A STRATEGY FOR OPTIMIZING RESEARCH ON AGRICULTURAL SYSTEMS INVOLVING WATER MANAGEMENT*

by

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ABSTRACT

The rationale for a model for optimizing agricultural systems through knowledge transfer is developed and presented. The model attempts to disaggregate the environment into significant components which are also measurable. It uses crop production as the overall integrator of the agricultural system response to the husbandry program imposed at a specific site. The model should aid in organizing available crop data and investigations. It should form a useful outline to guide thought processes involved in research program development and project analysis and provide a framework for a data retrieval system.

Key Words: Water Management, Model, Research, Agricultural Environment, Optimizing, Knowledge Transfer

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

A STRATEGY FOR OPTIMIZING RESEARCH ON AGRICULTURAL SYSTEMS INVOLVING WATER MANAGEMENT

by

INTRODUCTION

Optimal cropping systems are highly site-specific. That this has been recognized is demonstrated by the acceptance of extensive field trials as a basis for project design and for providing the extension-type information needed in initial developments or in changing agricultural patterns, both in advanced and developing countries. However, a consideration of transferable information using a systematic model should permit greater efficiency in the selection of both applied and basic research as well as in the design of agricultural development programs involving water management.

Presently, both the design of programs of research and of agricultural development are based primarily on expert judgment. In forming their judgments, experts draw on a reservoir of physical, biological and economic information gained by study and experience. The quality of the judgment made depends on the accessibility of information stored in the literature or in an expert's brain, and on the skill with which he weighs and synthesizes that information. The writers advance the suggestion that a computerized model which could predict crop production functions for changing environmental conditions could greatly enhance the efficiency of the expert. Such a model could have both information storage and processing as well as optimization character-

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istics. The model could also help guide the processes of characterizing the agricultural environment.

The model might be regarded as a sophisticated analogue of a hypothetical expert possessing all or most of the relevant information. Certain thought processes are used by engineers and scientists in characterizing the environment, selecting research, and choosing potential action programs in the water management field. However, little attention has been given to verbalizing these though processes. Without being verbalized these are somewhat obscure and perhaps even the investigators who possess certain capabilities for making decisions in this area would be at a loss if called upon to describe the rationales for their actions. Verbalization of these thought processes is the first step in formulating the desired model.

THE MODEL RATIONALE

Agriculture requires the superposition of biological production resources (culturable genetic materials, both plant and animal) upon an existing or to be modified set of environmental components. Biological production resources may be subdivided into various crops (or animals); these can further be subdivided into various plant varieties (or breeds). Each crop system will have varying physical and biological environmental conditions necessary for acceptable levels of production.

The model attempts to disaggregate the environment into significant components which are also measurable. Crop growth is viewed as having a number of intermediate production stages or indicators which will show a given response to each of the environmental components and a compounded response to combinations of them with the ultimate production being the overall integrater of crop growth.

Many of the environmental components are not fixed. They can be altered by various potential action programs or crop husbandry practices. Among the most important husbandry programs are irrigation and drainage. In turn, the selection of and success with crop programs is dependent upon the knowledge and ability to transfer information. The transfer process involves relating known environmental components and expected responses as affected by achievable husbandry programs to new environmental situations. The transfer process must also involve the techniques of categorizing the agricultural environment and optimizing the action programs needed to improve it. Biological production resources are not fixed either, but may be altered by plant and animal breeding programs both to improve quantity and quality of crops and to adapt to differing environmental components.

The model may thus be thought of as the interaction to two variable multi-dimensional vectors: *agricultural environment*, $\overline{E}$, and *production materials*, $\overline{M}$. The output vector is the response, $\overline{R}$; i.e., $\overline{R} = \overline{E} \times \overline{M}$. In the general model, $\overline{R}$ may be any designated objective. In the crop production model $\overline{R}$ becomes the crop response $\overline{R}_c$. The agricultural environment $\overline{E}$ reduces to $\overline{E}_i$, the intimate plant environment and $\overline{M}$ is the plant material.

Environmental Disaggregation

The single overreaching factor relevant to transfer of information and technology can be described as *agricultural environment*. Agricultural environment may be disaggregated into four general frameworks which are subdivided into various relevant descriptors, each with a number of measurable components as presented in Table 1.

Table 1. **Condensed Summary Model for Optimizing Comprehensive Agricultural Systems Involving Water Management**

INTIMATE PLANT ENVIRONMENTAL VECTOR				PLANT MATERIAL VECTOR		
FRAMEWORK	DESCRIPTOR	MEASURABLE COMPONENTS	HUSBANDRY PROGRAMS	PRODUCTION INDICATOR	KNOWLEDGE TRANSFER	EXPECTED RESPONSE
I PHYSICAL AND BIO-LOGICAL SITE CON-DITIONS	CLIMATE SOIL SOIL MOISTURE FERTILITY PESTS		CULTURAL PRAC-TICES SCHEDULING IRRIGATION DRAINAGE FERTILIZE PESTICIDES : PLANT MATERIAL	PLANTING GERMINATION EARLY GROWTH RAPID GROWTH FLOWERING FRUITING RIPENING HARVEST	EXPLICIT OBJECTIVE SUBJECTIVE UNKNOWN NONE : INADEQUATE	OPTIMUM GOOD FAIR POOR FAIL UNKNOWN
ALTERED AND INTEGRATED PLANT ENVIRONMENT				PRODUCTION		UNITS
EXTERNAL ENVIRONMENTAL VECTOR				HUSBANDRY PROGRAM VECTOR		
FRAMEWORK	DESCRIPTOR	MEASURABLE COMPONENTS	ACTION PROGRAMS	HUSBANDRY INDICATOR	EXPERIENCE TRANSFER	EXPECTED QUALITY
II PHYSICAL AND BIO-LOGICAL RESOURCES	HUMAN WATER ENERGY CHEMICAL		ENGINEERING DEVELOPMENT EDUCATION EXTENSION ENFORCEMENT ENLIGHTENMENT INFRASTRUCTURE INCENTIVES SUPPORTS ETC.	CULTURAL PRAC-TICES IRRIGATION DRAINAGE FERTILITY PRO-GRAM PEST CONTROL LOGGING AND SCHEDULING PLANT MATERIAL	EXPLICIT OBJECTIVE SUBJECTIVE UNKNOWN NONE : INADEQUATE	OPTIMUM GOOD FAIR POOR FAIL UNKNOWN
III INSTITUTIONAL	LEGAL EDUCATIONAL RESEARCH FINANCIAL					
IV ECONOMIC	INCENTIVES FACTOR MARKETS PRODUCT MARKETS			PROGRAM PRODUCTION		COSTS RETURNS

The concept of the frameworks was taken from Barlowe[2] who suggested a threefold framework in which land economics could be encompassed. The three frameworks suggested by Barlowe are the physical and biological framework, the institutional framework, and the economic framework. These he defined as follows:

> Briefly stated, the *physical and biological* framework is concerned with the natural environment in which man finds himself and with the nature and characteristics of the various resources with which he must work. The physical and biological factors involved in this framework provide the physical support, the site, and the raw materials for various activities. At the same time they provide not only the inanimate resources of the earth but also the vegetative, bacterial, insect, fish, animal and human resources that both help and hinder man in his use of land.
>
> The *institutional framework* is concerned with the role man's cultural environment and the forces social and collective action play in influencing his behavior as an individual and as a member of his family, his various groups, and his community. It is concerned with the impact of cultural attitudes, custom and tradition, habitual ways of thinking and doing things, legal arrangements, government programs religious beliefs, and other similar factors upon man-to-man and man-to-land behavior. Among its many facets, it also involves the effect of personal and household considerations -- an individual's nonmonetary goals or his family obligations -- upon one's decisions as a business operator.
>
> The *economic framework* is concerned with the operation of our price system as it affects each individual in his attempt to make profitable use of his land-resource base. This framework deals with man's tendency to maximize his returns. It is concerned with the effect that economic concepts such as value, costs, returns, and profits have upon his allocation and distribution of land resources and upon his use of these resources for production and consumption purposes.

In dealing with crop systems, the physical and biological framework must be divided into two groups of factors: *The intimate physical and*

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[2]Raleigh Barlowe, Land Resource Economics, Prentice Hall Publishing Company Inc., England Cliffs, N. J., 1958.

biological site conditions which form the immediate environment surrounding the plants in the field and the *external physical and biological resources* upon which the plant husbandry practices must depend. The successful application of these resources and the procurement of additional necessary resources for the husbandry of the crop system is dependent on the institutional and economic frameworks. As shown in Table 1, a second level of disaggregation identifies the *major descriptors* which are significant to the information transfer process related to crop husbandry and productivity. At a third level of disaggregation, the pertinent *measurable components* of each descriptor are listed (as will be presented later).

Crop Response

Crop Production is the overall integrator of the agricultural system response to the husbandry program imposed at a specific site. Transfer must be made in terms of specific crop varieties or crop systems. For each site-related environmental vector, there are large numbers of potential crop systems utilizing various plant materials. The failure or success of each plant material and the necessary husbandry programs can best be described at various production stages or indicator points which are related to the intimate plant environment.

Once the intimate plant environment has been defined, each measurable component of the environment can be looked upon in terms of its effect on various production indicator points related to the crop. The *crop production indicator points* selected are *planting opportunity, germination, early and rapid growth, flowering, fruiting, ripening, and harvest opportunity*, as shown in Table 1. Each intimate environmental component has some effect at one or more of these indicator points.

In order to optimize, one needs to know the existing plant environment, the quality of transfer, the *potential husbandry* program which might be taken in order to modify the environment and the quality of the *expected response*, i.e., whether it is *optimal, good, fair, poor, failure or unknown,* as shown in Table 1.

Various qualities of knowledge *transfer exist,* as indicated in Table 1. This column is not necessary to the model, but is included to give some qualification as to the nature of transfer. Sometimes *explicit* relationships or formulas which allow definite predicitions are available. More often the expert is confined to *objective* reasoning where only some data points or a mix of data and theory are available to provide a basis for information transfer. Simple interpolations or functions such as the empirical consumptive-use equations are examples. Often knowledge transfer capability is completely *subjective* and dependent totally upon experience and judgment. There are also classes of knowledge transfer which could be considered as *unknown,* where it is not known if one exists and the explicit case of *none*, where it is known that no transfer is possible.

The class of transfer considered as *inadequate* may be used as a qualifer to the above transfer qualifiers. It may also be used to depict an inadequate categorization of the environment due to either insufficient data or insufficient knowledge of methods of categorization.

Husbandry Programs

As far as the *external environment* is concerned the meaningful *response* is the ability to develop the physical and biological *resources* necessary for the *husbandry programs* directly related to crop production. For example, irrigation is a potential husbandry program which may affect the total crop environment of almost every crop at each growth indicator point. On the other hand, the ability to effectively irrigate can be greatly affected by the resources available and the institutional or economic environmental components dealing with water resources, water law and water costs. Obviously, certain *action programs* are available which can modify the external environment to enhance the possibility of achieving the desired husbandry program. Water resources can be developed, laws changed or enforced, and economic incentives altered. The above process is outlined in the lower portion of Table 1.

FORMULATION AND USE OF THE MODEL

Crop production is directly responsive only to the *intimate physical and biological site conditions*. The external environmental subvectors are relevant only as they impact on this one, through husbandry; i.e., $\overline{E}_i = f(\overline{E}_N, \overline{E}_R, \overline{E}_E, \overline{E}_S, \overline{H})$ where $\overline{E}_i$ represents the intimate plant environment which is linked to the natural existing site biological and physical environment $\overline{E}_N$, the external physical and biological resources $\overline{E}_R$, the economic component $\overline{E}_E$, the institutional component $\overline{E}_S$, and the husbandry programs $\overline{H}$. It is through $\overline{H}$ that $\overline{E}_N$ is altered to $\overline{E}_i$, i.e., $\overline{E}_i = \overline{E}_N \times \overline{H}$. This relationship is pictorially depicted in Figure 1.

At this point the intimate physical-biological-crop response components of an overall model can be partitioned off from the social and husbandry components. Table 1 has been expanded to give finer resolution to the important environmental descriptors and action programs associated with optimizing agricultural systems involving water management. Furthermore, the important measurable components of these environmental descriptors have been delineated. A portion of this expanded sub-model is presented in Table 2. In its simplest form,

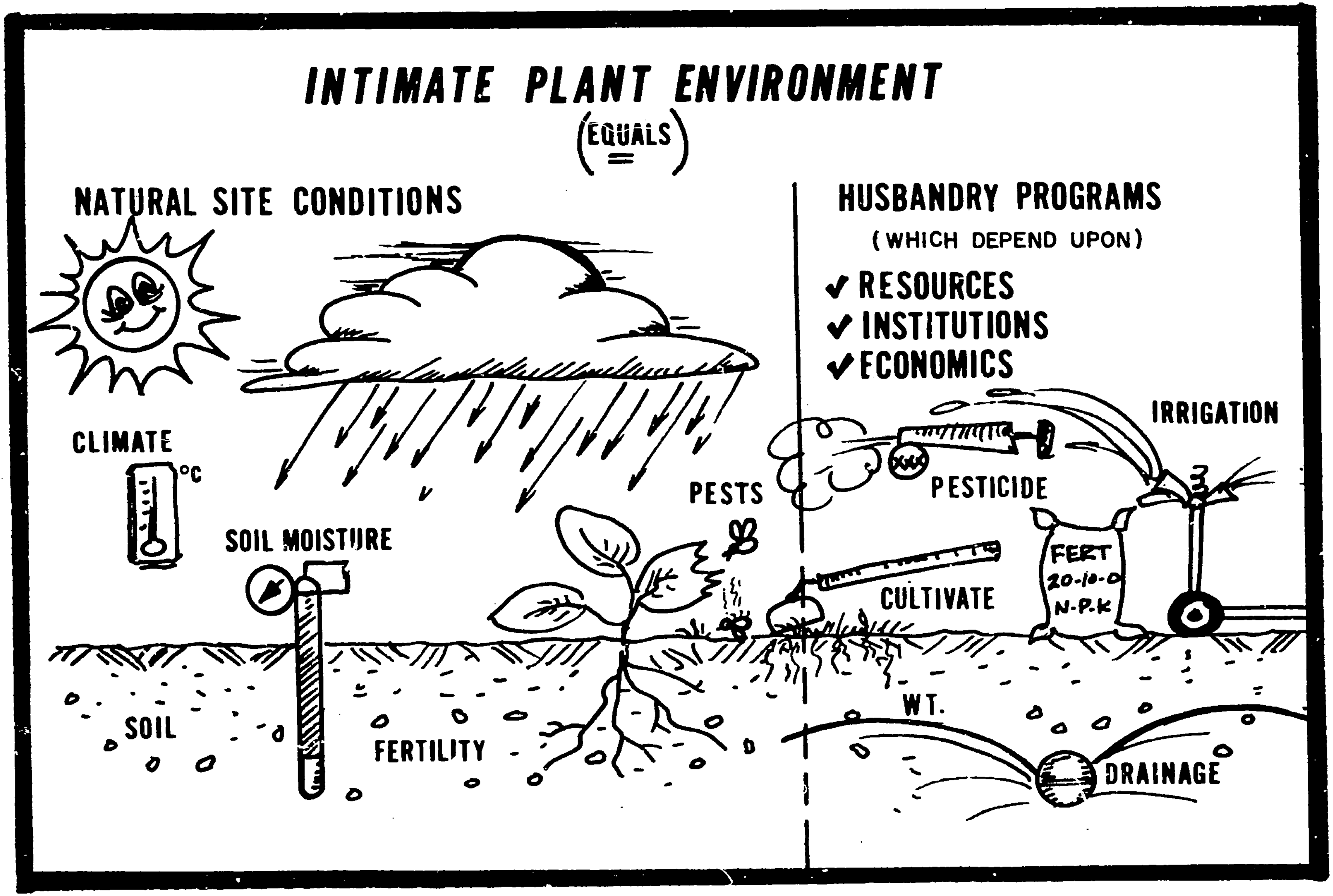

Figure 1. The Intimate Plant Environment Vector

Table 2. **Intimate Physical and Biological Site Conditions Portion of Model for Optimizing Comprehensive Research and Action Programs on Agricultural Systems Involving Water Management.**

INTIMATE PLANT ENVIRONMENTAL VECTOR			PLANT MATERIAL VECTOR		
DESCRIPTOR	MEASURABLE COMPONENTS	POTENTIAL HUSBANDRY PROGRAMS	PRODUCTION INDICATOR	KNOWLEDGE TRANSFER FUNCTION	EXPECTED RESPONSE
CLIMATE	TEMPERATURE Daily High Daily Low Frost Free Period Degree Days Hourly Variation Monthly Average HUMIDITY Daily High Daily Low Monthly Average RAIN Daily History Monthly Average Intensity Probability LIGHT Daily Intensity Day Length WIND, HAIL, SNOW History Probability	CULTURAL PRACTICES PLANTING DATE IRRIGATION SHADING Cover Crop Inter-plant CULTIVATION TRANSPLANTING SPECIAL HARVEST WIND BREAKS SUPPORT HOUSING LIGHTING NEW PLANT MATERIAL	PLANTING GERMINATION EARLY GROWTH RAPID GROWTH FLOWERING FRUITING RIPENING HARVEST	EXPLICIT OBJECTIVE SUBJECTIVE INADEQUATE UNKNOWN NONE	OPTIMUM GOOD FAIR POOR FAIL UNKNOWN
SOIL	TEXTURE PROFILE Surface Sub-surface Profile STRUCTURE PROFILE Surface Profile INFILTRATION CAPACITY PERMEABILITY SALINITY pH CHEMISTRY ORGANIC CONTENT BACTERIA TEMPERATURE TOPOGRAPHY	CULTURAL PRACTICES PLOWING SUB SOILING CULTIVATION RECLAMATION AMENDMENTS PLANTING DATE IRRIGATION DRAINAGE COVER CROP CROP ROTATION MANURING NEW PLANT MATERIAL			
SOILMOISTURE	QUANTITY PROFILE Surface 0 - 30 cm 30 - 60 cm 60 - 90 cm 90 + cm POTENTIAL PROFILE SALINITY PROFILE	CULTURAL PRACTICES IRRIGATION DRAINAGE CULTIVATION MULCHING COVER CROP AMENDMENTS PLANTING DATE CLIMATE MODIFICATION NEW PLANT MATERIAL			
FERTILITY	NATURAL PROFILE Nitrogen Phosphorus Potassium Trace EXCHANGE ION TIE-UP RESIDUAL HOLDING CAPACITY	CULTURAL PRACTICES FERTILIZE MANURING CROP ROTATION ADDITIVES CULTIVATION IRRIGATION DRAINAGE COVER CROPS NEW PLANT MATERIAL			
PESTS	FUNGUS INSECTS NEMATODES WORMS & SNAILS POLLUTANTS BIRDS ANIMALS RODENTS WEEDS	CULTURAL PRACTICES PLANTING DATE PESTICIDES MECHANICAL IRRIGATION DRAINAGE CULTIVATION NEW PLANT MATERIAL			
ALTERED AND INTEGRATED			PRODUCTION		UNITS

the sub-model would simply be a data bank partitioned by crops and capable of making interpolations or extrapolations as environmental factors are varied. To take this first step, crop production data under different environmental conditions should be collected in standardized form. All of the pertinent environmental factors should be measured. As a beginning, this could be done to develop data banks for major crops such as wheat, maize and rice.

One advantage of the disaggregation of Table 2 is that it represents an attempt to be comprehensive. All of the environmental factors should be accounted for or categorized at both experimental sites and contemplated development sites. Neglect of any single factor could prevent transferability of information from the research side and unanticipated difficulties and perhaps even failure on the development side. It is important to have at least a few experimental data points for which each of the environmental descriptors were measured.

The writers developed this paper in the context of discussions of water management programs for developing countries, thus world-wide data are contemplated. As the model is developed, basic physical and biological relationships may be utilized to simplify and refine the response surface in lieu of simple interpolations.

Plant Breeding

The possibility of developing new plant materials always presents the opportunity to improve production over that which might be expected using different varieties -- existing or to be created. How to build this factor into the predicitive model is troublesome. At first, within any one basic crop, productivity data might focus on the optimal variety at the test site with the thought that breeding or varietal selection could result in similar optimization at a new site. This approach would need to be used with caution. There would still probably have to be manual review or screening of variety limitations and potentials by crop geneticists for each prediction.

Interaction

This is implied in the model where various indicators or potential action programs or environmental components are cross referenced. For example, interaction is implied between soil moisture and fertility, since it is given as a potential husbandry program for each of these.

Knowledge Transfer

The need for the transfer of knowledge is implicit in the model. Without such an ability, the desired environmental site conditions obtainable through husbandry programs, the selection and application of these husbandry programs, and the expected production indicator responses could not be predicted.

COMPREHENSIVE EVALUATION

The sub-model would provide predicted production functions for alternative choices of crop systems and husbandry as prerequisites to economic and social evaluation. The resource, institutional and economic frameworks provide the qualitative and quantitative measures of the costs of inputs and the values of the expected responses. A summary of the total evaluation of the agricultural system is presented in Table 3. However, the only quantitative evaluation contemplated is economic, wherein the cost of the husbandry and action programs can be compared to the total economic value of the crop production and action programs to the farm unit or the region. Several operation -

Table 3. Comprehensive Evaluation of Agricultural Systems as a Basis for the Decision Process.

ASPECT	COSTS TO REGION	BENEFITS TO REGION
Economic Balance	Monetary cost of action and husbandry programs.	Monetary value of production and support programs.
Social Statement	Social cost of action programs to the region.	Social benefits of action programs and production.
Environmental Statement	Environmental costs of development programs.	Environmental value of the action programs.
TOTAL	Comprehensive political decision by policy makers.	

research type techniques have been devised for optimizing economic returns given certain levels of resource and marketing constraints. See, for example, Windsor and Chow.[3]

The "social" and "environmental" statements dealing with costs and benefits are, for the most part, qualitative, but some consideration of these categories may be imposed *quantitatively* on the evaluation in the form of constraints. Social and environmental consequences are important, however, in providing policy makers with the information necessary to make comprehensive decisions.

APPLICATION OF THE MODEL

The two important vectors operative at the production level are thus the intimate plant environmental vector depicted by the disaggregated measurable components as altered by husbandry programs and the biolocical production (plant) material vector imposed upon it. The action is two-fold: a husbandry program is imposed on the site environment to make it more hospitable, and this modified intimate environment is imposed upon the plant material.

The availability and quality of the husbandry programs depends upon the external environment which may, in turn, have been modified by some action program. Figure 2 shows a flow diagram of the model process and points out the imputance of knowledge transfer.

The response of the plant material to this modified site environment is checked at a number of production indicator stages, and ultimately the expected productivity is estimated. The disaggregation of production into a number of production indicator points or stages is important

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[3]Windsor, J. S., and Chow, V. T., "Model for farm irrigation in humid areas, "Journal of the Irrigation and Drainage Division, ASCE, Vol. 97, No, IR3, Sept., 1971.

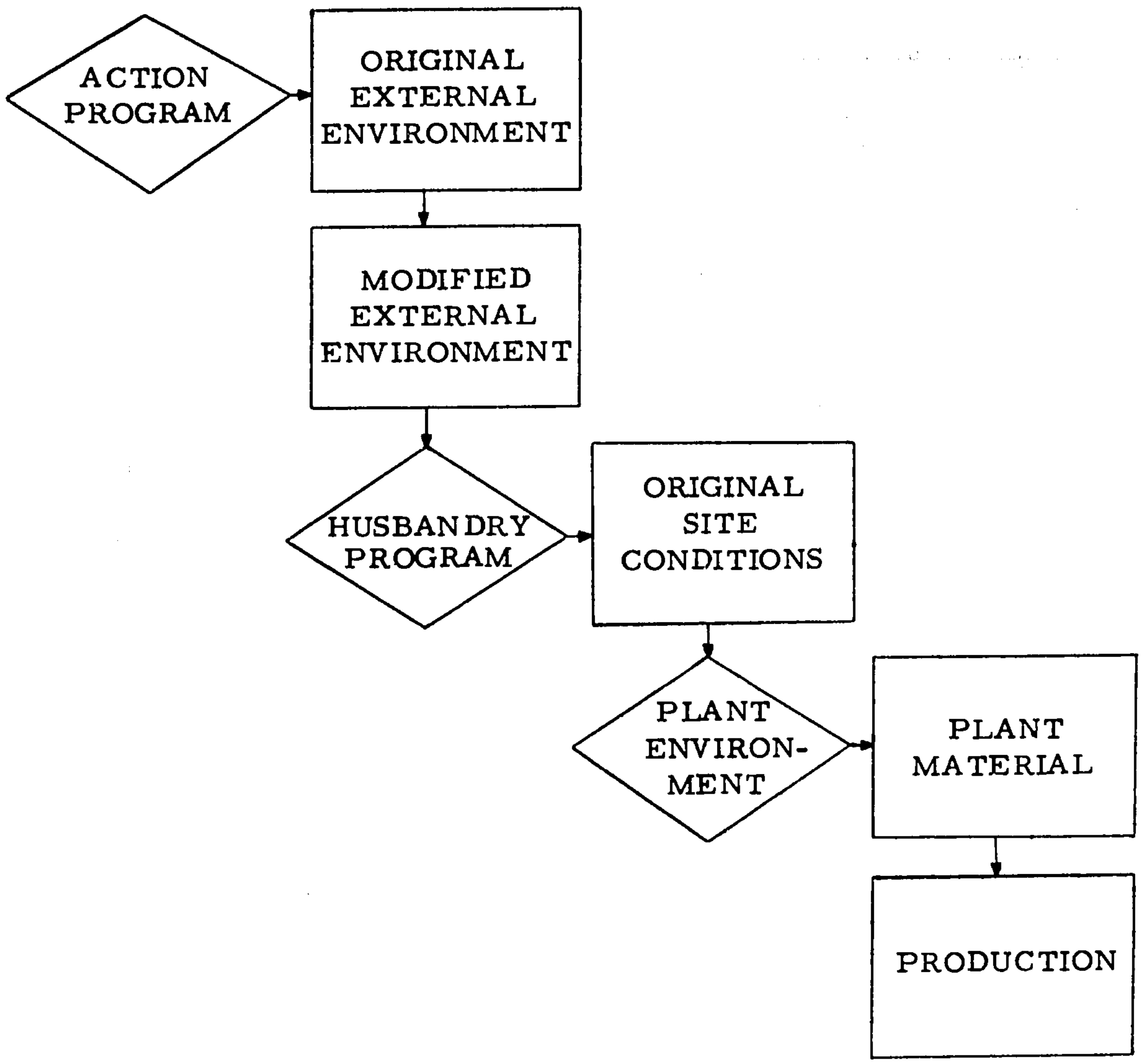

Figure 2. Flow Diagram of Model - Knowledge Transfer is Implicit at all Arrows.

in systematically selecting potential modifications to the husbandry program and estimating productivity.

Plant materials which have low production expectations at the given environmental site under reasonable husbandry programs are discarded in favor of more promising plant materials. The selection process is continued to the conclusion of the optimization process. This process implies that there is a data bank, the environment is characterized, and knowledge of applying husbandry programs and crop response expectations are transferable from one to another environment.

Agricultural Engineering

In general, agricultural engineering technology is transferable. For example, irrigation system design parameters including details such as the expected sprinkler performance in wind can be estimated if the environment has been adequately characterized and sufficient sprinkler performance data is available. The reason for inadequate estimates results either from insufficient wind records or insufficient sprinkler performance data. Sprinklers should not be tested at the project site if it is more convenient or economical to adequately characterize the wind and use sprinkler test data which is already available.

The effective application of engineering technology to achieve practical husbandry programs implies that the desired alteration of the natural site environment is known. The technological processes required in the husbandry program which are best suited within a given set of external environmental restraints can be selected from the technological data bank. Thus test site operations are only needed for the final onsite fine-tuning and demonstration of the operating programs. For example, within various environmental restraint circumstances the following technology is transferable: irrigation, drainage, and cultivation methods; fertilizer and pesticide application methods; and planting, thinning and harvesting processes.

Plant Requirements and Responses

Much of the information regarding the intimate environmental requirements of specific crops and varieties and expected responses to site conditions is transferable. Two sets of data are required before this information can be applied, however

1) The existing site environment must be categorized.

2) The achievable husbandry programs and resulting plant environment conditions must be estimated.

The information transfer process breaks down if either the "categorization" of the expected plant environment or the "data bank" of plant needs is inadequate.

An obvious example of applying the model as a check list for crop and varietal selection is:

a) Bananas fail in freezing climates - the temperatures in Alaska are well below freezing much of the year - no reasonable husbandry program other than green houses could alter the temperature sufficiently to create a hospitable environment for bananas in Alaska -- failure of bananas can be expected.

A more subtle application is:

b) In parts of South America it would be desireable to grow corn under irrigation during the dry season. (Since there is little cloud cover, dry season corn should do better than wet season corn). Many say corn doesn't do well during the dry season because of experience with planting the wet season varieties for a dry season crop. The problem results from temperatures being too high during the dry season for pollinization of wet season varieties. If the model had been applied, more suitable dry season varieties which would pollinate at higher temperatures might have been selected and been successful.

Characterizing the Environment

The detailed study of many aspects which characterize the environment does not need to be carried out on or near the site. It is often most efficient to bring the component under study to an established laboratory rather than bring the laboratory to the site. This is especially true when highly sophisticated techniques are involved. The model will help pinpoint the most efficient strategy for characterizing the environment.

Optimizing Research

Much of the basic information necessary for optimizing agricultural systems can be obtained from data already available in the literature. This is possible since much of the information required is transferable.

If adequate measurements are made in site-specific field trials under different environmental conditions, specific points in the model space can be delineated. With even a few such points the geometry of the model space can begin to be understood with the result that more valid transfer interpolations can be made. As additional data are collected, the resolution of the model can be improved as well as its geographical scope.

The application of this model should be most useful in organizing research efforts to minimize the number of site-specific studies necessary. The potential for optimizing research efforts to fill in the model space by utilizing transferable information, using the more sophisticated research facilities effectively, and conducting site-specific field trials only to bridge critical areas is perhaps the most important contribution of the model. Furthermore, the model should afford a useful framework for the cataloging and retrieval of research information from a data bank.

Much information dealing with soil-water-plant-climate relationships is transferable. However, it is not unusual to find field research being conducted to determine crop response where it could easily have been predicted if the environment had been adequately characterized. For example, is it unnecessary to grow: (a) cotton to find that the growing season is too short, (b) rice to find that the temperatures are too cool, (c) organge trees to find out it freezes, (d) alfalfa to determine optimum moisture requirements, etc., (e) wheat to find it is too wet to harvest at the proper time, etc. On the other hand, site specific research is necessary to determine: (a) varietal disease susceptability, (b) interactions between climate-moisture-pest controls for various plant materials, etc.

CONCLUSION

Hopefully, this model will aid in setting up and guiding the activities of investigating teams. *Too* often proposed projects are viewed by "teams of experts" who go no further than measuring a number of environmental components. This may be a worthy and necessary effort, however, the ultimate success of projects depends on the level of knowledge transfer capability. The *real and most unique experts* are not technicians who measure the environmental parameters, but the few engineers and scientists who are capable of optimizing the agricultural system through knowledge transfer. The model disclosed herein should help in organizing and defining the necessary processes.

In addition to forming a useful outline to guide the thought processes involved in research program development and project analysis, the model could form the framework for a data retrieval system. It is being proposed that the work be extended in an effort to make the model more complete and to form a world data bank for at least one important grain or fiber crop.