USE OF BIOPHYSICAL SIMULATION IN PRODUCTION ECONOMICS

Wesley N. Musser and Bernard V. Tew

Simulation has become a standard methodology in agricultural economics with models being used in all aspects of the profession. Johnson and Rausser identify two major types of production simulation models in their recent survey of the topic—firm and process models. Firm models, especially those concerned with growth, are most prominent in the agricultural economics literature. However, Johnson and Rausser also review some application of process models, which emphasize specific types of firm decisions. Biophysical simulation models are a specific form of these models concerned with the interaction of weather, soil, and/or biological processes in agricultural production and/or environmental loadings. In the recent agricultural economics literature, these models often are identified as bio-economic simulators. However, similar models are being utilized to evaluate erosion. Since erosion is largely a physical process, biophysical simulation seems more appropriate for the general classification of models considered in this paper.

Biophysical simulation is a relatively new research methodology in agricultural economics. While Johnson and Rausser reviewed some of the precursors of current models, most of the development has been subsequent to their survey. Subject to the usual caveats concerning historical events, the studies of Mapp and Eidman on irrigation published in 1975 and 1976 are benchmarks in the use of biophysical simulation. In 1979, Reichelderfer and Bender published another early biophysical simulation study concerning Mexican bean beetle control on soybeans. In 1983 publications using this methodology have begun to accelerate. Examples include the studies of Boggess et al. and Boggess and Amerling on irrigation scheduling, of Brorsen et al. on stocker cattle growth, and of McGuckin on alfalfa management. This methodology builds on an extensive literature in other agricultural sciences which is not reviewed in this paper. Interested readers are referred to the agricultural economics articles for citations to other disciplines.

The overall purpose of this paper is to review the current use of biophysical simulation and to evaluate its potential as a method in production economics. While the simulators are being used for extension activities, this paper largely is confined to research applications which is the scope of experience of the authors. The next section presents a general definition of biophysical simulation and delineates differences from other simulation models in production economics. Then, a survey on the current scope and use of such simulators in production economics is summarized. A digression on philosophy of research in production economics is presented in the next section to set the stage for an evaluation of these simulators. Next, the use of these simulators in production economics is reviewed in order to outline reasons for their current popularity. The paper concludes with a summary of advantages and potential pitfalls of such models.

A GENERAL VIEW OF BIOPHYSICAL SIMULATION

In general, simulation is a technique for modeling systems; therefore, any representation of a process is a form of simulation. A more precise, useful definition of simulation is that it is a number of interlocking mathematical components representing a complex real process (Johnson and Rausser). Following this definition, a biophysical simulator is a complex mathematical model of some process with explicit attention to biological and/or physical determinants of agricultural production.

Biophysical simulation can be related to production functions. Following Dillon (p. 104),

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a general formulation of a production function for agriculture is as follows:

$$(1) \quad Y = f(X_1, X_2, \ldots X_n; X_{n+1}, \ldots X_k; X_{k+1}, \ldots X_m)$$

where:

Y = output,
$X_1, \ldots X_n$ = input decision variables,
$X_{n+1}, \ldots X_k$ = predetermined input variables, and
$X_{k+1}, \ldots X_m$ = uncertain input variables.

In reference to standard theory, decision variables refer to variable inputs, part of the predetermined variables are fixed inputs, and the remaining predetermined variables and uncertain variables are environmental influences on production. While the environmental influences are not input commodities, this specification does make the influence of the environment explicit. A biophysical simulator uses a set of mathematical equations to model equation (1). Environmental influences are given particular attention in these models. Many or most of the decision inputs are not included in the model; the implicit assumption of these models is that most decision inputs are predetermined at unlimiting levels for the range of decision variables relevant for the model.

A crop production simulation model is presented in Figure 1 to further illustrate the biophysical systems approach.[1] Irrigation is the only decision input in this simulator with all other inputs being predetermined on an unlimited basis. The model has many subsystems and three principal focal points of system interaction, including the soil-plant interface, the atmosphere-plant interface, and the atmosphere-soil interface (Feddes, Kowalik, and Zaradny). The soil-plant interface receives input from several subsystems which model the corresponding physical processes. Transpiration, infiltration, evaporation, and runoff are among the most important processes in this interface. The atmosphere-plant interface contains models representing germination, vegetative growth, and yield response while the atmosphere-soil interface has an infiltration and an evaporation subsystem. As with most biophysical simulations, major emphasis is placed on evnironmental inputs and their interrelationships.

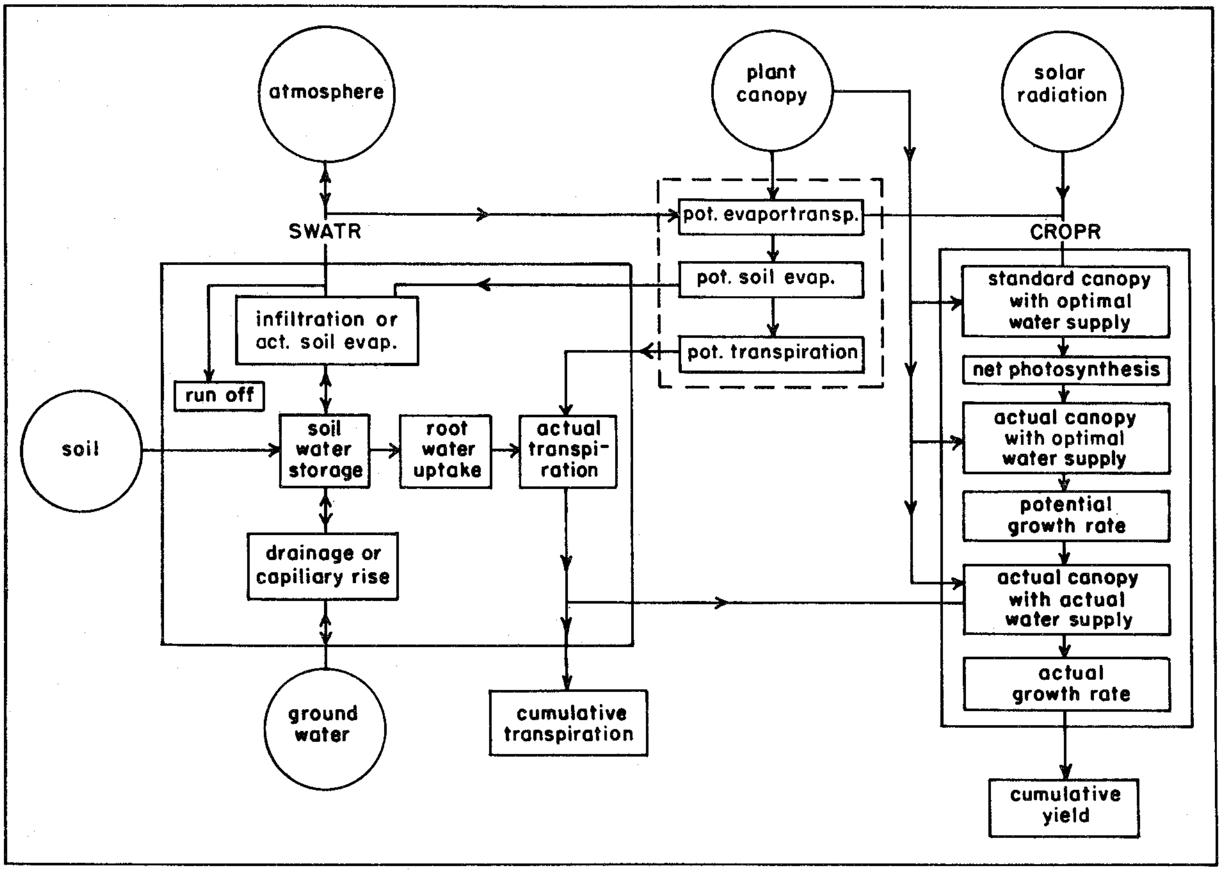
Standard basic steps in simulation—investigation, model translation, specification, and validation—can be related to the model in Figure 1 (Feddes, Kowalik, and Zaradny). The first step, systems investigation, has a critical role in the overall applicability of the simulator because the fundamental concept and success of the systems approach depends on correctly designing each subsystem and analyzing the interactions among the subsystems. With respect to the crop simulator, the unique technical characteristics of each subsystem must be analyzed in addition to the respective interactions.

The second and third components of the simulation process are model translation and specification. Accurate mathematical representation of each subsystem and interaction phase including the extreme points of each relationship is vital to the realization of representative results. For example, the soil-plant interface and all associated subsystems included in Figure 1 are conceptually related to a water response function for the particular crop being modeled. If extreme drought conditions and very wet conditions are not accurately modeled, the responsiveness of the simulator is limited. Consequently, the credibility and usefulness of the entire simulation effort is suspect.

Validation of the simulator is the final step in the simulation process. The simulator should contain the same problems, response characteristics, intersystem relationships, and generate similar results as the system being modeled. Evaluation of the simulator requires development of confidence intervals for solutions. Since crop simulators typically provide yield per acre as a solution, the model can be validated by examining the descriptive statistics between results of the model and results of the system for an established parameter set.

The simulator in Figure 1 has several dramatic differences compared to typical firm simulators. Yield, the output of crop simulators, is one of the basic inputs or initial processes in most firm simulators. At the most, the effect of environmental production variables in firm simulators is reflected in output being a random variable in the simulation. Unlike firm simulators, the relationships reflected in biophysical simulators are largely outside the scientific expertise of agricultural economics. While the general expertise of agricultural economists in systems analysis can contribute to building such a simulator, agricultural economists are largely users rather than designers and/or implementors of the simulators. Potential users should be aware of this difference. Use of simulation involves combining economic components with the output. As part of this use, agricultural economists will be concerned with validation for their particular problem interest. Recently, agricultural economists have become more concerned with validation particularly for firm models (McCarl and Nelson; Hanson and Eidman). While this

[1] Brosen et al. present a detailed flow chart for a stocker cattle simulator.



issue will be further discussed in the next section, biophysical simulators are much easier to validate than firm models because they are not concerned with human behavior. Brorsen et al. and Boggess et al. include excellent discussions of validation of their simulators.

CURRENT USE OF BIOPHYSICAL SIMULATORS

As preparation for this paper, a survey was distributed to participants in S-180, which is a regional research project on firm risk management that began January 1, 1983. The project is national in scope with 28 institutions and 54 scientists participating. All sections of the country, except the Northeast, are well represented on the Technical Committee. While the survey is not a random sample of the agricultural economics profession, it does provide some information on characteristics of the simulators currently being used in the profession. This section summarizes the results of the survey. Tew and Musser provide more details concerning results of the survey.

The survey involved a mail questionnaire concerning use of biophysical simulators and some basic questions concerning development and characteristics of the simulators for users. A total of 24 responses, representing all regions of the country included in S-180, were received. In some cases, project participants who were not using these simulators had colleague users complete the questionnaire. Fourteen respondents indicated past or current use of biophysical simulation. Given the number of questionnaires mailed, this response indicated considerable current use of this methodology. The respondents typically have used this type of simulator for less than 5 years; however, one individual has been using biophysical simulation for approximately 15 years. Simulators are currently used in research, extension, and teaching activities although research applications account for 85 percent of the current usage.

Responses indicated that Southern institutions are heavily committed to this effort. With the South defined as the states of the Confederacy plus Kentucky and Oklahoma, a plurality of responses came from this region. Furthermore, the majority of the simulators in use were developed at Mississippi State and Oklahoma State Universities. Several other institutions, especially Florida, are now active in development of simulators; however, these two universities clearly dominated earlier efforts.

Irrigation is the most frequent research application although other production practices currently under investigation are fertilization rates, soil conservation management practices, integrated pest management, size of tillage equipment, and grain drying and storage. Enterprises being simulated include row crops, wheat, forage crops, fruits, hogs, and beef cattle. Corn, soybeans, grain sorghum, peanuts, and cotton are the row crops being studied. Forage simulators include alfalfa, clover, and various grasses. Apples and peaches are fruits being simulated. In addition, several simulators focus on soil erosion rather than commodities.

Models in the survey were usually initialized with a large number of physical parameters. General soil characteristics, seeding rates, tillage, and in the case of livestock simulators, weight gain variables were the more frequent parameters required for initialization. Stochastic data required includes precipitation, temperature, solar radiation among others; these data generally were from historical records with two exceptions which used probability distributions. Output of these simulators typically is yield per acre for the crop models, pounds of gain per acre for the livestock models, and topsoil loss in acre-inches or tons per acre for the soil erosion models.

Validation responses in the survey were very interesting. Approximately 50 percent of the simulators were validated through comparisons with field level and/or farm firm data while the others were validated with experimental data. Both sources of validation data have advantages which are well known to production economists. Experimental data oftentimes indicate higher response than available under farm conditions; however, farm data often are confined to a narrow range of input-output response that limits accuracy of the simulator outside this range.

A DIGRESSION OF RESEARCH METHODOLOGY

An understanding of the contribution of biophysical simulation to production economics is facilitated by a brief consideration of research methodology. A full review of the continuing dialogue concerning the subject is beyond the scope of this paper. However, an explicit treatment of the fundamental methodological views of the authors hopefully will facilitate understanding of various views on simulators. This section of the paper will sketch these views and briefly contrast them with other standard approaches.

Most of the standard paradigms have fundamental problems as a general approach to production economics. The behavioral theory of the firm is proposed as an alternative in this paper. The three main assumptions of this theory, which are familiar to most agricultural economists, include: (1) limited knowledge about goals or objectives and the relevant choice set, (2) limited cognitive ability of decisionmakers, and (3) and operational satisficing rather than maximizing objective (Simon). As a research paradigm, this theory has several implications. Most directly, additional information about the choice set and the relationship of the choice set to objectives are useful in decisionmaking. This information is implicit in most of the activities of agricultural economists and indicates the promise of this paradigm for production economics.

Another more controversial implication of the paradigm is that goals or objectives of individuals are so obtuse and complex that agricultural economics research on the structure of goals is unlikely to provide much useful information for decisions. In part, many of these goals are external to standard economic analysis even though economic decisions have consequences for these goals. Furthermore, specification of the correct goals for individuals seems to largely be outside the realm of scientific endeavor. Unless one accepts the normative views of Johnson, these goals have a personal, subjective basis and are not subject to verification. A corollary to this proposition is that prescriptive research is not very useful to decisionmakers. Prescriptive research confined to economic goals ignores other relevant goals while full specification of all goals is outside the expertise of agricultural economists and is impossible given the cognitive limits of decisionmakers. Former research on multiple goals, recently reviewed by Patrick and Kliebenstein, has made a methodological contribution in demonstrating that goals are complex but has limited usefulness for economic analysis of farm decisions. These conclusions about the usefulness of further research in this area contrast sharply with those of Ladd. While these differences may partially arise from different interpretations of the literature, they also reflect fundamental differences in basic paradigms, which will become clearer as this section is completely read.

The preceding view of the nature of goals or values does suggest that useful production economics information concerns the nature of the choice set and its relationship to quantifiable goals. The consistency of these views with positive methodology does not require endorsement of the extreme positive views recently rebutted by Groenewegan and Clayton. Positive analysis can include consideration of the relationships between values and the choice set as long as normal scientific standards of verification are utilized. These views appear to be consistent with the positions of Debertin.

Information on production must also be consistent with the limited information processing ability of decisionmakers. The satisficing objective is accommodated with partial analysis of decisions, which are not necessarily interrelated in a comprehensive framework. Following Friedman, the economic theory of the firm with its general equilibrium framework is useful in generating aggregate hypotheses but is inconsistent with individual decisionmaking. Even though partial analysis may abstract from some economic consequences, it is more likely to be clear and adaptable to particular decisions than complex comprehensive analyses. For example, the irrigation simulator discussed in the previous section abstracts from many inputs also important to crop production. If all factors of production were included, management implications for particular production situations would not be as apparent as the partial analysis. Comprehensive, large models can include so many details that adaptation to particular situations is impossible, especially for firm management. While these large models may be consistent with alternative methodological views, behavioral theory of the firm implies parsimonious analysis if it is to provide useful information for decisionmakers.

This implication is undoubtedly troublesome to most agricultural economists who have a commitment to the general equilibrium nature of modern economic theory. These individuals will not likely view biophysical simulations as having much promise because of their, current at least, limited decision variables—Lacewell and McGrann are an example. However, it must be stressed that the paradigm under consideration does not propose to identify *optimal* plans for firm managers. Rather, it proposes to provide information which most likely has qualitative value for farm managers. In reality, most production economics analysis is more consistent with this view than more comprehensive analyses since abstractions from the complete neoclassical theory almost always are present.[2]

A related reason for the limited scope of most empirical models is the limited resources including cognitive ability of agricultural economists. Comprehensive models are expensive to develop, evaluate, and interpret. As the scope of the model expands, less confidence can be placed in conceptual relationships and the parameter estimates simply because analytical effort must be spread over more and more items. Results from large models often cannot be interpreted; the senior author of this paper is on record in reference to this weakness in some of his earlier research (Musser, Martin, and Reid). Being unable to explain results from large models severely damages credibility with clientele of production economists.

Acceptance of the limited cognitive ability of agricultural economists is also likely to be controversial. However, several participants at a recent conference in firm modeling (Taylor, Miller, Reichelderfer, Miranowski, and Bradford) made related implications. Biophysical models may not be subject to the size limitations problem as much as purely economic models because the technical relationships may be more clearly defined and other scientists will be participating in the process. However, it is interesting to note that Mississippi State, which was a leader in developing the current generation of limited models, did have plans for very comprehensive models (Parvin and Tyner). The view that useful biophysical simulators will continue to have limited decision variables is at least a plausible working hypothesis.

The preceding discussion is not meant to imply that research work in production economics should revert to its empiricist roots. One of the mistakes that agricultural economists have made in adopting the neoclassical theory of the firm as the basis for production economics is that it was applied too literally. Since most of the theoretical constructs are measurable, the theory of the firm could be directly applied to firm production decisions even though it was inconsistent with the managerial process. A more appropriate use of the traditional theory of the firm would be similar to the use of the behavioral theory of the firm in this section—a conceptual framework and source of hypotheses concerning relationships in production economics. Even if models have limited frameworks, analysts must be aware of the potential weaknesses compared to comprehensive analysis. Finally, theory is particularly crucial if one remembers that agricultural economists also have cognitive limits.

PRODUCTION PROBLEMS FOR BIOPHYSICAL SIMULATION

Enterprises and input decisions utilizing biophysical simulations were summarized in a previous section. As with most economic problems, these applications have some similarities which make biophysical simulation a useful methodology. This section focuses on three general problem areas in production economics for which biophysical simulation has advantages: (1) organization of input-output data, (2) risk analysis, and (3) dynamic decisions.

Organization of Input-Output Data

Estimation of production functions has been an important activity of production economists

[2] The prominence of spline functions in recent research on fertilizer response (Perrin; Hall; Adams, Farris and Menkhaus) provides further support for the assumptions of unlimited input quantities in production economics models.

under the neoclassical theory of the firm paradigm. In 1948, Heady proposed emphasis on this activity as a crucial effort in implementing the neoclassical theory of the firm for farm management. Dillon and Woodworth have recently reviewed the empirical effort in this area. Despite the serious attention to empirical production functions, resource limits, including the rarely recognized limited ability of experimental scientists, precluded achievement of a fully estimated version of equation (1). Consistent with the paradigm outlined in the previous section, only a few decision variables and some environmental variables were included in the estimated equations. Environmental variables have been included on an ad-hoc basis to model differences in response to decision variables over space and time. Recently, firm production function estimation has received less emphasis. In response to this trend, Woodworth and Lacewell and McGrann have called for more research efforts to accommodate recent technological change. Thirty years of pursuing the goal of estimation of complete production functions of the firm raises a serious question about its ultimate achievement. A perennial problem with this goal is that experimental scientists do not cooperate in providing the data for production functions—Lacewell and McGrann (p. 70) note this problem. This claim is a perfect example of the pitfalls of using the neoclassical theory as a basic paradigm for production economics. Resource requirements, especially for management of the experiments, to provide rich enough data sets to estimate multi-input production functions under most relevant environmental conditions would be prohibitive. Given the limited resources for agricultural experiments, the continued pursuit of this goal will never be successful in providing the production information recent review articles claim is deficient.

Biophysical simulation provides an alternative method to represent the production process. On a conceptual level, a comprehensive simulator could be considered to represent a production function. However, the components of a simulation such as outlined in Figure 1 are concerned with biophysical processes which are realistic concerns to agricultural experimental scientists. Cooperation in representation of these processes is more consistent with the disciplinary interests of various agricultural scientists than estimation of a production function. Because production functions are such a fundamental component of economic theory, agricultural economists forget that such functions are not universal theoretical constructs in all disciplines. Simulators also have several operational advantages over estimation of production functions. The concept of simulation is much more flexible in terms of data requirements. While response functions are necessary for certain processes in the simulators, these functions frequently can be limited as to number of inputs, with different inputs being represented in different response functions. At least on a preliminary basis, different data sets or even synthesized estimates can be utilized for different processes. In addition, environmental influences are an explicit part of the model rather than being ad-hoc additions as in production functions. Therefore, capacity can be built into the model to allow evaluation of a wider range of environmental conditions than would normally be experienced under typical experimental conditions.

These conceptual and operational advantages provide a basis for improved interaction between agricultural economists and other agricultural scientists. Most fundamentally, the focus in simulation on components of production processes is consistent with the interests of other agricultural scientists. Summarizing existing data in simulators not only has utility for agricultural economists but also assists experimental scientists in identifying gaps in their research. The on-going process of building models, validation, respecification of the model and revalidation, provides a mutual reinforcing process, which should facilitate interdisciplinary cooperation. This spirit of cooperation does require that agricultural economists take a lower profile than in the past. Grandiose systems analysis schemes can be organized to give priority to the concerns of agricultural economists. For example, Parvin and Tyner suggested a systems organization for an agricultural experiment station with all research efforts flowing into a farm management model. Besides being inconsistent with the behavioral paradigm, such an organization implicitly places the rest of the agricultural experiment station into an subsidary role to agricultural economics. Without mutual respect for professional interests, a spirit of cooperation will almost never arise.

Risk Analysis

The output of biophysical simulations can be utilized for most kinds of production economics analysis, in which input-output relationships are utilized. As Johnson and Rausser noted in reference to early production process simulators, linking the output of a biophysical simulator to an economic objective function provides the basis for economic analysis. One of the areas in which these simulations can make a major contribution is in risk analysis. This section reviews their potential contribution in this area.

Under standard theoretical formulations of risk analysis, information on the probability distribution of decision alternatives is a key component. Decision theorists advocate that subjective probability distributions be elicited from decisionmakers in order to implement risk analysis (Anderson, Dillon, and Hardaker; Bessler). However, this approach has not been widely utilized in agricultural economics. Recently, psychologists have begun to document that individuals have limited capacity to make sound statistical judgments so that eliciting subjective probability distributions only codifies existing limited information and makes no contribution to augmenting available information (Musser and Musser). Perhaps most agricultural economists intuitively recognized this limitation of elicitation.

Most previous risk research has used secondary data to generate information about probability distributions. As Young recognizes, this approach has the advantage of allowing agricultural economists to utilize their statistical knowledge in providing estimates of risk for producers. In production economics, most of these analyses utilize data collected by the U.S. Department of Agriculture. This approach has limited the scope of risk analyses since only prices and crop output data are available from this source. While experimental data sometimes can be utilized as a source of data on output, rarely is a particular experiment continued for a long enough period of time to provide satisfactory time series data. As a result, most previous risk analyses have abstracted from alternative input decisions and relatively neglected livestock production. Risk analyses therefore have had not much broader problems of formulations than the pioneering study of Freund. Musser, Mapp, and Barry document this view in reference to risk programming models.

Biophysical simulation can make a contribution in this area because of the explicit modeling of the sources of risk in agricultural production. Crop growth simulators focus on the interaction between pests and/or weather and crop growth while the beef simulators focus on the interaction between forage and livestock growth. Many of the simulation studies reviewed in this paper have stochastic features as an integral component of the model. For example, the irrigation simulators have weather variables as fundamental components. A historical probability distribution of different irrigation strategies can be generated with time series data on weather which is readily available at most geographical sites. Not all the simulators have been stochastic. For example, Brorsen et al. utilized expected values of forage feed values, and Reichelderfer and Bender utilized nonstochastic insect population equations. The models presumably could be modified to accommodate time series data on forage and insects. Alternatively, the linkage between basic environmental variables and forage or insects could be modeled. Historical data on such variables as forage output and insect levels are often available in agricultural experiment stations when the output implications under particular management practices would not be. Creative use of available data sets in biophysical simulations can provide a potential for risk analysis of many neglected topics in production economics.

These simulated data have some advantages and disadvantages compared to historical data. With historical data, technological change provides a source of variation in output which must be separated from variations due to risk influences. The classic problem of detrending the data to accommodate this problem requires several assumptions, for which definitive methodology does not exist (Young). On the other hand, a simulated time series reflects the effects of stochastic environmental effects under a constant technology which precludes the need for detrending. Another advantage is that simulation does not require that historical production actually occurred or that production data were collected. For example, soybean yields could be simulated for weather patterns long before they were a major crop. Thus, a longer time series can often be simulated than would be historically available, particularly for new crops or production practices. On the other hand, simulated output usually will not reflect all the stochastic influences affecting output. For example, the output of irrigation simulators will not reflect stochastic influences of disease or insect problems. Variance of data from such simulators will undoubtedly understate the variance of farm level output. However, historical county level yields also understate farm level yield variance due to aggregation (Carter and Dean). Full representation of farm level probability distributions for risk analysis is an unrealistic goal. Risk analysis of simulated data does provide important information about the relative risk effects of different management practices.

The output of biophysical simulators has been used in several different forms for economic analysis. Some analyses have applied economic criteria directly to the simulated data—Boggess et al. summarized returns in a mean-variance framework while Boggess and Amerling and McGuckin used stochastic dominance. The output has also been used as input into firm risk models—Mapp and Eidman (1975) and Tew incorporated simulated data into firm simulation and mathematical programming models, respectively. Resolution of the appropriate economic model for analysis of simulated data is beyond the scope of this paper. The important point is that these data can be used in most, if not all, economic risk models. The appropriate economic model will depend on the research context.

Biological simulators have a large potential to enlarge the scope of analysis of risk in farm management. Another issue in production economics, for which the simulators appear to have a potential, concerns risk of environmental loadings. Previous research on non-point source pollution from agricultural production has been non-stochastic. If the level of loadings considered in this research is considered the mean level, other aspects of the probability distribution of loadings could be of concern to society. Environmental disasters may occur from infrequent rather than mean production conditions. Furthermore, management practices, which may be efficient in controlling mean loadings, may be inadequate for these rare events while other practices may preclude the disastrous events at not much more cost than those efficient for mean levels. The stochastic erosion simulators currently being utilized at several sites have a potential to investigate this important issue.

Dynamics of Agricultural Production

Dynamics is a term much used in agricultural economics in many different contexts. This paper utilizes some specific dynamic concepts which are defined and will follow. In the conventional theory of the firm under risk, the level of decision inputs are typically assumed to be non-stochastic since they are specified before the beginning of the production period (Dillon). However, a production period can be meaningfully divided into T time components, with decision inputs and noncontrollable inputs having a value for each component. Under these assumptions, equation (1) can be rewritten as follows:

$$(2) \qquad Y = f(X_{1t}, X_{2t}, \ldots X_{nt}; X_{n+1}, \ldots X_k; X_{(k+1)t}, \ldots X_{mt})$$

where X_{it} is a Tx1 vector, $t=1,2, \ldots T$. For decision variables, X_{it} would only have positive entries for the periods in which inputs can be made. Under standard assumptions, the input vectors would be fully specified before the production process. However, dynamic input decisions would involve allowing the decision inputs to be stochastic; the level of X_{it} is determined at time t based on levels of all decision and uncontrollable variables in $t=1,2, \ldots t-1$. Dynamic optimization techniques (Intriligator) are concerned with similar problems, and our concept of dynamics would be consistent with such techniques.

The production problem in equation (2) is a more realistic formulation of many production problems, such as irrigation and pest control. The classic advantage of simulation in multiperiod analysis is reflected in the concentration of biophysical simulators in these areas where input decisions are stochastic and dynamic. Most of the research applications of these simulations are consistent with this dynamic formulation. The consequences of using information on levels of uncontrollable inputs to set levels of decision inputs throughout the production period on level of output are a central focus of the research. However, the economic analysis is consistent with standard static analysis under risk in that Y and X_i are the subjects of the economic analysis. Harris and Mapp is an exception in their use of biophysical simulation in a dynamic optimization framework.

These dynamic features of production simulators have particular potential in extension activities. This use concentrates on the probable consequences of particular decisions at time t based on observed values in $t=1, \ldots, t$ and historical probabilities in periods $(t+1) \ldots T$. Such an approach would provide valuable ongoing information for current production decisions throughout the production period. The increase in availability of microcomputers in county extension offices and in individual farm businesses make this an increasingly feasible extension activity. Alteration of simulators to accommodate this function is already underway among the extension activities reported in the survey. As the profession gains more experience with biophysical simulation, more activity in this direction is likely. Complex, multiple input simulators may be incompatible with many microcomputer systems, which reinforces the methodological observations made early in the paper.

CONCLUSIONS

Biophysical simulation is a relatively new methodology in agricultural economics; both the research literature and the survey summarized in this paper indicate that the use of these models is accelerating in production economics. The primary use of this methodology is to provide input-output data when dynamic risky input decisions are prevalent. For these general classes of production problems, simulators have definite advantages over traditional production functions and other sources of data. Johnson and Rausser noted that most simulation models deal with non-continuous, dynamic, risky problems. Uses and advantages of biophysical simulation are consistent with these general methodological advantages of simulation.

While this paper has stressed the advantages of biophysical simulation in production economics, it must be stressed that this methodology is not a panacea for all empirical production problems. Like all generally accepted methodologies in production economics, biophysical simulation is useful for some, but not all, problem situations. In general, agricultural economists have a penchant for advocating particular empirical methods as being the best methodology for all research. We do not wish to make these claims for this methodology. However, biophysical simulation definitely warrants inclusion among the methods currently being used.

Several major disadvantages of biophysical simulation can be stressed. Because of the explicit modeling of biophysical processes, cooperation of other agricultural scientists with production economists is essential for their development and use in particular problem contexts. This cooperation may be better received for biophysical simulation than for other methodologies in production economics. However, users must ascertain the possibility of multidisciplinary cooperation for each particular situation. Another potential disadvantage of biophysical simulation, at least with current models, is that many decision and uncontrollable inputs are predetermined. While reasoning to support this characteristic has been presented, many agricultural economists will probably find this a major disadvantage.

A final comment concerns the behavioral theory of the firm as a overall research paradigm for production economics. This paradigm does seem to be consistent with most production economics research and extension activities and does support the value of current forms of biophysical simulation. More exploration of its appropriateness as a paradigm appears warranted. Psychological research on cognitive processes has made great strides since the behavioral theory was first advanced (Musser and Musser). Some of this research may be helpful in formulation of economic information of particular relevance for agricultural economics clientele.

REFERENCES

Adams, R. M., P. J. Farris, and D. J. Menkhaus. "Response Functions and the Value of Soil Test Information: The Case of Sugar Beets." *No. Cen. J. Agr. Econ.* 5(2)(1983):77-82.

Anderson, Jock R., John J. Dillon and Brian Hardaker. *Agricultural Decision Analysis.* Ames, Iowa: Iowa State University Press, 1977.

Bessler, David A. "Subjective Probability." *Risk Management in Agriculture,* Peter J. Barry, editor. Ames: Iowa State University Press, forthcoming.

Boggess, W. G., and C. B. Amerling. "A Bioeconomic Simulation Analysis of Irrigation Investments." *So. J. Agr. Econ.* 15(2)(1983):85-92.

Boggess, W. G., G. D. Lynne, J. W. Jones, and D. P. Swaney. "Risk-Return Assessment of Irrigation Decisions in Humid Regions." *So. J. Agr. Econ.* 15(1)(1983):135-144.

Bradford, Garnett L. "Optimizing Models: Some Observations and Opinions on the State of Progress." *Modeling Farm Decisions for Policy Analysis,* Kenneth H. Baum and Lyle P. Schertz, editors. Boulder: Westview Press, 1983, pp. 358-63.

Brorsen, W. Wade, Odell L. Walker, Gerald W. Horn, and Ted R. Nelson. "A Stocker Cattle Growth Simulation Model." *So. J. Agr. Econ.* 15(1)(1983):97-102.

Carter, H. O., and G. W. Dean. "Income, Price and Yield Variability for Principal California Crops and Cropping Systems." *Hilgardia* 30(1960):175-218.

Debertin, David L. "Discussion: Value Judgments and Efficiency in Publicly Supported Research." *So. J. Agr. Econ.* 15(1)(1983):9-10.

Dillon, John L. *The Analysis of Response in Crop and Livestock Production,* Second edition. Elmsford, N.Y.: Pergamon International Press, 1977.

Feddes, R. A., P. J. Kowalik, and H. Zaradny. *Simulation of Field Water Use and Crop Yield.* Wageningen, Netherlands: Pudoc Publishing, 1978.

Friedman, Milton. *Essays in Positive Economics.* Chicago: University of Chicago Press, 1953.

Groenewegen, John R., and Kenneth C. Clayton. "Agricultural Price Supports and Cost of Production: Reply." *Am. J. Agr. Econ.* 65(1983):626-8.

Hall, Harry H. "Economic Evaluation of Crop Response to Lime." *Amer. J. Agr. Econ.* 65(1983):811-17.

Hanson, Gregory D., and Vernon R. Eidman. "Farm Size Evaluation in the E1 Paso Valley: Comment." *Amer. J. Agr. Econ.* 65(1983):340-3.

Harris, Thomas R., and Harry P. Mapp, Jr. "A Control Theory Approach to Optimal Irrigation Scheduling in the Oklahoma Panhandle." *So. J. Agr. Econ.* 12(1)(1983):165-72.

Heady, Earl O. "Elementary Models in Farm Production Economics Research." *J. Farm Econ.* 30(1948):201-25.

Intriligator, Michael D. *Mathematical Optimization and Economic Theory.* Englewood Cliffs: Prentice-Hall, Inc., 1971.

Johnson, Glenn L. "Agro-Ethics: Extension, Research and Teaching." *So. J. Agr. Econ.* 14(1)(1982):1-10.

Johnson, S. R., and G. C. Rausser. "Systems Analysis and Simulation: A Survey of Applications in Agricultural and Resource Economics." *A Survey of Agricultural Economics Literature,* Vol. 2, G. G. Judge et al., editors. Minneapolis: University of Minnesota Press, 1977, pp. 157-301.

Lacewell, Ronald D., and James M. McGrann. "Research and Extension Issues in Production Economics." *So. J. Agr. Econ.* 14(1)(1982):65-74.

Ladd, George W. "Value Judgments and Efficiency in Publicly Supported Research." *So. J. Agr. Econ.* 15(1)(1983):1-8.

Mapp, Harry P., Jr., and Vernon R. Eidman. "A Bioeconomic Simulation Analysis of Regulating Groundwater Irrigation." *Amer. J. Agr. Econ.* 58(1976):391-402.

Mapp, Harry P., Jr., and Vernon R. Eidman. "Simulation of Soil Water-Crop Yield Systems: The Potential for Economic Analysis." *So. J. Agr. Econ.* 7(1975):47-53.

McCarl, Bruce A., and A. Gene Nelson. "Model Validation: An Overview With Some Emphasis on Risk Models." *Risk Management Strategies for Agricultural Production Firms: Perspectives and Research issues.* Okla. St. Univ., Dept. of Agr. Econ. AE-8350, May 1983, pp. 80-106.

McGuckin, Tom. "Alfalfa Management Strategies for a Wisconsin Dairy Farm: An Application of Stochastic Dominance." *No. Cen. J. Agr. Econ.* 5(1983):43-50.

Miller, Thomas A. "Understanding and Human Capital as Outputs of the Modeling Process." *Modeling Farm Decisions for Policy Analysis,* Kenneth H. Baum and Lyle P. Schertz, editors. Boulder: Westview Press, 1983, p. 91-5.)

Miranowski, John A. "Micromodeling: A Systems Approach at the National Level." *Modeling Farm Decisions for Policy Analysis,* Kenneth H. Baum and Lyle P. Schertz, editors. Boulder: Westview Press, 1983, p. 286-8.

Musser, Wesley N., Harry P. Mapp, Jr., and Peter J. Barry. "Applications II: Risk Programming." *Risk Management in Agriculture,* Peter J. Barry, editor. Ames: Iowa State University Press, forthcoming.

Musser, Wesley N., Neil R. Martin, Jr., and Donald W. Reid. "A Polyperiodic Firm Model of Swine Enterprises." *Modeling Farm Decisions for Policy Analysis,* Kenneth H. Baum and Lyle P. Schertz, editors. Boulder: Westview Press, 1983, p. 289-309.

Musser, Wesley N., and Lynn Mather Musser. "Psychological Perspectives on Risk Analysis." *Risk Management in Agriculture,* Peter J. Barry, editor. Ames: Iowa State University Press, forthcoming.

Parvin, D. W., Jr., and Fred H. Tyner. "The Systems Approach—Research or Research Management?" *So. J. Agr. Econ.* 6(1974):57-66.

Patrick, G. F., and J. B. Kliebenstein. *Multiple Goals in Farm Firm Decision-Making: A Social Science Perspective.* Purdue Ag. Exp. Sta. Bul. 306, Dec., 1980.

Perrin, R. K. "The Value of Information and the Value of Theoretical Models in Crop Response Research." *Amer. J. Agr. Econ.* 58(1976):54-61.

Reichelderfer, Katherine H. "Positive Farm Models: A Comment on Aesthetic Versus Functional Value." *Modeling Farm Decisions for Policy Analysis,* Kenneth H. Baum and Lyle P. Schertz, editors. Boulder: Westview Press, 1983, p. 281-5.

Reichelderfer, Katherine H., and Filmore E. Bender. "Application of a Simulative Approach to Evaluating Alternative Methods for the Control of Agricultural Pests." *Amer. J. Agr. Econ.* 61(1979):258-67.

Simon, Herbert A. *Models of Man: Social and Rational.* New York: John Wiley & Sons, Inc., 1957.

Taylor, C. Robert. "Complimentarities Between Micro- and Macro-Systems Simulation and Analysis." *Modeling Farm Decisions for Policy Analysis,* Kenneth H. Baum and Lyle P. Schertz, editors. Boulder: Westview Press, 1983, p. 63-72.

Tew, Bernard V. "An Expected Value-Variance Analysis of Alternative Production Systems: A Study of Irrigation Schedules in the Georgia Coastal Plain." University of Georgia, Unpublished Ph.D. dissertation, In process.

Tew, Bernard V., and Wesley N. Musser. *A Survey of Use of Biophysical Simulation in Agricultural Economics.* University of Georgia, Dept. of Agr. Econ. Faculty Ser., In process.

Woodworth, Roger C. "Agricultural Production Function Studies." *A Survey of Agricultural Economics Literature,* Vol. 2, George G. Judge, et al., editors. Minneapolis: University of Minnesota Press, 1977, p. 128-54.

Young, Douglas L. "Risk Concepts and Measures for Decision Analysis." *Risk Management in Agriculture,* Peter J. Barry, editor. Ames: Iowa State University Press, forthcoming.