PN-AAF-019
ISN 33020

AGROECOSYSTEM DETERMINANTS

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Presented at the symposium: Agricultural Ecosystems--Unifying Concepts. Ecrlogical Society of America, AIBS meetings at Penn State University, August 12, 1982.

DETERMINANTS OF AGROECOSYSTEM STRUCTURE AND FUNCTION

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The analysis of agricultural ecosystems (agroecosystems) requires a combination of the approaches used by systems ecologists, systems engineers, and social scientists. Agroecosystems have all of the properties of natural ecosystems, (material, energy, and information processes) and concepts such as energy flow and nutrient cycling can be used to explain much of their behavior. However, information processes in agroecosystems and natural ecosystems are very different. For this reason, the effect of the environment on agroecosystems and natural ecosystems structure and function is also quite different.

Information processes in natural ecosystems occur at the organism, population, community and ecosystem levels. While many organisms participate in both material and energy processes as well as information processes, some herbivores and most predators, parasites and pathogens have an impact on the ecosystem that is disproportionate to the amount of energy and materials that they consume (Caswell, et al., 1972). These organisms monitor different sources of information, make decisions and take actions that control material and energy flows. Decisions are made when genetic and behavioral information is compared with information found in the behavior of other organisms or populations, and in vegetation patterns and environmental patterns.

Information processes in agroecosystems occur not only at the organism, population, community, and ecosystem levels, but at the suprasystem (the farm or pastoral system) as well.

In this paper, I identify five types of factors that affect agroecosystem information processes (the ecological environment, agricultural resources, the household, other agroecosystems, and the state of the agroecosystem). These factors influence two types of decisions (design and control) that, in turn, affect agroecosystem structure and function. Conceptualizing agroecosystem-environment relationships in terms of determinants and decisions leads to specific hypotheses that, when tested, can contribute to the understanding of agroecosystem information processes. The proposed concepts are illustrated using examples from Central America. The practical implications for agricultural research and development and the theoretical implications for agroecosystem and natural ecosystem research are briefly discussed.

CONCEPTS

Like natural ecosystems, agroecosystems are composed of a set of interacting biological and physical components. The presence of specific components and the arrangement of these components in space and time (structure) is determined by the environment. This arrangement of components is capable of processing environmental inputs and producing outputs (function). Environmental factors that affect function, either directly through inputs or indirectly through effects on the structure, are defined as "determinants".

In agroecosystems, many of the information processing roles of herbivores, predators, parasites, and pathogens are taken over by man. It is noteworthy that these organisms are usually thought of as the natural enemies of farmers. The farmer monitors the environment and the energy and material processes and implements controls that affect the system's structure and function.

Most systems theorists distinguish between a system's environment and its suprasystem, the system in which the phenomenon of interest functions as a subsystem (Miller, 1978). Information processing in agroecosystems cannot be analyzed without considering the fact that agroecosystems are subsystems of farm or pastoral systems. Farms or pastoral systems are composed of a socio-economic subsystem (the household, resources that are allocated to different activities, etc.) and one or more agroecosystems (Hart, 1981a). Different types of determinants affect different types of decisions that are made within the socioeconomic subsystems of farm and pastoral systems. A first step in analyzing information processses that affect agroecosystem structure and function is to classify determinants and decisions, and to formulate and test determinant-decision hypotheses.

Farm or Pastoral Systems

Figure 1 is a diagram of a farm system showing the flows of materials and energy (solid lines) and information (dotted lines) between the ecological and socioeconomic environment and the farm subsystems. Flows of

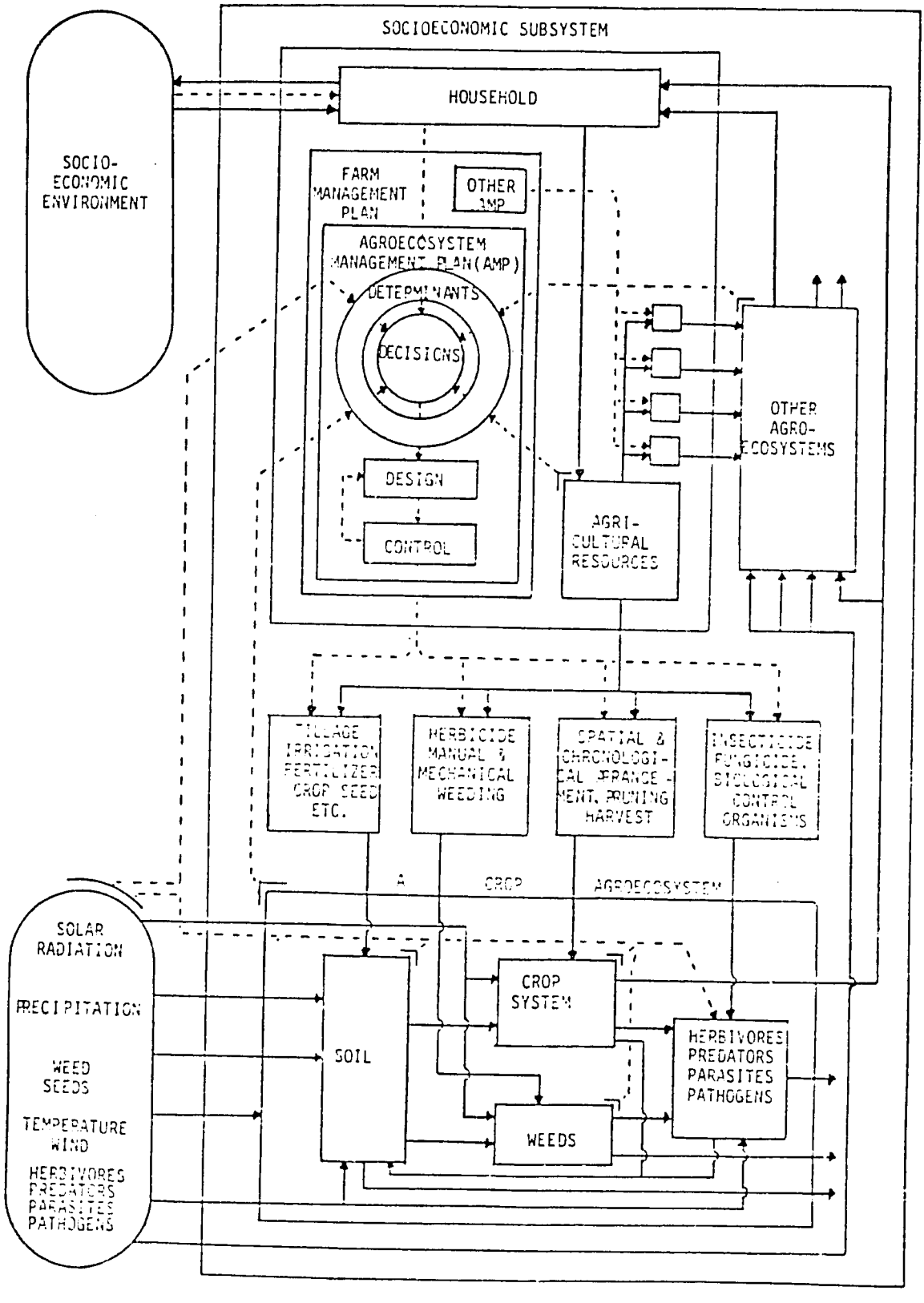

Figure 1. The flow of energy and materials (solid lines) and information (dotted lines) in a farm system.

money between the farm and the socioeconomic environment have not been included in the diagram, but it is recognized that, with exception of some subsistance farms, money is used as medium of exchange for flows of materials and energy between the farm and the socioeconomic environment.

In the diagram, the information processing activities required for the management of an agroecosystem are included within the socioeconomic subsystem. Also included in this subsystem are the pool of agricultural resources that can be used as inputs to the different agroecosystems found on the farm, and the social and economic components associated with the household.

Decision-making within the socioeconomic subsystem of a farm system is an extremely complex process, and its analysis is beyond the scope of this paper. Agricultural decision-making has been studied with mixed success by sociologists, anthropologists, and economists. In general, social scientists have had little success in attempts to use formal decision models to predict economic behavior in nonindustrial countries (Johnson, 1980). However, Gladwin (1976) and others have used simple decision-making flowcharts to explain how farmers consider "aspects" such as profit, risk, capital, and knowledge to decide which crops or cropping systems to plant. In general, social scientists studying agricultural decision-making have focused on farmers' objectives. There has been little research on how these socioeconomic objectives are combined with what is ecologically feasible. How farmers combine crops or livestock to design an agroecosystem, and how they make specific management decisions, has been studied even less.

For purposes of this analysis, farm system decision-making has been conceptualized as three subprocesses: (1) definition of socioeconomic objectives, (2) design of a farm management plan that includes agroecosystem plans for each agroecosystem, and (3) control decisions that are made after the design has been implemented and the system is functioning. As suggested earlier, the first process (definition of objectives), is essentially a suprasystem decision and beyond the scope of this paper. In the farm system diagram (Figure 1), socioeconomic objectives are assumed to be an output from the household. The second and third processes (design and control) are part of the information processing subsystem of an agroecosystem and must be considered in any analysis of how environmental factors affect agroecosystem structure and function.

Design and Control Decisions

Agroecosystem design and control are usually cyclical. Design decisions are made during planning, while control decisions are made during implementation. Identification of these cycles is relatively easy in annual-crop agroecosystems; more difficult in livestock-based agroecosystems and most difficult in perennial-crop agroecosystems.

Design decisions are usually seasonal. For example, during the winter in temperate climates or the dry season in the wet-dry tropics, a farmer or pastoralist decides which components to include in the agroecosystem, how they will be arranged in space and time, and the quality, quantity,

and timing of inputs and outputs. The product of this decision-making process is a model (usually mental) of the structure of the agroecosystem and a predicted function. Depending on the level of confidence in this prediction, the pastoralist or farmer may include in the design the possibility of implementing optional control activities.

Control decisions are continuous. Once the structure has been designed and the system starts to function (processing inputs and producing outputs), the control phase begins. During this phase, the predicted, real, and projected states of the agroecosystem are continuously evaluated. Some control decisions are programmed and are triggered by the calendar (based on past experience). Other control decisions may require that a combination of factors meet a combination of criteria. For example, a farmer may design a maize agroecosystem that includes a control decision to plant maize only when the calendar, rainfall, and labor availability meet the criteria of "the first week in May, 25 mm of rainfall during the last week in April, and 5 man-days of labor are available."

Some control decisions are not programmed as part of the original design. When the real behavior of an agroecosystem is very different from the expected, unplanned control decisions must be made. This may require an unplanned return to the design phase (starting over), or in some cases, information processing may be "returned" to the herbivores, predators, parasites, and pathogens (giving up).

Types of Determinants

Agroecosystem design and control decisions are made on the basis of one or more of the following types of determinants:

1. The ecological environment. Some environmental factors are relatively static (soil physical properties, soil fertility, solar radiation); others are very dynamic and less predictable (rainfall patterns, temperature in temperate climates, invasion of pests). These factors affect the agroecosystem (a) directly through the availability of energy and material inputs, and (b) indirectly, when design and control activities are triggered by environmental factors.
2. Agricultural resources. These factors include land, labor, capital, management capability, and agricultural inputs, such as agrochemicals and animal and machine energy. Factors that affect resource availability, and therefore indirectly affect the agroecosystem are (a) the socioeconomic environment, (b) the household, and (c) the state of other agroecosystems. The household and other agroecosystems can also directly determine design and control decisions and for this reason are listed below as "determinants."
3. The household. The principal direct effect (as opposed to indirect effects through other agroecosystems or the resource pool) of the household on the agroecosystem is through design decisions. The definition of socioeconomic objectives (for example, minimize risk) or the demand for specific outputs (for example, goat milk) can

greatly affect the design process. Control decisions can also be effected by sudden changes in household demand, for example, animals may be sold earlier than planned because of an unexpected economic crisis.

4. Other agroecosystems. The principal direct effect (as opposed to indirect effect through the resource pool) of other agroecosystems is through the flow of materials or energy among agroecosystems. Examples include the use of crop residue from one agroecosystem to feed livestock in another, and the use of animal energy or manure from one agroecosystem to produce crops in another.

5. The agroecosystem. As suggested earlier, control decisions are triggered by comparing the real and predicted state of the agroecosystem. The cumulative experience with the performance of the agroecosystem is also an important information source for design decisions.

Determinant-Decision Hypotheses

Table 1 lists examples of different types of determinants that could affect two types of decisions, and therefore the structure and function of agroecosystems. Specific determinants can be combined with decisions to form determinant-decision hypotheses. In the analysis of an agroecosystem, all of the control or design decisions that alter a material and energy process must be identified and specific hypotheses as to which factor or combination of factors determine the decisions must be identified and tested.

Specific determinant-design or determinant-control hypotheses can be tested separately, or a complete agroecosystem management plan, with all the design and control decisions and determinants that trigger them, can be tested. As in the validation of any model, the same data used to identify the hypothesis cannot be used to test it. Validation can be done by beginning with decisions and predicting the existence of specific levels of determinants, or by beginning with the determinants and predicting the existence of specific decisions.

It is also possible to identify determinant-control and determinant-design hypotheses by deductive logic or intuition. In a heterogeneous geographic area where the hypothesized determinants exhibit high enough variation so decisions, and therefore the structure and function of agroecosystems can be expected to vary, both determinant and decision data can be collected and analyzed to see if the predicted determinant-decision relationships are statistically significant.

AGROECOSYSTEM DETERMINANTS IN CENTRAL AMERICA

The Centro Agronomico Tropical de Investigacion y Ensenanza (CATIE) has conducted agricultural research in a broad range of environments in Central America, and is specifically interested in the relationship between environmental factors and farmers' choice of cropping system and the management of specific cropping systems (Moreno, 1980). The primary objective of most of CATIE's research is to identify potential alternatives to what farmers are presently doing. This has required an

approach that includes the analysis of predominant agroecosystems (Hart, 1981a), the farm systems in which they function (Hart, 1981b), and the factors that determine design and control decisions. Examples from various CATIE studies are cited below.

Example of Design Determinants

Diaz (1982) has studied the relationship between various factors and intercropped maize and beans (M + B); maize and sorghum (M + S); and maize, beans, and sorghum (M + B + S). The study was based on a survey of 368 farmers in Honduras. Data was collected on cropping systems, farm systems, and soils and climate. Hypotheses relating potential determinants to design decisions were evaluated by analysing the percentage of farmers using a specific cropping system (for example, M + B) at different intervals along environmental gradients; and by using principal component and multiple regression techniques to determine the relationship between potential determinants and different management practices (for example, soil fertility and spatial arrangement of crops).

The study cited above has not been completely analyzed, but some examples from a preliminary analysis illustrate how different types of determinants affect different design decisions. An ecological determinant that was directly associated with the presence of either M + B, M + S, or M + B + S was altitude above sea level (a proxy for temperature). The M + S cropping system was found between sea level and 750 m

above sea level, with the highest concentration between 0 - 250 m. The M + S + B system was found between 0 - 1250 m, but was concentrated between 500 - 1000 m. The M + B system was found over a wide range of altitudes (0 - 2000 m), however, different species of beans were intercropped with maize at different altitudes. *Vigna spp.* was planted below 500 m, *Phaseolus vulgaris* was planted at intermediate altitudes, and *P. coccineous* was planted above 1750 m.

A resource determinant (labor availability) affected chronological arrangement. The requirements of other agroecosystems were identified as determinants of the quality and quantity of biomass removal. Of the farmers with M + S or M + B + S, 80% fed maize and sorghum stover to cattle, while only 40% of the farmers with M + B had cattle and only 53% used the maize stover for feed.

Examples of Control Determinants

In spite of the fact that agricultural research has been done with many different agroecosystems in Central America, there have been very few studies of how farmers make control decisions. It is often assumed that farmers decide what to do, and then simply implement the package they have designed. In reality, the product of the design process is usually a complex set of options that are triggered by different determinants. A few examples from Central America are cited below.

A group of extension agents in El Salvador were asked how farmers make decisions in the management of intercropped maize and sorghum (Hart, 1980a). Many decisions are triggered by a combination of factors. For example, planting is done either in May after it has rained twice within a two-week period, or in June after one rainfall. Weeding, fertilizer application, hilling-up maize and planting sorghum are "designed" to occur sequentially beginning three weeks after planting maize, but in reality are done within a two- to five-week period depending on rainfall. If rainfall occurs during the flowering of maize, maize grain yields will probably be adequate and the intercropped sorghum may be removed before it is mature and fed to livestock, instead of letting it produce grain for human consumption.

An example of farmers implementing control decisions that completely alter the structure and function of an agroecosystem can be cited from Honduras (Hart, 1981b). Farmers in the community of Yojoa usually plant double-cropped maize (maize followed by maize) and a rice-bean rotation (rice followed by beans). The rice-bean rotation is "designed" to be planted in May; however, if the rainy season is delayed until June, maize is planted instead. A control decision (what crop to plant) made on the basis of rainfall (an ecological determinant) produces a major short-term change in the agroecosystem. This decision can, in turn, affect the farm system (agricultural resources, other agroecosystems, etc.), and the long-term design decisions that are made during the next dry season.

PRACTICAL AND THEORETICAL IMPLICATIONS

An understanding of how the environment and suprasystem affect agroecosystem structure and function, through the interaction of information and material and energy processes, is of both practical and theoretical value. Agricultural scientists doing applied research that interfaces directly with development activities are interested in how the farmers' systems operate. Agricultural scientists doing theoretical research are interested in identifying general principles that can make applied research more efficient.

Ecologists have often conceptualized agroecosystems as natural ecosystems that have been "subverted" or "degraded" by man, overlooking the fact that, as ecosystems with information processing concentrated in one species, they may be ideal for the study of ecosystem information processes. An understanding of the theoretical basis for information processes in agroecosystems will contribute to the theoretical understanding of natural ecosystems as well as agroecosystems. The practical and theoretical implication of conceptualizing agroecosystems in terms of decision determinants are discussed below.

Farm and Pastoral System Research

Agricultural research institutions in some third-world countries have recently shifted emphasis away from commodity-oriented research towards research directed at production systems. The change was based on a

recognition that agricultural technology must be designed to fit existing farm systems or pastoral systems. Two important implications are that (1) the suprasystem must be analyzed, since the evaluation of any agroecosystem change must be done on the basis of the performance of the farm or pastoral system, and (2) the direct participation of the farmer or pastoralist can no longer be just an abstract goal; it is now a necessity.

Agroecosystem research is an integral part of any farm or pastoral system research program. An understanding of how determinants affect design and control decisions is needed to understand how a specific farmer's or pastoralist's present system works, so that alternatives can be designed and tested. The "alternatives" are usually agroecosystem-level recommendations, rather specific inputs, varieties, etc. The most logical way to organize the information that is the product of applied agroecosystem research is as an agroecosystem management plan. This plan, by definition, must include design and control decisions and the determinants that trigger these decisions.

One criticism of farm and pastoral system research is that it tends to be site-specific. It is possible to study one specific type of farm system in one small geographic area and successfully identify potential alternatives, but it is not economically feasible to do research of this type with every community of farmers or pastoralists. The question is, how can agricultural technology be transferred among similar environments so that research done in one area can be applied in another? When

this general question is addressed, the first specific question is, which environmental factors should be considered in identifying "similar" environments? An obvious answer is, the determinants of agroecosystem design and control decisions. If a factor is not a determinant, then two areas that differ considerably as to that factor can still be "similar enough" for an agroecosystem management plan to be transferred from one area to another. If a factor is a determinant, the levels of this factor in two areas must be sufficiently similar so that a farmer would take the same decision when confronted with the two levels.

Agricultural Systems Modeling

Van Dyne and Abramsky (1975) reviewed and evaluated the literature on agricultural system models. Most agricultural system models are either simulation models (differential, difference, algebraic, or matrix equations), or optimization models (linear, nonlinear, or dynamic programming). Simulation and optimization models are seldom combined, and there is a distinct tendency to separate decision-making processes from biological processes. Natural ecosystem models can depict most flows between components as a constant coefficient times a state variable; agroecosystem models must include the possibility of, not only sudden changes in coefficients that will affect the function of the system, but also sudden changes in the structure of the system as entire populations are removed (for example, when crops or livestock are harvested).

Clymer (1972), in a discussion of the next generation of models in ecology, states that man is almost always included in agricultural ecosystem models as "an exogenous entity" or an "off-stage forcing function," rather than as a component, and suggests that man should be included "in every ecosystem that is modeled as an applied problem." If this suggestion were to be followed, the almost complete lack of tested determinant hypotheses would be immediately obvious.

At a minimum, it would seem that agroecosystem models should include control decisions. This can be done quite easily by combining differential equations to simulate material and energy processes and logic circuits to simulate information processes, such as in the approach developed by H. T. Odum (1972). Using this approach, a coefficient can be changed when a forcing function or state variable (or combinations) satisfy certain criteria. The problem, once again, is a lack of tested hypotheses as to which determinants affect specific decisions. At what level does an environmental factor, an agricultural resource, a household demand, the state of another agroecosystem, or a state variable trigger a decision? For a model even to begin to simulate reality, the logic circuit must include the possibility of implementing controls that are triggered by any (or combinations) of these five types of determinants.

In a model of a bean, maize, and cassava agroecosystem (Hart, 1974), the decision as to when to weed was assumed to be determined by "time after planting". However, in the validation process using data from an

environment with higher weed growth, it immediately became obvious that the amount of weeds (state of the agroecosystem) must also determine when to weed, or the weeds would out-compete the crops. In reality, farmers often decide when to weed, or whether to weed at all, on the basis of both time after planting, the amount of weeds in the field and soil moisture criteria. An hypothesis as to how these factors determine the control decision must be formulated and tested before it can be included in an agroecosystem model.

Natural Ecosystem Information Processes

In the preceding discussion, the differences between information processes in agroecosystems and natural ecosystems have been emphasized. The fact that many of the information processing roles of herbivores, predators, parasites, and pathogens in natural ecosystems are assumed by man in agroecosystems does not make the principles and theoretical concepts derived from the study of one type of ecosystem of no value in the study of the other. In fact, the study of agroecosystems has been based almost completely on principles and concepts derived from the study of material and energy processes in natural ecosystems. It is possible that what is learned from the study of information processes in agroecosystems may be of value in the study of natural ecosystems.

A discussion of the key issues of interest to theoretical ecologists and how the study of agroecosystems can contribute to ecological theory is

beyond the scope of this paper. However, for illustrative purposes, a few brief comments on population interaction, natural succession, and ecosystem optimization are presented below.

Herbivores, predators, parasites, and pathogens are part of nutrient cycles and energy flows, but they also use genetic and behavioral information to monitor environmental and community patterns and take actions that affect the long-term evolution (design) and short-term function (control) of the ecosystem. For example, a change in the environment can trigger bird migration, and a change in the diversity of vegetation can trigger insect population outbreaks. The determinant-decision concept proposed for the study of agroecosystems may be applicable in the analysis of how genetic, behavioral, vegetation pattern, and environmental pattern information is processed by herbivores, predators, parasites, and pathogens.

Cybernetics and information theory are often used to describe ecosystem structure and function (Margalef, 1968). However, Johnson (1970) suggests that "it is doubtful whether information theory has offered experimental biologists anything more than vague insights and beguiling terminology," and concludes that what is needed is a qualitative factor that considers biological relevance. In discussions of ecosystem cybernetics, predator-prey (plant-animal and animal-animal) relationships are often presented as examples of negative and positive feedback control. However, predator-prey relationships are usually modeled using variables such as number of individuals with rates determined by

population density, self-inhibiting effects, and resource availability and information proceses are not emphasized (for example: Smith, 1974).

In agroecosystems, there is an interesting relationship between the amount of information that goes into seed dispersal, the information content of the vegetation pattern that is produced, and the amount of information required by herbivores to maintain a specific herbivory rate. Man plants crops in rows (high order; low information) so harvesting will be easier (require less information). Unfortunately for farmers, natural herbivores also require less information and natural herbivory is also high. Perhaps, theories relating information to energy could be tested by measuring the energy expended by herbivores as the information content of vegetation patterns are changed.

Interest in using biological controls in agroecosystems and in the study of their effect on community stability (see discussion by Watt, 1965) would seem also to offer an opportunity to study predator-prey relationships in terms of information processes. For example, the difference between the amount of information required by farmers using strategies of minimum biological control (high chemical inputs), introduced biological control (imported organisms), and natural biological control (managing existing predators, parasites, and pathogens) might allow the effect of predators, parasites, and pathogens on herbivores, and the effect of herbivores on plants to be quantified in information terms.

An understanding of natural succession may provide useful information for the design of agroecosystems (Hart, 1980b), but it may also be true that the study of what determines a farmer's decision to change cropping systems may contribute to an understanding of natural succession. E.P. Odum (1969) describes natural succession as an orderly process controlled by the community in which the physical environment determines the pattern, the rate of change, and sets the limits as to how far development can go. The process culminates in a stabilized ecosystem with high information content. Its "strategy" (objective) is to maximize internal control of homeostasis.

Questions that are asked in both the study of agroecosystems and successional ecosystems are: How does the community control the process? How does the environment determine patterns, rates of change, and set limits? What is the general "objective"? The study of design and control decisions and their determinants in slash-and-burn (successional) agroecosystems might yield some interesting insights into information processes during natural succession. In these agroecosystems, farmers are continuously changing community structure. Crop species and cropping patterns that are planted after cutting and burning the forest are changed as soil fertility decreases and weeds, herbivores, predators, parasites and pathogens increase.

Spedding (1975) defines an agricultural system as an ecosystem with a purpose. It is interesting to note that to explain natural ecosystem behavior, ecologists have also used teleological concepts such as

"maximizing gross production" (E. P. Odum, 1971) and "maximizing power" (H. T. Odum, 1972). Evolution is said to operate "as a mechanism that maximizes fitness, or the relative contribution of a genotype to future generations" (Cody, 1974). The study of the relationship between a farmer's or pastoralist's objectives (maximizing output per unit of resource input, minimizing risk, etc.) and the type of agroecosystem that is designed may even provide insights into the "objective" of natural ecosystems.

Summary

An important difference between agroecosystems and natural ecosystems is that many of the information processes that are controlled by herbivores, predators, parasites, and pathogens in natural ecosystems are controlled by man in agroecosystems. The decisions that directly affect the structure and function of an agroecosystem can be subdivided into design decisions (planning) and control decisions (implementation). These decisions are affected by the state of the agroecosystem and determinants from the ecological environment and the suprasystem (farm or pastoral system). Included within the suprasystem determinants are other agroecosystems, resource availability, and the household. To analyze an agroecosystem, hypotheses relating specific determinants to specific decisions must be identified and evaluated. Examples of determinant-decision hypotheses that have been tested in Central America include temperature to cropping system selection (a design decision), and rainy season onset to selection of the first crop in a rotation

system (a control decision). An understanding of information processes in agroecosystems is of practical value for agricultural research and development, and of theoretical value in identifying principles that can contribute to a general understanding of the interaction among energy, material and information processes in natural ecosystems as well as agroecosystems.

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