SYSTEMS MODELLING AND TECHNOLOGY EVALUATION: AN APPLICATION

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Abstract

Evaluation of technology is an integral part of agricultural research. A systems approach to agricultural research logically leads to modelling as a method for technology evaluation. The usefulness of systems modelling in the process of agricultural research is illustrated with an example from the semi-arid tropics of India.

1. Introduction

Technological change, defined as any change in the mode of production resulting from purposeful resource-using activity directed to the development of new knowledge embodied in designs, materials and organisation (Hayami and Ruttan 1971, p.56), has been recognised as a powerful engine of growth in agricultural productivity. Following on the early successes of the green revolution, there has been rapidly accelerating investment in agricultural research by national and international agencies. World expenditure on agricultural research is now substantial and it is thus important to endeavour to ensure its efficient allocation. The lack of an efficient market for the allocation of research resources due to the public goods nature of research necessitates the evaluation of its effects through alternative approaches.

It may be useful to classify the process of technology evaluation into ex-ante and ex-post, depending on whether the evaluation takes place before or after the technology is made available to farmers. A large number of ex-post studies in which attempts have been made to evaluate the impact of new technologies and identify the constraints to their wide spread adoption have been carried out in the context of the green revolution (Sidhu 1974, Binswanger and Ruttan 1978, Feder and O'Mara 1981, Anderson, Herdt and Scobie 1986). The results of such analyses are useful for formulating research policy. Ex-ante evaluation, whereby the likely impacts of prospective technologies are studied in detail before the technology is made available to farmers may be less common (Valdes, Scobie and Dillon 1979, Goodwin, Sanders and Hollanda 1980, Joseph 1987) but not less important. Information from ex-ante evaluation is an important input to research planning and management.

It is advocated in this paper that systems modelling is an appropriate tool for ex-ante evaluations. The perspective is that of an economist working within the farming systems program in an agricultural research organisation. The scope is a modest one of illustrating the use of a simulation model for evaluating one of the components of a prospective technological package designed for the semi-arid tropics of India.

2. The Process of Technology Generation

The process of research leading to a new technology may be classified into five somewhat overlapping stages. The first stage is diagnostic leading to identification of problems which can be solved by changing the mode of production. It is important to bear in mind that not all problems can be solved efficiently by new technology. For example, if institutional constraints (such as access to input and output markets) have restricted growth in productivity, a more effective solution may be to implement appropriate institutional reforms. Where technological solutions are considered, problem diagnosis leads to the second stage of identification of technological options. To use Anderson and Hardaker's (1979) terminology, new technologies at this stage are 'notional' or 'quarter-baked'. In the process of research, these largely hypothetical notional options are refined in several cyclical steps. The process of refinement may be broadly called ex-ante evaluation. Many of the notional options are discarded, others modified and tested to form preliminary (or 'half-baked') technologies which are still unrefined and require additional testing. Technologies which are fully refined are ready for the fourth stage of extension to farmers. Monitoring and ex-post evaluation of the extended technology are the activities in the final stage.

A new technology is useful only if it is adopted by farmers. Hence the assessment of effects at the farm level is at the heart of the overall evaluation process. The impact at the farm level and the probability of adoption depends on how well the requirements of the technology fit into the 'niche' in which the farmers operate. The requirements of a technology may be divided into socio-economic and biophysical. Similarly, farmers' niche is described by a particular endowment of these resources. Four possible combinations are represented in Figure 1. The screening at the farm level is passed only by the Type I technology. Type III and Type IV are failures. Type II may be successful if appropriate institutional changes to expand the endowment of socio-economic resources can be implemented.

The impacts of Type I technologies, which are favourable at the farm level may or may not be consistent with national objectives. The debate on efficiency vs equity effects of green revolution is a case

		SOCIO-ECONOMIC	
		REQUIREMENTS WITHIN LIMITATIONS	REQUIREMENTS BEYOND LIMITATIONS
BIOPHYSICAL	REQUIREMENTS WITHIN LIMITATIONS	I	II
	REQUIREMENTS BEYOND LIMITATIONS	III	IV

Figure 1: Types of Technology according to Bio-physical and Socio-economic Requirements and Limitations

Source: Zulberti, Swanberg and Zandastra (1979).

in point. Although it is unlikely that future consequences of adoption could be anticipated with much accuracy at the stage of ex-ante evaluation, some assessment of the effects at the aggregate level will be useful so that appropriate policies to mitigate unfavourable consequences may be designed. Where such policy options do not exist, some features of the technology may have to be changed.

Ex-ante analysis may be conducted in a research station or on farm. A high level of control that can be exercised over experiments in research stations permits a sharper focus on particular aspects of the technology. However, such sharpened focus is obtained only at the cost of the inevitable abstraction from reality. Despite the complementarity of on-farm and on-station research, notional technologies are likely to need higher on-station research efforts for them to be refined enough for on-farm testing.

3. Systems approach

A systems approach whereby phenomena (or subsystems) to be explained are considered in dynamic relation to other interacting phenomena rather than in isolation, is being increasingly accepted as a philosophical approach that can lead to a better understanding and control of these phenomena (Dillon 1976). The rationale for a systems approach is quite clear--whenever various components are interacting, the behaviour of the system can not be inferred by simply aggregating the behaviour of various components. Instead, the whole of the collection of components must be studied as a system.

Farming systems are highly complex, stochastic systems with many interacting subcomponents (Ruthenberg 1980). They are characterised by the active role played by farmers in an attempt to control the physical-biological system so as to satisfy their objectives. The system is dynamic and intrinsically stochastic, with the climate and socio-economic systems acting as the environment. Climatic factors broadly limit the physical performance of the system (or what the farmers can do) while socio-economic factors influence the goals of the farmers (or what they would like to do) and largely determine the economic performance of the action.

The farming systems approach is a generally accepted approach to agricultural research and technology evaluation as is evidenced by the literature in this area (Byerlee, Harrington and Winkelmann 1982, Shaner, Philipp and Schmehl 1982, Dillon and Anderson 1984). Although there are many versions and acronyms used, the basic features of a farming systems research are that they are problem-solving, holistic in outlook and multidisciplinary in nature (Hardaker, Anderson and Dillon 1985)

4. **Modelling**

The acceptance of systems approach naturally suggests systems modelling as an important tool for technology evaluations. At a broad level a model may be defined as the representation of reality as perceived by the analyst (Petit 1981). A model thus may be a simple verbal description of the system or a complex mathematical representation. Due to cognitive limitations of human mind and resource constraints, models are necessarily imperfect. Modelling is a major analytical tool in the hands of social scientists because the system they study may not yet exist or the cost of experimenting with the real system may be prohibitively high.

The importance of modelling in the overall process of agricultural research is discussed in some detail by Anderson and Dillon and Hardaker (1985). In particular, modelling the existing system helps to identify possible solutions (technological or otherwise) to the perceived problems. Where technological solutions are considered appropriate, modelling helps to identify the necessary characteristics of the technology and to evaluate prospective technologies at an early stage so that the task of research management becomes more efficient. Similarly, for technologies which are more developed (i.e., testing is advanced), the assessment of effects at a more aggregate level than is possible with on-farm trials can be conducted by experimenting with the model. This may also involve the examination of second round effects (such as price effects, multiplier effects) which may be large orders of magnitude (Hazell and Anderson 1985). Such evaluations may provide basis for implementing institutional changes such that the likely unfavourable consequences can be avoided. The quantitative issues involved in evaluation at the aggregate level have been discussed by Anderson and Pandey (1985).

Models may be classified basically into two types: optimising and non-optimising. In the former are included mathematical programming models. These models provide optimal decision rules using an optimising algorithm. However, mathematical rigidities of the programming approach do not permit a fuller representation of stochastic and dynamic aspects of farming systems. Simulation models are basically non-optimising, have a flexible mathematical structure and hence are more appropriate for modelling stochastic and dynamic production relationships. The biological complexities involved in agricultural production can be better represented by linking up disaggregated simulation models of basic production processes (e.g., models of various physiological processes involved in crop growth). The usual production function representation involves gross simplification of the biological processes and hence is unlikely to be very useful in providing answers to many problems of relevance to farmers (Boggess 1984, Trapp and Walker 1985). Recently, many farm management problems have been studied using biophysical simulation models(e.g., Haith, Farmer and White 1987, Doyle, Morrison and Peel 1987, Parsch and Loewer 1987). A comprehensive review of earlier applications to agriculture is given by Anderson (1974).

5. A Systems Framework for Technology Evaluation

The basic model for the evaluation of technology from farmers point of view consists of submodels of five broadly defined subsystems--climate, crop (and/or livestock), economic environment, farm and farmer (Figure 2). Stochastic inputs of weather data such as rainfall, temperature and radiation are provided by a climate model. The response of crop to climate and decision variables are represented in the crop growth model. The level of complexity may vary from simple production function to a highly complex physiologically-based model. A model of economic environment is required for obtaining stochastic forecasts of appropriate economic variables such as prices.

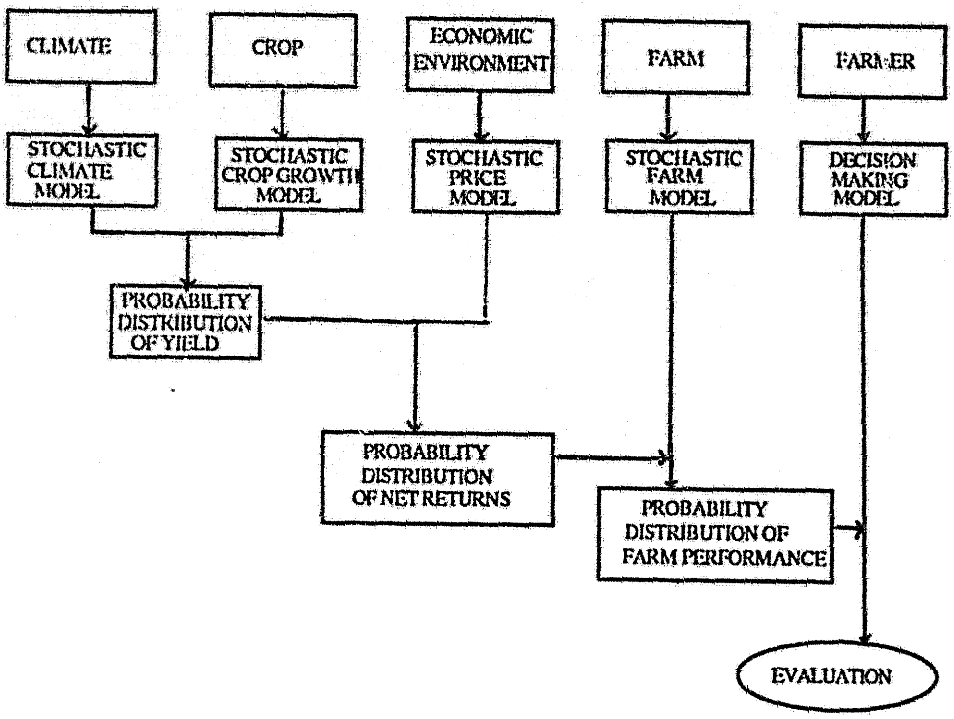

Figure 2: A Model for Technology Evaluation

Adapted from: Anderson (1981).

Integration of interactions between various farm enterprises is achieved in the farm model. The decision making behaviour of the farmer is incorporated in the farmer model. Evaluation is conducted by comparing probability distributions of various attributes of the farm performance (for example, net income).

6. Simulation Modelling

A typical process of simulation modelling may be considered to consist of seven stages which are definition of systems, systems analysis, systems synthesis, validation, sensitivity analysis, systems experimentation and finally analysis and interpretation of results (Anderson 1974). The boundary of the system under study are defined in the first stage. In the second stage, existing information on the various components of the system are studied in detail, and where necessary, new information is generated by real-world experimentation. Such information are then synthesised to form an overall 'model' of the system. The model is then validated to ensure that the essential aspects of reality have been captured in the model. Sensitivity analysis can be conducted using the validated model to identify parameters and relationships which are imprecise and to which the model performance is particularly sensitive. The analysis may indicate a need to obtain more precise estimates of parameters and relationships by further research. Thus sensitivity analysis is an important stage which can lead to the identification of researchable problems. In the context of ex-ante evaluation of notional technologies, this can be a very important stage because ignorance about the systems behaviour will most probably be very high. At the model experimentation stage, benefits from following various management strategies are evaluated in an attempt to identify superior strategies. The results may be useful for providing guidelines for implementing a more efficient program for real-world experimentation. As the cost of model experimentation is low compared to that of real-world experiments, performance of a large number of options can be evaluated using a model. The final stage consists of presenting recommendations in a suitable form. A wealth of useful information is generally accumulated at the end of a successful simulation exercise. New information can be readily incorporated in the existing model and further evaluations made. Thus, as noted by Anderson and Dent (1972), simulation modelling is an efficient method of complementing the more conventional mode of technology evaluation via real world experimentation.

7. An Example

Consequences of fallowing in the rainy season in certain regions of the semi-arid tropics of India are forgone production and increased soil erosion. With a new soil and crop management technique developed at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), two crops can generally be grown in these areas. However, one of the major constraints to double cropping is the need to provide presowing irrigation to the dry season crop (which is mostly wheat) if rainy season cropping is practiced. Collection and use of excess runoff from an appropriately designed block of land for irrigating the dry season crop is a promising alternative. However, no information was available on the biophysical and economic viability of this component of technological options. Following a more traditional approach to agricultural research, information could have been generated by conducting real-world experiments. However, given that the technology was still notional, it was judged appropriate (cost-effective) to generate more information through modelling technique.

For a given block of appropriately designed land (loosely termed a watershed here), the critical variables determining systems performance are the size of the reservoir, the area downside of the reservoir (or command area) and the area upside of the reservoir (or catchment area). Excess runoff from the catchment area is collected in the reservoir and is used for irrigating the command area.

In keeping with the framework discussed above, a simulation model of the system consists of the following submodels :

(a) weather model,
(b) rainfall-runoff model,
(c) water-balance model of reservoir,
(d) crop yield response model to irrigation,
(e) price forecasting model, and
(f) farm model.

Only a brief description of these submodels is provided here. For details see Pandey (1986).

In keeping with the simplicity of the overall model, historical climatic records were directly used as stochastic inputs into the model. As noted by Phillips (1971) such an approach can however be criticised because a particular set of historical records represents only a sample from the true distribution of climatic variables.

A simple rainfall-runoff model was used for predicting runoff for the given soil type and cropping pattern. The model was developed and validated by hydrologists at ICRISAT. Daily runoffs were predicted using the model. Using 30 years of daily climatic data, average annual runoff potential was estimated to be approximately 400 mm. Even though model development was at a very early stage, such intermediate information was useful to make judgements about the feasibility of the technology.

The water balance model of reservoir was simply a system of equations keeping track of the volume of water stored in the reservoir.

The yield response model to irrigation consisted of two components : yield response to evapotranspiration deficit and soil moisture model. The former was considered to have a stronger biological basis than water production functions in which yields are directly related to the quantity of water applied. Irrigation was related to yield through a soil water balance model which was used for predicting evapotranspiration deficit. Semi-empirical relationships were used to describe various dynamic processes such as leaf and root growth . A soil water balance model for wheat planted after the harvest of the rainy season crop (which was soybeans) was run to determine the frequency with which wheat could be grown without a presowing irrigation. It would be possible to grow wheat after soybeans if enough rains were received around the sowing date. The simulation indicated that in two out of three years, upper soil layers become too dry for a successful germination of wheat following soybeans. This observation provided further basis for proceeding ahead with a more complete modelling. Had the results of the water balance model indicated adequacy of soil moisture at the sowing time of wheat, the case for water harvesting would have been weakened.

The soil water balance model also indicated that the rainy season crop never suffered from moisture stress in any of the thirty simulated years. The result indicated the problem of allocating stored water between the rainy and the dry season crops to be unimportant. This allocation problem was originally considered to be an important one. Thus additional information obtained during the model development phase (i.e., systems analysis and systems synthesis) can be useful for modifying various aspects of notional technology.

Statistical time series analysis of price data indicated crop prices to be stochastic but without any significant trends. Truncated normal distributions were used for prices of wheat and soybeans. Input prices were assumed to be deterministic.

At this preliminary stage of modelling, interactions among different farm enterprises were not considered. Other enterprises were assumed not to influence the profitability of the new technology.

Farmers were assumed to maximise net present value or the expected utility of net present value (assuming risk-aversion).

Estimates of seepage losses from the reservoir were very imprecise and site-specific. A priori, seepage rate was considered to be a critical parameter. The results of sensitivity analysis supported the a priori belief. Additional research for estimating seepage rate more accurately was hence emphasised. Similarly, the need to obtain more precise estimates of yield response of wheat to irrigation was highlighted by the sensitivity analysis.

The main design parameters of interest are the sizes of the catchment and command area and the reservoir size. For a given watershed, the size of the catchment area is the residual when the size of the command area and the reservoir size are known. A 5X5 grid points on reservoir size and command area was used for experimenting with the simulation model. Results from 30 years of stochastic simulation were used for estimating a 'response surface'. The response surface indicated that the response of net present value to changes in command area was sharper than that due to changes in reservoir size. Thus an accurate determination of the location of the reservoir was found to be more important than the determination of its size. The results also helped to explain the failures of some real-world experiments in which the location of the reservoir was not carefully chosen.

The water harvesting technology was found to be economically desirable for seepage rates lower than 20mm/day. During the stage of sensitivity analysis, seepage rate was found to be one of the critical parameters. Assuming that seepage rate can be precisely measured, the magnitude of benefits from seepage control can be estimated by comparing simulation results for different seepage rates. The results indicated that the maximum amount that can be spent for reducing seepage by 10mm/day is approximately Rs10/m^2. Such estimates were valuable to scientists involved in the development of cost-effective seepage control measures.

The model was originally run using agroclimatic data for a particular geographical location in the semi-arid tropics of India. Before the commitment of more resources for a detailed evaluation of the farm level effects, it was considered useful to make some assessment of the absolute size of benefits to the country as a whole. Some simple calculations using simulation results helped to estimate the possible extent of geographical coverage. The technology was found to be feasible only if the average annual rainfall is more than 1000mm. Total potential benefit was estimated by multiplying the area with rainfall more than 1000mm by benefits per unit area.

The simulation exercise thus helped generate a large quantity of information on the nature of the water harvesting technology. Such information were useful not only for identifying critical parameters of the system but also for designing real-world experiments for a more complete ex-ante evaluation.

8. Summary and Conclusions

The role of modelling in the overall process of agricultural research and technology evaluation was emphasised in this paper. Particular attention was given to illustrate the application of systems modelling for ex-ante evaluation of a notional technology conceptualised at ICRISAT. Modelling approach provided a framework to integrate information from disciplinary research on various aspects of the technology in a structured manner. The interdisciplinary nature of the modelling exercise was very useful to identify research directions which were worth pursuing. Evaluation of technology in a holistic framework was facilitated by a systems perspective.

So much for the joys of systems modelling ! It is important not to forget that modelling is just an aid not a substitute to human judgment and intuition. No formal model can represent systems in the all-encompassing totality that human minds can. Thus as noted by Anderson and Hardaker (1979), technology evaluation is best facilitated by a careful blending of human intuition and formal modelling.

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