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Mathematical Models in Farm Planning: A Survey

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MATHEMATICAL MODELS IN FARM PLANNING: A SURVEY

JOHN J. GLEN

University of Edinburgh, Edinburgh, Scotland

Farm planning has increased in complexity and importance as agriculture in the developed world has become concentrated in larger, more specialized farm units. These changes have stimulated the development of formal planning techniques based on mathematical models. Although this approach is characteristic of operations research, the profession's direct involvement in agricultural planning has been limited: much of the published work is associated with agricultural economics. In this paper, we provide an OR-oriented introduction to the problems involved in agricultural planning, particularly at the farm level. We describe the planning problems of both the crop and livestock sectors and outline the models that have been proposed for solving these problems. Researchers, and agricultural extension and advisory services, have been the main users of these models, but the widespread availability of microcomputers gives considerable scope for developing models for use by farmers.

Modern agricultural systems have evolved largely as a result of advances in technology and the associated development of, for example, agricultural equipment, fertilizers, pesticides, new plant varieties and livestock with improved genetic potential. Since many of the new technologies are capital intensive— for example, agricultural machinery and environmentally controlled livestock housing—the adoption of many of the new production systems has been accompanied by an increase in the scale and degree of specialization of farm operations. In the developed world agricultural production has therefore become concentrated in larger, more specialized units, and as a result, farm planning has increased in complexity and importance.

Traditionally, judgment based on experience has been the basis for planning in agriculture, but increased specialization and the adoption of capital-intensive production systems have stimulated the development of more formal planning methods based on the construction and analysis of a mathematical model. Once a solution to the model has been derived and tested, the solution can be implemented and its performance monitored and controlled. Although this approach has been identified as the operations research (OR) approach, much of the published work that utilizes it is associated with agricultural econom-

ics. The contribution of OR to agricultural planning has been largely indirect. One of the objectives of this paper is therefore to provide an OR-oriented introduction to the problems involved in agricultural planning, particularly at the farm level.

In the agricultural sector, analysts have developed models at the farm, regional and national level, as well as for closely related areas such as forestry and food processing. However, to allow more detailed discussion, this survey mainly focuses on farm level problems in the developed world. Farm level planning usually involves financial objectives such as profit maximization, although other factors—for example, peer group standing (Gasson 1973), or a relatively stable level of income (Barnard and Nix 1973)—are also relevant. Even when farmers are strongly profit-motivated, models need to consider personal idiosyncracies, such as a preference for crop production (Arnold and Bennet 1975). However, financial objectives are commonly used in farm planning, with the range of possible solutions being limited to reflect nonfinancial objectives through, for example, restrictions on the crops that can be grown. Since many of the problems at farm level relate to either crop or livestock production, we consider these two aspects separately. This paper outlines the problems in these two sectors and discusses the models that have been

proposed for these problems. Tables I and II summarize the main features of selected models in each of these two sectors.

1. Crop Production Models

Crop production methods depend on crop type but generally involve a sequence of seasonal operations. In planning crop production, farmers must consider the seasonal nature of the operations and the associated equipment and labor requirements; harvesting requires particular attention because most crops must be harvested during relatively short periods. Crop yield at harvesting depends on weather conditions and the effect of pests and diseases. The use of fertilizers to improve the nutrient supply, and chemicals to control pests and diseases, can reduce the variation in crop yield. Since crop nutrient requirements can generally be specified in advance, the fertilizer application policy can often be determined at the planning stage. However, pest and disease control strategies are more difficult to evaluate since they involve the interaction of complex biological processes and uncertain weather conditions.

We divide our discussion of crop production models into four sections:

(i) the determination of cropping policy;
(ii) methods for planning harvesting operations;
(iii) techniques for evaluating capital investments; and
(iv) methods for evaluating pest and disease control strategies.

We begin by considering cropping policy since it is of fundamental importance in crop production.

Cropping Policy

Planning crop production involves determining the crops to be grown, the area to be used for each crop, the fertilizer application policy and the crop rotation policy. A number of techniques have been used to plan crop production while accounting for known operational constraints. Mathematical programming models have been widely used in this area since Heady (1954) illustrated the use of a simple linear programming (LP) model to determine the allocation of arable land to two crops (Nix 1979). LP models that are more realistic than Heady's model have been used as the basis of crop planning systems. McCarl and Nuthall (1982) suggest that, if an LP-based planning system is to be used by nonspecialist staff, the system should include both a matrix generator and a report writer (see, for example, Bond, Carter and Crozier 1970; and McCarl et al. 1978), although standard matrices of typical farms have also been used to reduce data collection (for example, James 1972).

Most LP-based crop planning models involve maximizing a profit function subject to limitations on resources and other requirements such as crop rotation. Farmers motivated by other factors could account for their objectives in a goal programming model, i.e., an LP model whose objective function represents the overall weighted level of over- or under-achievement of goals (see Romero and Rehman 1984), but it can be difficult to determine the weights to attach to the goals (Barnett, Blake and McCarl 1982).

Table I
Selected Crop Production Models

Authors	Issues Addressed	Methodology	Remarks
Amir, Arnold and Bilanski (1978)	Machinery selection for hay production	Mixed integer programming	Binary variable for each set of machinery.
Audsley and Boyce (1974)	Grain harvesting and drying	Enumeration	Uses cost model to evaluate systems.
Audsley, Dumont and Boyce (1978)	Cropping policy/harvest timing	LP	Uses continuous variables for equipment: obtains integer solution by rounding.
Babcock et al. (1984)	Fertilizer blending and use	LP	Separate LP for each blending option.
Barry (1972)	Farm expansion by land purchase	LP	Considers each investment option separately.
Bates, Rayner and Custance (1979)	Farm machinery replacement	Simulation	Analysis incorporates influence of inflation and tax allowances.
Bond, Carter and Crozier (1970)	Farm land use	LP	Planning system for advisory work.
Boyce and Rutherford (1972)	Combine-harvester selection	Enumeration	Cost model based on average daily use.

Table I—*Continued*
Selected Crop Production Models

Authors	Issues Addressed	Methodology	Remarks
Brown, McClendon and Jones (1979)	Pesticide use in cotton crop	Simulation	Includes interactions between crop, pests and insect predators of the pests.
Brown and Schoney (1985)	Machinery size for grain farms	Spreadsheet	Microcomputer based iterative approach: ignores taxation and inflation.
Burt and Allison (1963)	Crop rotation	Stochastic DP	Decisions—plant wheat or leave fallow.
Carlson (1970)	Disease control	Decision theory	Illustrates use of subjective probabilities in Bayesian approach.
Carter, Dixon and Rabbinge (1982)	Forecasting aphid outbreaks	Simulation	Ignores effect of natural enemies.
Cocks (1968)	Crop yield uncertainty	Stochastic LP	Demonstration application in farming.
Conway et al. (1975)	Pest control in sugar cane crop	Deterministic DP	Examines spraying strategies to control a pest with four generations per year.
Corrie and Boyce (1972)	Cauliflower harvesting	Deterministic DP	Crop harvested selectively, with value of cauliflower head varying with time.
Crabtree (1981)	Equipment replacement	Enumeration	Includes inflation and tax allowances.
Dalton (1971)	Grain harvesting equipment requirements	Simulation	Considers different farm sizes and equipment combinations.
Danok, McCarl and White (1978)	Machinery selection and crop planning	Mixed integer programming	Integer variables for numbers of each type of machine purchased.
Danok, McCarl and White (1980)	Machinery selection and crop planning	Mixed integer programming	Binary variable for each set of machinery: examines effect of weather variability.
Donaldson (1968)	Harvesting capacity	Simulation	Early application of simulation in assessing harvesting capacity.
Fisher and Lee (1981)	Disease and weed control	Deterministic DP	Decisions—cropping policy and herbicide use.
Fokkens and Puylaert (1981)	Daily harvest operations	LP	Uses simulation to determine harvest capacity to use in the LP model.
Godden and Helyar (1980)	Fertilizer carryover	Heuristics	Number of simplifying assumptions: results generally non-optimal.
Hall and Norgaard (1973)	Pesticide use	Marginal analysis	Only one pest and one application of pesticide.
Hazell (1971)	Mean and variance in returns	Portfolio theory	Large data requirement: limited practical value to farmers.
Heady (1954)	Land use for two crops	LP	Simple demonstration model.
James (1972)	Farm land use	LP	Operated by advisory service.
Kennedy et al. (1973)	Fertilizer carryover	Deterministic DP	Residual fertilizer proportional to availability at start of period.
Krutz, Combs and Parsons (1980)	Equipment evaluation	LP	Uses crop planning LP model to evaluate specified sets of equipment.
Maruyama (1972)	Yield and price uncertainty	Stochastic LP	Difficult to estimate coefficients.
McCarl et al. (1978)	Grain farm land use	LP	Integrated planning system with matrix generator and report writer.
Miyake et al. (1979)	Tobacco harvesting	Stochastic DP	Used to determine harvesting start date and decision rules for hiring labor.
Morey (1979)	Grain drying methods	Simulation	Examines system capacity and heat use.
Morey, Peart and Zachariah (1972)	Corn and soybean harvest scheduling	Stochastic DP	Weather a stochastic element affecting harvest rate.
Mumford (1981)	Pest control	Decision tree	Illustrates decision tree approach.

Table I—*Continued*
Selected Crop Production Models

Authors	Issues Addressed	Methodology	Remarks
Philips and O'Callaghan (1974)	Machine use/harvesting capacity	Simulation	Simulates harvesting using recorded hourly weather data.
Pleban, Labadie and Heermann (1983)	Irrigation scheduling	Mixed integer programming	Includes location factors in order to irrigate adjacent fields sequentially.
Rae (1971a, b)	Variability in crop yields	Stochastic LP	Extends Cocks' model (1968): model may be very large.
Reichelderfer and Bender (1979)	Pest control strategies in soybean crop	Simulation	Simulates crop growth and pest population development: examines chemical and biological pest control strategies.
Reid, Musser and Martin (1980)	Farm growth	LP	Integer variables should be used for investment decisions.
Rijsdijk (1982)	Pest and disease control	Decision support system	Uses data from regular crop observations to make recommendations for action.
Ryan (1973)	Cereal harvesting systems	Simulation	Simple model using limited weather data.
Sanders and Lalor (1972)	Harvesting equipment capacity	Inventory theory	Regards harvesting capacity as inventory: ignores discrete nature of equipment.
Scott and Baker (1972)	Risk and minimum income	Portfolio theory	Difficult-to-interpret results.
Shoemaker (1979)	Integrated pest control strategies in alfalfa crop	Deterministic DP	Pest population a function of initial pest and parasite populations, time of harvest and insecticide use.
Shoemaker (1982)	Integrated pest control strategies in alfalfa crop	Stochastic DP	Includes pest population age structure and weather uncertainty in model for pest with one generation per year.
Stauber, Burt and Linse (1975)	Fertilizer policy	Stochastic DP	Models fertilizer carryover as (S, s) inventory control problem.
Stoecker, Seidmann and Lloyd (1985)	Aquifer depletion	LP, DP	Uses LP to determine one-year policy; uses results in multi-year DP model.
Swaney et al. (1983)	Irrigation policy	Simulation	Policies—irrigate immediately or wait a specified number of days.
Talpaz et al. (1978)	Pest control in cotton crop	Simulation	Considers only one pest—the boll weevil: ignores effect of other pests.
Taylor and Burt (1984)	Weed control in spring wheat	Stochastic DP	Decomposes problem because of number of state variables, but results may not be optimal.
Teng, Blackie and Close (1977)	Disease control in barley	Simulation	Outlines model of barley leaf rust epidemic and problems of validation.
Trava, Heermann and Labadie (1977)	Irrigation scheduling	Mixed integer programming	Uses binary variables for field irrigation decisions.
Webster (1977)	Pesticide use	Decision theory	Determines utility maximizing strategy, but requires farmer's utility function.
Whan, Scott and Jefferson (1976, 1978)	Sugar cane crop rotation	Markov process	Considers only long-run steady state.
Wheeler and Russell (1977)	Farm land use	Goal programming	Generates a range of plans for further investigation, e.g., by LP.
Yang and Sowell (1981)	Tobacco harvesting	Integer programming	Includes integer variables for number of barns used each day for tobacco curing.
Yaron and Dinar (1982)	Irrigation scheduling	LP, DP	Uses shadow prices from LP model in DP model, but ignores range of validity of shadow prices.

A further disadvantage of the goal programming approach is the limitations it imposes on post-optimal analysis, although Wheeler and Russell (1977) argue that goal programming could be used to generate a range of plans that merit investigation in greater depth using LP.

Several researchers have suggested mathematical programming methods that incorporate uncertainty in planning crop production. For example, Cocks (1968), in a stochastic LP model, represented all possible outcomes in crop production by their probabilities of occurrence. Rae (1971a,b) extended this model to accommodate forecasts and different types of utility function, but this model—like the stochastic LP model of Maruyama (1972) which incorporated uncertainty in the objective function, the constraints and the input-output coefficients—is very large in comparison with the deterministic model. Portfolio theory (Markowitz 1959) has also been used to provide a framework for analyzing agricultural decisions under uncertainty, with quadratic programming being used to determine the set of E-V efficient decisions, i.e., the set of decisions that maximize expected return for a specified variance. Hazell (1971) suggested minimizing mean absolute income deviation as a linear alternative to the quadratic programming approach, but in both these approaches and in extensions involving, for example, lower income bounds (Scott and Baker 1972) it is difficult to relate the results to the decision making behavior of individuals. Other researchers, (for example, McInerney 1969, Hazell 1970) have used game theory models solved by LP (for example, McInerney 1967) to deal with uncertainty in farm planning, but again it is difficult to relate the results to practical decision making.

Mathematical programming models that incorporate uncertainty require more computational effort and are more difficult to interpret than the corresponding deterministic model. Brink and McCarl (1978) examined the decision making behavior of farmers who had been using a stochastic LP model and concluded that the benefits from incorporating risk in the model were small. However, the results from a deterministic crop-planning LP model can be of considerable value to the farmer. Debertin et al. (1981) found that farmers were influenced by the results from deterministic LP models, but noted that the main benefits arose from improved understanding of the interactions within a farm business.

Deterministic and stochastic dynamic programming (DP) models have provided another approach for evaluating cropping policy. For example, Burt and Allison (1963) used a stochastic DP model, with soil moisture content as the state variable, to determine the crop rotation system in the dry farming regions of the United States. Fisher and Lee (1981) developed a deterministic DP model to determine the crop rotation policy for disease and weed control in an Australian wheat crop, using soil moisture content, disease level and weed population as the state variables. Although these researchers did not account for the stochastic nature of these variables, an important consequence of this work was that it initiated studies to gather the information required for developing this type of model. Taylor and Burt (1984) extended this approach to incorporate stochastic elements by decomposing the problem into three separate DP problems, but the validity of the approach is unclear.

Researchers have also suggested other approaches for evaluating crop rotation policy. For example, Whan, Scott and Jefferson (1976) used a Markov model to determine crop rotation policy in sugar cane production. In a later paper (1978), the same authors extended this model to include crop quality as a stochastic element and then used linear programming to determine the long-run, steady-state policy. However, since individual producers are influenced by market price expectations, this long-run solution is likely to be of limited value in dealing with a crop subject to wide price fluctuations.

The policy for fertilizer application should also be considered in planning crop production. Babcock et al. (1984) developed an LP-based approach for sourcing blending and application of commercial fertilizer mixtures to supply crop nutrient requirements at minimum cost. However, because the authors did not model all of the logical conditions for the interdependent blending and application costs, they considered each blending option as a separate LP model. Most crop planning LP models assume that fertilizers are used at some specified rate. They do not consider crop yield as a function of the amount and type of fertilizer applied, and ignore the effect of residual fertilizer from previous applications. Kennedy et al. (1973) developed a DP model that does account for residual fertilizer in evaluating a fertilizer application policy; they solved the model using an inductive procedure for the case in which the residual fertilizer in any period is proportional to the fertilizer available initially. In an alternative approach, Godden and Helyar (1980) assumed that fertilizer carryover was a simple function of the time since each application but, as noted by Kennedy (1981b), the solution obtained using the proposed heuristic method will generally not be optimal. In a DP model for evaluating fertilizer application policy, Stauber, Burt and Linse (1975)

considered both the cost of fertilizer application and the stochastic nature of fertilizer carryover.

In many parts of the world, crop production depends on irrigation. Trava, Heermann and Labadie (1977) developed a mixed-integer programming model for short-term irrigation scheduling, using Boolean variables to represent whether or not a particular field was to be irrigated on a particular day. Pleban, Labadie and Heermann (1983) modified this model to account for the savings associated with irrigating adjacent fields sequentially and applied this model using short term forecasts. For regions with stable weather conditions, Yaron and Dinar (1982) proposed an approach for evaluating the irrigation policy for an entire season. They first used an LP model to select from a set of specified irrigation scheduling activities defined in terms of the quantity of water and the time of use. Using the shadow prices from this LP model, they then used a DP model to determine a new irrigation scheduling activity to include in the LP model, and repeated the process of generating new activities until convergence occurred. There is, however, no guarantee that this approach will yield the optimal solution since the procedure does not consider the ranges of validity of the shadow prices. Swaney et al. (1983), among others, have also suggested simulation models to evaluate irrigation policies and account for some of the sources of uncertainty, but, clearly, these models can evaluate only a limited set of policies. In areas where irrigation water is pumped from an aquifer, aquifer depletion influences long-term cropping and irrigation policy. Stoecker, Seidmann and Lloyd (1985) examined this problem using an integrated LP and DP approach, assuming that all farmers using the aquifer adopt similar long-term policies.

As we have seen, researchers have suggested a number of different models for use in evaluating cropping policy. Many of the models are deterministic; although deterministic models can improve understanding of the operation of a farm business, the results must be reviewed in the light of known sources of uncertainty. Advisory and extension services appear to be the main users of crop planning models. Few of the models are designed for direct use by farmers, but the availability of microcomputers should encouarge the development of related planning tools for these potential users.

Harvesting Operations

Although the scheduling of harvesting operations is an important aspect of planning crop production, most crop planning models ignore the complexities of harvest scheduling. Since the harvesting capacity of a farm is limited, the whole crop cannot be harvested when it ripens and the scheduling of harvesting operations should consider timeliness costs, i.e., losses incurred if harvesting does not take place when the crop ripens. Uncertainty in weather conditions is another important consideration in harvest scheduling, since weather conditions affect both the ripening of the crop and the ability of the farmer to perform harvesting operations.

Because of the complexity of harvesting operations, the agricultural community has made wide use of simulation models to evaluate aspects of harvesting policy, such as harvesting capacity (e.g., Donaldson 1968), machine use policies (e.g., Ryan 1973, Philips and O'Callaghan 1974), and the start time of harvesting operations (e.g., Chen and Chi-Chen Yang 1980). The community has also developed mathematical programming models for scheduling harvesting operations. However, the LP framework has difficulty incorporating the relationship between crop value, weather conditions and time of harvesting. Many LP models that incorporate harvesting operations treat weather conditions as deterministic (e.g., Audsley, Dumont and Boyce 1978). Fokkens and Puylaert (1981), using forecast and historic weather data, developed an LP model for planning daily harvesting operations, having first used simulation to determine the harvesting capacity that minimized costs, including the cost of field losses. Van Elderen (1980) compared the use of simulation and LP models in scheduling harvesting operations using historical weather data. The schedule produced by LP had significantly lower (though not necessarily realizable) costs largely because the LP model incorporated weather data for an entire harvest season, whereas in practice it would be necessary to use forecast weather data.

Researchers have also developed a number of DP models for scheduling harvesting operations. For example, Morey, Peart and Zachariah (1972) proposed a stochastic DP model for scheduling corn and soybean harvesting. This model incorporated harvesting rate and weather conditions, defined in terms of the probability of working on any day, as its stochastic elements, but assumed harvesting rate to be independent of the probability of working. Miyake et al. (1979) investigated tobacco harvesting strategy using a DP model with weather as the stochastic element. The authors derived from historical data the probability of a day being suitable for harvesting, but it would be more appropriate to use short-term weather forecast data.

In cereal crops, the time at which harvesting can begin depends partly on the grain moisture content. By using grain driers, farmers can begin harvesting at a higher grain moisture content, which may enable harvesting equipment to be used more efficiently. Some researchers (see Sharp 1982) have used simulation models of the drying process to design drying equipment and to investigate operating policies. For example, Audsley and Boyce (1974) examined harvesting and drying strategies using a model of a high temperature grain drier, while Morey (1979) investigated operating policies for low temperature grain driers.

A number of crops are harvested in a series of selective harvests as the individual elements (e.g., fruit, vegetables) mature. The critical decisions in harvesting these crops are the timing of each selective harvest and the size or grade of individual elements to be harvested. A number of different models examined these decisions for various crops. For example, Corrie and Boyce (1972) used a deterministic DP model to investigate policies for harvesting cauliflower, a crop that matures over an extended period. Tobacco is also harvested as it matures and may then be put in barns for curing. Yang and Sowell (1981) used a mixed integer programming model to schedule tobacco harvesting operations of this type, using integer variables for the number of barns filled on any day. Both of these models are deterministic, and therefore cannot consider the effect of weather on crop maturation and harvesting. Chen, Sowell and Humphries (1976) included the effect of weather on harvesting in a stochastic simulation model used to evaluate multistage policies for harvesting cucumbers. However, no models appear to account for the influence of weather on both crop growth and harvesting.

The wide range of models developed for harvest scheduling reflect, in part, the fact that harvesting operations vary from crop to crop. Most crops must be harvested during a relatively short period of intensive activity, and techniques that aid the planning of such activities can be of substantial economic benefit. The use of models has made an important contribution to the design of equipment and the evaluation of harvesting systems, but apart from large-scale operations (see, for example, Fokkens and Puylaert), models do not appear to be widely used to plan the harvesting operations of individual farms.

Capital Investment for Crop Production

Crop production in the agriculturally developed world depends on capital investment, particularly in equipment. Although most cropping operations require equipment, major equipment investment tends to be associated with harvesting. Determining equipment requirements is an important aspect of farm planning, and since most types of equipment have a limited life, equipment replacement policies are also important.

Since many operations in crop production are machine dependent, models of cropping operations can also be used to evaluate equipment requirements. By changing the availability of equipment, simulation models of crop production (Donaldson; Dalton 1971; Ryan 1973; and Philips and O'Callaghan can evaluate specified set of equipment, but cannot consider either the method of achieving a desired set of equipment or the possibility of hiring equipment and/or subcontracting some operations. Crop-planning LP models can also evaluate equipment requirements by changing the equipment availability constraints (for example, Krutz, Combs and Parsons 1980). Some crop-planning LP models include equipment levels as variables, but the solution must be modified to allow for the discrete nature of equipment. For example, Audsley et al. rounded the solution to the nearest integer and re-solved the LP with the variable constrained to the integer value. However, this approach cannot consider scale economies, and the solution procedure will not guarantee an optimal solution.

Other approaches for evaluating equipment investment decisions also fail to consider scale economies and the discrete nature of equipment—for example, the simple cost-based model of Boyce and Rutherford (1972) and the stochastic inventory model of Sanders and Lalor (1972), in which harvesting capacity constitutes an inventory for which weather conditions indirectly create a demand. These limitations can be overcome by adopting an integer programming formulation in which integer variables represent each type of machine (e.g., Danok, McCarl and White 1978) or possible sets of equipment (e.g., Amir, Arnold and Bilanski 1978). Although these integer programming models are deterministic, they can be used to examine the influence of weather conditions on investment decisions. For example, Danok, McCarl and White (1980) ran a mixed integer programming model under different weather conditions, defined in terms of the number of field operating days, to find a set of machinery that performed well over a wide range of weather conditions. This analysis found a robust solution, but the associated set of equipment was not optimal under any particular weather conditions. This result illustrates the importance of performing sensitivity analysis on models of this type. However,

although integer programming provides a sound theoretical framework for evaluating equipment investment decisions, models of this type are more costly to construct and solve. Hence, although integer programming models may be valuable as research tools, they are not suitable, in their current form, for use by individual farmers since software for solving these models is not yet widely available.

Agricultural equipment deteriorates with age and use. Models for evaluating equipment replacement policies should account not only for machine performance but also for tax allowances (Chisholm 1974). Since tax allowances are generally based on historic costs, while inflation affects both the cost and the resale value of equipment, Bates, Rayner and Custance (1979) extended the model of Kay and Rister (1976) to incorporate inflation in determining the optimal replacement policy for farm equipment over an infinite time horizon. Crabtree (1981) took account of tax and inflation in evaluating machinery investment and noted that any analysis should also include savings arising from technological progress, although this quantity is difficult to forecast. However, one limitation of this approach is that it assumed that machinery must be replaced after a specified period.

Other models evaluate capital investment in facilities other than equipment. For example, Barry (1972) developed a multiperiod LP model for planning the expansion of a farm through the purchase of additional land in multiples of indivisible units of fixed area. However, an unsatisfactory feature of this model is that it assumed that land becomes available when required. Planning the long term development of a farm should also account for taxation factors. Reid, Musser and Martin (1980) outlined a method for incorporating U.S. investment tax credit in a multiperiod mathematical programming model for evaluating farm investment proposals. A more productive approach might have been to formulate the problem using integer variables, but there is no evidence that the authors did so.

As we have noted, a number of authors have proposed models for evaluating capital investment decisions in agriculture. However, as in the case of crop planning models, the use of most of these models is limited to research and advisory services. Individual farmers appear to use simple cost-based methods to evaluate equipment investment decisions. Extensions of these methods are available for use with spreadsheet software on microcomputers (e.g., Brown and Schoney 1985), but these methods generally fail to consider timeliness costs.

Pest and Disease Control

Pests and diseases can substantially reduce both the yield and the value of crops. As an insurance against crop damage, farmers often use chemical pesticides and fungicides for pest and disease control, partly because long-term control strategies are difficult to evaluate. The effects of pests or disease involve complex biological processes, and although the scientific community has conducted considerable research in applied ecology, Conway (1977) noted that only recently have analysts attempted to link ecological and economic factors through the use of mathematical models.

The effect of a pest on a crop depends on the dynamic interaction between biological factors (for example, the size and age structure of the pest population, the presence of predators and parasites, and the stage of development of the crop) and other factors such as weather conditions and the effectivess of any control agents. Investigations of pesticide application policy generally define the "economic threshold" as the pest population level at which a control action should be initiated. Hall and Norgaard (1973), in developing the work of Headley (1972), used marginal analysis to investigate the timing of a single pesticide application to control one pest in a crop. In practice, farmers frequently use multiple pesticide applications to control pests. Chatterjee (1973) developed a model that incorporated multiple pesticide applications, but he did not specify explicitly the functions used in this model. Talpaz and Borosh (1974) also developed a model that incorporated multiple pesticide applications, but they assumed that pesticide applications were equally spaced and that each application reduced the pest population to the same level as the previous application. Crop rotation is another strategy for controlling pests. Lazarus and Swanson (1983) extended the economic threshold concept to examine the use of insecticides and crop rotation in pest control. However, largely because of the nature of the model, it is difficult to estimate the values of some of its parameters.

Most pests exposed to pesticides over an extended period will develop some resistance to the pesticide, and thus the effectiveness of the pesticide will decrease with use. Hueth and Regev (1974) investigated the effect of decreasing pesticide effectiveness by using a model that considerably simplified several features, in particular, the nature of the pest's susceptibility to the pesticide. No pesticide is completely effective in controlling insect pests, and insects that survive can move from farm to farm. Regev, Gutierrez and Feder (1976)

used a simple model of a crop-pest system to examine the effects of pesticide application at both individual farm and regional levels but, because of the limitations of their approach they considered only the steady-state solution. Although the dynamic aspects of this problem have been modeled (see, for example, Lazarus and Dixon 1984), it is difficult to obtain the required data.

The major limitations of these models of crop-pest systems are that they do not consider weather conditions and the influence of predators, parasites and other pests. In some cases researchers have adopted these simplifications because the solution method (e.g., marginal analysis) was unable to cope with the complexities of the underlying biological processes. Since a simulation approach can overcome these difficulties, researchers developed simulation models for a wide range of crops and pests. These models should consider the development of both the crop and the pest population. Reichelderfer and Bender (1979) adopted this approach for a deterministic simulation model of the Mexican bean beetle in a soybean crop, although they ignored the effect of weather conditions on both the crop and pest.

Many pests have natural predators, but insecticides will affect both pests and predators. For example, in cotton crops the insecticide used to control the boll weevil also destroys insects that help to regulate other pests, principally the cotton bollworm and the tobacco budworm. The simulation model developed by Talpaz et al. (1978) did not consider these other pests. However, Brown, McClendon and Jones (1979) took account of these other two pests by interfacing a cotton growth model with a modified version of the boll weevil simulation model of Jones et al. (1977) and a model of the other two pests. Models of crop-pest systems are often of limited value in practice because they ignore the complex nature of the system—for example, the simulation model used by Carter, Dixon and Rabbinge (1982) in an attempt to develop simple rules for forecasting cereal aphid outbreaks. Comprehensive models of the type developed by Brown et al. are likely to be useful in investigating integrated pest control policies, that is, the use of a combination of chemical, cultural and biological control methods.

A simulation model for evaluating pest control strategies may impose a substantial computational load since each strategy requires a separate set of runs. An optimization approach can overcome this difficulty. For example, Conway et al. (1975) used a DP approach to investigate insecticide spraying strategies for controlling the sugar cane froghopper. These researchers modeled the population dynamics of this pest using

Leslie (1945) matrices—i.e., the model is essentially a Markov model: it considers crop damage as a function of pest population but ignores the influence of weather conditions. Shoemaker (1979) developed a deterministic DP model to evaluate integrated pest control policies for controlling the alfalfa weevil in an alfalfa crop under a specified weather pattern. In an extension of this work, the same author (1982) demonstrated the use of a stochastic DP model in control of the alfalfa weevil, the main stochastic element in this model being weather. Feldman and Curry (1982) noted that DP is a powerful technique for modeling pest-crop systems because it allows an optimization model to incorporate stochastic features, but they stressed the need to develop a theoretically sound framework for the evaluation of optimal pest control strategies.

In spite of the development of disease-resistant plant varieties, disease is still a major source of crop damage. Much of the work in modeling crop disease uses regression to relate yield losses to the observed level of the disease (see, for example, King 1976, Melville, Griffin and Jemmett 1976, and Mundy 1973), but does not consider causal factors. Some authors have proposed simulation models for evaluating crop disease control policies, although these models can be difficult to validate: the barley leaf rust simulation model of Teng, Blackie and Close (1977) is an example. To make additional progress, models for evaluating crop disease control should consider both crop growth and disease spread (Teng and Gaunt 1980) and incorporate causal factors such as the presence of a pathogen and the influence of weather. However, constructing models of this type requires the design of agronomic experiments to provide the information required (Anderson 1971).

Most models for evaluating pest and disease control strategies have been developed for use as research tools, although some could be adapted for use at the farm level, especially with the availability of cheap computing facilities. However, other approaches for evaluating crop protection strategies may be more suitable for use at farm level. For example, some farmers have used payoff matrices (e.g., Norton 1979), although this approach can consider only a limited number of outcomes, such as levels of attack. Other researchers have proposed decision theoretic approaches (see Carlson 1970, Webster 1977) but these models assume a knowledge of the utility function and require the assessment of subjective probabilities. Mumford (1981) proposed a simple decision tree approach for controlling pests in sugar beet. Cox (1981) argued that the use of a set of discrete pesticide

application rates is a weakness of this approach, but this criticism is not valid when these rates are prescribed by law.

The ultimate aim of model building in this area is to develop effective systems for controlling pests and diseases in crops. An example of the type of system that can be produced is EPIPRE, a computer-based pest and disease management system for wheat, developed initially for the Netherlands (Rijsdijk 1982). In this system the farmer makes regular observations of the crop. Data from these observations become inputs to the model of the crop system, which makes recommendations to the farmer concerning, for example, the use of pesticide and fungicide. The very limited information reported on the model has been encouraging. This system is at present mounted on a mainframe computer, but a microcomputer-based system for use by individual farmers is under development.

2. Livestock Production Models

Methods of livestock production range from traditional methods, based on foraging, to intensive methods that supply livestock with food. Intensive methods of livestock production have proven to be more efficient economically than traditional methods and have increased in importance in the developed world, but traditional livestock production systems have also become more effective as a result of advances in pasture management. The operations involved in livestock production depend on the type of livestock, the production system used and the nature of the product— for example, meat, eggs or milk. The provision of an adequate source of food, in the form of either foraging or feedstuffs supplied directly to the livestock, is of fundamental importance, but other operations such as breeding, livestock replacement and waste disposal may also have a significant impact on system performance.

Intensive operations must supply food to the livestock at all times, while pasture-based systems might supply food only at certain times—for example, during winter or during drought conditions. The formulation of feeds to meet specified nutrient requirements may therefore be an aspect of planning in both intensive and traditional production systems; we therefore first consider feed formulation methods. Because of the differences in production systems, we consider separately models for evaluating feeding policy in intensive operations and models for evaluating pasture-based systems. We then discuss methods used for planning livestock breeding and replacement

policies, and examine methods for evaluating waste disposal policies in intensive livestock operations. Finally, we consider methods for planning livestock production that account for the interactions with other farm activities such as crop production.

Table II summarizes the models that address these issues.

Diet Formulation

In the context of livestock feeding, a diet is defined by the proportions of constituent foodstuffs, while a ration is defined by the quantities of constituent foodstuffs. The formulation of least-cost diets of specified nutrient content by LP (see Dent and Casey 1967, and Beneke and Winterboer 1973) was one of the earliest uses of LP in agriculture. Initially, only extension services and feed mix companies used LP in diet formulation, but with the advent of microcomputers individual farmers now use this technique.

In the LP model of the least-cost diet formulation problem, the coefficients specifying the nutrient contents of feedstuffs are constants estimated from analysis of a large number of samples. However, since this LP approach ignores the variability in nutrient content, some least-cost diets will not meet the nutrient specification. Protein is often the limiting factor in livestock feeding. Van de Panne and Popp (1963) suggested a quadratic programming diet formulation model that incorporates protein content variability as measured by variance, while Rahman and Bender (1971) used a linear approximation of variance to enable the stochastic diet formulation model to be solved by linear programming. Although approaches that consider the variability in nutrient content are theoretically superior to the deterministic approach, the postoptimal analysis that can be performed with these models is limited. A deterministic model could account for the variability by including a safety allowance in the specification of the mix. The shadow prices from this model could be interpreted directly—for example, to provide information concerning the sensitivity of the diet to these allowances. However, models that treat the variability in nutrient content can be used to set safety allowances in a more rational way. For example, Chen (1973) used the quadratic programming model to determine the relationship between diet cost and the probability of meeting a feed specification.

Ration Formulation

The major limitation of least-cost diets for livestock feeding is that they do not consider livestock performance—for example, liveweight gain or milk yield. If

Table II
Selected Livestock Production Models

Authors	Issues Addressed	Methodology	Remarks
Ashour and Anderson (1975)	Development of beef feedlot operations	LP	Land used for growing feedstuffs and waste disposal: growth rate of cattle must be specified.
Ashraf and Christensen (1974)	Effect of water pollution regulations on dairy farm	LP	Permits land spreading of waste: model solved for each waste disposal system.
Blackie and Dent (1974)	Farm planning	Simulation	Develops 'skeleton' model of animal production and applies it to pig unit.
Blackie and Dent (1976)	Pig production strategies	Simulation	Simulation model part of information system.
Brokken (1971a, b)	Beef cattle ration formulation	Separable programming	Formulates rations to meet nutrient standards of NRC (e.g., NRC 1976).
Brokken et al. (1976)	Beef feedlot operating policy	Enumeration	Evaluates profit function for different diets and selling weights.
Brown and Chandler (1978)	Dairy cattle ration formulation	LP	Uses stepwise solution procedure because of method for representing milk yield.
Chen (1973)	Variability in diet formulation	Quadratic programming	Examines diet cost and probability of meeting diet specification.
Clark and Kumar (1978)	Beef cattle feeding and marketing	DP	Considers narrow range of policies: ignores timing of cash flow from sales.
Congleton and Goodwill (1980)	Cattle breeding policies	Simulation	Examines effect of mating policy on herd age structure: ignores feeding policy.
Coote, Haith and Zwerman (1976)	Waste disposal in dairy farm	LP	Evaluates specified waste management policies and environmental impact.
Crabtree (1977)	Pig feeding policy	Econometric analysis	Analyzes growth response and carcass quality, but considers feed intake and dietary protein separately.
Dean, Bath and Olayide (1969)	Dairy cattle feeding	LP	Piecewise linearization of nonlinear response of milk yield to energy intake.
Dent (1971)	Pig production policy	Simulation	Considers development of groups of pigs: pig-selling price stochastic.
Dodd, Lyons and Herlihy (1975)	Use of cattle waste as fertilizer	LP	Evaluates cattle manure as fertilizer in production of winter feed for cattle.
Fawcett, Whittemore and Rowland (1978a, b)	Pig feeding	LP	Formulates least-cost rations to produce weight gains of specified composition.
Forster (1975)	Effect of pollution control regulations on beef feedlots	Simulation	Uses data to estimate beef prices; price expectations dominate results.
Galbraith et al. (1980)	Grazing and stocking policy of a sheep farm	Simulation	Combined sheep growth and pasture growth submodels: difficult-to-validate model.
Gartner and Herbert (1979)	Replacement of dairy cows	Simulation	Includes milk yield improvements, but feeding policy must be specified.
Gebremeskel and Shumway (1979)	Calf marketing strategies	LP, Decision theory	Analyzes results from LP model using decision-theoretic concepts.
Glen (1980a)	Beef cattle ration formulation	Parametric LP	Procedure to formulate rations meeting nutrient standards of MAFF (1975).
Glen (1980b)	Beef feedlot operating policy	LP, DP	Decision variable—liveweight gain: least-cost rations formulated by LP.
Glen (1983)	Pig feeding policy	DP	Defines state of pig by liveweight and body protein content.

Table II—*Continued*
Selected Livestock Production Models

Authors	Issues Addressed	Methodology	Remarks
Halter and Dean (1965)	Cattle ranch/feedlot operations	Simulation	Weather conditions and market prices stochastic: very simple feedlot model.
Heady, Sonka and Dahm (1976)	Pig production policy	Enumeration	Considers three weight gain intervals and evaluates rations for each interval.
Howard et al. (1968)	Rations for dairy cattle	LP	Ignores effect of ration on milk yield.
Johns and Pearse (1970)	Lamb production policies	LP	Time of mating affects feed costs, lamb yields and market prices obtained.
Jones et al. (1980)	Dairy cattle feed formulation	LP	System operated by extension service.
Karp and Pope (1984)	Rangeland management	Stochastic DP	Stocking rate and pasture treatment the decision variables: validation problems.
Kennedy (1972)	Beef cattle feeding policy	LP, DP	Grazing/feedlot system, with least cost rations (formulated by LP) in feedlot.
Kennedy (1973)	Planning and control systems for beef production	LP, DP, Decision theory, Simulation	Formulates rations by LP, determines feeding policy by DP, and uses Bayes's theorem to classify animal performance.
Kennedy et al. (1976)	Broiler unit operating policy	DP	Evaluates feeding and marketing policy for unit of specified floor area.
Killen and Keane (1978)	Calving policy and effect on milk production	LP	Milk production costs are seasonal: dual gives prices to pay milk producers.
Klein, Salmon and Larmond (1979)	Turkey feeding policies	LP	Used to evaluate feedstuffs for turkeys, but diets to be used must be specified.
Leung, Liang and Mi (1979)	Design of animal production systems	Simulation	Develops general simulation framework: used to evaluate pig production systems.
Long, Cartwright and Fitzhugh (1975)	Evaluating breeding systems	LP	Basic model also used by Fitzhugh et al. (1975) and Cartwright et al. (1975).
Lovering and McIsaac (1981)	Beef cattle production system	Simulation	Considers forage growth, crop harvesting and cattle feeding: validation problems.
Low and Brookhouse (1967)	Replacement policy for hens in egg production unit	DP	Considers only replacement policy: ignores egg production and feeding policies.
Melton et al. (1978)	Beef feedlot feeding policy	Enumeration, Separable programming	Defines rations by silage content: uses separable programming to determine rations for specified weight gains.
Meyer and Newett (1970)	Beef feedlot operating policy	DP	Solution may not be optimal since least cost diets, rather than rations, used as decision variable.
Miller, Brinks and Sutherland (1978)	Operating policy for a cattle ranch	LP	Sensitivity analysis revealed opportunities for expansion.
O'Callaghan, Pollock and Dodd (1971)	Disposal of pig waste	Simulation	Examines effect on water, soil and crop of land spreading of waste.
Rahman and Bender (1971)	Variability in diet formulation	LP	Uses linear approximation of variance in stochastic diet formulation model.
Reyes et al. (1981)	Milk production policy	LP	Separate run for each lactation policy.
Ryan (1974)	Beef feedlot operating policy	Simulation	Investigates effect of stochastic feeding response on operating policy.
Safley, Haith and Price (1979)	Waste disposal policies in a dairy farm	LP	Evaluates waste handling systems and land spreading using separate LP models.

Table II—*Continued*
Selected Livestock Production Models

Authors	Issues Addressed	Methodology	Remarks
Schneeberer, Freeman and Boehlje (1982)	Selecting sires for artificial insemination	Portfolio theory	Measures genetic improvement by milk yield of offspring—many assumptions.
Smith (1973)	Replacement of dairy cows	Stochastic DP	State defined by milk production and lactation number: replacement cows have higher milk yield.
Spahr (1977)	Rations for dairy cattle	LP	Uses several rations in lactation cycle, but does not evaluate milk production level.
Stewart et al. (1977)	Replacement of dairy cows	Deterministic DP	Considers income from milk and beef sales but ignores any milk yield improvements.
Swart, Smith and Holderby (1975)	Long-term planning of large dairy farm	LP	Used to plan long-term livestock and crop activities.
Topham (1979)	Calf feeding policy	DP	Limited range of feeding policies: very simple treatment of home-grown feeds.
Trebeck and Hardaker (1972)	Cattle farm planning under risk	Simulation, Stochastic LP	Uses LP subroutine to determine feeding policy for different weather conditions.
Van de Panne and Popp (1963)	Nutrient variability in diet formulation	Quadratic programming	Measures variability in nutrient content of diet ingredients by variance.
Walsingham, Edelsten and Brockington (1977)	Rabbit production systems	Simulation	Does not consider costs.
Wensink and Miner (1977)	Treatment of waste from beef feedlot	Simulation	Evaluates size and operating policy of waste treatment ponds.
White and Morley (1977)	Sheep production policies	Simulation	Considers effect of stocking rate on value of wool: validation difficult.
White (1959)	Replacement of laying hens	Deterministic DP	Could form basis for stochastic model.
Wilton et al. (1974)	Integrated beef and crop production	LP	Growth rates and selling weights of animals must be specified.
Yager, Greer and Burt (1980)	Replacing breeding cows in beef cattle operation	Stochastic DP, LP	Evaluates cow feeding and marketing strategies, with LP-formulated rations.

the nutrients—i.e., the energy, protein, minerals, vitamins, and so forth—required to produce a specified level of performance, are known, then it is possible to calculate the ration required to produce this level of performance at least cost. Bodies such as the National Research Council (NRC) in the United States and the Agricultural Research Council (ARC) in the United Kingdom recommend systems for specifying the nutrient requirements of different livestock. However, these bodies generally adopt different systems for specifying the nutrient requirements, and these differences affect the method for determining least-cost rations.

We can illustrate the influence of the system used to specify nutrient requirements by considering the formulation of least-cost rations for beef cattle. In the United States and the United Kingdom, the NRC and the Ministry of Agriculture, Fisheries and Food (MAFF), respectively, have adopted different systems for specifying the nutrient requirements of beef cattle (NRC 1976; MAFF 1975). These systems specify the

energy, protein and minerals required to produce a specified daily liveweight gain in an animal of given liveweight. The main difference between these systems is the method adopted to specify the energy requirements.

The system adopted by MAFF is based on the ARC system (ARC 1965). In this system the animal's metabolizable energy (ME) requirement—that is, food energy less fecal, urinary and methane losses—depends on the ME concentration of the ration, which is a function of ration composition. Least-cost rations satisfying these nutrient standards can be determined, as suggested by Kennedy (1972), by using LP to determine the least-cost ration of specified ME concentration, and then repeating this process for different values of the ME concentration of the ration. However, in practice this approach can consider only a limited number of values of ration ME concentration. The approach developed by Glen (1980a) overcomes this limitation. It uses parametric programming

to derive a piecewise relationship for the cost of the ration as a function of its ME concentration, and then uses differential calculus to determine the least-cost ration.

NRC (1976) uses the net energy system developed by Lofgreen and Garrett (1968) to specify the energy requirements of beef cattle. In this system the animal's net energy requirement, that is, the metabolizable energy less heat production, depends on the composition of the ration. Brokken (1971a) suggested a separable programming model to account for these interdependencies, and Glen (1980b) developed a parameterization procedure to reduce the computational load involved in calculating a large number of least-cost rations. Brokken (1971b) extended the ration formulation of his (1971a) model to allow for the effects of heat or chill stress by considering the heat increment, i.e., the difference between metabolizable energy and net energy.

The major limitation of the systems recommended for beef cattle by MAFF and NRC is that they do not consider the composition of the carcass, for example, its fat-free and fatty tissue content. NRC (1976) assumes that the chosen feeding system will not have a major effect on carcass composition when farmers adopt economic cattle feeding policies, but others have questioned this assumption (see Moe and Tyrrell 1973). It is very important to consider carcass composition in feeding pigs since pig carcasses are graded by their composition, and lean meat brings higher prices. Both ARC (1967) and NRC (1979) have recommended nutrient allowances for growing pigs but, as in the case of cattle, in neither case are allowances expressed in terms of the nutrients required to produce liveweight gains of specified composition. However, Whittemore and Fawcett (1976) developed a pig growth model that separates daily liveweight gain into fat free and fatty tissue components, and Fawcett, Whittemore and Rowland (1978a, b) incorporated this model in an LP model for formulating least-cost rations to produce daily liveweight gains of specified composition.

In dairy farming, researchers have long recognized the importance of milk yield in feeding dairy cattle (Redman 1952), but many of the LP applications in formulating rations for dairy cattle, for example, Howard et al. (1968), fail to treat milk yield. Brown and Chandler (1978), in an extension of an approach proposed by Dean, Bath and Olayide (1969), developed an LP model for determining profit-maximizing rations for dairy cattle. They approximated the nonlinear relationship between milk production and food intake using sets of linear equations and solved the

model using a stepwise solution procedure. However, it is not clear that the solution obtained will be globally optimum. A simpler approach, such as running the least-cost-ration LP model of Jones, Murley and Carr (1980) for a number of different milk production levels, would probably yield more acceptable results. Formulating rations for dairy cows is even more complicated because the milk production from an individual cow varies during a lactation—i.e., the milk production period after calving—with peak production occurring in about the fifth week after calving. Farmers often practice group feeding for dairy cows maintained in confinement, and since it is very difficult to control the feed intake of an individual animal, they often group the cows in a milking herd according to each cow's stage in the lactation cycle. Spahr (1977) considered the problem of evaluating least-cost rations for cows in each group, with cows moving from one group to another depending on lactation stage and daily milk production, but he did not consider the problem of determining the appropriate level of milk production.

The formulation of a rationing policy is an important aspect of livestock production, especially in intensive operations. An LP-based approach can generally overcome the difficulties that arise in formulating rations to supply the nutrients required for specified levels of livestock performance. These LP-based methods are widely used by extension services but, unlike the case of diet formulation, the methods do not appear to be widely used by individual farmers because the models are more complex. However, with the increase in power of microcomputers, it seems certain that ration formulation software will be developed for use by farmers.

Feeding Policy for Intensive Livestock Production

In intensive livestock systems, the use of least-cost rations will ensure that livestock can achieve specified liveweight gains at minimum cost. However, the economic efficiency of this type of operation also depends on the daily sequence of rations, i.e., the feeding policy, and the liveweights at which the livestock are sold, i.e., the marketing policy. In an evaluation of feeding policy, the ration used should change daily to reflect the increase in liveweight. However, because of the administrative problems associated with daily ration changes, in practice it may be necessary to modify feeding policy.

Barnard (1969) noted that, although in theory marginal analysis could evaluate feeding policy, the practical application of this approach was limited because of the constantly changing nature of the input-output

relationships. Traditional economic analysis of livestock feeding is thus inadequate because it is difficult to incorporate factors such as rate of gain, fattening period, individual differences between animals, and differences in initial and final weights in the production function framework (Brokken et al. 1976).

Since livestock feeding is a sequential decision process, it can be modeled using DP. Meyer and Newett (1970) proposed a DP model to determine the optimal operating policy for a beef feedlot, i.e., a beef production system in which cattle are purchased at some initial liveweight and transported to the feedlot where they are fed on high energy rations until they attain some specified liveweight. The state variables in the DP model were animal liveweight and the time it took to reach this liveweight, while the decision variables were the diet used and the number of periods during which this diet was fed. However, because of the form of this net energy system, and because least-cost diets are used as decision variables in the DP model, the solution to the model is therefore unlikely to be optimal, although there is insufficient data to determine whether the approach produced a near-optimal solution.

If planners can determine the least-cost rations to produce specified liveweight gains in animals of known liveweight, then, by using liveweight as the state variable and liveweight gain as the decision variable, they can use dynamic programming to determine the optimal livestock feeding policy. Kennedy (1972) used this approach to evaluate feeding and marketing policies for beef cattle fed according to the ARC nutrient standards (ARC 1965). This model assumed that cattle were fed intensively for part of the year, and could graze during the pasture-growing season. Although the model required a number of simplifying assumptions to include pasture grazing, it incorporated the important decisions associated with this type of enterprise, and could provide the basis for further work. Glen (1980b) used a similar DP approach to evaluate feeding and marketing policy in a beef feedlot with animals fed according to the NRC nutrient standards (NRC 1976). A limitation of these DP models of beef cattle feeding is that they do not consider the grade of beef, and hence the value of the animals produced, as a function of feeding policy. Nutrient standards that relate feed intake to the composition of liveweight gain are not available for beef cattle. However Glen (1983), using the pig growth model of Fawcett et al. (1978a, b), extended the DP model of Glen (1980b) to account for liveweight and body protein content in evaluating pig feeding policy. This DP model could be used with any type of livestock

and any model of livestock growth that considers two components of growth, such as liveweight and body protein content, provided that it is possible to derive the least-cost rations to produce specified changes in these components.

Researchers have also used a number of other DP models to evaluate livestock feeding policy. For example, Kennedy et al. (1976) used a DP model to determine the feeding and selling strategy in broiler production, although the relationships used in this model were based on limited feeding trials. Clark and Kumar (1978) used a simple DP model to determine the feeding and marketing strategies for beef production, but since the model evaluated the imputed value of liveweight gain at the end of each stage in the solution procedure, it did not consider the influence of cash flow. Topham (1979) developed a DP model to evaluate calf feeding policies, taking account of the milk from the mother. However, he evaluated only a narrow range of feeding policies, and did not consider the possibility of purchasing a feed which could be grown on the farm.

Although LP has been widely used in formulating diet and ration plans, the use of LP in evaluating feeding policy is more limited. For example, Wilton et al. (1974) and Ashour and Anderson (1975) included animal feeding in models that integrated aspects of crop and beef production. However, both these studies used predetermined rates of liveweight gain throughout the fattening period, and the model determined the rations to produce these liveweight gains. Klein, Salmon and Larmond (1979) used an LP model to evaluate feeding policies for turkey production, particularly in relation to the use of a recently developed type of rapeseed meal. However, the modeling approach assumed that the rapeseed and energy content of available diets can be specified in advance.

Some researchers have used enumerative techniques to evaluate livestock feeding policies (see, for example, Battese et al. 1968; Heady, Sonka and Dahm, 1976; Melton et al. 1978; and Bhide et al. 1980) but, as Kennedy (1981a) has noted, the solution technique probably constrained the problem formulation and DP would have been a more satisfactory approach in these cases. Brokken et al. proposed an approach that requires the underlying functions to be differentiable and assumes that both the diet and the rate of liveweight gain remain constant throughout the fattening period. Crabtree (1977) used econometric analysis to evaluate feeding policies in bacon pig production, while accounting for carcass composition. However, the approach is of limited use since it used only one diet and fixed final liveweight.

Simulation models are also suitable for evaluating feeding and marketing policy in intensive livestock operations. These models may include an LP subroutine for least-cost ration formulation, but the simulation approach still requires a separate set of runs to evaluate each policy. Dent (1971) simulated the development of groups of pigs. His model, which assumed all pigs in a group were sold at the same time, contained only one stochastic element—the market price of pigs. Ryan (1974) incorporated the stochastic nature of the feeding response of individual animals in a beef feedlot simulation model. He used this model to investigate the effect of selling animals individually once they attained a particular weight, rather than selling animals in groups. Although analysts have recognized the importance of individual differences in the feeding response of livestock (Barnard; Dent), selling individual animals imposes additional administrative work and may incur a high opportunity cost for underutilizing a portion of livestock housing (Dent). The practical significance of modeling individual differences in feeding response may therefore be limited.

The major disadvantage of simulation methods in evaluating feeding and marketing policies for livestock is that they are inefficient for evaluating a large number of possible policies since the analysis of each policy requires a separate set of runs of the simulation model. However, simulation models are generally easier to explain than other types of models and may therefore be more readily accepted by decision makers.

Livestock Production on Pasture

In spite of the development of intensive livestock production systems, pasture grazing still plays an important role in livestock production, especially in the beef, dairy and sheep sectors. Even in North America, where farmers extensively use intensive beef production systems, pasture grazing contributes significantly to beef production since in most cases cattle are reared on pasture before being transferred to a feedlot. The adoption of improved methods of pasture management, and the use of concentrates to supplement feeding outside the pasture growing season, has improved the economic efficiency of extensive livestock production. Although extensive livestock production cannot, like intensive operations, control the feed intake of the livestock, this approach can regulate feed intake to some extent by grazing strategy. Evaluating extensive livestock production systems is therefore more complex than evaluating intensive systems, since it must account for not only livestock feed requirements but also the seasonal variation in both pasture growth and digestibility. Moreover, the growth and digestibility of pasture depends not only on uncertain weather factors but also on controllable variables such as the stocking rate (i.e., the number of animals per unit area), the application of fertilizers, and the use of irrigation.

Simulation is widely used in modeling pasture-based livestock systems since it provides a convenient framework for integrating livestock and pasture submodels. For example, Loewer et al. (1981) developed a simulation model of beef production on pasture, while Galbraith, Arnold and Carbon (1980) combined a pasture-growth simulation model with a sheep-growth model (Arnold, Campbell and Galbraith 1977) to investigate grazing and stocking policy in sheep farming. However, models of this type rely heavily on subjective assessment of relationships that influence the economic performance of pasture-based systems (for example, the effect of grazing on pasture growth and the effect of stocking rate on feed intake). As an illustration, stocking rate in sheep farming affects feed intake per animal and hence liveweight, wool weight and wool fiber diameter. Both wool weight per animal and fiber diameter decrease with stocking rate, but since finer fiber generally attracts a higher price, the effect of stocking rate on economic performance is complex. White and Morley (1977) included the influence of stocking rate on both wool production and wool fiber diameter in a simulation model of sheep production, but the relationships between these factors were highly subjective. Although simulation approaches are widely used in modeling extensive livestock systems, some researchers have developed optimization models. For example, Karp and Pope (1984) examined rangeland management policies using a stochastic DP model, taking stocking rate and a range improvement treatment as decision variables. However, their results were difficult to validate because of shortage of data.

Other models for livestock production systems have used pasture grazing for only part of the production process. For example, Halter and Dean (1965) constructed a simulation model of an enterprise with cattle reared on a ranch and transferred to a feedlot at a rate determined mainly by the feed supply on the range. This model considered both weather and grazing as stochastic elements, but considered intensive feeding simply in terms of average costs. Kennedy (1972) and Wilton et al. have developed optimization models of production systems based partly on pasture grazing, but they do not consider the dynamic nature of pasture growth and the influence of weather conditions.

Modeling of pasture-based livestock systems should consider both livestock development and pasture growth. However, many models are based on subjective assessment of some of the pasture grazing relationships and are therefore difficult to validate. These difficulties will be overcome only by further research on pasture growth and the grazing behavior of animals.

Livestock Breeding and Replacement

Agriculturally advanced countries have developed livestock through selective breeding to accentuate economically desirable traits. Since experimental evaluation is both costly and time consuming, model-building methods have proven to be useful for evaluating breeding systems. For example, Smith (1964) used a simple index to estimate the genetic improvement obtained by different breeding schemes. Moav (1966) evaluated crossbreeding systems assuming that the profit in commercial livestock production could be expressed as a function of the reproductive performance of the parents and the productive efficiency and quality of their offspring. Schneeberer, Freeman and Boehlje (1982) applied portfolio theory to select dairy sires for use in artificial insemination, but interpreting the results requires a knowledge of the decision maker's utility function. However, a major weakness of these methods is that they do not consider other factors, such as feeding and marketing policy, that influence the economic efficiency of livestock production.

Other researchers have examined breeding systems in the context of the operating environment by incorporating breeding activities in models of livestock production systems. For example, Long, Cartwright and Fitzhugh (1975) used an LP model of a beef production enterprise to evaluate straightbred breeding systems that differed in the mature weight of the breeding females. Fitzhugh, Long and Cartwright (1975) used the same model to evaluate crossbreeding systems from mating straightbred sire and dam lines; Cartwright, Fitzhugh and Long (1975) used it to evaluate more complex breeding plans. Morris and Wilton (1975) used an LP model (Wilton et al.) that included breeding and rearing activities to evaluate straight-breeding systems differing in mature cow weight. However, since these LP models must specify a breeding scheme and feeding policy, their use would require many runs to evaluate the complete range of operating policies. Neither of these models considered the timing of breeding or the effect on the age structure. However, other models have included these factors. For example, Johns and Pearse (1970) included the time of

mating in an LP model of lamb production, while Congleton and Goodwill (1980) used a simulation model to examine the effect of breeding policy on the age structure of a beef cattle herd, although their model did not consider feeding policy.

In both milk and egg production, farmers replace livestock when their performance deteriorates. Because of the sequential nature of these decisions, DP is a natural modeling tool for evaluating livestock replacement decisions. White (1959) and Low and Brookhouse (1967) developed deterministic DP models to examine replacement policies for hens in egg production units; neither study considered feed costs as a function of egg production rate. Smith (1973) and Stewart et al. (1979) used DP models to investigate replacement policies in dairy herds. Smith (1973) attempted to model the increase in milk yield obtained by using replacement cows of improved genetic potential, but the interval used between successive milk production states in the DP model may mask these improvements. In beef production, the replacement policy depends on the marketing policy, a relationship that can be included in models of these operations (Wilton et al.). However, the replacement of cows in the breeding herd of a beef production enterprise also affects economic performance. For example, the spring calving policy of many U.S. beef producers results in a seasonal pattern in the supply and price of cows removed from the breeding herd. Yager, Greer and Burt (1980) included the market price of cows as a stochastic element in a DP model for evaluating feeding and marketing policies for these cows and found that significant benefits could be obtained from alternative cow disposal strategies.

Simulation models have been another modeling approach for evaluating livestock replacement policies. For example, Walsingham, Edelsten and Brockington (1977) used a simulation model of commercial rabbit production to evaluate replacement policies for breeding stock, although the model did not consider the cost of these policies. Gartner and Herbert (1979) used a simulation approach to evaluate dairy cow replacement policies, taking account of the genetic improvement resulting from the use of artificial insemination. However, they used a fixed feeding policy, and the model is very difficult to validate.

Models for breeding and replacement policies should incorporate interactions with other livestock operations, but this modeling approach is difficult to adopt since many of the relationships associated with livestock breeding are not fully understood. Although the evaluation of breeding schemes is important for

the long-term development of agriculture, the evaluation of livestock replacement strategies is of more immediate benefit to individual farmers. The most widely used models are those for evaluating replacement policies, particularly in large-scale dairy and egg production. Models of breeding schemes are likely to be of greatest value as research tools.

Waste Disposal

The handling and disposal of livestock waste is an important issue in livestock production, particularly in intensive operations. Since livestock waste has considerable value as a fertilizer, land spreading is often the preferred method for waste disposal, especially when some of the feeds used in livestock production are grown on land owned or leased by the producer. However, the need to reduce the environmental impact generally restricts waste disposal. Treating some types of waste will reduce their pollution potential, and some models do investigate the design and operating policy of waste treatment facilities (for example, Wensink and Miner 1977).

Whenever suitable land is available, land spreading of livestock waste is generally the most economic method of waste disposal. O'Callaghan, Pollock and Dodd (1971) developed a simulation model to evaluate policies for collecting, storing and land spreading of the waste from a pig fattening unit, using empirical relationships to estimate the amount of waste produced by pigs fed according to a specified feeding system. Ashour and Anderson used an LP model to determine limits on the development of beef cattle feedlots in an area where land served for both feed production and waste disposal. However, the model calculated only one least-cost ration for animals of all liveweights, and used waste disposal costs independent of the ration plan. In less intensive operations, the waste produced may not be sufficient to satisfy crop nutrient requirements, leading to the requirement of additional nutrients from other sources such as chemical fertilizers. Those LP models of pasture-based beef and dairy farms that consider the nutrient requirements of the crops and the nutrient content of the waste (Dodd, Lyons and Herlihy 1975; Coote, Haith and Zwerman 1976; and Safley, Haith and Price 1979) can be used to determine land spreading policy and additional fertilizer requirements.

The methods of waste disposal that livestock producers can adopt are generally affected by statutory regulations, and available models can investigate the effect of these regulations. For example, Forster (1975) used a deterministic simulation model of a typical U.S. beef feedlot to evaluate the impact of possible water pollution control regulations. The model's estimates of price expectations of producers and prices realized, were based on historic data, but the results were dominated by the cyclic nature of these prices, and therefore the model would be of little value to individual producers. Ashraf and Christensen (1974) included variables for different methods of waste disposal in an LP model that investigates the impact of water pollution regulations on dairy farms. Because each waste disposal system involved a discrete investment, the authors solved the model case by case for each system. This model could be used to evaluate waste disposal policies for individual operators if it included farm specific factors such as rainfall, soil type and water pollution level, although clearly an integer programming formulation would be more appropriate.

Waste disposal is a major problem in modern livestock production systems. Modeling techniques, especially LP, have been widely used to evaluate policies for land spreading of waste. These models appear to be applied most often when the quantities of waste are sufficiently small to impose little danger of pollution. Although LP has also been used for situations with large quantities of waste, the major difficulty lies in ensuring that the pollution constraints adequately reflect the long term environmental impact.

Planning in a Livestock Production Unit

In the operation of a livestock production unit several factors interact dynamically. An intensive livestock production unit might involve only livestock-related factors such as livestock feeding and replacement and waste disposal, but when livestock production forms only part of the operations of an enterprise, interactions with the other activities, such as crop production, are relevant as well. Ideally the models used for planning livestock operations should incorporate these interactions, but because of the complexity of the systems and the limitations of particular techniques, many of the moels are restricted to particular aspects of livestock production.

In intensive livestock fattening operations, many of the models have concentrated on evaluating feeding and marketing policies, with mathematical programming models being widely used (Kennedy et al. 1976; Glen 1980b and 1983). Mathematical programming models have also incorporated some of the other activities associated with operations of this type, but the use of these models has been restricted by the nature of the simplifying assumptions. For example, although Ashour and Anderson included waste dis-

posal activities in an LP model of beef feedlot operations, the model requires a specified rate of liveweight gain. Wilton et al. included calf rearing, cattle feeding and crop production in an LP model, but the model required that cattle growth rates and marketing policy be specified.

In dairy farming, the milk production of an individual cow varies during a lactation and depends on the feeding policy. The evaluation of operating policies for dairy farms should also consider other factors, such as the replacement policy for cows. However, many dairy production models have been restricted to ration formulation, and frequently researchers have considered only average or overall milk production levels (Brown and Chandler, Jones et al.), although Reyes et al. (1981) used an LP model to determine the optimal level of milk production during a lactation. In pasture-based dairy herds, the seasonal growth of grass influences calving decisions, and hence milk production levels and costs. By taking account of these seasonal factors in an LP model, Killen and Keane (1978) determined the calving pattern that minimized milk production costs subject to demand constraints. They used the solution to the dual problem to determine the seasonal prices that should be paid to milk producers to reflect the seasonal nature of production costs. However, this model is not suitable for use by individual producers since it considers neither stocking rate nor the age distribution of the herd. Swart, Smith and Holderby (1975) included both livestock and cropping activities in an LP model of a large dairy farm. They classified cattle by age and sex, and simplified the model by specifying the ration for animals in each class.

The planning of livestock operations should also consider the risks arising from uncertainty in, for example, market prices and weather. Although LP models of livestock production do not incorporate these uncertainties, LP has been used in combination with other techniques to deal with some of these risks. For example, Gebremeskel and Shumway (1979) illustrated the development of a risk-constrained LP model of a cow-calf operation based on the grazing of pasture. They used this model to produce farm plans using decision theoretic concepts that assumed a knowledge of the utility function of the farmer. However, this type of approach may add complexity without providing the insight that can be obtained by analyzing the results of a traditional LP model (Miller, Brinks and Sutherland 1978). Trebeck and Hardaker (1972) used a stochastic LP model to determine operating policy for an Australian cattle farm under different rainfall conditions. The model simulated the

rainfall encountered, and derived the distribution of profit, but ignored the uncertainty in market prices.

Simulation models are well suited to dealing with the variability and complex nature of livestock production, although it may be difficult to establish some of the underlying relationships, such as grazing behavior and pasture growth. To be of practical value for planning, a simulation model of a livestock production system must contain sufficient detail of the operation of the real system. Even large models might omit parts of the production system; for example, Lovering and McIsaac (1981) did not include pasture grazing and the raising of replacement cows in their simulation model of a milk production system. However, the scale of an individual unit may not justify the cost of building a model, particularly for small enterprises. Blackie and Dent (1974) argued that these difficulties could be overcome by representing the logical structure of a livestock unit in a "skeleton" model which, with appropriate data, can be applied to a specific enterprise (see Blackie and Dent 1976). Leung, Liang and Mi (1979) advocated a similar approach for simulating livestock production systems. However, this type of approach may not be appropriate whenever livestock production is based on extensive grazing, or is combined with crop production.

Planning in agriculture takes place in an uncertain environment, and therefore producers must monitor performance and update plans regularly. Kennedy (1973) proposed a planning and control system for a beef feedlot. This system classified animals in terms of their gain potential, and used Bayes's theorem to revise the classification of individual animals on the basis of the weight gain achieved. The author illustrated the operation of this system using a simulation model. Although additional costs are involved in monitoring livestock performance, he argued that systems of this form would improve the economic performance of livestock production, particularly in intensive operations. Large-scale dairy and poultry systems use similar control systems, but do not use Bayesian methods to revise classifications.

Conclusions

Researchers have developed a large number of mathematical models of farming systems, but because of the complexities of these systems, the models concentrate on particular aspects of farm operations. Although the ultimate objective of model building in agriculture should be to improve decision making, few models are used directly by farmers (Kennedy 1973; Nix; Bywater 1981). However, advisory and

extension services use many models, and because of the position of these services in the agricultural sector, many farmers use the results from these models. A large number of models have been developed as research tools or teaching aids. This use of models can help to improve understanding of agricultural systems, particularly those involving the dynamic interaction of many biological processes. In some cases—for example, in crop-pest systems—there is a need for further research to establish the relationships between the system components. The improved understanding gained through model building can be valuable in directing research to provide the basic data required. Developing models as research tools may therefore be the first step toward producing practical aids for farm decision making.

Several researchers have attempted to incorporate mathematical models in planning systems suitable for use by individual farmers. Nix, citing experience with LP-based planning systems designed for ease of use, noted that even systems designed in this way have not received widespread acceptance by farmers. However, in these cases farmer involvement was limited to supplying data and then examining the results some time later. The experience of Debertin et al. has suggested that whenever computer-based models can be run interactively or the results can be made available quickly, the use of techniques such as LP can have a significant impact on framers' decision making behavior. Although the scope of their evaluation was limited, these researchers concluded that the experience gained from using the model improved understanding of the problems involved in planning farm operations. Benefits of this kind are difficult to evaluate, but can make an important contribution to decision making.

Part of the problem associated with farm use of many planning models is that the solution phase of the model requires the use of a computer. In the past, farmers have generally used remote computing facilities, and have depended on the postal service, with its associated delays, to transmit both input data and results. However, the development of microcomputers has drastically reduced the cost of computing equipment, and powerful computing facilities can now be purchased by individual farmers at relatively low cost. Farmers will most likely employ microcomputers initially to perform simple tasks such as budget preparation and cash flow analysis. As they become accustomed to using the equipment, however, they will very likely become more receptive to the idea of employing it to perform more sophisticated analyses based on the use of mathematical models. Some of the planning systems developed on mainframe computers for advisory and extension services could be adapted for such use. Consequently, there is considerable scope for the development of computer-based farm planning models suitable for use by individual farmers.

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