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Department of Agricultural Economics
Texas A&M University
Texas Agricultural Experiment Station
College Station, Texas

The authors are, respectively, Assistant Professor, Texas A&M University; Professor, University of Arkansas; Professor, University of Illinois; and Head, Climate and Meteorology Section, Illinois State Water Survey.

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Dynamic Programming Model
of the Corn Production Process
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Recent studies on crop production in the United States show a dichotomy on the treatment of dynamic factors. For example, Lazarus and Dixon, and Taylor and Burt consider a dynamic decision process but are concerned with between year production and not the dynamics within a single crop year. Two recent books on risk and modeling define the decision process mainly in terms of a single crop year. These efforts by Barry, and Baum and Schertz, however, spend little, if any, time discussing the dynamics of the farm production process. Hence, while there has been some attention paid to considering the dynamics of crop production it would appear little attention has been given to the dynamics of the within year production process.

Antle discusses how intraseasonal dynamics are important because models which incorporate intraseasonal dynamics more closely reflect how farmers actually behave than static models. One important aspect of this intraseasonal dynamics is that risk is accounted for because maximizing profits is a function of risk if the uncertain variable enters nonlinearly (Antle; Taylor). In fact in discussing Antle's work Chambers states "... that risk is especially important in a dynamic context; and if we are going to help farmers to make better management decisions, we should take the dynamics of agricultural production into account" (p. 1114).

This study reports on the development of a single year's corn production model for east-central Illinois. Inputs are considered as being sequentially injected into the production process. For example, fertilizer application can occur in the fall before planting, preplant in the spring, or sidedressed. Modeling the dynamic nature of the impact of individual production practices requires considerable data. As stressed by Antle, "A major obstacle for implementation of dynamic production models is data limitations" (p. 1105). Data limitations encountered when developing the corn production model are overcome by using physiologically-based simulation models to develop a synthetic data set. It appears unlikely that field experiments will ever become sufficiently detailed to directly provide data for dynamic decision analyses. Synthetic data sets, based on numerous experiments and expert judgements, provide an efficient means to help overcome data problems.

The remainder of the study is organized as follows. The next section describes the dynamic programming (DP) model of the corn production process. Three features which distinguish the corn production DP model from other DP models are illustrated in this section. First, the number of state variables relevant to the decision making process varies at each stage. This allows a larger number of state variables to be included in the model than normally found in DP models. Second, the stochastic nature of the state varibles varies by stage. That is, a state variable may be stochastic at one stage and deterministic at another stage. Third, as many as 60 decision alternatives are evaluated at some of the stages, a number larger than included in most DP models. The last section discusses ex-post validation of the corn decision model. Estimation results of a dynamic production function, and results from the DP model are discussed.

CORN PRODUCTION MODEL

Use of DP requires appropriate specifications of stages, state variables, management decision alternatives, and the Markovian relationship between state variables (transition equations) for each decision alternative at the different stages. The Markovian relationship depicts the state of the process in the next stage given the current state, variables, and the decision alternative chosen. For the corn production model each of the preceding components are discussed in the following sections. For an even more detailed discussion of the corn model, see Mjelde.

Stages and Decision Alternatives

The time periods forming the model's stages are fall preceding planting (Fall), early spring (ESp), late spring (LSp), early summer (ESum), midsummer (MSum), late summer (LSum), early harvest (EH), and late harvest (LH). In six of these stages decisions can be made and in the remaining two stages no decisions can be made. The six decision stages are Fall, ESp, LSp, ESum, EH, and LH. These correspond to the time periods when major input decisions are made by corn producers in east-central Illinois. The stages when no decisions can be made are MSum and LSum. These stages are included because of the substantial effect of climatic conditions on corn yield during these time periods. Therefore, a total of eight stages are included in the intrayear dynamic corn production model. Table 1 summarizes the stages and decision alternatives available in the DP decision model. As many as 60 decision alternatives are available in some stages.

The decision alternatives available in the DP model are: 1) when to apply nitrogen, 2) how much nitrogen to apply, 3) when to plant, 4) which hybrid to plant, 5) at what planting density to plant, and 6) when to harvest. The fertilization decisions consider only the application of nitrogen[1]. Because a review of the agronomic literature did not produce any quantitative relationships between such practices as tillage operations and pesticide application and climatic conditions, these management practices are omitted from the decision model. The 60 decision alternatives associated with ESp and LSp are every combination of 6 nitrogen levels, 3 hybrids and 3 plant densities plus the 6 nitrogen decision alternatives without planting. During Fall and ESum the producer has the option of choosing 6 different nitrogen levels. During the two harvest stages the decision alternatives are to harvest or not.

The decision model is developed for a single acre in which only corn can be planted. This restrictive assumption is made for two reasons. First, the size of a DP model is limited by the curse of dimensionality (Burt). The second problem concerns the type and quantity of data required to estimate the transition equations required for a multicrop model. Such data are not readily available as is discussed later.

Another limiting assumption imposed on the DP model is the lack of explicit time or machinery constraints. To impose restrictions on, say, which acres are planted and which acres are fertilized would require additional state variables. As discussed in the next section, state variables are selected to provide maximum information and still have the DP model solvable in terms of computational resources. A constraint relating climatic conditions to available field work days is included in the production decision model to limit operations if rainfall is heavy.

State Variables and Transition Equations

Three different biological and physical phenomena govern the state transitions between stages. From Fall to ESp the primary concern is loss of nitrogen through leaching and denitrification. For the growing season, ESp, to EH, the state variable transitions are represented by a dynamic, corn production function. During the harvest period, the producer is concerned with the drydown of the corn kernel and field losses. Each of these relationships, nitrogen loss function, dynamic production function, and corn drydown function, are discussed below[2].

Five state variables used in the DP model to describe the biological or physical aspects of the production process are denoted as: nitrogen, plant, climate, grain moisture, and October climate state variables. The nitrogen state variable gives applied nitrogen in pounds per acre. The plant state variable gives the effect of planting date, plant density and hybrid planted on yield. The climate state variable denotes the cumulative effect of climatic conditions on yield. Transitions for both the plant and climate state variables are governed by an estimated production function. Both the grain moisture and October climate state variables are important during the harvest period. The grain moisture state variable gives the percent moisture of the corn kernel. The October climate state variable is used to calculate the effect of climatic conditions occurring in October on field losses at LH. A sixth state variable models availability of field work time (denoted as field) and is discussed in the Optimization Model section. The seventh state variable is a linear combination of the nitrogen and climate state variables. Nitrogen and climate state variables are combined at ESum to reduce the dimensionality of the model. The ESum stage has been shown to be the stage when applied nitrogen interacts with climatic conditions (Hollinger and Hoeft). The combined nitrogen and climate state variable transitions are given by the estimated production function. Using a linear combination of state variables helps alleviate dimensionality problems (Burt).

The special structure of the corn production process modeled here allows seven state variables to be included within the model (a number greater than usually found in DP models). However, at any one stage, no more than four state variables are relevant for decision making. This means that the state variable at a particular stage must be able to assume more than one value to be relevant in decision making. For example, the relevant state variables for ESp are nitrogen and field, whereas, for LSp the relevant state variables are nitrogen, field, plant and climate. Table 2 presents the state variables and the number of possible values for each state variable at any given stage[3]. This table also presents abbreviations used throughout this study for the state variables.

Synthetic Data Set

A major obstacle in implementing intrayear dynamic production models is data availability (Antle; Chavas et al.). An extensive review of the agricultural literature confirmed the above obstacle as a major problem. Although there is an extensive literature on the individual effects of various production practices and climatic conditions on corn yield, the usefulness of this literature for obtaining the parameters associated with the transition equations is limited. Experimental designs employed in past field studies do not examine the effects of varying all management practices over a wide range of climatic conditions.

To overcome data limitations, a corn growth model developed by Reetz was augmented with a nitrogen-climate interaction model (Hollinger and Hoeft) to obtain a synthetic data set of corn growth observations for east-central Illinois. Used together, the two models simulated yield results from all possible combinations of five planting dates[4], three planting densities, three hybrids with different maturity ratings, eight applied nitrogen levels, and fourteen years of actual, observed climatic conditions (1970-83).

The experimental design employed in this study provides a useful way of obtaining a large data set without incurring the time and resource constraints needed to conduct field experiments. Together, the models performed 14 years of identifical experiments conducted using the same location and production technology. Because the models are based on physiological and biological concepts along with actual field data, such an approach can provide reasonable estimates of the relationships between management practices and climatic conditions (Musser and Tew; Ahmed et al.).

Dynamic Production Function

For purposes of this study, a requirement placed on the production function is that it must be partitioned in the time dimension using the three state variables whose transitions are governed by the production function; plant, climate, and the combined nitrogen and climate state variable. (Recall that remaining state varibles are governed by other processes.) Following Burt and Stauber, a general class of functions which satisfies this requirement for a DP model is given by:

$$\psi(Y) = h[\sum_{i=1}^{m} \phi_i (A_i)] \tag{1}$$

where Y is crop yield, A_i is a vector of climatic variables and management practices to which the crop is subject during period i. The symbol h denotes any arbitrary function, ϕ_i a vector of arbitrary functions, ψ is a monotonic transformation of yield, and m is the number of time periods. Equation (1) enables simple state variable transition relationships to be specified. The state variable vector at time period j is the partial sum $\phi_1(A_1) + \phi_2(A_2) + \ldots + \phi_j(A_j)$. The function h gives the monotonic transformation of crop yield in the final time period.

Using this general form and the synthetic data set, a dynamic production function is estimated. The explanatory variables are hybrid planted, planting date, plant density (seeds per acre), a climatic index

(Mjelde and Hollinger) for each of the stages ESp, LSp, ESum, MSum, and LSum, applied nitrogen, and nitrogen-climate interaction at ESum. The estimated coefficients at each stage represent the ϕ_i in equation (1). Detailed assumptions involved in estimating the production function, along with the results, are reported in Mjelde, Mjelde and Hollinger, and Hollinger (1985a). In general, the estimated model displayed a reasonable fit and conformed with agronomic experts' prior expectations in both the magnitude and effect of the coefficients. Results of the corn-simulation model validation can be found in Hollinger (1987).

The Optimization Model

The decision maker is assumed to maximize expected short-run returns net of variable costs (NRVC) for one corn acre, where short-run is defined as a single crop year. Maximizing NRVC, rather than utility, is chosen as the objective because of the difficulty associated with specifying producer's utility functions (Lin et al.). Further, as noted earlier, Antle argues that incorporating intrayear sequential decisions (dynamics) may be more important than incorporating risk preferences in production analysis. Also, Taylor shows that when a stochastic variable is included nonlinearly, its variance is taken into account under profit maximization. For these reasons maximizing NRVC is chosen as the objective.

Applying Bellman's Principle of Optimality to the corn decision model gives the following general recursive equation:

$$\begin{aligned} V_n \text{ (SNit, SClim, SNC, SPlant, Field, GM, Oct)} &= \\ \max_{D_n} \text{NRVC}_n \text{ E(SNit, SClim, SNC, SPlant, Field, GM, Oct, } D_n) & \\ + \text{ E } V_{n-1} \text{ (SNit, SClim, SNC, SPlant, Field, GM, Oct)} & \qquad (2) \end{aligned}$$

where $NRVC_n$ is the net return at stage n given the state of the process (state variable notation defined in Table 2) and decision D_n, V_n denotes the expected optimal value at stage n given the state of the process, and E is the expectation operator. Equation (2) utilizes the backward numbering of stages usually employed in DP formulations.

The transition equations for each stage transition are given below. Because of the unique nature of the transitions associated with this DP model, the transition equations are given for each stage. Any state variable transition which goes from having only one possible value at stage n to only one possible value at stage n-1 (e.g. Oct. climate between Fall and ESp) is omitted (see Table 2). An asterisk (*) denotes stochastic transitions. Transitions for the corn production decision model are:

Transitions: EH to LH

$$GM_{LH} = f(GM_{EH}, CI_{EH})^* \tag{3}$$

$$Oct_{LH} = (CI_{EH})^* \tag{4}$$

$$SPlant_{LH} = \begin{cases} SPlant_{EH} \text{ if not harvested} \\ 1 \text{ if harvested} \end{cases} \tag{5}$$

$$SNC_{LH} = SNC_{EH} \tag{6}$$

Transitions: LSum to EH

$$SPlant_{EH} = SPlant_{LSum} \tag{7}$$

$$SNC_{EH} = SNC_{LSum} + \beta_{LSum} (\ln CL_{LSum})^* \tag{8}$$

$$GM_{EH} = f(\text{Stage planted, hybrid planted})^* \tag{9}$$

Transitions: MSum to LSum

$$SPlant_{LSum} = SPlant_{MSum} \tag{10}$$

$$SNC_{LS} = SNC_{MSum} + \beta_{MSum} (\ln CI_{MSum})^* \tag{11}$$

Transitions: ESum TO MSum

$$\mathrm{SPlant}_{\mathrm{MSum}} = \mathrm{SPlant}_{\mathrm{ESum}} \tag{12}$$

$$\begin{aligned}\mathrm{SNC}_{\mathrm{MSum}} = {} & \gamma_1(\ln X) + \gamma_2(\ln X^2) + \gamma_3(\ln X)\ (\ln \mathrm{CI}_{\mathrm{ESum}}) \\ & + \gamma_4\ [(\ln X)\ (\ln \mathrm{CI}_{\mathrm{ESum}})]^2 \\ & + \mathrm{SClim}_{\mathrm{ESum}} + \beta_{\mathrm{ES}}\ (\ln \mathrm{CI}_{\mathrm{ESum}})^*\end{aligned} \tag{13}$$

where,

$$X = \mathrm{SNit}_{\mathrm{ESum}} + \text{pounds of nitrogen applied at ESum } (D_{\mathrm{ESum}}) \tag{14}$$

Transitions: LSp to ESum

$$\mathrm{SPlant}_{\mathrm{ESum}} = \begin{cases} 1 \text{ if not planted} \\ \mathrm{SPlant}_{\mathrm{LSp}} \text{ if planted in ESp} \\ \ln A + \alpha_{\mathrm{LSp}} \ln \mathrm{Den}_{\mathrm{LSp}}(D_{\mathrm{LSp}}) + \delta_{\mathrm{LSp}}\ \mathrm{Vardum}_{\mathrm{LSp}}(D_{\mathrm{LSp}}) \\ \text{if planted in LSp} \end{cases} \tag{15}$$

$$\mathrm{SClim}_{\mathrm{ESum}} = \mathrm{SClim}_{\mathrm{LSp}} + \beta_{\mathrm{LSp}}\ (\ln \mathrm{CI}_{\mathrm{LSp}})^* \tag{16}$$

$$\mathrm{SNit}_{\mathrm{ESum}} = \mathrm{SNit}_{\mathrm{LSp}} + D_{\mathrm{LSp}} \text{ (in pounds of nitrogen)} \tag{17}$$

$$\mathrm{Field}_{\mathrm{ESum}} = f(\mathrm{CI}_{\mathrm{ESum}})^* \tag{18}$$

Transitions: ESp to LSp

$$\mathrm{SPlant}_{\mathrm{LSp}} = \begin{cases} 1 \text{ if not planted} \\ \ln A + \alpha_{\mathrm{ESp}} \ln \mathrm{Den}_{\mathrm{ESp}}(D_{\mathrm{ESp}}) + d_{\mathrm{ESp}} \mathrm{Vardum}_{\mathrm{ESp}}(D_{\mathrm{ESp}}) \\ \text{if planted in ESp} \end{cases} \tag{19}$$

$$\mathrm{SClim}_{\mathrm{LSp}} = \mathrm{SClim}_{\mathrm{ESp}} + \beta_{\mathrm{ESp}}\ (\ln \mathrm{CI}_{\mathrm{ESp}})^* \tag{20}$$

$$\mathrm{SNit}_{\mathrm{LSp}} = \mathrm{SNit}_{\mathrm{ESp}} + D_{\mathrm{ESp}} \text{ (in pounds of nitrogen)} \tag{21}$$

$$\mathrm{Field}_{\mathrm{LSp}} = f(\mathrm{CI}_{\mathrm{LSp}})^* \tag{22}$$

Transitions: Fall to ESp

$$\text{Field}_{ESp} = f(CI_{ESp})* \tag{23}$$

$$\text{SNit}_{ESp} = .891\ C \tag{24}$$

where

$$C = X + 1 - (X + 1)^B \tag{25}$$

$$B = 1.0113 - 0.000253\ (Y_1 - 380)\ Y_2 \tag{26}$$

$$Y_2 = \begin{cases} 1 \text{ if } y_1 > 380 \\ 0 \text{ if } Y_1 \leq 380 \end{cases} \tag{27}$$

(where Y_1 is winter precipitation in millimeters and X is fall applied nitrogen in kilograms/hectare.)

where the α, β, and γ's refer to the estimated production function coefficients, D_n denotes the decision alternative set chosen (Table 1), Den_n denotes the plant density in seeds/acre, Vardum_n denotes the planting date-hybrid dummy, CI_n the climate index, and n the stages. The estimated production function coefficients and associated t-ratios are given in Table 3 and discussed in the Model Validation section.

Before discussing the stochastic nature of the model, some distinctive features of the state variables should be mentioned. The nitrogen transition from Fall to ESp is a function of winter precipitation which determines the nitrogen loss due to leaching and/or denitrification, and is based on a function developed by Hollinger (1985b). From ESp to ESum the nitrogen transition is in applied pounds per acre. The grain moisture transition during harvest is dependent on corn kernel percent moisture. This grain moisture transition is based on a corn drydown simulation model developed by Bruns. The October climate state variable determines field losses at late harvset as a function of climate (Johnson and Lamp).

Within the model the climate index for each stage in the growing season is allowed to take on one of three values (conditions): good, fair, or poor. The probability of a specific index value (e.g. good) is based on the frequency of its occurrence during the 1970-1983 period at Urbana, IL. The index measures the impact of yield and, for example, good indicates conditions which favor higher yields (see Mjelde and Hollinger for the developemnt of this index).

In the ESp, LSp, and ESum stages the number of field operations are limited for certain climatic conditions. The field state variable takes on the values of the climate index that occurs during each of these three stages. The ESp restrictions are that if poor climatic conditions occur only one field pass can be made, either planting or nitrogen application. Two restrictions are placed on LSp. First, if poor climatic conditions occur in LSp and if the field has been planted, no field operations can occur. Second, if the field is not planted in LSp, then the ESp restrictions hold. During ESum the restriction is that if good climatic conditions occur, then no field operations can take place. These restrictions are necessary since high rainfall and the height of the corn plant in ESp, LSp, or ESum limits the number of field passes that can be made.

Stochastics

The stochastic nature of the corn production model derives from the uncertainty of climatic conditions whose impacts are reflected in the state variable transitions within the model. Climate is assumed to be exogenous to the model and is not Markovian with respect to the stages defined in this study. Therefore, the probability distribution of the climatic conditions at any state is independent of the climatic conditions occurrng at any of the other stages.

The assumption of a non-Markovian occurrence of climate is not contradictory to the Markovian climate state variable defined earlier. By definition, the climate state variable shows the cumulative effect of climatic conditions on corn yield. This cumulative effect can be represented in a Markovian relationship of the type given by the corn production function.

The varying impact of climatic conditions on corn production provides for a feature which distinguishes the present model from previous DP applications. As shown in equations (4-27), the stochastic nature of each state variable transition is dependent on the stage of the process. At some stages a state variable's transition is stochastic, while at other stages it is deterministic. Also, the changing nature of the state variables relevant to the decision-making process dependent upon the state (i.e., field state variable is relevant only in the ESp, LSp, and ESum stages) distinguishes the corn production DP model from most DP models.

MODEL VALIDATION

Ex-post model validation requires examining two aspects of the model. The first aspect to be considered is results obtained from the estimated dynamic production function. Recall that the production function is estimated from synthetic data. Also discussed is the aggregation of estimated coefficients from five planting dates to two planting stages, ESp and LSp. Secondly, the optimal decision rules derived from the DP model are discussed.

Production Function Estimates

Before discussing production function estimation results, notation used and assumptions made for estimating the production function are presented. First, it is assumed that effective fall, spring, and summer (side-dress) applied nitrogen have the same impact on yield. Only the production function parameters associated with one linear and one quadratic term of applied nitrogen are estimated, that is, there is no stage effect for nitrogen. In the data set only total applied nitrogen is given and not the stage when the nitrogen is applied. For Drummer soil in east-central Illinois this is likely a valid assumption. Findings in Swanson et al. for Urbana agronomy test plots indicate that there is no statistically significant difference between spring and summer applied nitrogen on yield. The test plots were of Drummer soil type and the data were for 1968-1971.

Second, prior knowledge on the climate-nitrogen interaction provided by Hollinger and Hoeft is used in developing the synthetic data set. Their findings indicate only the climate occurring during the early summer substage, June 11 to July 15, has a significant interaction with nitrogen. Using this prior knowledge the production function is estimated with only a nitrogen-climate interaction term for the early summer substage. This interaction is denoted by $NxCI_3$ in Table 3.

The variables denoted by $Var_Z dum_Y$ where Z=1,2,3 and Y=1,2,3,4,5 in Table 3 are a set of fifteen zero-one dummies. Each corresponds to a different hybrid (Z=1 is short, Z=2 is medium, and Z=3 is full) planted at a different date (Y=1 is 4/20, Y=2 is 5/5, Y=3 is 5/15, Y=4 is 5/25, and Y=5 is 6/5). To clarify this notation, $Var_1 dum_1$ takes on the value of one for a short season hybrid planted on April 20th and is zero otherwise. The other dummies are interpreted in a similar fashion. This formulation follows for any interaction between hybrid and planting date. Var_3Dum_5 is deleted to avoid a singular regressor matrix.

Notation for plant density, the number of plants planted per acre at a given planting date, in Table 3 is Den_1 through Den_5 corresponding to the five planting dates. CI_1 through CI_5 are the climate indices for each of the five stages within the growing season. These indices are defined in Mjelde and Hollinger. Applied nitrogen (N) and planting density are set equal to one if the applied nitrogen level is zero or if the planting density at a particular planting date is zero. By setting the variable equal to one instead of zero the logarithm can be taken.

Table 3 presents the estimated production function coefficients. Different estimated model specifications of the production function can be found in Mjelde and Hollinger. The coefficients for planting density and hybrid selection cannot be analyzed separately. Separate analysis is not possible because associated with every planting date is a planting density coefficient and three hybrid coefficients. To examine the effect of varying the planting date on yield given a specific hybrid, involves four coefficients, the two different planting density coefficients and the two hybrid coefficients associated with the two planting dates. For example, to determine the difference in yield between planting a short season hybrid on April 20 versus June 5, the following four coefficients are needed. For April 20th the density coefficient is Den_1 and the short season hybrid coefficient is Var_1dum_1, whereas for June 5 these two coefficients are Den_5 and Var_1dum_5. Examining the coefficients in this fashion shows that later planting dates have a lower yield than earlier planting dates, ceteris paribus.

The t-ratios given in Table 3 indicate that all but four of the coefficients are significant at the .1 level of probability. Because of the interrelations of the coefficients discussed above, all of the coefficients are used in developing the DP decision model.

As expected, the five coefficients associated with the climate index indicate a positive relationship between yield and the index. The estimated production function conforms to prior expectations and fits the synthetic data adequately having an adjusted coefficient of determination of .85. Analogous to the hybrid and planting date coefficients the effect of applied nitrogen and climatic conditions cannot be determined separately. Table 4 contains corn yields calculated using the estimated production function and different ESum climatic conditions. The climatic conditions for the remaining stages are set at their respective mean values. Consider applying either 150 or 267 pounds of nitrogen per acre. Results presented in Table 4 show an increase of 2.0 bu/A for poor ESum climatic conditions and 18.1 bu/A for good climatic conditions, respectively. These changes in yield conform to prior expectations for applied nitrogen. That is, during years with poor climatic conditions, increasing applied nitrogen rate should have little effect on yield, whereas, in good years the increase in nitrogen should have a large effect on yield.

Aggregation - Five to Two Planting Dates

The estimated production function has five planting dates, but to make the DP decision model manageable, these five dates are aggregated into two dates, ESp and LSp. A weighted averaging scheme is used to aggregate the five planting dates into two planting stages. By the definition of variables within the estimated production function, only the parameters associated with planting density and hybrid need to be aggregated.

The weighting scheme is based on the following assumptions: 1) no planting can occur before April 20th, and 2) planting date three, May 15, is considered to have an impact in both ESp and LSp, because May 15 is the division point between ESp and LSp (Table 1). Because April 20th and May 15th are endpoints, they are given one-half the weight of the second planting date in determining the early spring coefficients. Therefore the ESp weights are 1/4, 1/2, and 1/4 for planting dates one, two, and three, respectively. The weights for LSp are 1/5, 2/5, and 2/5 for planting dates three, four, and five, respectively. The difference in the weighting scheme arises because the fifth planting date is not the endpoint of the LSp stage. The fifth planting date is June 5th, but the LSp stage runs until June 10. The weighted average coefficients associated with the management variables, density and hybrid, give an average effect of planting in that particular stage, rather than the effect of an exact planting date. Table 5 gives the weighted average coefficients for density and hybrid.

Optimal Decision Rules

The second necessary component to ex-post validate the corn production decision model is to examine optimal decision rules obtained from the model for different climate, corn price and input cost scenarios. Table 6 presents the costs of inputs which are not varied in this validation section. Price levels for the inputs that are varied are presented in Table 7. Note that the purpose of this model is to examine the dynamic relationship between corn production and climatic conditions. Therefore, cost of inputs not included in the model, such as interest charge on land, insecticide and herbicide costs, etc. are not included in the model. Therefore, net returns generated from the model are higher than given from accounting measures of net returns.

Before discussing the optimal decision rules some generalization between economic and climatic scenarios are presented. In general, the applied effective nitrogen between the various economic scenarios decreases when the cost of nitrogen increases, the interest rate charged on operating capital increases or with a lower corn price. In the DP model there is a definite drying cost effect on the decision of when to harvest. In economic scenarios with higher drying costs, in general, harvest was delayed until late harvest. Under the high drying cost scenarios only corn at 15 percent moisture is harvested at early harvest. Economic scenarios with lower drying costs show a corn price effect on when the optimal harvest occurs. Scenarios with higher corn prices harvest the corn crop with grain moisture levels of 15 and 20 percent at early harvest. In contrast, for scenarios with low corn prices, only corn crops at 15 percent moisture are harvested early.

This corn price effect reflects the tradeoff between drying costs and interest payments received. In the corn model the producer receives interest payments on the expected NRVC for the time period EH to LH. The optimal decision rule indicates with the higher corn price, the interest received from harvesting earlier is larger than the additional costs incurred by harvesting corn at 20 percent moisture and artificially drying to 15 percent moisture. With a lower corn price these interest payments do not cover the additional drying costs.

The above short discussion on the optimal decision rules supports the validity of the corn production decision model. In general, the production decision model behaves in accordance with microeconomic theory, in its response to changing output price, input costs and interest rate. A more thorough discussion is found in Mjelde.

Given that the major purpose of the model is to examine the relationship between climatic conditions and production practices in a dynamic framework, a discussion of the optimal decision rule by year is presented. The optimal decision path using historical climatic probabilities (last line in Table 8) is discussed first to give a reference point for the discussion of each individual yearly optimal path. The optimal fall decision is to not apply any fall nitrogen, reflecting the probability of a loss of nitrogen. Planting a full season hybrid in ESp at 32,000 plants per acre are the planting decisions. The amount of nitrogen applied and timing depends on the state of the process at each stage. No single optimal path when using historical probabilities can be described because of the stochastic nature of the climatic conditions.

Table 8 also presents the optimal path for each of the fourteen years, 1970-1983, under the base economic scenario given in Tables 6 and 7. The production decisions that vary between the years are the rate and timing of nitrogen application and the optimal harvest period (Table 8). Total effective nitrogen given in Table 8 differs from the amount applied for two reasons. First, winter precipitation affects the effective amount of fall applied nitrogen by the transition equations developed earlier. Low winter precipitation (good climatic conditions) result in a higher effective nitrogen level, whereas high precipitation (fair and poor climatic conditions) result in a lower effective nitrogen level than the application rate in pounds per acre. Second, because of the discrete nature of the nitrogen state variable, the effective and applied rates may differ. In the corn decision model, the discrete nitrogen state variable values differ from the decision alternatives on nitrogen application rates. The model places the decision process in the state variable value closest to the application rate.

The optimal decision paths in Table 8 are best examined in conjunction with Table 9, which gives the climatic condition categories for each stage within each year. Also included in Table 9 is the grain moisture state variable level for a full season hybrid planted in ESp. The optimal planting decisions under the base economic scenario are to plant a full season hybrid at 32,000 plants/acre in ESp regardless of the year. (It should be noted under different economic scenarios the hybrid planting decision varied.) The optimal harvesting decision is to harvest at EH if the corn is at either 15 or 20 percent moisture at EH. Harvest is delayed until LH for the grain moisture state variable values of 25, 30, and 35 percent moisture. Poor October climatic conditions do not affect the optimal decision path because the two years having poor October conditions, 1977 and 1983, are harvested early because of their low grain moisture percent at EH.

The nitrogen application rates and timing indicate that climatic conditions affect this production input. ESum is the stage in which the direct interaction between climatic conditions and applied nitrogen occurs. The result of this interaction is easily seen in Tables 8 and 9. In years with poor ESum climatic conditions (1970, 1972, 1973, 1977 and 1982), the effective nitrogen is either 133 or 200 pounds per acre depending on the specific year. The years with fair ES conditions (1978, 1979, and 1980) have either 200, 267 or 300 pounds per acre of effective nitrogen applied. For the years with good ES climatic conditions, the optimal level of effective nitrogen varies. For the years 1971, 1973, 1974, and 1976 the optimal effective nitrogen is quite high, either 233 or 267 pounds of nitrogen. The optimal effective nitrogen for 1981 is 133 pounds/acre and for 1983 is 100 pounds/acre.

The nitrogen application rates show that the climatic conditions in ES are not the only important stages in determining nitrogen application. It can be inferred from Tables 8 and 9 that at a minimum, MSum and LSum are stages which are also important in determining nitrogen application rates. Consider the years with poor, ESum climatic conditions. The years in which fair and/or poor climatic conditions occur at both the MSum and LSum stages, 200 pounds/acre of effective nitrogen is the optimal application rate. In years in which at least one of the two stages, MSum or LSum, had good climatic conditions, only 133 pounds/acre of effective nitrogen are applied. The importance of the MSum and LSum stages in determining nitrogen application rate is illustrated by examining 1970 and 1975. These two years have the same climatic conditions in the stages ESp, LSp, ESum. In these two years, the MSum and LSum stages climatic conditions vary. The different climatic conditions in the MSum and LSum stages cause the optimal effective nitrogen rate to vary from 200 pounds in 1970 to 133 pounds in 1975.

The years with fair ESum climatic conditions also show the effect of the MSum and LSum stages. The year 1980 has the highest amount of effective nitrogen applied. In 1980, poor climatic conditions occurred in both MSum and LSum stages. Of the years with fair ESum climatic conditions, 1979 has the lowest amount of nitrogen applied. In 1979, good climatic conditions occurred in both MSum and LSum. The third year with fair ESum climatic conditions is 1978. The effective nitrogen in 1979 is between the effective nitrogen applied in 1979 and 1980, reflecting the fact that the MSum has poor climatic conditions and LSum has good climatic conditions.

The years with good ESum climatic conditions show the same effect with the exception of two years, 1981 and 1983. Poor and fair climatic conditions occurred in MSum and LSum, respectively, in 1971. This year has the highest effective nitrogen (267 lbs./acre) of all the years with good early summer climatic conditions. The remaining years 1973, 1974, and 1976 have 233 pounds/acre of effective nitrogen as the optimal level.

Because 1983 had poor climatic conditions occurring in both ESp and LSp, 1983 is a unique year in the data set. By having poor conditions in both ESp and LSp, 1983 is affected by the field state variable restrictions in both of these stages. With the optimal decision to plant in ESp, no nitrogen application can occur other than in the fall. Winter precipitation in 1983 is in the fair category. Therefore, effective nitrogen is less than the fall applied nitrogen. The optimal path for 1983 reflects the following components in the corn model: (1) increase in yield given by planting in ESp over LSp, (2) the field state variable restrictions, (3) and the winter precipitation conditions. Even though 1983 had good ESum climatic conditions, the effects of the above variables keep the nitrogen application rate low.

With the two exceptions noted above, the following generalizations can be made from Tables 8 and 9. ESum climatic conditions appear to be the most important stage in determining nitrogen application rates. Years with poor climatic conditions occurring in ESum have the lowest nitrogen application rates. Years with fair or good climatic conditions in that period have higher nitrogen application rates. The stages MSum and LSum are also important in determining the optimal nitrogen application rates. Better conditions in these two stages result in a lower nitrogen level than years with poorer conditions.

The importance of MSum and LSum in determining nitrogen application rates is most likely because corn yield is highly dependent on these stages. Although no direct interaction between nitrogen and climatic conditions occur at these stages within the production function, these stages are important in determining final yield. By combining the nitrogen and climate state variables, these two stages are important in determining the final value of this combined nitrogen and climate state variable.

The fall decision on whether to apply nitrogen or not reflects the winter precipitation levels with the exception of 1983, discussed above. Only if the winter precipitation is in the good climatic condition did fall application of nitrogen occur. This reflects the fact that higher effective nitrogen over the amount applied is obtained in these years but not in all years with good winter precipitation did fall nitrogen application occur. The only explanation that can be given for this fact, is that the expected values between the various paths within the model are close.

The above discussion has centered around the base economic scenario's optimal paths given in Table 8 and provides an ex-post validation of the decision model with respect to climatic conditions. Mjelde presents addition optimal paths for different economic scenarios with respect to the fourteen years of climatic conditions.

CONCLUSIONS

A dynamic model of the corn production decision process is developed in this study. Kennedy in his excelelnt review of DP is pessimistic about the usefulness of DP models applied to farm planning in general. In contrast, Burt voices optimism " ... such applications will not be routine formulations and will require a major research effort, but DP is still the most promising analytical model for the conceptual problems included" (p.

391). The present study provides support for Burt's conjecture. With today's computer capacity and supercomputers on the horizon, analysis should move away from the static intrayear models to the more realistic, stochastic, dynamic analysis of intrayear crop production.

Ex-post model validation indicate that the DP decision model, in general, conforms to economic and production theory. The DP model is sensitive to varying input costs and output prices, and differing climatic conditions. Results from the model indicate that the generation of synthetic data from crop-growth simulation models is a valuable solution to data problems plaguing dynamic production analyses.

Footnotes

1) In the model the impact of effective nitrogen on yield is cumulative so that the timing of application has no impact except for winter leaching and denitrification. Swanson et al. find that this is a plausible assumption for Drummer soils which are assumed in this study. Moreover, as suggested by Hollinger and Hoeft, nitrogen is modeled to have an interaction effect with climate only in the early summer substage.

2) These three time periods are not disjoint. There is an overlap of corn drydown with the LS to EH transition. That is, a corn drydown function is also used in the transition of state variables from LS to EH.

3) The model uses a discrete approximation for some of the state variables to make the DP algorithm manageable. The procedure used to discretize the nitrogen, and combined nitrogen and climatic state variable is: (1) find the range of possible values, (2) divide this range into the appropriate number of equal length intervals, and (3) use the midpoint of each interval as the state variable value. The remaining state variables are not approximated.

4) A weighted averaging scheme is employed to aggregate the five planting dates into coefficients associated with the two planting stages, ESp and LSp.

Table 1. -- Stages and Decisions Alternatives Modeled in the Corn Production Decision Model

Stage (Production Period)	Management Decision	Critical Growth Stage
Fall previous harvest-March 31	Nitrogen Application 0,50,150,200,225, 267 lbs. N	Not Applicable
Early Spring(ESp) April 1 - May 15	Nitrogen Application 0,50,150,200,225 267 lbs. N	Germination and Emergence
	Hybrid Selection Full Season Medium Season Short Season	
	Plant Density 20,000 plants/acre 24,000 plants/acre 32,000 plants/acre	
Late Spring(LSp) May 16-June 10	Same as Early Spring	Germination,Emergence and Early Vegetative Growth
Early Summer(ESum) June 10-July 15	Nitrogen Application 0,50,150,200,225 267 lbs. N	Rapid Vegetative Growth and Development
Midsummer(MSum) July 15-July 31	Do Nothing	Silking Pollination and Early Grain Fill
Late Summer(LSum) Aug. 1-Sept. 30	Do Nothing	Grain Fill and Maturation
Early Harvest(EH) September 30	Harvest Corn Crop Delay Harvest	Corn Drydown
Late Harvest(LH) October 22	Harvest Corn Crop Do Not Harvest	Not Applicable

Table 2. -- State varibles Included in the Corn Production Model and the Associated Number of Possible Values of Each State Variable at Every Stage

	Stage							
State Variable[1]	Fall	Early Spring (ESp)	Late Spring (LSp)	Early Summer (ESum)	Mid Summer (MSum)	Late Summer (LSum)	Early Harvest (EH)	Late Harvest (LH)
Nitrogen (SNit)[1]	1	10	10	10	1	1	1	1
Climate (SClim)	1	1	3	9	1	1	1	1
Combined Nitrogen & Climate (SNC)	1	1	1	1	20	20	20	20
Plant (SPlnat)	1	1	10	19	19	19	19	19
Field (Field)	1	3	3	3	1	1	1	1
Grain Moisture (GM)	1	1	1	1	1	1	6	5
Oct. Climate (Oct)	1	1	1	1	1	1	1	3

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[1] See text for definition of the state variables.

[2] Abbreviations used to denote the state variables.

Table 3. -- Estimation Production Function Used in Developing the Corn Decision Model (5040 Observations)

Management Variable	Estimated Coefficient	Variable	Estimated Coefficient	Variable	Estimated Coefficient
Intercept	1.4482 (7.19)*	Var_2Dum_2	.48529 (4.77)*	Var_3Dum_5	--
Den_1	.33738 (15.14)*	Var_3Dum_2	.54084 (5.31)*	CI_1	1.0029 (15.76)*
Den_2	.40549 (18.20)*	Var_1Dum_3	.031840 (.31)	CI_2	.83707 (15.76)*
Den_3	.45695 (20.51)*	Var_2Dum_3	.19871 (1.95)*	CI_3	1.3780 (5.13)*
Den_4	.47739 (21.43)*	Var_3Dum_3	.25765 (2.53)*	CI_4	.49662 (28.26)*
Den_5	.49466 (22.20)*	Var_1Dum_4	-.13659 (-1.34)	CI_5	.43194 (13.57)*
Var_1Dum_1	.68402 (6.72)*	Var_2Dum_4	.040136 (.39)	N	.29494 (3.49)*
Var_2Dum_1	.83847 (8.24)*	Var_3Dum_4	.10052 (.99)	N^2	-.042063 (-5.36)*
Var_3Dum_1	.88580 (8.70)*	Var_1Dum_5	-.26325 (-24.93)*	$NxCI_3$	-.26276 (-1.83)*
Var_1Dum_2	.32179 (3.16)*	Var_2Dum_5	-.060763 (-5.75)*	$(NxCI_3)^2$ (5.27)*	.11825
$\bar{R}^2 = .85$					

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[1] Asymptotic t-ratios in parentheses for model 2 in Table 4.

*Indicates significantly different from zero, $\alpha = .10$.

Table 4. -- Calculated Yields Using the Estimated Production Function

	Yields in Bushel/Acre[1]			
Nitrogen lbs/Acre	1	100	150	267
Climatic Condition[2]				
Poor	55.8	91.6	93.5	95.5
Average	62.5	116.5	122.8	132.3
Good	67.3	138.7	149.9	168.0

[1] Full season variety planted on June 5 at a density of 32,000 plants per acre.

[2] Climatic conditions set at the mean value for each stage with the exception of the early summer stage. The early summer index value is set at the following values, poor - early summer at lowest value, average - early summer set at its mean and good - early summer set at its highest value.

Table 5. -- Weighted Average[1] Production Function Coefficients for Planting Density and Hybrid Planted for the Two Planting Periods (Stages) in the DP Decision Model

Coefficient	Early Spring	Late Spring
Density	.40133	.48021
Short Season Dummy	.33986	-.15357
Medium Season Dummy	.50194	.03149
Full Season Dummy	.55628	.09174

[1] Weighted according to scheme set forth in the text.

Table 6. -- Cost of Inputs and Field Operations Which are Held Constant Within the Corn Decision Model

Field Operation or Production Input	Cost $/Acre
Spread P_2O_5 - K_2O_5	1.08
Disc stalks, 18 1/2′	2.83
Field cultivate, 24′	2.69
Rotary hoe	.86
Row cultivate, 8 row, 30"	2.74
Disc and apply herbicide, 18 1/2′	3.45
Limestone	4.50
Plant, 8 row, 30"	3.48
Apply anhydrous ammonia, 30′	2.19
Combine, 8 row, 30"	9.61
Haul to market	.0257/bu.
Atrazine	14.22
P_2O_5	13.61
K_2O_5	4.20

Source: Guides for Custom Contract Farming Rates, by Royce A. Hinton, Oct. 1982. University of Illinois Valuing Farm Inputs Handbook Section 4, No. 4.

<u>USDA Agricultural Price Summary</u> was used to obtain cost of non-nitrogen fertilizer and herbicide, simple average of 1983, 1982, and 1981.

Table 7. -- Base Levels for the Variable Inputs, Corn Price, and Interest Rate Within the Corn Decision Model

Component	Base	Alternative
Input cost		
Fall nitrogen[1]	$.144/lb.	$.216/lb.
Spring nitrogen	.153/lb.	.2295/lb.
Seed costs[2]	68.33/bu.	102.50/bu.
Dry cost[3]	.0225/bu. point	.03375/bu. point
Interest rate	.1646	.05
Corn price	$2.83	$2.02/bu.

Source: USDA Agricultural Price Summary

Agricultural Finance Databook, Jan. 1984, Monthly Series Table 401.1 interest rate for other banks, non-real estate farm loans.

[1] Fall nitrogen is Oct. 15 price for North Central Fertilizer Region. Spring nitrogen is May 15 price.

[2] Seed price is April 15 corn hybrid price for Illinois.

[3] Dry cost base is from Farm Economics Facts and Opinions, Dept. of Ag. Econ., U. of I., Aug. 1, 1984, 84-10/Guide for Adjusting Custom Rate and Machine Rental Rates for 1984-1985 by Royce A. Hinton.

Table 8. -- Optimal Decision Path Using Each Year's Climatic Conditions: Corn Price = $2.83, Input Costs at Base Levels and Interest Rate = .1646

Year	Value	Fall	Plant	Side	Eff.	Date	Den.	Hybrid	Harvest[3]
1970	270.37	0	0	200	200	ESp	32	Full	EH
1971	297.98	225	0	0	267	ESp	32	Full	EH
1972	279.03	0	50	50	133	ESp	32	Full	LH
1973	301.34	0	0	225	233	ESp	32	Full	EH
1974	250.57	0	225	0	233	ESp	32	Full	LH
1975	252.00	0	50	50	133	ESp	32	Full	EH
1976	295.54	0	0	225	233	ESp	32	Full	LH
1977	270.37	0	0	200	200	ESp	32	Full	EH
1978	259.58	0	0	267	267	ESp	32	Full	EH
1979	305.36	0	0	200	200	ESp	32	Full	EH
1980	255.86	267	0	0	300	ESp	32	Full	EH
1981	278.26	50	0	50	133	ESp	32	Full	LH
1982	279.03	0	50	50	133	ESp	32	Full	LH
1983	138.79	150	0	0	100	ESp	32	Full	EH
Prior	259.82	0	V[4]	V	V	ESp	32	Full	V

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[1] Nitrogen application rates in the previous fall at planting and sidedressing. Eff. nitrogen is the level of nitrogen input into the production function. Eff. nitrogen may vary from applied nitrogen because of the discrete nature of the model and winter precipitation (see text).

[2] Optimal date of planting, early spring (ESp) or late spring (LSp) planting density in thousands and hybrid type, either a full, medium, or short season.

[3] Stage in which the optimal harvest occurs either early harvest (EH) or late harvest (LH).

[4] V means that the optimal level or decision varied, depending on the state of the system.

Table 9. -- Climatic Conditions and Grain Moisture Level at Early Harvest for a Full Season Hybrid Planted in Early Spring for the Years 1970-83.

Year	Fall	ESp	LSp	ESum	MSum	LSum	Oct	Moisture[2]
1970	G[3]	G	F	P	F	F	F	15
1971	G	F	F	G	P	F	G	20
1972	G	F	G	P	G	F	F	30
1973	P	P	F	G	F	F	G	15
1974	P	G	P	G	F	G	F	35
1975	F	G	F	P	G	P	G	20
1976	F	P	F	G	G	G	F	30
1977	G	G	G	P	F	P	P	15
1978	F	P	G	F	P	G	F	20
1979	F	F	F	F	G	G	F	20
1980	G	F	G	F	P	P	F	15
1981	G	P	G	G	P	G	F	30
1982	F	G	F	P	G	F	F	25
1983	F	P	P	G	F	P	P	15

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[1] Stages within the production model, previous fall (winter precipitation), early spring, late spring, early summer, midsummer, late summer and October, respectively.

[2] Grain moisture percent level at early harvest.

[3] Climate condition good (G), fair (F), or poor (P).

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