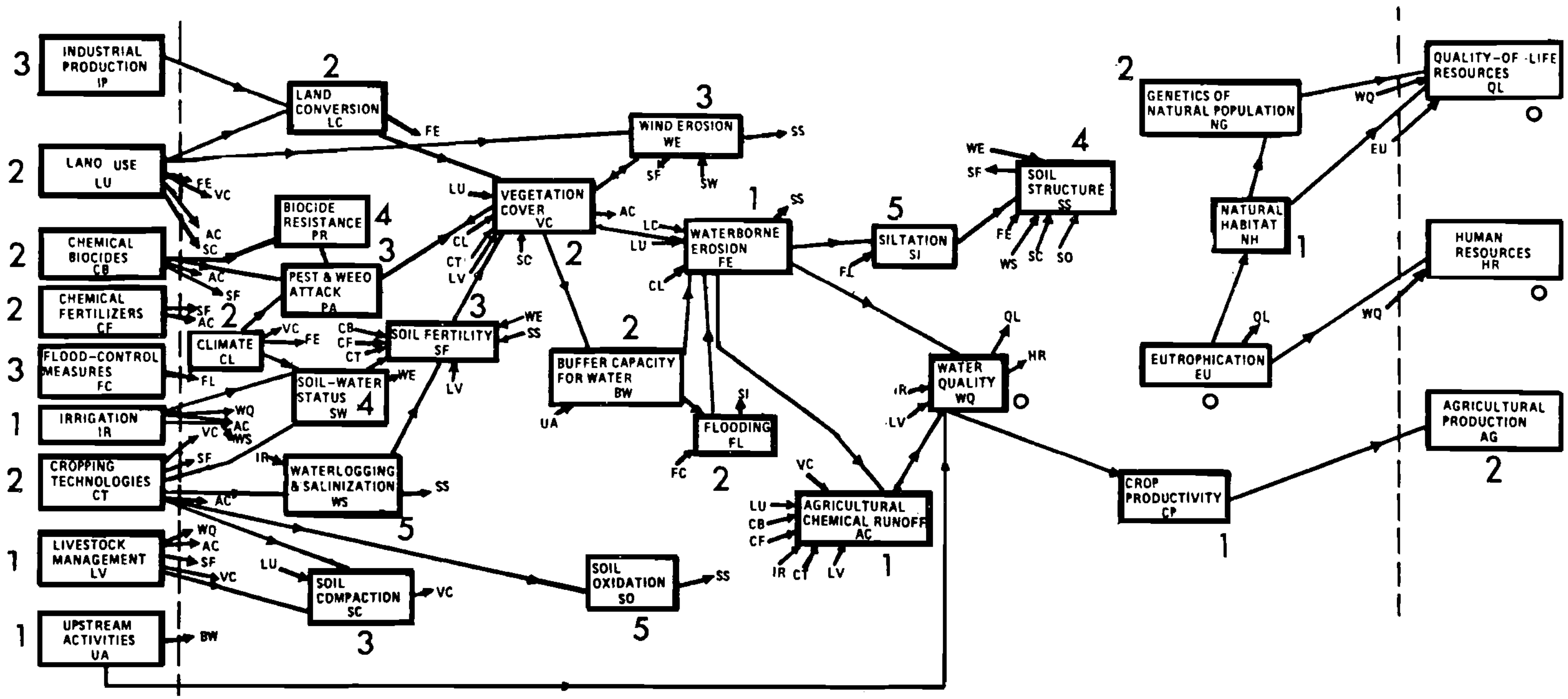

Figure 8. Construction of a simplified problem chain for agriculture-related water pollution making certain simplifying assumptions about the sensitivity of certain subsystems. See text for details regarding differences between this figure and figure 7.

Table 3. Mapping of 26 issue areas, 9 control inputs, and 3 monitoring points into 6 basic phenomena.

	C	W	B	M	G	L
Industrial Production				XX		XX
Land-Use Patterns			XX			XX
Chemical Biocides	XX			XX		
Chemical Fertilizers	XX			XX		
Flood Control		XX				
Irrigation		XX				
Cropping Techniques		XX	XX	XX	XX	XX
Livestock Management	XX		XX			
Upstream Activities	XX	XX				
Quality-of-Life Resources	XX	XX	XX		XX	XX
Human Resources	XX	XX	XX			
Agricultural Production			XX			XX
Soil Fertility	XX	XX	XX	XX		
Wind Soil Erosion	XX		XX	XX		XX
Waterborne Soil Erosion		XX	XX	XX		XX
Soil Oxidation	XX					XX
Soil Compaction			XX	XX		XX
Waterlogging & Salinization	XX	XX				
Soil Structure	XX	XX		XX		
Soil-Water Status		XX		XX		
Land Conversion			XX	XX		XX
Vegetation Cover		XX	XX			
Natural Habitat		XX				XX
Natural Genetic Resources					XX	XX
Climate		XX	XX			
Water Quality	XX	XX		XX		
Eutrophication	XX	XX	XX			
Waterborne Disease		XX	XX			XX
Flooding		XX		XX		
Buffer Capacity for Water		XX	XX			
Siltation				XX		
Agricultural Chemical Runoff	XX	XX	XX	XX		XX
Crop Productivity	XX	XX	XX	XX	XX	
Crop Genetic Base					XX	XX
Biocide Resistance	XX				XX	
Pest & Weed Attack	XX		XX		XX	
Air Pollution				XX		
Air Quality	XX			XX		
	Chemical	Water-related	Biological Growth	Mass Balance	Genetic	Land-related

restructure the problem chain somewhat. But the mapping of problem chains to basic phenomena on a module-to-module basis provides a powerful organizing mechanism to keep track of a multitude of complex notions in a simple, straightforward way.

Indeed a further step is also feasible, although a specific formulation such as that presented below may be less widely applicable than the general notions presented so far: because the links connecting interest areas in the problem chain represent information, they can be described as in Table 4, and the problem chains can be adapted to document the flow of information throughout the chain. Figure 9 shows the problem chain introduced in Figure 8 with the character of the information linkages shown.

Because the problem chain represents, among other things, a set of contingencies, we can go one step further and use it as the basis for a model of the system. This model will relate outputs (O) to inputs (I) by functional relationships of the form:

$$O = f(I) \quad .$$

In establishing the model, the following symbology is used (Table 6). The basic character of the information variable is used as its identifier. The source of the variable (i.e. the subsystem in which it was calculated or introduced) appears as a superscript coded as in Table 5. A prefix superscript indicates whether the variable represents control (c) or monitoring (m) information. Lagged information is also indicated by prefix superscripts (t) or (t-1). The model of the problem chain indicated in Figure 8 is presented in Table 6.

The analytical problem then becomes quite familiar. The relationships must be specified and parameters identified. This can mean several things, depending on the approach and purpose of the analysis. For a modeling approach, all relationships must be specified mathematically and parameters identified rigorously. A semiquantitative approach requires little more than a

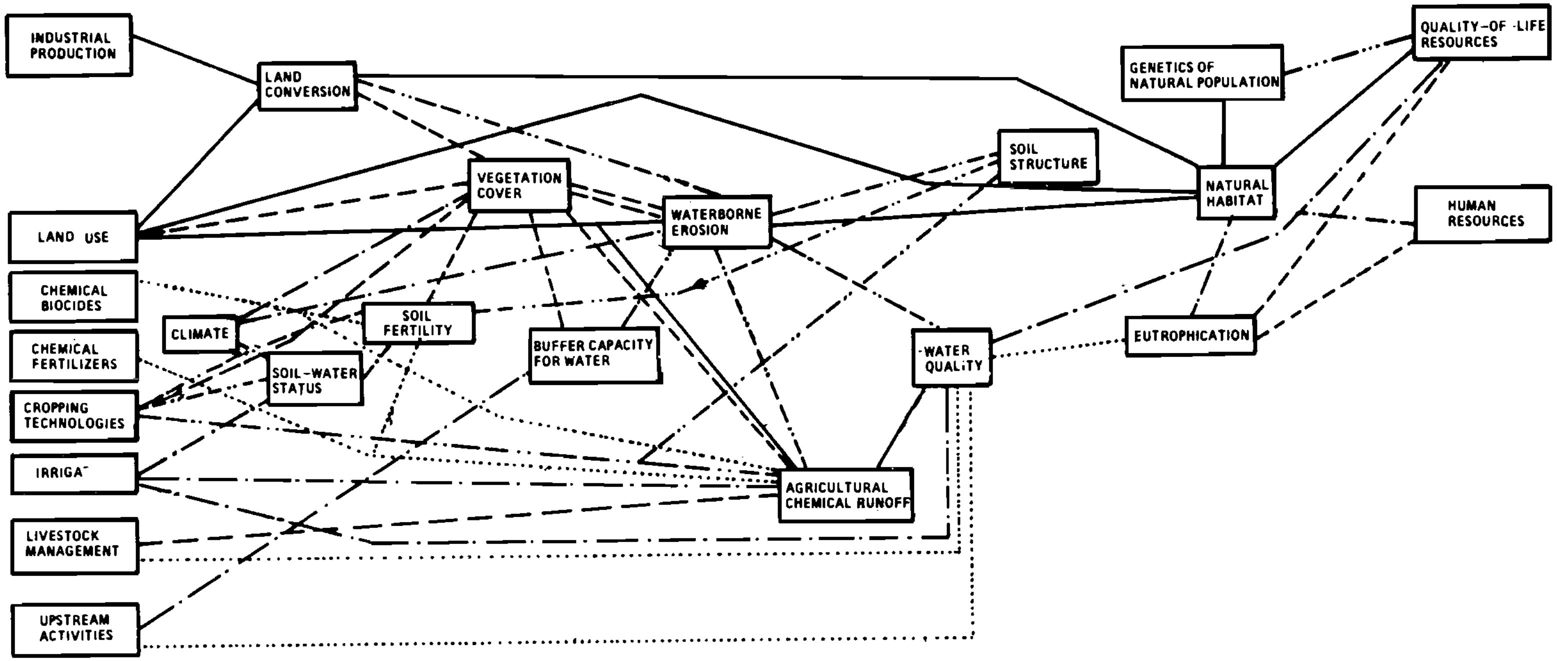

Figure 9. Flow chart of problem chain showing basic character of linkages for simplified consideration of agriculture-based water pollution shown in figure 8.

Table 4. Inputs to each issue area and monitoring point, with code. (See Table 5 for explanation of code.)

AP air pollution

$c_M{}^{ip}$	pollutants from industrial process
$c_M{}^{cb}$	chemical biocides and residues escaping into the air
$c_M{}^{cf}$	fertilizer and breakdown products lost into the air
$c_M{}^{cr}$	soil lost directly to the atmosphere as a result of mechanical tillage

AQ air pollution

M^{ap}	the masses of primary and secondary pollutants in the atmosphere
M^{we}	soil etc. lost thru wind erosion from everything other than mechanical tillage

LC land conversion

$c_L{}^{ip}$	demand for land by industrial development
$c_L{}^{lu}$	detailed information on relative land use changes

PA pest attack

$c_C{}^{cb}$	amount and pattern of biocides used
G^{pr}	genetic status of pest population & potential predators w/r pest control resistance
B^{cp}	proneness of the crop to pest attack due to its luxuriance
B^{vc}	character of the vegetation: refuges for predators, types & proneness for pests
W^{cl}	climate

PR biocide resistance

$c_C{}^{cb}$	amount and patterns of biocide used

FE waterborne erosion

B^{vc}	character of the vegetation (esp. erosion-modifying factors)
M^{lc}	materials available for erosion because of specific land uses (e.g. taillings, construction)
$c_L{}^{lu}$	proneness to erosion for specific land use
W^{wb}	water-throughput buffer capacity inherent in environment
W^{fl}	amount & intensities of flooding
W^{cl}	climate

WB water buffer capacity

B^{vc} character of the vegetation (esp. water-buffering segments)

C_W^{ua} amount of water delivered to environment due to upstream activities

FL flooding

W^{wb} relationship between rainfall and runoff for given area

C_W^{fc} effectiveness of flood-control system on modifying water movement patterns

AC agricultural chemical runoff

B^{vc} character of the vegetation (esp. as regards nutrient and soil movement)

C_L^{lu} characteristic of lands used for agriculture: proneness to erosion

C_C^{cb} amount and patterns of biocide used, with residue characteristics

C_C^{cf} amount and patterns of fertilizer used, with residue characteristics

C_W^{ir} amount and patterns of irrigation

C_M^{cr} effect of tillage practices on distribution, etc. of nutrients & water in furrow slice

M^{fe} amount of soil eroded

C_B^{lv} amount and distribution of livestock and livestock wastes

WD waterborne disease

C_L^{lu} characteristics of land used for irrigated agriculture: proneness to disease vector habitat

C_W^{ir} technology of irrigation: likelihood of water to be snail (etc.) prone

VC vegetation cover

C_B^{lu} alteration or loss in vegetation cover directly attributable to changes in land use

B^{lc} alteration or loss of vegetation cover indirectly attributed to land use changes via land conversion

B^{we} destruction or changes in vegetation resulting from wind erosion and deposition

B^{fe} destruction or changes in vegetation resulting from water erosion

B^{sc} change of vegetation resulting from soil compaction

${}^{c}B^{cr}$ character of the crop w/r the characteristics of vegetation cover

B^{sf} potential responses of vegetation to changes in soil fertility

B^{pa} impacts of pests on vegetation

W^{cl} climate

SF soil fertility

C^{we} changes in soil fertility brought about by wind erosion

${}^{c}C^{cb}$ chemical nature of pesticides & residues in soil

${}^{c}C^{cf}$ chemical nature of fertilizers once they have been spread

${}^{c}M^{cr}$ effect of tillage practices on distribution, etc. of nutrients in furrow slice

M^{ss} effect of soil structure on soil fertility

C^{ws} changes (ceteris paribus) in soil fertility from waterlogging & salinization

W^{sw} effect of soil water status on soil fertility

WE wind erosion

B^{vc} character of the vegetation (esp. erosion-modifying factors)

M^{sw} resistance to erosion due to water, clay, organic content of soil

${}^{c}L^{lu}$ proneness to erosion for specific land uses (esp. urbanization, construction)

NH natural habitat

L^{lc} habitat changes as function of land conversion

L^{we} habitat changed by wind erosion

${}^{c}L^{lu}$ land use changes which alter habitat

L^{fe} habitat altered by erosion by water

W^{eu} habitat altered by eutrophication

NG natural genetic resources

L^{nh} changes in habitat of natural population (esp. w/r range size requirements)

SI siltation

M^{fl} materials removed/available from flooding

M^{fe} materials removed/available from normal waterborne erosion

WQ water quality

M^{fe} solid materials introduced in water by erosion by water

C^{ac} nutrients and chemicals from agricultural chemical runoff

c_C^{lv} nutrients and chemicals incident to livestock management schemes

c_C^{ua} nutrients and chemicals incident to upstream water uses

c_W^{ir} salt content and volume of irrigation return water

CG crop genetic resources

c_G^{cr} genetic resources of particular cropping types

c_L^{lu} role of land uses in determining tradeoffs between different genetic strategies

WS waterlogging and salinization

c_W^{ir} amount and technology of water available by irrigation schemes

c_W^{cr} use patterns of irrigation water by different specific cropping schemes

SW soil water status

c_M^{cr} tillage practices insofar as they affect water movement, evapotranspiration

c_W^{ir} water added to soil by irrigation: how much, patterns

W^{cl} climate

SC soil compaction

c_L^{lu} character of lands used for agriculture: proneness to compaction

c_M^{cr} tillage practices: role of mechanization, large machines

c_B^{lv} role of livestock: role in compaction locally or regionally

SO soil oxidation

c_L^{cr} characteristics of land used for agriculture: proneness to oxidation

SS soil structure

M^{we} changes in soil constitution as a function of wind erosion

M^{si} addition to soil constitution as a function of siltation

M^{fe} changes in soil constitution as a function of erosion by water

W^{ws} changes in water distribution as a result of waterlogging

M^{sc} movement in soil materials resulting from soil compaction

C^{so} change in basic chemical constitution of soil as result of soil oxidation

${}^{c}{}_{M}{}^{cr}$ tillage practices: effects on distribution of soil particles, nutrients, etc.

EU Eutrophication

C^{wq} amount and types of nutrients added by changed water quality

CP crop productivity

M^{we} direct impact of wind erosion on the crop (mainly destruction)

M^{fe} direct impact of waterborne erosion on the crop (mainly destruction)

C^{aq} direct impact of air quality changes on the crop

W^{wq} direct impact of irrigation water quality on the crop

W^{fl} direct impact of flooding on crop (destruction)

C^{sf} role of soil fertility in crop production responses

B^{pa} pest density and activity

${}^{c}{}_{B}{}^{cr}$ plant types chosen for growth

${}^{c}{}_{M}{}^{cr}$ tillage practices and direct effects outside of soil fertility maintenance

G^{cg} crop responses to inputs as a function of crop genetic characteristic

${}^{c}{}_{W}{}^{ir}$ amount and patterns of irrigation water use

W^{cl} climate

QR quality-of-life resources

C^{aq} air quality

G^{ng} genetic state of natural population and consequent stability

L^{nh} status of natural habitat

W^{fl} amount & intensity of floods

B^{eu} algal blooms, biota of the watercourse

W^{wq} water quality

HR human resources

C^{aq} air quality

W^{fl} amount & intensity of flood

B^{wd} population density of disease organism & vectors

B^{eu} noxious organisms that accompany eutrophication

W^{wq} water quality

AG agricultural production

L^{lc} agricultural land-base changes implicit in land conversion

c_L^{lu} land-base changes in land use of agricultural land

B^{cp} crop productivity

Table 5. Coding of variables by basic phenomenon, issue area, and control inputs.

Basic Phenomena

Chemical	C
Water-related	W
Biological growth	B
Mass balance	M
Genetic	G
Land-related	L

Issue Areas

Soil fertility	sf	Water quality	wq
Wind soil erosion	we	Eutrophication	eu
Waterborne soil erosion	fe	Waterborne disease	wd
Soil oxidation	so	Flooding	fl
Soil compaction	sc	Buffer capacity for water	wb
Waterlogging & Salinization	ws	Siltation	si
Soil structure	ss	Agricultural chemical runoff	ac
Soil water status	sw	Crop productivity	cp
Land conversion	lc	Crop genetic base	cg
Vegetation cover	vc	Biocide resistance	pr
Natural habitat	nh	Pest & weed attack	pa
Natural genetic resources	ng	Air pollution	ap
Climate	cl	Air quality	aq

Control Inputs

Industrial production	ip
Land use	lu
Chemical biocides	cb
Chemical fertilizer	cf
Flood-control measure	fc
Irrigation	ir
Cropping techniques	cr
Livestock management	lv
Upstream activities	ua

Table 6. Model of agriculture-based water pollution for problem chain shown in Figure 9.

Land Conversion

$$L^{lc} = f({}^{c}L^{ip}, {}^{c}L^{pg}, {}^{c}L^{lu})$$

$$M^{lc} = f({}^{c}L^{ip}, {}^{c}L^{pg}, {}^{c}L^{lu})$$

$$B^{lc} = f({}^{c}L^{ip}, {}^{c}L^{pg}, {}^{c}L^{lu})$$

Soil-Water Status

$${}^{t}W^{sw} = f({}^{c}M^{cr}, {}^{c}W^{ir}, {}^{t}W^{cl}, {}^{t-1}W^{sw})$$

Soil Fertility

$${}^{t}B^{sf} = f({}^{c}C^{cb}, {}^{c}C^{cf}, {}^{c}M^{cr}, {}^{t}W^{sw}, {}^{t-1}M^{ss}, {}^{t-1}B^{sf})$$

Vegetation Cover

$${}^{t}B^{vc} = f({}^{c}B^{lu}, {}^{c}B^{cr}, {}^{t}B^{sf}, {}^{t-1}B^{fe}, {}^{t}W^{cl}, {}^{t-1}B^{vc})$$

Buffer Capacity for Water Management

$${}^{t}W^{wb} = f({}^{c}W^{ua}, {}^{t}B^{vc}, {}^{t-1}W^{wb})$$

Waterborne Erosion

$$M_1^{fe} = f(W^{wb}, B^{vc}, {}^{c}L^{lu}, M^{lc}, W^{cl})$$

$$M_2^{fe} = f(W^{wb}, B^{vc}, {}^{c}L^{lu}, M^{lc}, W^{cl})$$

$$M_3^{fe} = f(W^{wb}, B^{vc}, {}^{c}L^{lu}, M^{lc}, W^{cl})$$

$$L^{fe} = f(W^{wb}, B^{vc}, {}^{c}L^{lu}, M^{lc}, W^{cl})$$

$${}^{t}B^{fe} = f(W^{wb}, {}^{t}B^{vc}, {}^{c}L^{lu}, M^{lc}, W^{cl})$$

Soil Structure

$${}^{t}M^{ss} = f({}^{c}M^{cr}, M_1^{fe}, {}^{t-1}M^{ss})$$

Agricultural Chemical Runoff

$$C^{ac} = f(M_2^{fe}, B^{vc}, {}^{c}L^{lu}, {}^{c}C^{cb}, {}^{c}C^{cf}, {}^{c}M^{cr}, {}^{c}W^{ir}, {}^{c}B^{lv})$$

Water Quality

$$
\begin{aligned}
{}^{m,t}W^{wq} &= f(M_3^{fe}, C^{ac}, {}^{c}W^{ir}, {}^{c}C^{lm}, {}^{c}C^{ua}, {}^{t-1}W^{wq}) \\
{}^{t}C^{wq} &= f(M_3^{fe}, C^{ac}, {}^{c}W^{ir}, {}^{c}C^{lm}, {}^{c}C^{ua}, {}^{t-1}W^{wq})
\end{aligned}
$$

Eutrophication

$$
\begin{aligned}
{}^{t}W^{eu} &= f(C^{wq}, {}^{t-1}W^{eu}) \\
{}^{m,t}B_1^{eu} &= f(C^{wq}, {}^{t-1}W^{eu}) \\
{}^{m,t}B_2^{eu} &= f(C^{wq}, {}^{t-1}W^{eu})
\end{aligned}
$$

Natural Habitat

$$
\begin{aligned}
{}^{t}L_1^{nh} &= f(L^{lc}, {}^{c}L^{lu}, L^{fe}, {}^{t-1}L_1^{nh}) \\
{}^{m,t}L_2^{nh} &= f(L^{lc}, {}^{c}L^{lu}, L^{fe}, {}^{t-1}L_2^{nh})
\end{aligned}
$$

Genetics of Natural Population

$${}^{m,t}G^{ng} = f(L_1^{nh}, {}^{t-1}G^{ng})$$

general description of the shape and range of the relationships. There is a continuum between these extremes, depending on how much of the system is specified and to what detail. Depending on the purpose of the analysis, it may be useful to treat the entire system at the same level of mathematical precision or to concentrate on a relatively small part and use the rest as a set of driving relationships or to test the system's sensitivity to identifiable options. The choices are very wide, and depend on the purpose of the analysis.

It is significant that the problem chain yields a scheme which is not only intuitively reasonable but also computable. Most aspects of the natural stratum can be treated as a throughput system. Exceptions are that pest and weed attacks depend on and affect both vegetation cover and crop productivity, while vegetation cover depends on and affects both wind and water erosion. In both cases, it is possible to use the first approximation that only one direction of the interaction is important or to treat the relationships as "per-unit output" (e.g. pest and weed attack on crops is per-unit crop productivity). This is equivalent to calculating a basic response to the inputs assuming a base level of the affected variable and then adjusting the effect when the actual level is known. Another exception to a throughput stratum is the effect of soil structure on soil fertility. But this effect is properly lagged. The evolution of soil structure is generally a long-term phenomenon and changes building up during one iteration are felt during the next.

CONCLUSIONS

The problem chain approach to organizing the analysis of the natural stratum of a human ecosystem is probably not an obvious one, but it is a simple, straightforward method of assuring maximum consideration of the myriad interconnectedness of the system while assuring also that the interstratal connections are clear. It can be regarded as a special case of a flow chart, but it is much more aggregated than the normal case. It concentrates on the linkage among problems rather than variables, and it is explicitly multilevel in that the "ends" of the chains must necessarily be where control and monitoring information cross strata.

It must be emphasized that as with all flow-charting approaches, the construction of problem chains is a highly qualitative art, and the general picture which emerges as the first step (i.e. analogous to Figure 5) will differ for different ecosystems, different analysts, and different forms of analysis. This is as it should and must be. These considerations will also force different approaches to the simplifying assumptions which are made to justify neglecting side branches of the main chain. But at the very least, the construction of a problem chain can give a sufficient pre-assessment of a problem that the analysis can be organized efficiently. Those portions needing special study can be identified at very early stages. At its least, it can also provide the basic framework for a model of the stratum as a whole. In general, it insures that enough of the system is considered to capture both the real dynamics of the natural stratum and also the control and monitoring linkages to the society over that stratum. At present, it is probably the simplest, yet complete approach to the analysis of significant problems facing human ecosystems.

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